Workshop Introduction

Program 219: Steam Turbines & Auxiliary Systems
Program 220: Generators & Auxiliary Systems

Eric Prescott
Area Manager, Senior Program Manager, Program Lead

2025 WANO Steam Turbine & Generator Workshop
Shanghai, China
3-6 November 2025

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Meeting Agenda

TOPIC
DAY 1: Experience Sharing *Monday, November 3rd*
DAY 2: Steam Turbine Focus *Tuesday, November 4th*
DAY 3: Generator Focus *Wednesday, November 5th*
DAY 4: Huaneng Advanced Cycle Working Session *Thursday, November 6th*

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Meeting Objectives

Our responsibilities…

- Engage to understand user challenges
- Provide technical insights and information
- Support discussion to effectively apply industry experience and available technologies

Your responsibilities…

- Exhibit patience while we deliver the information through translation services
- Ask questions
- Identify research needs



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Today's Discussions



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DAY 1 - WORKSHOP TOPICS

Monday, November 3, 2025

Time	Topic	Lead
9:00a	Opening Remarks & Participant Introduction	E. Prescott, EPRI
9:30a	Steam Turbine/Generator Program Introduction & Overview	E. Prescott, EPRI
10:15a	Break	All
10:30a	User Update/Challenges Presentation	CGN
11:15a	User Update/Challenges Presentation	CNNP
12:00p	Lunch	All
1:00p	User Update/Challenges Presentation	SPIC
1:45p	User Update/Challenges Presentation	Huaneng
2:30p	Summary of Industry Regional Challenges	E. Prescott, EPRI
3:00p	Break	All
3:15p	Summary Presentation of August TGUG Topics • *Operating Experience & Technology Presentations* • *Generators* • *Steam Turbines*	R. Steele, EPRI
5:00p	Adjourn	All

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Steam Turbine & Generator Research Program Overview

Program 219: Steam Turbines & Auxiliary Systems

Program 220: Generators & Auxiliary Systems

Eric Prescott
Area Manager, Senior Program Manager, Program Lead

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Program 219 & 220

Steam Turbines, Generators, & Auxiliary Systems

- Asset Integrity
- Plant System Integration & Operation
- Online Equipment Health Monitoring
- Maintenance Management Technology
- Inspection & Testing Technology
- Repairs & Material Technology
- Risk Management Tools

Mission

Continuous improvement in the safety, reliability and availability of steam turbines and generators (incl. auxiliary systems) through research in life management, preventive maintenance, condition assessment, advanced monitoring, and control.

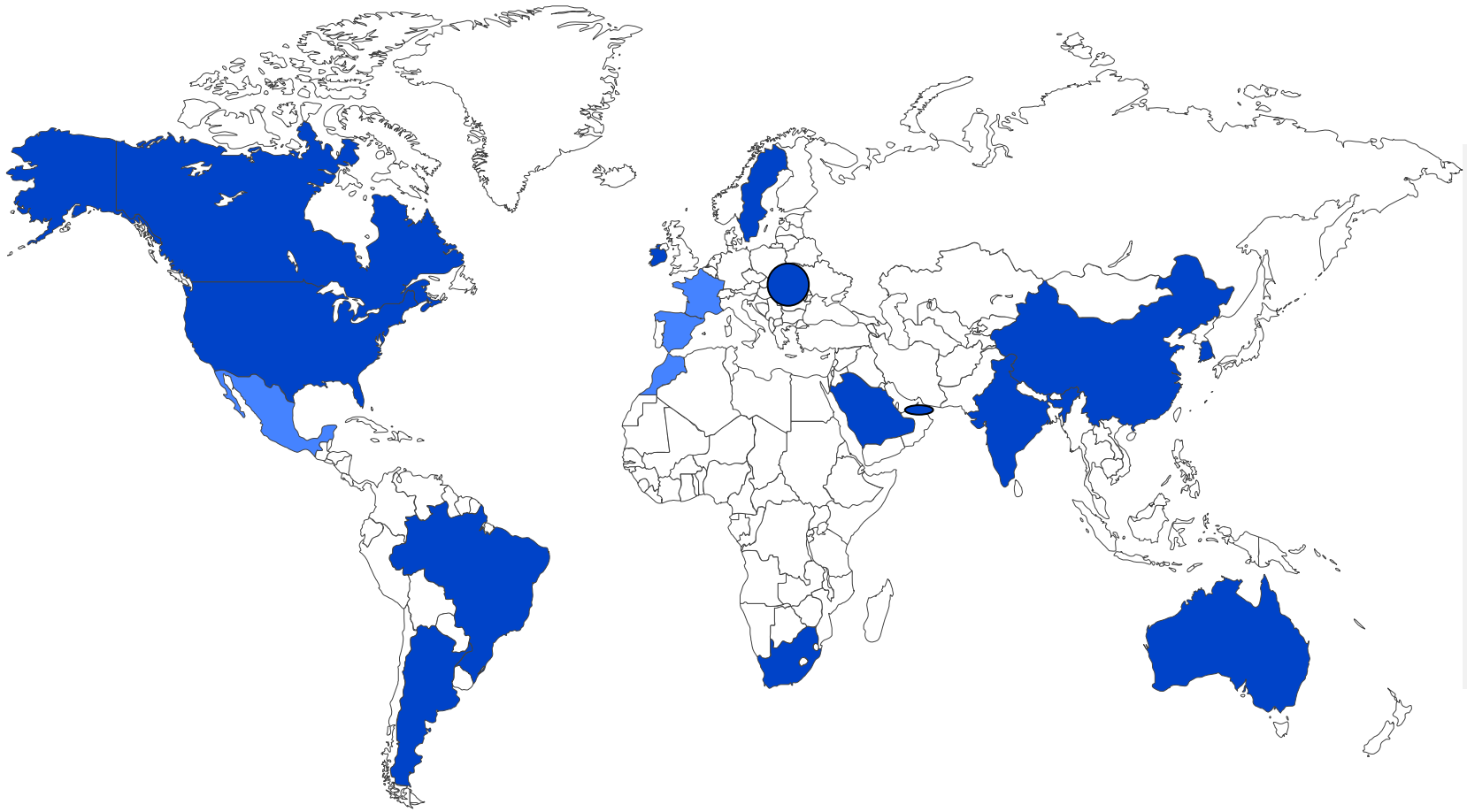
Asset Applications

- Nuclear Cycle
- Fossil Cycle (boiler/HRSG/CT)
- Solar
- Geothermal
- Hydropower
- Synchronous Condensers



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Global Engagement
全球参与



BROAD PROGRAM PARTICIPATION
广泛的项目参与

- ✓ *Fossil & Nuclear*
- ✓ *Utility Power & Industrial*
- ✓ *Diverse Energy Mixes and Growth*

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Program Approach

WHY? | VALUE

Research Focus 研究重点 → ***Engagement Focus*** 参与重点

P219 Steam Turbines | **P220** Generators

Strategic Research	Risk Management Guidance	O&M Guidance	Technical Webcasts	Technical Workshops	Broad Industry Engagement
长期、多年及新兴技术。 **参考**项目参与者**和行**业趋势。	**着眼于短期、策略性，旨在**应对**当前挑**战。 **参考**项目参与者**和行**业趋势。	**内容翔**实，具有教育**意**义，旨在促进发展。 **由**电力研究所 (EPRI) **确定，并由**项目参与**者**优先排序。	**内容翔**实，具有教育**意**义，旨在促进研究**成果的技**术转移。 **由**EPRI创建，并参考**了**项目参与者的意见。	**内容翔**实，具有教育**意**义，旨在促进研发**成果的技**术转移。 **主**题由项目参与者确**定**。	**促**进同行、服务提供**商和原始**设备制造商**之**间的技术交流。 **由**电力研究院 (EPRI) **主**导，以确保客观性，**并由**项目参与者确**定**优先级。

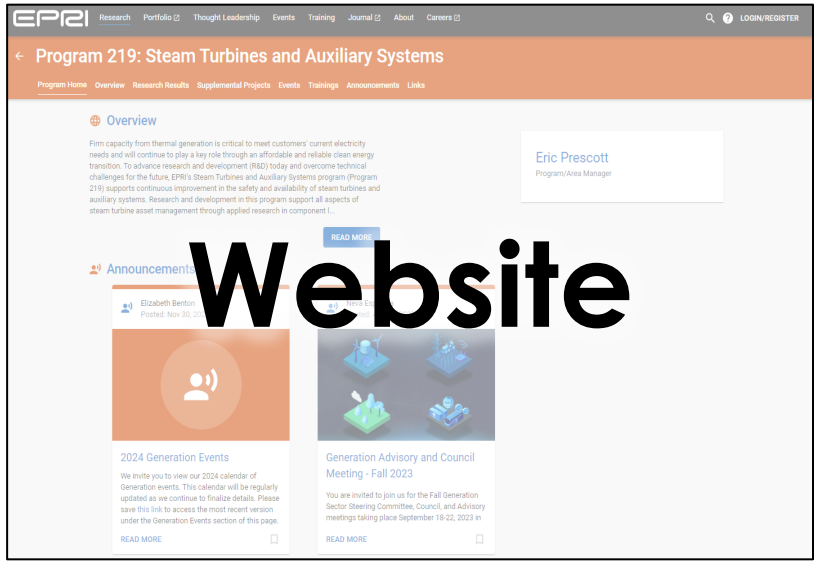
Annual Research Portfolio Activities
年度研究组合活动

Supplemental Opportunities
补充机会

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Key Resources to Consider…

需要考虑的关键资源……

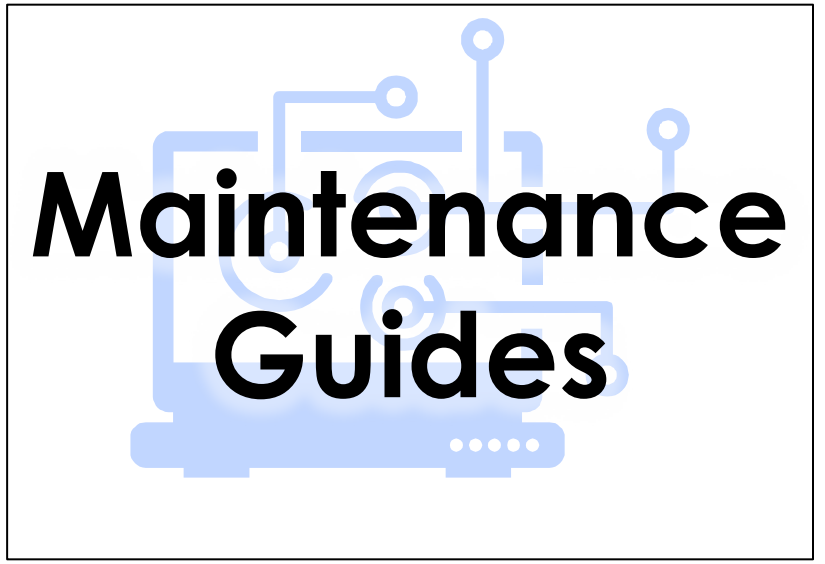












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TGUG

asktgug@epri.com

Turbine Generator Users Group Summer 2025

August 11-15, 2025

Minneapolis, MN
(virtual option available)

Turbine Generator Users Group Winter 2026

January 12-16, 2025

Tampa, FL

Turbine Generator Users Group Summer 2026

August 10-14, 2025

Kansas City, MO
(virtual option available)

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2025 Steam Turbine Research: Ongoing Focus Areas

Last Stage Blade Reliability

Understanding Erosion

Measuring Damage…

- *Steam Turbine Last Stage Blade Liquid Erosion Damage - Investigation of Eddy Current Arrays for Detection of Airfoil Cracking*
- *Steam Turbine Last Stage Blade Liquid Erosion Damage -Damage Characterization*
- *Steam Turbine Last Stage Blade Liquid Erosion Damage - 3D Scanning Technologies Comparison Study*

Predicting Erosion…

- *Predicting LSB Recirculation Flow without Measurement*

Managing Risk…

- *Hydrophobic Coating Application*
- *Life Extension thru Repair (P229)*
  - ❑ *Jethete*
  - ❑ *17-4PH*
  - ❑ *Titanium*

Steam Turbine Health Assessment Tools

Screening Units…

- *Steam Turbine Health Assessment Screening Tool*
- *Steam Turbine Flexibility Screening Tool*

System-specific Risk Analysis…

- *Steam Turbine Health Assessment Tool Data Collection Sheets*
- *Risk Register Template*
- *Risk Register Plotting Tool*

Emerging Risks

Nuclear Resurgence…

- *Nuclear Restart Guidance*
- *New Nuclear Technology Evaluation*
  - ❑ *Full Speed, Wet Turbine Design*
  - ❑ *Full Speed, Superheat Turbine Design*

Torsional Interactions w/ Grid…

- *Grid Risk Screening Methodology (P40)*

Material Risks & Properties

Rotor Forging Alloys…

- *ST10/2TS*
- *ST459TS*

Valve/Casing Casting Alloys…

- *Stg9T*
- *CrMoV*
- *CA6NM*

Degradation Insights…

- *D11 HP Outer Casing Life Prediction Study*
- *Leaf Spring Degradation Evaluation for Axial Entry Last Stage Blades*
- *ST10/2TS (IP) RTB Welded Rotor Feature Damage Evaluation*
- *Stg9T Casting (IP) Characterization & Weld Development*
- *CrMoV Casting (HP) Characterization & Weld Development*

Steam Turbine Engineer Information Resources

Maintenance & Operation…

- *Turbine Water Induction Protection System: Owner's Guide*
- *ST Engineering Service Supplier Tool*
- *System Walkdown Checklists*
  - ❑ *Conventional Rankine*
  - ❑ *Combined Cycle*
  - ❑ *PWR*
  - ❑ *BWR*
- *Lube Oil System Maintenance*
- *Lube Oil System RAMS Case Study*
- *Lube Oil System Remedy Guide*

Engagement…

TGUG 2025

January – Orlando, FL
August – Minneapolis, MN

Enhanced Information Resources…

- TGUG WIKI
- **ST OUTAGE** ***Guidelines*** WIKI

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2025 Published Deliverables

Steam Turbines & Auxiliary Systems



- Development of Vine Robotics
- ECT for LSB Erosion Inspection
- LSB Erosion Damage Characterization
- LSB Erosion Measurement Technology Evaluation
- LO System Reliability Model Demonstration
- Supplier Capability Lookup Tool

Published Research Results

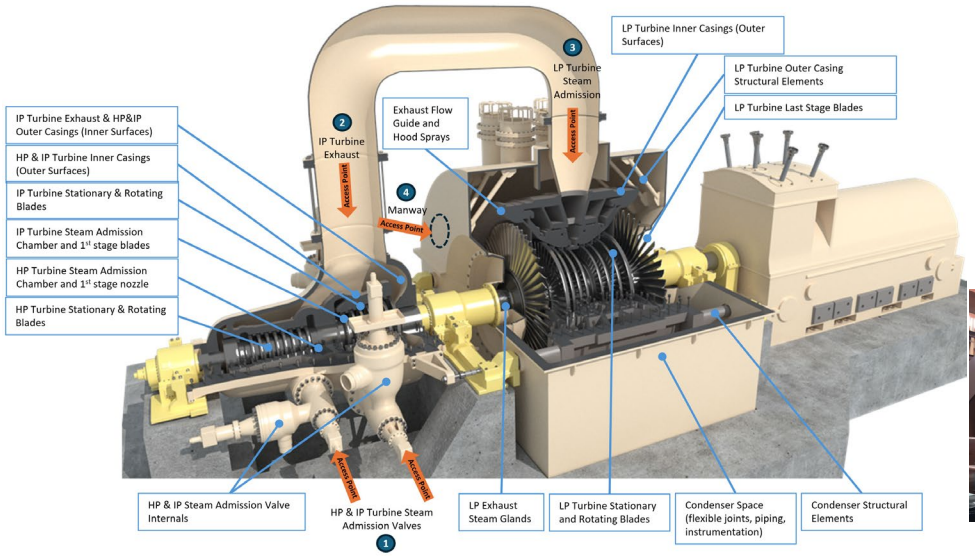
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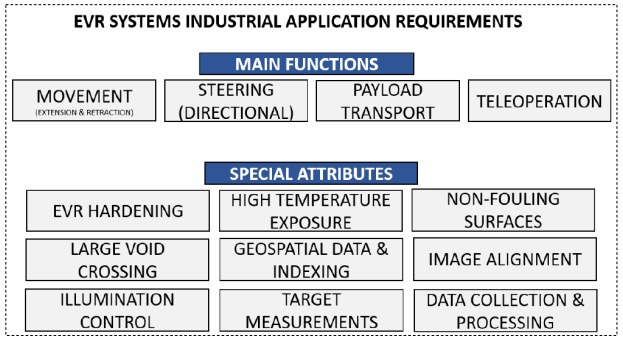
Everting Vine Robots (EVR) for Industrial Inspections

Technology Review and Feasibility Study

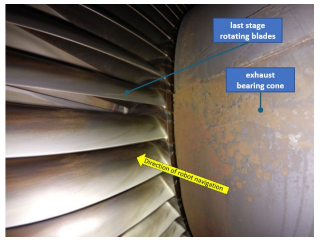
Brief Project Overview

- The project explored the recent developments with everting vine robot technology based on the research demonstrations and tests performed by various universities and research institutes (mostly in laboratory environment)
- The research included a review of the most important requirements for industrial applications
- Potential inspection scenarios for the everting vine robots for steam turbine equipment were described
- A future research roadmap for the development of an industrial grade robot that could be used in power plant applications is provided

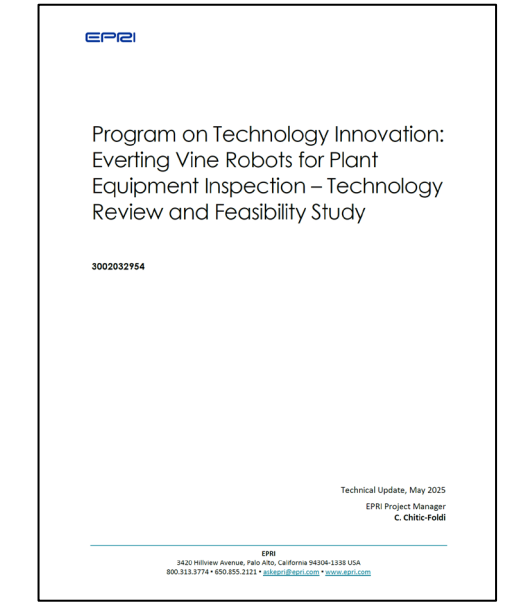












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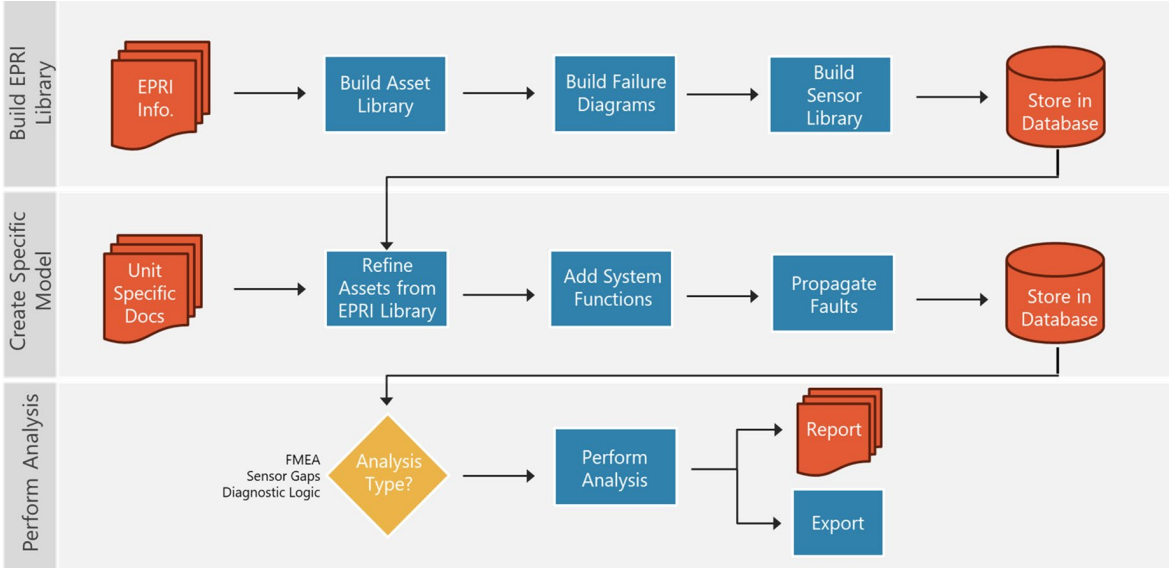
Lube Oil System Failure Modes Effects Analysis: Model-Based System Analysis Tool Demonstration – 3002029934

Premise

- Build representative LO system model to demonstrate technology application
- Iterate with unique configurations

Summary Findings

- Model-based FMEA approach requires similar information input as a manual FMEA approach.
- Model can be changed partially using a generic library and customizing for a specific instance
- A system model enables semi-automated analysis including sensor gaps and diagnostic logic.
- The amount of effort to assemble an FMEA between manual and model-based are comparable.
- Lube oil systems robust, resilient in the face of degradations.
- Current deployment of sensing and monitoring technology sufficient for survival.



