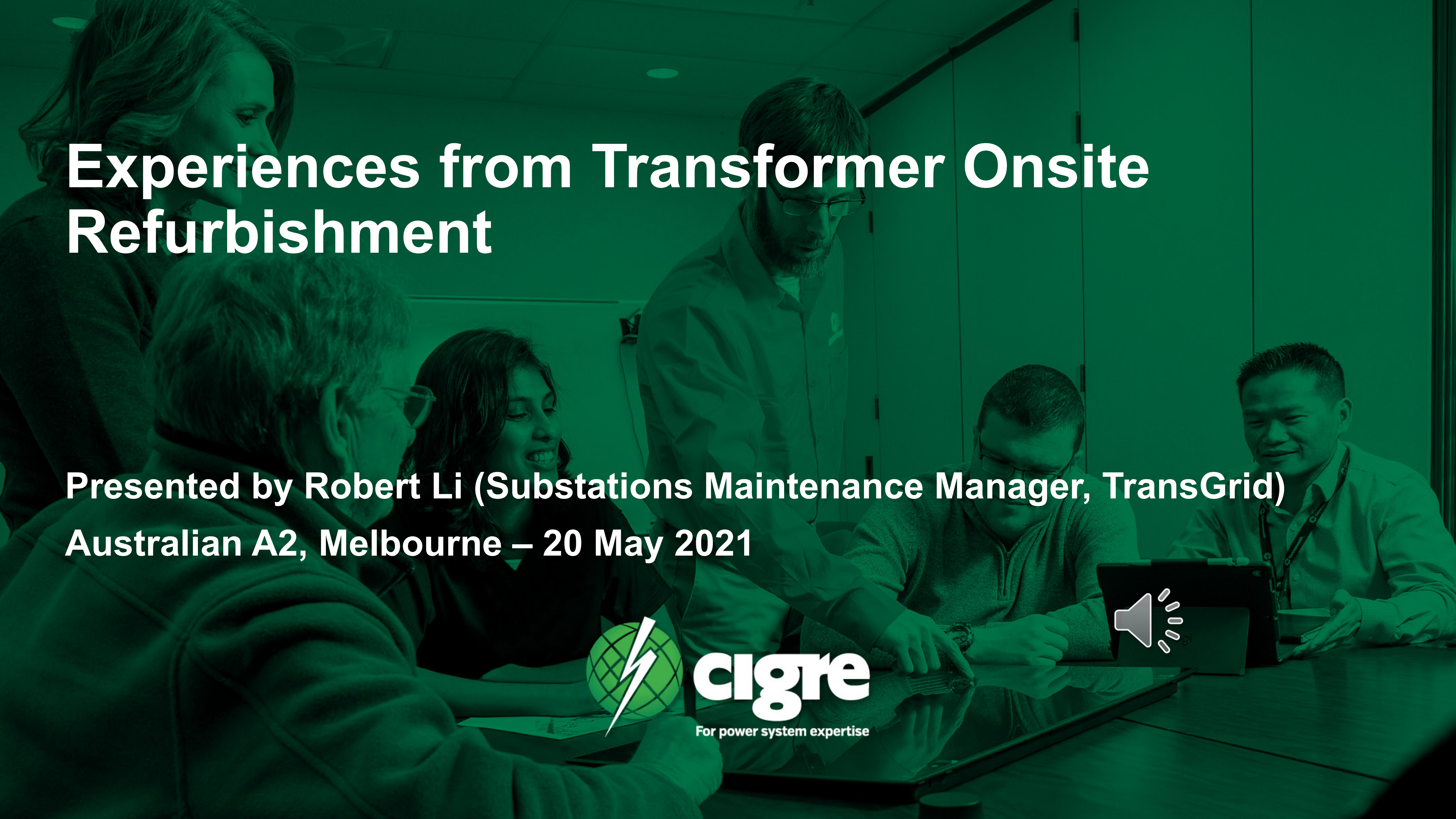

Experiences from Transformer Onsite Refurbishment

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Australian A2, Melbourne – 20 May 2021

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Overview of the Transformer Refurbishment Program

- The characteristic of the TSO's transformer fleet : lightly loaded, avarage age of 25, varying degree of oil leaks among older units, no issue with moisture ingress
- Past replacement justification were based on higher load demand or failures
- Load demand was peaked in 2011, future demand flat or slight increase for most of the transformers. ROI of refurbishment out-weight replacements for the selected group.
- The health indicators, defects, forced outages and trips, operation and maintenance history of the entire transformer fleet were reviewed. A group of 16 transformers from the bottom 20% of the population with the worst condition and highest criticality were selected for refurbishment from 2014 to 2019.
- TSO's regional maintenance staff had been performing infrequent small-scale transformer refurbishments since the 2000s. Due to concerns of staff competency, it was decided that the best approach was to use a number of specialised contractors for the first few refurbishments as individual projects. Able to capture the know-how and determine which specific tasks during a refurbishment are best contracted out.

