

# 19<sup>th</sup> SYMPOSIUM ON INDUSTRIAL APPLICATIONS OF GAS TURBINES



Operator Experience with Non-Gas Path Power Turbine  
Disc Corrosion as an Emergent Equipment Integrity Threat

by

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# Operator Experience with Non-Gas Path Power Turbine Disc Corrosion as an Emergent Equipment Integrity Threat

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2. Recent History & Power Turbine Disc Corrosion Cases
3. Hot Corrosion Considerations
4. Contaminates and Sources of Sulfur
5. Role of Wash Migration
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2. Recent History & Power Turbine Disc Corrosion Cases
3. Hot Corrosion Considerations

**NOTE**: Figures, Captions and References are as Documented in Paper 11-IAGT-304. Exceptions are for clarifying images introduced here, where appropriate references are provided herein.

4. Generalized Corrosion Considerations
5. Implications for Life Extension
6. Implications for Life Extension
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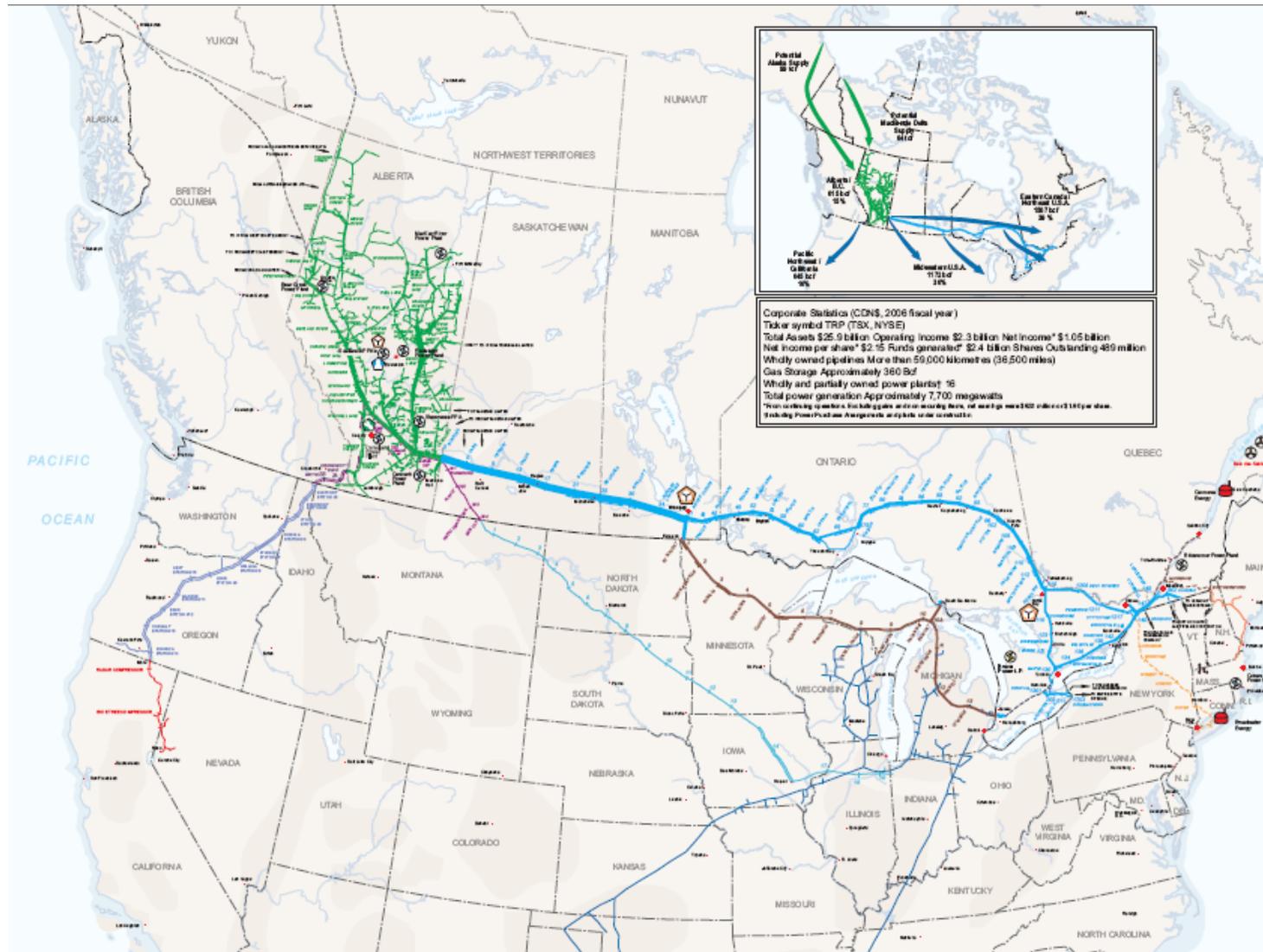


# 1.0 - Background

- TransCanada Operate a large fleet of gas turbine engines (423) in many different duties.
- Installations are throughout Canada, The US and Mexico; Operating theaters include sub-arctic, Rocky Mountains / Foothills, desert, prairie, coastal and even one off-shore unit.
- This presentation concerns recent experiences and findings during overhauls of the driven – power turbines from such equipment.



# 1.0 - Background



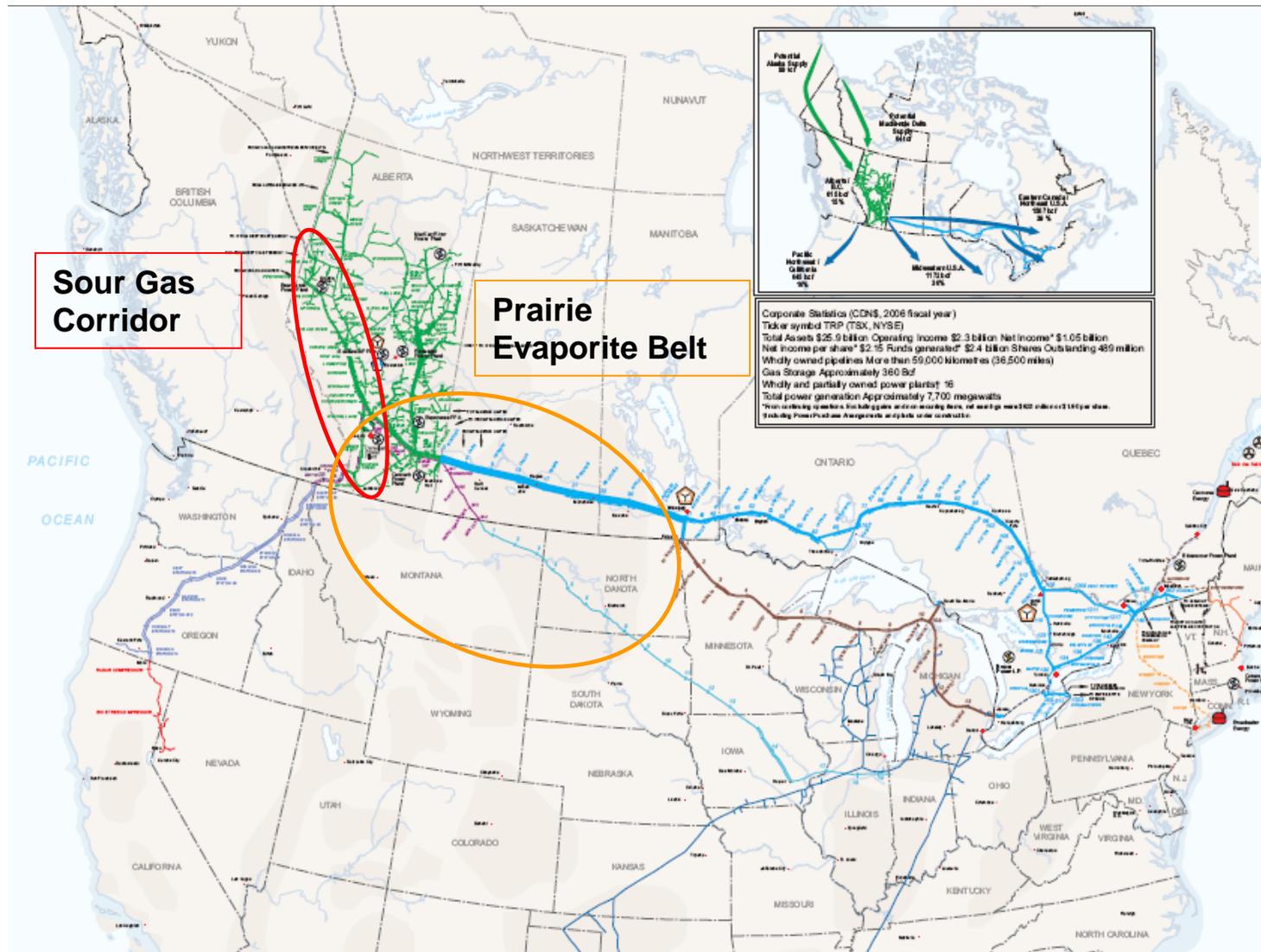
TransCanada Asset Distribution



## 2.0 – Recent Case History

- Over the past 2.5 years, TransCanada has experienced three power turbine disc cracking cases. Subsequent investigation revealed two other cases since 2000.
- In the same time period, attrition has occurred with at least five discs having been retired due to corrosion and pitting.
- In all cases investigated, the corrosion was in the absence of obvious hot corrosion on gas path components (blades and vanes) in the same machine trains.

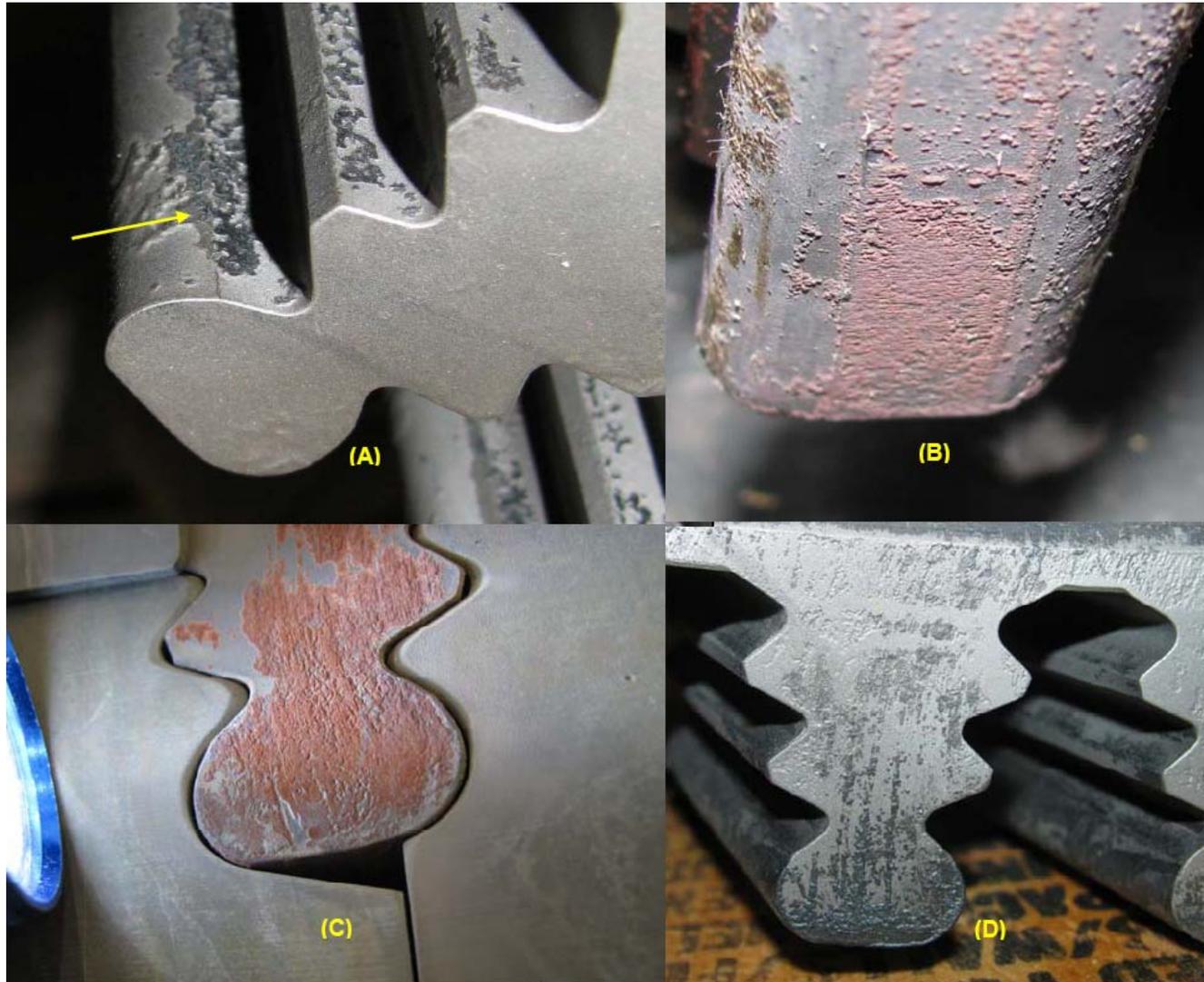
# 2.0 – Recent Case History



Operating Theatres In Discussion

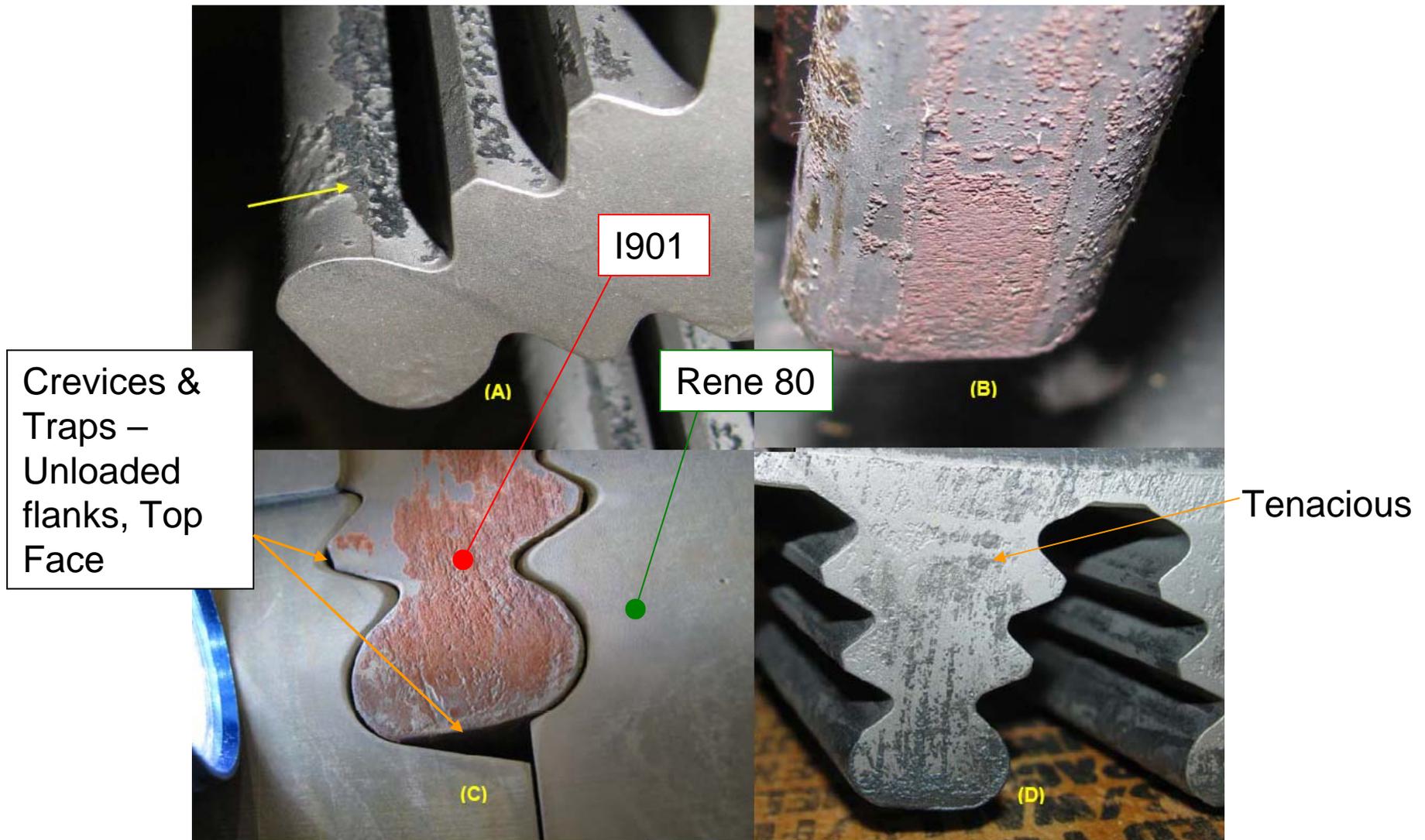


## 2.1 – Cases (Disc Rim / Posts)



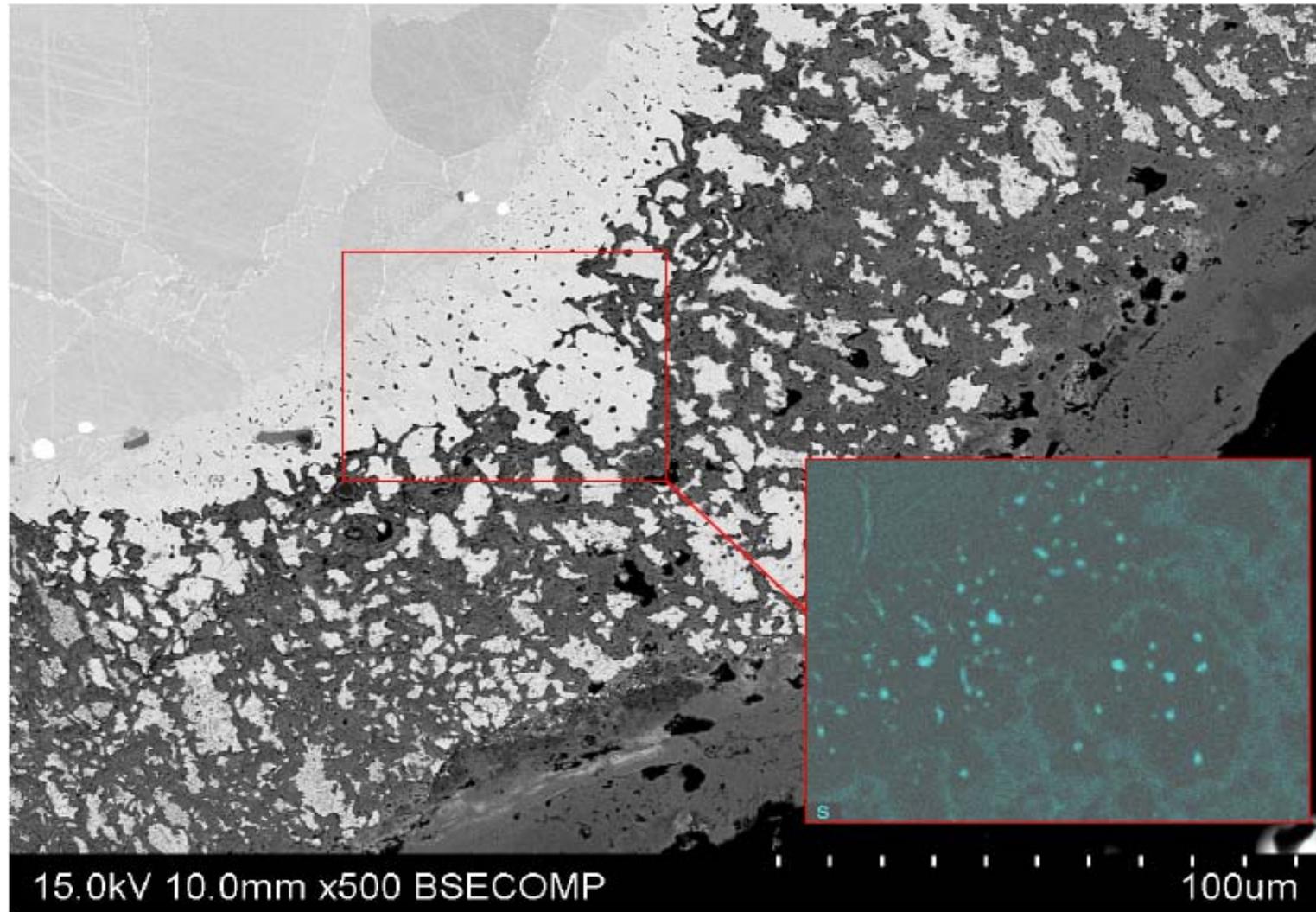
**Figure 1:** Example post conditions; A – Scale on serrations loaded surface (A-286); B – Scale on Post unloaded top face (I901); C – Post End face corrosion (I901); D – Identical disc (I901) after cleaning;

