DARLINGTON NUCLEAR
POWERING
TOMORROW, TODAY

Primary Heat Transport (PHT) Motor Rotor Retaining Ring Failure

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Ontario Power Generation Darlington

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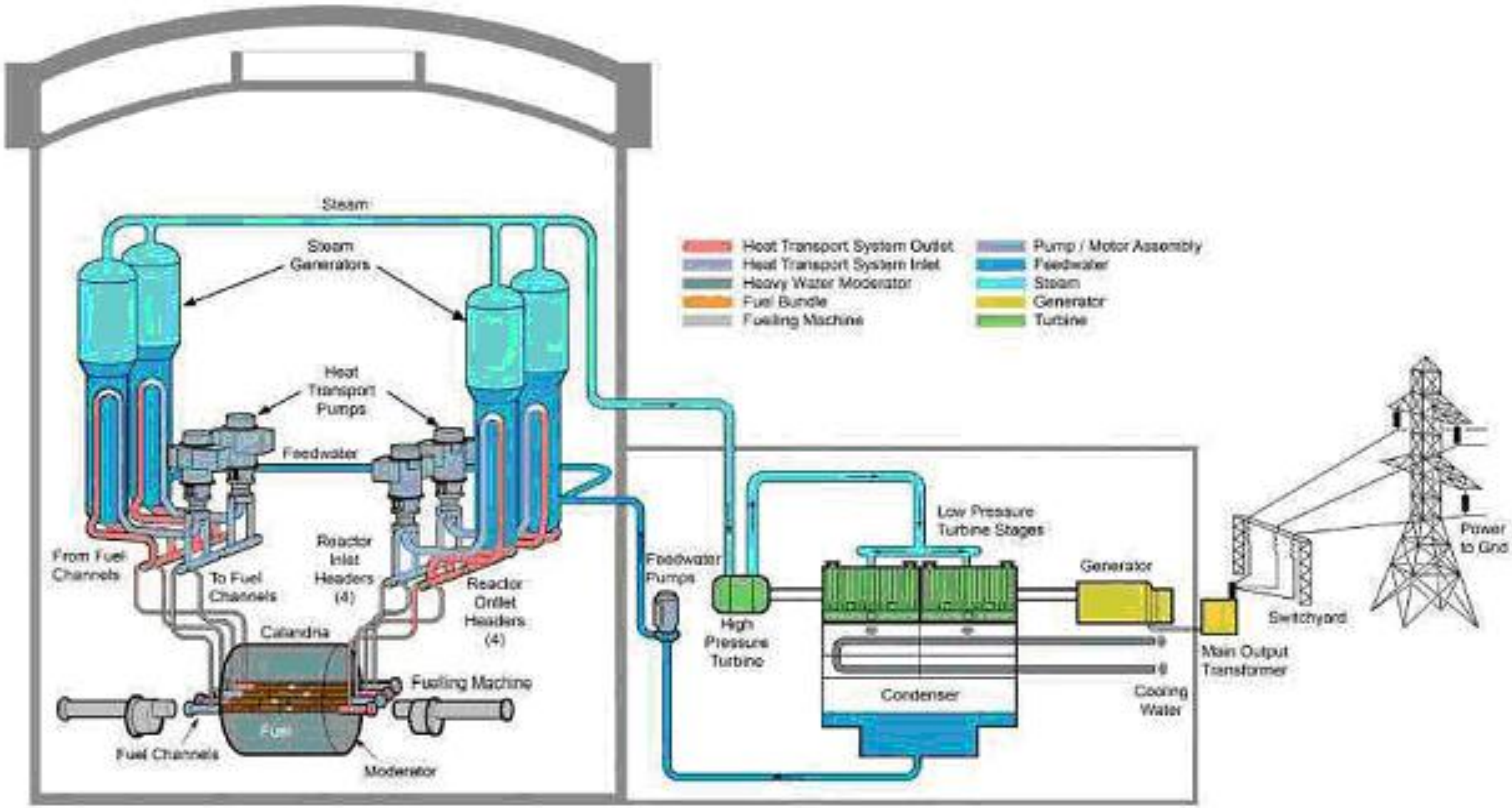
- Darlington Nuclear Generation Station is a Canadian nuclear power station located on the north shore of Lake Ontario in Clarington, Ontario.
- Darlington Station has 4 CANDU (CANadian Deuterium Uranium) nuclear reactors with a total output of 3,512 MWe (~ 878MWe per unit)
- It provides about 20% of Ontario's electricity needs, enough to serve city of two million people

CANDU Reactor

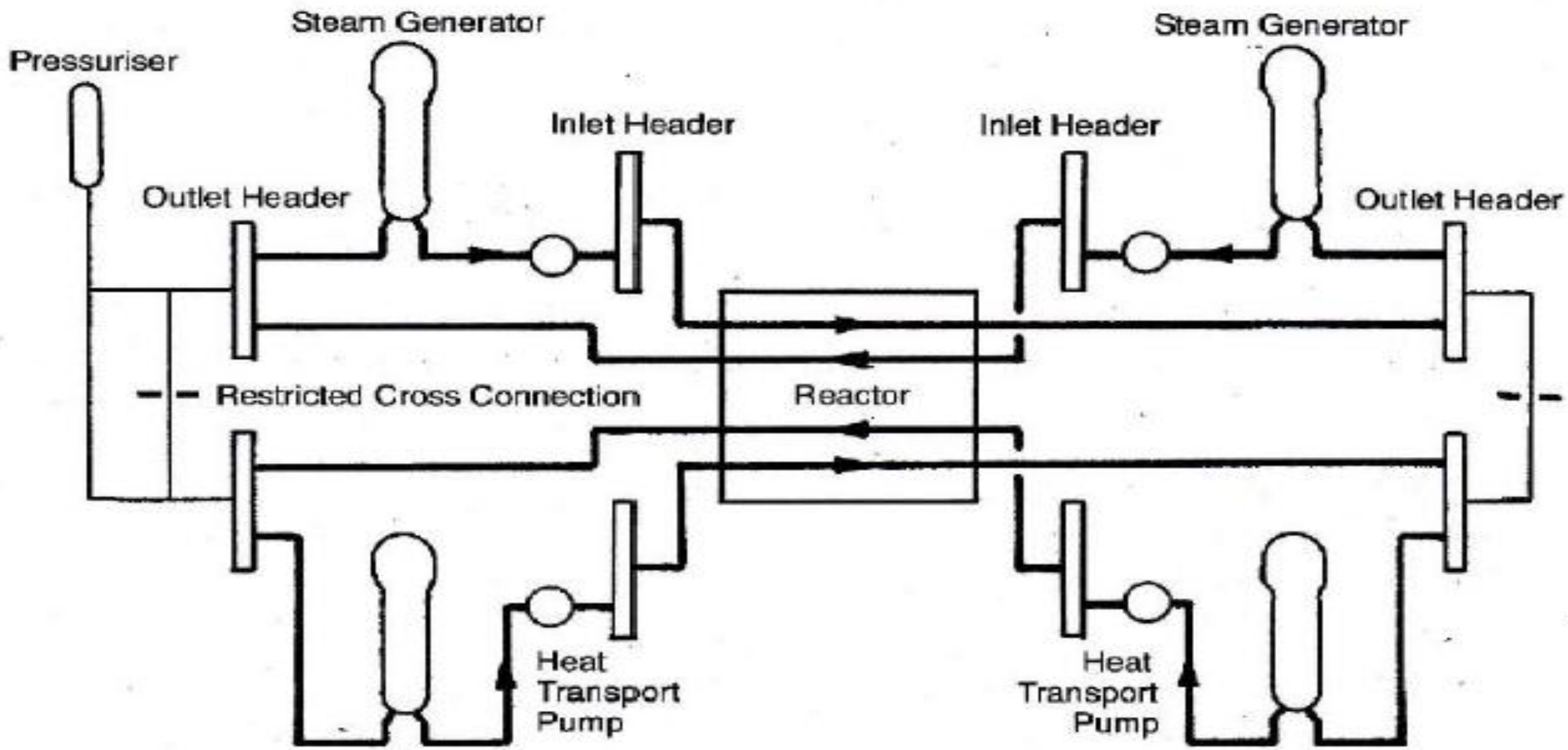
- CANDU Reactor is Pressurized Heavy Water Reactor (PHWR)