List of Refurbished Transformers

Transformer	Voltages	MVA Rating	Phase	YoM	Vector Group	Construction	Refurbishment Date
A, B	132/66/11	120	3	1983	YNyn0d1	Double Winding	Aug – Oct 2018
C, D	132/66/11	120	3	1984	YNyn0d1	Double Winding	Aug – Nov 2016
E	330/132/11	375	3	1979	YNa0d1	3 Phase Auto	Early 2014
H, I, K, L	330/132/11	375	3	1981	YNa0d1	3 Phase Auto	Nov 16 – Aug 17
F, G	330/132/11	375	3	1982	YNa0d1	3 Phase Auto	First half 2016
J	330/132/11	375	3	1985	YNa0d1	3 Phase Auto	Mid 2017
M, N, O & P, Q, R	500/330/33	400	1	1984	YNa0d1	Single Phase Auto	Nov 2018 to first half 2019
S, T	132/22	15	3	1968	YNzn1	Star ZigZag	Late 2017

Refurbishment Scope

Refurbishment Tasks	Details
Pre-Refurbishment Condition Assessment	• Oil sample for DGA and oil quality (dielectric break down strength, interfacial tension, moisture, DDF and PCB); • Winding Insulation moisture assessment using DFR; • Winding Insulation Resistance, DDF, Capacitance, primary, secondary and tertiary winding resistances, ratios; • Tap Changer slope and ripple forward and reverse through entire tapping range • Core/Frame insulation resistance; • Low voltage excitation current and watt loss
Leak Repairs and Corrosion Treatment	• Welding of Main tank lid and selector switch lids; • Re-gasket bushing turret, replacement of bushing seals; • Surface corrosion treatment and repaint.
Cooling System Overhaul	• Radiators, Butterfly Valves, Pipework; • Oil pumps inspection and overhaul by external specialist companies (winding and insulation resistances, seals, O-ring and bearing replacement; check conditions of impeller, shaft and repaint) • Fans motor bearing, noise, IR and load current checks; • Oil flow sensor; • Expansion joint couplings replacement.
Main tank internal inspection and winding clamping pressure check	• Inspect for evident of major fault and loose insulations; • Inspect and clean any debris on the tank bottom; • Selector switch maintenance (contact terminal cleaning etc); • Collect winding lead paper and send for DP test in specialised lab; • Winding clamping pressure check, re-clamp if necessary (done by contractor specialists - selected transformers only)
Insulation Oil Filtration or Replacement	• Replace if the oil is PCB contaminated (> 2ppm); • Test for corrosive sulphur, add passivator if necessary; • Filtration; • Hot oil circulation & vacuum drying if main winding insulation paper has high moisture level (> 3%)
Bushing	• Test for IR, DDF and Capacitance, using both 50Hz and Dielectric Spectroscopy techniques; • Replacement of older SRBP type with new RIP type; • Replacement of poorly performing bushings (based on diagnostic data) with new RIP type; • Leak repair
Tap Changer	• Diverter switch shunt contact tolerance and surface condition; • Diverter switch compartment oil replacement; • Drive shaft inspection and repair (excessive wear etc); • Braided contact leads and flexible resistor leads replacement
Main Transformer Accessories	• Conservator Bag integrity check and replacement where necessary; • Check functionality of level indicator and condition of sight glass; • Functionality check, gasket replacement, corrosion treatment for Buchholz relay gas alarm, OLCT surge relay, Pressure relief device, pressure relays; (Replace internal wiring if necessary) • Inspect WTI and OTI (replace if they are old age and non-standard type and lack of spare) • Core earth box corrosion treatment and earthing terminal bushing replacement
Auxiliary Transformer	• Leak repair and corrosion treatment; • Inspect condition of 11kV cables or conductor termination, repair any defect found.
Post Refurbishment Tests	• Repeat tests from pre-refurbishment assessment; • Pressure test (30 kPa) to verify leak repairs; • HV applied test as per AS 2374.3; • Induced Overvoltage Test (@1.1 pu); • Partial Discharge tests as per AS 2374.3; • Frequency Response Analysis.

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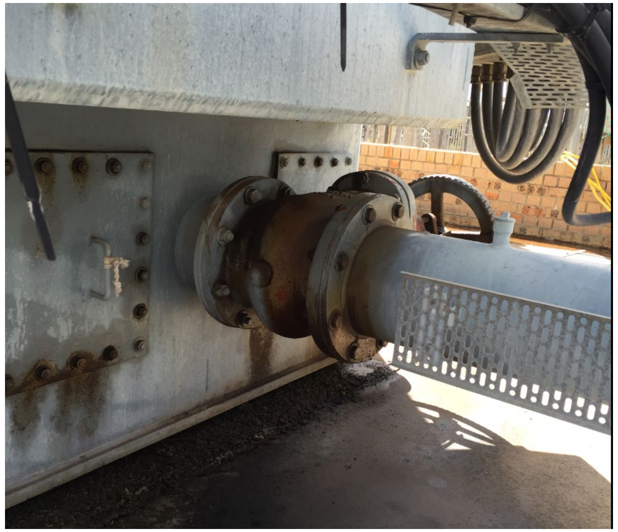
Example of a 330kV Transformer Prior to Refurbishment



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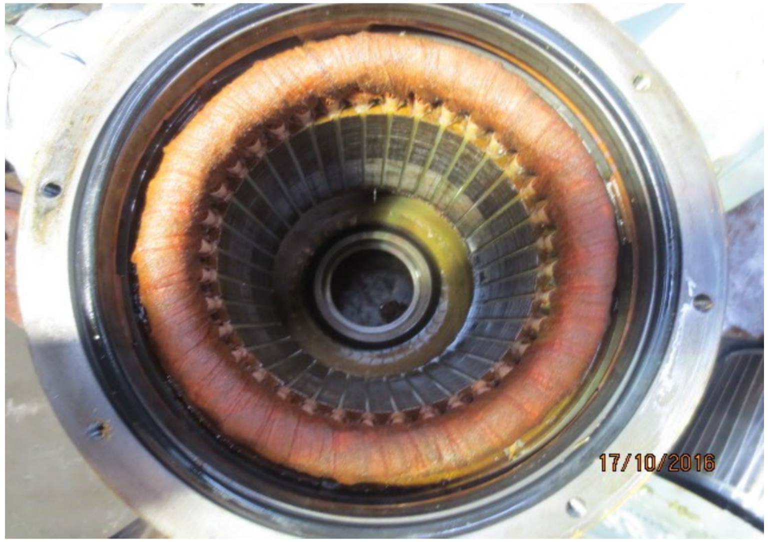
Cooling Fan motors and Oil pump integrity check