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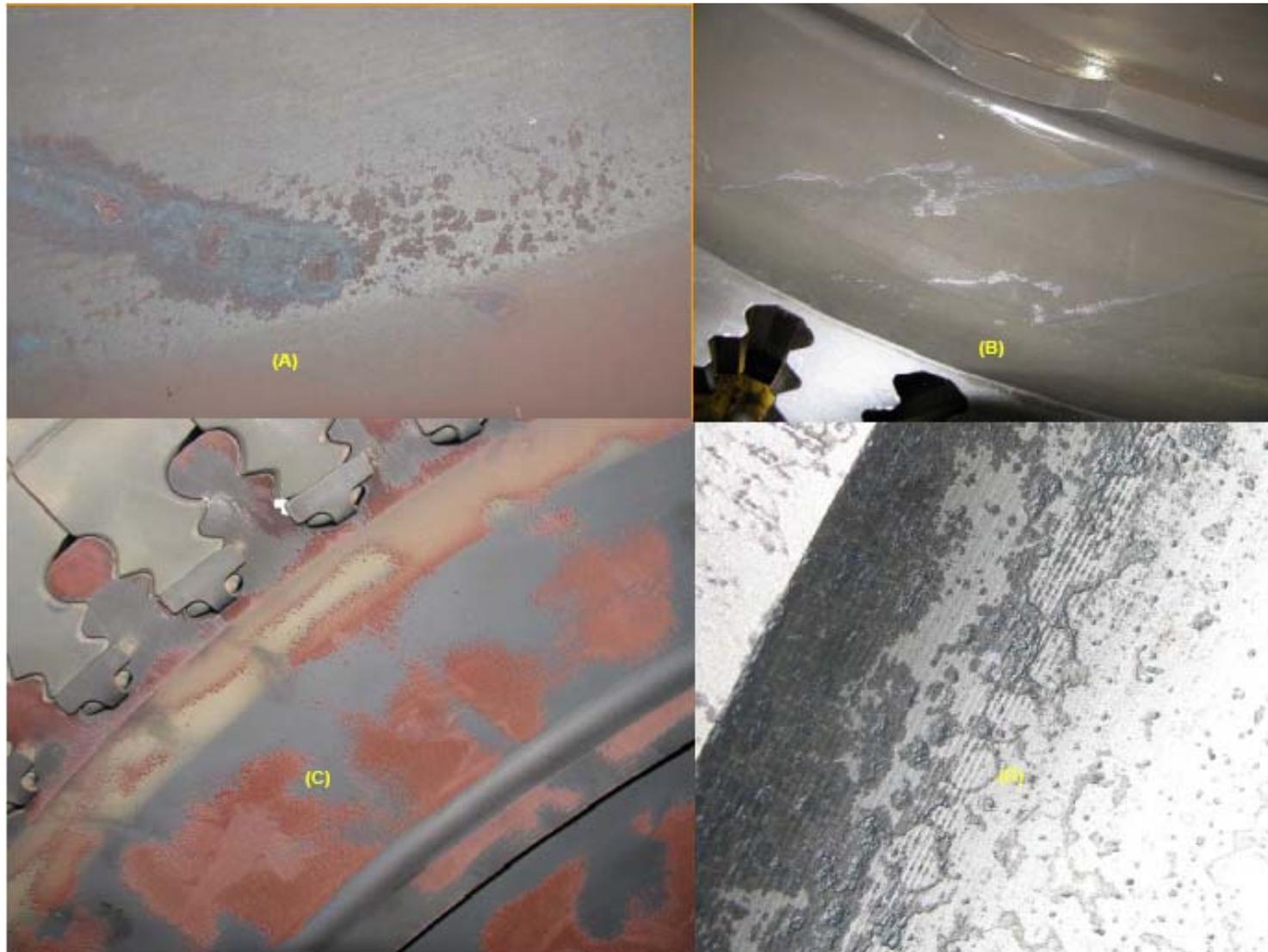


**Figure 2:** Sample corrosion on a post loaded serration (similar to Figure 1 (A)), featuring sulfide particles in a denuded zone under the scale. SEM Images courtesy G. White – RRRESI Materials Lab. [4]

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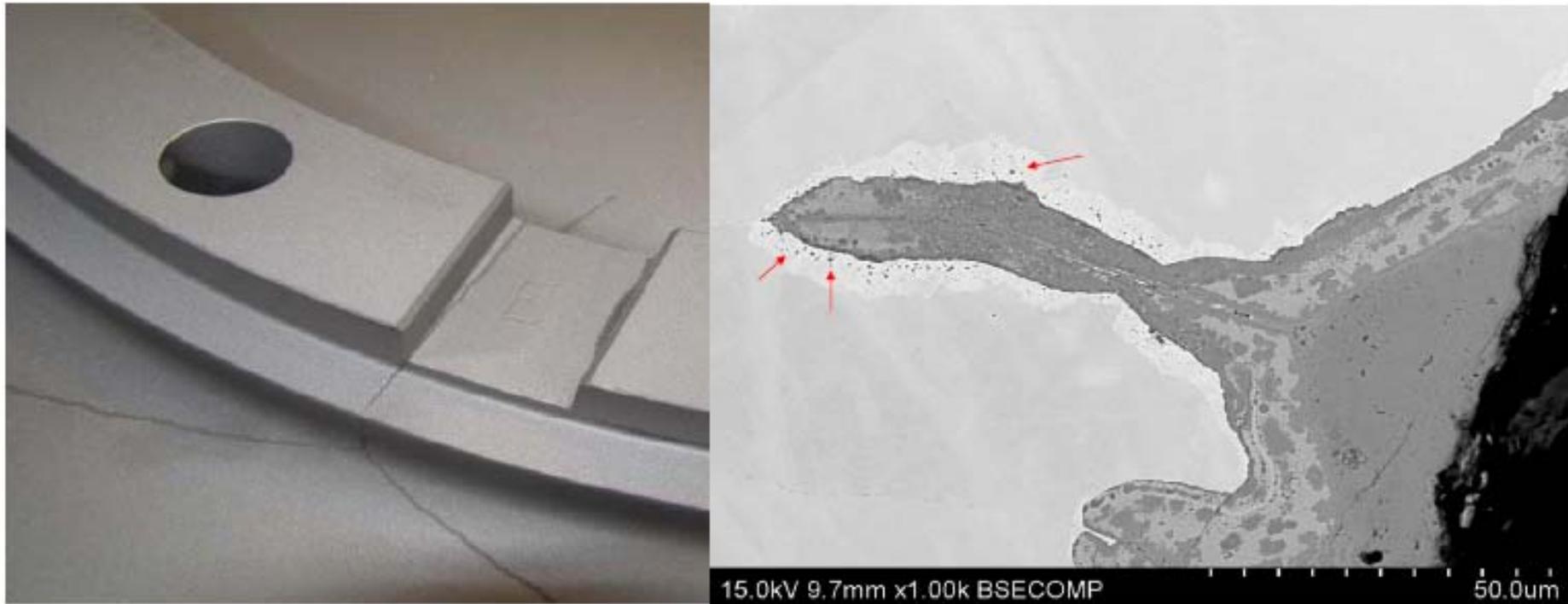
- Such scales have been investigated and have been found in some cases to show elevated molybdenum and sulphur, with products extending above the original surface some 27  $\mu\text{m}$  with a total reaction zone of 50  $\mu\text{m}$ . [1]
- In other cases, scales have featured Sodium, Magnesium, Calcium, Silicon, Cobalt, in addition to Sulphur and occasionally phosphorous. A hypothesis here involves foreign contaminants, from the environment and/or possibly remnant glass bead fines, play a role in forming a slag. It is suggested Cobalt may be a product of corrosion of the airfoil material that has transferred due to fretting action. Extreme cases found the thickness of the scale to be 114  $\mu\text{m}$ . [2] However, It has also been found that such scales can form on disc that have NOT been overhaul processed.
- Separate analysis of blade serration contact surfaces has revealed pitting with features typical of hot corrosion with sulphidation of underlying base alloy, under the pit and penetrating as far as 50  $\mu\text{m}$  along grain boundaries. Pit depths were as large as 100  $\mu\text{m}$ . However, It was specifically evaluated and found that the same blade airfoil showed typical of oxidation with no evidence of base alloy sulphidation. [3]
- Searches have found that some instances of similar attack appeared as far back as 1988.

## 2.2 – Cases (Disc Web)



**Figure 3:** A – Corrosion and pitting near a drip like deposit on a web (A-286), B – localized scaled drip like deposit (I901), C – Patchy corrosion areas that extend above original surface (I901) D – Same disc as C after cleaning.

## 2.3 – Cases (Hub / Torque Transmission Areas)



**Figure 4:** A crack at a torque transmission feature and a corrosion spike identified near the origin, featuring a chromium depleted area and sulphides (identified by red arrows) under thick scale. SEM Image courtesy G. White – RRESI Materials Lab. [12]

## 2.3 – Recent Case History

- Features as those shown near the hub / torque transmission features are obviously a significant concern. Whereas rim is an area where creep is a primary concern, the hub/flange areas are legitimate LCF areas. Adding corrosion spikes in such areas is problematic.
- Case in Point: All cracked discs were less than **550** cycles, whereas OEM have peaking power generation applications where such equipments have successfully been beyond 3500 cycles.
- These issues raise some intriguing questions:

**1. How does one manage to get hot-corrosion like attack in disc areas, without the same being manifest in the gas path components?**

## 2.3 – Recent Case History

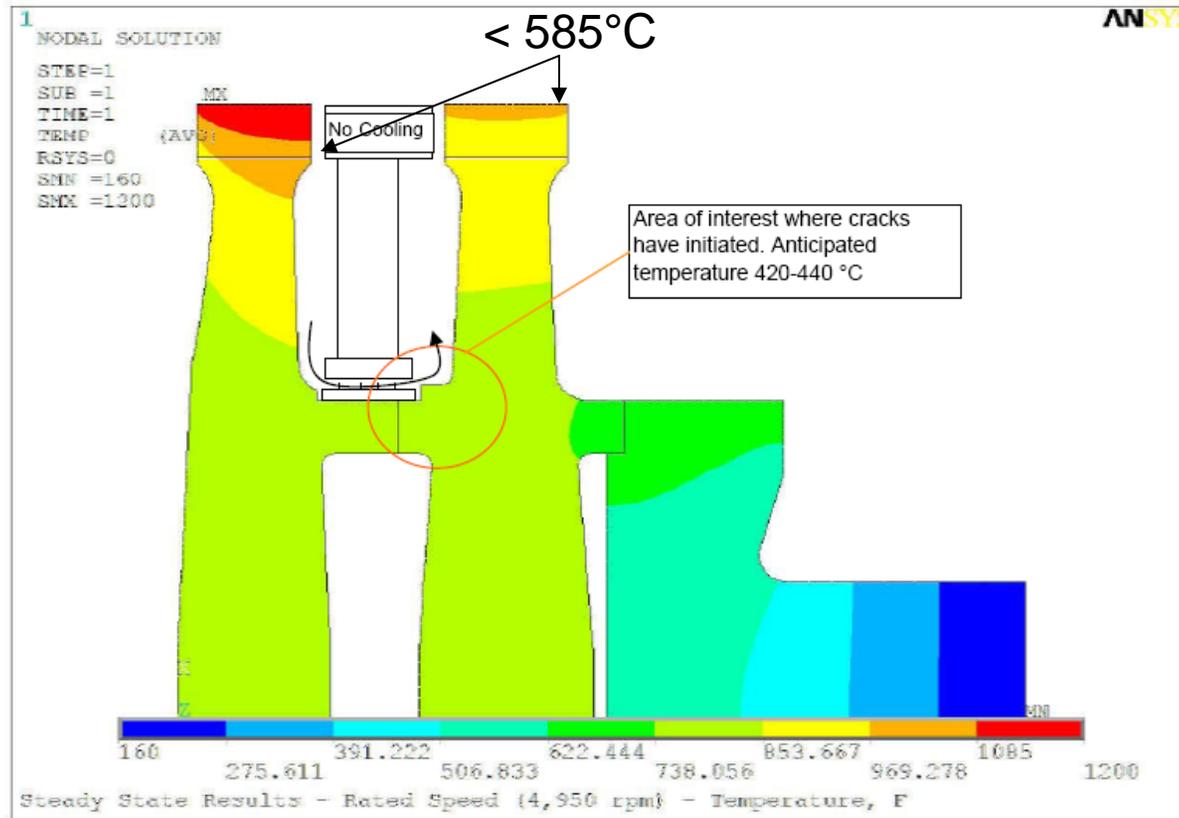


Figure 5: RT56 Steady State Thermal Analysis for rated Condition. [16]

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- These issues raise some intriguing questions:
  1. How does one manage to get hot-corrosion like attack in disc areas, without the same being manifest in the gas path components?
  - 2. How is this possible when the thermal environment in such regions is regarded to be insufficient by “conventional” explanations?**

# 3.0 – “Conventional” Hot Corrosion

A review of any good text covering “Hot Corrosion”, of which there are an abundance, will show:

- The generally accepted understanding of the process requires the formation and deposition of alkali salts and the proper thermal environment to support the reactions needed.
- More generally, a molten sulphate (such as sodium sulphate  $\text{Na}_2\text{SO}_4$  or often Vanadates in Liquid Fuel situations) is needed to react with and damage protective surface oxides on the material, after which further damage and reaction (propagation) with the alloy can proceed.
- The often offered temperature ranges for superalloy hot corrosion (which do vary from source to source) are regarded as 650-816 °C for Low Temperature Hot Corrosion (LTHC or Type II) and 871-1093 °C for High Temperature (HTHC or Type I). LTHC and HTHC are differentiated by their propagation modes and chemistry (acidic versus basic fluxing) involved in the breakdown of oxides and alloy. [13]
- LTHC also requires a relatively high partial pressure of  $\text{SO}_3$ .
- A mixed-mode has also been described that bears features of both.



## 3.0 – “Conventional” Hot Corrosion

- The context of much of the “traditional” hot corrosion research and literature that was involved in the development of this knowledge base did tend to concentrate on Nickel and Cobalt Based superalloys. This is owed to the fact that extremely premature and severe degradation would occur in a few thousands of operating hours, and was a an obvious issue for the gas turbine industry.
- By and large, these texts mostly suggest sulphur is borne in the fuel and alkali species is usually present in the air. When concentrations are correct, in a combustion environment, these form the salts that could be deposited on the affected gas-path hardware.

## 3.1 – “Less - Conventional” Hot Corrosion

- In reality, the temperature ranges inferred above for LTHC and HTHC are actually somewhat variable and fluid owing to:
  - The upper end being fixed by the dew point of the corrosive species which depends on the impurities in the flue gas. [15]
  - The lower limit is defined by the lowest eutectic melt that can be formed depending on the composition of the deposits and the material of the components. [15]
- Hence, determining contaminants that are in play is paramount to developing and understanding of the true temperature range in a given case.
- In respect to rates, researchers concentrated on liquid phases since diffusion is a rate limiting process and will be better matched to the then-observed phenomenon rates at which attack occurred.
- However, even if a salt deposit freezes on the component surfaces, reactions with existing oxide scales can reduce the melting point of the deposit by hundreds of degrees, which can set the stage for corrosion at lower component temperatures. [17]
- In this instance, we are concerned with 50-100K hours, in lieu of 3-5K hours.



## 3.2 – The Role of Alloy Chemistry

- Another consideration has to do with alloy chemistry. In some cases, disc alloys more resemble true nickel-based superalloys but in others, they are actually Iron-Nickel austenitic precipitation hardened alloys or even martensitic high-temperature steels in some designs.
- Table 1 provides a listing of some common turbine disc alloys that are of interest in respect to TCPL's fleet.

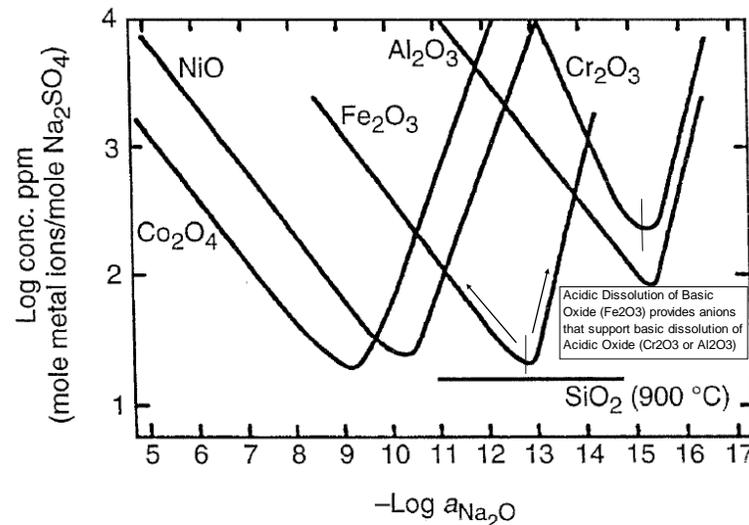
**Table 1:** Common Disc Alloys in Power Turbines and Combustion Turbines

Composition (%)											
Alloy	Cr	Ni	Co	Mo	Nb	Ti	Al	Fe	C	V	Mn
Waspalloy	19.50	57.0	13.5	4.30	-	3.0	1.4	<2.0	0.07	-	-
IN718	19.00	52.5	-	3.00	5.1	0.9	0.5	18.5	0.08	-	-
I901	12.50	42.5	-	6.00	-	2.7	-	36.2	0.10	-	-
A-286	15.00	26.0	-	1.25	-	2.0	0.2	55.2	0.04	-	-
M152	12.00	2.5	-	1.75	-	-	-	83.3	0.15	0.35	-
FV535	10.50	0.5	5.0	0.70	-	-	-	82.1	0.10	0.20	0.90

## 3.2 – The Role of Alloy Chemistry

- Rule of Thumb: More Chromium is beneficial to protective chromia formation, but it may impact other desirable material properties.
- Refractory metals (Mo, W, V) have been determined to be less desirable [15,18] as their formed oxides, if coexisting under a  $\text{Na}_2\text{SO}_4$  deposit, can give rise to “alloy induced” acidic fluxing whereby the salt is made more acidic [20].
- Similarly, synergistic dissolution of co-existing  $\text{Fe}_2\text{O}_3$  and  $\text{Cr}_2\text{O}_3$  oxides under a sodium sulphate deposit have been studied. [15,18]. Acidic dissolution of the former provides ions that feed the basic dissolution of Chromia and may have a bearing on the relative corrosion resistance of higher iron content materials.