CANDU Reactor
(courtesy AECL)

Primary Heat Transport System

- Heat Transport System is to circulate the heavy water coolant and transport heat from the fuel elements to the steam systems
- Heavy water coolant is used to minimize neutron absorption.
- There are 4 heat transport pumps which are driven by electrical motors; failure of any of the 4 motors will cause the reactor to trip.



Primary Heat Transport Pump Motors

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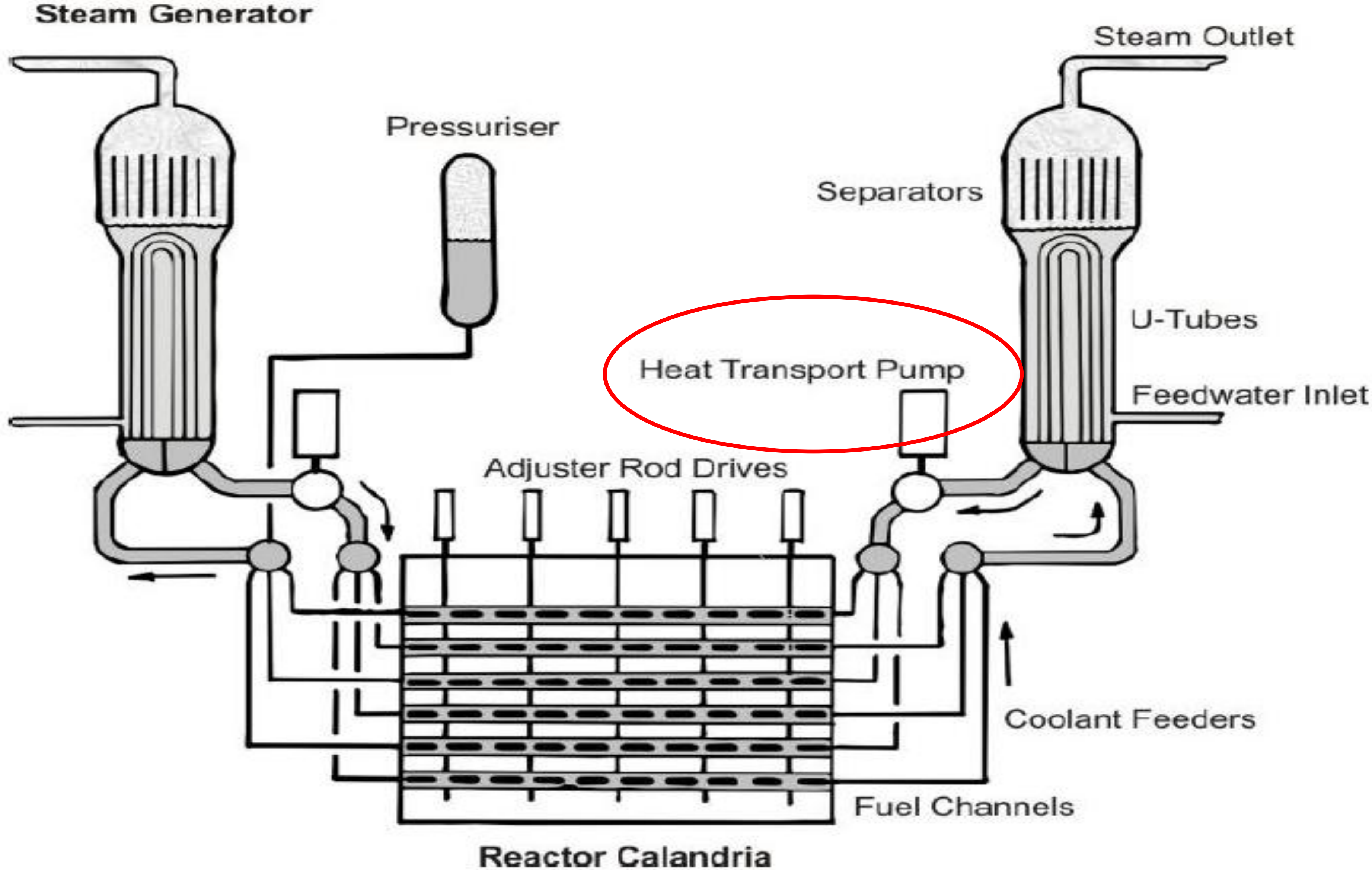

Primary Heat Transport Pump Motors

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Motor Operating History

- Darlington PHT motors are squirrel cage induction motors
  - 13.8kV, 9400kW, 60Hz, Total Enclosed Water-Air Cooled,
- Key events:
  - 1991:
    - 1-PM1 installed and commissioned
    - Condition Monitoring Techniques: Vibration, Oil analysis, temperature monitoring, offline electrical testing, stator cooler inspections (3 years)
  - 2009-2011:
    - Partial discharge monitoring and ozone sampling implemented
    - High Partial discharge and high ozone concentration
  - 2014 May :
    - Scheduled replacement (with new motor) delayed due to schedule slip on new motor manufacturing.
  - 2015 December:
    - Motor failure due to rotor retaining ring fracture.

