Exhibit E

Structural Integrity Associates, Inc.®

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Mechanism and Root Cause of L-1 Blade Failure
and
Assessment of Cycle Chemistry
at
Xcel's Comanche Unit 3

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Executive Summary

Following the L-1 blade failure at Xcel's Comanche Unit 3 in January 2020, Structural Integrity Associates (SI) was requested to conduct an assessment to identify the mechanism, the most probable root cause and the contributing factors of the failure and damage. As the failure was initially considered to be cycle chemistry influenced Xcel also requested specific and general reviews of the cycle chemistry treatment and controls. The work was entirely conducted during March and April 2020 in SI offices in the UK and US because a plant visit could not be made due to the serious worldwide Corona Virus pandemic. SI requested and received hundreds of related documents from [redacted] Also, seven teleconferences were arranged and chaired by [redacted] to review the assessments as they developed with a broad range of Comanche and Xcel staff.

SI used a deterministic assessment approach to identify the mechanism of failure, the possible causes and the most probable root cause. The mechanism had been identified by Xcel as pit induced stress corrosion cracking (SCC). This was confirmed by SI to have initiated at the blade/snubber interface where there was a concentration of aligned pits. The mechanism was broken down into seven sequential steps or mechanism factors which had to line up at the same location on a blade surface for the mechanism to reach failure. These included: nucleation of concentrated condensate droplets from superheated steam as it expands across the saturation line; formation of concentrated liquid films on the L-1 blade surface; formation of deposits on the blade surface; oxygenated moisture formation during non-protected shutdowns; pit nucleation and growth; initiation of micro-cracks and finally SCC. The most probable root cause of the failure situation at Comanche, as for any mechanism of failure, must relate to the individual parts/factors of the mechanism of failure and needs to be at the most basic level which allows all the seven factors to take place. The formation of deposits and liquid films were focused by the snubbers. The presence of oxygenated moisture on blade surfaces during unprotected, long (> 3 days) shutdowns, after repetitive cycles of operation and shutdown, led to the formation of pits which provided the initiation sites for the micro-cracks and SCC. At Comanche, it is clear that without the pits there would not have been micro-cracking, cracking and failure so the presence of moisture during shutdown became the critical most probable root cause step in the overall process of the failure.

SI reviewed the cycle chemistry at Comanche and found that the overall chemistry has been poorly managed since COD in 2010. Seven Repeat Cycle Chemistry Situations (RCCS) were identified with some of these having direct influence on the seven mechanism factors of the L-1 blade failure. The predominant one, and the most probable root cause of the blade failure, is the lack of any chemistry shutdown protection using dehumidified air (DHA) for the steam turbine. Others of major importance in the mechanism include: chemists/operators ignoring alarm and shutdown limits and maintaining operation during contamination events; not using optimum chemistry treatments (OT); and unreliable chemistry instrumentation. The information reviewed by SI throughout the investigation suggests that the condenser contaminant event of March 2012 initiated the mechanism by contaminating the plant's internal surfaces which were not cleaned after the event. The operating practices were seriously deficient during this time: the chemistry alarm system was either not working, turned off or ignored, and most importantly the unit should have been shut down in accordance with any international shutdown guidelines. Deposition occurred preferentially at and near the snubber, leading to pitting in oxygenated moisture during multiple non-protective shutdowns between 2012 and 2019. Other possible contaminant events were investigated in detail and although there has not been similar contamination as the March 2012 condenser leak, there has been repetitive exceedances of sodium contamination in the main steam (MS) and hot reheat (HRH).

SI reviewed the seven RCCS and has provided 8 Action Plan outlines so that Xcel/Comanche can address them as expeditiously as possible. This will prevent further cycle chemistry influenced failures and damage, and put the plant on the path to worldclass performance. Discussion focused during the seven teleconferences with the Xcel technical and management staffs on the following areas of cycle chemistry which need improvement: monitoring feedwater corrosion products; assessing deposits in boiler waterwalls; establishing shutdown protection; using the latest chemistry treatments (OT); addressing and controlling air in-leakage and high condensate oxygen levels; developing a Comanche Chemistry Manual and operating with guidelines representing the latest international standards.

Summary of Management Actions. Overall, the following areas appear to be the priorities for the Xcel management to address:

i) Development of shutdown/layup procedures and techniques to provide chemistry protection to the boiler, reheater, feedwater heaters and steam turbine.
ii) Move the Chemistry at Comanche to full Oxygenated Treatment (OT).
iii) The operating chemistry limits should be in alignment with the latest international guidance (SI has provided Table 4).
iv) Incorporate all the chemistry activities into the development of a Comanche Chemistry Manual (SI has provided Table 5 as outline).
v) Upgrade operational practices linked to upgraded cycle chemistry controls. These include the use of auxiliary steam, by-passing the condensate polishers, and attemperation.
vi) Develop procedures and protocols to measure total iron around the cycle using the IAPWS Technical Guidance Document as base.
vii) Upgrade the whole cycle chemistry instrumentation system to be a major resource for the Comanche Unit. This will involve purchasing some new unique instruments (not shared/sequenced), more frequent calibration/maintenance, and ensuring the instruments work during startups.
viii) Training of operators in the upgraded chemistry procedures in relation to failure mechanisms that can occur in supercritical plant.
ix) Consider an early boiler waterwall chemical clean to avoid future boiler tube failures (BTF).
x) Investigate/inspect the internal surfaces of the reheater to check for signs of pitting.
xi) Consider an inspection of the repaired LP steam turbine after about one year with a concentration on the areas around the snubber.

1.0 Background on Plant Equipment and Relevant Experience for Current Assessments

1.0 Introduction

Xcel Energy's Comanche Unit 3 which is located in Pueblo, Colorado experienced an L-1 blade failure in the phase transition zone (PTZ) of the low pressure (LP) steam turbine in January 2020. The blades are manufactured in a 17-4PH (precipitation hardened) stainless steel.

Xcel requested assistance from Structural Integrity Associates (SI) in identifying the mechanism, the most probable root cause and the contributing factors of the failure and damage. Because the mechanism had been identified very quickly as stress corrosion cracking, Xcel also requested that specific and general reviews of the cycle chemistry treatment and controls needed to be included in the overall investigation.

Detailed assessments were undertaken by SI in March and April 2020 to confirm the mechanism of failure and to identify the most probable root cause and associated factors influenced by the cycle chemistry. SI prepared a detailed listing of the information that would be required. Originally the work was proposed to include a plant visit by the SI Team, but this was precluded by the travel restrictions imposed by the worldwide Corona Virus situation. Thus, the investigative work was conducted at SI offices in the UK and US by review of documents and information provided by [redacted] and through seven teleconferences organized and chaired by [redacted], (Director of Fleet Engineering). These teleconferences involved Xcel and Comanche management, chemistry and operations staff.

The report contains sections on:

- Section 1. Introduction to the failure and the methodology of assessment. Major Comanche equipment and early inspection of the steam turbine in 2011 are included.
- Section 2. Failure mechanism including metallurgical analysis and NDE inspections.
- Section 3. Detailed cycle chemistry assessment.
- Section 4. Development of the mechanism and root cause understanding of the L-1 blade failure.
- Section 5. Action Plan outlines to address the cycle chemistry deficiencies.

1.1 Major Equipment and Demographics

The major equipment at Comanche Unit 3 includes:

- Boiler. Alstom. Supercritical.
  - Main steam (MS) conditions: 1050°F / 3600 psi
  - Hot Reheat (HRH) steam conditions: 1100°F / 720 psi
  - Economizer Inlet: 580°F / 4,440 psi
  - Waterwalls, T12 and T23 tubing

- Economizers, SA 210C tubing
- Superheaters, T91 and T92 tubing
- Reheaters, T12, T22, T92 and S304H
- 17 BTF had occurred up to 2020. Review by SI indicates that none were cycle chemistry influenced.

• Steam Turbine. MHI. HP/IP combined in same case with two double flow low pressure (DFLP) turbine rotor and cases.
• Condenser. GEA. SeaCure tubing. Cooling tower operated between 13 - 14 times cycles of concentration. Cooling water contains ~10 ppm chloride and ~26 ppm sulfate.
• Air-cooled Condenser (ACC). GEA and downstream deaerator (DA). Carbon steel heat exchangers with aluminum outer coating.
• Feedwater system.
  - LP heaters (1A & B, 2A & B, 3 and 4)
  - HP heaters (6A & B, 7A & B, 8A & B)
  - All feedwater heaters are tubed in 304 stainless
  - LP heater shells are SA 387 11-2 (carbon steel)
  - HP heater shells are SA 516-Gr70 (carbon steel)
• COD was July 2010. Operating hours to L-1 blade failure were 76,201 hours.

1.2 Early Steam Turbine Inspections

MHI conducted the Turbine Warranty Inspection between 12th September and 9th December 2011. With regards to the DFLP blading they commented that it was in "good condition requiring no action". As far as SI could discern there were no observations of deposits or flow patterns on the LP blades. But a report on Steam Path Appraisal by D. Brandon in September 2011 indicates that deposits had caused losses representing 4,644 kW (48% of total losses) with most in the LP. Unfortunately, there were no photographs or analyses of any deposits included in this report, or any indications of specific locations.

Although the MHI and Brandon photographs provided by Xcel staff of the L-1 blade row in 2011 showed evidence of liquid film flows concentrated around the snubbers, there were no indications of any pitting on the blades. Analysis of deposits (no details of location) on the L-1 rotating blade at that time indicated the presence of sodium (6%), chloride (2 %), iron (6%) and copper (13%). Deposits on the stationary row (again no location details) showed the same approximate composition as well as aluminum (2%).

In summary, the L-1 blades before the major condenser leak in 2012 did not have any visible deposits or pits but did show some obvious liquid film flow markings around the snubbers. Based on the information provided to SI no other inspections of the LP turbine were performed prior to the January 2020 failure event.

2. Failure Mechanism

2.1 Metallurgical Analyses

The metallurgical examination by the Xcel metallurgist ([redacted] 31st January 2020) of the failed L-1 blade (material: 17-4PH) clearly showed that the mechanism of failure was stress-corrosion cracking (SCC) initiated at pits on the top side of the mid-span snubber (suction side of the blade) near the blade leading edge. This mechanism is referred to throughout this report as "Pit-Induced SCC". Final failure occurred by high cycle fatigue (HCF). It is also clearly evident that the blade surfaces are pitted but no quantification by Xcel was undertaken. The adjacent blade showed pitting and crack initiation at the same blade/snubber location along a line parallel to the snubber/blade surface. Chemical analysis on fracture surfaces indicated sodium, sulfur and chloride as well as copper and aluminum. In separate analyses the same chemicals were found in deposits on blade surfaces.

Further metallurgical analyses were conducted by SI on the same Xcel samples following the initial mechanism and root cause work conducted by SI which allowed highlighting of some of the important aspects of phase transition zone (PTZ) cracking, which is summarized in Section 4 of this report. The SI metallurgical analysis will be provided as a separate report memo. The mechanism was confirmed to be pit-induced SCC initiated from pits aligned along the blade surface parallel to the blade/snubber interface. Detailed metallography of this surface also showed micro-cracks initiated from the jagged bottoms of pits. SI was also provided with two blades which had been shot blasted for the NDE inspections reported in Section 2.2. As also reported in Section 2.2 these blades showed extensive pitting in a line parallel to the snubber/blade interface. Figure 1 shows this damage. Other pits were visible at other regions of the blades near the platform, and on both the pressure and non-pressure surfaces.

In summary, the metallurgical analyses confirm the mechanism as pit-induced SCC and a high density of pits in a location parallel to the snubber/blade interface. This is most significant in this deterministic mechanism and root cause analysis conducted by SI.

Figure 1. Showing a line of concentrated pitting parallel to the snubber.

2.2 NDE and Inspection Observations

Inspection by 3 Angles (29th January 2020) of all the L-1 blades after shot blasting indicated that "pitting was found on all blades, mostly around the snubbers". This is a most important observation which indicates that the LP turbine was not protected during the multiple long (> 3 day) shutdown periods. 1 – 1.5 in crack-like indications were also observed on the discharge side of all snubbers, with cracks on all blades on the admission side towards the blade roots. Pitting (and erosion) was also observed on all L-0 blades as well as foreign object damage. The pitting on the L-0 blades supports the lack of any shutdown protection. It has not been possible to create a quantitative geography of pitting but the observations in this section and in Section 2.1 are thought to clearly illustrate the susceptibility on the blade surface parallel and close to the snubber.

Additional photographs and data provided information on pitting around the snubber. There were indications of cracks associated with pitting above the platform locations on the pressure side of the blades. These also show increased levels of deposits especially associated with the same snubber/blade region. Analyses of deposits on the L-1 blades by Xcel (again locations not known) show up to 0.5% Cl, up to 5% Cu, and up to 11% Al.

In summary in terms of the current deterministic analysis, the important observations from the metallurgical and inspection analyses are that there is concentration of deposits, pitting, micro-cracking and SCC all in the same location along the snubber/blade interface. It must be noted that pits are observed at other blade locations indicating the lack of any shutdown protection for the complete LP turbine, but to date none of these have been metallurgically examined to determine if there is any micro-cracking. But post-failure NDE inspection revealed surface cracks at locations of pitting near the blade platforms.

3. Cycle Chemistry Assessment of Comanche 3

As Section 2 has indicated that the L-1 blade failure and damage is cycle chemistry influenced, it became necessary in this SI deterministic analysis for mechanism and root cause that a detailed assessment was required of the cycle chemistry employed at Comanche. This section contains the results of that analysis.

This assessment followed the usual cycle chemistry evaluation procedures that have been conducted by SI at over 220 plants worldwide. These assessments have included numerous mechanism and root cause analyses for major plant equipment including steam turbine Phase Transition Zone (PTZ) damage and failure. The emphasis is always to first develop an understanding of how the chemistry on the unit works for more than 90% of the time (defined as "normal" chemistry), and then it includes a review of the chemistry associated with abnormal situations, which in the case of Comanche is to identify deficiencies and features that could be related to the blade failure, blade deposits, pitting and cracking. But in this section, SI has not only concentrated on the chemistry aspects relating directly to the blade failure, but also to the overall cycle chemistry treatments and controls used at Comanche because it very quickly became obvious that the chemistry was below optimum for a supercritical unit operating on all-volatile treatment (AVT(O)) or oxygenated treatment (OT).