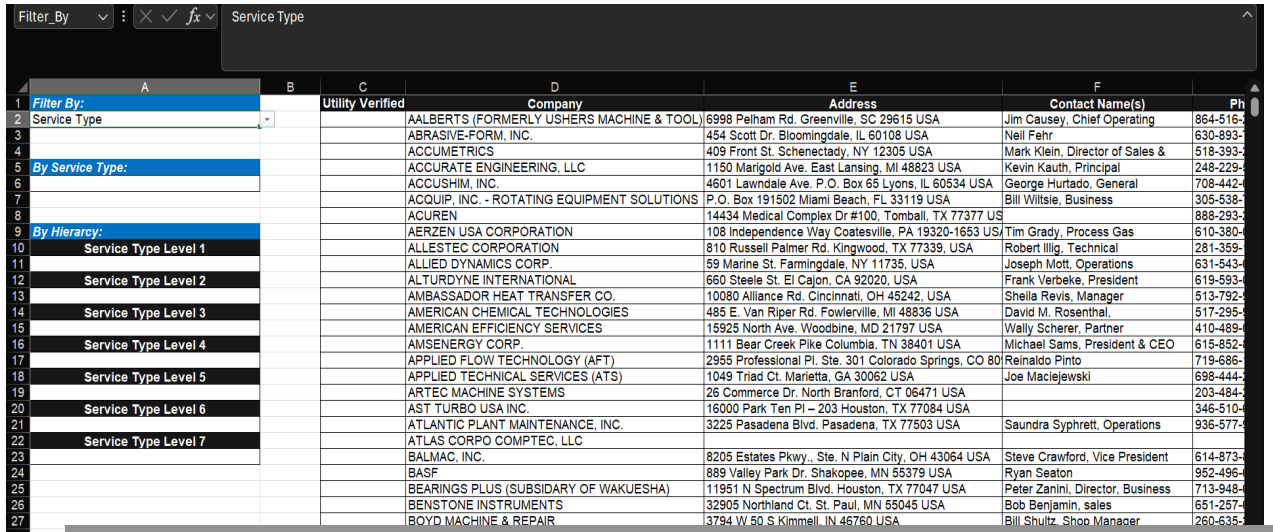
Opportunity for Meaningful Digitalization

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ST Vendor Survey Tool v1.0

Premise

- MS Excel Spreadsheet that identifies suppliers and their claimed capabilities
- Supports utilities sourcing activities for specialized engineering services
- Enables users to download/modify attributes
- ST Vendor Survey Tool v1.0 Tutorial



Engineering Services

Consulting Services
- Technical Field Advisement/Engineering
- Product Quality/Surveillance
- Outage Planning
- Technical Specification Development
- Root Cause Analysis
- Materials Analysis
- Fluid Maintenance
- Turbine Control Systems

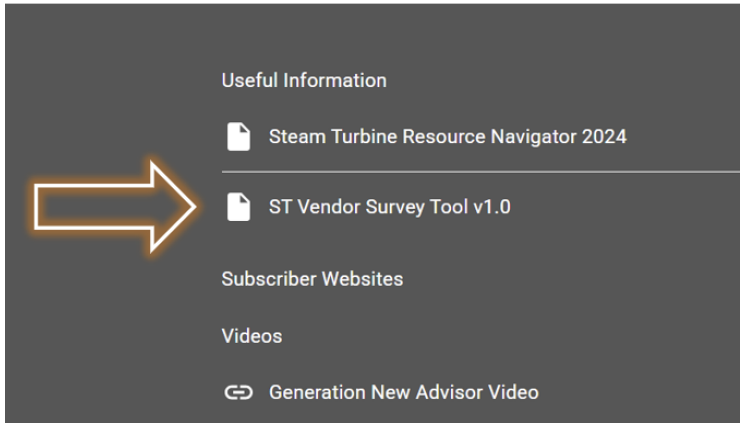
Inspection & Measurement
- Alignment Services
- Specialized NDE
- Vibration Measurements
- Metrology

System Operational Troubleshooting
- Rotating Machinery Dynamics
- Cycle Analysis
- Steam Path Performance Analysis

Mechanical Integrity Calculations
- Structural Stress Analysis
- Structure Dynamic Analysis
- Life Analysis
- Rotating Machinery Dynamic Analysis
- Blade Dynamic Analysis
- Last Stage Blade Fluid-Structural Analysis

Operational Change Design and Implementation
- Starting & Loading Optimization
- Valve Characteristic Optimization
- Stress Controller Optimization
- Control System Optimization & Integration

New on the Program Website



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2025 Project Status Updates

Steam Turbines & Auxiliary Systems



- Fluid Systems Research
- Health Assessment Tools
- Materials Property Development
- Ex-service Component Damage Characterization
- LSB Weld Repair
- D11 Outer Casing
- LSB Spring Degradation Model
- System Walkdown Guidance

Ongoing Research Activities

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Fluid System Research

Remedy of Fluid Symptoms

Objective

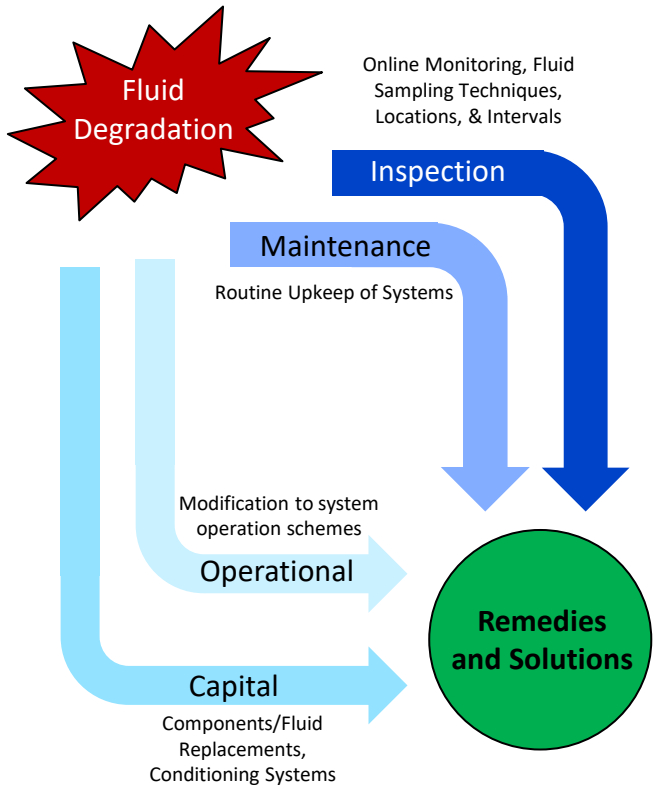
- Provide multiple methods to address fluid degradation symptoms to facilitate and sustain operation
- Support quick decision making to improve operational availability
- Establishes maintenance and capital investments of fluid systems
  - Mineral Oil (Lubrication)
  - Phosphate Ester (Control Systems)
  - Water (Stator Cooling)
  - Gas (Hydrogen, Air, CO_2)
  - Alternative Fluids

Project Approach

- Provide multiple methods to address fluid degradation symptoms to facilitate and sustain operation

Outline

- Provide summary of various fluid symptoms frequently observed in steam plants and methods to address
- Identify:
  - Common degradations
  - Typical Discovery Methods
  - Operational, Maintenance, and Capital/Long-term Recovery Methods



Lube Oil System Maintenance Guide Update

Premise

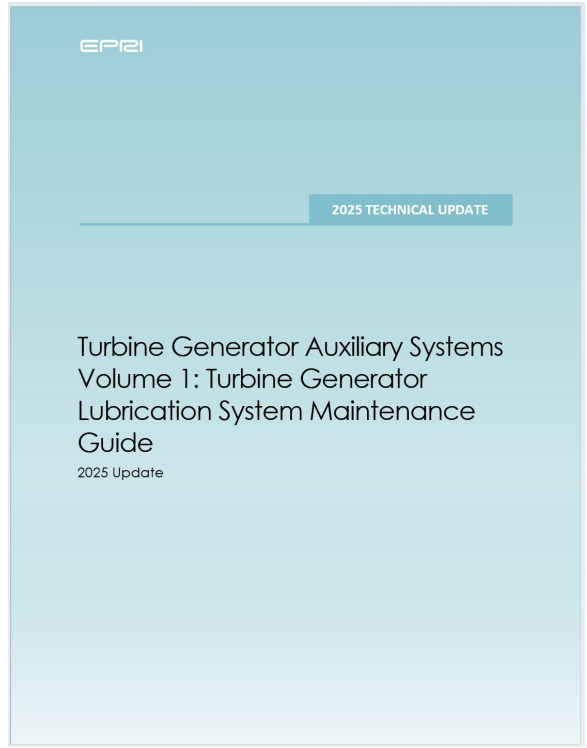
- Update Turbine-Generator Auxiliary Systems Volume 1: Lubrication System Maintenance Guide **1025331** (2012)
- Address new designs, methods, standards, and upgrades
- Add new media

Status

- Final edits in progress
- Submitted to publications

Deliverable Proposed

- 2025 Maintenance Guide Update



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Steam Turbine Health Assessment Tools

Our Goals:

- Simplified input requirements focused on the major components
- Reasonable insights obtained by any system engineer responsible
- Consistent outputs expressed in terms for management decision making
- Pathways to deepen risk understanding for capital and maintenance planning

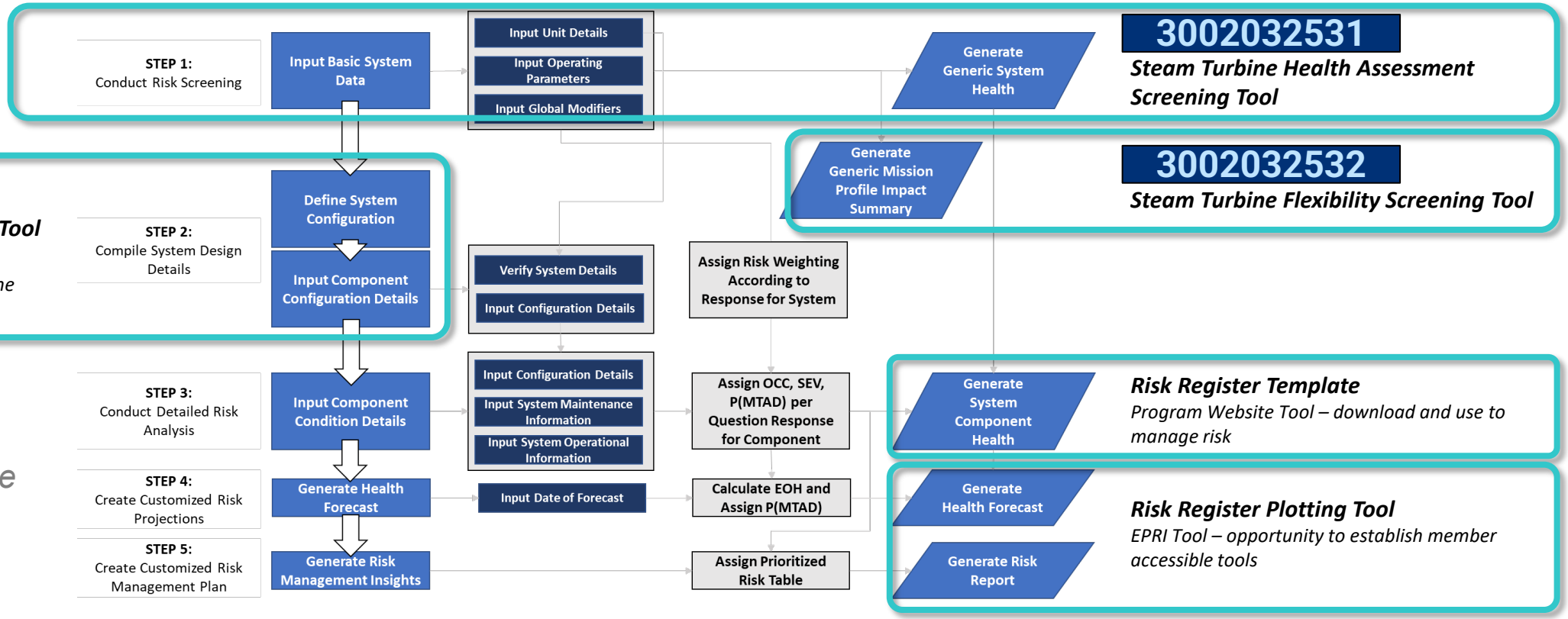
Accepted Tool Limitations:

- Details matter, vulnerabilities vary by OEM, design features, and operating profiles
- Effects of system externalities
- Cannot assess quality of maintenance task, inspection or monitoring approach (also a critical aspect in applying PMBD)



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Steam Turbine Asset Management Integrity Analysis

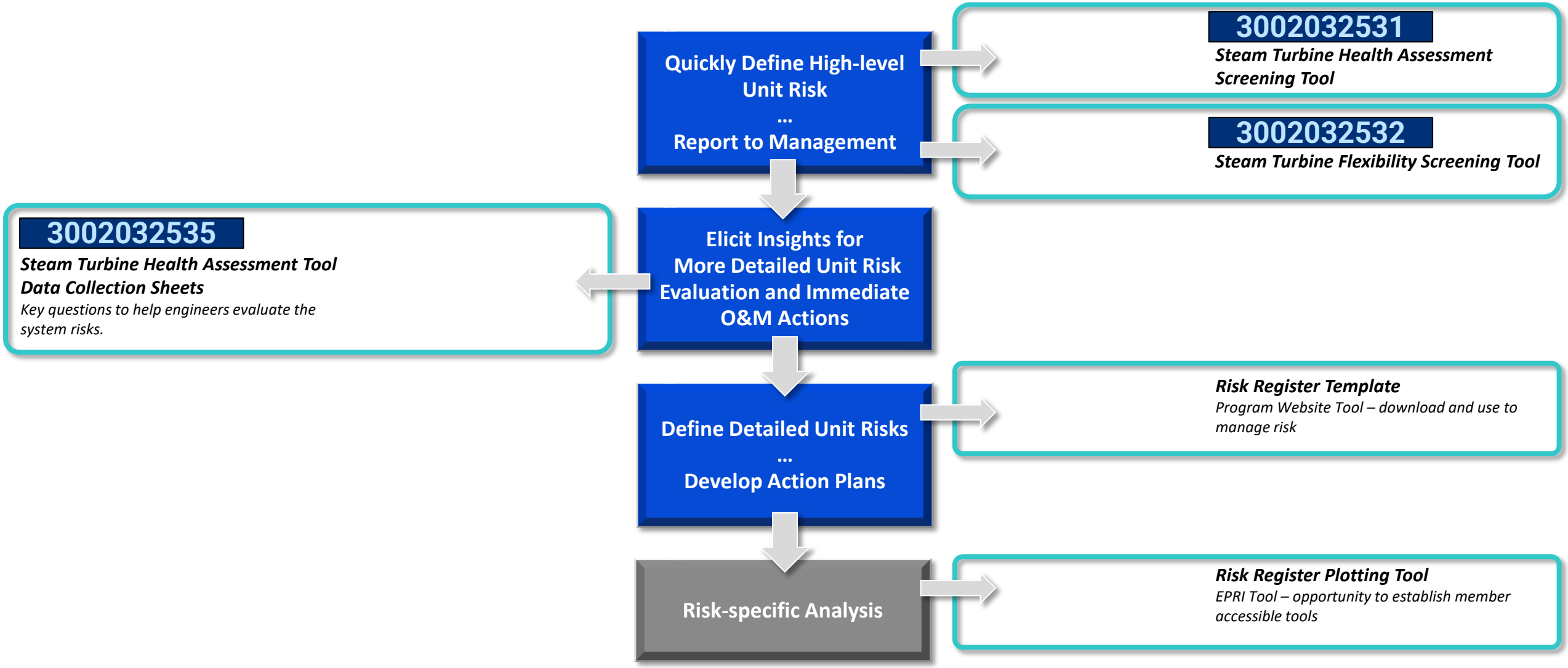


Health is complex, more analysis may be needed to make decisions…

2025 STATUS UPDATE

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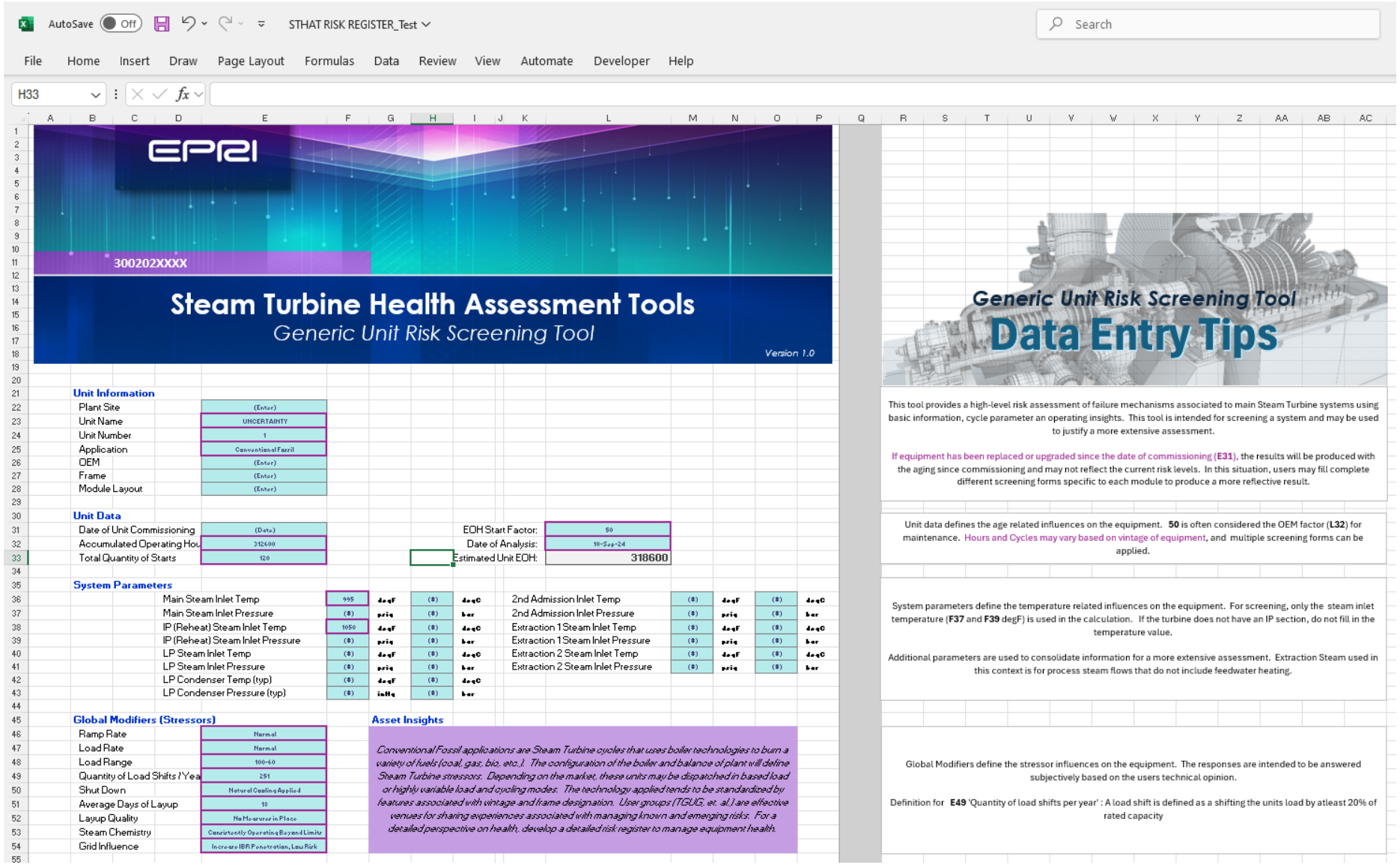
Steam Turbine Asset Management Integrity Analysis