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Main Issues Found

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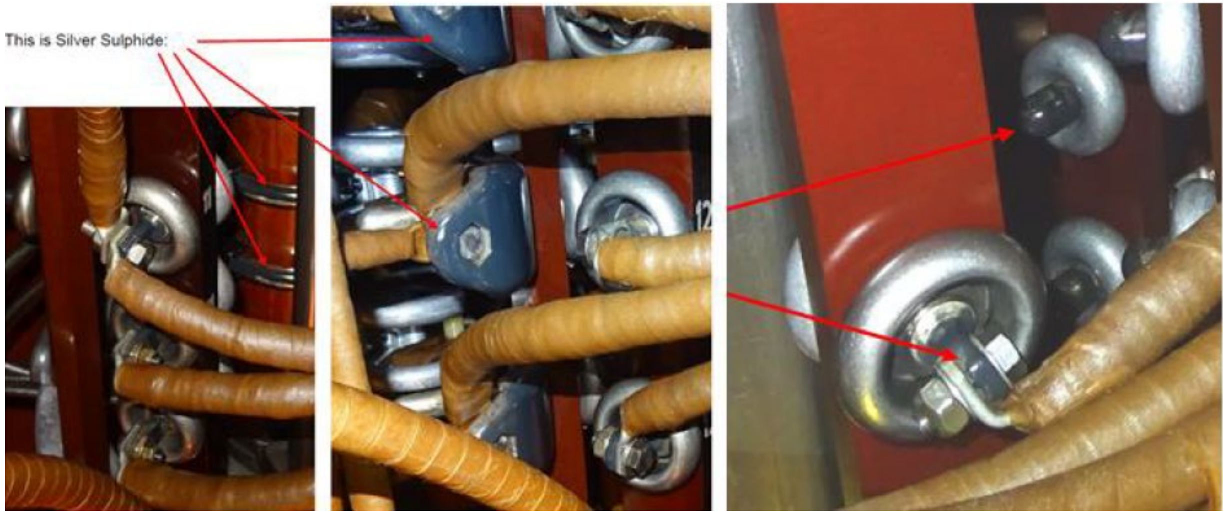
Silver Sulphide Corrosion

Silver Sulphide Deposit on the selector contacts of Transformer H & K



- Various degrees of silver sulphide corrosion were found on selector switch contacts of Transformers S, H, K and G. These transformers' health indicators and available service history prior to refurbishment could not account for this silver sulphide corrosion.
- The past Fuller's earth oil treatment starting from late 1980s to early 1990s is highly likely to be the contributing factor. Two units failed due to silver built on infrequently operated K switch.
- Oil from the refurbished group of transformers were tested for corrosivity to silver only and all of them are non-corrosive. Only oil from Transformer E was tested to have corrosive oil and it had passivator added during refurbishment.
- DBDS) in oil was tested only for Transformer H. However, the result was less than 1.10 mg/l.
- DIN 51353 (silver strip) test was performed on oil from Transformer K, the result was also negative (oil was replaced in 2010).