3.1 Normal Comanche Operating Chemistry (90% of Time)

3.1.1 All-volatile Treatment (AVT) and Oxygenated Treatment (OT)

Comanche 3 is a supercritical unit which was designed to operate on OT in the feedwater to minimize feedwater corrosion (and FAC) of the carbon steel components and feedwater corrosion product transfer (magnetite and hematite) to the boiler. It was reported by Xcel that prior to commercial operation in July 2010 Shaw operated the boiler "under poor chemistry conditions": these were not detailed. Following this in the first five years of operation up to the 2015 chemical cleaning (Section 3.1.7), the unit was operated on all-volatile treatment (oxidizing), AVT(O), with high levels of air in-leakage. After the clean the operators were trained on OT (August 2016) but this treatment only operated for about five months because of a failure of the injection equipment. A newly designed system with oxygen supply from a low pressure liquid oxygen bulk tank was put into service in May 2018. After numerous teething problems OT was finally operated from 2019. This means that for the first nine years of Comanche 3 operation the cycle chemistry was not optimum: the feedwater corrosion product transport at the Economizer Inlet (EI) could not reach the achievable levels for supercritical units which would lead to elevated waterwall internal deposits and the need to chemical clean the boiler on a shorter time period. These features were experienced (see Sections 3.1.5 and 3.1.7). Also, the optimum internationally accepted operation (IAPWS) for OT involves: one injection point for oxygen downstream of the condensate polishing system and operation with the vents on the feedwater heaters (HP and LP) and deaerator (DA) closed. (IAPWS is the International Association for the Properties of Water and Steam). On Comanche 3 the chemists indicated that a second oxygen injection point is used at the suction of the BFPs which would make oxygen control very difficult. It appears from the venting schedule that only the DA and HP heater vents have been vented. It has been found internationally that it is difficult to operate with LP heater vents continuously closed if the plant experiences high air in-leakage as at Comanche.

3.1.2 Chemistry Manual, Guidelines for Operation and Shutdown

There is no Chemistry Manual for Comanche 3. In terms of chemistry guidelines for Comanche 3, Xcel provided the MHI "Steam Purity Recommendations for Comanche". Although these are dated 2008, a quick review by SI indicated that they were out of date by at least 20 years. Xcel also provided a set of "Comanche 3 Chemistry Guidelines" dated April 2011 as well as two versions of a set of Normal Guideline Values at cycle locations (not dated). These guideline values were reasonably in synchronization with the latest international standards (IAPWS) with the exception that some of the parameter normal values are too tight which usually results in an increased number of (nuisance) alarms and operators ignoring alarms and/or turning them off. As part of the overall assessment SI has supplied a set of normal guideline values for Comanche Unit 3 (Table 4) which have been customized from the latest international guidance. Table 5 provides suggestions for a Comanche Chemistry Manual.

The 2011 guidelines, referred to as "Comanche Guidelines" in later sections of this report, provide responses to excursions of the chemistry parameters and also a number of unit shutdown limits. In summary, these are:

- At the Condensate Pump Discharge (CPD) the Comanche response for a serious condenser leak is to shut off the condensate pumps, drain the water boxes and run the condensate cooling on only the ACC.
- At the Condensate Polisher Outlet (CPO), immediate shutdown is required when CACE > 1 μS/cm or sodium > 50 ppb (μg/kg). If elevated sodium relates to condenser leakage, then the same response is given as for the CPD in regards to moving the condensate cooling to the ACC.
- At the Economizer Inlet (EI), immediate shutdown is required when CACE > 1 μS/cm.
- In Main Steam (MS) or Hot Reheat (HRH), immediate shutdown is required when CACE > 1 μS/cm or sodium > 20 ppb (μg/kg).

These most important unit shutdown limits are not in agreement with the international standards (IAPWS) which indicate that unit shutdown must have a time requirement:

- CACE in the feedwater exceeds 2 μS/cm for two minutes and is increasing.
- Sodium level at the CPO exceeds 20 μg/kg (ppb) in the same time period and doesn't show any decreasing trend.

Clearly there needs to be a consistent up-to-date set of cycle chemistry guidelines and limits for Comanche 3, which are in agreement with the latest international (IAPWS) standards. These should represent the materials in the feedwater, the chemical addition locations and the uniqueness of a supercritical unit having both an ACC and wet condenser with cooling tower. This information should be included in a comprehensive Plant Chemistry Manual. In order to do this, the IAPWS Technical Guidance Documents (TGD) for Volatile Treatments (2015), Corrosion Product Sampling (2013), and Steam Purity (2013) can be used as these represent the international standards for fossil plant cycle chemistry. These documents are freely downloadable from the IAPWS website (www.IAPWS.org).

3.1.3 Cycle Chemistry Instrumentation

P&IDs and a Shaw document (Steam/Water Sampling System) dated 13th April 2007 indicate that steam and water sampling points were designed with the following chemistry instruments:

- Makeup to condenser (MU) or Deaerator (DA): conductivity, oxygen (shared/sequenced with CPD), silica, sodium and grab sample
- Condensate Pump Discharge (CPD): conductivity, DCACE, oxygen (shared/sequenced with MU), pH, sodium and grab sample
- Condensate Polisher, AB and BC vessel outlets and common outlet (CPO): conductivity, CACE, silica (shared/sequenced with EI, MS, HRH), sodium (shared/sequenced with AB, BC), sodium for CPO (shared/sequenced with EI, MS and HRH) and grab sample
- Condensate after chemical feed: conductivity
- Economizer Inlet (EI): conductivity, CACE, oxygen, pH, silica (shared/sequenced with CPO and MS), sodium (shared/sequenced with CPO, MS and HRH), and grab sample
- Main Steam (MS): conductivity, CACE, silica (shared/sequenced with CPO, EI and HRH), sodium (shared/sequenced with CPO, EI and HRH), and grab sample
- Hot Reheat (HRH): conductivity, CACE, silica (shared/sequenced with CPO, EI and MS), and sodium (shared/sequenced with CPO, EI and MS).

The plant was designed with additional sampling locations at the deaerator inlet and outlet (DAI and DAO), and on HP Heaters 6A and B drain lines. Table 4.1 in the Shaw document provides details of the chemistry instruments designed at each location which, if all were unique (not shared/sequenced), and had been employed from 2010 to 2020, would be in approximate agreement with the international fundamental level of instrumentation for a supercritical unit. But as indicated in the bullets above the number of shared/sequenced instruments is high for a supercritical plant. In relation to the L-1 blade failure it should be particularly noted that oxygen is shared/sequenced at MU and CPD, and sodium is shared/sequenced at CPO, EI, MS and HRH. The sodium design is particularly bad as this is a key measurement to provide protection to the PTZ of the steam turbine.

Also, review of the extensive on-line data for 2015 – 2019, examples of the operators' DCS chemistry screen, and the chemistry situation during the condenser leak of March 2012 suggests that not all the instruments are calibrated and maintained on a regular basis, are not all reliable, are not all audibly alarmed in the control room for the operators, and that the plant has relied heavily on grab samples taken every four hours. There are also numerous examples when the key instruments (sodium at EI, MS and HRH) are not recording data for startup periods, and are out of service for long periods of time (six months). Examples are provided in Section 3.2. The international standards (IAPWS) clearly indicate that a supercritical unit should have 100% of the fundamental level of continuous cycle chemistry instruments, not shared or sequenced, which are maintained and calibrated on a regular basis, and have audible alarms in the control room which are directly customized from the latest international guideline values. These instruments can then be relied on so that the operators can take action. Grab samples should be minimized with the manhours being more usefully used for the calibration and maintenance activities. Grab samples should never be used to control supercritical units.

It has also been noted during the assessment that there is no instrumentation on the supply of auxiliary steam from Units 1 and 2. Any steam supply should be sampled and monitored in the future even if a new source of steam is introduced for Comanche 3.

In summary, the importance of the cycle chemistry instrumentation, action and shutdown levels at Comanche have been minimized by operations and chemistry staff from early operation. The operators could not rely on them and have simply ignored alarms and most importantly action levels and unit shut down situations. Xcel will need to make some drastic improvements in this area to develop procedures to make the continuous cycle chemistry instruments a major resource for the plant and operators by purchasing/installing a number of upgraded key instruments (sodium and CACE in MS and HRH) which will operate during startups with correct flow requirements, and by introducing a regular reliable maintenance and calibration program. These need to become an important part of a Comanche Chemistry Manual.

3.1.4 Normal Operating Values

This section provides information on the "normal" chemistry on Comanche Unit 3. The cycle chemistry information presented in this section of the report was gathered from documents and drawings provided by Xcel, and from teleconferences which included two Comanche plant chemists.

To develop an understanding of the cycle chemistry and control on Comanche Unit 3 a detailed review of three monthly periods (June 2015, June 2019 and September 2019) was undertaken. These periods were chosen as it appeared from startup/shutdown data and the plant event log that the unit operated under reasonably constant conditions without any major events in these periods. June 2015 represented a period when the unit operated under AVT(O) and June 2019 represented an OT period. June 2019 provided validation of some of the values. From these sources the parameter values for more than 90% of the time were developed as typical for Comanche Unit 3 outside of startup periods and the possible contamination periods discussed in Section 3.2; these are referenced as such throughout this report section as XX (YY) where XX is for June 2015 and YY is for September 2019. Another period just before the L-1 blade failure (January 2020) was reviewed to confirm the June 2019 values and also to assess whether there were any chemistry excursions just before failure.

It should first be noted that the chemistry values in this section do not represent all the values that were available. SI has only included those parameters and values which are also of major interest and concern to the current assessment of mechanism and root cause of the L-1 blade failure.

a) Condensate

Ammonia and oxygen are added downstream of the condensate polishing plant. When the unit operates on OT a second injection of oxygen is accomplished at the Deaerator Outlet (BFP suction). There are 3 x 50% condensate polishing vessels with 300 ft^3 of resin in a 2:1 cation:anion ratio and operating in the ammonium form operation (AFO).

The Comanche Guideline limits at the condensate pump discharge (CPD) for oxygen is < 10 ppb for AVT and < 200 ppb for OT (Note: this OT limit is too high for the CPD), for sodium is < 2 ppb, for pH is 9.6 – 9.8 and for DCACE is < 0.15 µS/cm. The values for more than 90% of the time from June 2015 (September 2019) were: for oxygen 50 – 200 ppb (<20 ppb); for sodium 3 – 5 ppb (< 0.4 ppb); for pH ~9.3 (~9.6) and for DCACE out of service in 2015 (< 0.1 µS/cm). The values for 2020 are in agreement with the 2019 data.

The Comanche Guideline limits at the condensate polisher outlet (CPO) for sodium is < 1 ppb and for CACE is < 0.15 µS/cm. The values for more than 90% of the time from June 2015 (September 2019) were: for sodium ~ 1 ppb (< 1 ppb) and for CACE out of service in 2015 (< 0.1 µS/cm). The values for 2020 are in agreement with the 2019 data.

As well as these normal CPO values, it was noted that for sodium in the June 2015 timeframe the levels were often elevated into the ~20 ppb range on multiple days always around 11:00 pm and lasting sometimes to 4:00 am (for example on the following June dates: 8th, 10th, 11th, 12th, 19th, 20th, 26th, 28th and 29th). The same situation was observed for the EI, MS and HRH indicating that this was not an instrument deficiency, although Xcel chemistry staff indicated instrument problems relating to a solenoid situation and that all four sample streams are connected to the same analyzer.

It is also important to note that sometimes the CPP is by-passed by manual valve operation because of temperature constraints on the resin. Also, operation of polishers in the AFO mandates that shutdown protection is provided to reheaters to prevent pitting BTF in the long term. (**Note: this is outside current scope but SI's vast experience indicates that RH pitting and failure under these conditions is very probable in the future unless shutdown protection is provided to the RH).

The Comanche Guidelines limits includes a limit for conductivity after chemical feed of 8.5 – 9.5 µS/cm (pH ~9.6).

Air in-leakage (AIL) has been a serious problem for the Comanche unit throughout the time period 2015 – 2019; sometimes oxygen at the CPD was in the hundreds of ppb (for example on the following dates in 2019: September 7th, 9th, 16th and 17th). SI reviewed three AIL Inspection Reports (AES, May 2011, August 2014 and December 2017). The first inspection (2011) included the ACC and identified 16 locations of AIL with major leakage at BFP shaft seals and condenser expansion joints. The second inspection (2014) included the ACC (no leakage) and identified 11 locations of AIL with major leakage at BFP flange, SJAE valve and Gland Steam Exhauster. The third inspection did not include the ACC and identified major leakage at the LP turbine rupture discs and at the BFP flanges.

These high AIL levels would have resulted in serious performance losses for the unit. From the cycle chemistry aspect this would have made both AVT(O) or OT difficult to control and may be the reason that LP heater vents have not been closed during operation. As discussed in Section 4 this is not likely to be a problem or part of the SCC mechanism in the L-1 blade failure development. But the poor AIL situation at Comanche is a Repeat Cycle Chemistry Situation (RCCS) (Sections 3.3.2 and 5.1E) that needs to be addressed. There is an IAPWS TGD for AIL which can be the basis for an AIL section in the Comanche Chemistry Manual.

b) Feedwater.

The Comanche Guideline limits at the economizer inlet (EI) for pH is 9.6 – 9.8, for oxygen is < 10 ppb for AVT and < 200 ppb for OT, for sodium is < 1 ppb and for CACE is < 0.15 µS/cm. The values for more than 90% of the time at the EI from June 2015 (September 2019) were: for pH ~9.4 (~9.6); for CACE < 0.1 µS/cm (< 0.1 µS/cm); for sodium 3 – 4 ppb (0.3 – 0.5 ppb) and for oxygen 2 – 6 ppb (70 – 100 ppb). The values for 2020 are in agreement with the 2019 data.

This pH range is not consistently high enough to provide two-phase FAC protection especially at the ACC tube entries (see the Dooley – Aspden relationship). As on other international supercritical units with ACC, this is probably a contributing aspect of waterwall internal deposits and the requirement for frequent chemical cleans (Section 3.1.7).

As well as these normal EI values, it was noted that for sodium in the June 2015 timeframe that the levels were often elevated into the 10 - 20 ppb range on multiple days in the same timeframe as the elevations at the CPD (for example on the following June dates: 11th, 12th, 19th 21st, 22nd, 23rd, 24th and 29th) (Note: discussion on this same feature under condensate).

c) Steam.

Steam on Comanche 3 is monitored at two locations: main steam (MS) and hot reheat steam (HRH). The Comanche Guideline limits at both locations for sodium is < 1 ppb and for CACE is < 0.15 µS/cm. The values for more than 90% of the time at the MS and HRH from June 2015 (September 2019) were:

for sodium < 1 ppb (0.2 – 0.4 ppb) and for CACE < 0.1 µS/cm (0.2 – 0.4 µS/cm). The values for 2020 are in agreement with the 2019 data.