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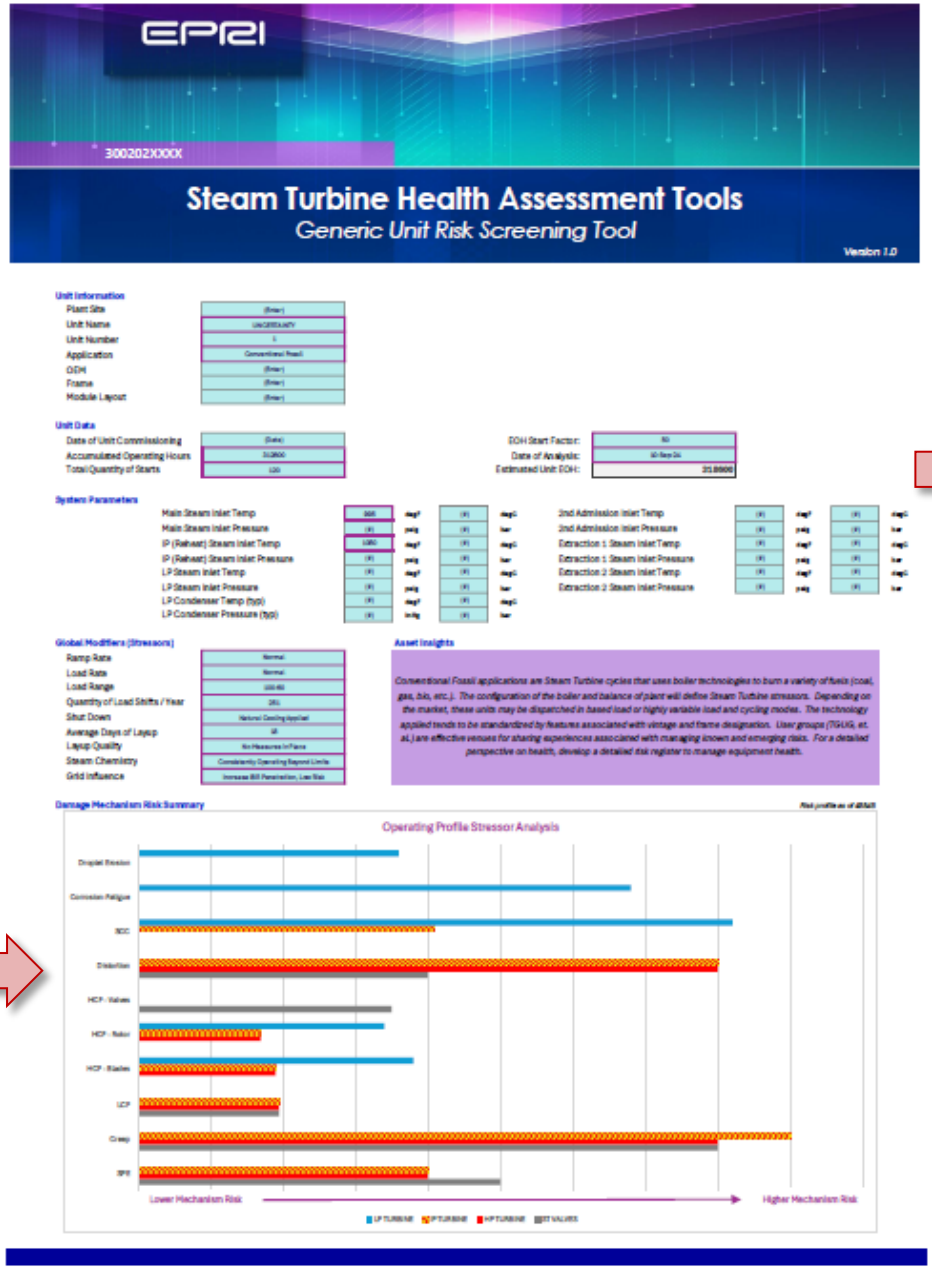
P219 Steam Turbine Health Risk Screening Tool

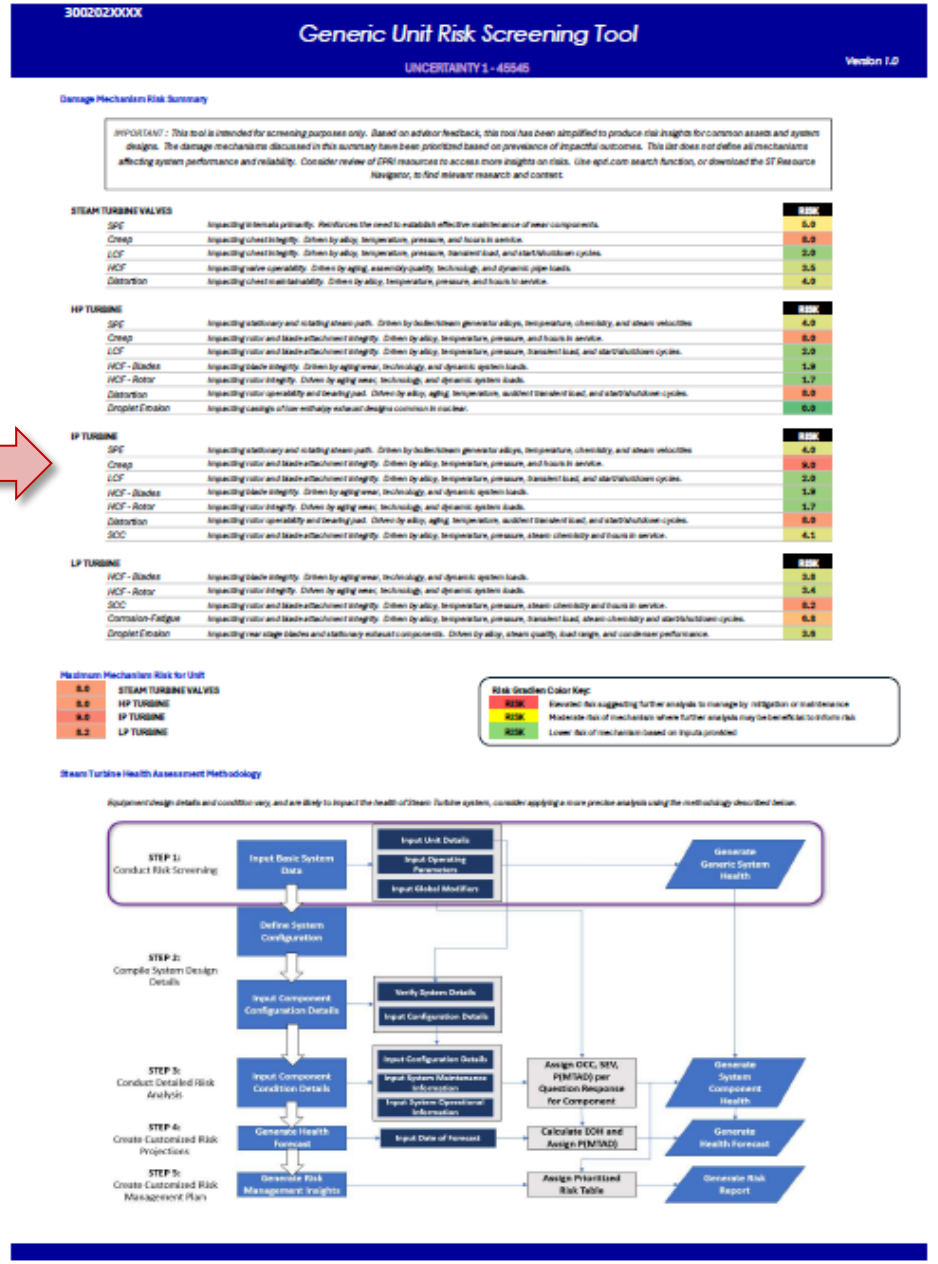
MS Excel Spreadsheet Interface



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Print PDF Output

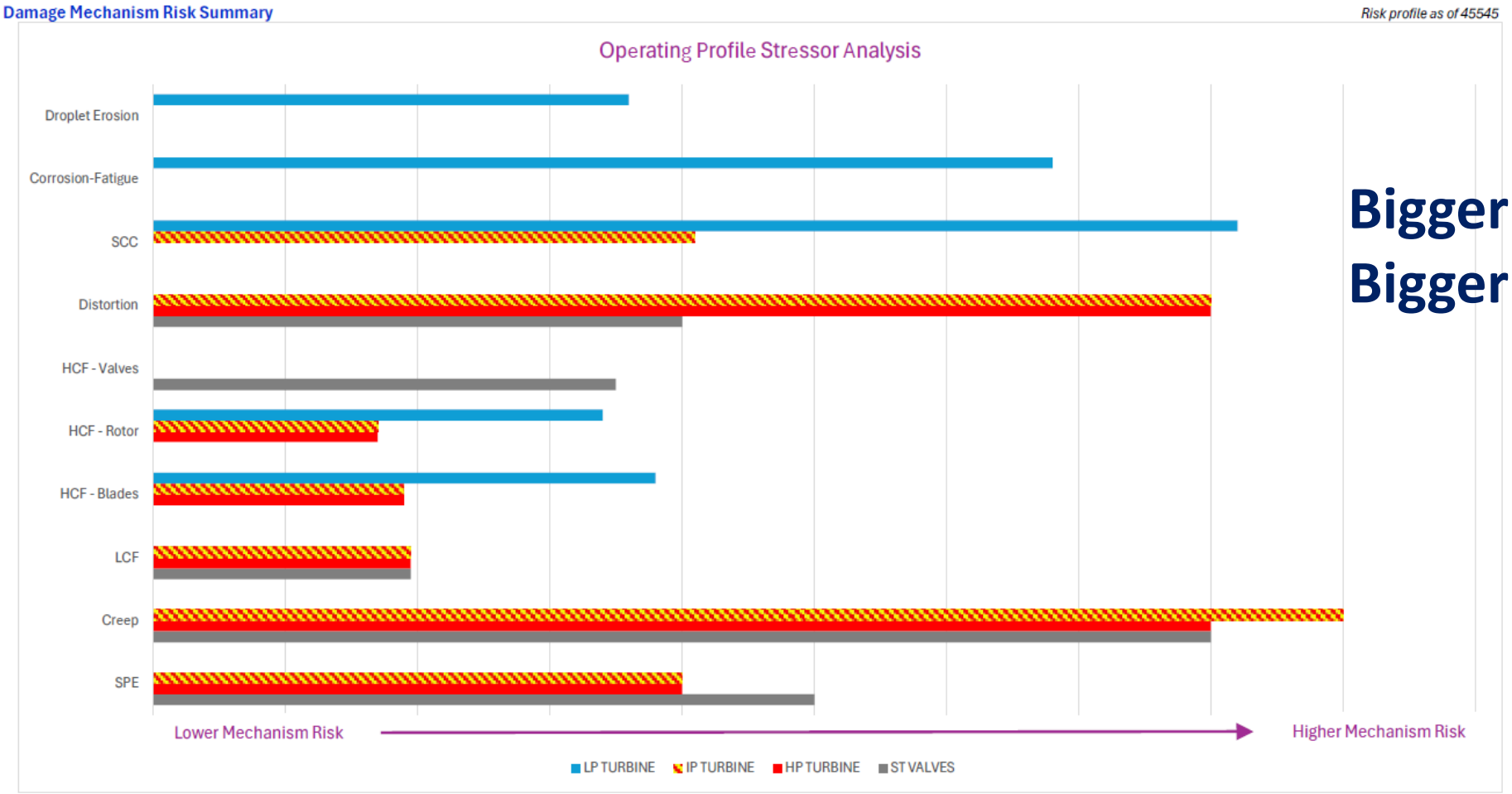




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P219 Steam Turbine Health Risk Screening Tool

Bar Plot of Mechanism Risks by Component



Bigger the bar,
Bigger the risk

Information to help inform operation & maintenance decisions

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P219 Steam Turbine Health Risk Screening Tool

Mechanism Risks Summary by Component

STEAM TURBINE VALVES		
SPE	*Impacting internals primarily. Reinforces the need to establish effective maintenance of wear com*	
Creep	*Impacting chest integrity. Driven by alloy, temperature, pressure, and hours in service.*	
LCF	*Impacting chest integrity. Driven by alloy, temperature, pressure, transient load, and start/shutdown cycles.*	2.0
HCF	*Impacting valve operability. Driven by aging, assembly quality, technology, and dynamic pipe loads.*	3.5
Distortion	*Impacting chest maintainability. Driven by alloy, temperature, pressure, and hours in service.*	4.0

HP TURBINE		RISK
SPE	*Impacting stationary and rotating steam path. Driven by boiler/steam generator alloys, temperature, chemistry, and steam velocities*	4.0
Creep	*Impacting rotor and blade attachment integrity. Driven by alloy, temperature, pressure, and hours in service.*	8.0
LCF	*Impacting rotor and blade attachment integrity. Driven by alloy, temperature, pressure, transient load, and start/shutdown cycles.*	2.0
HCF - Blades	*Impacting blade integrity. Driven by aging wear, technology, and dynamic system loads.*	1.9
HCF - Rotor	*Impacting rotor integrity. Driven by aging wear, technology, and dynamic system loads.*	1.7
Distortion	*Impacting rotor operability and bearing pad. Driven by alloy, aging, temperature, suddent transient load, and start/shutdown cycles.*	8.0
Droplet Erosion	*Impacting casings of low enthalpy exhaust designs common in nuclear.*	0.0

IP TURBINE		RISK
SPE	*Impacting stationary and rotating steam path. Driven by boiler/steam generator alloys, temperature, chemistry, and steam velocities*	4.0
Creep	*Impacting rotor and blade attachment integrity. Driven by alloy, temperature, pressure, and hours in service.*	9.0
LCF	*Impacting rotor and blade attachment integrity. Driven by alloy, temperature, pressure, transient load, and start/shutdown cycles.*	2.0
HCF - Blades	*Impacting blade integrity. Driven by aging wear, technology, and dynamic system loads.*	1.9
HCF - Rotor	*Impacting rotor integrity. Driven by aging wear, technology, and dynamic system loads.*	1.7
Distortion	*Impacting rotor operability and bearing pad. Driven by alloy, aging, temperature, suddent transient load, and start/shutdown cycles.*	8.0
SCC	*Impacting rotor and blade attachment integrity. Driven by alloy, temperature, pressure, steam chemistry and hours in service.*	4.1

LP TURBINE		RISK
HCF - Blades	*Impacting blade integrity. Driven by aging wear, technology, and dynamic system loads.*	3.8
HCF - Rotor	*Impacting rotor integrity. Driven by aging wear, technology, and dynamic system loads.*	3.4
SCC	*Impacting rotor and blade attachment integrity. Driven by alloy, temperature, pressure, steam chemistry and hours in service.*	8.2
Corrosion-Fatigue	*Impacting rotor and blade attachment integrity. Driven by alloy, temperature, pressure, transient load, steam chemistry and start/shutdown cycles.*	6.8
Droplet Erosion	*Impacting rear stage blades and stationary exhaust components. Driven by alloy, steam quality, load range, and condenser performance.*	3.6

Information to help inform operation & maintenance decisions

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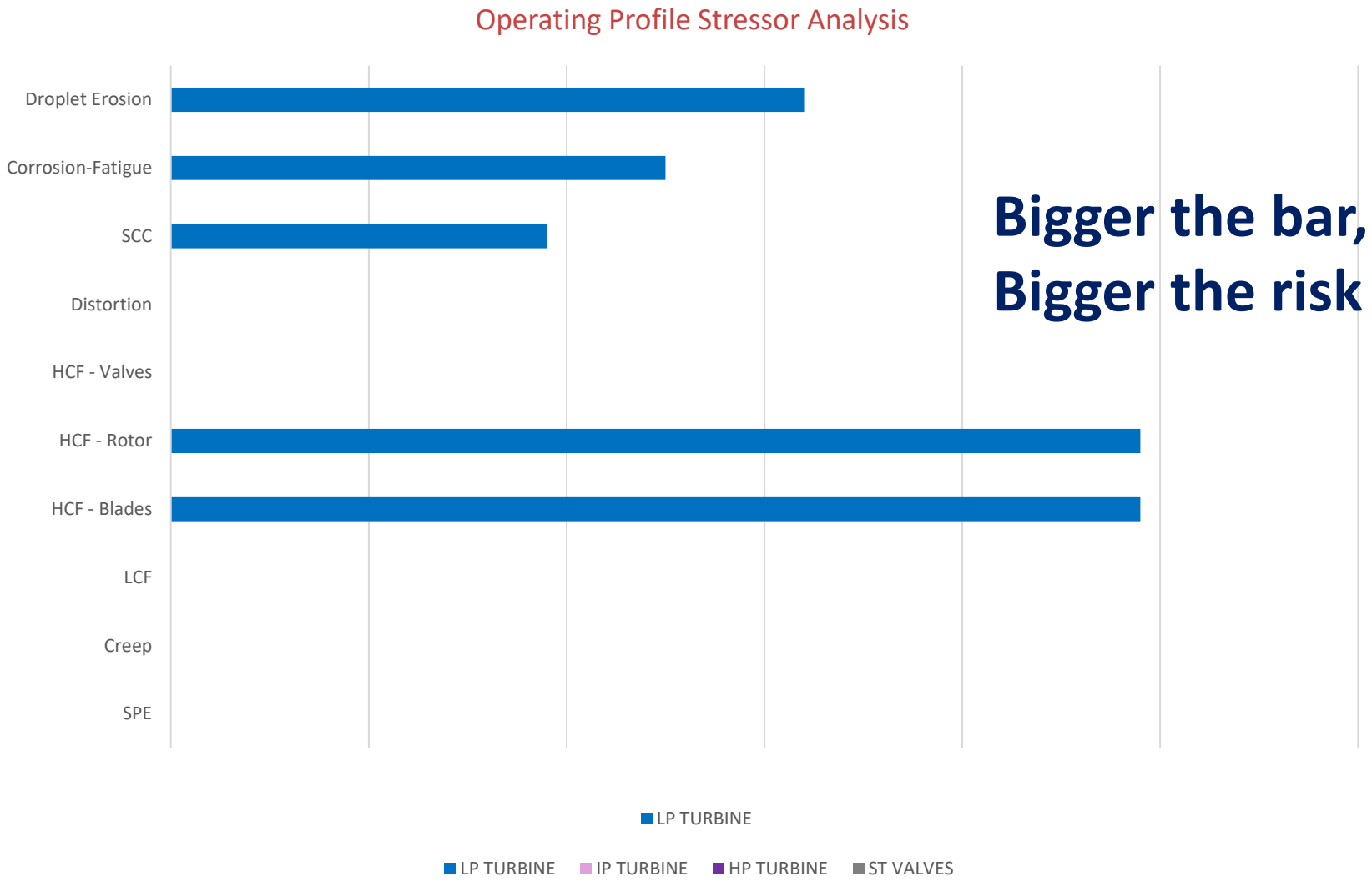
Dealing with Module Replacements and Upgrades

3002032531

Steam Turbine Health Assessment Screening Tool

- Enter the unit data with revised hours, cycles and operating regime
- Complete the data for the new module/retrofit
- Disregard assessment of total system components

Should we build a module specific tool to enable refined screening?



Bigger the bar, Bigger the risk

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Digging into the Risks…

3002032535

Steam Turbine Health Assessment Tool

Data Collection Sheets/Guide

Key questions to help engineers evaluate the system risks.

EPRI

Steam

Data Collect

1. INTRODUCTION

The industry seeks a consistently applied and structured approach for determining the health of power generation asset systems and critical components. *Equipment health* is a term with mixed meanings across industries. In many cases, reliability engineers quantify health using a percentage of observed performance or findings and wear-out statistics (similar to the life consumption associated to a degradation mechanism). For steam turbine systems, the risk associated with performance and interrupted operation can vary greatly. Cycle performance tools and rotating vibration diagnostic systems are commonly applied as a foundation to understand equipment condition. However, there are many damage mechanisms that cannot be detected or diagnosed without enhanced monitoring, routine maintenance, or targeted inspection. Operationally undetectable risks and poor statistically relevant failure data sets challenge the effectiveness of management to make sound decisions on defining capital projects, maintenance scope, and intervals.

Funders of EPRI Program 219 (Steam Turbines and Auxiliary Systems) are typically in a role supporting both operation and maintenance and, therefore, are seeking a health index that will account for a spectrum of degradations that will impact safety, performance, reliability, and availability. The Steam Turbine Asset Management Integrity Analysis (see Figure 1) provides a risk-informed approach. This process and associated tools are intended to inform management decisions by identifying and communicating health concerns using a variety of tools that communicate risks in a structured and simplified manner. This report defines user inputs to prompt the development of a risk register that can be used to evaluate the integrity of steam turbine systems.