Motor Operating History

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- The PHT motors are the original motors of Darlington Nuclear Generating Station and have been operating for approximately 26 years.
- The PHT motors have never had a complete refurbishment performed until 2016.

- Onsite predictive maintenance tests consists of:
  - Winding resistance
  - Insulation resistance
  - Polarization index
  - Partial discharge – (online)
  - Ozone monitoring – (online)
  - Winding and bearing temperature monitoring
  - Vibration monitoring (frame and shaft)
  - Oil analysis

- Corrective maintenance activities have consisted of:
  - Stator air cooler replacement due to ozone damage
  - Upper bearing oil cooler replacement

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PHT Motors Refurbishment Plan

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- A decision was made to refurbishment and rewind the PHT motors to support Plant Life Extension for another 30 years of operation.
- A parallel path to procure some new PHT motors was also implemented to support Plant Life Extension.
- Motor repair shops were evaluated and one chosen to provide refurbishment and rewind services for the PHT motors.
- Upon disassembly of the PHT motors it was apparent that they were showing signs of aging degradation in the both the electrical and mechanical components.

It should be noted that many of the degraded conditions discovered during disassembly could not be detected with available predictive maintenance.

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PHT Rotor Retaining Ring Failure

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- On December 04, 2015, Darlington Unit 1 PHT pump motor 1-PM1 electrical protection tripped. Onsite investigation of the failure indicated that the opposite drive end (ODE) rotor stainless steel retaining ring came loose from the rotor in two pieces. One piece of the retaining ring was retrieved onsite from its resting place on top of one of the stator air coolers after its ejection from the rotor. This resulted in a complete winding failure, and a 20-day outage.

Failure of Rotor Retaining Ring

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The PHT motors are a Totally Enclosed Water to Air Cooling (TEWAC) design.

The shroud enclosure contained the ejection of the failed rotor retaining ring.

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Failure of Rotor Retaining Ring

Damaged PHT Motor with Shroud Removed.

Failure of Rotor Retaining Ring

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Damaged Endwinding Air Baffle Cover from Ejected Rotor Retaining Ring

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Failure of Rotor Retaining Ring

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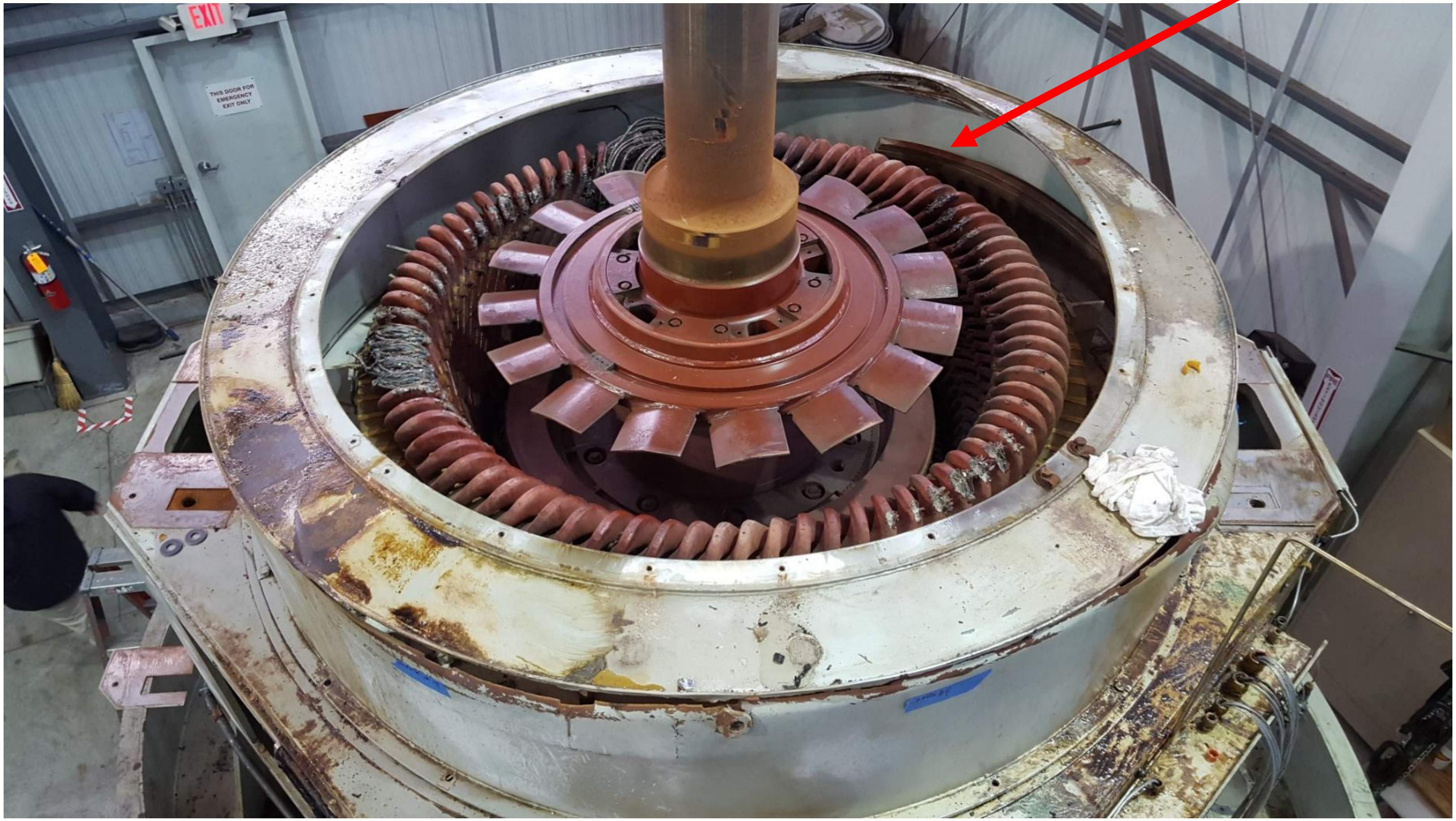
Endwinding Cover and Winding Damage from Ejected Rotor Retaining Ring