As well as these normal MS and HRH values, it was noted that for sodium in the June 2015 timeframe that the levels were often elevated into the 10 - 20 ppb range on multiple days in the same timeframe as the elevations at the CPD and EI (for example on the following June dates it was elevated in both MS and HRH: 2nd, 8th, 10th, 11th, 13th – 15th, 19th, 20th, 24th and 29th). (Note: discussion on this same feature under condensate).

3.1.5 Total Iron Measurement

For supercritical units the total iron values are a critical measurement which provides the key indicator that the chemistry (particularly OT) is optimized. This is most important for single- and two-phase FAC in the feedwater. There is not thought to be an involvement or influence with regards to the L-1 blade failure other than needing the cycle chemistry control to be excellent.

Some iron measurements were available for review (Spreadsheet of Results from 2010 to December 2019, and a [redacted] summary, 2016). The procedure at Comanche involves integrated sampling at the EI using flow through a 0.45 µm filter paper. Typically, two to four days of sampling collects 500 – 2,500 liters and this includes unit changes of load and trips. Historically up to about December 2017 the iron results reported were < 0.5 µg/L (ppb), then up to about December 2018 the values were 1 – 3 µg/L (ppb). Results at the HP Heater 6 drain lines were between ~2 and 5+ µg/L (ppb). These procedures and results are not in line with the international standard for monitoring total iron, so the low results clearly do not represent the corrosion processes within the feedwater system, and do not relate to the need for frequent chemical cleans (as reported in section 3.1.7). Therefore, the iron results cannot be used to assess whether the cycle chemistry on Comanche Unit 3 has been optimized or not. The plant needs to adopt the procedures in the IAPWS Corrosion Product Technical Guidance Document (the TGD is freely available on the IAPWS web site), so that the chemistry at Comanche Unit 3 can be directly compared with the large number of other supercritical units worldwide that SI has assessed. Consistent and achievable total iron levels using the internationally accepted procedures for supercritical units operating with optimum OT are: at the EI < 1 ppb, condensate downstream of the ACC and after a filter < 5 ppb.

3.1.6 Chemistry Aspects of Unit Shutdown and Shutdown Protection

The document on Shutdown Operating Procedures for Comanche 3 defines hot, cold and warm starts as:

- Cold Start. Boiler separator metal temperature < 212°F and boiler pressure is 0 psi (typically shutdown for > 36 hours)
- Warm Start. Boiler separator metal temperature > 212°F and boiler pressure is < 400 psi (typically shutdown for < 36 hours)
- Hot Start. Boiler separator metal temperature > 600°F and main steam pressure is > 1200 psi (typically shutdown for < 36 hours)

The unit shutdown procedure document provided by Xcel, and the P&IDs indicate locations for nitrogen blanketing of the boiler and feedwater heaters. But plant chemistry staff indicated that this has not been used since 2012. Most importantly in regard to the L-1 blade failure, there have been no facilities for providing dehumidified air (DHA) to the LP steam turbine for shutdowns.

The major activity in a plant to prevent pitting on steam turbine surfaces in the Phase Transition Zone (see IAPWS Steam Purity TGD) involves applying DHA for shutdown periods of longer than 3 days. An MHI document (untitled and undated) on storage and shutdown was provided to SI; this has a table of techniques which includes "Forced Ventilation Method with Dry Air" (DHA) for steam paths. In a 28th August 2006 e-mail [redacted] asked a general question on whether DHA should be considered for Comanche 3 as EPRI (Dooley) at this time was advising that LP turbines (both new and existing) should be supplied with DHA systems to prevent pitting as the initiator of PTZ cracking. In a response e-mail (29th August 2006) [redacted] (turbine group in the NSP region of Xcel) indicated that he hadn't heard of DHA and thought it would be expensive to install and maintain. Overall DHA was not installed on the Comanche Unit 3.

In SI's opinion based on investigating numerous PTZ blade failures, pits are always the initiating centers for stress corrosion cracking (the failure mechanism at Comanche 3) and corrosion fatigue (the other most common PTZ failure mechanism). This 3-day period is generally regarded as the time for the PTZ surfaces to reach ambient, but could be shorter or longer depending on the actual turbine, and operators are always advised to discuss this period with the manufacturer. To illustrate the situation at Comanche, the number and extent of shutdown periods equal to, or greater than, three days from 2012 to 2019 was derived from the "Unit 3 Shutdown and Trips Log" provided by Xcel:

Table 1. Number and Extent of Shutdowns of more than Three Days

Year	Total Starts/yr	Outages (3 days or more)	Days Unprotected
2012.	19	3	55
2013	14	4	54
2014	14	8	91
2015	5	1	79
2016	9	4	38
2017	10	3	52
2018	10	6	28
2019	8	6	49

It was noted during this derivation that annual outages are also included, but most of the shutdown periods were due to BTF and their repair. The table illustrates that over the years since the major condenser leaks in 2012 there have been many long unprotected periods of shutdown. So, particularly in light of the chemistry history at Comanche 3, it is not surprising that the PTZ blade surfaces are pitted. A more detailed description of the processes is included in Section 4 as this is the major step in the development of passivity breakdown, pitting, microcracking from pits, and crack propagation (SCC).

It is also noted by SI that as well as Unit 3 at Comanche not having DHA for shutdown periods of more than three days, Xcel should investigate whether any other systems could add to the shutdown moisture in the condenser exhaust and around the LP turbine. Such systems could be deaerator drain, gland seal steam and hot well steam sparger.

3.1.7 Waterwall Deposits and Chemical Cleaning

The cycle chemistry on supercritical units is designed to minimize deposition on the internal waterwall surfaces as this influences a number of BTF mechanisms. OT was introduced into the US in 1991 (Dooley) as a replacement for AVT with the primary purpose to minimize both the transport of feedwater corrosion products and their deposition on internal waterwall surfaces. Prior to the introduction, supercritical units typically had to chemically clean frequently (every 2 – 5 years). SI continues to provide guidance on the application of developing the optimum OT for supercritical units worldwide (recently in Malaysia, India, China and Turkey) to minimize these deposits, and can assist Xcel if requested.

Comanche 3 was pre-operationally cleaned (citric acid). The plant has had a program of waterwall tube removal and analysis for internal waterwall deposits. Results were extracted from two documents ([redacted] 2016 and "Comanche 3 Boiler Cleaning Rational" 12th December 2019). A summary of the results is provided in Table 2.

Table 2. History of Deposit Loadings on Comanche Waterwalls

Year	Deposit Loading (g/ft^2)	Observations
2013.	8 - 12	Grey Internal Surfaces
2014	12 - 19	Reddish Internal
2015	18 (Hot), 13 (Cold)	Grey
2017	10 (Hot), 10 (Cold)	
03-2019	13 (Hot), 12 (Cold)	
01-2020	18 (Hot), 18 (Cold)	

Based on these results the first operational clean occurred in 2015 (inhibited di-ammonium EDTA). Up to that time the unit had operated on AVT but with large amounts of air in-leakage. The initiation of OT by the plant was expected to reduce the deposition rates but as Section 3.1.1 has indicated the OT was not thought to be optimized until 2019. There also appears to have been no campaigns to optimize the condensate / feedwater pH to minimize feedwater corrosion products. Then the deposition data in Table 2 indicated that the Comanche boiler needs to be chemically cleaned a second time after only 4 years, which is a remarkably short period these days for supercritical boilers. But the next outage is in 2023, which unless the Comanche cycle chemistry is improved will mean that the deposits will far exceed the recognized chemical cleaning limit. SI suggests that Xcel reconsider bringing the chemical clean forward.

Although this important supercritical chemistry activity is not related to the L-1 blade failure, it is an indicator of the relatively poor chemistry treatment and control at Comanche. In summary, allowing waterwall deposition rates to be high due to inadequate feedwater treatment is often a key part of thermal fatigue and/or creep BTF in supercritical waterwalls. Currently there is a disconnect in information between tube samples, the need to chemical clean, and feedwater corrosion products (Section 3.1.5).

3.1.8 Chemistry and FAC Aspects of the Air-cooled Condenser (ACC)

It is most important that a unit with an ACC uses the optimum cycle chemistry to prevent FAC at the tube entries in the upper ducts (streets). International information (Dooley & Howell) has shown that a condensate/feedwater pH of close to 9.8 will be required to prevent very high levels of corrosion products (magnetite) being transported into the feedwater and depositing on internal heat transfer surfaces. Review of the condensate chemistry at Comanche (Section 3.1.4a) indicates that normally the pH prior to 2015 was ~9.3 and in 2019 was 9.6 – 9.7, neither of which is high enough to minimize FAC in the ACC and iron transport. The corrosion index for ACC (DHACI)(Dooley, Howell ACC Corrosion Index) was developed to provide an indication of the chemistry control and is used worldwide. In practice, a plant needs to move from a higher (range 1 – 5 with 5 being the highest level of FAC) to a lower DHACI number. At Commanche four ACC inspections have been conducted with the following DHACI values:

- September 2011. DHACI was 2B
- September 2014. DHACI was 1B
- April 2017. DHACI was 3B
- 2020. DHACI was 3X. (The DHACI was estimated by SI from photographs provided by P. Nguyen (1st April 2020). The X is because there were no photographs of the lower ducting).

This photographic evidence shows that there was FAC at the tube entries in April 2017 and 2020 which represented a change from the previous two inspections. From SI's vast experience of ACC inspections a DHACI of 3B would be accompanied by an elevated level of condensate corrosion products. These observations provide verification that the condensate/feedwater pH was not consistently high enough. It was also recognized by [redacted] in 2017 that the pH range (9.45 – 9.6) was too low.

At Comanche 3 there are two filters prior to the CPP resin with 47 cartridge iron filters per full flow. Originally the filters were 10 µm absolute and then changed to 3 µm absolute (date not known but prior to 2014). Internationally it has been shown that the optimum filter size is 5 µm absolute to make it possible for the condensate iron level to be < 5ppb. Information was not available from Xcel on time in service, but when removed the filters were red colored.

3.2 Confirmed and Possible Contaminant Ingress Events

The previous sections (3.1.1 – 3.1.8) have provided information on the normal (90%) chemistry values at Comanche under AVT and OT. But as the focus of the SI assessment is directed towards identifying the mechanism and root cause of the L-1 blade failure, cracking and pitting, the discussion in this section is focused on confirmed contamination events and possible contamination routes into the LP steam turbine. This is a most important chemistry section in this report as it highlights the well documented major contamination source in 2012 (condenser leak) and also provides information on other possible/probable contamination sources. In once-through supercritical plants any increased levels of contamination at the CPO, EI, MS and HRH will influence the composition of the liquid film formed on PTZ surfaces, and thus the rate of micro-cracking and SCC in the LP turbine.

The SI detailed review has identified that there are a number of possibilities:

- Condenser leakage in March 2012. Details on the condenser, cooling tower and cooling water composition are provided in Section 1.1. This condenser leak is covered in detail in Section 3.2.1.
- Any other condenser leaks. The SI assessment based on discussions with Xcel staff on two teleconferences and with [redacted] (telecom 3rd April 2020) has not been able to identify any other condenser leaks on Comanche Unit 3 except in May 2012. This is covered in Section 3.2.2. It is also recognized that there was an eddy current inspection of the condenser in 2014 when cracks were identified at the roll transition but there were no indications of any associated condenser leaks. A recent inspection (March 2020) found the condenser in "excellent condition" with only three tubes in the West Waterbox that had suspicious crack-like signals. There were no reports of any leaks.
- Contaminated levels (high sodium) in condensate, feedwater and steam (MS and HRH) were reported in Section 3.1.4. This is discussed further in Section 3.2.3.
- Superheat and Reheat Attemperation. Attemperation during the March 2012 condenser leak is discussed further in Section 3.2.4 and shown in Figures 2 and 3.
- Provision of auxiliary steam from Units 1 and 2. Steam is supplied from Units 1 and 2 for sparging Comanche Unit 3 during startups and sometimes this can last for a day or more. Sparging and auxiliary steam is discussed further in Section 3.2.5.
- Operation of the condensate polishing plant (CPP) in the AFO mode leads to slippage of anions into the condensate (usually and mainly sulphate). This has been mentioned in Section 3.1.4a as a possible source of future RH pitting failures if shutdown protection is not provided to RH.
- By-passing of the CPP because of condensate temperatures being elevated above 145 F. Xcel indicated on during the 23rd March 2020 teleconference that this is only up to a 20% by-pass. The only example that could be indicated by Xcel staff was during the startup of 25th

November 2019 during the same time as auxiliary steam was used for sparging. This is discussed in Section 3.2.5 and shown in Figure 4.
- Any other route. None have been found during the SI review or suggested by Xcel.

During the three teleconferences with Xcel staff and the additional one with [redacted] SI has requested if there were any other events that could have resulted in elevated contamination levels in steam (MS and HRH). None have been reported.

3.2.1 Condenser Leakage, March 2012

SI received the following detailed information on the condenser leakage on 26th – 28th March 2012 as follows:

- The condenser leak appears to have started around 13:00 on 26th March 2012. Prior to this the sodium at the CPD was < 1 ppb. At 13:48 it was 27 ppb. By 16:30 it had steadied out at ~15 ppb. On 27th March 2012 at 23:00, the sodium increased to 35 ppb. By 1:12 on 28th March 2012 the sodium at the CPD was at 1000 ppb with DCACE at 0.99 µS/cm (instrument maxed out). Chloride was estimated to be 900 ppb.
- The condensate polisher A and B resins were exhausted by 3:10 on 28th March 2012, and C was put into service. A was returned to service with new resin at 4:50 but by 5:30 A & C were exhausted.
- At 8:00 the lower waterbox was drained and the contamination at the CPD was eliminated. But at 13:18 with new resin for B in service, there was no replacement resin available until 00:12 on the 29th March 2012.
- The unit was kept operating during all this contamination period whereas the unit should have been shut down according to the Comanche shutdown limit provided in Section 3.1.2, and definitely if in agreement with the international standard.
- In summary:
  - At the CPD from 1:12 to 7:30 Sodium was > 2000 ppb
  - At the CPO from 3:42 to 13:00 Sodium was > 20 ppb (maxed out)
  - At the EI from 4:00 to 13:30 Sodium was > 20 ppb (maxed out)
  - At MS from 6:12 to 8:06 Sodium was > 20 ppb (maxed out)
  - At HRH from 6:30 to 8:30 Sodium was > 10 ppb
- The chemists at Comanche also provided the following summary information:
  - Sodium went from < 1 ppb to > 1 ppm (upper limit of instrument)
  - CACE went from < 0.15 µS/cm to > 1 µS/cm (upper limit of instrument)
  - Conductivity went from < 10 µS/cm to > 60 µS/cm
- Each of these chemistry values clearly represents a serious contamination situation requiring an immediate shutdown based on Comanche and international guidance. However, the unit was not shut down by the operators, and the condenser leak was repaired on line.