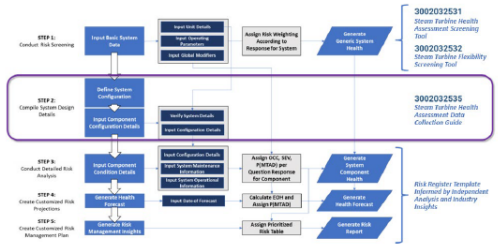


Figure 1. Steam turbine asset management integrity analysis

7. VALVE CASING DATA SHEET

Unit name:	(input)
Valve casing name:	(input)

Basic Data for Valve Casing

No.	Input Prompt	Data Entry Field	Comments	Degradation Risk
BD1	Date of valve casing commissioning	(date)	Change if casing replaced	
BD2	Accumulated operating hours	(#)	Change if casing replaced	Creep
BD3	Quantity of starts	(#)	Change if casing replaced	Fatigue and SPE
BD4	EOH start factor	(#)	Apply based on OEM guidance or experience	
BD5	Date of analysis	(date)		
BD6	Estimated component EOH	calculated		
BD7	Valve configuration	(select)	**A) Admission** 1) Combined 2) Combined (sequential) 3) Single 4) Multi-valve chest **B) Reheat/intercept** 1) Combined 2) Other **C) Second admission/ overload** 1) Single 2) Other **D) Extraction control** 1) Single 2) Other	
BD8	Valve casing delivery condition	(input)	Define if forged or cast	Creep and fatigue
BD9	Valve casing composition	(input)	Specify composition (i.e., 1CrMoV)	Creep and fatigue
BD10	Shell-mounted or stand-alone?	(select)	1) Shell-mounted 2) Stand-alone	Inlet/loop piping relevance Valve internals configuration impact
BD11	Material	(select)	1) Cast iron 2) Low-alloy steel 3) 1.5% Cr 4) 2.25% Cr 5) 9% Cr 6) 12% Cr	

System Condition Modifiers for Valve Casing

Date of last inspection:	(date)
Date of last fastener replacement:	(date)

No.	Input Prompt	Data Entry Field	Comments	Degradation Risk
CM1	Has creep damage been detected?	(select)	1) Replicas or samples extracted—no damage observed 2) Replicas or samples extracted—Stage I creep 3) Replicas or samples extracted—Stage II creep 4) Replicas or samples extracted—Stage III creep 5) No replicas or samples evaluated	Casing creep
CM2	Has cracking been detected?	(select)	1) Full NDT—no findings 2) Full NDT—findings 3) Partial NDT—no findings 4) Partial NDT—findings 5) No NDT conducted	Casing creep or fatigue
CM3	If CM2 ≠ 1, has remaining useful life been determined?	(select)	1) Yes, enter value in CM4 2) Yes, life extension and mitigation for long term (200k EOH) 3) No, assume medium-term degradation (100k EOH) 4) No, assume short-term degradation (50k EOH)	Casing creep or fatigue (see CM4)
CM4	If CM3 = 1, enter remaining life estimate.	(input)	OH, EOH, or starts	Casing creep or fatigue
CM5	Has the bolting been assessed for future use?	(select)	1) Pressure boundary joint bolting assessed; replacement interval has been determined—enter value in CM6 2) Pressure boundary joint bolting not assessed for continued service 3) Pressure boundary shear ring applied	Fastener creep or fatigue (see CM6)
CM6	If CM5 = 1, enter remaining life estimate.	(input)	OH, EOH, or starts	Fastener creep or fatigue

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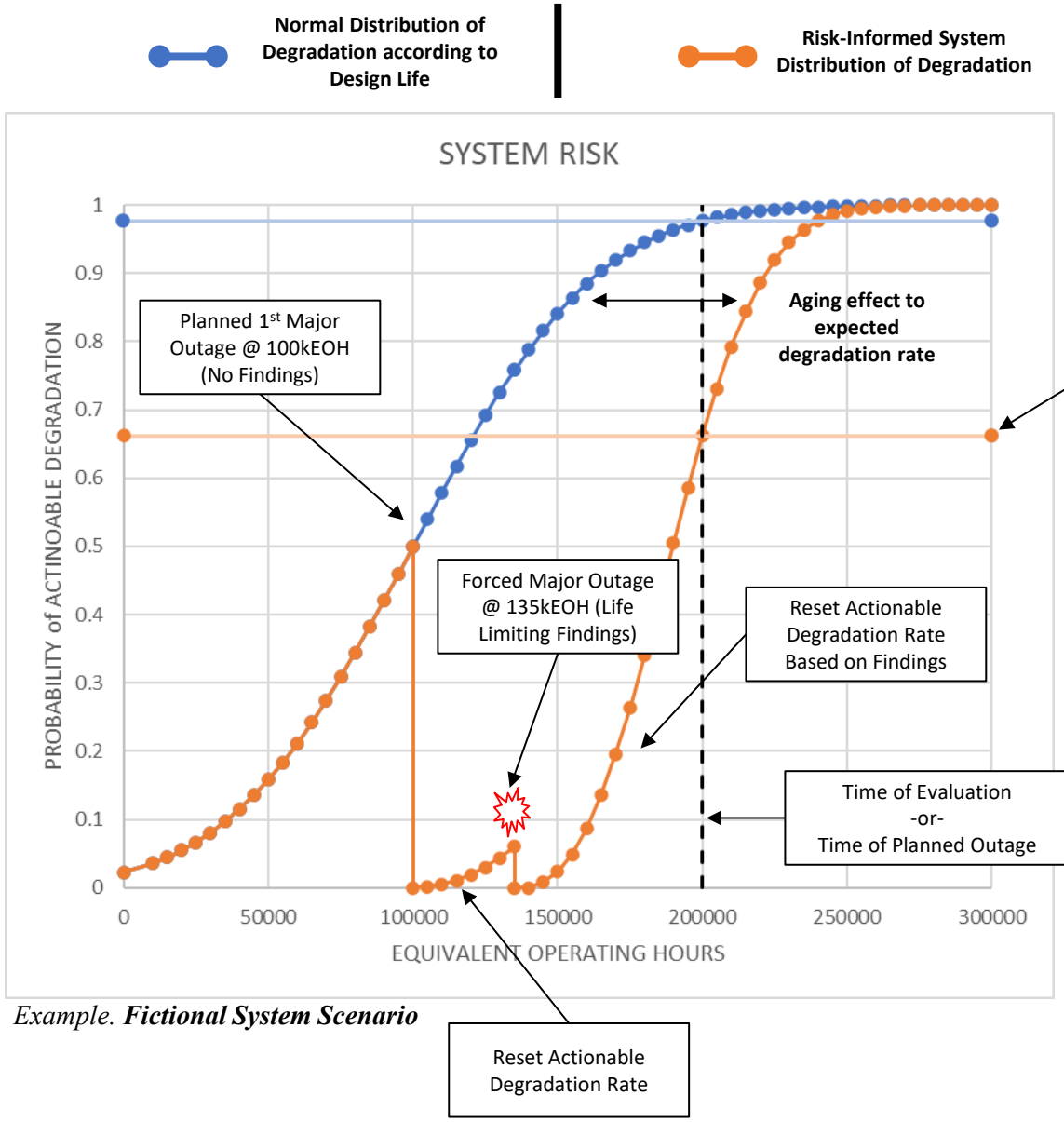
Building a Risk Register

STEAM TURBINE HEALTH ASSESSMENT RISK REGISTER TEMPLATE	v1(2025.06.01)											
Plant Site	(Enter)											
Unit Name	(Enter)											
Unit Number	(#)											
Equipment Group	System - Component	Location Comments	Mechanism	Most Likely Consequence	SEV	Likelihood of Consequence	OCC	FMRPN	Component Inspection Interval	Last Inspection Date	Hours Accumulated Since Last Inspection	Starts Accumulated Since Last Inspection
<verify>	<select from drop box>	<overwrite clarification text - suggested attributes automated>	<select from drop box>	<select from drop box>	<lookup>	<select from drop box>	<lookup>	<calc>	<select from drop box>	<enter date>	<enter hrs /use calc>	<enter hrs /use calc>
1		2	3	4	5	6	7	8	9	10	11	12
LP	LP STATIONARY STEAM PATH - RADAX	Airfoil, End Blades	LCF	Disruption in Operation, MODERATE to LOW cost to recover, MINIMAL impact to unavailability	2	Med-High: Conditions of the equipment strongly suggest the mechanism will occur	4	8	100,000 EOH	12/21/2024	75,000	250

Start EOH Factor	EOH Accumulation Since Last Inspection	Total Equipment Starts Accumulated	Total Hours Accumulated	Total EOH Accumulation	Modifier: Aging	AM	Age Adjusted: Calculated Life	Modifier: Condition	CM	Modifier: Operational Stressors	OM	Modifier: OEM Bulletin	BM	Modifier: Calculated Life	Degradation Probability P(TAD) (Weibull 2P Assumption)	Risk Index Score	Risk Response
<apply guidance>	<calculated>	<enter hrs>	<enter hrs>	<calculated>	<select from drop box>	<lookup>	<calculated>	<select from drop box>	<lookup>	<select from drop box>	<lookup>	<select from drop box>	<lookup>	<enter hrs / use calc>	<calculated>	<calculated>	<lookup>
13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
25	21,000	1,500	201,335	238,835	Wear Component (200k life): 200k < EOH	0.5	63000.00	VERY HIGH RISK: Operating in damaged condition (25% of maintenance life remaining)	0.25	LOW RISK: No stressors observed to limit maintenance interva (100% maintenance life remaining)	1	Reliability Issue Immediately Impacting System	0.25	34540.2	25%	98%	Mitigation suggested

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System Risk Analysis Results

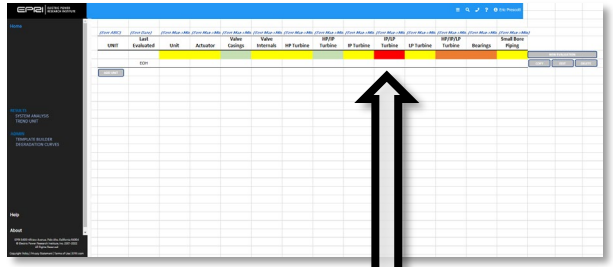


Example. ***Fictional System Scenario***

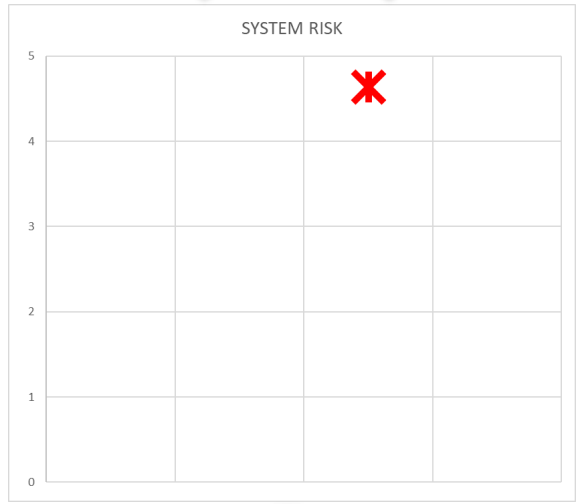
P(TAD)	OCC Score	PROB Score	SEV Score
66%	7	4.6	3

Calculated probability of actionable degradation at date of interest

EPRI Tool Interface



69.5%



	Negligible	Marginal	Critical	Catastrophic	
	1	2	3	4	
5	25%	50%	75%	100%	High
4	20%	40%	60%	80%	Med-High
3	15%	30%	45%	60%	Med
2	10%	20%	30%	40%	Med-Low
1	5%	10%	15%	20%	Low

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Summary

- You cannot accurately predict the life of any equipment with certainty.
- Extending operation life after reducing O&M for on plants marked for decommissioning can lead to costly reliability challenges.
- Steam Turbines are designed to power cycles and are influenced by design choices, operation, and maintenance quality throughout their history of operation.
- Details matter
  - The more information, the better it can inform your risk.
  - Big Data and AI tools with poor data leads to poor decision making.
- EPRI has tools to apply and experience to contribute.
- The suite of ***Steam Turbine Asset Management Integrity Assessment*** Tools can be used to compliment your understanding and communicate to management.

We need your feedback to improve the tools

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Materials Property Development

Project Objective and Scope

- Develop materials test data of service exposed (~50,000 hours) and long-term aged 1CMV HP and 9Cr IP turbine casings
- Evaluate ability to execute alternative weld repairs of casing components without PWHT

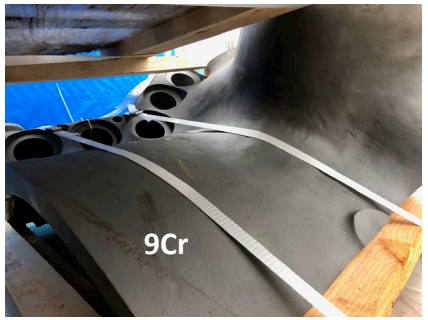
Key Developments and Updates

- Time-independent test data development to investigate the materials degradation due to service aging
- Creep test data development for lifetime assessment
- Long term thermal ageing for test data development on simulated degraded material
- Simulated weld repair fabrication using different filler metals w/o PWHT

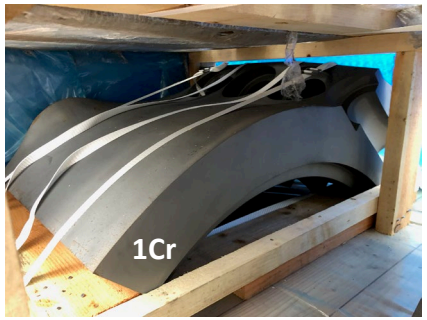
Schedule and Upcoming Work

- On-going test data development for service exposed and lab-aged material
- Large-frame creep testing of simulated repair weld

555degC @ 36.5bar
1063degF@529.4psi



560degC@155bar
1040degF@2175.6psi



Purpose	Material property data	9Cr Casting (Virgin)	9Cr Casting (Ex-service)	1Cr Casting (Virgin)	1Cr Casting (Ex-service)
Thermal and elastic stress calculation	Density	✓		✓	
	Elastic modulus	✓		✓	
	Thermal expansion	✓		✓	
	Thermal conductivity	✓		✓	
Material degradation and remaining life assessment	Hardness	✓	○	✓	○
	Monotonic tensile	✓	○	✓	○
	Impact toughness	✓	○	✓	○
	Fracture toughness	✓	○	×	○
	Creep deformation and rupture	✓	○*	✓	○*
	Low-cycle fatigue	✓	×	×	×
	Cyclic stress-strain curve	×	○*	×	○*
	Fatigue crack growth	×	×	×	×
	Creep crack growth	×		×	

✓	Available in EPRI report or literatures	○	Data collected from EPRI testing program	×	Potential material data gap

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Ex-service Component Damage Characterization

Project Objective and Scope

- Perform metallurgical assessment of local damage and oxidation of the service-exposed IP rotor components.
- Develop materials test data for the lifetime assessment of service-exposed IP rotor forging (ST10)

Key Developments and Updates

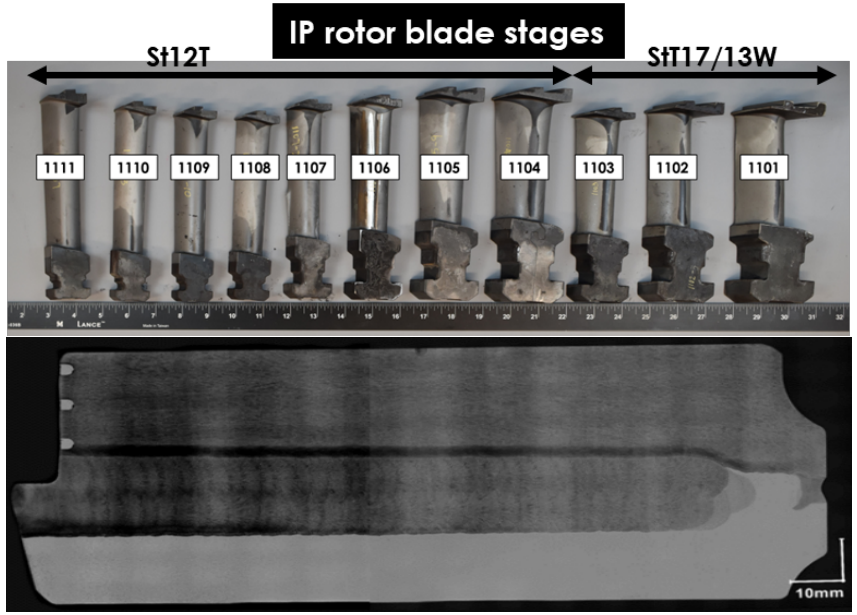
- Metallurgical evaluation of rotor welds and front-stage groove to investigate potential material damage and degradation due to plastic deformation and aging
- Oxidation layer measurement of blade attachments and root grooves to investigate the oxide layer growth at different rotor stages

Schedule and Upcoming Work

- Develop and testing plan for the IP rotor forging that accounts for the weld, and potential inhomogeneity of the rotor microstructure.
- Technical brief expected in 2025

Rotor feature	Stage(s)	Elemental mapping	Hardness Mapping	Metallurgical analysis	Oxide layer measurement
Blade attachments and shims	1101-1104, 1110, 1111	NA	NA	O	O
Rotor grooves	1101, 1102, 1104	NA	O	O	O
Rotor weld	1110-1111	✓	✓	✓	NA
Rotor cavity wall	1109	NA	✓	NA	NA
Rotor radial section	Inlet section	O	✓	O	NA

✓	Completed	O	On-going



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Last Stage Blade Spring Degradation Model

Project Status

Background:

- PAUT applications have helped manage the risks associated with cracking in the blade and rotor attachment areas (= interval extension in some cases)
- Spring replacement is a typical activity during blade out inspections of axial entry last stage blading

Objective:

- Understand the potential effects associated with loose axial entry blading

WINTER 2025 TGUG OEM PRESENTATIONS

Status:

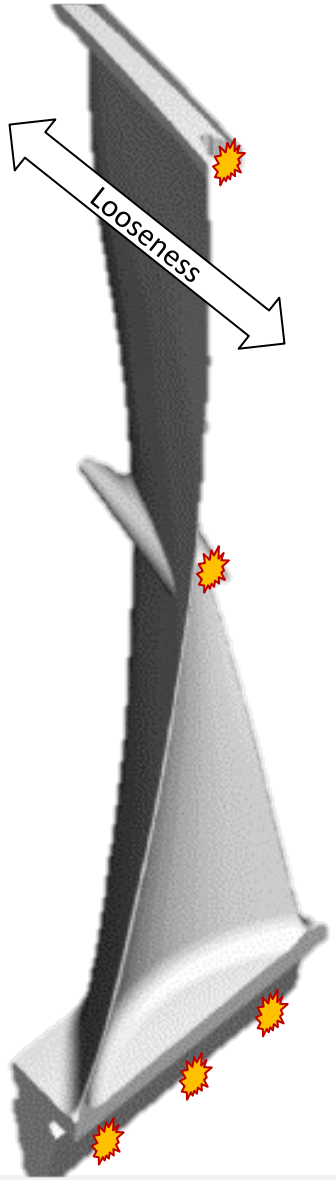
- Geometric data (applied ND56 dataset on hand)
- Performed structural and dynamic blade analysis
- Characterized the spring rate reduction

Next Steps:

- Evaluate the effect to the assembly for the risk of fretting, galling and clash impact damage
- Issue summary report of findings - delayed 2025

Update to Industry Issue

- Blade looseness has been discovered on many OEM designs.
- Audible clashing of Alstom ND48 was determined to be due to a blade installation quality deviation
  - Blader appeared to have selectively ground the spring during installation
  - The blade did not have any spring load for low speed operation
  - No adverse root and steeple findings were reported
  - Blades were reinstalled per design intent with no other observations reported
- Practices to consider
  1. Know the risks
  2. Have spare installation hardware on-hand
  3. Plan for outage scope contingency
  4. Move the blades by hand, blades should be firmly loaded and unaffected by gravity of orientation



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Focus on Workforce & Quality…

Turbine Water Induction Protection Update

- More frequent water induction events
- Reduces life and leads to piping, casing, shell and rotor cracking
- Accumulation of undetected events adversely impacts equipment, leading to significant findings…
  - Extended outages to repair
  - Repair quality in question
  - May necessitate component replacement

3002030002 ***2025 Deliverable***

System Walkdown Checklist

- Walkdown inspections have historically been used to identify issues before they impact unit reliability
- Discovery of deviation or even identification of good condition is valuable information for outage planning and CM/PM dispatch
- This activity has been negatively impacted by workforce reduction and scope elimination
- Goal is to provide asset-based guidance and inform PMBD updates
- Product: series of checklists to be used as instruction and training aids

300203XXXX ***2026 Deliverable***

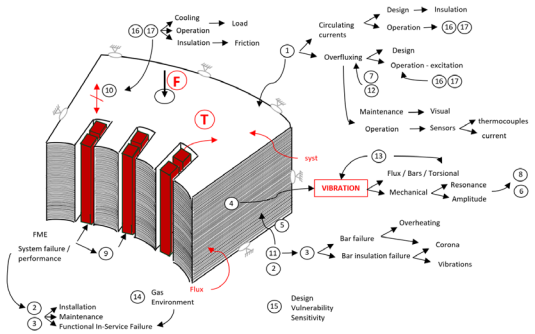
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2025 Generator Research: Ongoing Focus Areas

Generator Reliability

Understanding Useful Life…

- *Stator Core Remaining Useful Life Project Roadmap*
  - ❑ *Failure Modes*
  - ❑ *Stressor Definition*
  - ❑ *Design Influence Analysis*
  - ❑ *Target Test Parameters*
  - ❑ *Testing Plan*
  - ❑ *Results Validation*



Enhancing Quality…

- *Generator Rewind Design Considerations: Technical Review Insights for System Owners*

Generator Health Assessment Tools

3002030030

Generator Health Assessment Tool (GHAT) v1.4

- *Technology Transfer sessions*
- *Supplemental Projects on-going*

3002021506

Hydro Generator Health Assessment Tool (HGHAT) v1.0

- *Limited engagement with EPRI on application*

Emerging Risks

Nuclear Resurgence…

- *Nuclear Restart Guidance*
- *New Nuclear Technology Evaluation*

Torsional Interactions w/ Grid…

- *Grid Risk Screening Methodology (P40)*

Material Risks & Properties

Retaining Ring Alloys…

- *Corrosivity of Condensate in Hydrogen-Cooled Generators Containing Sulfur Hexafluoride Tracer Gas: Phase II - Thermal Decomposition Trials*

Generator Monitoring & Diagnostics

Monitoring Insights…

- *Hydrogenerator Online Monitoring Guide*
- *Hydrogen Leak Monitoring for Water-Cooled Generator Stators*

Generator Engineer Information Resources

Maintenance & Operation…

- *Generator Outage Scope and Frequency Benchmarking (2025)*
- *Carbon Brush Optimization Tool*
- *Improved Stator Cooling Control Study, Phase I*

- *Lube Oil System Maintenance*
- *Lube Oil System RAMS Case Study*
- *Lube Oil System Remedy Guide*