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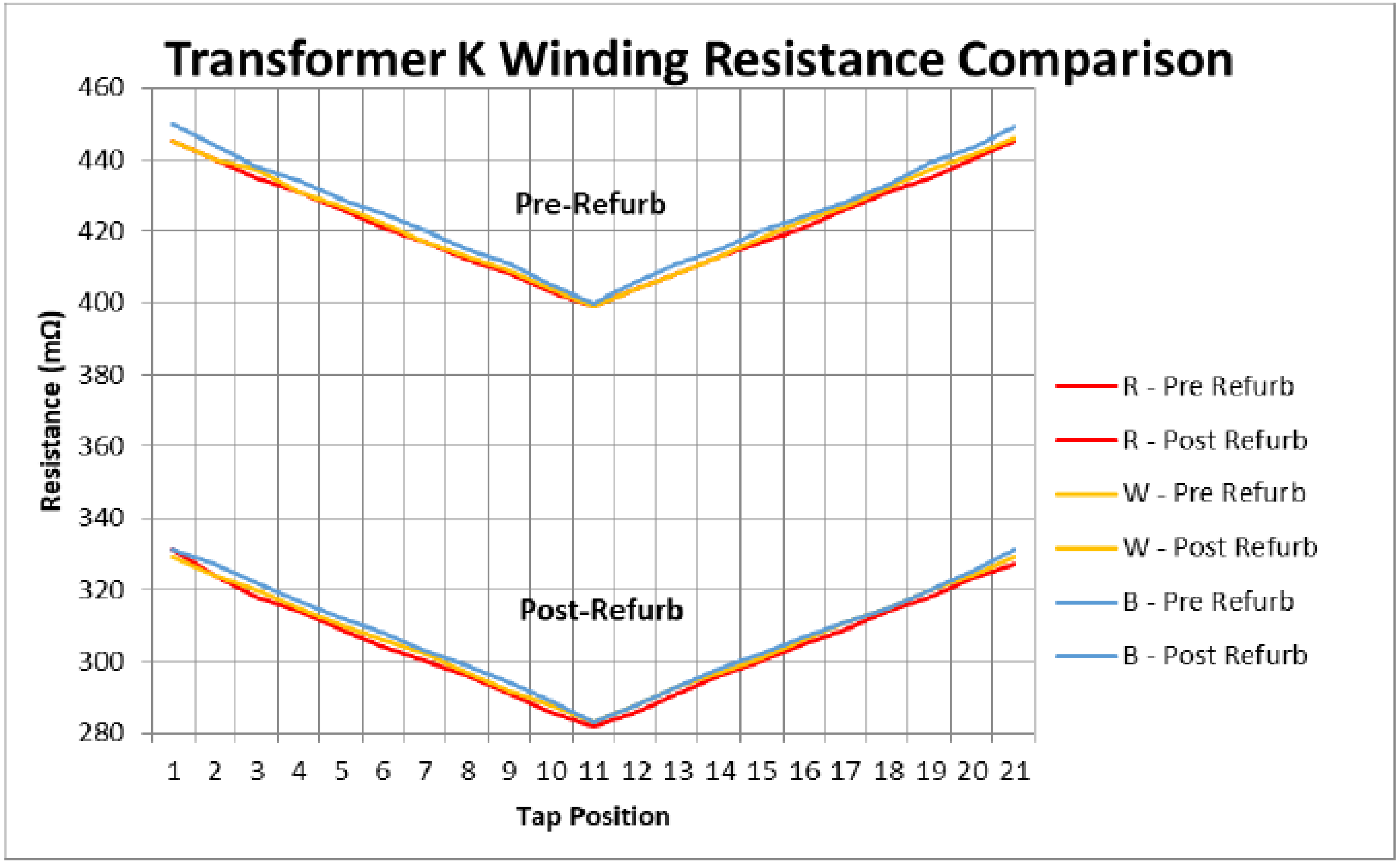
Silver Sulphide Corrosion on Selector Switch

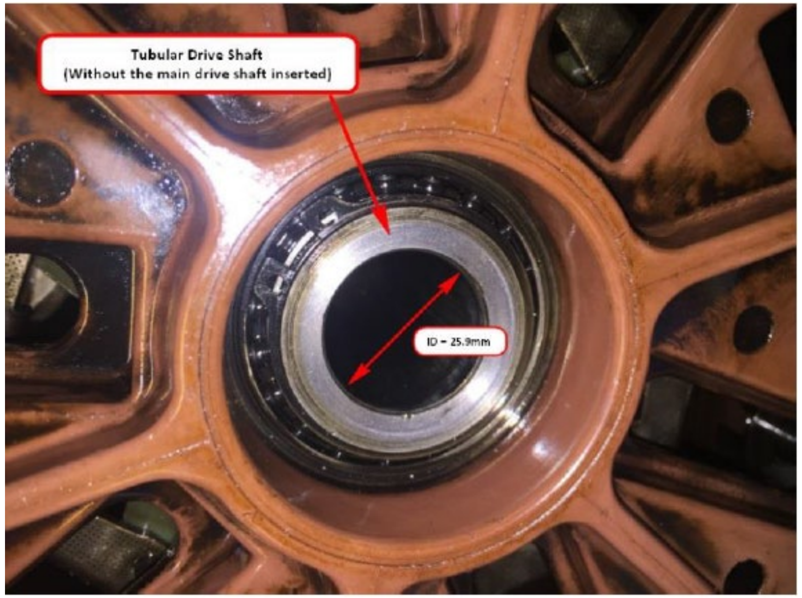
Transformer K's Winding Resistances Comparison through tap range before and after refurbishment



Tap Changer Drive Shaft Wear

Tap changer specialist was engaged to inspect the diverter switches of Transformer F (330kV, 375MVA, 1982). This Tx’s tap changer has more than 350,000 operations, one of the highest among the fleet.

Inspection found both drive shaft and inner sleeve on guide plate had significant wear on all three phases. Shunt contacts on two phases did not meet OEM’s tolerance.