Reheat and superheat attemperation during this condenser leak is covered in Section 3.2.3 and the load profile is shown in Figures 2 and 3. These indicate that the operators not only didn't abide by unit shutdown limits but even increased the load and kept attemperating.

3.2.2 Other Condenser Leakage, May 2012

The [redacted] report (Section 2.1) indicated another condenser leak had occurred in May 2012. The chemistry data was reviewed by [redacted] Comanche Plant Engineer, which showed that "there was no definitive data which indicated a tube leak". Some shift notes were found that indicated a leak was found after the unit tripped on low instrument air pressure. [redacted] (teleconference 3rd April 2020) provided confirmation that the small leak did not saturate the polisher and didn't need resin replacement; he provided photographs of the tube sheet. The appearance from the tube sheet looks identical to the March 2012 leak. The leak occurred on 21st May 2012 on the upper inlet side on the north end U turn. Review by SI of the detailed chemistry data from 20th to 25th May 2012 confirmed that there were no exceedances of sodium greater than 2 ppb at CPO, EI, MS and HRH except during the startup.

3.2.3 Random Elevations of Contamination (Sodium) and Poor Reliability of Key Instruments

Serious levels of contaminant (sodium) were identified by SI during the detailed assessment of the Comanche chemistry (Section 3.1.4) in the condensate, feedwater and steam. The contamination occurred at exactly the same time on the multiples days for example that were analyzed in June 2015, and the time periods of elevation were up to 4 – 6 hours. This suggested to SI, that because four sodium analyzers at four different sampling points were involved, the situation shouldn't be an instrument problem. However, the Xcel staff indicated that the instruments shared the same analyzer (confirming Section 3.1.3) and there was a deficiency associated with a solenoid. If these situations were the result of faulty instrumentation, the unit was still repeatedly operated on multiple occasions without the capability to accurately monitor the cycle chemistry.

A much more important point reflects on the poor calibration and maintenance of the analyzers. For example, when SI was investigating the effect of auxiliary steam additions to Comanche Unit 3 from Units 1 and 2 it was found that key instruments for sodium in the MS and HRH were out of service for very long periods. For example, chemistry data was reviewed for 12th and 20th July 2019 and 7th December 2018 and these instruments were out of service, so no data was available for the operators. It is of paramount importance that these vital instruments work on a continuous basis including startups of the unit. Xcel clearly needs to upgrade the maintenance and calibration activities on the chemical instruments to a much tighter frequency (every one or two weeks). Overall and as introduced in Section 3.1.3, the instruments are not calibrated and maintained on a regular basis, are not reliable, and are not all audibly alarmed in the control room for the operators. The plant appears to have relied heavily on grab samples taken every four hours. This is not the way to operate the chemistry on a supercritical unit, and clearly Xcel will need a completely new philosophy for chemistry instrumentation which will require purchasing new unique instruments (not shared/switched) and sampling systems which operate during startup situations.

3.2.4 Superheat and Reheat Attemperator Operation and Unit Load

It is well understood that attemperation provides a possible short circuit of contaminated feedwater into the MS and HRH steam, and thus to the PTZ of the LP turbine.

The situation with regards to the March 2012 condenser leak (Section 3.2.1) was investigated in detail during the SI assessment. Figures 2 and 3 present superheater and reheater historical operating data plots for 26th, 27th and 28th March 2012 during which the documented condenser leak occurred.

The plots in Figures 2 and 3 show that unit load had just decreased to 489 MW from 733 MW when the contamination event started at 13:00 hrs. on 26th March 2012. The plots also show that the superheater and reheater attemperators were in service prior to the contamination event. Two periods of increased load occurred during the contamination event. The first began at 17:00 on 26th March 2012 to a maximum load of 654 MW and lasting 4 hours and 11 minutes. The second began at 12:49 hrs. on 27th March 2012, reaching a maximum load of 809 MW and lasting 11 hours and 10 minutes.

Attemperator spray flow plots in Figures 2 and 3 show that the superheater attemperator operated the majority of the time and the reheater attemperator operated near-continuously during the contamination event.

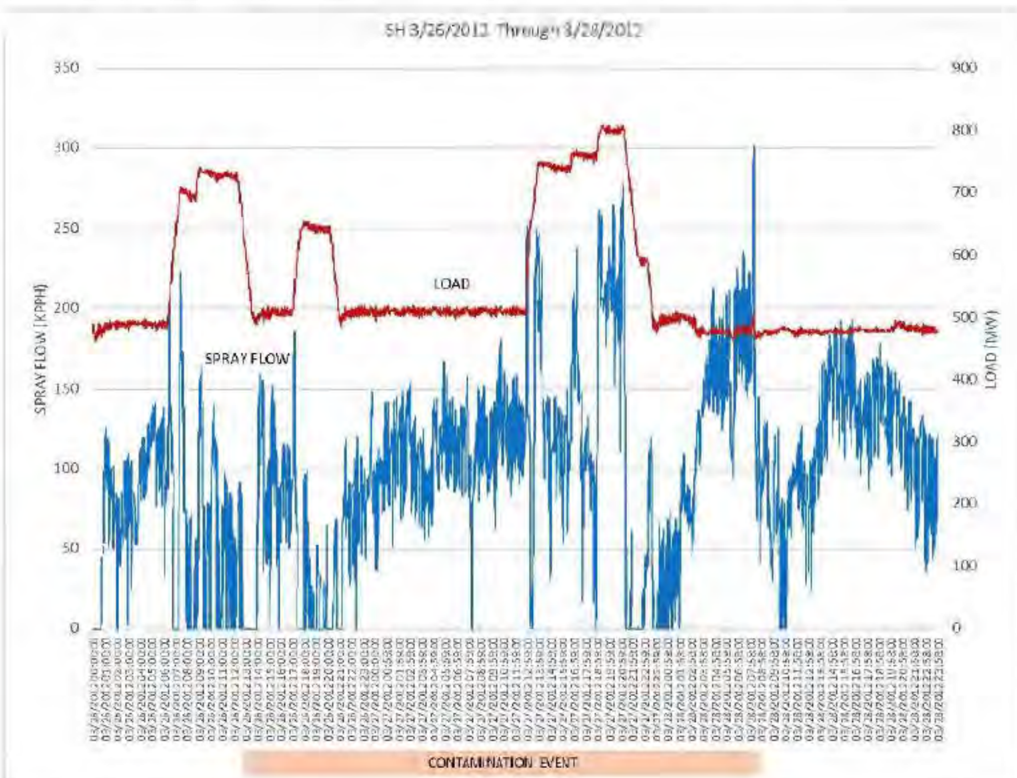

Figure 2 – Unit load and superheater attemperator spray water flow before, during and after the March 2012 condenser leak event

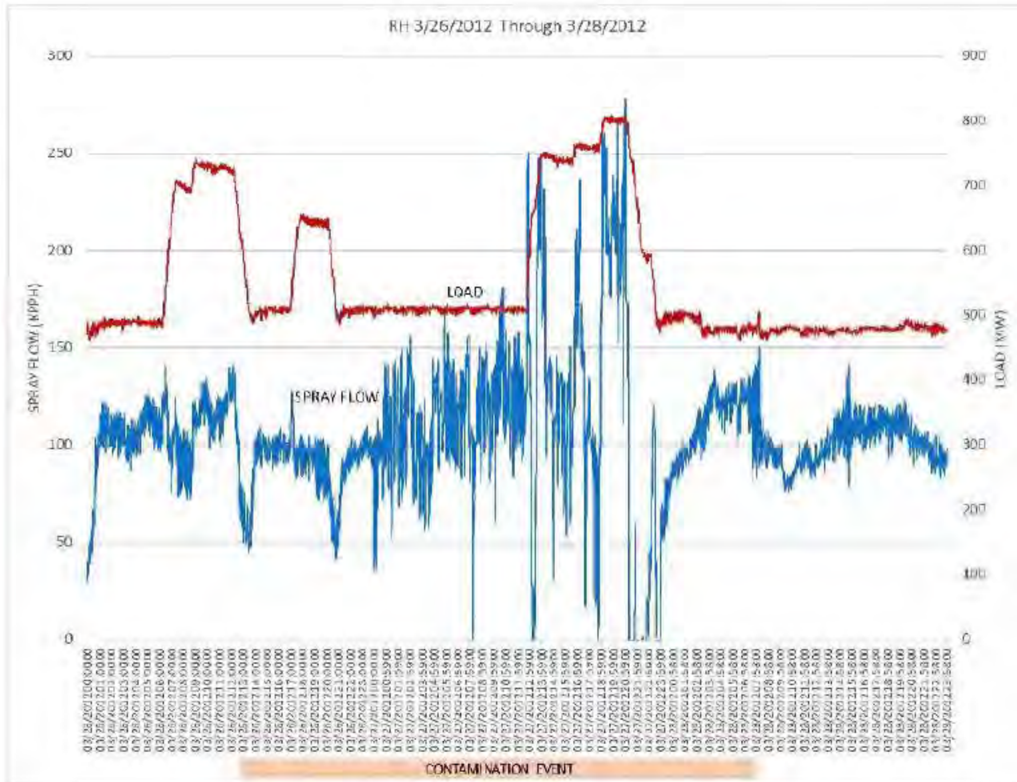

Figure 3 – Unit load and reheater attemperator spray water flow before, during and after the March 2012 condenser leak event

No other contamination events were identified between 2012 and the blade failure in 2020 to the same level of serious contamination, so no other data was generated on attemperation. But based on Figures 2 and 3, it is clear that Xcel will need to upgrade the operating and response procedures in relation to continuing attemperation during contamination events which exceed chemistry guideline limits as this will only exacerbate the concentration of contaminants in the liquid films on the blade surfaces.

3.2.5 Auxiliary Steam Supply from Units 1 and 2

Xcel staff were requested on the 23rd March 2020 teleconference to provide dates and chemistry data when auxiliary steam was supplied from Comanche Units 1 and 2. These are older drum units with guideline limits for steam (MS and SS) which are inferior to those for Comanche Unit 3. Xcel staff indicated that auxiliary steam is supplied on every startup and provided a table indicating the peak level of sodium resulting on startups between 2017 to 2019 inclusive. These were often between 10 – 20 ppb.

One particular startup on 25th November 2019 was analyzed because for this start the condensate polisher was also by-passed. It was the only startup that Xcel staff could remember when the polisher was bypassed. The data is shown in Figure 4.

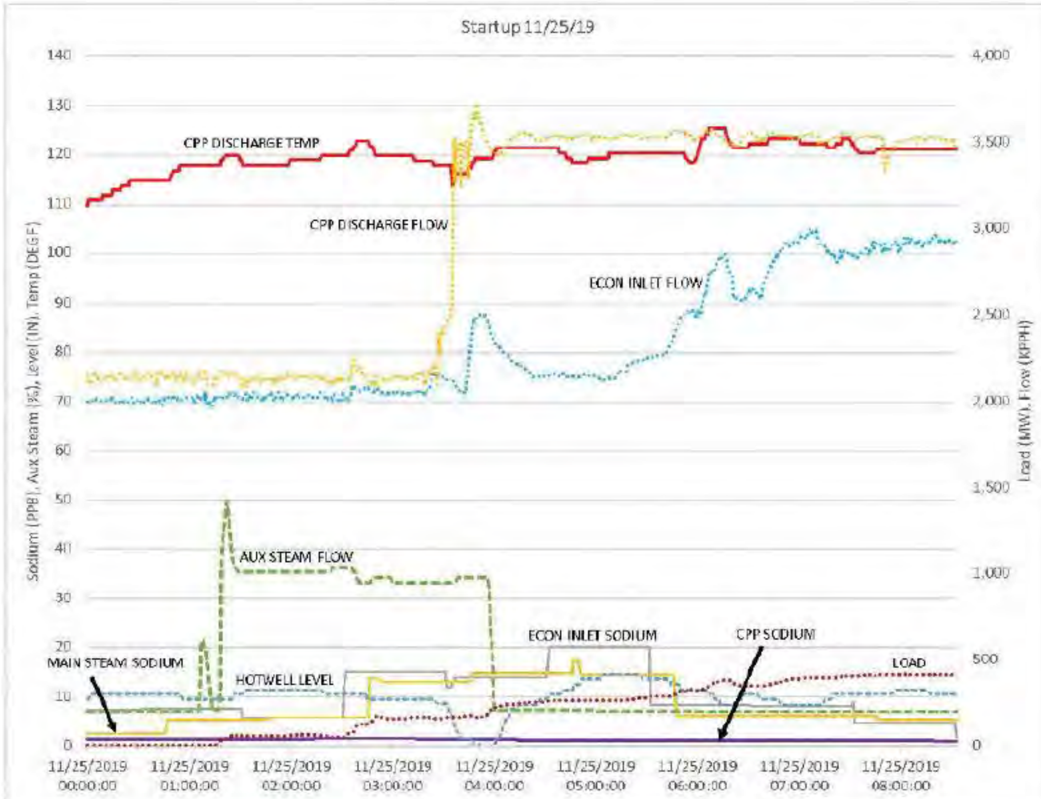

Figure 4 – Startup on 25th November 2019 when sparging steam was supplied and the condensate polishers were bypassed.

The plot shows that the EI and MS sodium levels were slightly elevated at unit startup but were further elevated due to auxiliary steam flow during the next six hours to about 20 and 15 ppb, respectively. It can be seen that the condensate polisher was partially by-passed until about 3:30 on the 25th November 2019 but the condensate polisher (CPP) sodium remained within limits (< 2 ppb) throughout. SI also reviewed the chemistry data in detail for other startups (for example: 7th December 2018, 12 and 20th July 2019) but as reported in Section 3.2.3 the sodium analyzer was out of service. Figure 4 however illustrates that the auxiliary steam can be a source of contamination for the steam supply to the Comanche Unit 3 turbine. Clearly an alternate supply for sparging steam is required.

In summary for this item on sparging steam it appears that it is a source of contamination during each startup. It has clearly been poor operating and chemistry practice to have operated since COD with EI, MS and HRH instruments that are not reliable or in-service for 6 – 8 hours. The purity of this auxiliary steam supply for Comanche Unit 3 should be monitored in the future even if Xcel decides to provide a new auxiliary boiler for supplying the sparging steam.