Engagement…

TGUG 2025

January – Orlando, FL
August – Minneapolis, MN

Enhanced Information Resources…

- *Hydrogenerator Failure Modes and Inspection Tutorial*

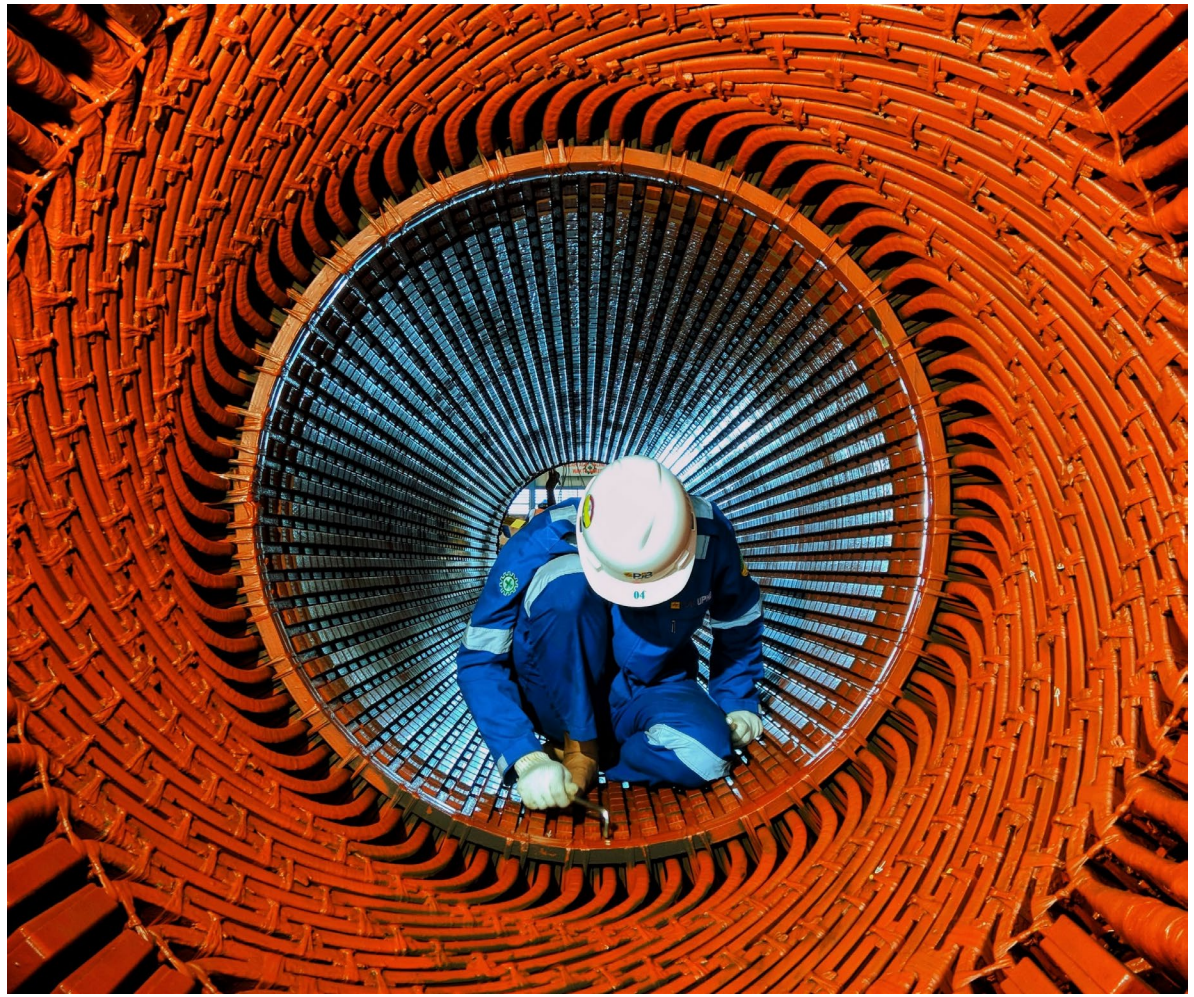
TGUG WIKI

ST&G OUTAGE *Guidelines* WIKI

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2025 Project Status Updates

Generators & Auxiliary Systems



- Fluid Systems Research
- Hydrogenerator Monitoring Guide
- Generator Rewind Technical Considerations
- Vibration Sparking in Air-cooled Generators
- SF6 Corrosivity
- Carbon Brush Optimization Tool
- Hydrogen Leak Monitoring
- 4-Pole Generator Stator Flexible Operation
- Stator Core Life

Ongoing Research Activities

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Generator Outage Scope & Frequency Benchmarking

Industry Issue/Project Description

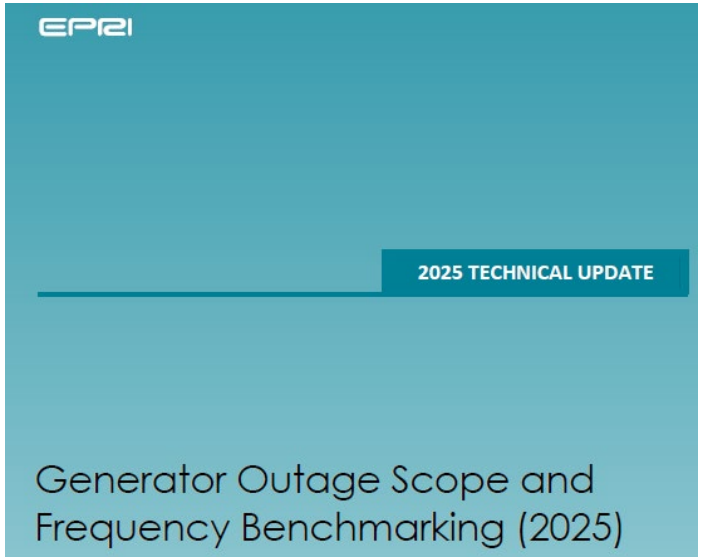
- There is significant variability in generator outage frequency, duration and scope.
- This Member survey summarizes those variations, identifying most common outage frequencies, duration and workscopes for generators.

Takeaways and Member Benefits

- Members can compare their outage practices, scope and frequencies with those identified as the most common in the study and decide if adjustments are necessary. One of the most significant variations across the industry is related to retaining ring inspection, including frequency and scope. That is highlighted along with other outage practices including EPRI perspectives.

Deliverable Format

- Published as Technical Update as planned.
  3002032551 available at www.epri.com



Cover page of published report shown above, and rotors in outage and under repair shown in photo below.



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Generator Rewinds – Technical Considerations

Industry Issue/Project Description

- What are the key questions to ask when proceeding with a generator rewind? What if an uprate is planned? This deliverable will provide insight into generator rewinds from a design engineer's focus.
- Fundamental concepts such as evaluation of I2R losses, strand eddy current losses and circulating current losses will be discussed. The importance of Roebel transposition determination will be made. Series connection designs will be included as well. Factors that should be addressed when changing design, such as GVPI to non-GVPI, will be included.

Takeaways and Member Benefits

- The published technical update will assist generator SME's and system engineers involved in generator rewinds including plant uprates and upgrades.
- The technical information will support evaluation of bid offerings to compare technical benefits and the risks of different solicitations.
- A design review checklist is included along with a sample rewind specification.
- Other plant components that should be evaluated from an uprate perspective, are also be discussed.

Deliverable Format

- Technical Update, Published by Year End 2025

GENERAL
Who will carry out the rewind and have they been assessed?
Key considerations: - Who will disassemble and reassemble the generator? - Who will commission the rewound generator? - Can the Supplier re-design the generator? - Where will the stator be rewound? - Who will manufacture the new bars? - Is the Supplier capable of a turnkey project or will other contractors be required? - If other contractors, who will manage them? - Who will take ultimate responsibility for the rewind?
What is required on the auxiliaries: - bearings and bearing oil systems - seal oil systems - cooling water system - control and instrumentation - protection
Is there a risk of asbestos in the insulation or blocking? If so has the supplier been made aware, and will they take suitable precautions? What about other safety considerations such as lead or formaldehyde?
CORE
What core tests are planned to assure the core is re-qualified prior to the rewind and also be reliable after the rewind?

Part of "Design Review Checklist" shown above.

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Vibration Sparking in Air-Cooled Generators

Industry Issue/Project Description

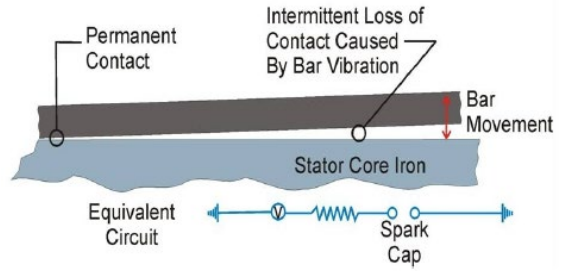
- Vibration sparking (VS) is a particularly “fast acting” failure mode, compromising the stator bar ground insulation, usually resulting in a ground fault. One of the first industry failures occurred in the 2007 time-frame. The problem has recently surfaced again on air-cooled Nuclear generators with water-cooled stator windings. Other instances in the industry have been reported.
- EMSA/EMI testing claims to have the ability to detect, online, vibration sparking also called Spark Erosion (SE). This claim was evaluated in this project.

Takeaways and Member Benefits

- The scope of this project focused on several key areas:
  - Determination if EMI testing can identify vibration sparking
  - Four, nuclear, air-cooled generators with a known history of VS/SE, were tested.
  - The ability to detect VS/SE, and also to evaluate the degradation level of the stator winding will be evaluated.

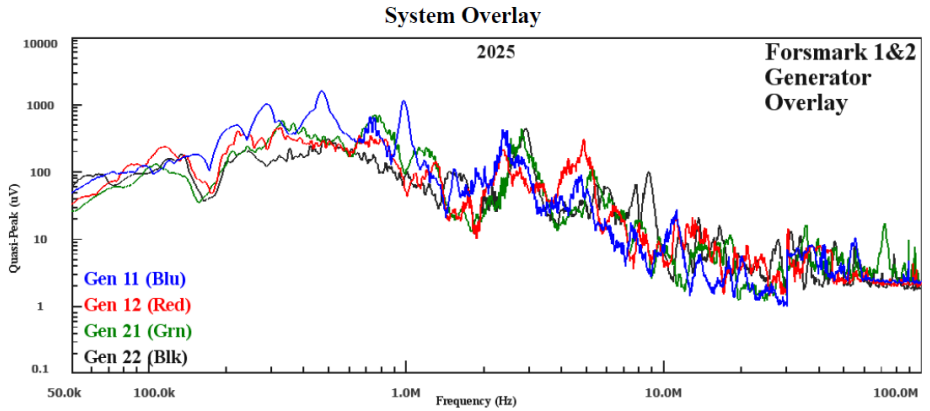
Deliverable Format

- Technical Update, Tentatively Planned for 2025 but Deliverable Number is Required





The image above shows how vibration occurs with loose bars. The graphs below is from recent testing done as part of this EPRI project.



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SF6 Corrosivity on Retaining Rings

Phase I – 3002030034, Corrosivity of SF6 in Hydrogen Cooled Generators

- Room temperature findings:
  - There was no detectable decrease in pH that could be attributed to reactions between 1% SF6 (bal. H2) gas with DI water under the test conditions employed at room temperature.
  - There was no detectable fluoride ion in the post-test solution after 500 h of continuous saturation with 1% SF6 (bal. H2) gas under the test conditions employed.
  - No apparent corrosion was found on the specimen that contained 18% Cr after the 500 h test in pure water with continuous saturation with 1% SF6 (bal. H2) gas.
  - Pitting corrosion was evident on the specimen that contained only 5% Cr after the 500 h test in pure water with continuous saturation with 1% SF6 (bal. H2) gas. The propensity for corrosion was likely attributed to the low Cr content of the alloy and not the presence of corrosive species, such as HF, generated from the breakdown of SF6.

Phase II - 3002032565, Corrosivity of SF6 in Hydrogen Cooled Generators: Thermal Decomposition Trials (ongoing)

- Elevated temperature findings:
  - There was no detectable decrease in pH that could be attributed to reactions between 1% SF6 (bal. H2) gas with water vapor at an elevated temperature of 130°C.
  - There was no detectable fluoride or sulfate ions in the condensate after 72 h of heated water vapor interaction with 1% SF6 (bal. H2) gas at 130°C.

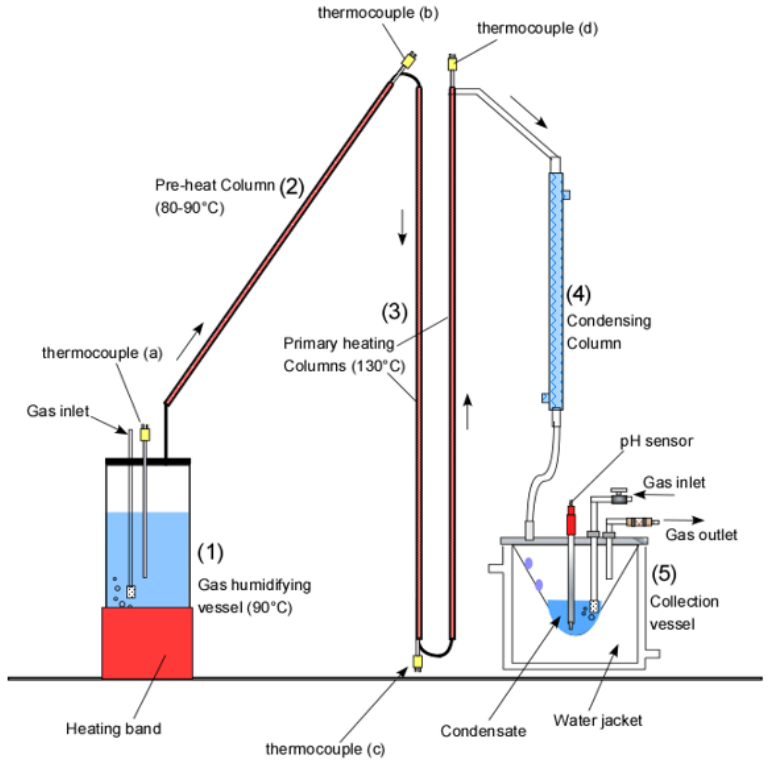


Figure 3-2
Schematic of experimental setup for high temperature water/gas condensation.

Next Steps:
- Longer Duration?
- Elevated temperatures due to abnormal events?

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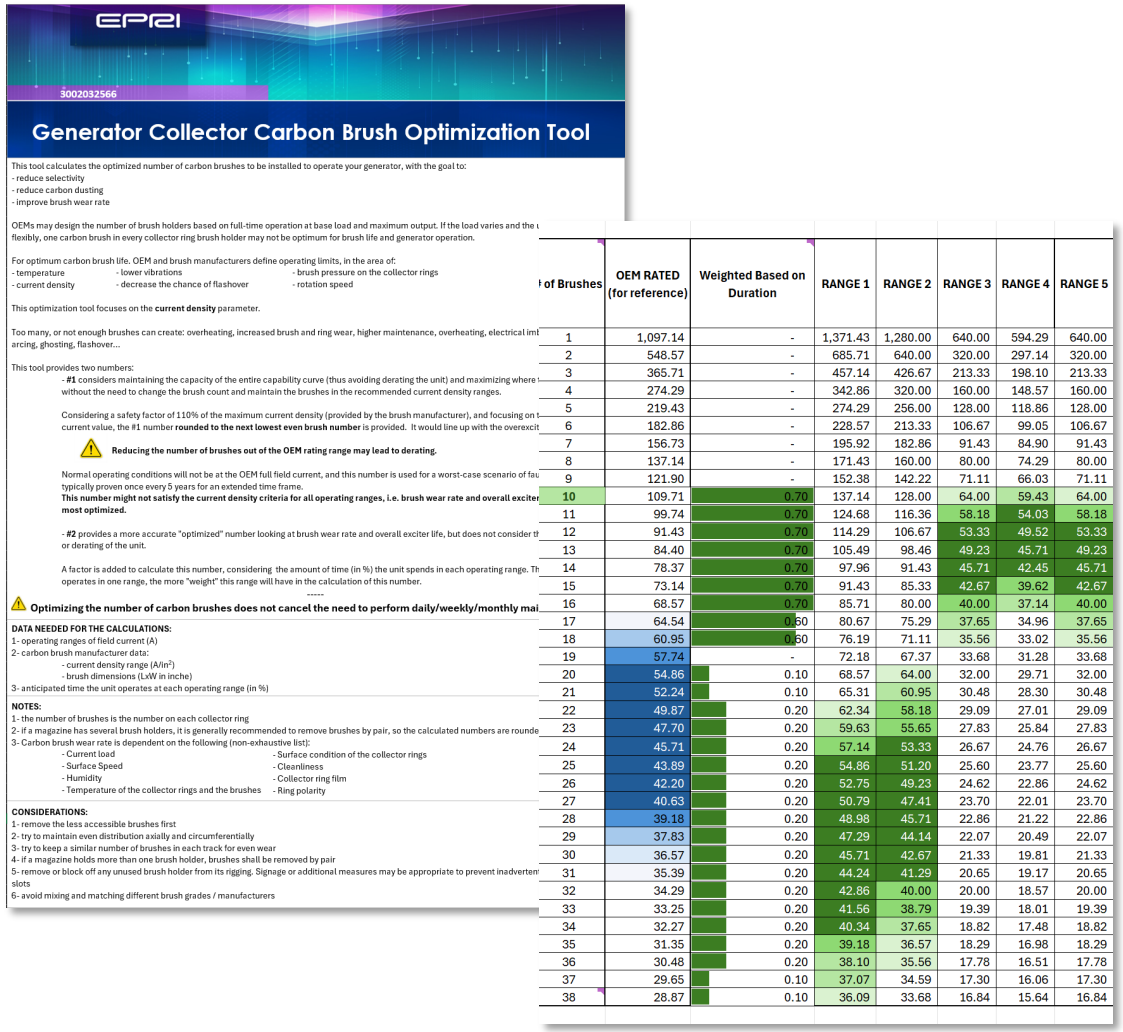
Generator Collector Assembly Carbon Brush Optimization

Industry Issue/Project Description

- For turbogenerators and hydrogenerators that load cycle, using all carbon brushes available may not be optimum. Excessive or inadequate brush current can promote a build up of carbon dust and also brush selectivity. Brush selectivity (having too much or too little current) can cause excessive brush wear and can lead to a flashover and forced outage.
- This project would capture the work done by our members providing recommendations for carbon brush count based on operating load range and frequency. Included will be an Excel tool for estimating the number of brushes the unit should operate with based on its expected load profile.

Member Benefits and Takeaways

- A readily available Excel spreadsheet tool to estimate optimized carbon brush count based on load profile.
- Members can benefit from using this tool to optimize brush count for any collector ring assembly.
- Most applicable to generators that load cycle frequently.
- Can minimize carbon brush dusting and brush selectivity.
- Publish by Year End 2025.


EPRI

3002032566

Generator Collector Carbon Brush Optimization Tool

This tool calculates the optimized number of carbon brushes to be installed to operate your generator, with the goal to:
- reduce selectivity
- reduce carbon dusting
- improve brush wear rate

OEMs may design the number of brush holders based on full-time operation at base load and maximum output. If the load varies and the u
flexibly, one carbon brush in every collector ring brush holder may not be optimum for brush life and generator operation.

For optimum carbon brush life. OEM and brush manufacturers define operating limits, in the area of:
- temperature
- current density
- lower vibrations
- decrease the chance of flashover
- brush pressure on the collector rings
- rotation speed

This optimization tool focuses on the **current density** parameter.

Too many, or not enough brushes can create: overheating, increased brush and ring wear, higher maintenance, overheating, electrical imb
arcing, ghosting, flashover...

This tool provides two numbers:
- **#1** considers maintaining the capacity of the entire capability curve (thus avoiding derating the unit) and maximizing where t
without the need to change the brush count and maintain the brushes in the recommended current density ranges.

Considering a safety factor of 110% of the maximum current density (provided by the brush manufacturer), and focusing on t
current value, the #1 number **rounded to the next lowest even brush number** is provided. It would line up with the overexcit

⚠ **Reducing the number of brushes out of the OEM rating range may lead to derating.**

Normal operating conditions will not be at the OEM full field current, and this number is used for a worst-case scenario of fau
typically proven once every 5 years for an extended time frame.
This number might not satisfy the current density criteria for all operating ranges, i.e. brush wear rate and overall exciter
most optimized.

- **#2** provides a more accurate "optimized" number looking at brush wear rate and overall exciter life, but does not consider th
or derating of the unit.

A factor is added to calculate this number, considering the amount of time (in %) the unit spends in each operating range. Th
operates in one range, the more "weight" this range will have in the calculation of this number.