Image: G.Y. Lai, High Temperature Corrosion and Materials Applications, ASM International, 2007. p.323.



**Fig. 11.4** The solubilities of various oxides in fused  $\text{Na}_2\text{SO}_4$  at  $927^\circ\text{C}$  ( $1700^\circ\text{F}$ ) and  $1.0\text{ atm O}_2$  (The solubility of  $\text{SiO}_2$  is at  $900^\circ\text{C}$ , or  $1650^\circ\text{F}$ ). Source: Ref 9

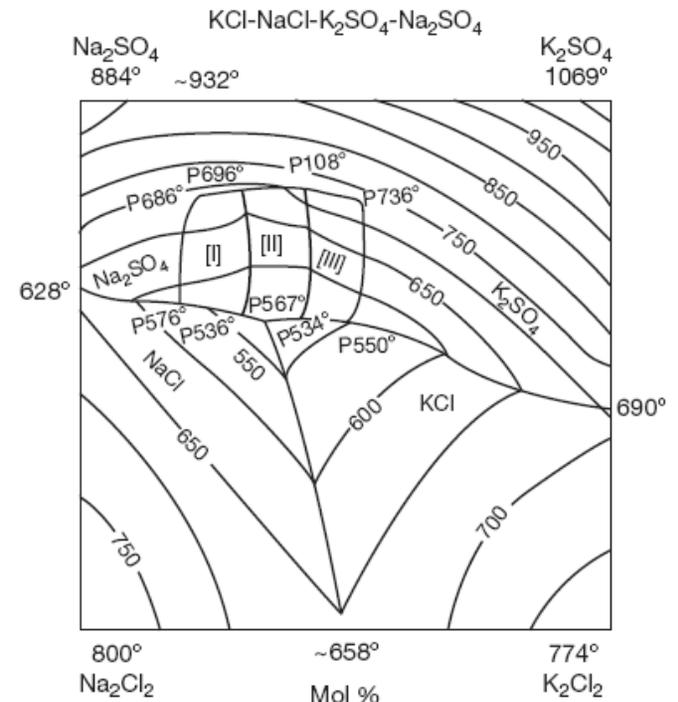
## 3.3 – Effect of Other Contaminates

- Contaminate Deposit Chemistry also can play a large role in this corrosion:
- Especially when one is considering the additional territory of Iron-Nickel and Specialty Steels within the spectrum of materials of interest. Superheater surfaces have been documented to corrode due to alkali iron-trisulphates at temperatures as low as 399 – 482 °C, although this requires reducing atmospheres with low oxygen levels. [7]
- Chlorides – in early studies chlorides were suspected of causing accelerated hot corrosion in marine environments. This can be attributed to the fact the melt point of Na<sub>2</sub>SO<sub>4</sub> can be reduced from 884 °C to 790 °C for a Na<sub>2</sub>SO<sub>4</sub>-NaCl deposit. [15] Others have observed the effect down to 620 °C. [63]
- Potassium – Although less studied, Potassium Sulphate (K<sub>2</sub>SO<sub>4</sub>) can act as the principle salt for the corrosion reactions. However, in a similar fashion, when forming a eutectic with Na<sub>2</sub>SO<sub>4</sub>, the deposit melting point drops to 831 °C. [15] Further, when NaCl is factored in, the melting points can be further depressed depending on the concentrations to temperatures as low as 550°C. [21]

# 3.3 – Effect of Other Contaminates

**Table 2:** Melting Point of Possible Corrosive Deposits [15, 22, 26]

Salt	Compound	Melting Point (°C)
Halite	NaCl	800
Aluminum Sulphate	Al <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub>	771
Calcium Sulphate	CaSO <sub>4</sub>	1449
Ferric Oxide	Fe <sub>2</sub> O <sub>3</sub>	1566
Ferric Sulphate	Fe <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub>	480
Nickel Sulphate	NiSO <sub>4</sub>	841
Sodium Sulphate	Na <sub>2</sub> SO <sub>4</sub>	884
Mixture	Na <sub>2</sub> SO <sub>4</sub> - NaCl	790
Sodium BiSulphate	NaHSO <sub>4</sub>	249
Sodium Pyrosulphate	Na <sub>2</sub> S <sub>2</sub> O <sub>7</sub>	399
Sodium Ferric Sulphate	Na <sub>3</sub> Fe(SO <sub>4</sub> ) <sub>3</sub>	538
Potassium Pyrosulphate	K <sub>2</sub> S <sub>2</sub> O <sub>7</sub>	325
Potassium Sulphate	K <sub>2</sub> SO <sub>4</sub>	1069
Zinc Sulphate	ZnSO <sub>4</sub>	680
Mixture	K <sub>2</sub> SO <sub>4</sub> -Na <sub>2</sub> SO <sub>4</sub>	831
Mixture	K <sub>2</sub> SO <sub>4</sub> -Na <sub>2</sub> SO <sub>4</sub> -ZnSO <sub>4</sub>	350
Mixture	Na <sub>2</sub> SO <sub>4</sub> - NiSO <sub>4</sub>	671
Mixture	Na <sub>2</sub> SO <sub>4</sub> - CoSO <sub>4</sub>	565



**Figure 15** Na<sub>2</sub>SO<sub>4</sub>-K<sub>2</sub>SO<sub>4</sub>-NaCl-KCl phase diagram. Reproduced from *Phase Diagrams for Ceramists*; American Ceramic Society, 1964.

Ref: JR Nichols NJ Simms “Gas Turbine Oxidation and Corrosion”, in *High Temperature Corrosion Environments*, 2010, Elsevier. P 531.

## 3.3 – Effect of Other Contaminates

- Zinc – In Waste to Energy boilers, Zinc Sulphate salts have proven to be problematic and have melting points when present (but dominant) with other alkali salts that can be below 425 °C. When combined with chlorides, hot corrosion attack has been reported as low as 200 °C. [15, 22] Zinc in itself can pose a problem on its own in that its low melting point of 420 °C facilitates LME in some austenitic stainless steels and nickel alloys. [23]
- Carbon deposits have been reported as an accelerating agent for the hot corrosion process by making sulphate deposits more basic. [7]
- Phosphorous and Lead: A study aimed at automotive applications with Nimonic 115 documented nickel containing alloys, the presence of phosphate salts such as lead phosphate or sodium phosphate, in combination with  $\text{Na}_2\text{SO}_4$  resulted in accelerated and heavy corrosion. It was also shown that a lead-phosphate/lead-sulphate mixture is also detrimental. [24]
- Calcium: Calcium Sulphate ( $\text{CaSO}_4$  – Anhydrite) can also act as the salt in the corrosion reactions and has been studied in corrosion experiments at 850 °C with carbon deposits employed to enhance sulfur activity. It was found that in such circumstances, replicating fluidised bed combustors, hot corrosion was found to occur at levels that replicated field findings. [25]

# 4.1 – Sources of Sulfur: Fuel

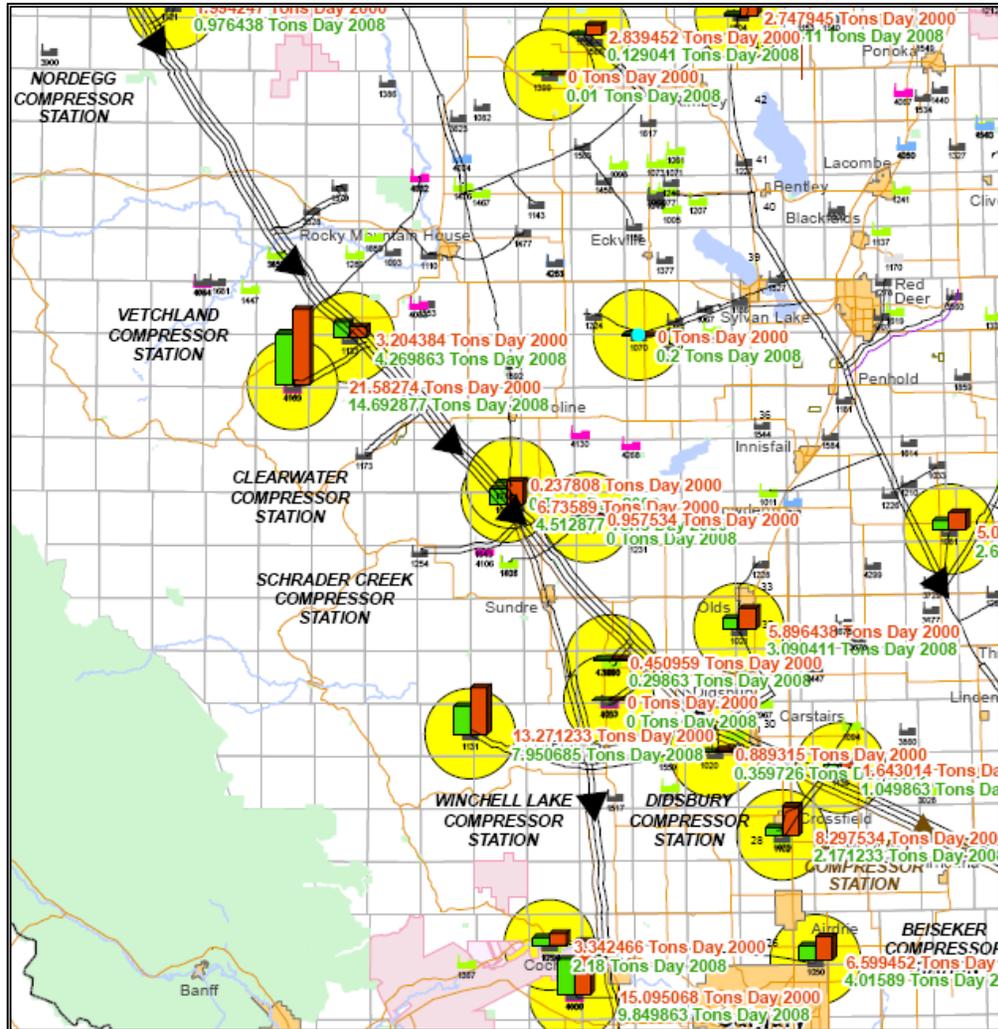
- Perspective on Sulfur Levels in Fuel: In days when sulphidation attack was common, problematic liquid (0.1% S by weight) and bunker (1-2% S) fuels contained significant sulphur levels.
- In contrast, the sweetened Natural Gas sulfur levels in the system in question (used as fuel gas) have pipeline tariffs allow a maximum of 23 mg/m<sup>3</sup> (16 ppm<sub>v</sub>) of H<sub>2</sub>S which is included in a tariff maximum total sulphur allowable level of 115 mg/m<sup>3</sup> (85 ppm<sub>v</sub>). [27]
- In reality, these numbers include some margin to account for major upsets, and average numbers in the Alberta System run Total Sulphur in the 2.7 mg/m<sup>3</sup> (2 ppm<sub>v</sub>) range while historically sustained Total Sulfur peaks can be approximately 9 ppm<sub>v</sub> (12.2 mg/m<sup>3</sup>).
- Finally, it is re-iterated that if the fuel was deemed to be responsible, one would expect the hot gas components to exhibit the symptoms as well.



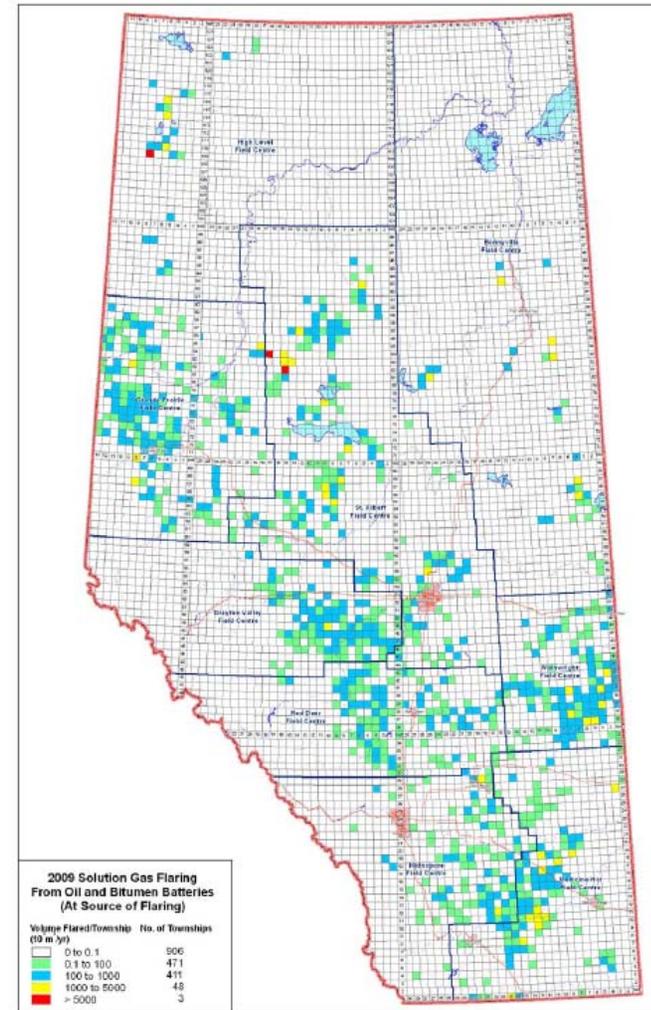
## 4.2 – Sources of Sulfur: Airborne

- Alberta has actually done a decent job in respect to cutting emissions of sulfur from sour gas processing facilities significantly over the past 15 years. (216 tpd in 2000, 120 tpd in 2008) [28]
- Similarly, restricting flaring from upstream operations has also seen a dramatic decline of release of sulphur dioxide and other species over the similar timeframe. (down to 500 tpd in 2009) [34]
- Coal and Oil Sands Operations add 356 tpd and 425 tpd respectively to the burden. [34] These are in localised areas (Wabamun, Fort MacMurray).
- Nonetheless, there are aspects of these emissions that are indeed unique to the region and need consideration. Indeed the fate of SO<sub>2</sub> in the “Sour Gas Corridor” of Alberta has been the subject of study and modelling with accounting remaining elusive. [29, 30, 31] It is noted that these facilities do tend to coalesce near mainline compression sites.

# 4.2 – Sources of Sulfur: Airborne



**Figure 6:** Active Sour Gas Processing Facilities near Schrader Creek Compressor Station – Average Daily SO<sub>2</sub> Output in 2008 is approx. 30 tpd within 50km. Yellow circles represent 5km radii from plants.



Province Wide Flaring: Image from ERCB ST60B-2010. [35]

## 4.2 – Sources of Sulfur: Airborne

- The concerns here include:
  1. Gaseous SO<sub>2</sub> from inlet air being available to react with other impurities in the combustion path to form species capable of being deposited.
  2. Gaseous SO<sub>2</sub> available to support reactions by affecting S<sub>2</sub> partial pressures.
  3. Available as an aerosol sulphate, formed by reaction with atmospheric dust (Ca, Mg) for presentation to the gas turbine inlet.
- Filtration cannot help for gaseous SO<sub>2</sub> forms. aerosol sulphate deposition may be arrested (to some efficiency level), but water soluble salts can deliquesce through most media currently employed in TC system.

## 4.2 – Sources of Sulfur: Airborne

- Air Quality Monitoring is carried out within Alberta by the government utilizing specialized mobile monitoring equipment. Alberta Ambient Air Quality Objective Threshold levels for SO<sub>2</sub> are as follows [36]:
  - 1-hour Average = 450 mg/m<sup>3</sup> = 172 ppbv.
  - 24-hour Average = 150 mg/m<sup>3</sup> = 57 ppbv.
  - Annual Average = 30 mg/m<sup>3</sup> = 11 ppbv
- For comparison, US EPA maintains a NAAQS SO<sub>2</sub> Standard as follows [37]:
  - 3-hour Average = 1308 mg/m<sup>3</sup> = 500 ppbv. (Secondary)
  - 24-hour Average = 366 mg/m<sup>3</sup> = 140 ppbv.
  - Annual Average = 79 mg/m<sup>3</sup> = 30 ppbv.
- Sampling Length and Frequency is somewhat less than desired for intent here.
- It has historically been accepted that occasional exceedences do occur during some local atmospheric conditions.
- Long term studies for a machine consuming 165 000 ACFM have not yet been undertaken but are of interest. Assuming At 0.172 ppmv, Sulphur inlet by weight would be the equivalent of approximately ~5.63 ppmv of sulphur in fuel. Some days more sulphur from Air than Fuel!



## 4.2 – Sources of Sulfur: Airborne

- Another potential airborne source of elemental sulphur (S<sub>8</sub>) as a very fine dust can be in handling, mechanical processing operations and transport associated with extracted sulphur if in proximity to such facilities.
- Some sulphur blocks have been re-melted and today in many cases slurry is piped away, but historically, these could have been an issue.



Ref: P. Crawford. "Are We There Yet?", Hydrocarbon Engineering, October 2009.

## 4.3 – Sources of Sulfur: Assembly Lubricants

- Another source of potentially problematic contaminants (sulphur and otherwise – Copper, Zinc, Silver, Chlorine, Lead, Potassium, etc.) is in anti-seize or anti-galling compounds. These may be introduced at rotor build, balancing operations, manipulation with fixtures and tooling, and/or at installation at site.
- These substances involve a number of specific purpose compounds in some form of grease.
- “Favourites” that tends to see misapplication for high temperature applications very often involve Molybdenum Disulphide ( $\text{MoS}_2$ ) as a wonder agent in many lubrication applications. In some cases, Sodium Sulphanol is also included in some as a surfactant (“wettability”).
- There has been considerable confusion over  $\text{MoS}_2$  use, particularly in respect to high temperature applications, with incorrect data on melting and sublimation temperatures. [39] While a dissociation temperature is quoted as  $1370\text{ }^\circ\text{C}$ , this is specifically in a non-oxidizing environment and sublimation temperature of  $1050\text{ }^\circ\text{C}$  is under vacuum. Therefore, **in vacuum or inert environments** it is thermally stable from cryogenic to high temperatures. [40]



## 4.3 – Sources of Sulfur: Assembly Lubricants

- The oxidation characteristics **in oxidizing/air** atmospheres however are quite different. Thermal oxidation rate of MoS<sub>2</sub> in air below 300 °C is slow and difficult to measure and that it remains slower than tungsten disulphide under 388 °C, although moisture tends to lower the onset of more rapid oxidation to 350 °C. [40] Above 370°C there is an increasingly rapid oxidation to molybdenum trioxide with the reaction classed by some as highly exothermic in the range 500-600°C. [40]



- **Recall also that Molybdenum oxides, if coexisting with Na<sub>2</sub>SO<sub>4</sub>, can support a self induced acid fluxing. In a crevice situation, where SO<sub>2</sub> is also generated from the above reaction, all the necessary conditions for corrosion are created.**
- A final concern with respect to remnant MoO<sub>3</sub>, which has a relatively low melting temperature of 795°C. [42] It can modify friction coefficients and some have even described it as abrasive, perhaps incorrectly.



## 4.4 – Sources of Sulfur / Contaminants: Road Dust

- Gravel Roads are invariably the network of access ways to reach remote compressor station locations in the prairie and in the mountainous foothills of the sour gas corridor. Whereas traffic on the prairie roads has not likely increased significantly (although perhaps changing with increased drilling activity in Saskatchewan), traffic on roads in the sour gas corridor has significantly increased since the time these older or legacy units were commissioned. This is owing to drilling activity, forestry activity, and well servicing that is much more active.
- The dust burden reaching inlets has increased, representing issues for filtration systems and associated costs but consequences of this include several additional potential contaminant sources.
  1. Depending on the source of the gravel used on the road and its maintenance, it can include associated minerals such as anhydrite ( $\text{CaSO}_4$ ) and pyrite ( $\text{FeS}_2$ ). As roads dry out, this mineral dust is added to the burden.
  2. Dust Suppression has become desirable in areas where residential areas have encroached. Dust suppression methods include application of sugar Beet Molasses, Sodium lignin sulphonate as well as calcium brines including  $\text{CaCl}_2$  and  $\text{MgCl}_2$  (25-40%). The latter two are of potential interest.
  3. Calcium brines have also fallen into favor as base stabilizers. These harden surfaces and reduce rutting, allowing grading intervals to be extended. In some cases, private roads such as CANFOR are said to be applying these.