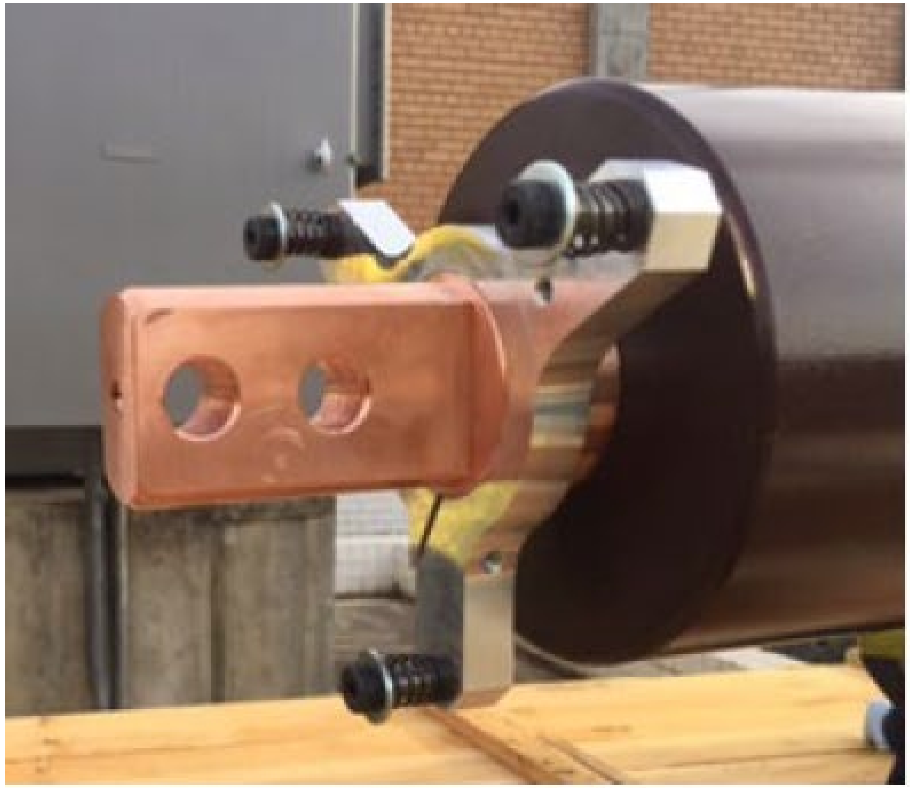


Ruptured Conservator Bag

- Conservator bag on a number of transformers were found ruptured – due to inapprioriate maintenance or installation

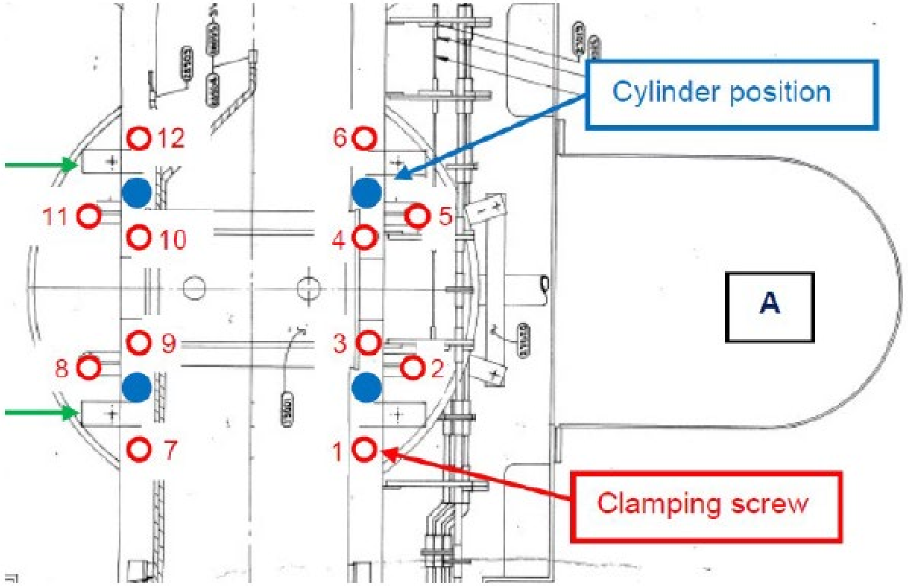
Issues with Bushing Replacements

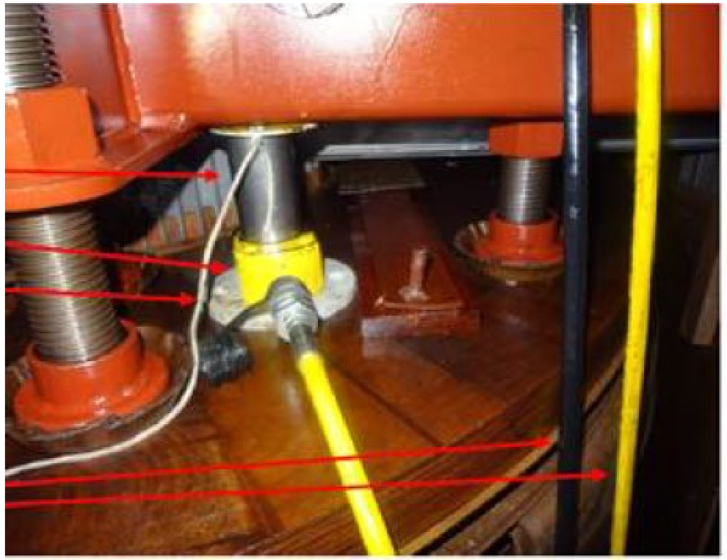
Solutions to fit the winding connection of new RIP bushings



Residual Clamping Pressure Check

- Winding clamping pressures were checked only on three transformers, G, J and K by contracted specialists
- The TSO’s upper limit for applying re-clamp pressure is 65% of the factory value (85 tonnes per phase): 55 tonnes - mitigates the danger of over-clamping that winding.
- With non-uniform relaxation of the insulation structure after 30 years, it is possible that one winding is taking a greater proportion of the total force.