3.3 Benchmarking and Repeat Cycle Chemistry Situations (RCCS) of the Comanche 3 Chemistry

When conducting plant cycle chemistry assessments or investigating major failures or conducting root cause analysis on plant failures, Structural Integrity (SI) always uses two key tools/processes to assess the current condition of the cycle chemistry on supercritical units to assist in the identification and the potential for future failure/damage. The first involves benchmarking the plant's cycle chemistry program against other similar plants worldwide. These processes have been used to evaluate over 220 plants worldwide and provide a total assessment of the cycle chemistry aspects. The second process identifies the repeat cycle chemistry situations (RCCS) which are occurring. These RCCS represent the basics of power plant chemistry and their elimination ultimately leads to improvements in the benchmark scores with concomitant improvement and optimization of the cycle chemistry and unit overall performance.

The benchmarking provides a key reactive indicator of past performance. The RCCS provide the key proactive indicators for future operation to avoid damage and failure. These processes discussed in the next two sub-sections identify the areas where improvement and optimization should take place as the Comanche unit continues to operate. Preliminary Action Plan outlines have been provided in Section 5.

3.3.1 Cycle Chemistry Benchmarking of the Comanche Unit

The Unit 3 at Commanche was benchmarked according to world class standards during the assessment and scored 21 points which is in the "Average" category. It should be noted that an average category does not indicate that acceptable practices are in place which is the situation for Comanche Unit 3. Xcel needs to review (Section 3.3.2) and address the RCCS (Section 5) which provide the indication for future reliability.

"Worldclass" Cycle Chemistry Programs (≤ 5 points) have the following attributes. Observations of the current Cycle Chemistry program on the Comanche unit made by SI during the assessment are provided in parentheses.

1. Zero cycle chemistry influenced boiler tube failure (BTF) over the last five years. (The overall BTF statistics were not provided to SI but review of the BTF Metallurgical reports provided by Xcel suggests that there has been no cycle chemistry influenced BTF).
2. Zero chemically influenced steam turbine phase transition zone (PTZ) damage, failure and deposits over the last five years. (The current investigation is addressing the pit induced SCC L-1 failure, which is clearly cycle chemistry influenced).
3. High level of continuous cycle chemistry instrumentation when compared with the IAPWS international standard. The instruments should all be audibly alarmed in the control room for the operator's use. (As reported in Section 3.1.3 the Comanche unit was designed with a high percentage of the international standard requirement, but many of the instruments are shared/sequenced which brings the number to about 71%. The SI assessment has also raised serious questions about the reliability of the

instruments, whether these are currently audibly alarmed in the control room for the operators (especially at the time of the condenser leak in 2012), and whether the calibration/maintenance is adequate.)

4. Optimum chemical cleaning frequency (> 10 years). (The Comanche unit has had one operational chemical clean in the 10 years of operation but currently needs another. This factor needs to be linked very closely with waterwall tube sample analyses, which to date has been conducted (Section 3.1.7), and the monitoring procedures for total iron feedwater corrosion products which need improvement (Section 3.1.5)).
5. Minimum number of Repeat Cycle Chemistry Situations (RCCS). (As discussed in the next sub-section, Comanche Unit 3 has seven RCCS).

The benchmarking factors of concern for the Comanche Unit 3 relating directly to the L-1 blade failure and for future reliable operation are the cycle chemistry repeat situations as delineated in the next sub-section.

3.3.2 Repeat Cycle Chemistry Situations (RCCS) at Comanche 3

SI staff has analyzed over 220 plant failures and assessments. This has clearly indicated that each incident can be related to a plant operating with a number of RCCS. Some general words are provided here in this report, but further reading on the 10 RCCS categories is available to develop an understanding the multiple factors in each category. (R.B. Dooley, K.J. Shields, and S.J. Shulder. How Repeat Situations Lead to Chemistry-Related Damage in Conventional Fossil and Combined Cycle Plants. PowerPlant Chemistry, 2008, 10(10), pp 564-574).

By themselves, an individual RCCS is not a major concern, but when multiples (more than 2 or 3) are allowed to continue then failure/damage has either occurred, as with the blade failure at Comanche, or is going to happen in the future, such as reheater pitting failures which are predicted at Comanche. Thus, SI considers that identification of, avoidance of, and prevention of RCCS is vital, and that these are critical to a plant's continued reliability. Repeat cycle chemistry situations are the cycle chemistry equivalents of root cause for other non-cycle chemistry influenced damage mechanisms. Normally SI suggests that Action Plans are developed for each RCCS and that each is eliminated within a certain time period (such as 6 months or less). This will improve the benchmark ranking and overall reliability of the unit.

During the current assessment of the L-1 blade failure SI identified the following seven RCCS factors applicable to Comanche 3. These will need to be addressed by Xcel:

A. Corrosion Product Transport.

As indicated in Section 3.1.5, total iron corrosion products have been monitored by integrated sampling at the EI and in the drains of HP heaters 6. Unfortunately, the procedures were not in compliance with international practices and the sensitivity of the analytical equipment was not good enough. This means that SI could not use the data to determine whether the chemistry (both AVT and OT) was optimized. As total iron is a vital indicator of whether the chemistry is optimized and FAC is occurring in supercritical units, Xcel should initiate a comprehensive program for monitoring total iron in compliance with the IAPWS Technical Guidance Document. Xcel should also adopt the international achievable limit for total iron at the EI of consistently less than 1 ppb for units on OT. Total iron measurements, when conducted properly, provide direct feedback on the effectiveness of the feedwater treatment program and indirect feedback on boiler waterside cleanliness as determined from analysis of deposits/oxides in waterwall tube samples.

B. Waterwall Internal Deposits and Chemical Cleaning.

Comanche 3 has operated 76,200 hours to March 2020 and has been operationally chemically cleaned once with another due. The total of internal waterwall deposits (from the feedwater) and indigenously grown duplex oxides on supercritical boiler waterwalls are of paramount importance in preventing boiler tube failures due to overheating and thermal fatigue, and which are related directly to the levels of total iron in the feedwater. The plant has taken waterwall samples frequently (Section 3.1.7) but does not appear to have conducted monitoring campaigns to reduce the feedwater corrosion products. The Xcel/Comanche staff need to introduce a program to monitor the deposits/oxides and deposition rates of feedwater corrosion products on the waterwalls of the boiler.

C. Air In-leakage (AIL)

The SI analysis in Section 3.1 has indicated that the CPD oxygen levels are too high for optimum operation of OT. This relates to the lack of a coordinated AIL program. Xcel and Comanche need an AIL program and AIL team applicable to the steam turbine, condenser and ACC.

D. Shutdown Protection

As discussed in Section 3.1.6, Comanche Unit 3 does not have any comprehensive procedures for protecting the boiler or feedwater heaters during unit shutdown. Also, most importantly as this is part of the root cause of the L-1 blade failure, there are no provisions for dehumidified air (DHA) to provide protection for the LP steam turbine during shutdowns of longer than three days. Table 1 has illustrated the large number of unprotected shutdown periods between 2012 and 2020 during which passivity breakdown and pitting occurred as precursors to the failure and cracking damage in the L-1 rows.

Film Forming Substances (FFS) (amine and non-amine based) have shown positive shutdown protection for plant equipment. Good results have been illustrated for reducing feedwater corrosion products and for reducing the DHACI in ACC. However, internationally there remains a question on whether FFS can provide protection to steam circuits, especially superheaters and reheaters.

E. Contamination Ingress

Section 3.2 has illustrated how the plant operators not only didn't react to exceedance of the Comanche Guideline limits and didn't shut the unit down when shutdown limits were exceeded, but they continued to keep firing the boiler.

Xcel also didn't clean the various equipment sections (condensate, feedwater, boiler) following the severe March 2012 contamination. Section 3.1 has suggested that there could be other periods when guideline limits were exceeded without any action being taken. Clearly as noted in F, a new set of guideline limits, action and shutdown levels need to be incorporated into a plant chemistry manual and into the operators' DCS with audible alarms. SI has provided initial guidance for OT in Table 4.

F. Challenging the Status Quo for the Comanche Unit 3.

There are two factors in this important RCCS category: a) optimizing the OT, and b) providing up-to-date guidance for the Comanche Unit 3. It was identified during the assessment (Section 3.1) that the cycle chemistry treatment and control for AVT and OT at Comanche reflect those of more than 10 years ago, and has not been upgraded to the latest international practices. The plant needs to move to fully optimized OT chemistry (see Section 3.1.1) as soon as possible to minimize the corrosion product transport of total iron and the deposition on the internal surfaces of waterwalls. This means identifying the feedwater pH which minimizes the total level of iron corrosion products being transported to the boilers.

The chemistry guidelines currently in use at the plant also reflect those of 20 years ago for feedwater and steam purity. Xcel / Comanche need to develop a specific comprehensive Chemistry Manual for the Comanche 3 unit (and maybe the plant). This should include integrated guidance for condensate, feedwater, boiler water and steam, and should be based on the latest guidance available worldwide. This should be signed by plant management each year to ensure it represents the latest cycle chemistry practices.

G. Summary Comments on RCCS at Comanche Unit 3

It is very rare that SI identifies seven RCCS factors at a plant and therefore it is not surprising that the chemistry/operation has been poor and resulted in the L-1 blade failure. The alleviation of RCCS at Comanche will need to be given a very high priority by Xcel management otherwise further cycle chemistry influenced failure and damage will occur.

3.4 Summary of Cycle Chemistry Control at Comanche Unit 3.

The previous sections have indicated that the normal cycle chemistry (90%) under AVT and OT treatment regimes is generally in agreement with the Comanche Guidelines from 2011, and that the Comanche Unit 3 benchmarks in the Average category on a worldwide basis for cycle chemistry of a supercritical unit. But when looked at in detail the overall chemistry has been poorly managed, and a number of deficiencies (seven RCCS factors) have been identified during the SI assessment. Some of these have directly influenced the L-1 blade failure, and some will affect the future reliability of the Comanche Unit 3 unless they are addressed expeditiously by Xcel. The predominant one relating specifically to the root cause of the blade failure is the lack of any chemistry shutdown protection (DHA) for the steam turbine. Others of major importance include: operators ignoring alarm and shutdown situations; not using optimum chemistry treatments

(OT); ineffective monitoring of total iron as the key indicator of the chemistry; and unreliable chemistry instrumentation.

The first thing that should be addressed is to move to full OT operation in agreement with international practice (Section 3.1.1). The second relates to developing a total iron monitoring program which can provide verification that the cycle chemistry, particularly the feedwater, is optimized for a supercritical unit. The third item is that shutdown protection should be provided for the boiler (particularly the RH) and steam turbine to prevent further damage. In parallel to these important items comprehensive cycle chemistry guidance with normal values, action levels and shutdown requirements need to become part of a Comanche Chemistry Manual and the operating procedures for Xcel. The operators will need to be trained in the important aspects of the updated program. All the chemistry practices and procedures need to be assembled into a Comanche Chemistry Manual which is fully approved by Xcel and Comanche management.

4 Developing Mechanism and Root Cause Understanding of Comanche Unit 3 Blade Failure

Now that the operational and chemistry aspects at Comanche have been covered in the previous sections, the assessment will focus on overlaying these operating and chemistry experiences on the development of the failure mechanism. Structural Integrity Associates (SI) has used a deterministic approach for the root cause analysis based on the latest understanding of how damage and failure in the Phase Transition Zone (PTZ) of steam turbines progresses.

4.1 Introduction to the Processes involved in a Steam Turbine leading to PTZ Pitting, Cracking and Failure

Over the last 20 years, the understanding of the driving force behind the PTZ damage mechanisms of stress corrosion cracking (SCC) and corrosion fatigue (CF) has changed. Up to 30 years ago, major research concluded that turbine corrosion mechanisms were driven by high oxygen levels in concentrated solutions containing extreme levels (up to almost 30%) of chloride, sulfate, and hydroxide on blade surfaces. Recent improved understanding of the turbine environment has identified the following as the most significant factors relevant to turbine corrosion in the PTZ:

- The dynamic environment during turbine operation. These are the local conditions formed by the condensation of steam as it expands through the PTZ of the turbine and crosses the saturation line, and by the deposition of salts, oxides and other contaminants directly onto steam path surfaces. It is important to note that the first condensed droplets and the liquid films on the blades have elevated levels (hundreds of ppb) of contaminants (chlorides, sulphates) but that there is no oxygen in them during operation.
- The environment produced during inadequate or unprotected shutdowns occurs when oxygenated moist / liquid films form on steam path surfaces as a result of hygroscopic effects (elevated moisture). These lead initially to passivity breakdown and then with repetitive shutdowns to pitting, which are always the precursor to SCC and CF. It is well understood that these repetitive unprotected shutdown periods are the predominant part of the crack/failure initiation process, and thus most often are the root cause.
- Steam purity and shutdown conditions are only two of the multiple parameters that lead to the corrosion damage. Adequate materials properties (composition, structure, internal stresses, etc.) and design (temperature, stresses, crevices, etc.) also play essential roles. Overall, it is also well understood that actual failure occurs at locations where concentrated liquid films and a localized high stress co-exist.

Stress corrosion cracking on blades in the PTZ is very complicated but the next few sections provide a short overview of the key technical steps that have to take place for cracking to result in failure. So, this section of the report provides the latest deterministic understanding of how these types of failures take place in the

PTZ of LP turbines, and application of this to the development of the most probable root cause of the Comanche blade failure. Firstly, the environment in the PTZ is described and then how this environment, controlled by the unit cycle chemistry, influences the mechanism. This determinism has allowed possible and most probable root cause(s) to be derived for Comanche Unit 3. A fuller description of the PTZ environment and associated cracking is available in the IAPWS Steam Purity Technical Guidance Document (TGD) which has recently become the international standard for steam turbine purity.

4.2 The Phase Transition Zone (PTZ) Environment in LP Turbines

Here it is necessary to consider the chemistry environment during operation of the turbine and most importantly during shutdown.

4.2.1 During Operation.

Over the last 25 years an established picture has developed which considers how the superheated steam environment entering an LP turbine expands, and as it approaches and crosses the saturation line droplets of moisture are nucleated heterogeneously on ions. The turbine Mollier diagram provides an understanding of this process (please refer to the IAPWS TGD on Steam Purity for more information on how the Mollier diagram can be overlaid with the steam chemistry). Almost everything about these "first condensate" droplets has been measured (see Dooley & Rieger publications). They are typically about 0.1 µm in size. They initially concentrate anions, which are usually at a low level in superheated steam, to about 150 - 200 times and thus initially have a reduced pH. The inlet steam (MS and HRH) on Comanche 3 during "normal" conditions has an estimated 1 – 3 ppb of chloride and sulfate, but review of the observations of elevated impurity levels in MS and HRH during the condenser leaks (Section 3.2) and startups (Section 3.1.4) will lead to an understanding of how the concentration of the impurity levels (sodium and chloride) will be markedly increased during these periods.