⚠ **Optimizing the number of carbon brushes does not cancel the need to perform daily/weekly/monthly mai**

DATA NEEDED FOR THE CALCULATIONS:
1- operating ranges of field current (A)
2- carbon brush manufacturer data:
- current density range (A/in²)
- brush dimensions (LxW in inche)

3- anticipated time the unit operates at each operating range (in %)

NOTES:
1- the number of brushes is the number on each collector ring
2- if a magazine has several brush holders, it is generally recommended to remove brushes by pair, so the calculated numbers are rounde
3- Carbon brush wear rate is dependent on the following (non-exhaustive list):
- Current load
- Surface Speed
- Humidity
- Temperature of the collector rings and the brushes
- Surface condition of the collector rings
- Cleanliness
- Collector ring film
- Ring polarity

CONSIDERATIONS:
1- remove the less accessible brushes first
2- try to maintain even distribution axially and circumferentially
3- try to keep a similar number of brushes in each track for even wear
4- if a magazine holds more than one brush holder, brushes shall be removed by pair
5- remove or block off any unused brush holder from its rigging. Signage or additional measures may be appropriate to prevent inadverten
slots
6- avoid mixing and matching different brush grades / manufacturers

of Brushes	OEM RATED (for reference)	Weighted Based on Duration	RANGE 1	RANGE 2	RANGE 3	RANGE 4	RANGE 5
1	1,097.14	-	1,371.43	1,280.00	640.00	594.29	640.00
2	548.57	-	685.71	640.00	320.00	297.14	320.00
3	365.71	-	457.14	426.67	213.33	198.10	213.33
4	274.29	-	342.86	320.00	160.00	148.57	160.00
5	219.43	-	274.29	256.00	128.00	118.86	128.00
6	182.86	-	228.57	213.33	106.67	99.05	106.67
7	156.73	-	195.92	182.86	91.43	84.90	91.43
8	137.14	-	171.43	160.00	80.00	74.29	80.00
9	121.90	-	152.38	142.22	71.11	66.03	71.11
10	109.71	0.70	137.14	128.00	64.00	59.43	64.00
11	99.74	0.70	124.68	116.36	58.18	54.03	58.18
12	91.43	0.70	114.29	106.67	53.33	49.52	53.33
13	84.40	0.70	105.49	98.46	49.23	45.71	49.23
14	78.37	0.70	97.96	91.43	45.71	42.45	45.71
15	73.14	0.70	91.43	85.33	42.67	39.62	42.67
16	68.57	0.70	85.71	80.00	40.00	37.14	40.00
17	64.54	0.60	80.67	75.29	37.65	34.96	37.65
18	60.95	0.60	76.19	71.11	35.56	33.02	35.56
19	57.74	-	72.18	67.37	33.68	31.28	33.68
20	54.86	0.10	68.57	64.00	32.00	29.71	32.00
21	52.24	0.10	65.31	60.95	30.48	28.30	30.48
22	49.87	0.20	62.34	58.18	29.09	27.01	29.09
23	47.70	0.20	59.63	55.65	27.83	25.84	27.83
24	45.71	0.20	57.14	53.33	26.67	24.76	26.67
25	43.89	0.20	54.86	51.20	25.60	23.77	25.60
26	42.20	0.20	52.75	49.23	24.62	22.86	24.62
27	40.63	0.20	50.79	47.41	23.70	22.01	23.70
28	39.18	0.20	48.98	45.71	22.86	21.22	22.86
29	37.83	0.20	47.29	44.14	22.07	20.49	22.07
30	36.57	0.20	45.71	42.67	21.33	19.81	21.33
31	35.39	0.20	44.24	41.29	20.65	19.17	20.65
32	34.29	0.20	42.86	40.00	20.00	18.57	20.00
33	33.25	0.20	41.56	38.79	19.39	18.01	19.39
34	32.27	0.20	40.34	37.65	18.82	17.48	18.82
35	31.35	0.20	39.18	36.57	18.29	16.98	18.29
36	30.48	0.20	38.10	35.56	17.78	16.51	17.78
37	29.65	0.10	37.07	34.59	17.30	16.06	17.30
38	28.87	0.10	36.09	33.68	16.84	15.64	16.84

The Excel tool calculates the optimized number of carbon brushes based on operating range. Tool will be applicable to both turbo and hydrogenerators.

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H2 Leak Monitoring for Water-Cooled Generator Stators

Industry Need

- Units operating with H2 leaks into the Stator Cooling Water System are a high concern. If the H2 leak is directly to the atmosphere, it is usually identifiable and correctable. However, a leak into the H20 system is more difficult to assess.

Takeaways and Member Benefits

- This report will review how leak monitoring systems work, including their features and diagnostic approach. Specific leak limits will be discussed. Pro's and con's will be reviewed of different systems. Actions needed for proper maintenance and troubleshooting will be identified. Past case histories will be included and reviewed.

Deliverable Format

- Technical Update. Year End 2025.



Hydrogen Leak Monitoring System

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Impact from Flexible Operation on 4-pole Generator Lifetime

Industry Issue/Project Description

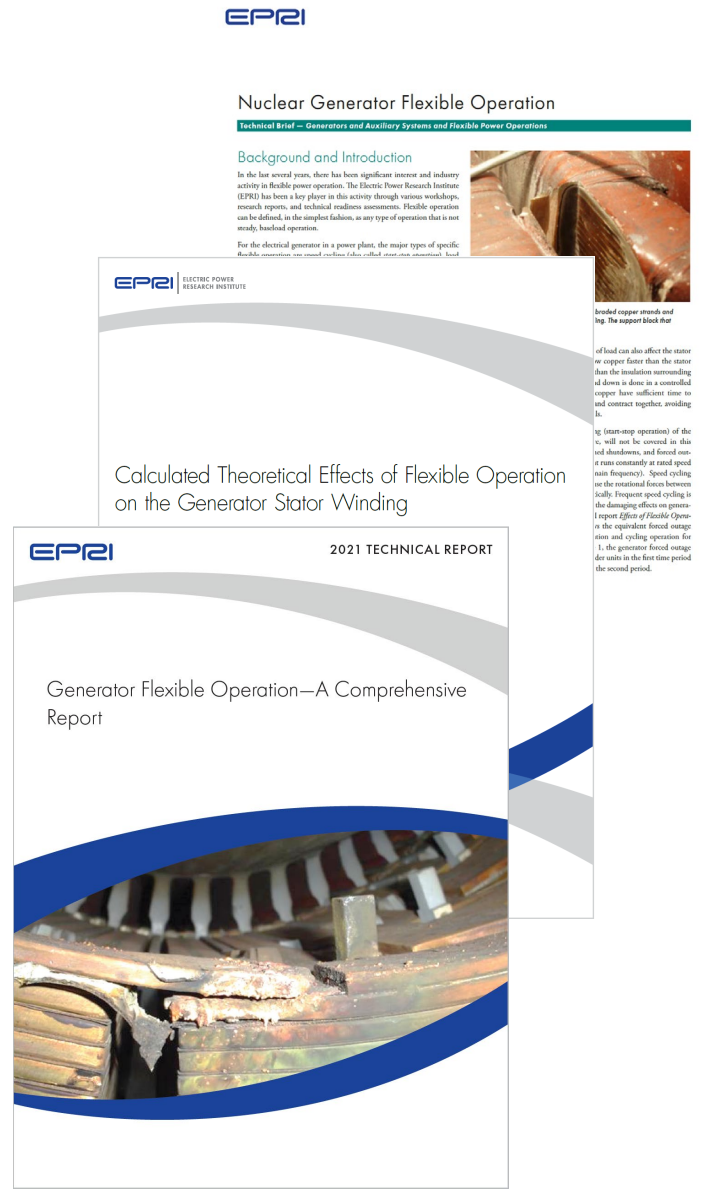
- Generators originally designed to operate as “base load” are now seeing changes of operating profile to introduce flexible operation and ancillary services
- Previous research was performed on the effect of flexible operation, **3002021533**.
- Phase 1 of this project seeks to quantify the impact on generator lifetime when introducing flexible operation or ancillary services by using a TA1500-78S generator model: 4-pole, 1450 MW, liquid-cooled generators with Stainless Steel hollow conductors

Member Benefits

- The 1st phase of this project will provide a list of impacted generator components, with impact and probability levels, to help estimate the reduction of generator lifetime
- The next phases of this project will focus on evaluating the impact of controlled generator cooling on thermal wear and overall generator lifespan, while also extending these findings to other 4-pole liquid-cooled generators. A supplemental project will be pursued to directly apply and verify the results across similar systems.

Deliverable Format

- Technical Update with details of calculations performed as well as model to estimate the reduction of generator lifetime. To be started in 2025 and completed in 2026.



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Generator Core Remaining Useful Life

Industry Issue/Project Description

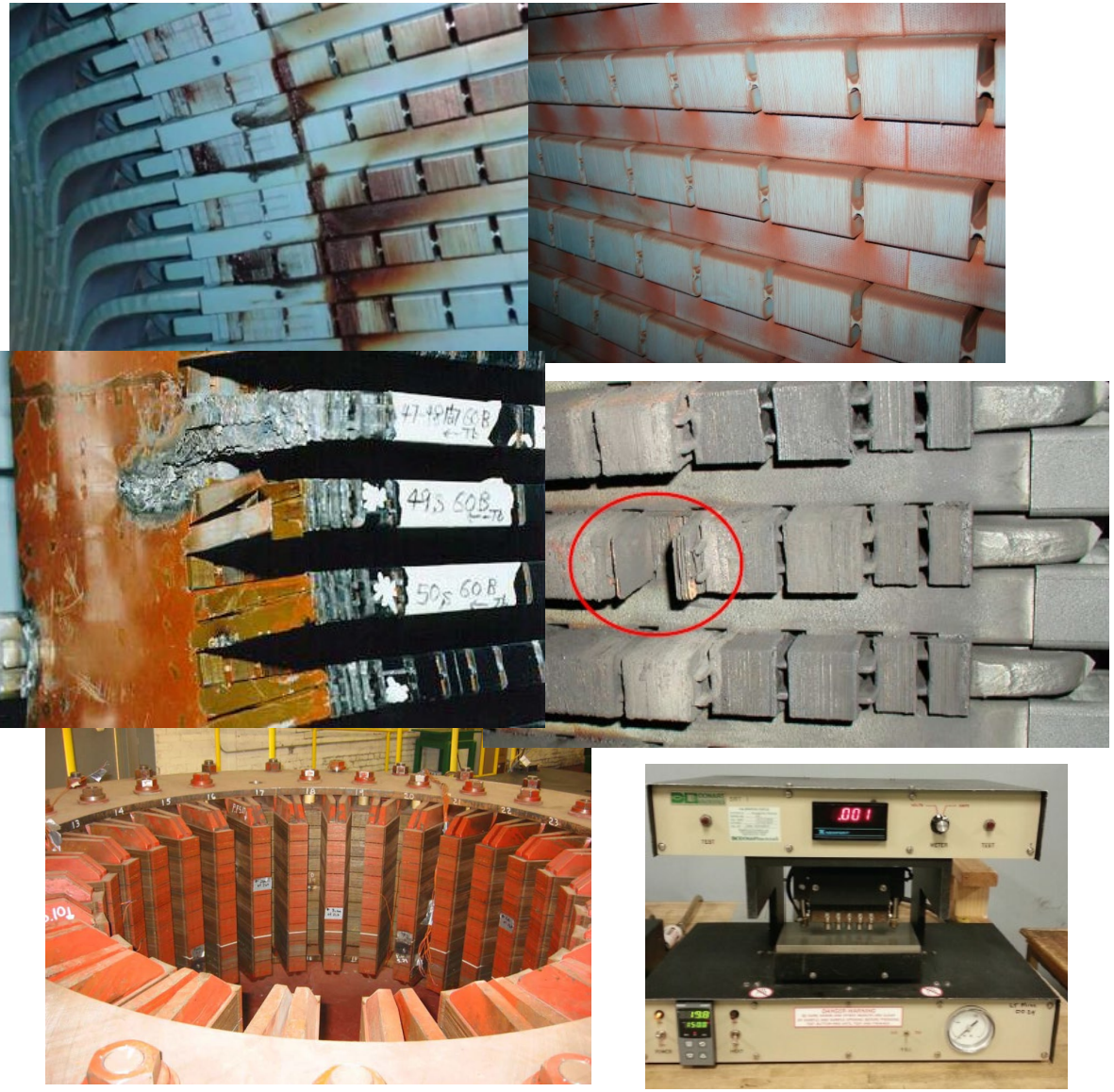
- How long will my generator stator core last? 30 years? 40? 60? 80?
- Should I restack the core on the 2nd rewind?
- Is core life influenced by the design? By the manufacturer?
- Photos on the right include generator core failures and damage as well as some core lamination testing methods.
- These are important questions the industry is facing.
- This research will focus on the industry information available on stator core life, including OE, surveys, and current testing, but will also research new ways to predict remaining life.

Member Benefits

- The research may provide methods to better evaluate remaining useful life for stator cores. Initially, a roadmap will be formulated to plan for testing and/or investigation.

Deliverable Format

- Technical Update, include definition of testing/lab experiments
- Published by Year End 2026

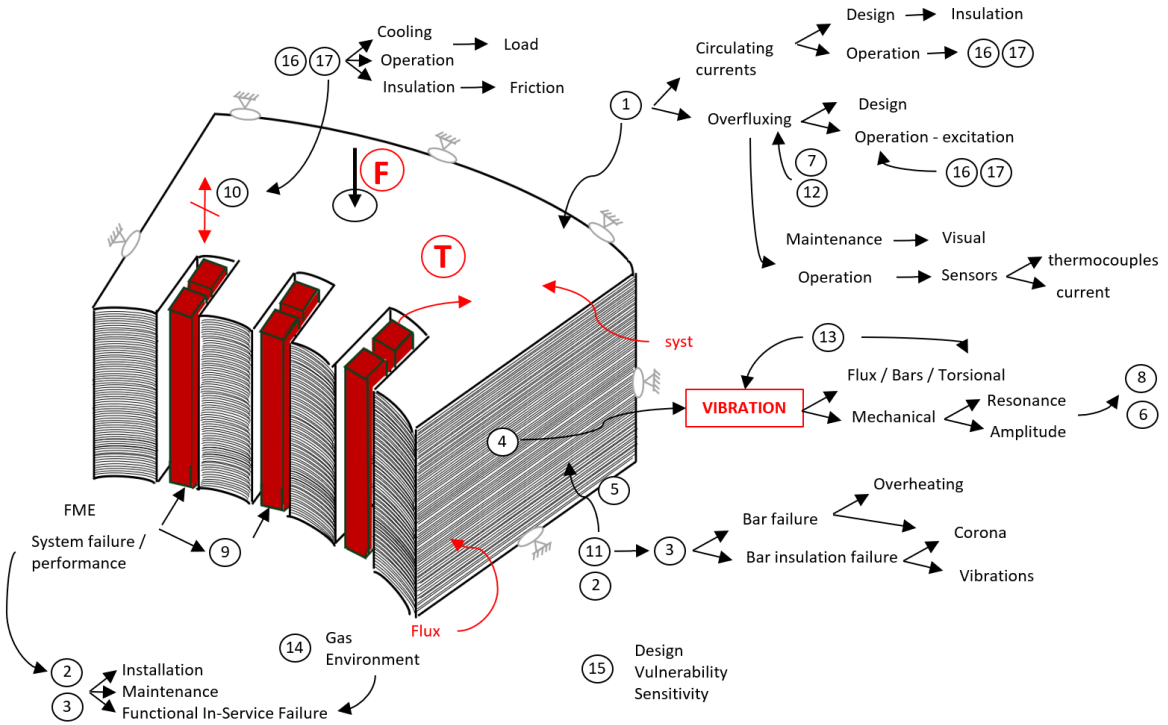


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Generator Core Remaining Useful Life

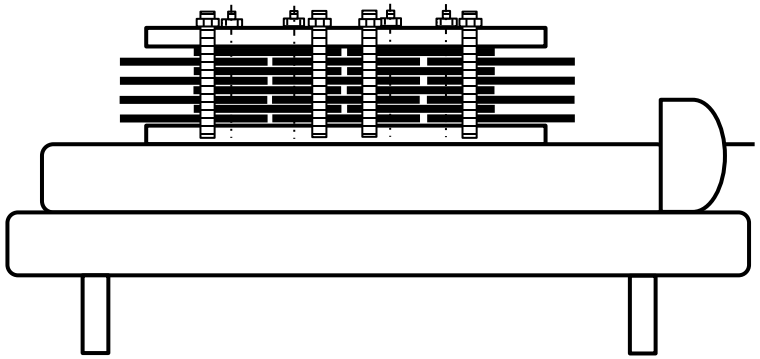
Phase I – Develop a Roadmap

- Describe the industry's understanding of damage mechanisms and life management approaches
- Apply FMEA techniques to inform degradation risk and test setup/loads



Phase II – Conduct Experimental Testing and Assess Findings

- Design a mock core assembly and test plan to accelerate the degradations that can be observed during operation
- Assess test data for actionable insights and opportunities to refine future testing



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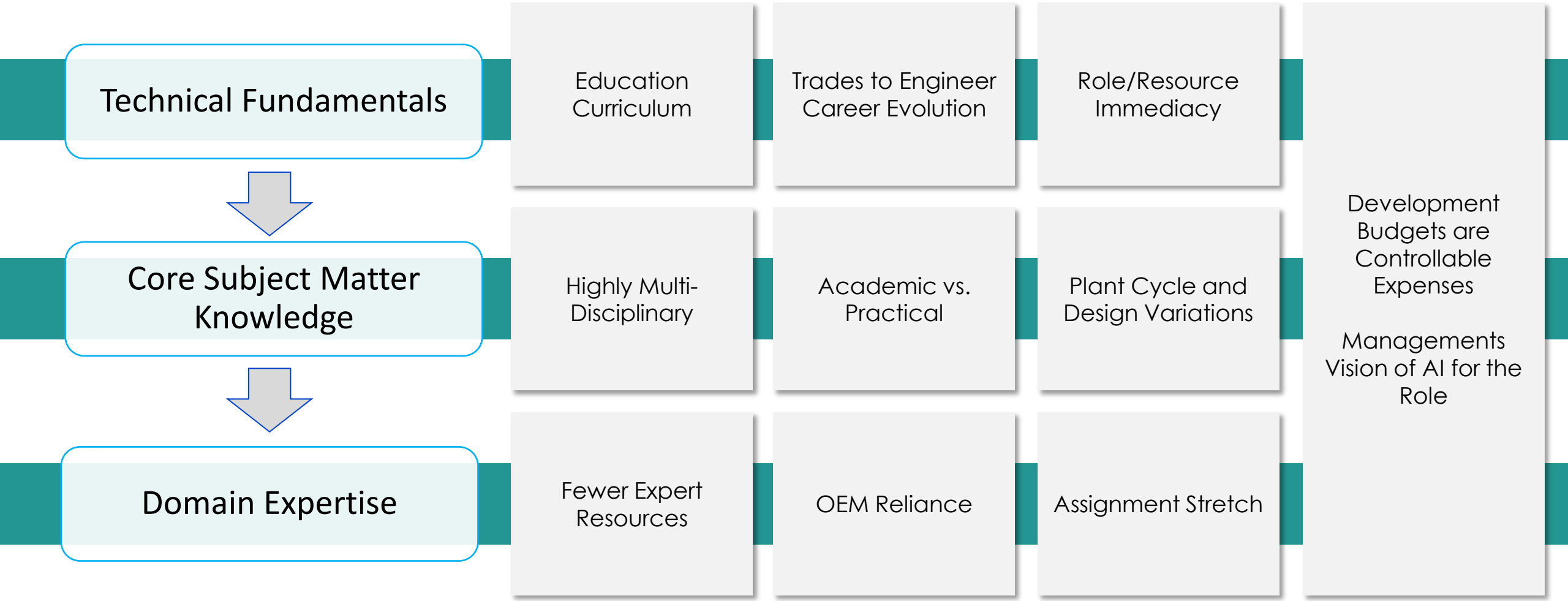
The future…?

Behavioral studies suggest learning by discussion creates 45% higher knowledge retention over reading

Interacting with research through large language models (LLM) instead of reading reports

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Engineer Role Development Challenges



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Enhanced Information Resources

Annual Research Results















TGUG

Turbine Generator Users Group Winter 2026

January 12-16, 2026
Tampa, FL (in-person only)

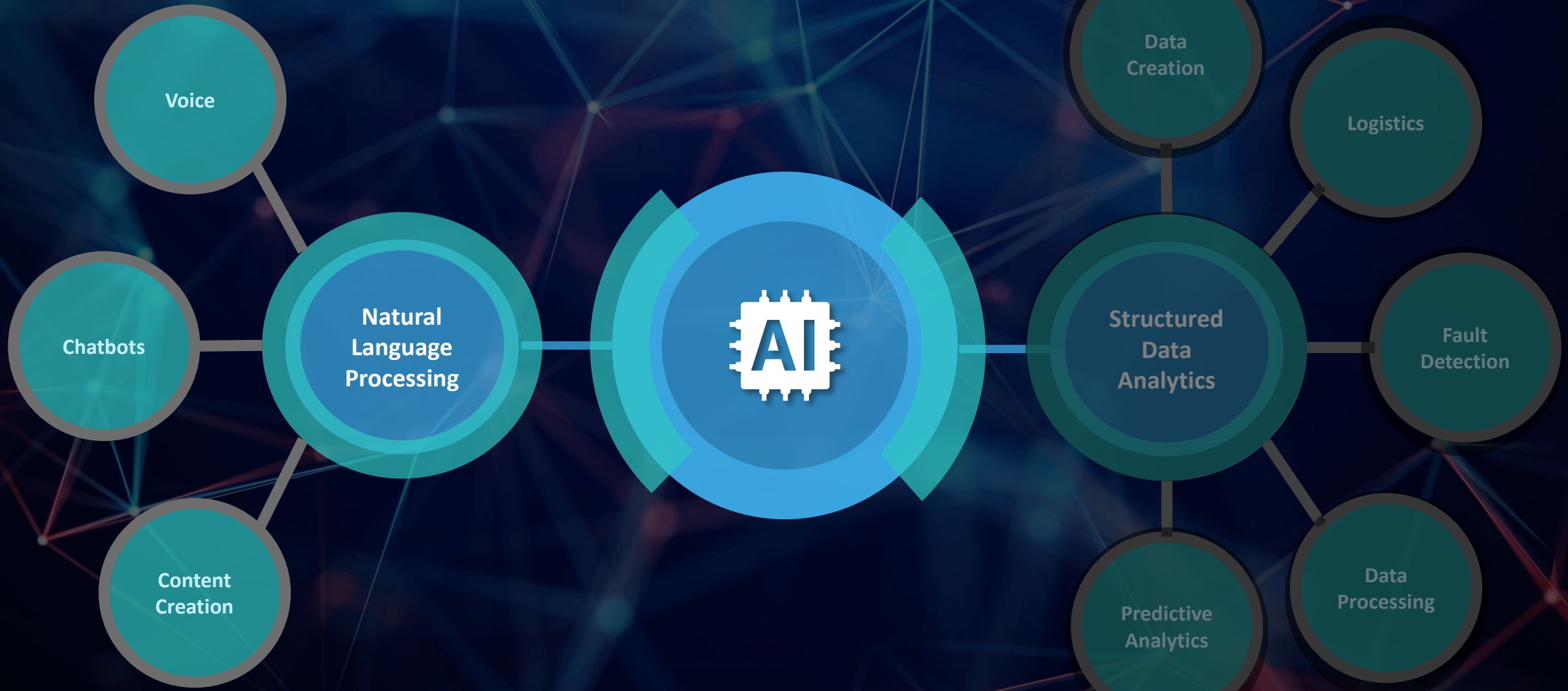
Turbine Generator Users Group Summer 2026

August 10-14, 2026
Kansas City, MO
(virtual option available)

How do we effectively leverage decades of research and insights to inform engineering resources?