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Residual Clamping Pressure Check

- Residual clamping forces of each phase of Transformer G, J, K in tonnes (% of factory original value)

Transformer	A phase	B phase	C phase
G	65 (77%)	69 (82%)	72 (85%)
J	50 (59%)	53 (62%)	51 (60%)
K	11 (13%)	22 (26%)	35 (41%)

- Hydraulic jack pressure (PSI) to release residual clamping force in each clamping screws in Transformer K

	1	2	3	4	5	6	7	8	9	10	11	12	Average PSI	Equivalent Force (Tonnes)
A phase	0	1000	3000	4000	0	0	0	1000	4000	3000	0	0	1333	11
B phase	3000	2000	2000	2000	2000	4000	3000	3000	3000	3000	3000	4000	2833	22
C phase	6000	3000	5000	3000	5000	4000	4000	4000	4000	5000	5000	5000	4416	35

Post Refurbishment Review

Defects Resulting From Refurbishment Works

New leak & Re-Emerged leak

- Transformer L's cooler bank gate valve leaks 9 months after refurbishment due to defective new gasket fitted
- Leak re-emerged from Transformer T's diverter lid 13 months after refurbishment due to insufficient bolts tightening

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Post Refurbishment Review

Aim of the review is to assess and improve the following:

- The effectiveness of the refurbishment work done;
- The adequacy of the refurbishment scope;
- Improvements in refurbishment scoping, methodology and execution;
- The renewed effective age and remaining life;
- The forecast future major expenditure timeframe and scope;
- Planning of refurbishment scope and timing for the rest of the transformer population

Post Refurbishment Review

Assumed reliability improvement is based on the following fact

	Impact of reliability
Major leaks addressed and so far all the repairs are effective, no more leaks from these transformers	Immediately improves reliability
Oil results have improved at least temporarily	Assess over longer term
Oil with PCB replaced with new oil	Immediately improves reliability
Some of the Bushings were replaced with new higher reliability RIP bushings	Immediately improves reliability
Tap changer and its selector switches have been thoroughly inspected, defects repaired, silver sulphide cleaned	Immediately improves reliability
Conservator bag inspected and replaced	Expected improvement in reliability
Surface corrosion treated and painted with three coats of highly effective paint	Expected improvement in reliability
Cooling systems (fans and pumps, pipes and sensors) thoroughly inspected and defects repaired	Immediately improves reliability

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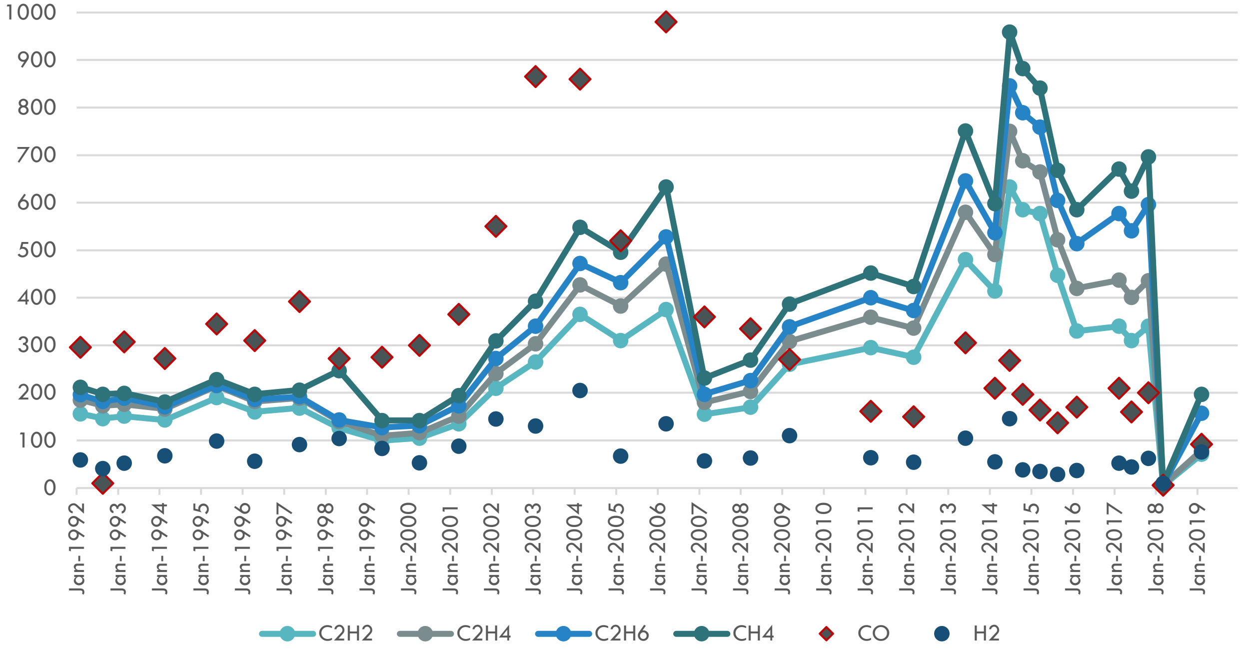
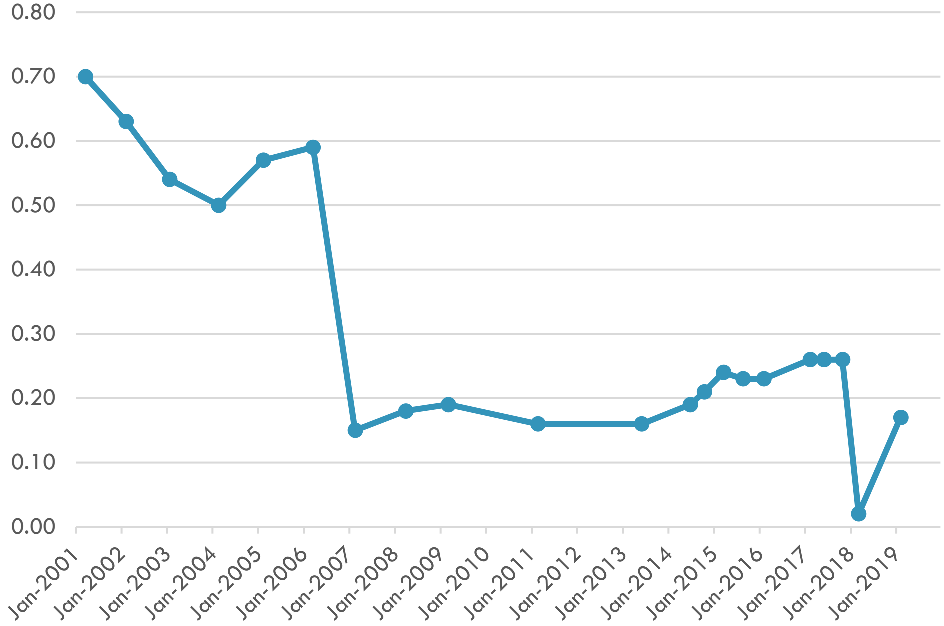
Key health indicators comparison – Transformer T & S (15MVA, 132/22kV, YOM 1968)