Notice half of the retaining ring is inside the endwinding cover



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Motor Failure Assessment

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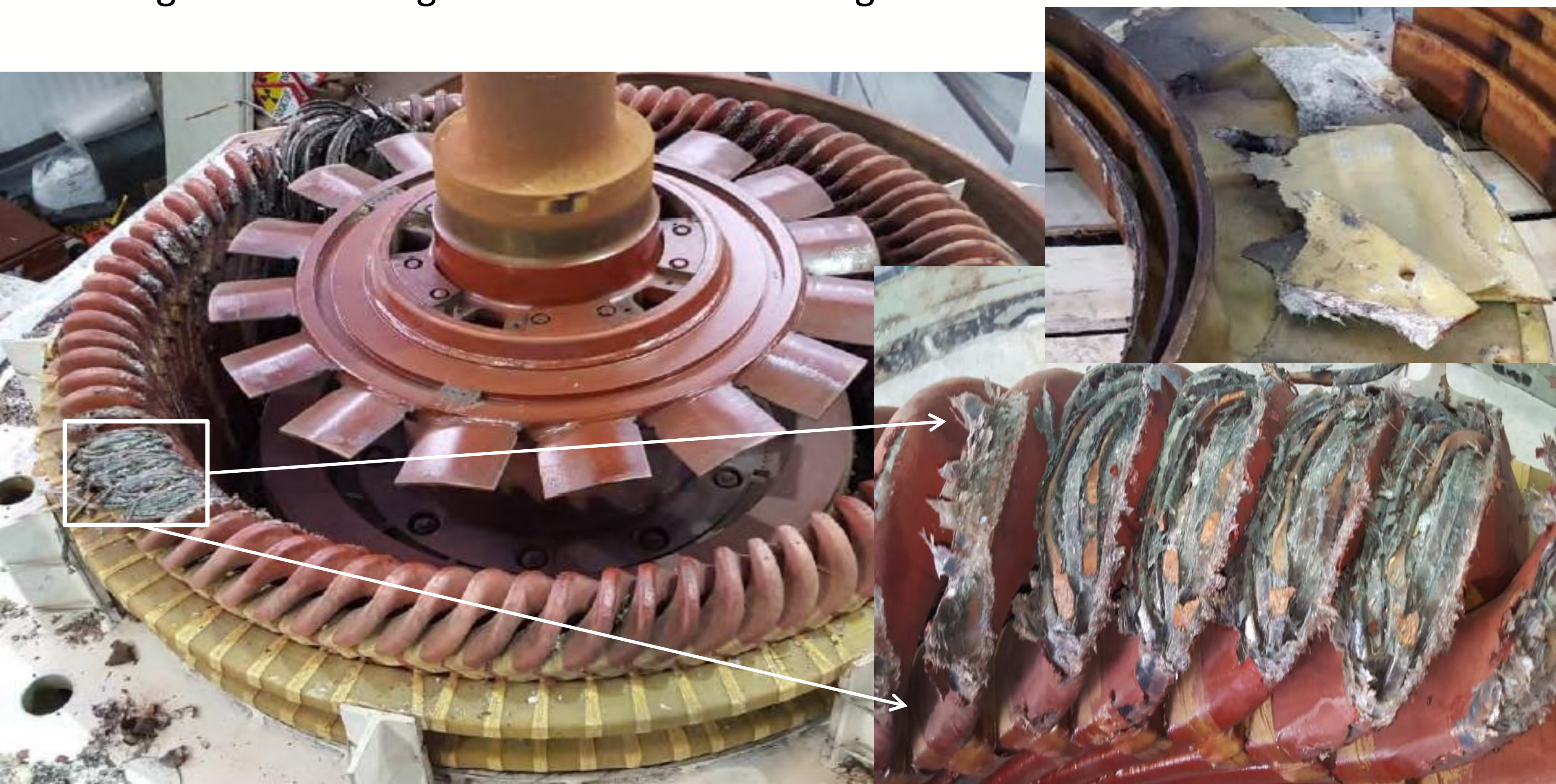
- The PHT 1-PM1 motor experienced a loss of structural integrity of the ODE rotor retaining ring. The ring broke into two pieces while the rotor was operating at full speed and the motor at full load. The retaining ring was propelled radially outward and axially upward toward the ODE endwindings, the endwinding metal cover, and fiberglass air baffles.

Initiating Event of Rotor Retaining Ring Failure

- Cracks found on the Drive End (DE) retaining ring set screw areas
- Three set screws 120 degrees apart – all had cracks as shown below

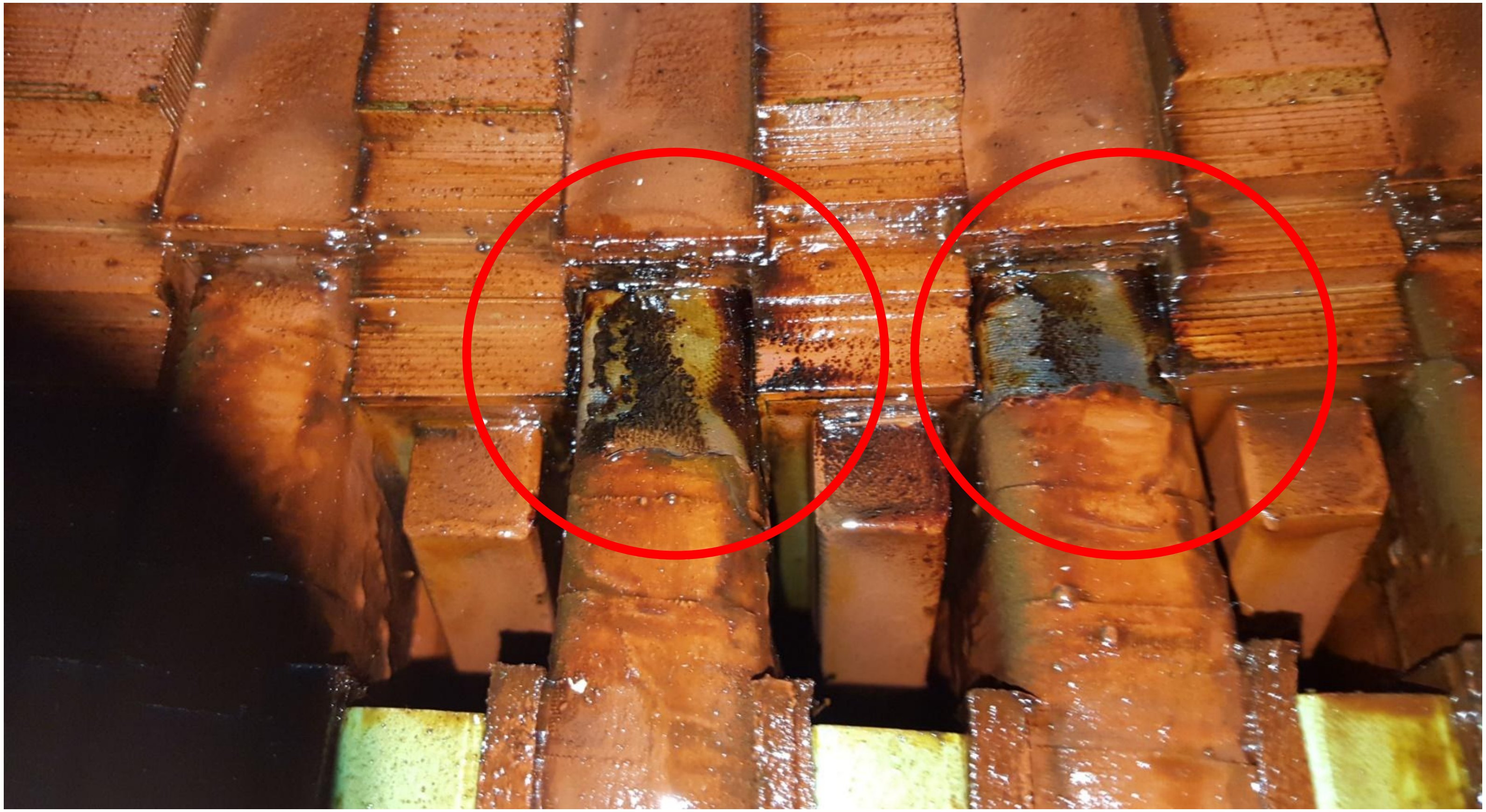
Key Damages (caused by retaining ring)