## 4.5 – Sources of Sulfur: Prairie Limno-Geology

- Limnology is the study of lake systems and their mineral deposits. A paper by Last and Ginn gives insight into of a large portion of TransCanada's operating theater in the Western Canadian prairies and the Dakotas.
- In much of the Northern Great Plains, saline and hypersaline lacustrine brines are the only surface waters present. This is attributed to the fact that the Missouri Coteau and adjacent areas has a lack of integrated drainage such that the area contains many closed basins with only three defined drainage paths by river systems. [43] The underlying geologic formations include stacked carbonate-evaporite cycles and dissolution of these by hydrologic process is suggested to have provided the source for the ions that are trapped in these closed basins in waters that make this region so remarkable (estimates range from 4-10 million lakes or wetlands in the region with densities as high 90-120 lakes / km<sup>2</sup>). [43]

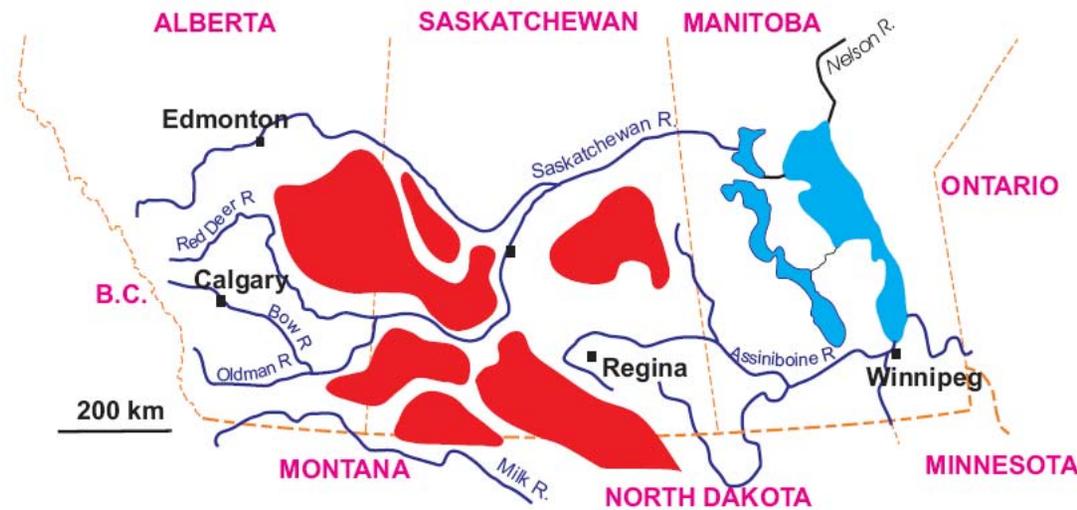


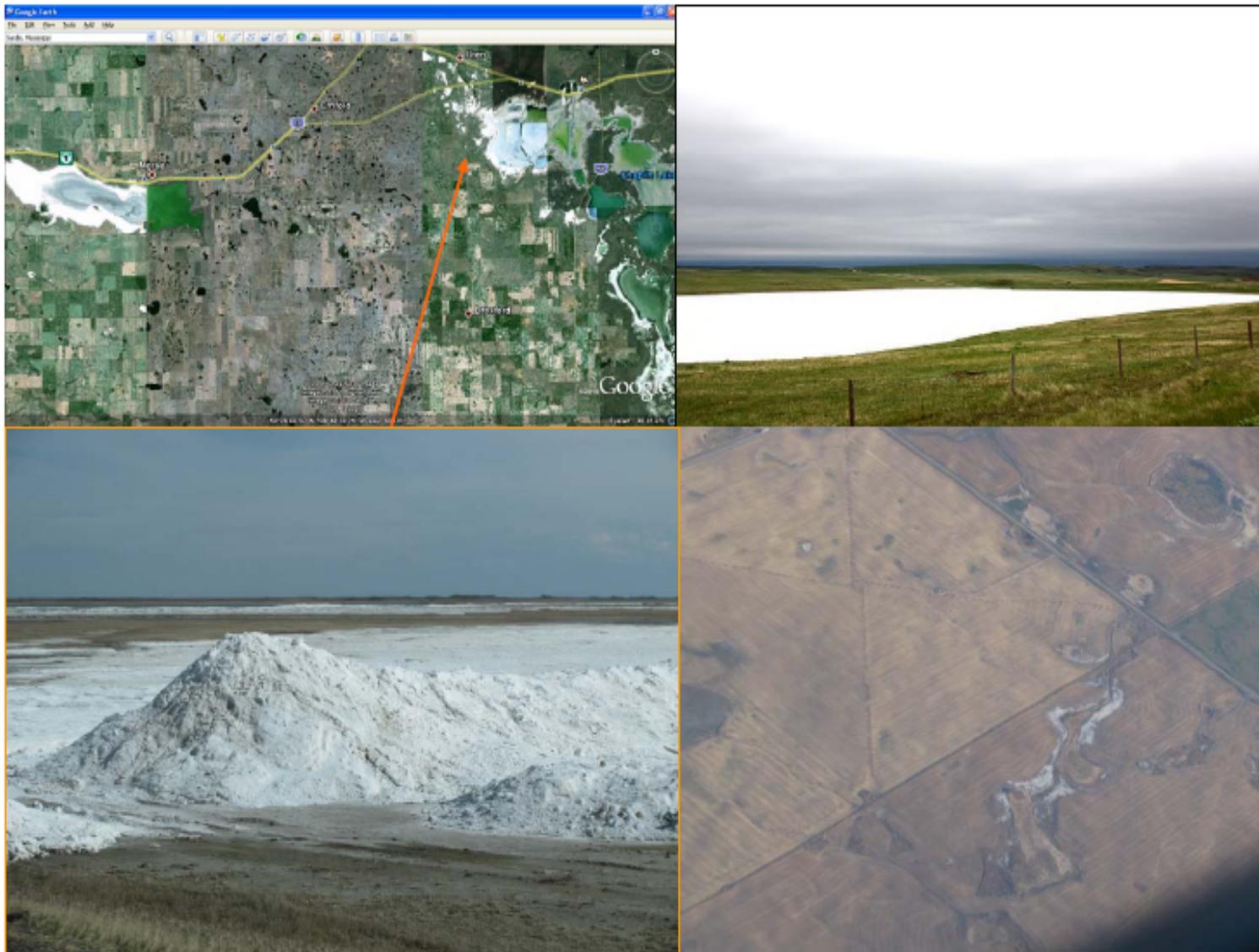
Figure 8: Closed basins of the Great Plains. Image Reproduced from [43].

## 4.5 – Sources of Sulfur: Prairie Limno-Geology

- Climatic factors including temperature and evaporation to precipitation ratio play a definite role in the function of the lakes with the region receiving 40 cm of precipitation / year while over 1.5 meters of water can be lost annually to evaporation from open water bodies. [43]
- In so far as the topic at hand is concerned, wind also dictates processes in the lakes, as average wind speed is moderate to high, which aids evaporation and in current and wave generation and therefore sedimentation and deposition and erosion.
- **Wind is also an agent for transport of sediment and salts into and out of the lakes. [43]**
- While all the lakes offer the potential for generation of loose, airborne salt contaminants, it is the smaller, most numerous (54% of the total) intermittent playas that spend a larger proportion of time dried out and capable of generating airborne dust and debris.
- In respect to salinity and composition, even though all the lakes in question have similar origins, the waters now show a remarkable diversity in respect to ionic composition. Although there was initially thought to be a predominance of sodium and sulphate components, it is now understood that sulphate and carbonate rich lakes dominate the Prairies (95%) and that fewer than 5% are Chlorine rich (including Chaplin, Quill Lakes and Bigstick) which again differentiates the region from the rest of the world. [43]

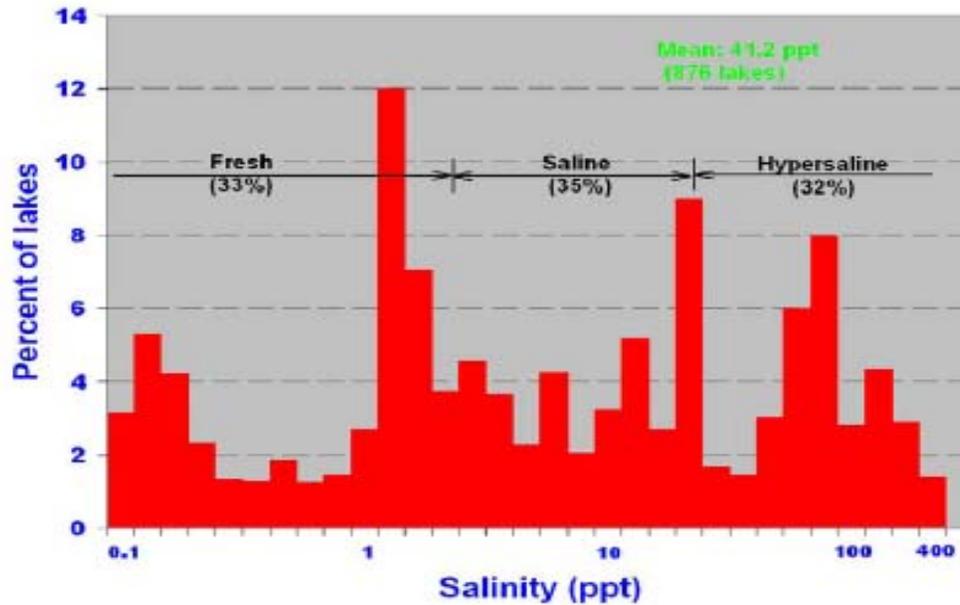


## 4.5 – Sources of Sulfur: Prairie Limno-Geology



**Figure 9:** Examples of Evaporite Lakes (Chaplin Lake, Red Lake) and an aerial view of a wet/dry playa. Lake Ingebright is North Americas largest  $\text{Na}_2\text{SO}_4$  deposit. [43]

# 4.5 – Sources of Sulfur: Prairie Limno-Geology



**Figure 10:** Salinity of lakes in the Great Plains region of Western Canada. Reproduced from [43].

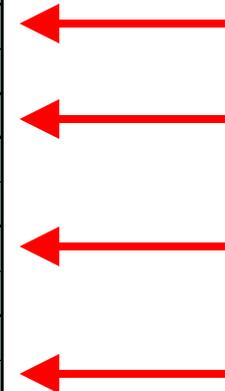
**Table 5 - Mean Brine Compositions of Saline and Hypersaline Lakes in Select Areas from [43].**

Region	Ca	Mg	Na	K	HCO <sub>3</sub>	CO <sub>3</sub>	Cl	SO <sub>4</sub>	TDS
	mmol/l	mmol/l	mmol/l	mmol/l	mmol/l	mmol/l	mmol/l	mmol/l	ppt
Eastern Prairies	4	24	4	1	6	1	2	24	3
Central Saskatchewan	19	149	193	5	7	3	54	251	22
SW Saskatchewan & SE Alberta	12	93	1088	4	96	36	29	1073	80
West Central Saskatchewan and East Central Alberta	3	144	1362	10	268	44	107	1125	102

## 4.3 – Sources of Sulfur: Prairie Limno-Geology

**Table 6:** Minerals Formed in Saline Lakes of the Great Plains. Adapted from [43].

Class	Mineral Name	Composition	Occurrence
Carbonates	Aragonite	CaCO <sub>3</sub>	Very Common
	Calcite	CaCO <sub>3</sub>	Very Common
	Magnesite	MgCO <sub>3</sub>	Common
	Magnesian Calcite	(Mg <sub>x</sub> Ca <sub>x-1</sub> )CO <sub>3</sub>	Very Common
	Protodolomite	CaMg(CO <sub>3</sub> ) <sub>2</sub>	Very Common
Sulphates	<b>Bloedite</b>	Na <sub>2</sub> Mg(SO <sub>4</sub> ) <sub>2</sub> 4H <sub>2</sub> O	Very Common
	Epsomite	MgSO <sub>4</sub> 7H <sub>2</sub> O	Common
	<b>Gypsum</b>	CaSO <sub>4</sub> 2H <sub>2</sub> O	Very Common
	Hexahydrate	MgSO <sub>4</sub> 4H <sub>2</sub> O	Common
	Kieserite	MgSO <sub>4</sub> H <sub>2</sub> O	Common
	<b>Mirabilite</b>	Na <sub>2</sub> SO <sub>4</sub> 10 H <sub>2</sub> O	Very Common
	Mercalite	KHSO <sub>4</sub>	Very Rare
	Potassium Alum	KAl(SO <sub>4</sub> ) <sub>2</sub> 12H <sub>2</sub> O	Very Rare
<b>Thenardite</b>	Na <sub>2</sub> SO <sub>4</sub>	Very Common	
Chlorides	Bischofite	MgCl <sub>2</sub> 6H <sub>2</sub> O	Very Rare
	<b>Halite</b>	NaCl	Rare



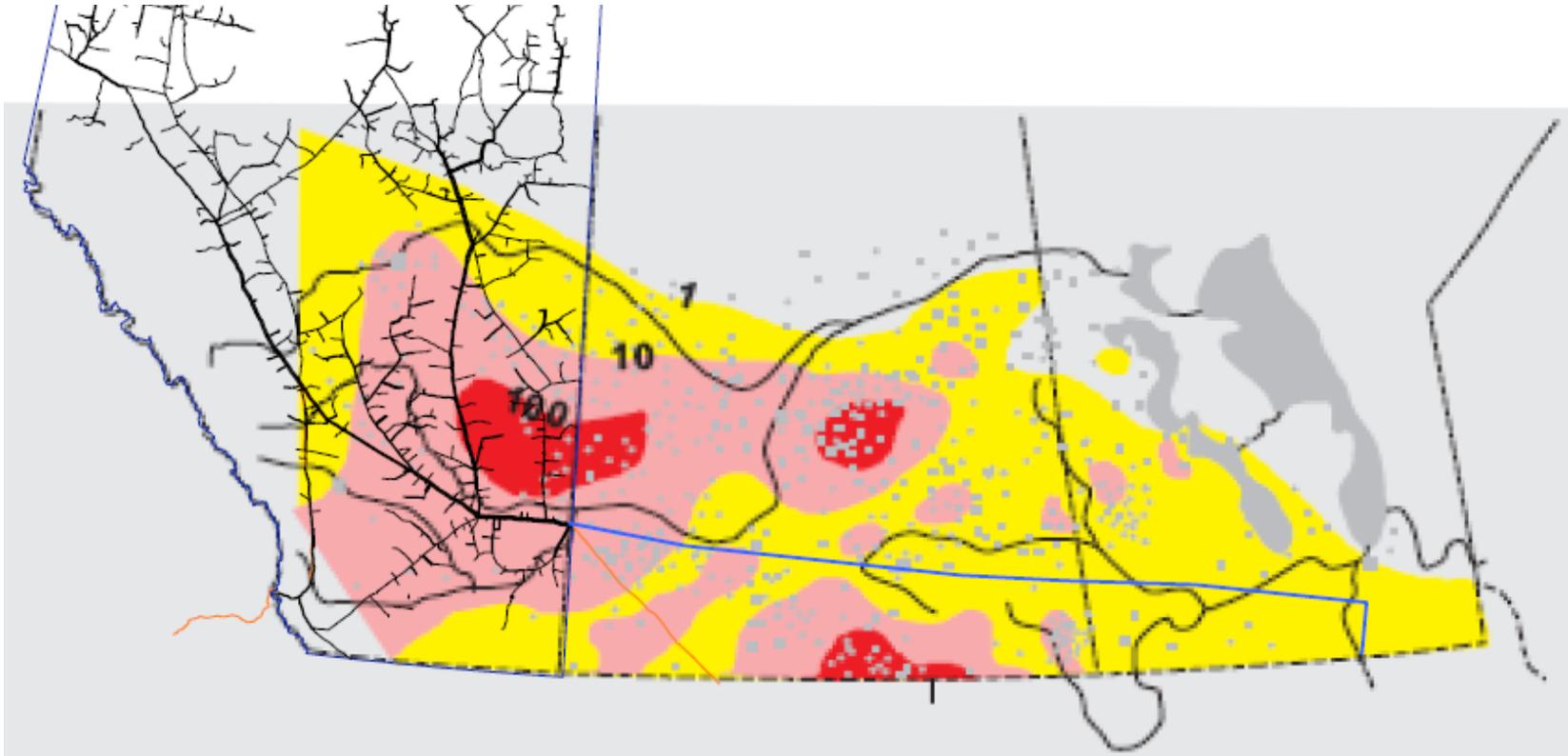
## 4.5 – Sources of Sulfur: Prairie Limno-Geology

Where are these Lakes & Playas?



## 4.5 – Sources of Sulfur: Prairie Limnogeology

Where are these Lakes & Playas?



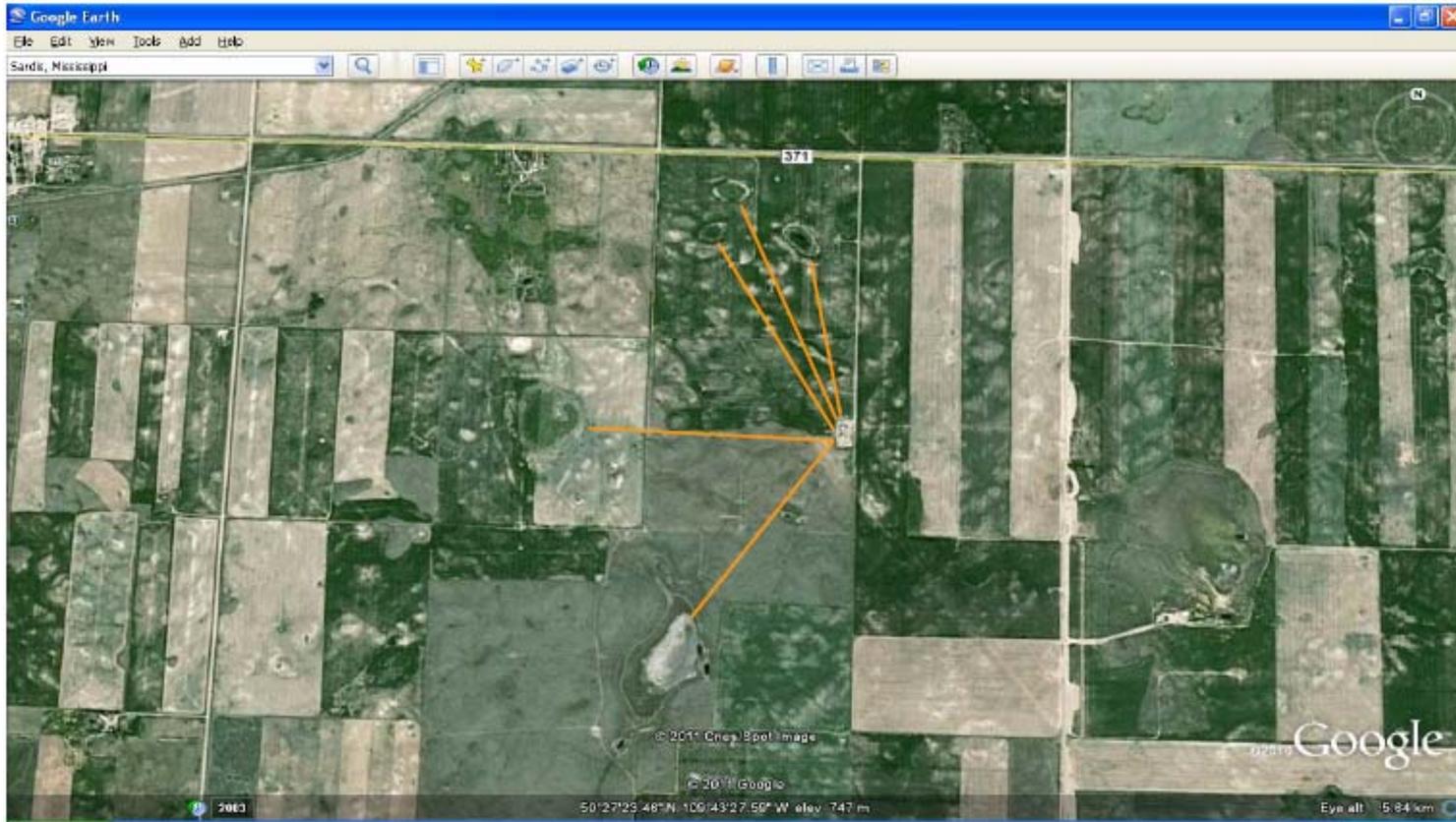
**Figure 11:** Variation of salinity (TDS – Contours are logarithmic) in lakes with TCPL facilities overlain. Adapted from [43].