Developing Engineers

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Chatbots Serving On-Demand Development with Discussion?

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Leveraging Artificial Intelligence

Industry Perspective

With a shortage of skilled engineers and operators, LLMs are helping bridge the gap by:

- *Acting as virtual assistants for plant operators, answering technical questions, and guiding troubleshooting.*
- *Providing training simulations and interactive manuals that adapt to the user's skill level.*
- *Translating complex technical documentation into more accessible formats.*

EPRI Efforts

EPRI (Electric Power Research Institute) is playing a leading role in advancing AI and large language model (LLM) applications in the power generation and utility sectors through its Open Power AI Consortium, launched in March 2025.

Developing improved LLM tools to leverage published research

Program Research Questions

How can we reduce response error, hallucinations and out of context responses?

What is the most effective information structure?

How do we manage legacy information that may be out of date?

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Should I Automatically Trip my Generator if a Ground Fault is Detected?

Copilot — FAIR

Whether you should **automatically trip your generator when a ground fault is detected** depends on several factors, including the **type of generator**, **application**, **safety requirements**, and **regulatory standards**. Here's a breakdown to help you decide:

✅ Reasons to Automatically Trip the Generator

1. **Safety**: Ground faults can pose serious risks, including fire, electrocution, or equipment damage. Tripping the generator immediately can prevent escalation.
2. **Protection of Equipment**: Sensitive electronics and generator components can be damaged by sustained faults.
3. **Compliance**: Many industrial and commercial installations are required by **NEC (National Electrical Code)** or **NFPA 70E** to trip on ground faults.
4. **Unattended Operation**: If the generator operates without supervision (e.g., backup power systems), automatic tripping ensures faults are addressed promptly.

❌ Reasons *Not* to Automatically Trip

1. **Critical Loads**: In hospitals, data centers, or emergency systems, maintaining power might be more important than immediate shutdown. In such cases, **alarm-only** or **delayed trip** strategies may be used.
2. **Fault Tolerance**: Some systems are designed to tolerate minor ground faults temporarily while alerting operators.
3. **Selective Coordination**: Tripping the generator might not be ideal if downstream breakers can isolate the fault more precisely.

Claude — NOT RECOMMENDED

Yes, you should definitely have your generator automatically trip (shut down) when a ground fault is detected. Here's why this is critical:

Safety Reasons:

- Ground faults can indicate damaged wiring, wet conditions, or equipment failure that could cause electrocution
- They create paths for electricity to flow through unintended routes, including potentially through people
- Automatic tripping prevents continued operation under dangerous conditions

Code Requirements:

- Most electrical codes require ground fault protection on generators, especially portable ones
- OSHA regulations mandate GFCI protection for construction sites and many workplace applications
- Many jurisdictions require GFCI protection for generators used in temporary installations

How It Should Work:

- Install a GFCI breaker or outlet on your generator
- The system should trip within milliseconds (typically 4-6 milliseconds) when it detects current imbalance as small as 5 milliamps
- After tripping, the system should remain off until manually reset after the fault is cleared

Practical Implementation:

- Many modern generators come with built-in GFCI protection
- For older generators, you can add GFCI outlets or breakers
- Consider having both GFCI protection at the generator and at individual outlets for maximum safety

The slight inconvenience of occasional nuisance trips is far outweighed by the protection against potentially fatal electrical shock. Never bypass or disable ground fault protection - instead, investigate and fix the underlying cause of any ground faults.

Grok — FAIR

Whether to automatically trip a generator upon detecting a ground fault depends on safety, operational requirements, and the specific application of the generator. Here's a concise breakdown to help you decide:

Reasons to Automatically Trip on Ground Fault

1. **Safety**: Ground faults can cause electrical shocks, fires, or equipment damage. Tripping the generator immediately minimizes these risks, protecting personnel and infrastructure.
2. **Equipment Protection**: A ground fault indicates a potential insulation failure or wiring issue. Tripping prevents further damage to the generator or connected loads.
3. **Code Compliance**: Electrical codes (e.g., NEC in the U.S.) often require ground fault protection for certain generator installations, especially in critical systems like hospitals or data centers, to ensure safety and reliability.
4. **System Stability**: In some setups, a ground fault could destabilize the electrical system, causing voltage fluctuations or cascading failures. Automatic tripping isolates the fault quickly.

Reasons to Avoid Automatic Tripping

1. **Critical Loads**: If the generator powers critical systems (e.g., life-support equipment, emergency lighting, or data centers), an automatic trip could disrupt operations, leading to significant consequences. In such cases, alarming the fault (without tripping) may be preferred to allow manual intervention.
2. **Fault Tolerance**: Some systems are designed to tolerate minor ground faults temporarily, allowing operators to investigate and address the issue without immediate shutdown.
3. **Nuisance Tripping**: In environments with frequent electrical noise or transient faults (e.g., industrial settings), automatic tripping could lead to unnecessary shutdowns, reducing uptime. Adjustable ground fault settings or delays can mitigate this.
4. **System Design**: In some configurations, like ungrounded or high-impedance grounded systems, ground faults may not pose an immediate danger, and tripping might not be required unless a second fault occurs.

Think Harder

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Enhanced Information Resources

Annual Research Results















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How do we effectively leverage decades of research and insights to inform engineering resources?

Developing Engineers

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Enhanced Information Resources

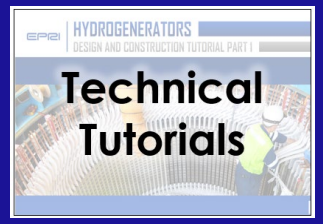
Annual Research Results



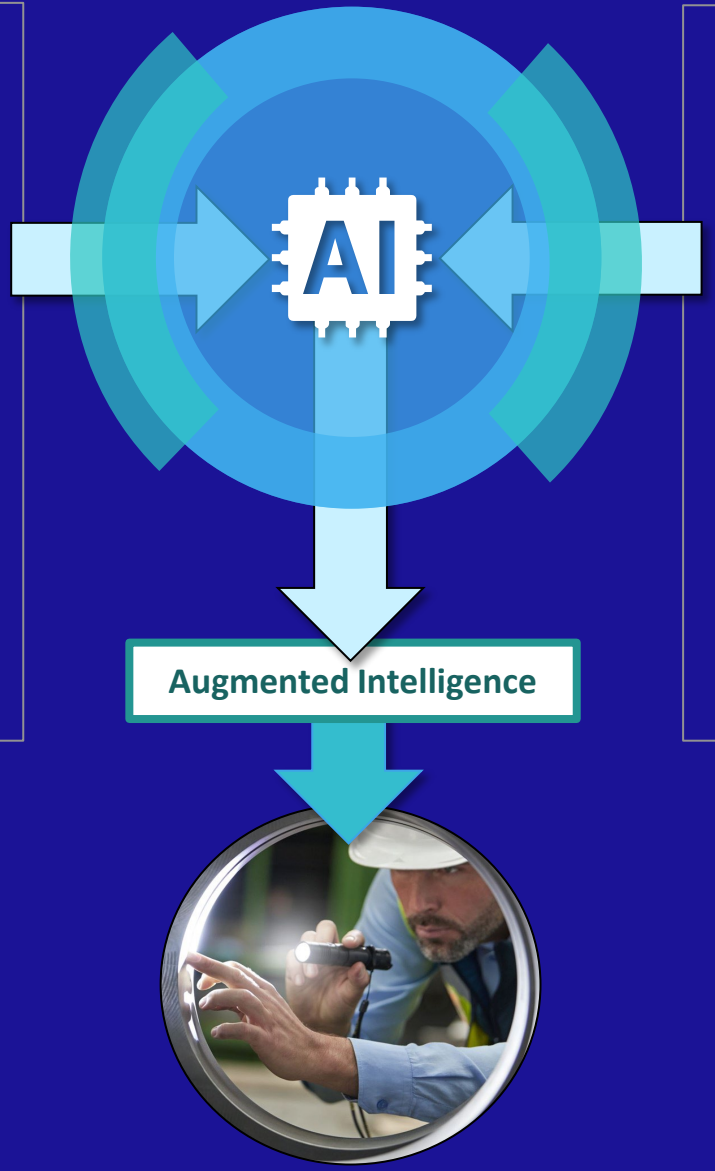












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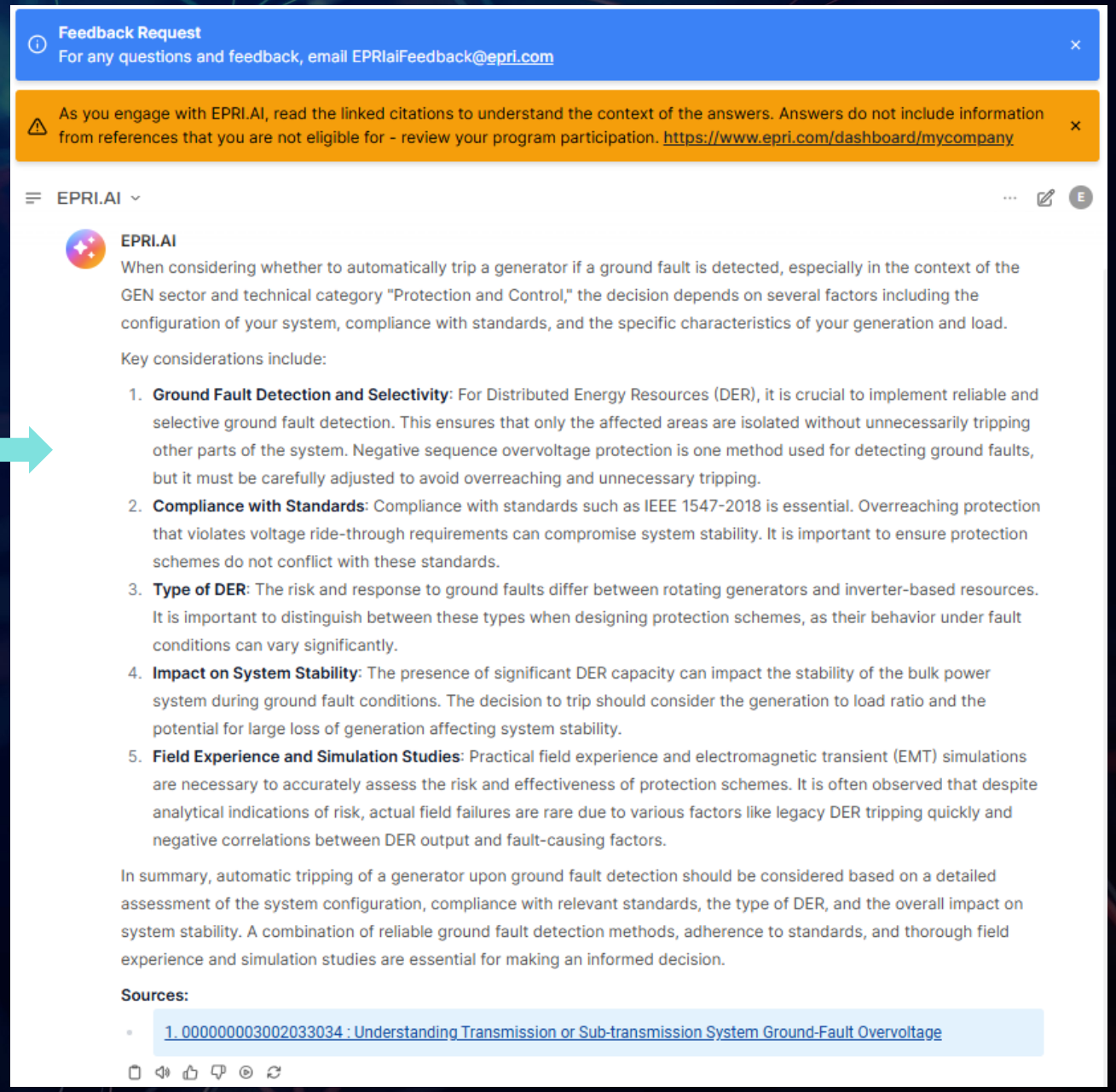
Truth is…

The answer requires nuance and understanding of equipment, operation, and damage indication.

Snapshot from EPRI.AI tool.

A different and more detailed perspective…

However, the results shown are focused on Energy Delivery perspective, and not that of the Generator Program…improving and learning.



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Enhanced Information Resources

2025

TGUG WIKI

ST&G OUTAGE *Guidelines* WIKI

2026 and Beyond…

- Build out ST&G Outage Guidelines WIKI
- Risk Management Site/Wiki
- Anonymized Member Assist Information Summaries
- Webcast Audio Information Transcripts
- Forum Information Summaries (re: TEN, IGTC)

- PMBD Update ???
- OPEX Database ???

Anything else to consider?

How do we effectively leverage decades of research and insights to inform engineering resources?

Developing Engineers

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TGUG Data Management

Objective

- Improve accessibility of Turbine Generator Users Group (TGUG) meeting content
- Create hierarchy and structure to allow facilitate event navigation and search

Research Value

- Current methods to access legacy meeting materials is cumbersome and flawed
- Search capability is limited, cannot effectively search underlying content

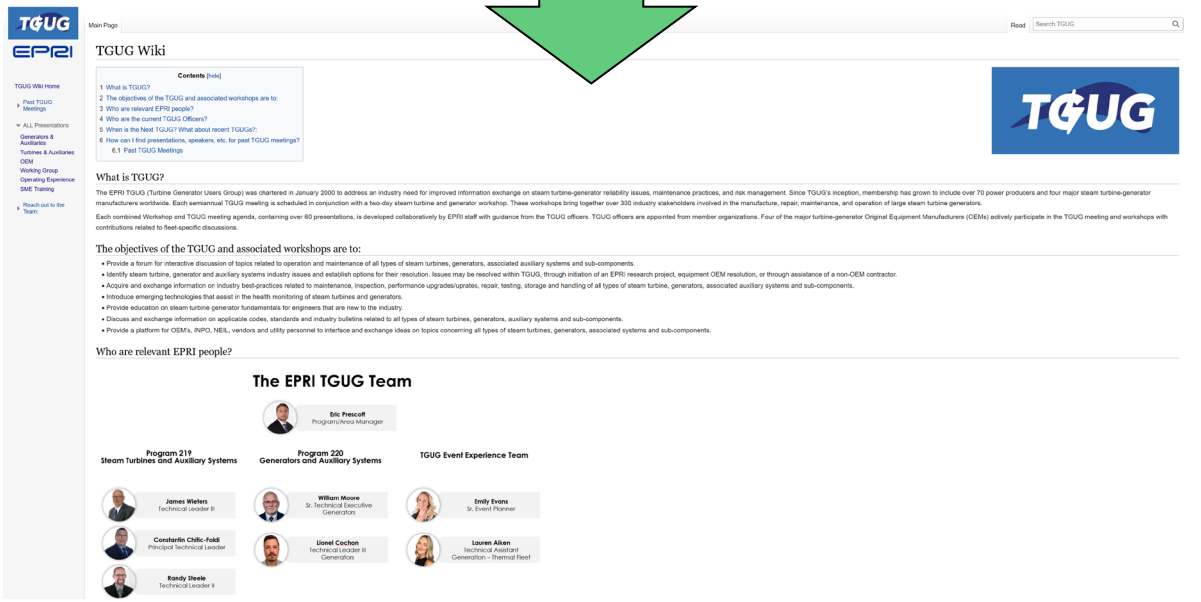
Project Approach

- Build TGUG Wiki site to capture and store TGUG content
- Enable functional search (including embedded files) of historical content
- Possibility exists to expand functionality of site
  - Add forum for engagement
  - Development of future meetings

TGUG Summer August 11-15, 2025 Hyatt Regency Minneapolis, Minneapolis, MN

	Monday	Tuesday		Wednesday	Thursday	Friday
	8/11/25	8/12/25		8/13/25	8/14/25	8/15/25
7:00 Breakfast/Registration						
	Technical Sessions - Generator Track	Technical Sessions - Turbine Track	Technical Sessions - Generator Track	Technical Sessions - Turbine Track	OEM Day In person only	TGUG DAY - Member Experience	Subject Matter Expert Training
8:00						
	Stator Endwinding Bracing	Main Steam Valves - Operational Risk	AVR, CTs, PTs, Circuit Breakers	Special Repairs / Equipment Upgrades	Toshiba (1 hour) Generator Topics ~ 8:00 - 8:25; Bulletin Review ~ 8:25 - 8:35; Turbine Topics ~ 8:35 - 9:00	Roundtable Discussions	Topic: Generator Rotor Removal, Transit, Receipt, and Installation
10:00 Break							
	Case Histories - Generators	Steam Turbine Investigations	Case Histories: AVR & Bushings	STG Testing and Advanced NDE Technologies	Siemens Energy (2.5 hours) Generator Topics ~ 9:00 - 10:15; Buleltin Review ~ 10:15 - 10:45; Turbine Topics ~ 10:45 - 12:00	Roundtable Discussions	Steam Turbine and Generator Engineer and Operator Walkdown Best Practices Discussion
12:00 Lunch Break							
	Isolated Phase Bus	Steam Turbine Operation and Control System Tuning	Generator Stator Core Horizontal Restack Development and its Execution	Nuclear ST Challenges	Mitsubishi (1 hour) Generator Topics ~ 1:00 - 1:25; Bulletin Review ~ 1:25 - 1:35; Turbine Topics ~ 1:35 - 2:00	TGUG Tools	
2:30 Break							
	Generator Rotors	Steam Turbine Operation Challenges	Auxiliaries or GRID	Recent Outage Experience & Best Practices	GE Vernova (2.5 hours) Generator Topics ~ 2:00 - 3:15; Bulletin Review ~ 3:15 - 3:45; Turbine Topics ~ 3:45 - 5:00	Operating Experience	TRAVEL HOME
	TGUG Technology Fair 4:30-6:30 pm	TGUG Technology Fair 4:30-6:30 pm			Working Group 5:30 - 7:30 pm Topic: Development of New Engineers	Optional Offsite Tour 5:30 ~ 7:00 WEG Electric Machinery	

Open to the Public
OEMs and Funders
Funders Only



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Re-Platform Outage Guidelines

Objective

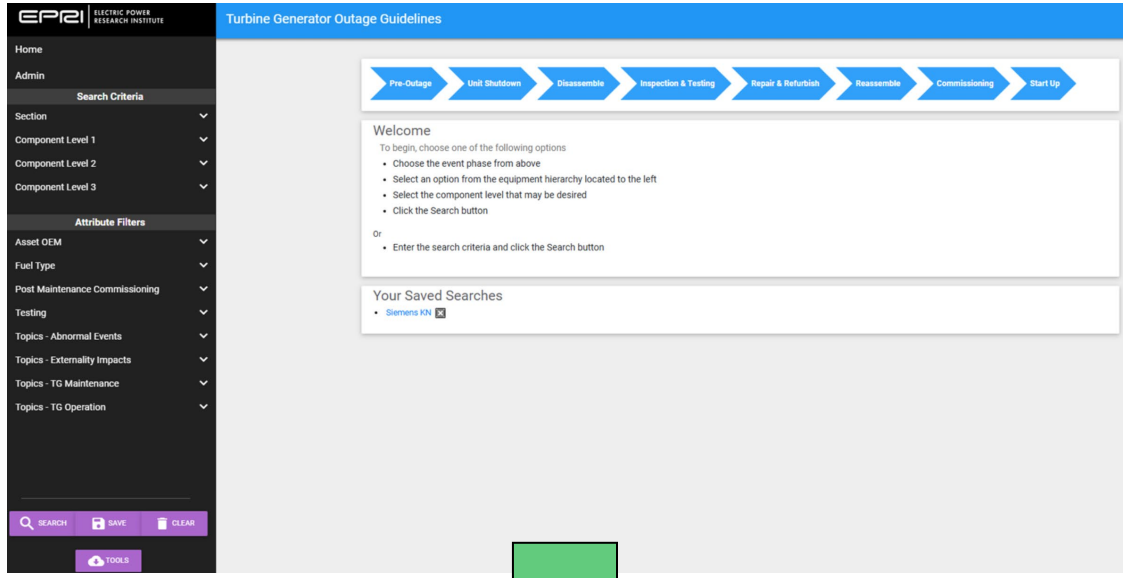
- Improve accessibility of Outage Guidelines
- Create hierarchy and structure to allow facilitate event navigation and search

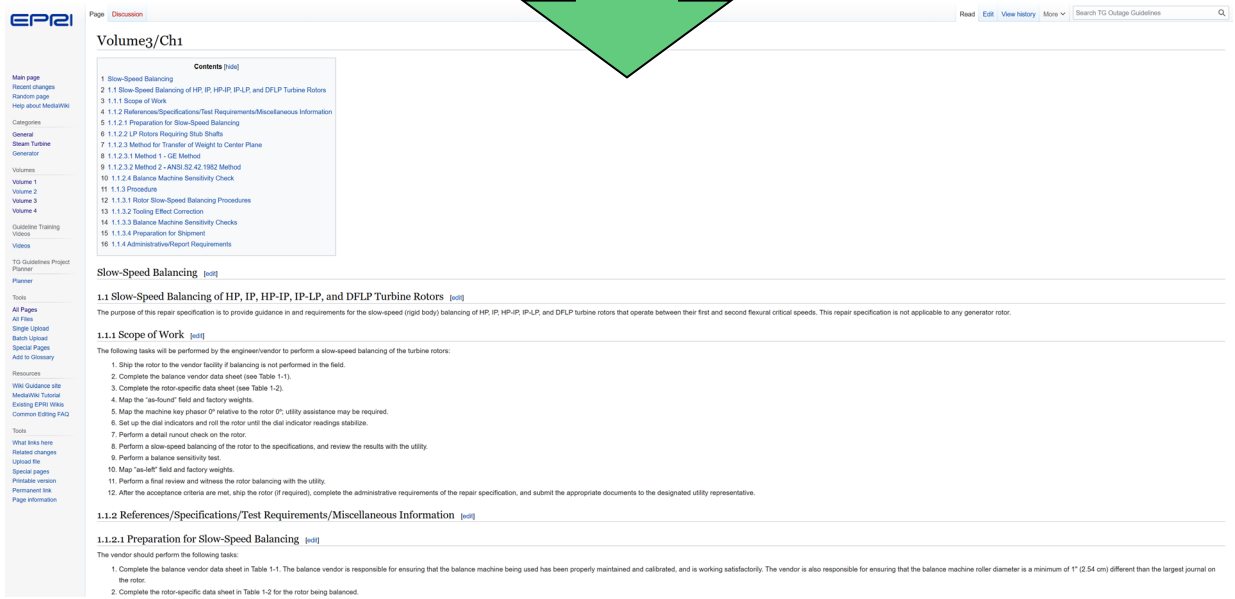
Research Value

- Current methods to access materials is cumbersome and flawed
- Search capability is limited, cannot easily access underlying content

Project Approach

- Build TG Outage Guidelines Wiki site to re-home .exe content
- Enable functional search (including embedded files) of historical content

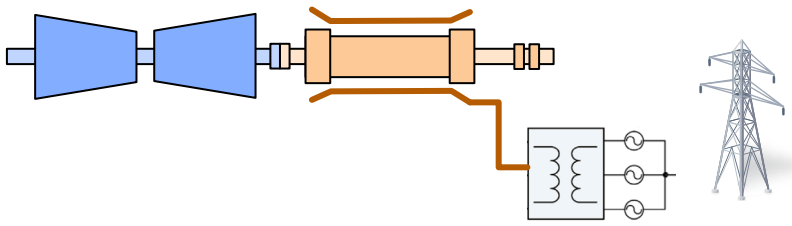




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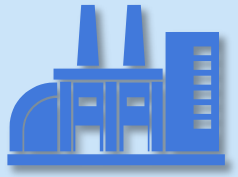
Emerging Energy Transition Impacts to Synchronous Dispatchable Generation

Turbine-Generator Systems



Affecting hydropower, steam turbine, gas turbine synchronous generation in Fossil, Nuclear and Renewable assets.