- A complete winding failure with extensive damage to the ODE endwindings
- Destruction of some of the ODE fiberglass air baffles
- Significant damage to the ODE endwinding metal cover



Additional Damages Found

- Partial discharge (PD) damage to the semi-conductive (corona) tapes on the line coils (coils connected directly to the bus connections on the line side) of the stator



Additional Damages Found

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Although the stator air coolers had been recently changed on this PHT motor, the photo below is from another PHT motor and illustrates the ozone/humidity nitric acid deposits that occur on these coolers. The ozone is generated by external partial discharge between the stator coils and stator core. Internal partial discharge does not produce ozone.

Partial Discharge Trend

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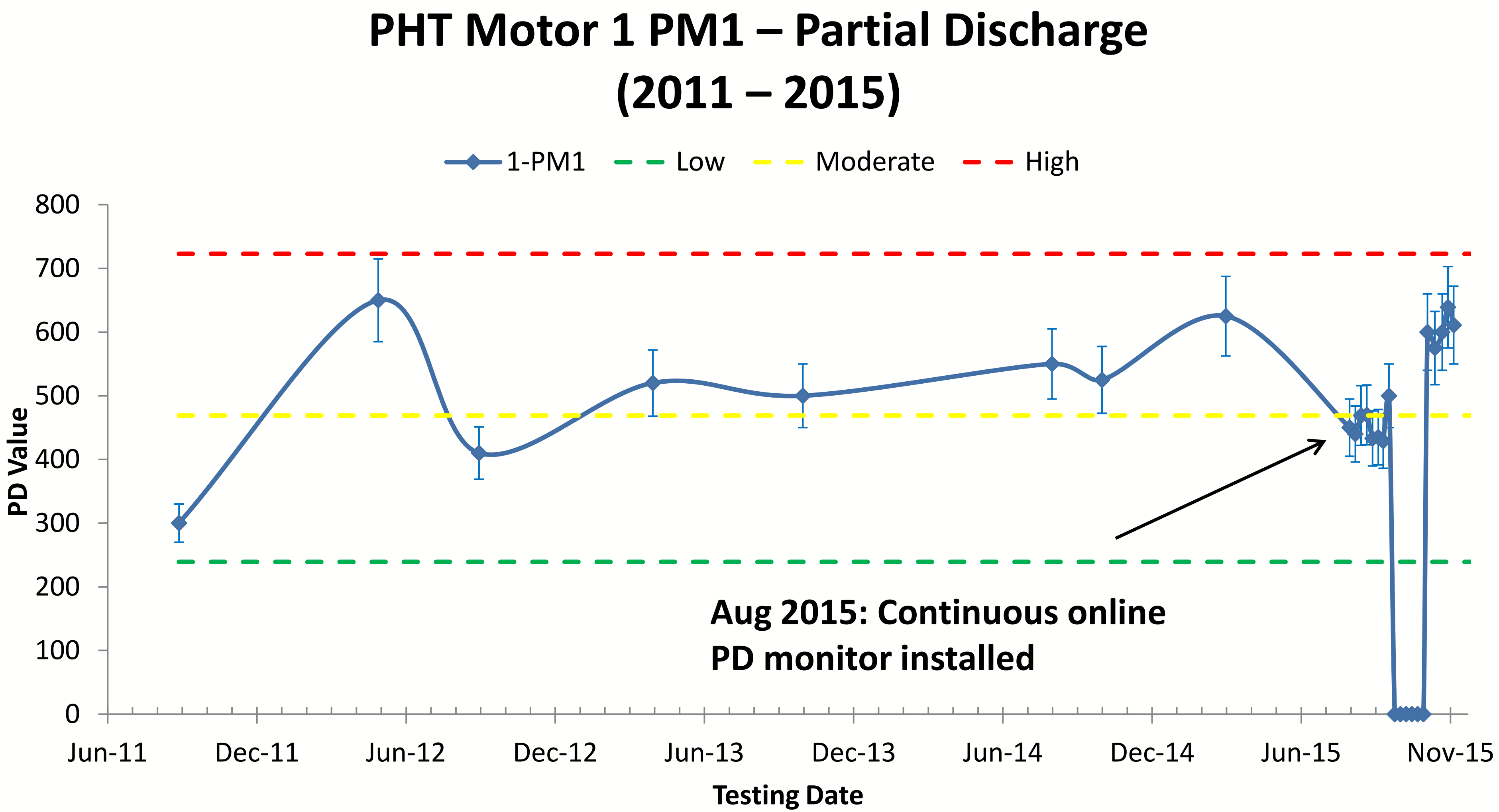

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Partial Discharge – Exploded View