One of the most important observations in the development of the latest understanding of the PTZ is that the dissolved oxygen level within the droplets is very low (< 1ppb) because of the partitioning to the steam phase (see the IAPWS Guideline on Henry's Coefficient). This applies to Comanche Unit 3 even when operating on OT or when air in-leakage (AIL) is high (as discussed in Section 3.1.4a). Formation of the droplets is associated with a high electrostatic charge which has been found to be a function of the operating chemistry on the unit. As the expansion takes place the concentration dilutes as the droplets grow by adding moisture. For a supercritical unit, at the exit of the LP steam turbine there is between 7-11% of moisture depending on the efficiency of the turbine and cycle. This mixture flows to the condenser (wet or ACC) where the associated subcooling causes the remaining steam to nucleate condensate homogeneously.

Liquid films form on the steam turbine materials as the steam flows through the PTZ. These are formed either by impaction of the liquid droplets or by heterogeneous nucleation on the blade material itself. These films can be up to 100 - 120 µm in thickness. They also result in a concentration of anions by up to a factor of about 1000 times and as with the droplets they have an electrostatic charge. It will be appreciated how the impurity content of the liquid film is elevated during periods of poor steam chemistry control at Comanche (Sections 3.1.4 and 3.2). It is also very important to note because Comanche has most recently operated on OT, that there will still be very low levels of dissolved oxygen in these liquid films (< 1 ppb) even at Comanche where the oxygen levels in the superheated steam (MS and HRH) are in the hundreds of ppb, or AIL is often high (section 3.3.2C).

These liquid films are very important in understanding the overall failure mechanisms in the PTZ because stress corrosion cracking needs an aqueous electrochemical solution for micro-cracking and crack growth to take place. The liquid films crossing the PTZ (including the L-1 diaphragm and blade stage) do not form in straight lines but are in a rather contortuous path unique by machine. Thus, a number of blade and diaphragm stages are always "touched". Unless measurements are made with a laser probe the exact profile can only be modeled or inferred. As is required by the SCC mechanism, this liquid film needs to encompass the crack initiation site at the snubber location at Comanche. It is most important in understanding the Comanche failure that the environment near the pitting and crack initiation site adjacent to the snubber on the L-1 blade has a low moisture content (0.5 - 1.0%). This would confirm that this liquid film is more concentrated in anions than at other sites on the blade surface which could vary to about 3% moisture with low concentration of anions (chloride). The turbine manufacturer (MHI) was requested and refused (7th April 2020) to supply the wetness profile for Comanche Unit 3 through the L-2 to L-0 stages. The SI assessment does not have such a profile for confirmation, but early observations were made (Section 1.2) of "stains" and "water lines" on the Comanche L-1 blades around the snubber location.

As summary, in relation to the formation of droplets and liquid films it should be noted that these are normal processes required by the thermodynamics of steam expansion. Even in units with worldclass cycle chemistries the concentration mechanisms take place. In units with higher levels of anions entering with the steam the concentration mechanisms will elevate the levels in the droplets and the liquid films. Translating this to the Comanche Unit: a) during normal chemistry (as defined in Section 3.1.4) the liquid films have a concentration of anions up to about 150 – 200 ppb, but b) during contaminant events such as the 2012 condenser leak (as discussed in Section 3.2) the concentration of anions in the liquid films would be much higher (percentage levels).

In parallel with the formation of droplets and liquid films, deposits form on the blade and diaphragm stages throughout the PTZ. This is an equally complex formation process which involves impaction of crystals of salts, oxides and other compounds, as well as deposit formation due to thermophysical and chemical processes such as: precipitation from superheated steam, evaporation of moisture, adsorption of impurities and loss of compound solubility. Deposition is a strong function of surface finish and of surface discontinuities. Translating this to the Comanche Unit 3 the snubber is a location of increased deposition (Section 2.2).

Research around the world in the mid-1990s with an international collaboration of 23 organizations worldwide (led by Dooley) found that deposits (essentially crystals of salt) can be expected on any turbine surface within the PTZ during operation even in units with the best cycle chemistries and cleanest steam (Dooley & Jonas). Obviously the cleaner the steam the less deposits form, and this led in the early 2000s to the steam limits of 2 ppb for sodium, chloride and sulfate (see IAPWS Steam Purity TGD). Thus, deposition of crystals of salt on to the Comanche Unit 3 blade surfaces is expected during normal operation and chemistry conditions (Section 3.1.4). But the major contamination in 2012 due to the condenser leaks (Section 3.2) will have contaminated all the condensate, feedwater, boiler, SH and RH surfaces by absorption. Because only the boiler has been cleaned in the interim period, these surfaces will have released salt crystals into the steam flow and thus provided a continuing supply of crystals for deposition and increased levels at the snubber location. As is discussed in the next Sections of this report, these then become the locators of the pits which have been observed on L-0 and L-1 blades (Section 2.2 and Figure 1).

4.2.2 <u>During Shutdown</u>.
When a plant is not operating then obviously no droplets or liquid films are formed on the blade surfaces, neither is there any deposition of salt crystals. But the various deposits already on blade surfaces will remain and it is these which become critical during the shutdown depending on whether the PTZ is protected or not. Under non-protected conditions the blade surfaces will become exposed to ambient conditions and the crystals of deposition will absorb moisture from the atmosphere and form local acidic conditions. Contrary to what happens during operation any liquids that form during shutdown will become oxygenated and a local corrosive anodic environment will exist at the deposit/blade surface. If the moisture level of a flowing dehumidified environment over the blade surfaces is kept below 40% then similar reactions will not take place.

4.2.3 <u>Pit Formation</u>. Failures of the type seen at Comanche Unit 3 in the PTZ involve alternating operational and shutdown environments as described in Sections 4.2.1 and 4.2.2. The large number of unprotected shutdowns at Comanche were discussed in Section 3.1.6 and shown in Table 1.

During non-protected shutdowns where the blade surfaces are open to the local atmosphere, any deposits particularly chloride or sulfate, which have formed on the blade surfaces in the PTZ during operation will become moist and lead to local acidic aqueous environments which will contain ppm levels of oxygen. This very local situation will lead initially to breakdown of the blade passivity then to a metastable pit and finally on repetitive cycles of shutdown to stable pits. Each shutdown period is followed by operation where the dynamic situation of droplet formation and liquid films occurs as described in Section 4.2.1. The formation of liquid films during operation in the areas where the passivity breakdown and metastable pits have occurred during shutdown can lead to repassivation of the local areas. However, during operation deposition will continue to occur as described in Section 4.2.1. Any deposition associated with the original breakdown of passivity or a metastable pit will, on the next extended unprotected shutdown, lead to further growth of the pit. Repetition of this process will eventually lead to a stable pit. The internal surfaces of these pits will be rather jagged as they result at active corrosion sites. Such jagged appearances of the initiating pits and others on the Comanche Unit 3 L-1 blade were observed (see Section 2.1). So, the different environments which exist during the repetitive operation and shutdown periods eventually lead to the initiation and growth of a number of pits on the surface. Also, pits are expected outside of the L-1 row because the crystal deposition mechanism and lack of shutdown protection is applicable to the whole LP turbine. At Comanche, pitting on other blade rows (L-0) has now been confirmed from the blade photographs provided by Xcel. In other blade failure investigations it is quite normal to develop a total geographic distribution to include the depth and the diameter of the pits but it is probably too late to do this at Comanche because of blade cleaning before NDE inspection (Section 2.2).

Translating this critical required initial stage in the development of SCC to Comanche Unit 3, the situation is very clear in that the snubber/blade interface has been shown to be a preferential site for deposits (Section 2.2) and pits (Section 2.1 and Figure 1). Also, analysis of the Shutdown and Trip Log supplied by Xcel indicated that there had been a minimum of 35 non-protected shutdowns of the Comanche Unit 3 for longer than 3 days (Table 1, Section 3.1.6) between 2012 and 2019. These times would have allowed the Comanche L-1 blades to have cooled to atmospheric conditions so that the deposits around the snubber could attract moisture. Thus it is expected that the pitting which initiated failure at Comanche formed initially during some of the early long shutdown periods after March 2012 and was uniquely located in an area of concentrated liquid film where the stress was also high locally.

Analysis of the deposits on the Comanche Unit 3 blades and diaphragms after the failure revealed chloride, sodium and sulfate (Section 2.2), but there is no indication of the sampling location and thus whether this included deposits around the snubber. SI has assumed the composition wouldn't be markedly different.

Pit growth is not expected to be the same per outage, and its growth would be dependent on the amount of deposition during operation to replenish the process during each non-protected shutdown. Unfortunately, SI has found in other investigations when the mechanism and root cause assessment occur some time after the event, as in the current case with Comanche, much specific and detailed information is missing on deposit analyses and pit distribution geography.

4.2.4 Transition of a Pit into a Micro-crack and Crack Propagation. Once pits become stable and reach a critical size (diameter and depth) a microcrack can initiate from the jagged surface at the bottom of a "dead" pit if the pit occurs in a region of both high enough stress and where there is a concentrated liquid film on the blade surface. The pit acts as a stress concentrator. This transition from a pit to a microcrack is the most difficult part of the deterministic model to understand and model as micro-cracks are rarely seen in after-failure analyses. Laboratory studies have indicated that a certain percentage of pits can initiate micro-cracks dependent on the material properties and the density of pits. SI needs to mention that the latter has not been measured on the Comanche blades. Micro-cracks (SCC) grow under blade steady centrifugal stresses to threshold size. The cracks then grow by stress corrosion cracking with final fracture by high cycle fatigue (Section 2.1). These are fully the features observed on the Comanche blades.

Translating to Comanche: this crack growth stage can only occur in a region where there is a concentrated liquid film and a high local stress. It is clear that the crack growth stages have taken place in aqueous environments as evidenced by the coloration of the fracture surface (Section 2.1). As indicated in Section 4.2.2 the liquid films during normal operation and chemistry are concentrated in anions, but in a supercritical unit these concentrations increase directly with contaminant levels in the condensate and feedwater (EI). Thus, the possible increases in steam (MS and HRH) contamination discussed in Section 3.2 would lead directly to increased crack propagation.

To fully validate the prognosis for the mechanism and root cause at Comanche it will be necessary to know the level of blade stresses associated with the region around the snubbers, and it must be pointed out by SI that no information has been provided to date, by the manufacturer or others, of a blade stress profile to confirm a peak stress at the snubber location of intiation. The current analysis can only relate to the fact that the pits at the crack initiation points were sufficient to act as stress concentrations, and that they were located at a region where the liquid film had the lowest moisture content (highest anion concentration) and where the stress was locally high otherwise failure, damage and micro-cracking would have been observed at other pit locations on the L-1 blade.

4.3 Development of Root Cause of L-1 Blade Failure in the PTZ of Comanche Unit 3 LP Turbine.

While the mechanism is clearly pit induced stress corrosion cracking (SCC) and the Comanche Unit 3 failure is one of the closest to following the deterministic model, adumbrated in Sections 4.2.1 to 4.2.4 for SCC in the PTZ that SI has seen, there are still a number of aspects which were not available during the assessment, were not measured or are not understood fully. As has been discussed, seven mechanism factors have to "line up" mechanistically at the same location on a blade surface for the mechanism to reach failure. These include:

i) nucleation of concentrated condensate droplets as steam expansion crosses the saturation line (concentration increases with contamination of MS and HRH),
ii) formation of concentrated liquid films on the blade surface (concentration increases with contamination of MS and HRH),
iii) formation of deposits and impaction of salt crystals on the blade surface,
iv) oxygenated moisture formation at the deposit/crystal location on the blade surface during non-protected shutdowns,
v) pit nucleation and growth during repetitive operation and shutdown,
vi) initiation of micro-cracks at the bottom of pits in regions of elevated stress at the locations of concentrated liquid films on the blade surface, and
vii) SCC under a high steady centrifugal stress coincident with a concentrated liquid film.

These seven factors describe the mechanism as a whole. The root cause of the failure situation at Comanche, as for any mechanism of failure, must relate to the individual parts/factors of the mechanism of failure. The root cause also needs to be at the most basic level and something that can be addressed and is key to allowing all the seven factors to take place. Items i) to iv) are influenced and controlled by the cycle chemistry on the Comanche unit. Items i) to iii) take place in every steam turbine, and the influence of each in the overall mechanism is increased by increasing levels of contamination in the MS and HRH such as occurred at Comanche (Section 3.2). At Comanche, items ii) and iii) are exacerbated by the presence of the snubber. The presence of oxygenated moisture (Item iv)) during shutdowns on blade surfaces results, after repetitive cycles of operation and shutdown, in the formation of pits which are observed on many turbines. But these pits only provide the initiation sites for micro-cracks and SCC if there is coincident influence of stress (items vi) and vii)) and a liquid film (item ii)) at the same location. The stress at the snubber/blade interface must be elevated and therefore focuses items vi) and vii).

Overall research has shown that the probability of blade failure by stress corrosion cracking or corrosion fatigue increases by at least a couple of orders of magnitude if the LP turbine is not protected during shutdown as compared to situations where protection is provided as this prevents oxygenated moisture forming on the blade surfaces (Dooley & Macdonald). At Comanche, it is clear that without the pits (item v)) there would not have been micro-cracking, cracking and failure so the presence of moisture during shutdown (item iv)) became the critical root cause step in the overall process of the failure.

<u>Stress</u>.
At Comanche, clearly there has to have been an elevated level of stress which was great enough at the pit sites at the blade/snubber location (Figure 1) to first initiate a micro-crack from the jagged surface at the bottom of the pit and then grow it to a threshold size. Then for the SCC crack growth mechanism there has to be a continuous stress focused at the same location to propagate the micro-crack to a critical size. It is again mentioned that SI has not received or conducted a stress analysis of the blade profile as is normal in investigations of this type. It appears clear from the preceding discussion in this section of the report that the blade/snubber interface is not only the location of increased deposition and concentrated liquid film formation (Section 2.2) but is also a region of elevated blade stress. No consideration has been given by SI to the possibility of the snubber design being responsible for an excessive peak stress.