## 5.0 – Deposition

- In the evaporite theater and the foothills “sour gas corridor”, sulphur/sulphates and other evaporites have been found:
  - Outside the inlet plena.
  - In inlet filter samples.
  - In some cases in the inlet plena on splitters and acoustic mesh (sometimes as reaction products with zinc from those structures).
  - On gas generator compressor blading and secondary air system pathways, and
  - On engine/PT exhaust diffusers and drains.
- Ultimately, during Power Turbine teardowns, reactive species K, S, and Na have been recovered and in some cases, enough of a sample to employ XRD and confirm  $\text{CaSO}_4$  and/or  $\text{Na}_2\text{SO}_4$ , amongst others.
- In respect to the GT, the salt deposits and other contaminants tend to accumulate most significantly in the first three or four stages of the axial compressors. This is consistent with experience on offshore units and that reported by others. [44]
- What follows are a series of figures depicting some examples and analysis from various sites.

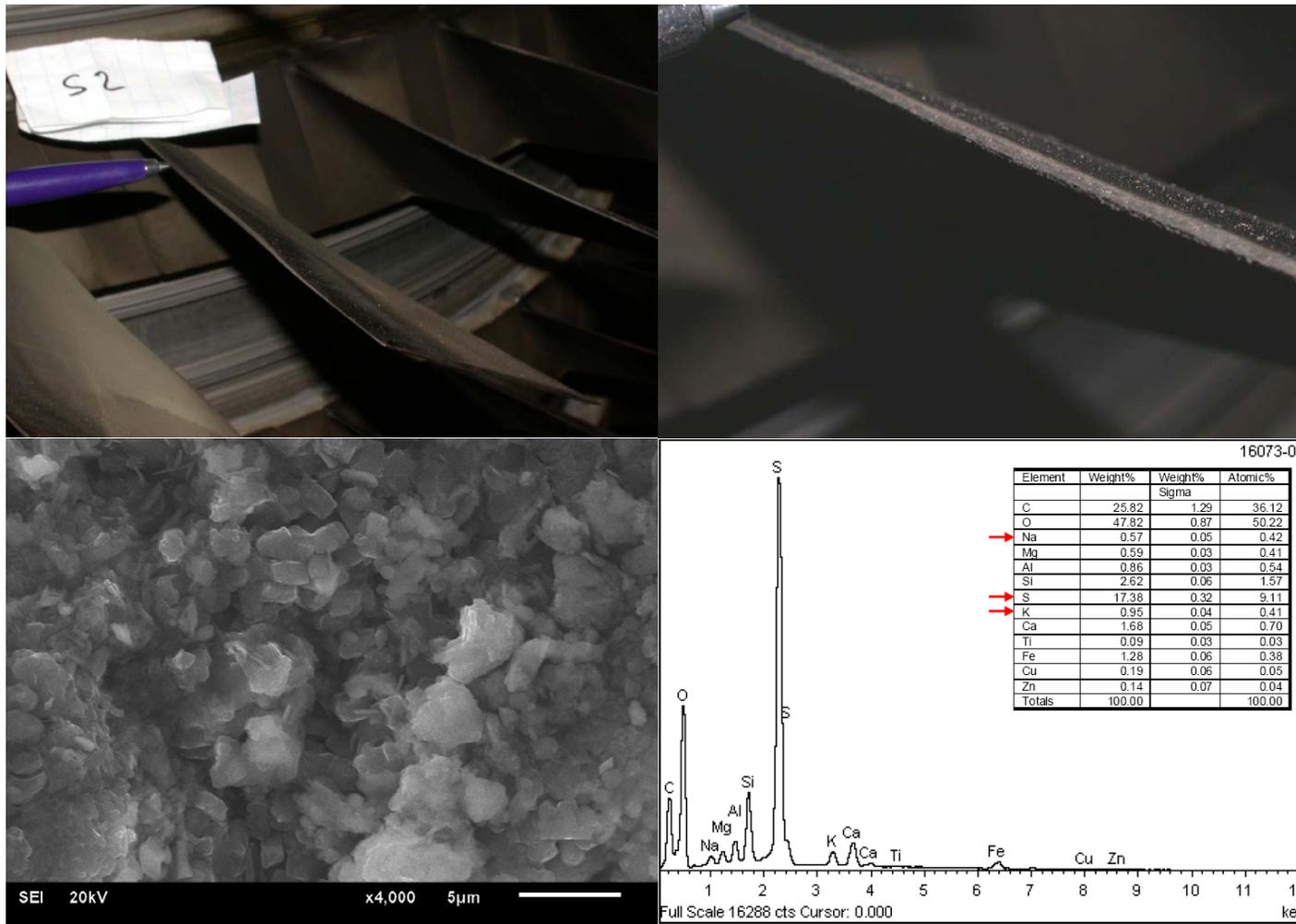


## 5.1 – Deposition Examples



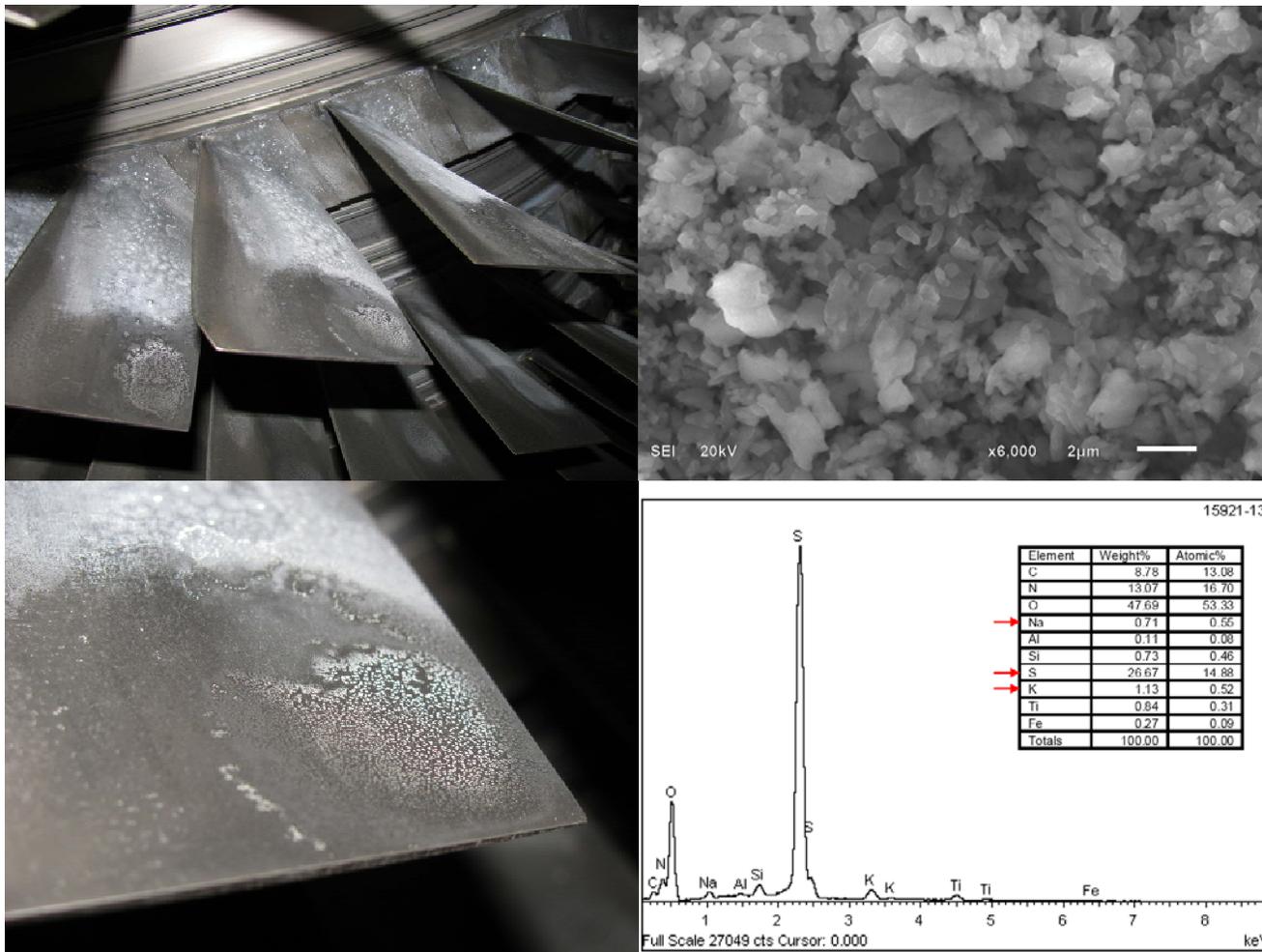
**Figure 12:** Richmond C/S (Sask) Surrounded by five lakes (within 950 m) and numerous small playas.

# 5.1 – Deposition Examples



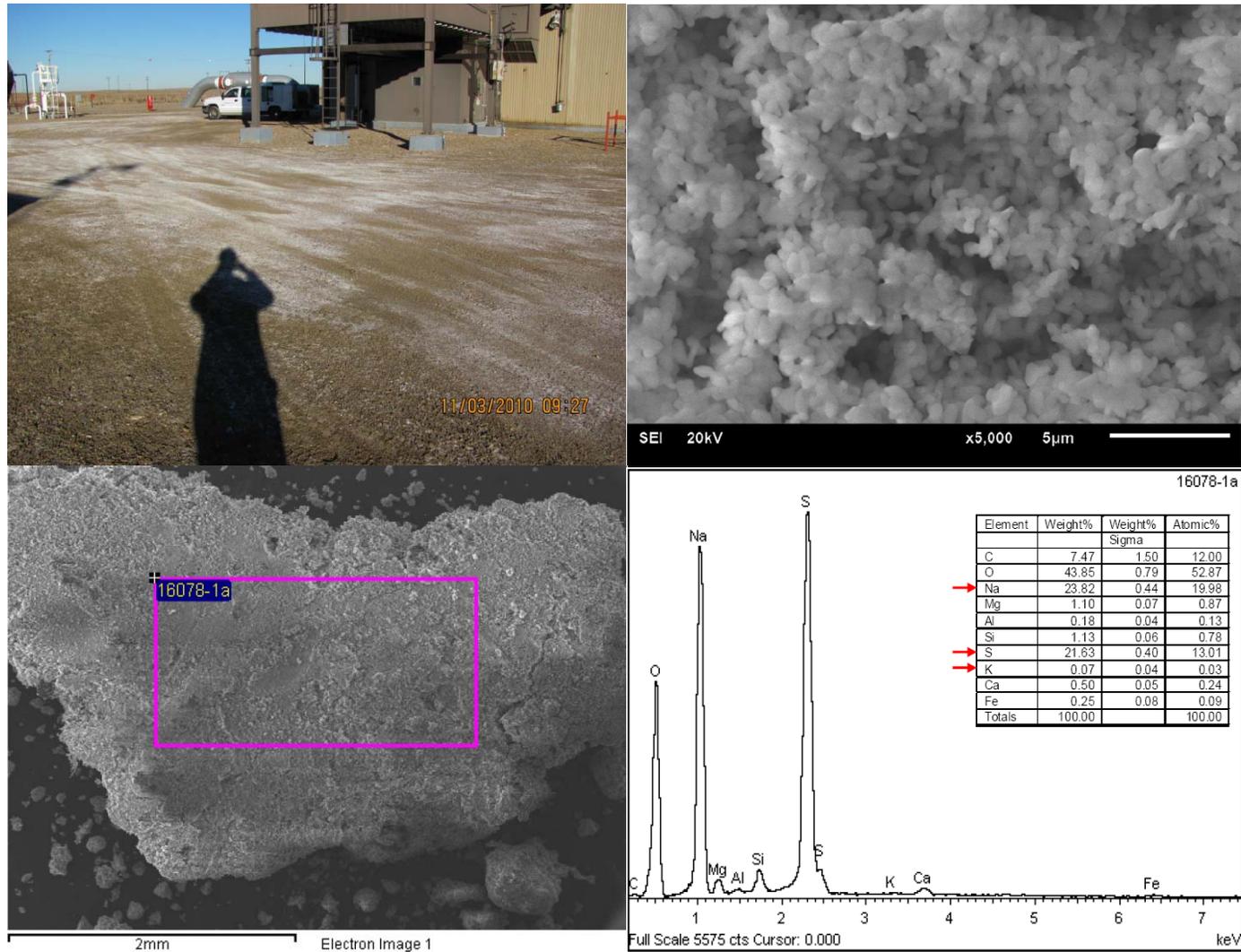
**Figure 13:** Richmond C/S: ESN 1750-116 IPC Stage Two blade deposits showing reactive species Na, S and K. GG was 3000 hours since last compressor wash. [45]

## 5.1 – Deposition Examples



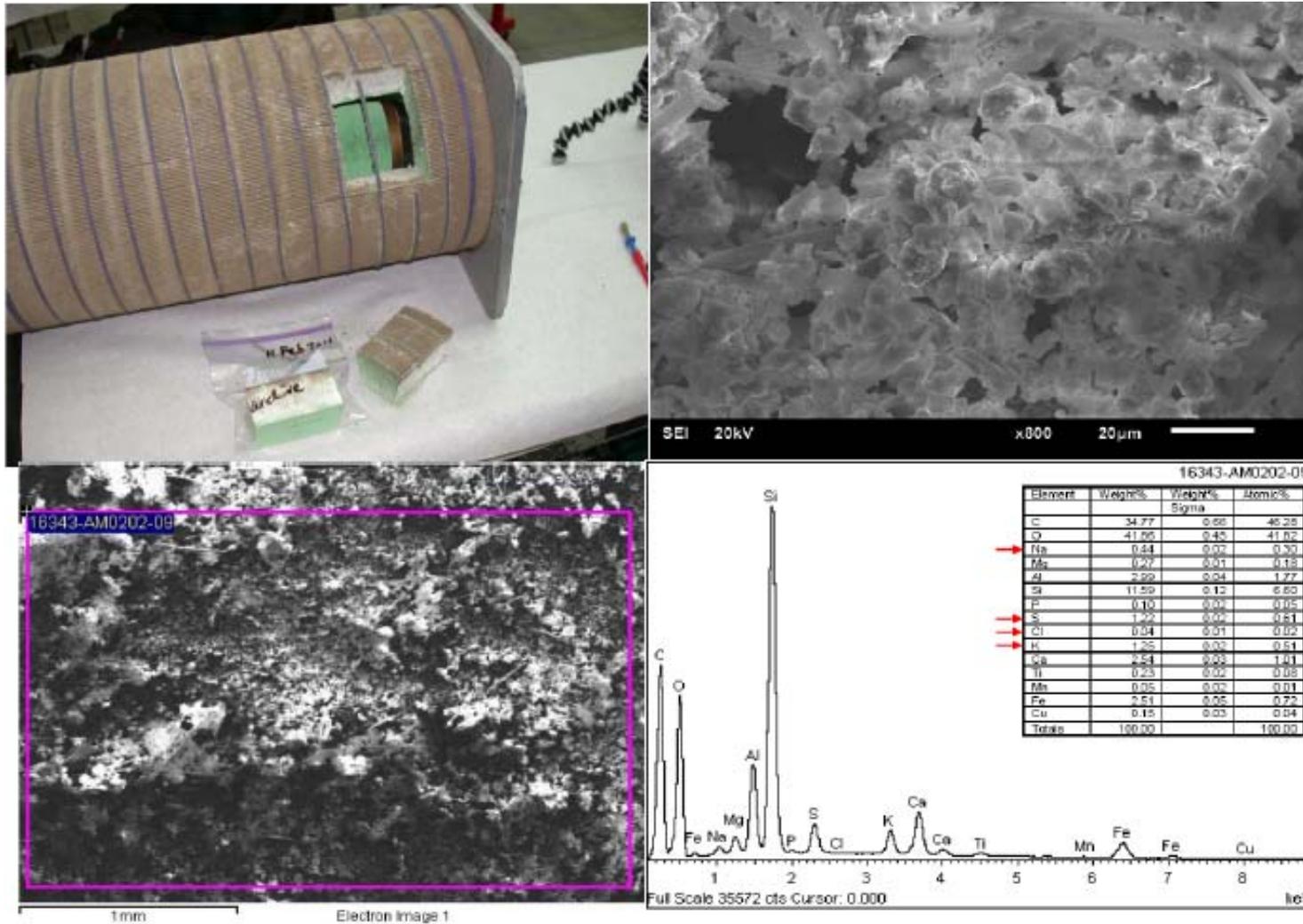
**Figure 14:** Deposits on IPC of ESN 1750-120 from Burstall (Sask) Compressor C/S. Engine was 530 hours since compressor wash. SEM Images from [46].