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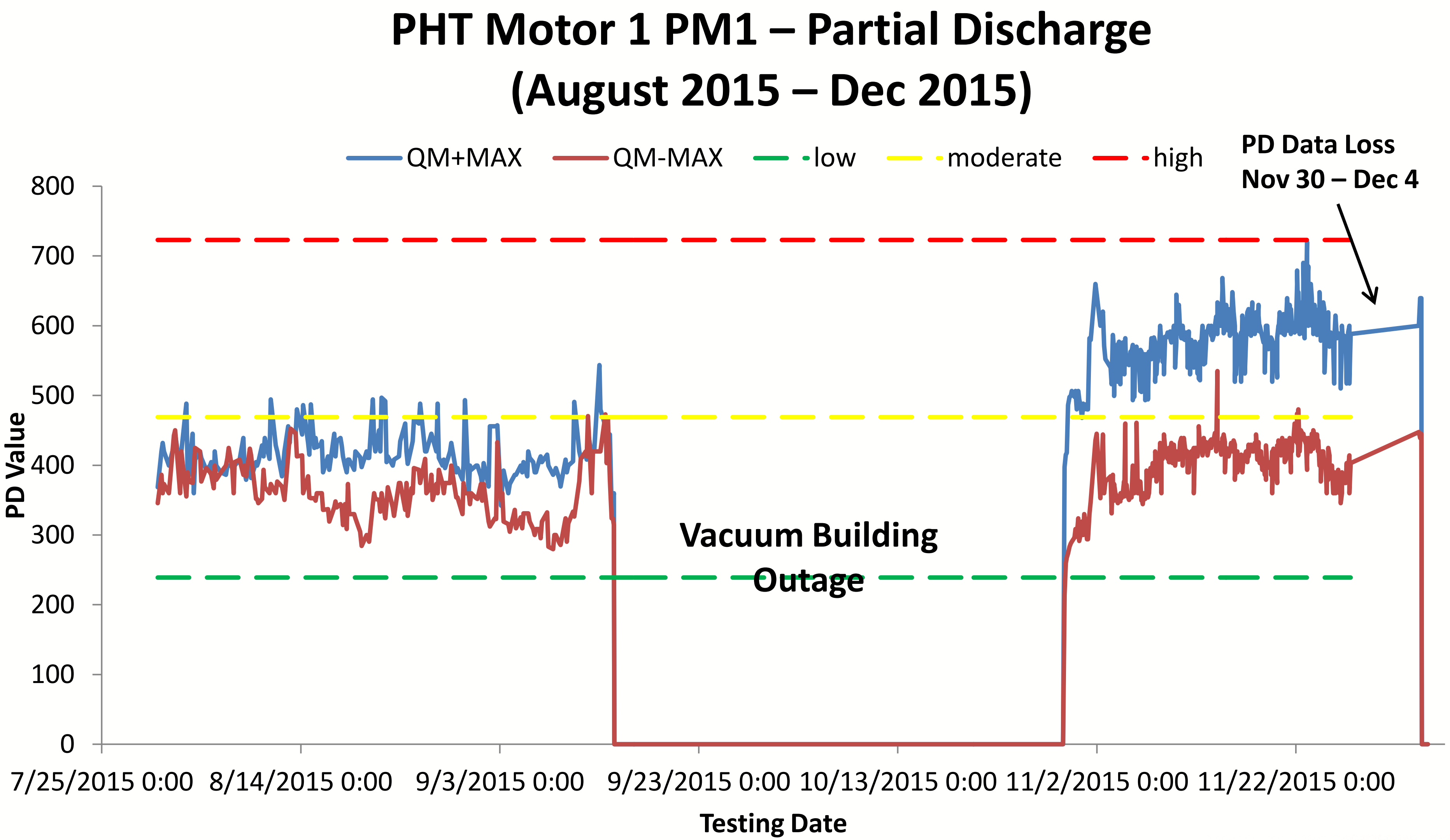

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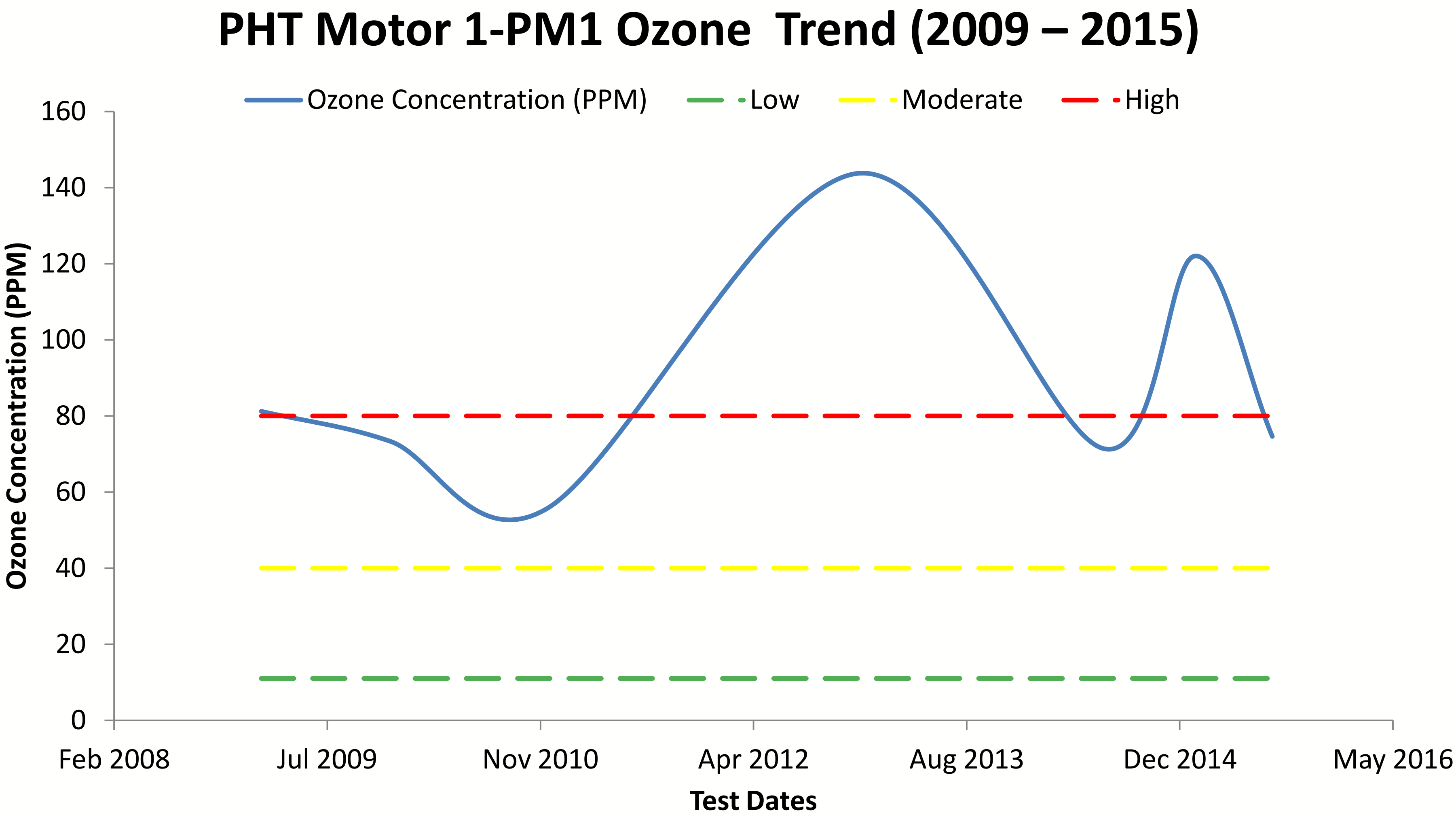
Ozone Trend


PHT Motor 1-PM1 Ozone Trend (2009 – 2015)
Ozone Concentration (PPM)
Low
Moderate
High
160
140
120
100
80
60
40
20
0
Ozone Concentration (PPM)
Feb 2008
Jul 2009
Nov 2010
Apr 2012
Aug 2013
Dec 2014
May 2016
Test Dates

Retaining Ring Failure Assessment

- Failure analysis concludes that the retaining ring failed due to stress corrosion cracking (SCC). The rotor retaining ring is made of alloy 18Mn-4Cr which is inherently susceptible to SCC. The extent of the SCC depends on various factors including environmental conditions, high stress areas, and operation-induced stresses which is discussed on the next slide.