- Two sister units in the same substations. Refurbished in Dec 17, the oldest of the group. DP: 603~697 (lowest among this group). Oil replacement in May 2006.
- No conservator bag. External nitrogen bag fitted in 2000 however its performance is questionable.
- Silver sulphide corrosion was found on the selector contacts of Transformer S only.
- Since refurb, furans have been slowly migrating from paper back into oil.

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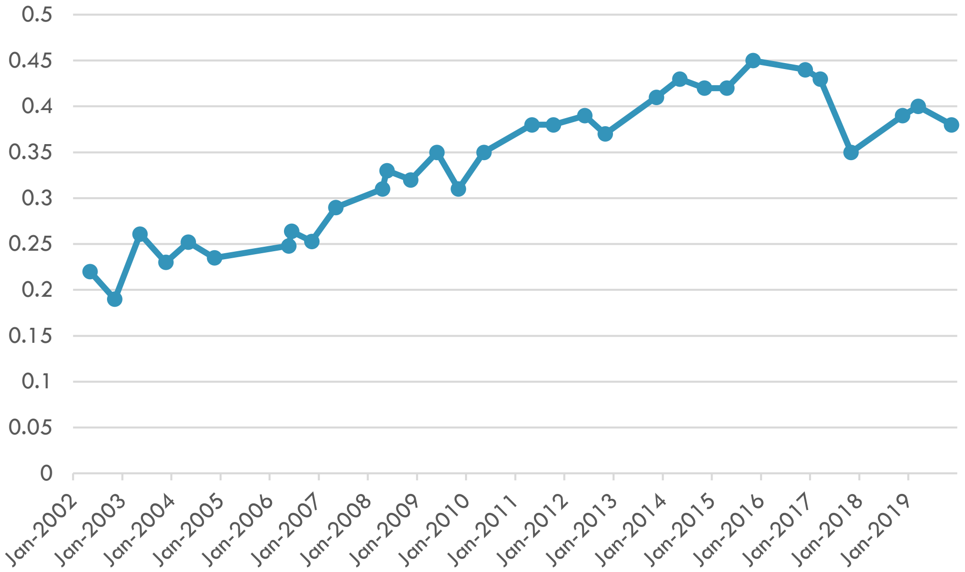
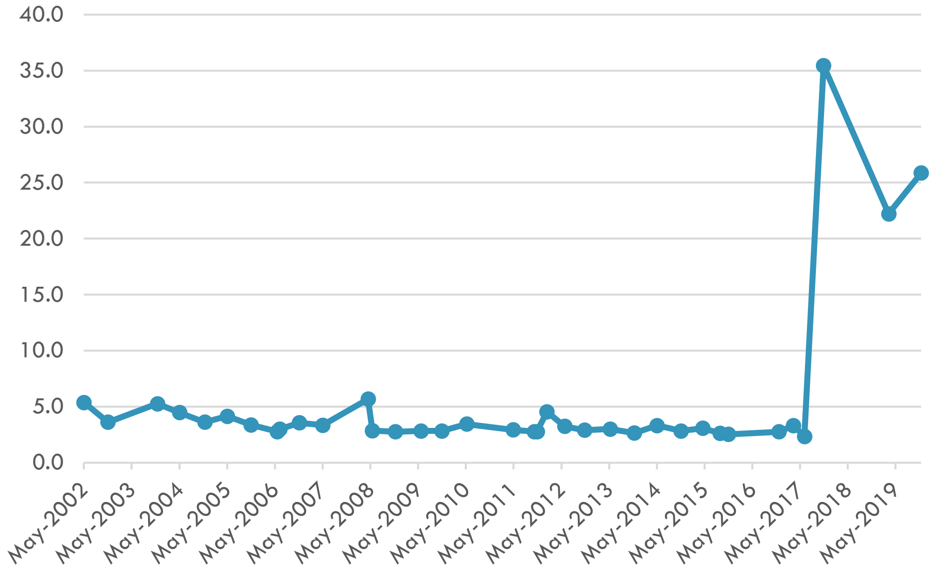
Key health indicators comparison – Transformer I (375MVA, 330/132kV, YOM:1981)

- Refurb completed in June 2017. This unit shares the same design as Transformer L, K, H, J, F, G, I and E from late 1970s to 1980s.
- Paper DP ranges between 711 to 880. Furans have been increasing from 0.2 to 0.45 ug/g in the last 14 years (highest Furan among this group). Furan has come back but stablised post refurbishment
- Conservator bag found defective and replaced during refurbishment. Effect of bag replacement on N2/O2 ratio in oil is shown below
- It has been suffering from severe chronic leak since 1997. Numerous forced outages due to low oil. Attempts to slow the leak have only partially worked. Prior to refurbishment, leak rate per year was 200L.
- Lack of conservator bag and severe leak over the past two decades are considered as the reason behind the high Furan level.