# 5.1 – Deposition Examples



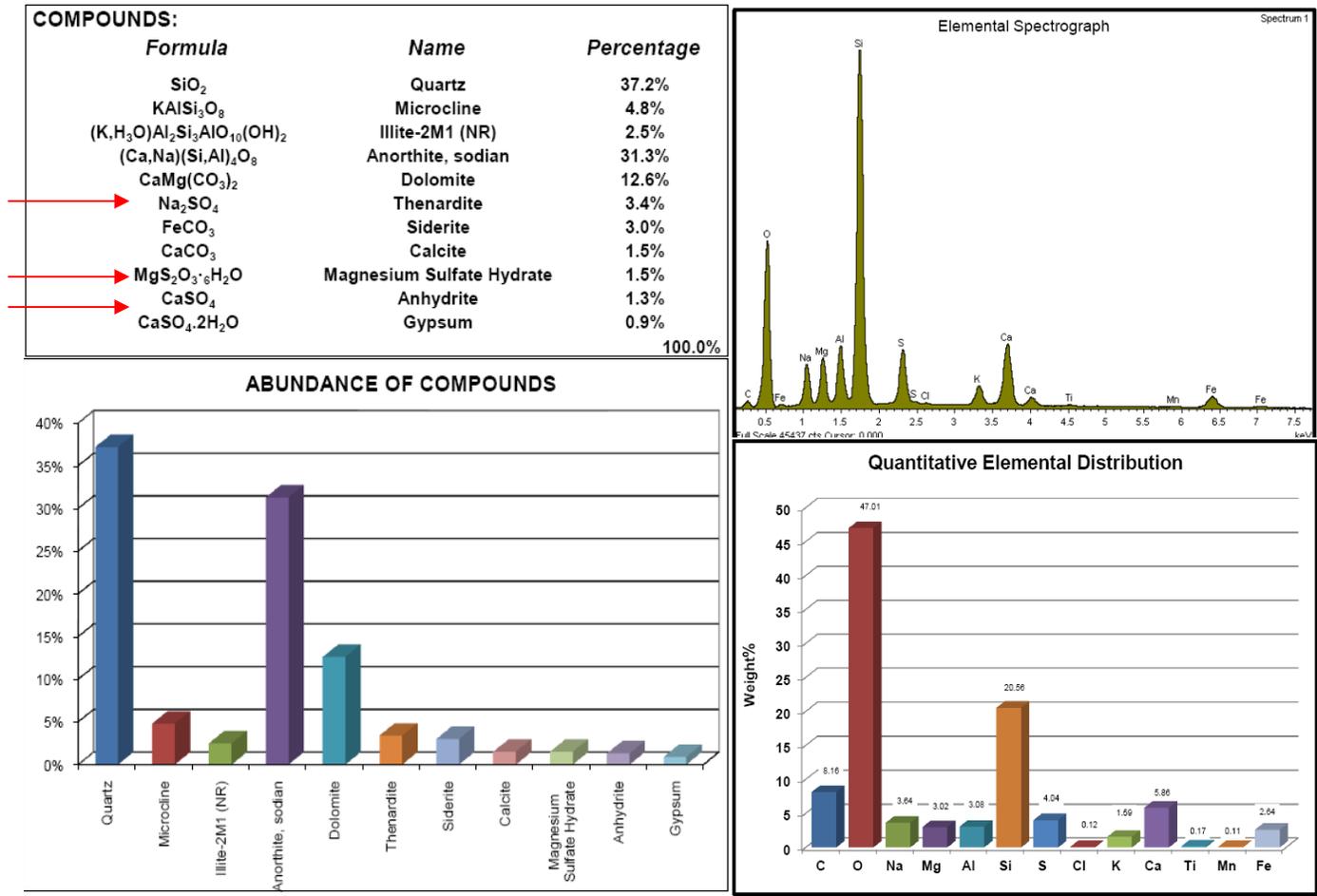
**Figure 15:** Jenner C/S (Alberta). Evaporite in yard and under plenum. SEM Images from [47].

# 5.1 – Deposition Examples



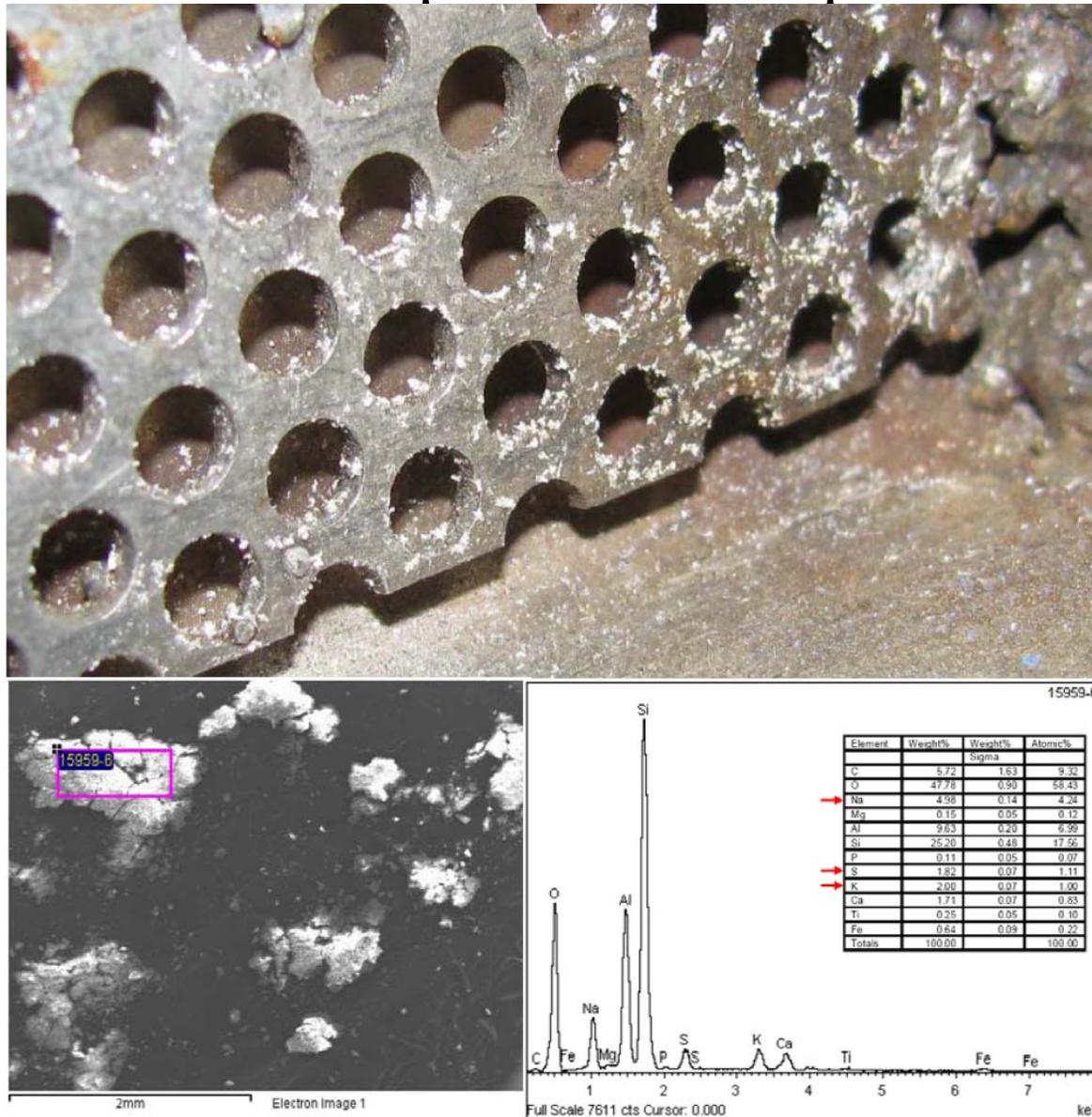
**Figure 16: Monchy C/S (Sask) Filter Debris Analysis by SEM [48].**

# 5.1 – Deposition Examples



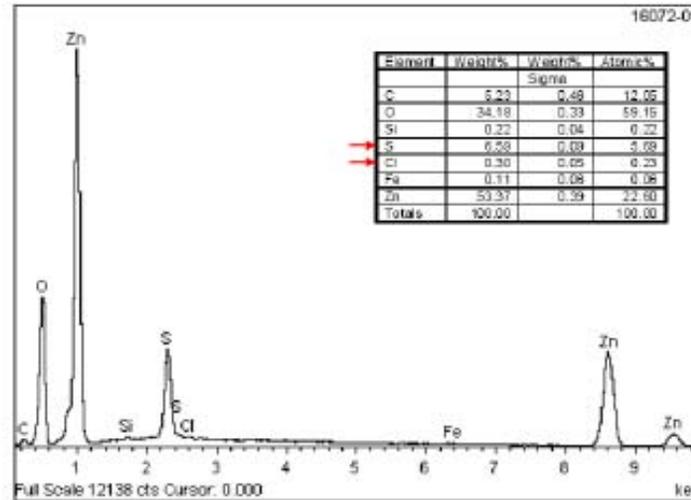
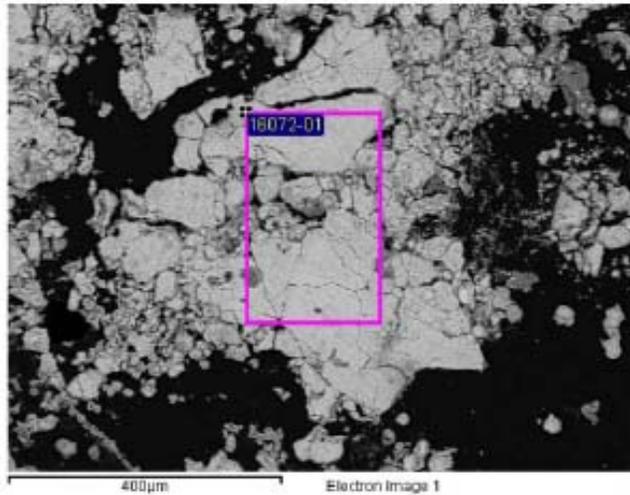
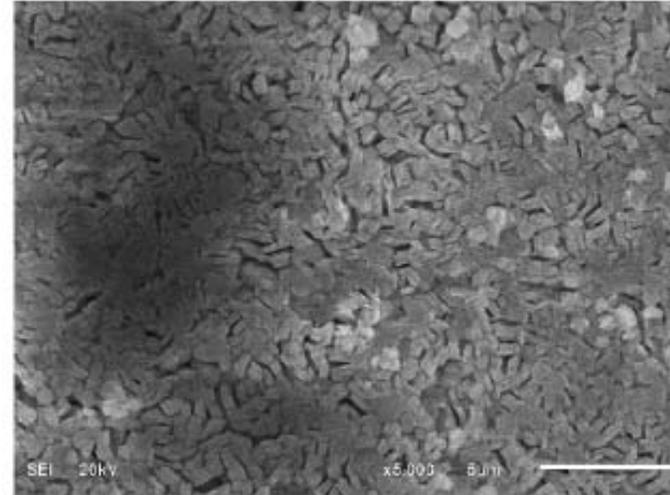
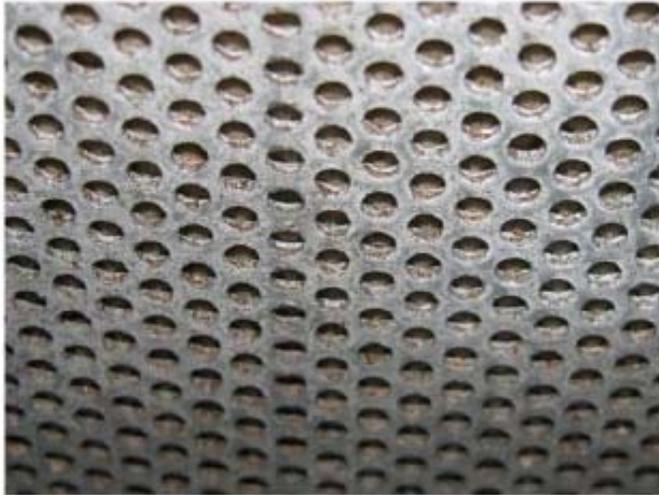
**Figure 17:** Monchy C/S (Sask.) XRD Analysis of gravel under filter hood. [48] This EDS & XRD analysis match what was in the filter (Fig.16). [48]

## 5.1 – Deposition Examples



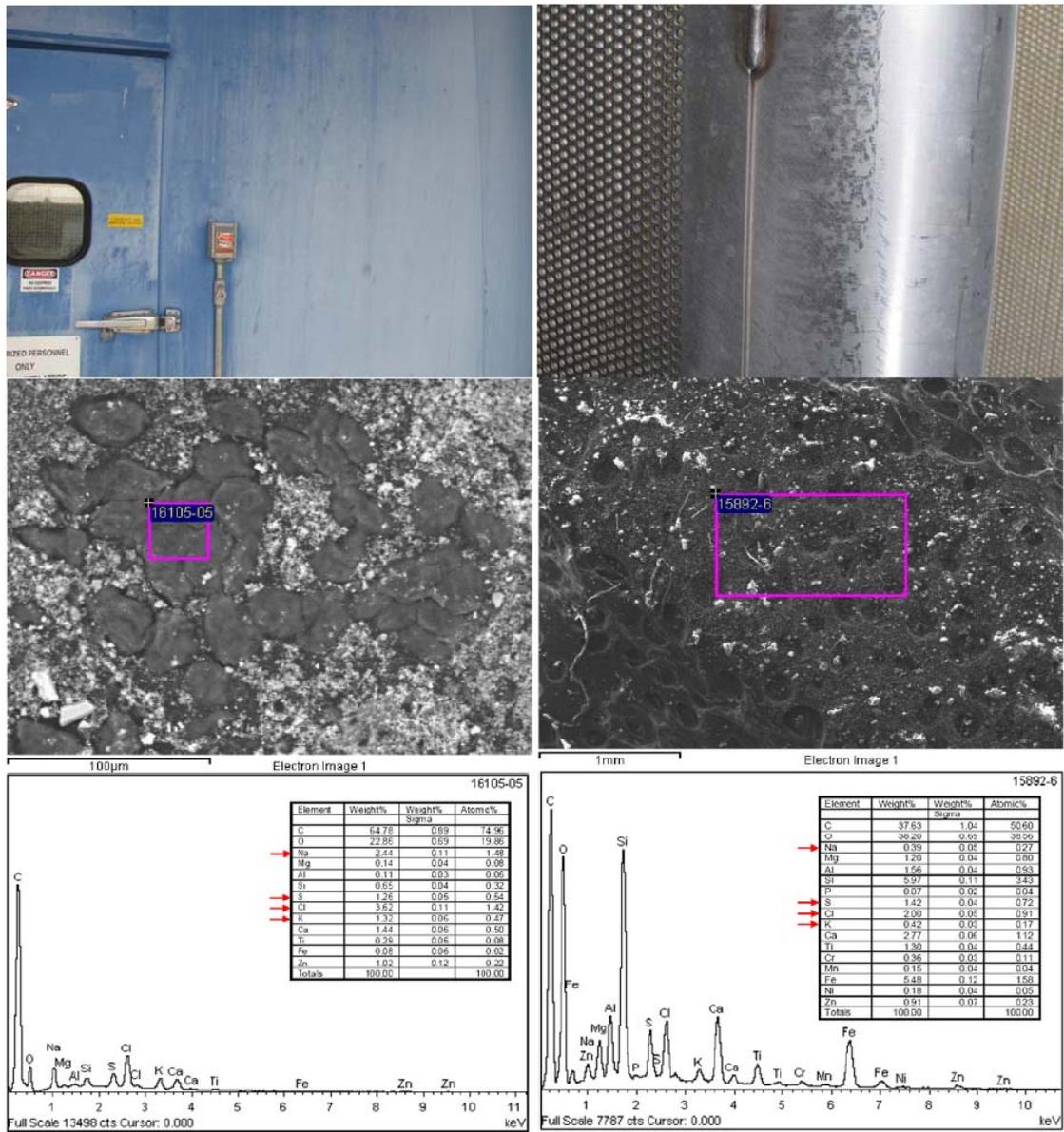
**Figure 18:** Latonell C/S (Alberta) White Crystalline deposits inside inlet plenum on acoustic lining, upstream of splitters. [49]

# 5.1 – Deposition Examples



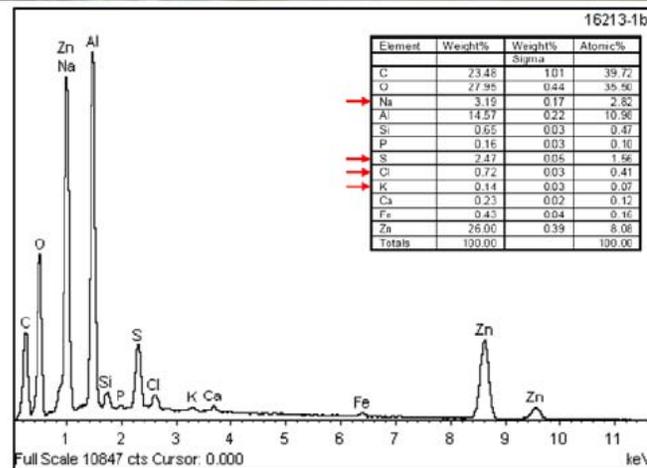
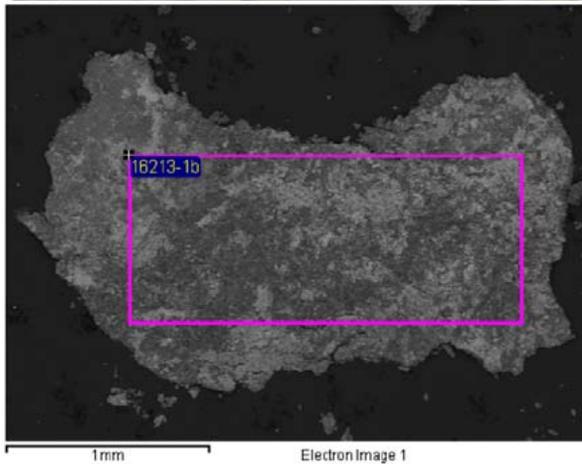
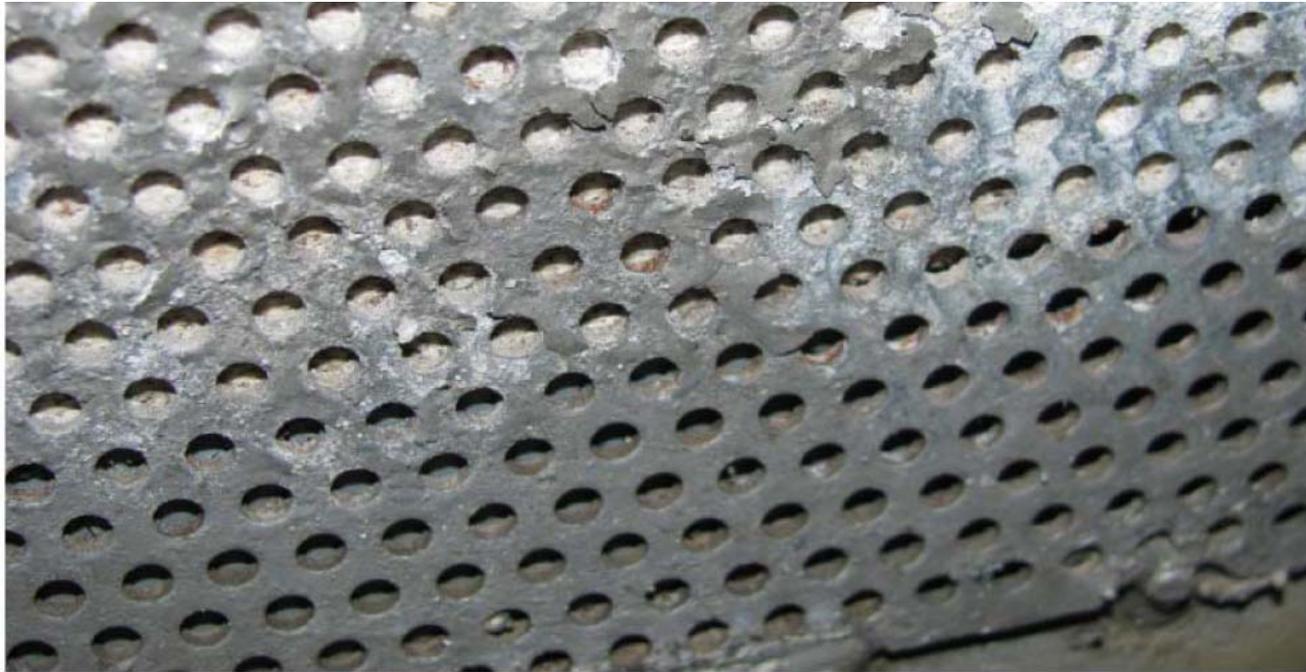
Vetchland C/S – Inlet Plenum deposits