Retaining Ring Failure Assessment (Cont.)

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- **Motor Operating Environment**
  - Partial discharge-generated ozone + H_2O (Humidity) = Nitric Acid.
  - Nitrate was also found at the crack tip.
- **High Stress Areas**
  - The threaded holes for the set screws and the two staking indentations per hole created high stress areas.
- **Operation-induced stress**
  - Operating-induced stress on the retaining ring is found to be high enough to initiate SCC[1] and the expected actual stress would be much higher at the fractured threaded hole due to stress concentration effect.

1. M. O. Speidel, *Preventing Failures of Retaining Rings, EPRI Proceedings* EL-3209: Retaining Rings for Electric Generator, August 1983

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Retaining Ring Failure Assessment

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- SCC was a slow process until the ring was weakened sufficiently to break apart from centrifugal forces all at one.

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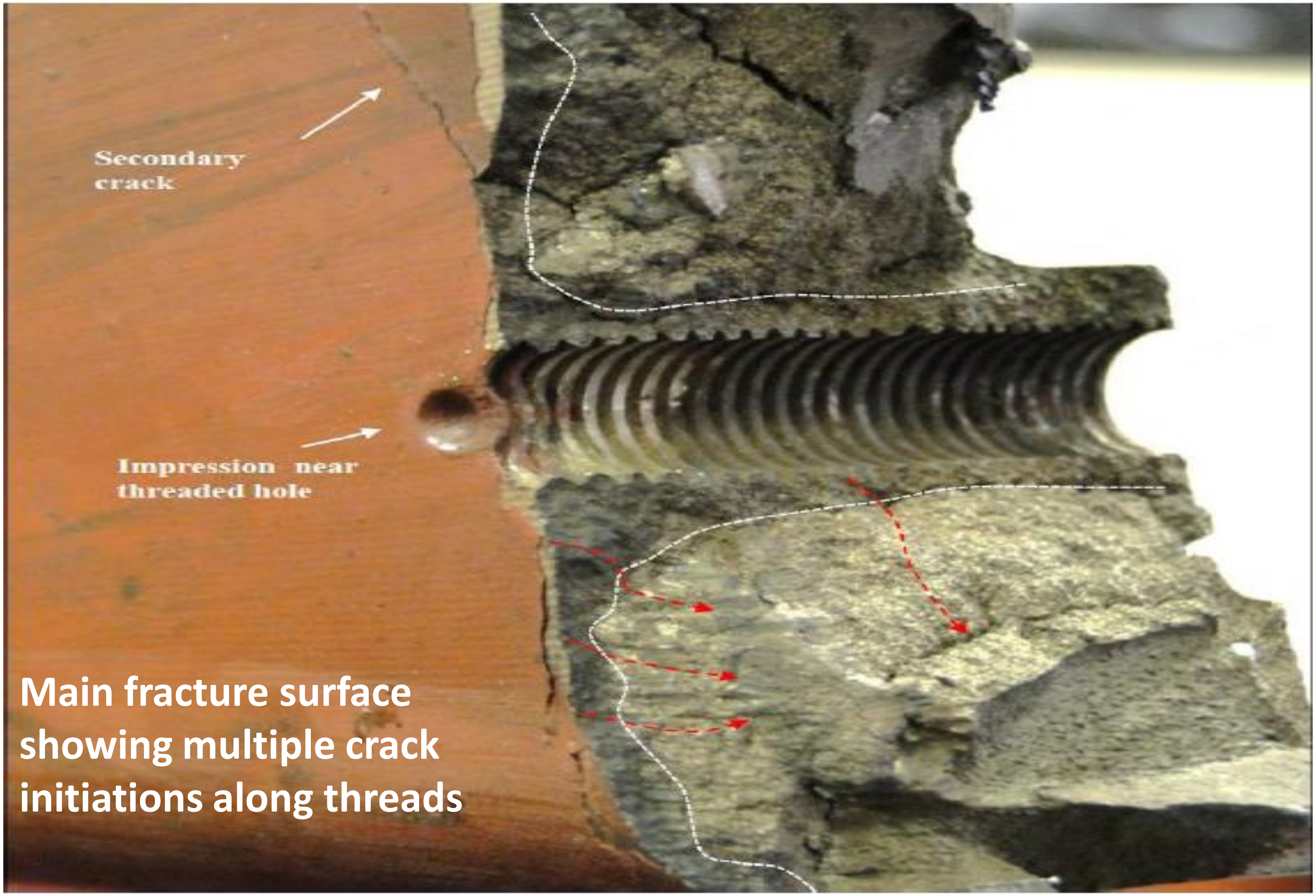
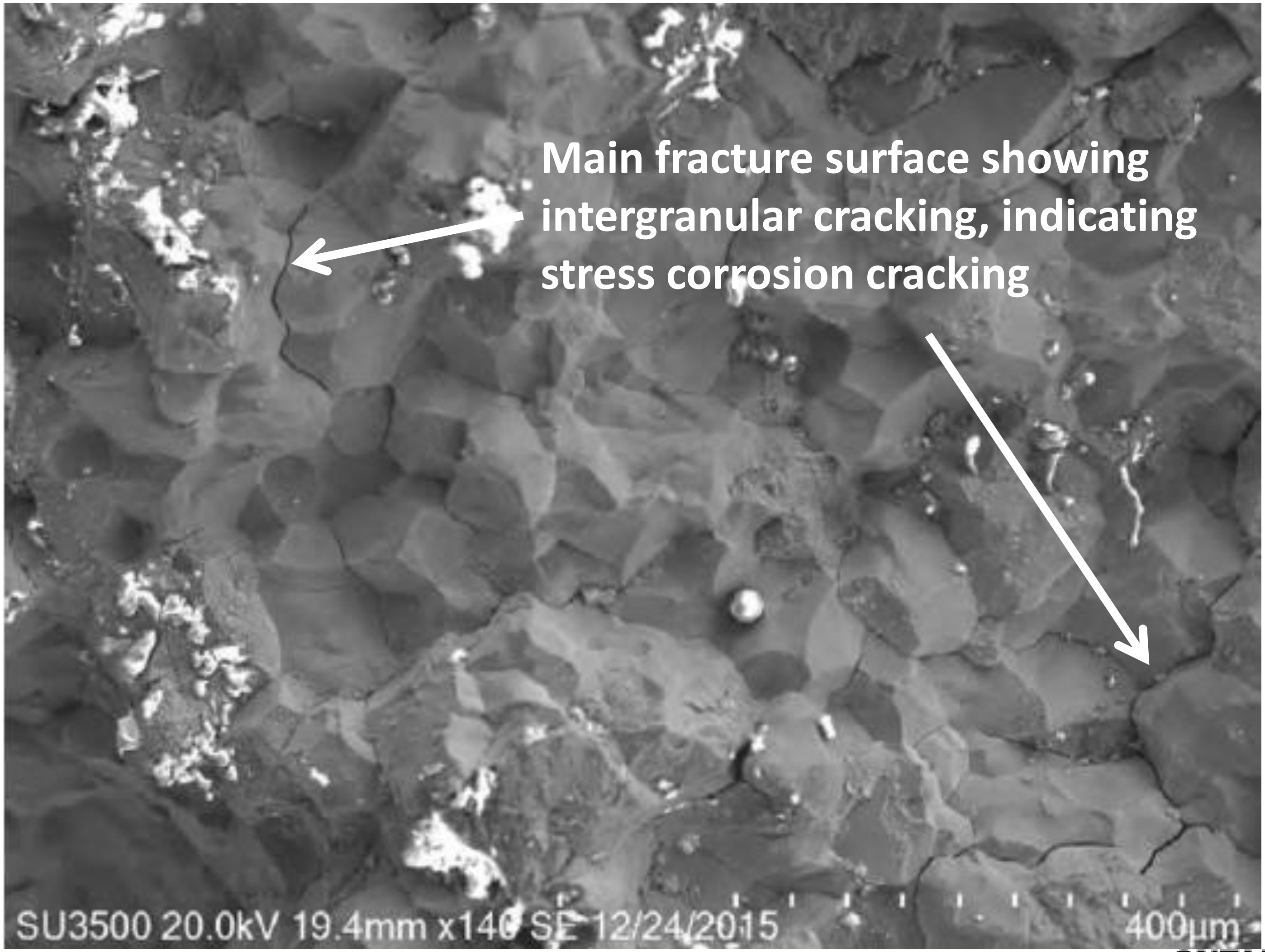
Retaining Ring Failure Assessment