<u>Cycle Chemistry</u>.
Section 3.4 summarized the cycle chemistry at Comanche and indicated that the overall chemistry has been poorly managed relative to international practice, and that seven RCCS have been identified during the SI assessment. Some of these have directly influenced the seven factors of the L-1 blade failure mechanism. The predominant one relating specifically to the root cause of the blade failure is the lack of any chemistry shutdown protection (such as DHA) for the steam turbine (item iv)). Others of major importance in the mechanism include: operators ignoring alarm and shutdown situations; not using optimum chemistry treatments (OT); and unreliable chemistry instrumentation. Each of these heavily influence items i) to iii) as they control the environment in the PTZ, both liquids and deposits. It has been explained how, even on units with the best chemistry, the processes of droplet nucleation, liquid film formation and blade deposits occur. The condenser contaminant event (Section 3.2) of 2012 exacerbated all these key steps and also contaminated the plant's internal surfaces. Because

the total unit was not cleaned after this serious condenser leak, these subsequently became additional resources for the salt crystals and the initiating centers for pitting (item iii)). A suggestion has been made that the deposition occurred preferentially at and near the snubber leading to pitting in oxygenated moisture during multiple non-protective shutdowns between 2012 and 2019 (see Table 1). This has now been confirmed by the photographic evidence (Section 2.2). It is very clear from the science and deterministic model that the lack of any shutdown protection was the key in transforming the normal PTZ processes into a failure situation. This is regarded as the key aspect of the root cause of the Comanche L-1 blade failure.

It is well understood for the SCC mechanism that the crack initiation phase is most often the longest, so it is expected that the formation of pits was more pronounced closer to the contaminant event. Other possible contaminant events were investigated in detail (Section 3.2) and although there has not been similar contamination as the 2012 condenser leak, there have been repetitive exceedances in the MS and HRH steam.

The bottom line on the cycle chemistry is that there is credible evidence that the cycle chemistry during the condenser leaks of 2012 contributed significantly to the mechanism processes (Sections 4.2.2 and 4.2.3). The operating practices were seriously deficient during this time (Section 3.2), the chemistry alarm system was either not working, turned off or ignored, and most importantly the unit should clearly have been shut down in accordance with any shutdown guidelines, Comanche or international. However, it is the lack of provision of a shutdown system using DHA for the LP turbine that provided an environment which allowed the deposits to become initiating centers for pits over a number of operation/shutdown cycles.

5 Suggested Action Plan Outlines to Address the Cycle Chemistry Deficiencies and RCCS Identified at Comanche Unit 3

The SCC mechanism of the January 2020 L-1 blade failure was heavily influenced by the cycle chemistry, which has been poorly managed and operated since the COD (Section 3). Seven RCCS have been identified and need to be addressed as expeditiously as possible so that further cycle chemistry influenced failures and damage can be prevented. Discussion focused during the seven telecoms with the Xcel technical and management staffs on the following areas of cycle chemistry:

i) Procedures for monitoring total iron and the need for baseline monitoring of the current chemistry
ii) Use of i) to develop optimum OT for Comanche
iii) Use of i) to assess and confirm any alternate chemistry such as increase of feedwater pH and the use of a film forming substance (FFS)
iv) Use of i) to minimize FAC in the ACC and total iron corrosion products flowing to the boiler
v) Confirmation of internal waterwall deposits to extend (at least double, but hopefully triple, the periods between chemical cleans)
vi) Policies and procedures to make the cycle chemistry continuous instrumentation a major resource for the Comanche plant
vii) Acquire equipment and develop procedures to provide shutdown protection for the boiler, feedwater heaters and the steam turbine. To include DHA for LP steam turbine and RH
viii) Optimize AIL procedures by formation of a Comanche AIL team
ix) Challenging the status quo of the chemistry treatments and control, and upgrade them to the latest international standard. The major item here is to develop a comprehensive Chemistry Manual for Comanche Unit 3
x) A key part of the Manual will be the development of Cycle Chemistry Guidelines which include normal, action and shutdown limits
xi) Training of operators to be aware of the Chemistry Manual and Guidelines especially realistic and audible alarms for Action and Shutdown limits. Operators also need to understand the failure mechanisms that can occur in supercritical plants

This report section provides initial outlines of the cycle chemistry activities suggested to address the RCCS, the Benchmark factors in Section 4 and the chemistry aspects associated with the L-1 blade failure.

5.1 Outlines of Action Plans to Address the Cycle Chemistry at Comanche Unit 3.

A. <u>Corrosion Product Transport.</u>

Proper monitoring of total iron at the economizer inlet provides confirmation of whether there is optimum chemistry control, whether flow-accelerated corrosion (FAC) is under control in the feedwater system, and whether the transport of iron is minimized. Monitoring of iron in the condensate provides an indication of whether FAC is controlled at the tube entries of the ACC. Most importantly such monitoring can be used at

Comanche Unit 3 to verify changes in chemistry control such as: a) optimizing the OT, b) closing the LP feedwater heater vents, and c) changes in feedwater pH. First, procedures and techniques need to be developed for monitoring total iron on the Comanche Unit 3. Then this process can be used to develop a baseline understanding of the current chemistry treatment. Once these activities are complete then the plant will be able to address any changes to the Status Quo as indicated below.

As discussed in Section 3.1.4, iron corrosion products have been monitored at Comanche using integrated sampling at the EI using flow through a 0.45 μm filter paper. These procedures are not in line with the international standard for monitoring total iron, so the low results clearly do not represent the corrosion processes within the condensate and feedwater system, and do not relate to the need for frequent chemical cleans (Section 3.1.7). Therefore, the iron results cannot be used to assess whether the cycle chemistry on Comanche Unit 3 has been optimized or not. The plant needs to adopt the procedures in the IAPWS Corrosion Product Technical Guidance Document so that the chemistry at Comanche Unit 3 can be directly compared with the large number of other supercritical units worldwide that SI has assessed. Consistent and achievable total iron levels using the internationally accepted procedures for supercritical units operating with optimum OT are: at the EI < 1 ppb, condensate downstream of the ACC or at the CPD < 10 ppb, and after the 3 μm absolute filter < 5 ppb.

Outline of Action Plan 1. Develop a Consistently Reliable Procedure for Monitoring Total Iron.

SI suggests that the Xcel staff introduce a total iron monitoring program including recognized accurate analytical techniques using ICP-MS or AA with graphite furnace. It is recognized that Comanche does not have this equipment but could use an outside laboratory or a chemical supplier. This program should address: a) the correct time to sample, b) digestion of particulate iron, and c) the use of an accurate analytical procedure. Once these procedures are fully working then the Xcel staff can develop the protocols to be used in the monitoring campaign.

It should be noted that there is an IAPWS Technical Guidance Document (TGD) on Corrosion Product Sampling and Analysis which should form the basis of the monitoring program.

Outline of Action Plan 2. Use Iron Monitoring Procedure from Action Plan 1 to Develop an Understanding of the Baseline (Current) Chemistry on the Comanche Unit 3.

At Comanche, total iron measurements should provide the vital indicator of whether the unit's cycle chemistry is optimized, whether FAC in the feedwater is under control, and most importantly whether the iron transport levels to the boilers are minimized. Initially it is necessary for the plant to assess the current chemistry; this is referred to as the "baseline series of tests". It is suggested that the final feedwater at the EI and the condensate at the CPD are monitored for total iron. The sampling locations at the HP Heater 6 A and B drains could also be monitored. For each monitoring campaign the data of the following key parameters as a minimum should be recorded in parallel: dissolved oxygen, CACE and sodium at the CPD and EI; pH at the EI; and CACE and sodium in the main steam.

It is suggested that the procedures based on the IAPWS Guidance (Action Plan 1) are used for a specific set of baseline tests so that the total iron values can be related to the specific OT chemistry under controlled operating conditions. These baseline tests should be run with the chemistry as of January 2020 and as outlined in Section 2. These could involve a feedwater pH of ~9.6. It is important for this series of tests that the operating conditions are similar for each set of samples collected. The IAPWS Technical Guidance Document (TGD) on monitoring total iron suggests that the samples should be taken only during steady high load conditions that have been maintained for at least 3-4 hours, not at the same time each day or when convenient for the chemist or operator. The test conditions should last for at least one month to ensure that the surfaces within the various circuits are stabilized. The frequency of sampling for these tests should be considered as once per week as the minimum. The total iron analyses should be conducted using the procedures developed in Action Plan 1, which have been found to have an adequate detection limit.

It is expected that results from this Baseline Series of tests (current chemistry) could be complete within three months. The procedures developed need to be inserted into the plant Chemistry Manual.

Iron testing only needs to be performed as needed to optimize the chemistry and for periodic verification that it remains so. Routine testing of iron is not required on a daily or weekly basis following this exercise: The IAPWS TGD suggests that once every six months will suffice once the chemistry is optimized. It should also be noted that there is no need to monitor iron in MS or HRH.

B. Waterwall Tube Deposits and Indigenously Grown Oxides.

This RCCS at Comanche is included because of the extreme importance for the boiler of managing internal waterwall deposits to prevent BTF. The possible BTF mechanisms that can emanate on the waterwalls of the Comanche Unit 3 are thermal fatigue (also called circumferential cracking) and overheating/creep. These are among the most important damage/failure mechanisms that occur in supercritical boilers. The key to avoiding them is to ensure that the deposits/oxides are identified and analyzed and that they do not exceed levels which can lead to failures and damage. The Action Plan to monitor corrosion products (Item A) should be linked directly to the program to measure internal waterwall deposits and the assessment of the need to chemically clean. Xcel should plot the total rate of increase for deposits and oxides for the Comanche boiler and thus be able to predict when/if a chemical clean is needed. The overall goal should be for the Comanche boiler to operate safely for at least 15 years without having to chemically clean the waterwalls. This will lessen the possibility for the supercritical boilers to experience overheating and/or thermal fatigue. The developed procedures should be inserted into the plant Chemistry Manual.

Outline of Action Plan 3. Developing an Overall Approach to Minimizing Deposition and Oxide Growth on the Internal Waterwall Surfaces of the Comanche Unit 3 Boiler

The growth of waterwall tube internal deposits is related to the transport of corrosion products (measured as total iron) from the feedwater. Minimizing corrosion product transport through optimization of the chemistry will minimize deposition on the waterwalls.

Xcel should continue the program of regular waterwall sampling on the Comanche boiler (Section 3.1.7) which identifies the deposit loading, deposition rate and indigenous oxide thickness in direct correspondence with, not divorced from, the monitoring of total iron. The analysis of these waterwall samples is most important and should follow a four-pronged approach which includes the following aspects:

- Level of total internal density (overall loading) in g/ft^2 using the ASTM standard for internal deposits, ASTM D-3483
- Optical metallography of cross-sections through the tube, indigenous oxide (magnetite and spinel) and deposit.
- Total thickness of the indigenous oxide and deposits from the optical metallography of cross-sections through the tube (micrometers or mils).
- Scanning electron microscopy and elemental mapping of cross-sections to determine the distribution of elements and any reaction products within the deposit. Sometimes it is necessary to use X-ray Diffraction (XRD) to identify the compounds within the deposits.

The total value of the "normal" deposit density/oxide thickness (g/ft^2) using the solvent or glass bead blasting removal method should be < 20 g/ft^2. This is the typical range above which consideration should be given to chemical cleaning boilers like Comanche Unit 3.

C. <u>Cycle Chemistry Instrumentation.</u>

This Repeat Situation involves the most basic item of cycle chemistry control for all fossil units. While the original instrumentation design for Comanche was in full agreement with the international standard for supercritical units (Section 3.1.3), the actuality of operation has been far removed (Section 3.1.3) from any international standard due to poor calibration, maintenance and reliability of the instruments. Not only this, the instruments have not provided accuracy for the operators to the point that serious contamination alarms limits and shutdown conditions have been ignored. The SI strong suggestion is to have a fundamental level of chemistry instruments alarmed in the control room for the operators' immediate attention with up to date chemistry normal limits which are in agreement with the international standards. This should be delineated in the Chemistry Manual.

<u>Outline of Action Plan 4. Upgrade the Comanche Unit 3 Instrumentation to the International Standard.</u>

As discussed in Section 3 there have been many times at Comanche when EI, MS and HRH sodium levels have all maxed out and continued at these high levels for up to 8 hours. Xcel staff have reported problems with flow to the instruments during startup, sharing of analyzers, and inadequate calibration /maintenance of the instruments. Supercritical units cannot be operated under these constraints or by using grab samples where operators can miss or ignore exceedances of normal chemistry limits. Xcel needs to make sure that the Comanche Unit 3 has the minimum level of key instruments (Table 3) that are unique (<u>not shared or switched</u>), and that all the instruments are frequently calibrated and maintained on a 1 – 2 week frequency. This will involve purchase of some new instrumentation. It will also involve ensuring that the sampling system and flow requirements are in full agreement with the IAPWS TGD on Instrumentation. One major problem for instrumentation at Comanche has been the startup periods. The emphasis must be to reduce the time to acquire correct and representative analyses and to identify any chemistry issues as soon as possible so that the chemistry does not restrict return to service and provides operators with the needed chemistry information to protect the steam turbine. There are also some advantages for keeping the key instruments (silica, conductivity and CACE) on a continuous refreshing cycle during the shutdown or off-line periods with demineralized water to keep the analyzer working. This should not be applied for the sodium probes as the sensitivity can be reduced if continuously flushed with high purity water.

This Minimum Key Level of Instruments should all be audibly alarmed in the control room or on the distributed control system.

It is also worth repeating a key message from Section 3.1.3. Grab samples should be minimized with the manhours being more usefully used for the calibration and maintenance activities. Grab samples should never be used to control supercritical units.

Table 3. IAPWS Minimum Key Level of Instrumentation customized to all-ferrous supercritical units with Condenser and ACC like at Comanche operating on OT. (The full IAPWS Guidance Document can be downloaded from www.iapws.org).

Parameter	Sample Locations
Conductivity after cation exchange (CACE)	Condensate Pump Discharge (CPD) Condensate Polisher Outlet (CPO) Economizer Inlet (EI) Main or Reheat Steam (MS or RH)
Degassed CACE	Condensate Pump Discharge (CPD) Main Steam (MS)
Conductivity	Makeup to Condenser (MU) Economizer Inlet (EI)
pH	Economizer Inlet (EI)
Sodium	Condensate Pump Discharge (CPD) Condensate Polisher Outlet (CPO) Main or Reheat Steam (MS or RH)
Dissolved Oxygen	Condensate Pump Discharge (CPD) Economizer Inlet (EI)

D. Shutdown Protection

Protection of the Comanche Unit 3 during shutdown was discussed in Section 3.1.6. The boiler and feedwater heaters were designed to have nitrogen blanketing applied at about 5 psi during shutdown periods, but these facilities have not been used since 2012. Although MHI recognized that protection for the LP steam turbine using DHA was desirable, facilities for this were not provided for Comanche by MHI or Shaw, so consequently the steam turbine PTZ has operated since COD without any protection during the large number of shutdown periods of greater than three days. This is unfortunate because, as discussed in Section 4.2.5, the presence of oxygenated moisture during shutdowns on blade surfaces is regarded, after repetitive cycles of operation and shutdown, as the key mechanism factor (root cause) for the formation of pits as the initiating centers for the SCC.