# 5.1 – Deposition Examples



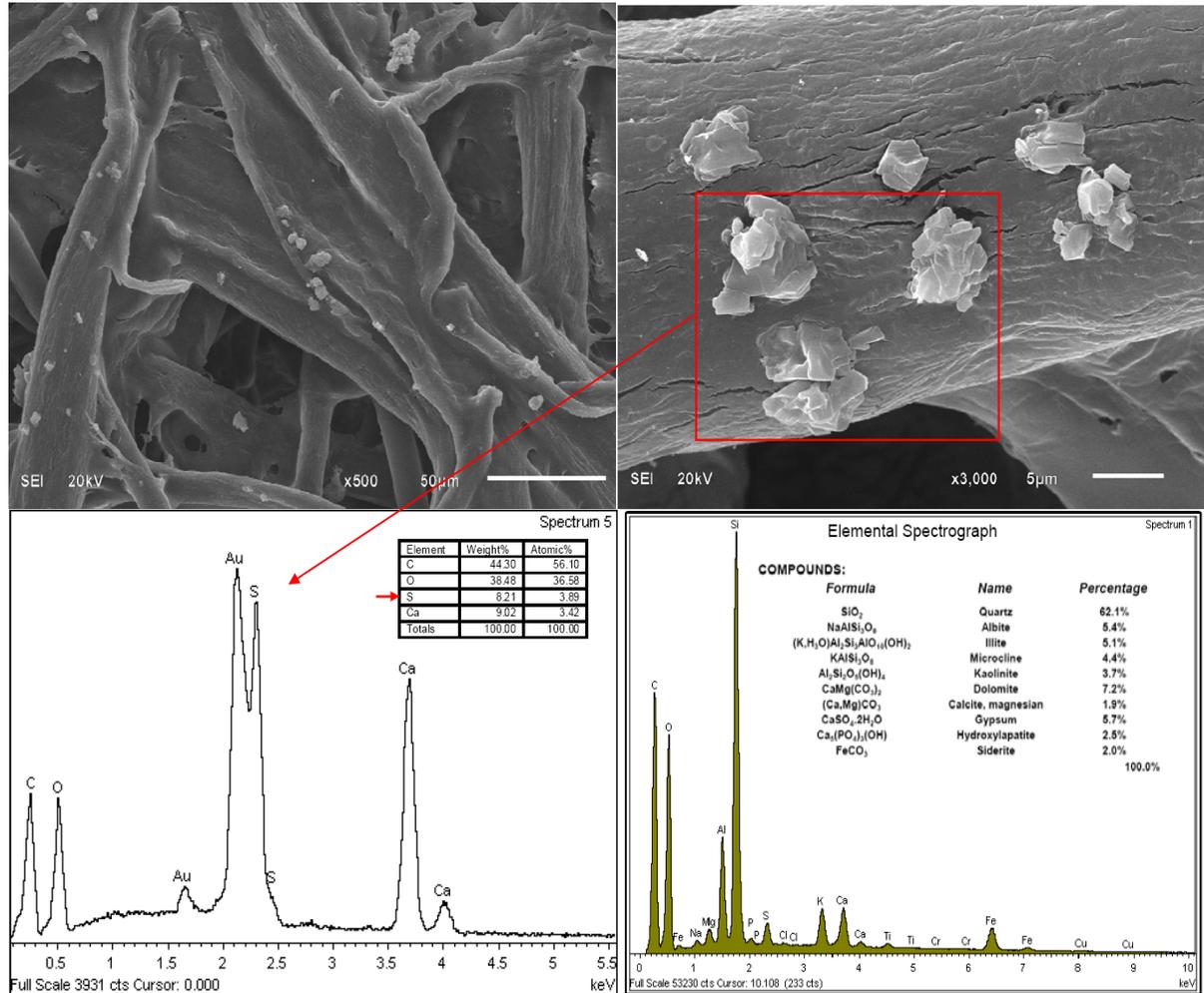
Vetchland C/S – Inlet Plenum deposits

# 5.1 – Deposition Examples



Station 17D – Inlet Plenum deposits

# 5.1 – Deposition Examples



**Figure 19:** Inlet filter analysis from Latornell C/S. Lower Right Hand Side is XRD of filter inlet side debris with Gypsum, K and Trace Chlorine. Downstream side particle EDS shows Ca, S and O. (Au Sputter). [49]

# 5.1 – Deposition Examples

## Latornell Filter

Mineral	Name	Filter % mass	Road % mass	Yard % mass
SiO <sub>2</sub>	Quartz	62.1	89.4	84.2
MaAlSi <sub>3</sub> O <sub>8</sub>	Albite	5.4	1.7	2.4
(K,H <sub>3</sub> O)Al <sub>2</sub> Si <sub>3</sub> AlO <sub>10</sub> (OH) <sub>2</sub>	Illite	5.1	1.3	1.6
KAlSi <sub>3</sub> O <sub>8</sub>	Microcline	4.4	2.7	2.4
Al <sub>2</sub> Si <sub>2</sub> O <sub>5</sub> (OH) <sub>4</sub>	Kaolinite	3.7	1.7	0.8
CaMg(CO <sub>3</sub> ) <sub>2</sub>	Dolomite	7.2	1	3.6
(Ca,Mg)CO <sub>3</sub>	Calcite, magnesian	1.9	-	-
CaSO <sub>4</sub> 2H <sub>2</sub> O	Gypsum	5.7	-	-
Ca <sub>5</sub> (PO <sub>4</sub> ) <sub>3</sub> (OH)	Hydroxylapatite	2.5	-	-
FeCO <sub>3</sub>	Siderite	2	0.3	0.6
(Mg,Fe,Al) <sub>6</sub> (Si,Al) <sub>4</sub> O <sub>10</sub> (OH) <sub>2</sub>	Clinchlore	-	1.3	0.8
CaCO <sub>3</sub>	Calcite, magnesian	-	0.6	3.6
Total		100	100	100



## Berland River Filter

Compound		Outer Cylinder (wt %)	Inner Cone (wt %)
Quartz	SiO <sub>2</sub>	64.1	52.0
Potassium feldspar	KAlSi <sub>3</sub> O <sub>8</sub>	3.3	5.6
Sodium feldspar	NaAlSi <sub>3</sub> O <sub>8</sub>	5.2	7.2
→ Gypsum	CaSO <sub>4</sub> •2H <sub>2</sub> O	9.0	14.8
Dolomite	CaMg(CO <sub>3</sub> ) <sub>2</sub>	5.8	8.5
Kaolinite	AlSi <sub>2</sub> O <sub>5</sub> (OH) <sub>4</sub>	3.8	4.7
Illite	(K,H <sub>3</sub> O)Al <sub>2</sub> Si <sub>3</sub> AlO <sub>10</sub> (OH) <sub>2</sub>	5.2	5.2

## Results of Some Filter Analyses

## 5.0 – Compressor Wash Migration

- It was necessary to understand how these contaminants were making their way through the system and accumulating as far rearward as the power turbine and finding their way into the rotor stator cavities.
- In one design, IP Compressor delivery air is fed as rim cooling air into both cavities.
- However, in the other design, where deposits were being found, no cooling air was provided to the second cavity.
- Compressor soak wash fluid migration studies were conducted. Effluent was captured from the various openings and drained and sent for analysis by ICP-OES.



# 5.0 – Compressor Wash Migration



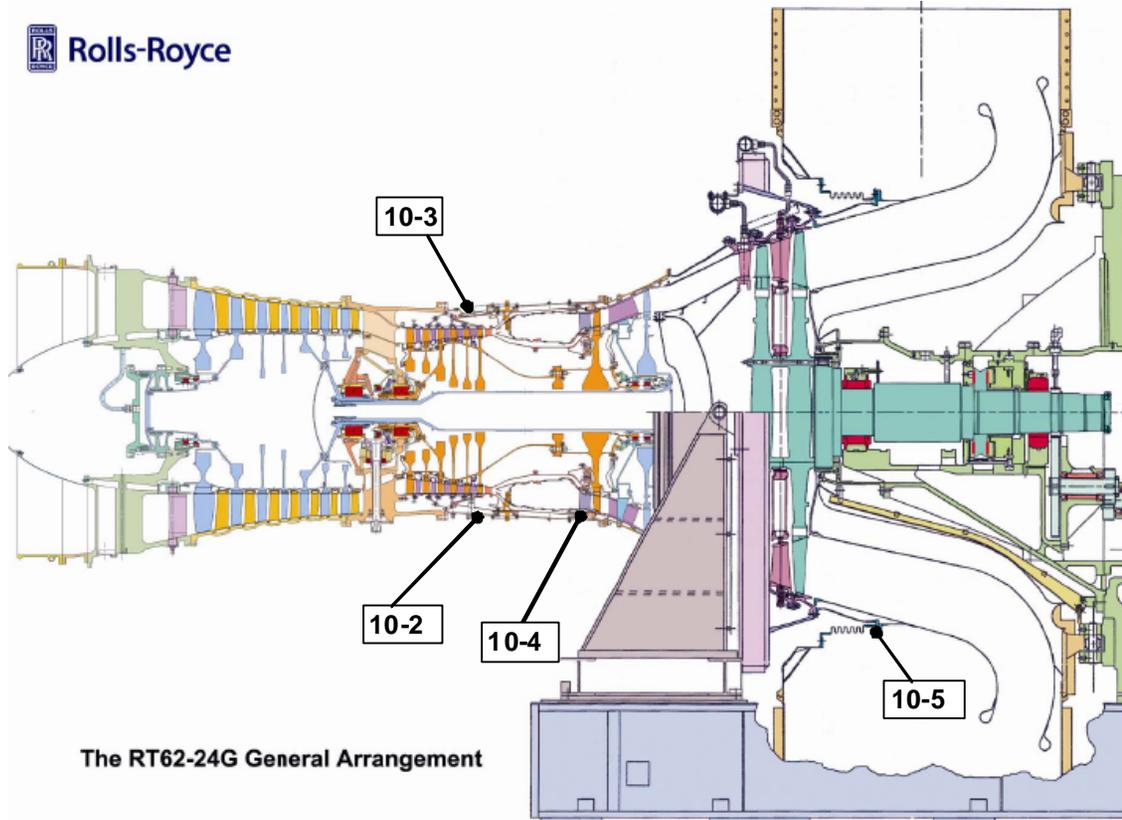
Fluid Capture Points

## 5.0 – Compressor Wash Migration



Fluid Did Make It to PT Exhaust (May be Process / Procedural Related)

# 5.0 – Compressor Wash Migration



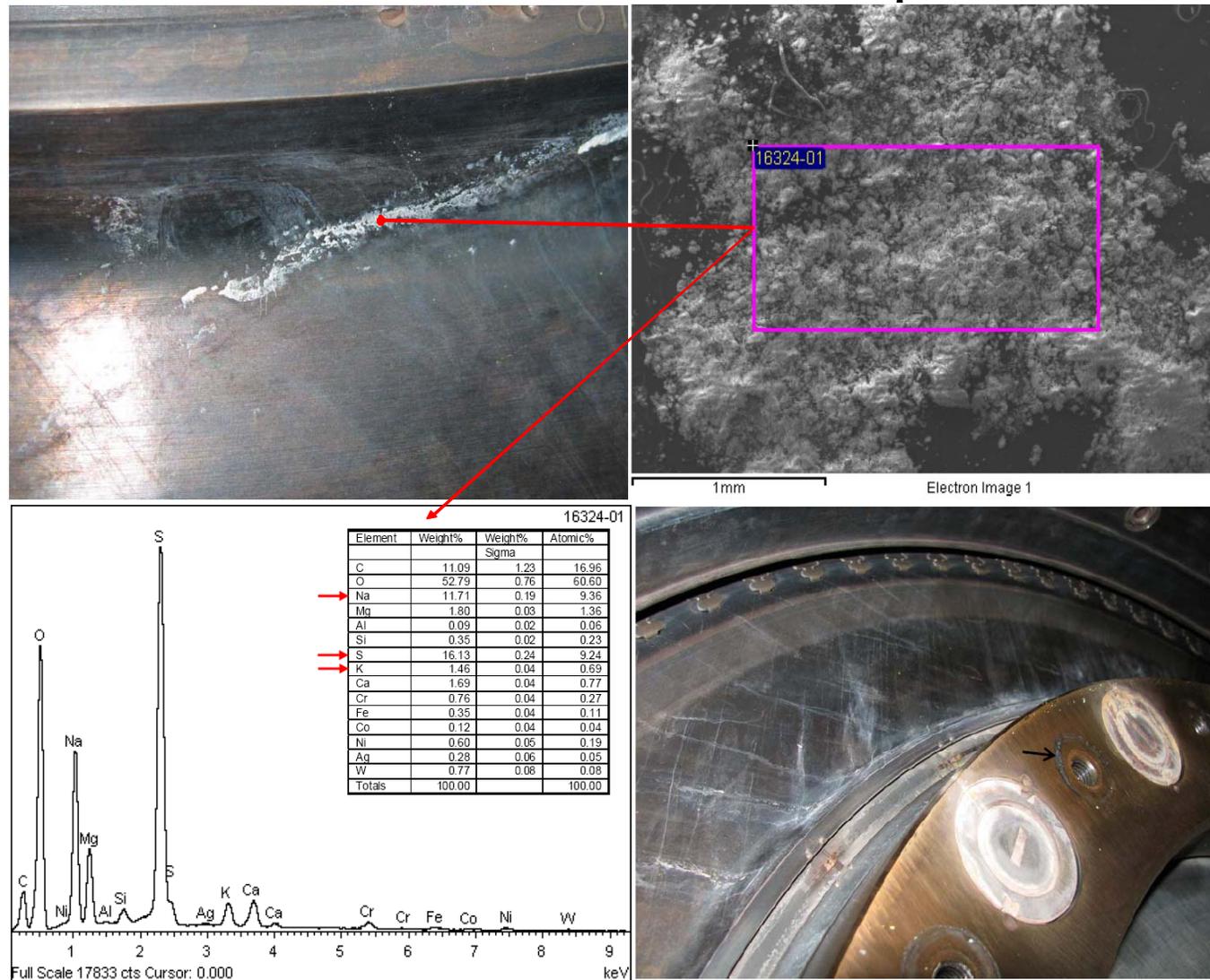
The RT62-24G General Arrangement

Sample	Sodium (ppm)	Chloride (ppm)	Sulphate (ppm)	Potassium (ppm)
#10-1 A2 Wash Water	-	0.19	0.53	-
#10-2 HP3 BOV Rinse	4.6	0.77	104	4.05
#10-3 SBOV Rinse	5.9	0.73	141	6.80
#10-4 04 Drain	16.7	20.4	359	25.1
#10-5 PT Exhaust Expansion Joint Split	21.7	1.4	411	28.8

**Figure 21:** ICP-OES Analysis results from [50]. Image courtesy of Rolls-Royce.

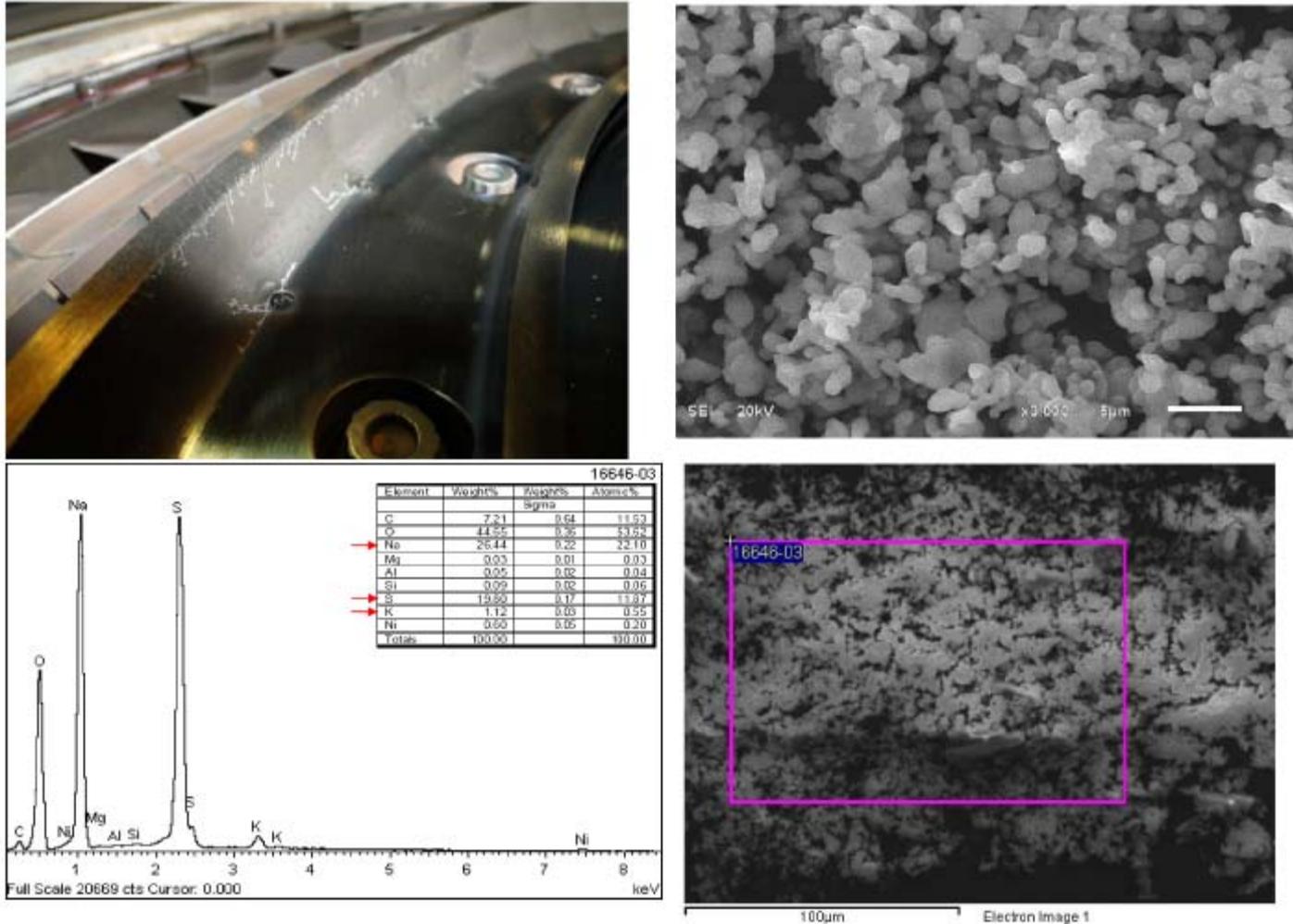


## 6.0 – Teardown Examples



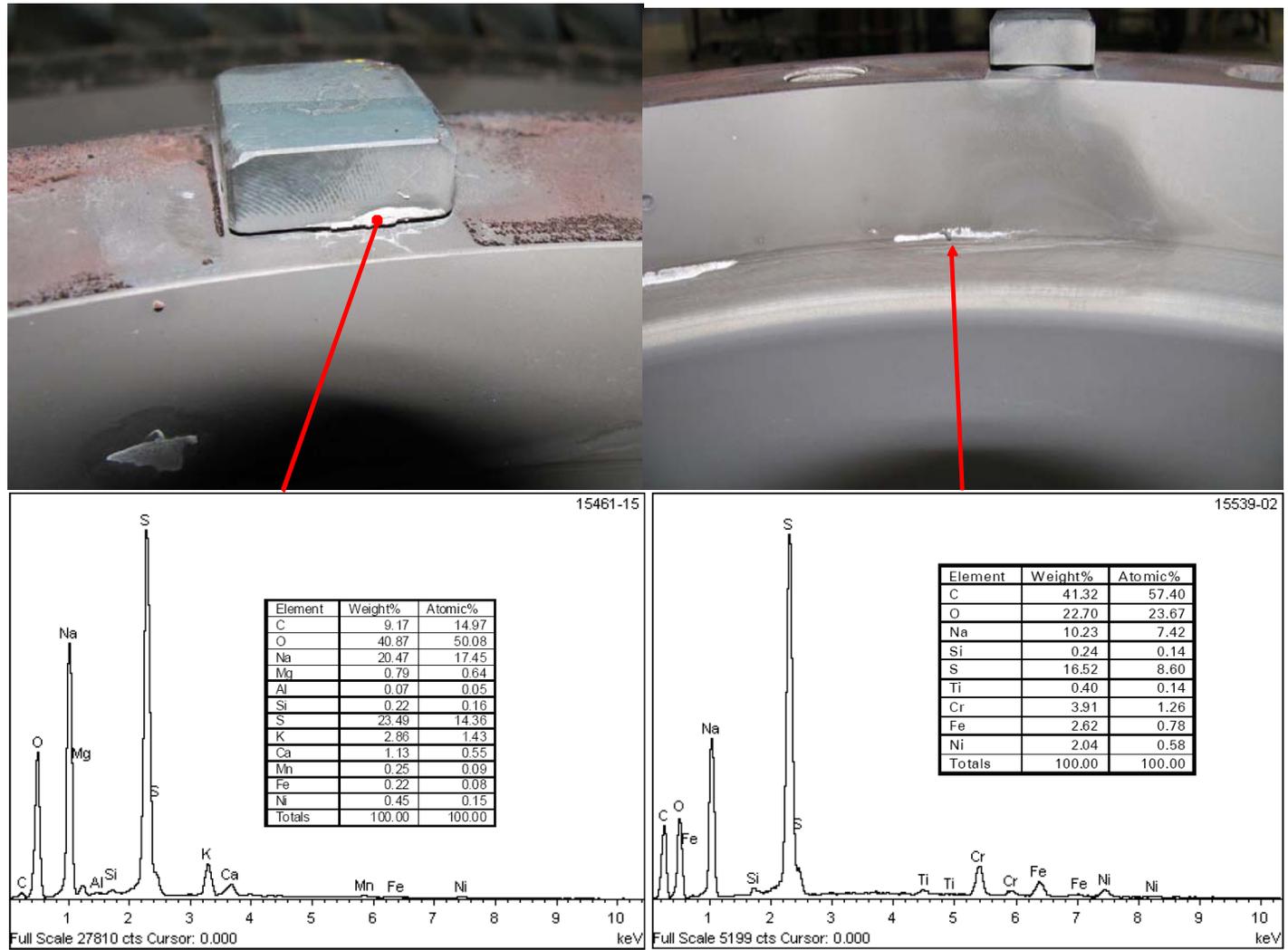
**Figure 22:** Vendor 2: prominent sodium and sulphur levels detected. Note the drip like pattern to the residue, which are suggestive that these were deposited when the unit PT was static as during soak wash. [52].