Retaining Ring Failure Assessment

- Multiple techniques were considered to detect this degradation however deemed not sufficient primarily due to access/space restrictions
  - Boroscope
    - Attempted but not successful due to space and access restrictions
  - Ultrasonics
    - Considered but deemed not sufficient as it requires direct contact with the retaining ring
  - Eddy current
    - Considered but deemed not sufficient as it requires direct contact with the retaining ring
  - Radiography
    - Considered but deems not sufficient as there are many layers of material which would attenuate the beam making it very difficult to resolve the required detail.

Retaining Ring Failure Assessment



Uniqueness of Retaining Ring Failure

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- This degradation mechanism was found to be the first of its kind and not detectable under the current motor predictive maintenance program.

Condition monitoring techniques	Level before failure
Bearing/Winding Temperatures	Normal
Vibration	Normal
Oil Analysis	Normal
Electrical Testing	Marginal (W/ surge capacitor installed)
Outage Inspections	Inaccessible
Partial Discharge	High and fluctuating
Ozone Concentration	High and fluctuating

- This motor has a history of high partial discharge and high ozone concentrations. However it was not known at the time that ozone, combining with moisture and operation induced stress, and the potential concentrated stress areas from the set screw retention design would have a detrimental impact on motor retaining rings.

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Uniqueness of Retaining Ring Failure

- A motor will degrade in many areas as it ages. However, PdM can only detect a limited number of areas of degradation.

- This degradation mechanism is only detectable by a complete condition assessment/ refurbishment where motor can be disassembled and each component is inspected and replaced as required.

Table 5.3, EPRI NP-7502, *Electric Motor and Predictive and Preventive Maintenance Guide, 1992*

TABLE 5-3
RECOMMENDED TESTS:
SQUIRREL CAGE INDUCTION MOTORS 200 HP AND ABOVE.
FORM WOUND STATOR, 4000 VOLTS AND HIGHER.
SLEEVE, PAD OR DISC BEARINGS. SAFETY RELATED
AND BALANCE OF PLANT

Recommended Tests/Inspections	Duty Cycle[1]		
	Continuous	Intermittent	Layup
Trendable			
Supply Voltage	24-48	24-48	
Running Current	6-12	12-24	
Motor Speed	24-48	24-48	
Bearing Temperature	6-9	6-9	
Winding Temperature	6-12	6-12	
Insulation Resistance	12-18	12-18	12-18
Polarization Index	12-18	12-18	12-18
Current Analysis	36-60	36-60	
DC Hipot (Step)	36-60	36-60	
Motor Vibration	6-9	6-9	
(Oil Analysis)[3]	C	C	
Winding Resistance	12-18	12-18	
Non Trendable			
External Inspection	12-18	12-18	12-18
Borescope Inspection[2]	60-72	60-72	
Disassemble/Inspect	120-180	120-180	
Surge Comparison	60-72	60-72	
Rotate by Hand			3-9

Legend

1. Numbers in charts are in months.
2. Borescope Inspection for 1000 HP and larger.
3. C refers to Appendix C, Table C-2 for oil lubricated bearings.
4. Off-line test =

Note: Performance of off-line tests on large critical motors should be scheduled to coincide with plant refueling cycles.

Conclusion

- There are unknown failure and degradation mechanisms that are occurring or will be occurring as motors age. These mechanisms may not be identifiable with the existing condition monitoring techniques.

- For critical motors (13.8kV and 4kV), periodic condition assessment/refurbishment every 10 – 20 years is required to fully evaluate the condition of each motor component. This will identify and address all possible degraded conditions prior to impact on motor operation.

Conclusion

- All of the PHT motors at the Darlington Nuclear Generating Station will either be refurbished (including a new stator core and winding) or replaced with a new motor to support Plant Life Extension for the next 30 years of operation

- Each PHT motor being refurbished will have the rotor retaining rings replaced with 18Mn-18Cr alloy steel that is less susceptible to stress corrosion cracking. The new motors have the upgraded material in their rotor design.

- A PHT motor refurbishment program is being developed to periodically perform a refurbishment offsite with a detailed component inspection – time frame will be between 15 – 20 years.

Conclusion

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- 3 Critical spare PHT motors will be made available utilizing the combination of the refurbished PHT motors and the new PHT motors to support the execution of periodic condition assessment/refurbishment as well as to minimize plant impact in the event of a motor failure

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Questions?