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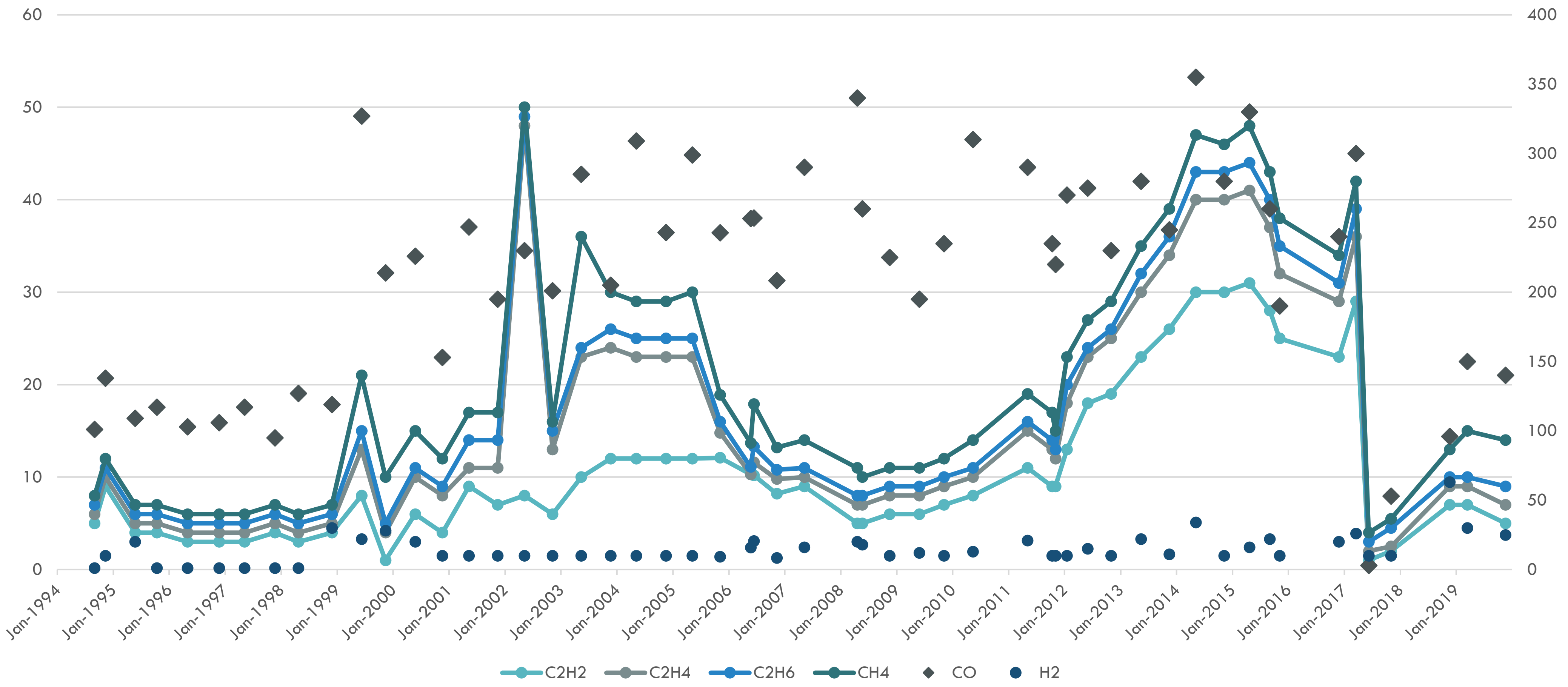

Consideration for Planning of Future Refurbishment Program

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Consideration for Planning of Future Refurbishment Program

- Justification of refurbishment work must consider the future projected network criticality and risk – eg: impact from increased renewable connections in rural areas. The reliability requirement of the development will change the criticality of the potential transformers and hence the refurbishment scope.
- For Tx A & B (120 MVA each), only 6 months after refurb, a 100 MVA solar farm was connected and more solar generation planned. This wasn't anticipated at the time of refurbishment justification.
- Refurbishment planning must take allowable outage duration and recall time into consideration – at certain locations (less connected part of the network), long outage with no recall is not permitted, this limits the refurbishment scope
- For some critical tasks which require longest recall duration, more resources were needed to facilitate longer working hours in order to reduce the operational risk. Health & Safety and QA needs to be managed well in these situations
- Special control and protection schemes may also need to be devised and implemented to allow contingency during refurbishment

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Conclusion

- With the future load demand flattening, it is often more economical to perform extensive mid-life transformer refurbishment
- The viability of refurbishment over replacement needs to assess network risk and development as well as technical condition to properly include the risk cost
- Actions which can address those components with a correctable poor condition, have to be weighed up alongside those components with irreversible processes of degradation in condition or involve very costly corrective actions
- Replacement decisions should consider the comparative cost-benefit of refurbishment and the issue of ‘soft failure’ such as inadequate rating, impedance, or tapping range due to change in demand and system requirements.
- Other significant benefits such as valuable training of internal staff, greater transformer knowledge and improved diagnostic and maintenance skills.