# 6.0 – Teardown Examples



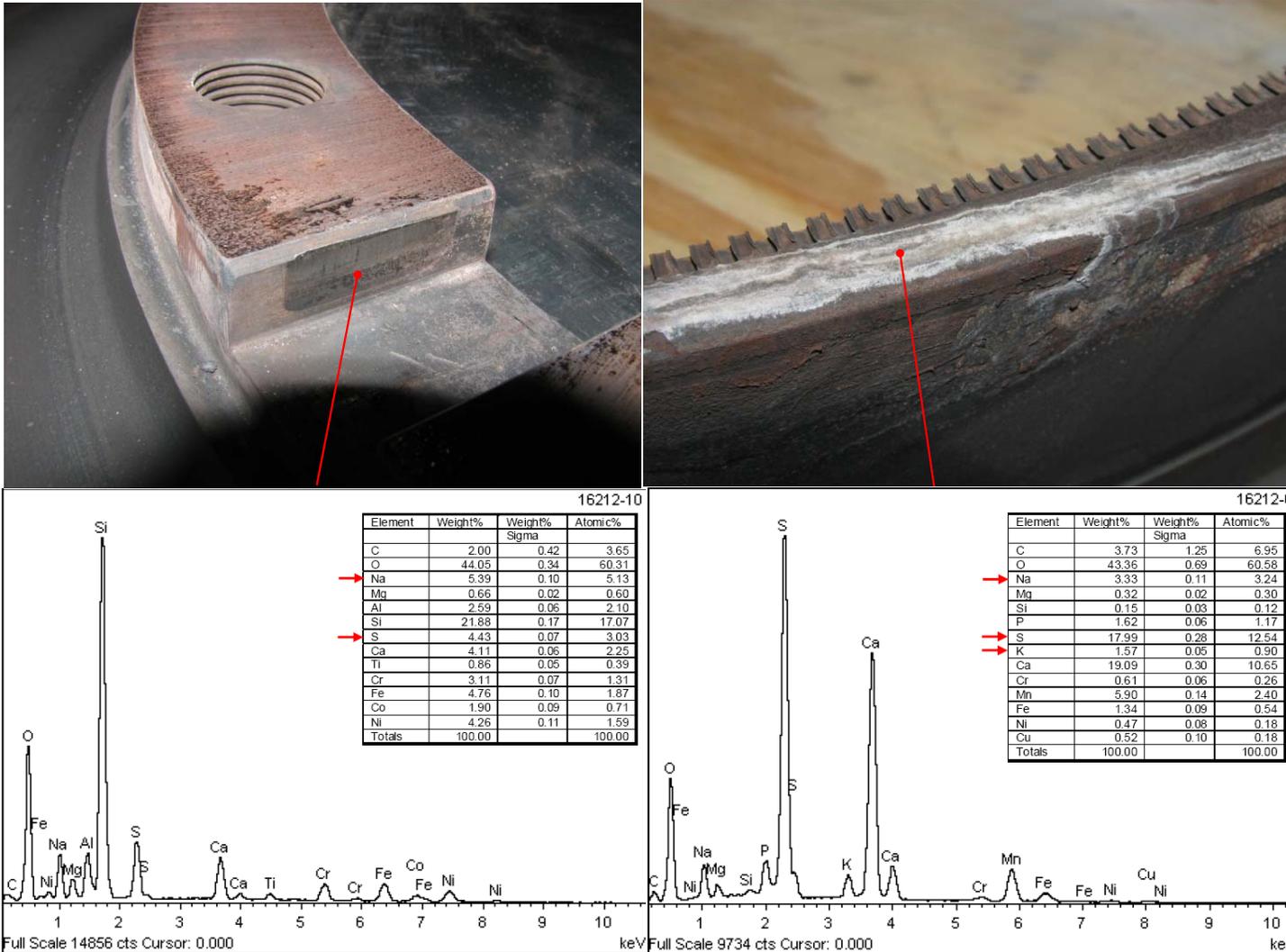
**Figure 23a:** Vendor 3. Evidence of crystalline deposits having worked through secondary air systems. [53]

# 6.0 – Teardown Examples



**Figure 24:** Deposits near torque transmission features on a power turbine from Red Deer River C/S (Alberta). [54]

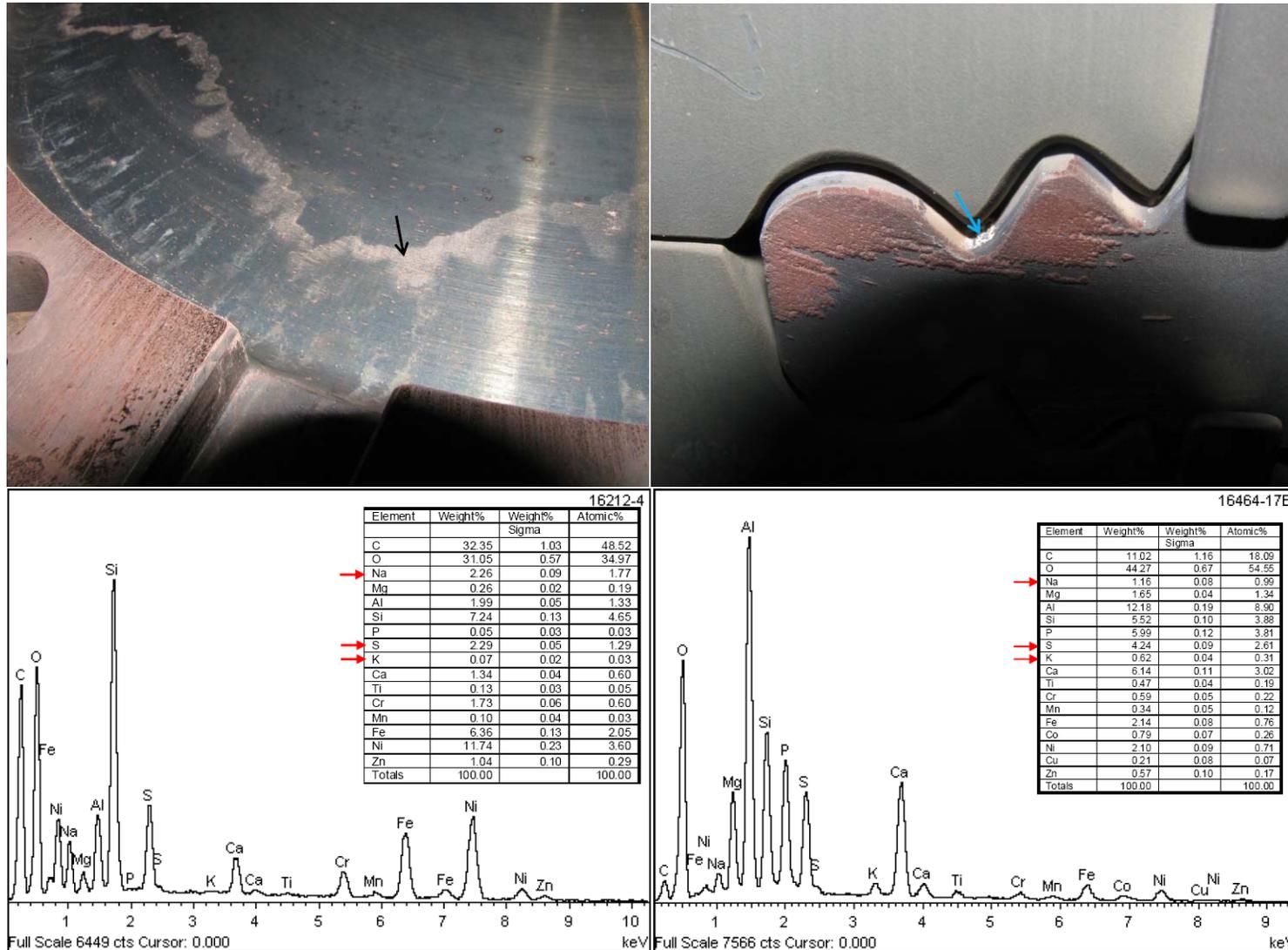
# 6.0 – Teardown Examples



**Figure 25:** Analysis of deposits from a power turbine from Acme C/S (Alberta).

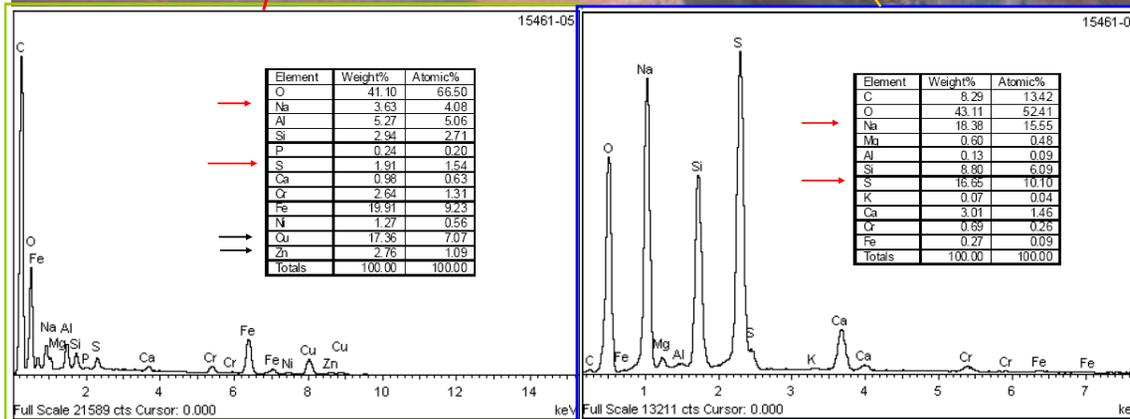
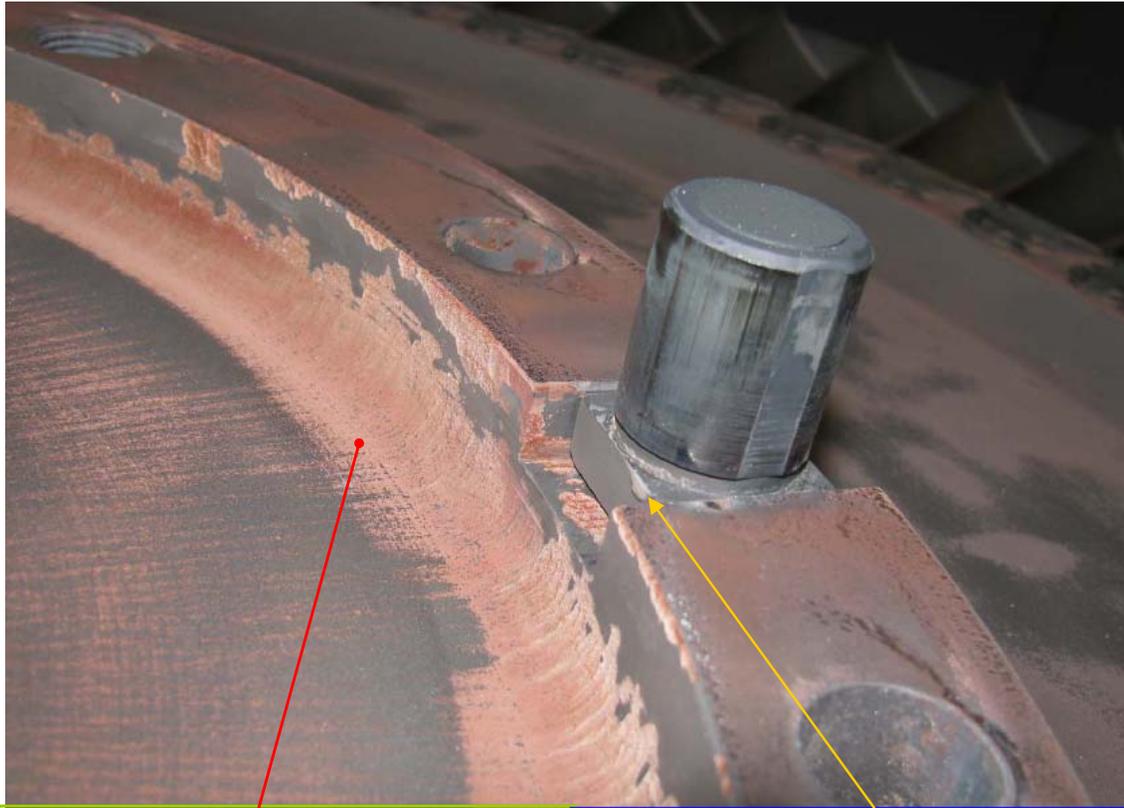
[55]

# 6.0 – Teardown Examples



**Figure 25:** Analysis of deposits from a power turbine from Acme C/S (Alberta).

[55]



**Figure 26** – Deposits and analysis from a PT from Berland River C/S (Alberta). [56]

# 7.0 – Mitigation & Remedy

## 7.1 - Overhaul Schedules / Adherence to OEM Intervals

- 100000 hours service interval with minimal maintenance requirement. A success, but perhaps “backhanded”. Such long service intervals afford deposits time to react, initiate and propagate unchecked.
- Consider augmented NDE inspections. LPI may be inadequate for some threats.
- Consider clawing back service intervals in at risk operating theaters.
- Upgrade to better materials if available (on older designs).

## 7.2 - Compressor Wash Protocols

- Water cleanliness / specification are paramount.
- Ensure no deviations from OEM procedures.
- Minimise likelihood and/or amount of carryover.
- In environments as described, fired washes not recommended.
- Consideration of post-compressor wash PT Rotor-Stator Cavity demineralised water rinse. (?)



# 7.0 – Mitigation & Remedy

## 7.3 - Control Of Assembly Lubricants

- Consult equipment OEM, understand their recommended products, but verify these are appropriate.
- Ensure quality programs and adequate definition for use in procedures, avoid excessive application.
- Can be introduced during assembly, manipulation, balancing, installations at site.
- Ensure they are controlled in all locations.
- In-Situ Inspections

## 7.4 - Improved Filtration

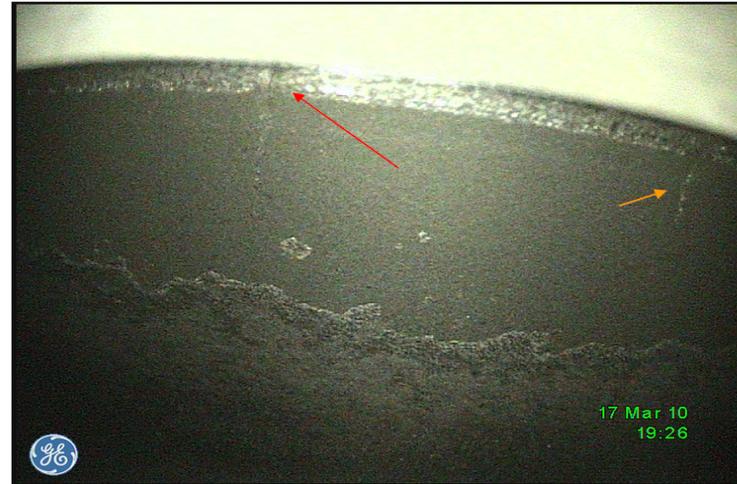
- A move to improved filtration capable of arresting salt penetration is a consideration.
- Some HEPA Filters Claim Capability as a bonus to reduced / eliminating recoverable performance loss.
- Do homework before selection.
- Rest of Inlet System also needs to be “HEPA Consistent”, otherwise benefit may be defeated.



# 7.0 – Mitigation & Remedy

## 7.5 – Develop In-Situ Inspection

- Enhance ability to identify deposits or onset of corrosion without complete disassembly or removal.
- Do not be discouraged regarding access. Modern boroscopes ~3.9 mm diameter.
- Visual inspection for:
  - cracks,
  - rubs,
  - impacts,
  - handling damage,
  - corrosion.



Case 1 - Boroscope Image – 1003170127.jpg; Was estimated at 3/16" at time.



Case 1 - Indication near T-Pin Slot B – left hand later confirmed by UT.

# 7.0 – Mitigation & Remedy

## 7.5 – Site Location and Inlet Filtration Planning Process

- Be thorough and detailed. Evaporite story appears to have been underappreciated.
- OEM's and GE Energy's GER-4253 and GMRC/SWRI "Guideline for Gas Turbine Inlet Systems" are useful resources that should be consulted.
- Realise that site is "dynamic" and situations and neighboring operations can change – re-assess periodically.

## 7.6 – Implications for Life Extension

- Be very careful when dealing with corrosion effects superimposed on "design life" expired discs and equipment, especially near stress concentrators.
- The principle that conservatism at design, coupled with better understanding from modern analytical tools, materials tests and detailed knowledge of service history can indeed demonstrate additional margin still holds. However, consider operating environment and augment NDE as appropriate.



# 7.0 – Mitigation & Remedy

## 7.7 – Future Work

- Long Term GT Inlet Air Contaminant Study in the Sour Gas Corridor to attempt to understand the fate of both SO<sub>2</sub> and aerosol sulphates from Sour Gas Processing and Upstream Oil and Gas Activity.
- Complete detailed disc corrosion characterisation study.
- Disc Alloy Corrosion Susceptibility Study for those Alloys identified in Table 1. Findings may be factored into life cycle cost planning or even selection of future equipment.