This RCCS is multi-faceted and important as serious pitting damage has been observed on the PTZ blades. Based on SI's experience worldwide, there is also a strong possibility that pitting and BTF will occur in the reheater tubing in the future. Numerous organizations have needed to replace reheater sections and introduce RH tube dryout procedures using DHA or compressed air. Similar blade failure situations as at Comanche have resulted in the use of DHA or turbine instrument air dehumidification for periods of shutdown greater than three days.

Outline of Action Plan 5. Develop Comprehensive Shutdown Protection Procedures for Comanche Unit 3.

The current shutdown protection regimes are not adequate for Comanche and SI suggests that an Action Plan is developed to provide a comprehensive shutdown protection scheme, and that this becomes an important section of the Chemistry Manual. The scope for a detailed design is beyond the scope of the current assessment, but SI suggests that the following items should be considered:

- Re-activate the nitrogen blanketing systems to provide 5 psi overpressure nitrogen for boiler and feedwater systems. Provide revised operating procedures for shutdown situations outlined in Section 3.1.6.
- Review of sources of moisture into the condenser during shutdown (Section 3.1.6)
- Evaluation, design and installation of DHA system for the LP turbines for periods when the unit is shutdown for more than three days. Commercial systems are available through Munters and Bry-Air. Develop operating procedures.
- Monitoring of humidity on the inlet and outlet air to ensure that condensation is being removed. The objective is to prevent condensation on turbine surfaces by maintaining the relative humidity of the air in contact with surfaces at or below 40% (Vernon curve).
- NDE inspection or sampling/analysis of RH tube samples.
- Provision of air or DHA to the reheater. Some plants have installed systems in conjunction with the use of DHA in the LP turbine.
- Evaluate the technical and economic aspects of developing shutdown protection procedures for the boiler, reheater, feedwater systems and the steam turbines.

E. Air In-leakage

High condensate dissolved oxygen (values > 10 ppb) is often present as a result of poor air in-leakage (AIL) control which was confirmed through the SI analysis and review of the cycle chemistry at Comanche Unit 3. This identified elevated levels of oxygen in the condensate (CPD) over most of the operating period since 2010 (Section 3.1.4a). In plants with ACC like Comanche, SI has found that in most cases the AIL results from equipment not associated with the ACC, and the AIL inspections (Section 3.1.4a) have confirmed that the major AIL locations since 2011 have been BFP shaft seals and flanges, LP turbine shaft seals, and condenser expansion joints. There is a Comanche Condenser Air Removal Systems Operation document (COOP-3-MCAR-01, dated 20th April 2016) which doesn't include the requirements for the necessary AIL inspections which appear to be conducted on a three year basis.

Outline of Action Plan 6. Develop a Comanche AIL Program.

High levels of condensate oxygen are a clear indicator of air in-leakage. The Xcel/Comanche staff should develop an air in-leakage program in full agreement with the IAPWS TGD on this topic: 1) measurement/monitoring of AIL by the operators, 2) recognition by the chemists/operators of elevated condensate oxygen, 3) use of an inert tracer gas (helium) to identify sources of AIL, and 4) correction of leak sources as a high priority maintenance item, not in a periodic fashion. SI has not seen an Air In-Leakage Guidance Document or been informed of an AIL Team at Comanche. Such a document should be developed and include an outline of the methods which are available and used to detect AIL. It should also outline procedures which should be developed by the plant to establish a prioritization matrix for testing, administrative action limits and a leak testing checklist. The document and procedures should become part of the plant Chemistry Manual.

It has been mentioned previously that there is an IAPWS TGD on AIL. It is planned to use this to develop the ACC Users Group Guideline.

F. Challenging the Cycle Chemistry Status Quo for Comanche Unit 3.

As well as the sub-sections A to E, previous sections in this report have discussed that the cycle chemistry operated on Comanche Unit 3 is very much out of date and needs bringing into current international alignment. The following items need to be addressed:

i) Operating on full OT as outlined in Section 3.1.1 with LP heater vents closed
ii) Define the optimum condensate/feedwater pH to provide FAC protection in the feedwater and ACC which will minimize feedwater corrosion product (total iron) being transported to the boiler
iii) Develop a comprehensive Chemistry Manual which includes an integrated up-to-date guidance for condensate, feedwater, boiler water and steam for Comanche Unit 3.

Items i) and ii) can be addressed through the following Action Plans using the Total Iron Monitoring Program developed in Action Plan 1 and the baseline results from Action Plan 2. Successful implementation of these Action Plans should enable the plant to reduce the risk for FAC, optimize the cycle chemistry control, and most importantly put the Comanche Unit 3 on the path to worldclass performance.

Outline of Action Plan 7. Conduct Monitoring Campaigns to Optimize the Cycle Chemistry in the Feedwater and Condensate of Comanche Unit 3 by Changing to Full OT with the Optimum pH to Minimize Corrosion Product Transport

Once the baseline (Action Plan 2) tests have been conducted with the current chemistry then the Xcel/Comanche staff will have an accurate understanding of the level of total iron in the feedwater and condensate and how close these are to the achievable levels for supercritical units with ACC. This will be the time to change the feedwater chemistry to full optimized OT and to conduct a second monitoring campaign using the same monitoring protocol as developed in Action Plan 1 and the same locations and parameters as used in Action Plan 2 in the following logical steps. At least a month will be needed for each of the following suggested tests to record consistent total iron levels at the EI and CPD:

i) The first suggested activity for OT is to use the same feedwater pH (~9.6) as used in the baseline testing. This should involve developing the procedures for: a) one oxygen injection point at the CPO, b) closing the vents on the LP Heaters, and c) ensuring the DA vents are closed. It should be noted that this activity could take 1 – 2 months or even longer. The key observance of full conversion will be when the EI oxygen level is above 90% of the oxygen level in the LP feedwater (at the DAI). A suggested oxygen level is 80 – 100 ppb. The total iron levels at this stage should be less than the levels from Action Plan 2.
ii) Once the total iron levels at the EI and CPD have stabilized, and if they are not consistently less than 1 and 5 ppb respectively, then a third monitoring campaign should be conducted with feedwater pH being elevated by 0.2 pH units.
iii) If later Xcel decides to consider an additional FFS treatment then the same monitoring procedures must be used.

Outline of Action Plan 8. Develop a Chemistry Manual for Comanche Unit 3 to Include the Latest International Guidance Limits.

As part of challenging the status quo the Xcel/Comanche staff should develop a Chemistry Manual and provide the latest Cycle Chemistry Guidance for the plant. In parallel with the other Action Plan outlines, the current chemistry specifications ("Comanche Guidance") should be updated by adopting the OT limits as shown in Table 4 which have been customized to the Comanche Unit from the IAPWS Technical Guidance Documents. A set of chemistry alarms will need to be developed once the chemistry has been upgraded. These limits should be in agreement with those available for the operators on their DCS screens. A most important further item is to develop the operating procedures so that the operators know how to respond correctly and quickly to any chemistry excursions on the units. This is one of the most important concerns for reliable future operation of Comanche Unit 3 and the shutdown limits should be in line with the IAPWS guidance for shutdown at a CACE in the feedwater (EI) which exceeds 2 µS/cm for two minutes and is increasing. Alternatively, a sodium level at the condensate polisher outlet (CPO) can be used which exceeds 20 ppb in the same time period and doesn't show any decreasing trend.

Training for the operators should also be conducted on this new guidance.

The Chemistry Manual should also include the other procedures which will be developed from the Action Plans included in this report section. The Manual should be reviewed each year and signed/approved by the Plant Manager; this will ensure that operators follow cycle chemistry guidance, action and shutdown levels.

SI has supported clients in the development of plant and unit specific Plant Cycle Chemistry Manuals worldwide helping to ensure that the program properly applies the IAPWS TGD information on cycle chemistry and instrumentation. A typical outline of a comprehensive document is included as Table 5.

Table 4. Suggested Guidance for Continuous Instrumentation on Comanche Unit 3 operating with optimized OT (See Section 3.1.1). This is customized from the IAPWS Technical Guidance Document for Volatile Treatment for a supercritical unit with a once-through boiler, all-ferrous feedwater system, hybrid cooling (ACC and wet condenser), and a condensate polishing system.

Locations / Parameters	Normal / Target Values for OT
Condensate Pump Discharge (CPD)	
CACE (DCACE), µS/cm	< 0.3 (< 0.2)
Dissolved Oxygen, ppb (µg/kg)	< 10
Sodium, ppb (µg/kg)	< 3
Condensate Polisher Outlet (CPO)	
CACE, µS/cm	< 0.15
Sodium, ppb (µg/kg)*	< 2
Economizer Inlet (EI)	
Conductivity, µS/cm	Consistent with pH
CACE, µS/cm*	< 0.15
pH (actual pH to be based on monitoring Fe)	9.6 – 9.8
Dissolved Oxygen, ppb (µg/kg)	30 - 150
Main Steam (MS) / Hot Reheat Steam (HRH)	
CACE (DCACE), µS/cm	< 0.2
Sodium, ppb (µg/kg)	< 2
Makeup (MU)	
Conductivity, µS/cm (on line from DST to condenser)	< 0.1

*__*Table Footnote*__: *Unit Shutdown Limits: For supercritical units, a CACE in the feedwater which exceeds 2 µS/cm for two minutes and is increasing should be used. Alternatively, or in addition, a sodium level at the condensate polisher outlet can be used which exceeds 20 ppb in the same time period and doesn't show any decreasing trend.*

Table 5. Typical Content of Plant Chemistry Manual.

Section	Subject
1.0	Introduction
2.0	Purpose
3.0	Objectives and Goals of Chemistry Program
4.0	Programme Roles and Responsibilities
5.0	Program Benchmarking (Cycle Chemistry, FAC and DHACI for the ACC). Annual Assessment
6.0	Repeat Cycle Chemistry Situations (RCCS). Annual assessment
7.0	Cycle Chemistry Instrumentation. Calibration and Maintenance
8.0	Cycle Chemistry Treatment Chemicals (ammonia and oxygen)
9.0	Feedwater Treatment. Oxygenated Treatment (customized from the IAPWS TGD)
10.0	Monitoring Total Iron (customized from the IAPWS TGD)
11.0	Cycle Chemistry Targets, Action and Unit Shutdown Levels (customized from the IAPWS TGD) and Corrective Actions
12.0	Air In-leakage (AIL) Monitoring and Control (customized from the IAPWS TGD)
13.0	Monitoring and Controlling Boiler Waterside Cleanliness
14.0	Shutdown Protection of Steam-Water Cycle Components
15.0	Makeup System
16.0	Grab Sample Analysis Procedures (only for validation)
17.0	Equipment Inspections (DA, ACC, Steam Turbine)
18.0	References and Source Documents

6 Concluding Remarks

Structural Integrity Associates (SI) used a deterministic assessment approach to identify the mechanism of failure, the possible causes and the most probable root cause of the L-1 blade failure which occurred in January 2020. The mechanism had been identified by Xcel as pit-induced stress corrosion cracking (SCC). This was confirmed by SI to have initiated at the blade/snubber interface where there was a concentration of aligned pits. The mechanism was broken down into seven sequential steps or mechanism factors which had to line up at the same location on a blade surface for the mechanism to reach failure. These included: nucleation of concentrated condensate droplets from superheated steam as it expands across the saturation line; formation of concentrated liquid films on the L-1 blade surface; formation of deposits on the blade surface; oxygenated moisture formation during non-protected shutdowns; pit nucleation and growth; initiation of micro-cracks and finally SCC. The most probable root cause of the failure situation at Comanche, as for any mechanism of failure, must relate to the individual parts/factors of the mechanism of failure and needs to be at the most basic level which allows all the seven factors to take place. The formation of deposits and liquid films were focused by the snubbers. The presence of oxygenated moisture on blade surfaces during unprotected, long (> 3 days) shutdowns, after repetitive cycles of operation and shutdown, led to the formation of pits which provided the initiation sites for the micro-cracks and SCC. At Comanche, it is clear that without the pits there would not have been micro-cracking, cracking and failure so the presence of moisture during shutdown became the critical most probable root cause step in the overall process of the failure.

SI reviewed the cycle chemistry at Comanche and found that the overall chemistry has been poorly managed since COD in 2010. Seven Repeat Cycle Chemistry Situations (RCCS) were identified with some of these having direct influence on the seven mechanism factors of the L-1 blade failure. The predominant one, and the most probable root cause of the blade failure, is the lack of any chemistry shutdown protection using dehumidified air (DHA) for the steam turbine. Others of major importance in the mechanism include: chemists/operators ignoring alarm and shutdown limits and maintaining operation during contamination events; not using optimum chemistry treatments (OT); and unreliable chemistry instrumentation. The information reviewed by SI throughout the investigation suggests that the condenser contaminant event of March 2012 initiated the mechanism by contaminating the plant's internal surfaces which were not cleaned after the event. The operating practices were seriously deficient during this time: the chemistry alarm system was either not working, turned off or ignored, and most importantly the unit should have been shut down in accordance with any international shutdown guidelines. Deposition occurred preferentially at and near the snubber, leading to pitting in oxygenated moisture during multiple non-protective shutdowns between 2012 and 2019. Other possible contaminant events were investigated in detail and although there has not been similar contamination as the March 2012 condenser leak, there has been repetitive exceedances of sodium contamination in the main steam (MS) and hot reheat (HRH).

SI reviewed the seven RCCS and has provided 8 Action Plan outlines so that Xcel/Comanche can address them as expeditiously as possible. This will prevent further cycle chemistry influenced failures and damage, and put the plant on the path to worldclass performance. Discussion focused during the seven teleconferences with the Xcel technical and management staffs on the following areas of cycle chemistry which need improvement: monitoring feedwater corrosion products; assessing deposits in boiler waterwalls;

establishing shutdown protection; using the latest chemistry treatments (OT); addressing and controlling air in-leakage and high condensate oxygen levels; developing a Comanche Chemistry Manual and operating with guidelines representing the latest international standards.