INDUSTRY DEMAND



EPRI 1011679 & 1013460 describes historical turbine-generator failures associated with electrical network system frequencies and industry sources.

VARIABLE GENERATION



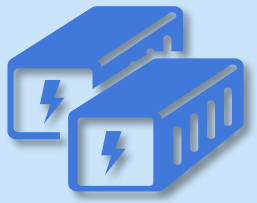
Known source of harmonic distortion (total, demand, and rated-current). See EPRI 3002020011.

Increased penetration has led to deeper investigation using lumped mass models. See EPRI 3002024877.

EPRI supplemental project 3002010532 identified increased system frequency content related to wind generation, increased excitation energy and modulated frequency.

Consideration for additional testing and enhanced model approaches .

DISPATCHABLE STORAGE

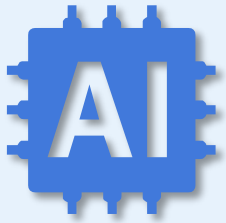


Energy storage systems are a key technology to leverage high-capacity generation in times of low consumer demand.

Scaling of these technologies represent new risks in the energy system.

Conventional battery systems charge (rectifier) and discharge (inverter) functions represent a risk similar to historical industry demand and variable generation (IBR) challenges.

DATACENTER DEMAND



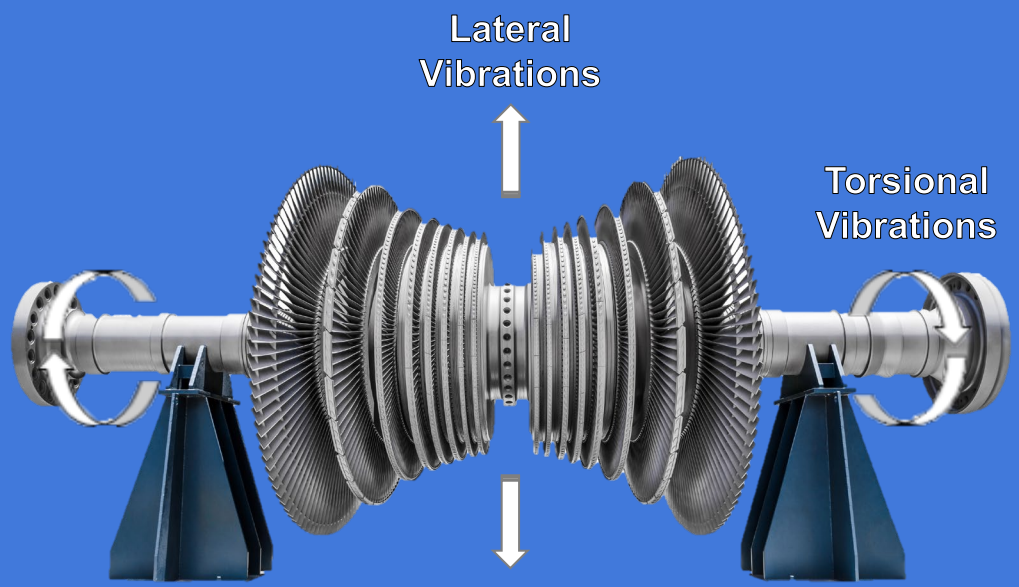
"Data Centers Are Booming in Texas. What Does That Mean for the Grid?" – *The Associated Press, Jan 24, 2025*

"Data center growth puts unprecedented pressure on power grids" – *NETWORKWORLD, Jan 24, 2025*

The forecasted demand due to data centers represents a clear supply challenge (MW), but are the system challenges completely understood?

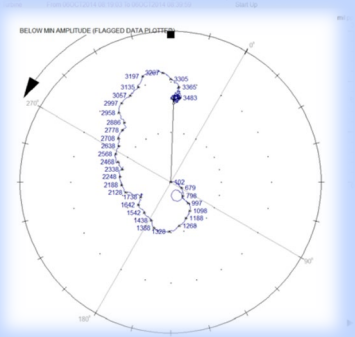
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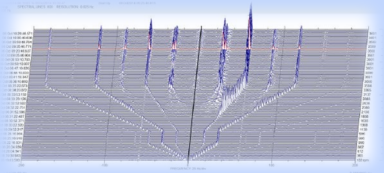
Differentiating Shaft Vibrations



Lateral Vibrations

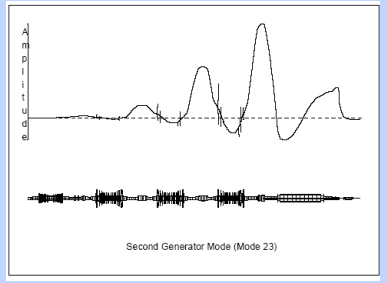
- Common problem
- Caused by imbalance, misalignment, etc.
- Physically Detectable (feel and hear)
- Damped by oil film, predictable at the design stage
- Installed Vibration Instrumentation and available trip logic

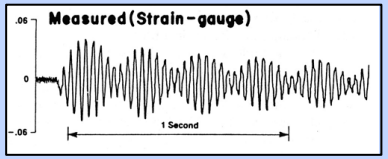




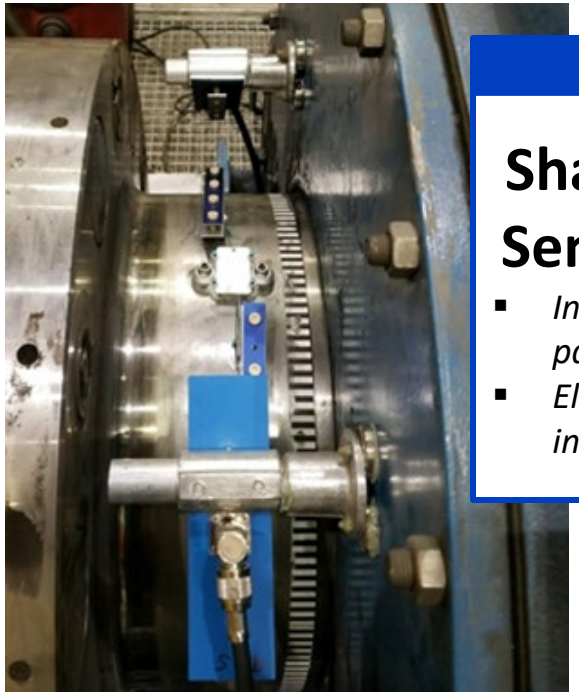
Torsional Vibrations

- Historically un-common problem
- Influenced by generator/grid harmonics/external events
- No observable symptoms
- Very little damping; also, damping mechanism and loads complex, difficult to predict at the design stage
- No Vibration Instrumentation (Standard Arrangement), only generator protection





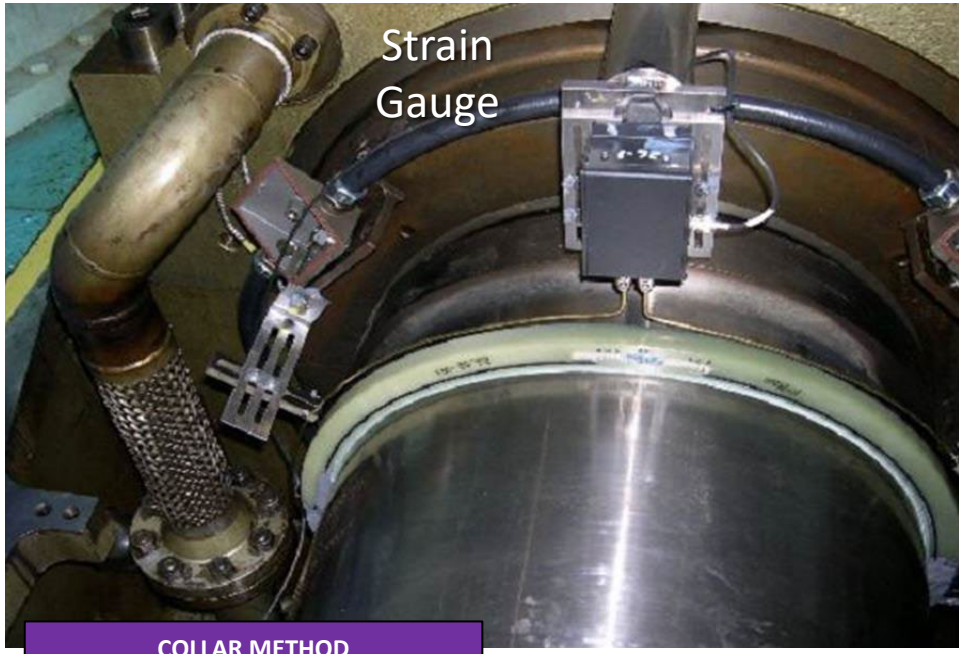
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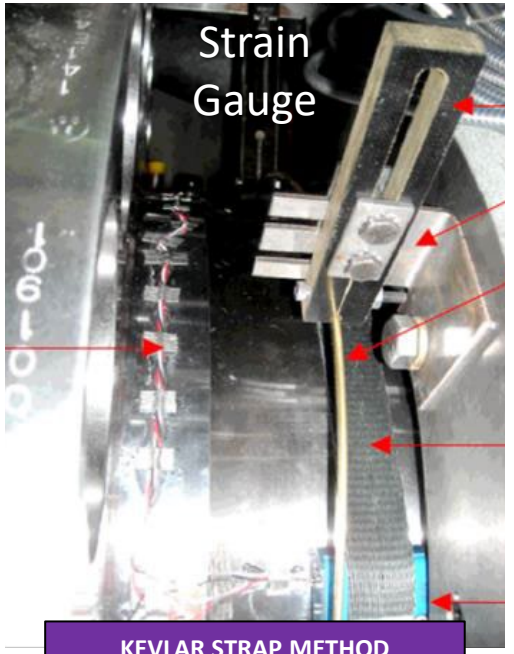
EPRI TDMS

Shaft-mounted Sensor Package

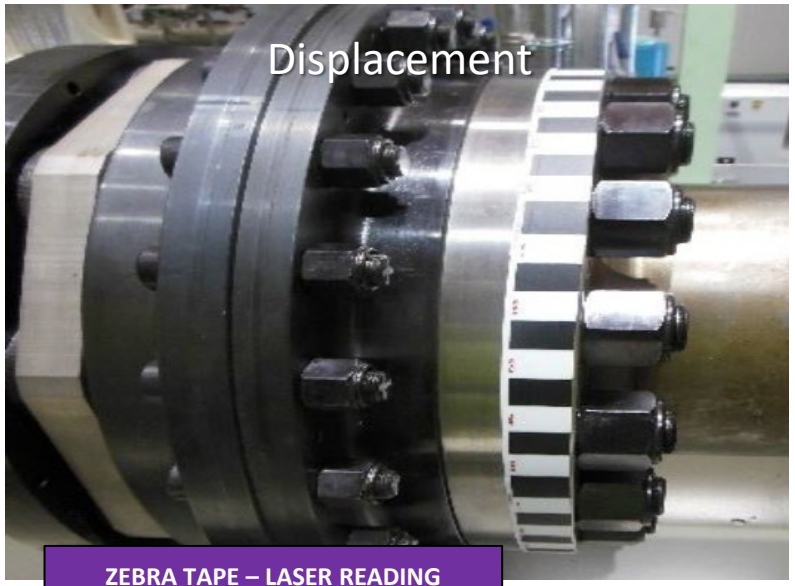
- *Increased measurement parameters*
- *Eliminates machine induce noise*



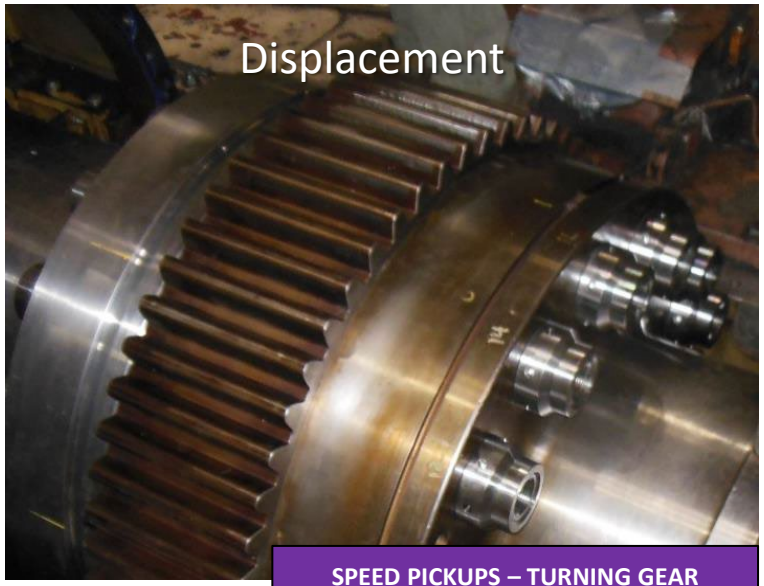
COLLAR METHOD



KEVLAR STRAP METHOD



ZEBRA TAPE – LASER READING



SPEED PICKUPS – TURNING GEAR



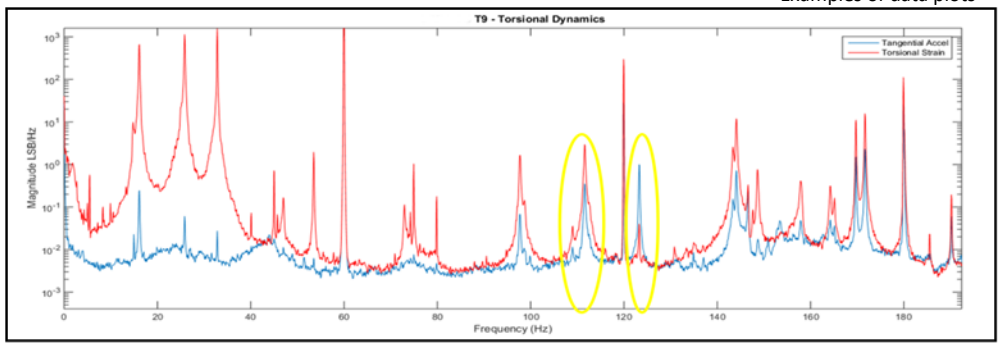
SPEED PICKUPS - SPEEDWHEEL

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Torsional Testing Application

- Torsional models are a reliable sources of information on the torsional mode shapes, however mode frequencies will have some uncertainty due to the modelling assumptions
- The measured frequencies are compared with the predicted torsional mode shapes and calculated frequencies – focused on verification of T-G system modes near 2X frequency
- The test instrumentation should be able to detect all mode frequencies up to 150Hz
- STG shaft torsional modes are ***system*** properties – all shaft sections are involved in each mode
- Desired torsional test attributes:
  - test instrumentation can measure both shaft torsional strain and motion
  - very high frequency resolution to discriminate close modes, or mode frequencies very close to shaft speed harmonics
  - high signal-to-noise (SNR) so low amplitude mode indications are not hidden in noise

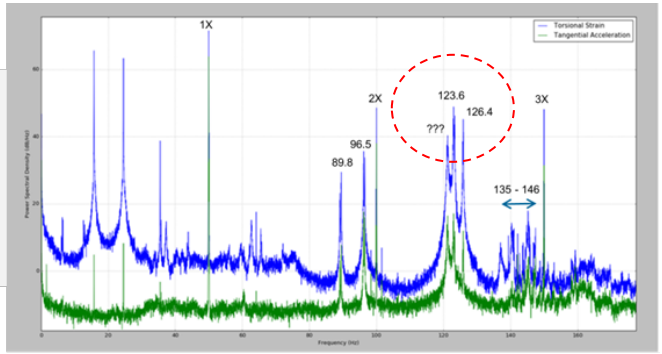
Examples of data plots



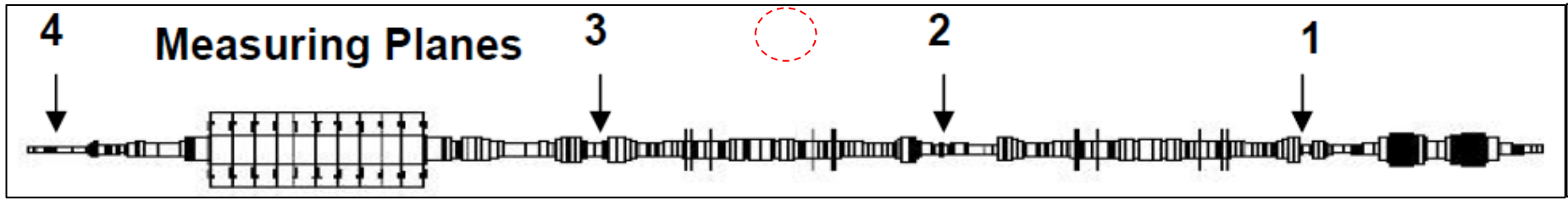
Peak amplitudes for strain and acceleration indicate relative participation of motion and strain energy

Example of TDMS sensitivity: 50Hz unit showing shaft frequencies associated with LSB modes

Note: log scale



FFT zoom capability enables very high frequency resolution when needed (ex. near twice grid frequency)



Depending the torsional test results **analytical model re-calibration** and **equipment detuning** might be required

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Managing Turbine-Generator Equipment Reliability Risks Associated with Grid Interactions

- Increased Industrialization
- Increased Renewable Penetration
- Large Scale BESS Deployment
- Datacenter Demand Forecast



TDMS
TURBINE DYNAMICS MONITORING SYSTEM

EPRI sponsored development of shaft mounted sensor package and telemetry system to measure shaft strain and acceleration with increased precision and reduced signal-to-noise ratio.

Proactive response to emerging equipment reliability risks applying Torsional Monitoring

- Increased grid harmonic content impacting vibratory stresses on synchronous machinery
- Aging systems with degradations detectable by torsional characteristics
- Demonstrated in Nuclear, Hydro, Fossil, and Synchronous Condenser applications for design verification and troubleshooting of complex reliability challenges

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Lunch

Summer TGUG 2025 Recap

Program 219: Steam Turbines & Auxiliary Systems
Program 220: Generators & Auxiliary Systems

Randall Steele
Senior Technical Leader

2025 WANO Steam Turbine & Generator Workshop
Shanghai, China
3-6 November 2025

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2026 Turbine Generator Users Group Meetings

Winter TGUG sessions will be in-person only!

Saddlebrook Tampa Bay
Wesley Chapel, FL
January 12-16, 2026

Traditional 4½ day agenda with workshop, OEM session, and user's group

Register here: https://cvent.me/Kd7Z12
Book hotel here: Saddlebrook Resort

Summer TGUG sessions will be hybrid (virtual + limited in-person)

Kansas City Sheraton
Kansas City, MO
August 10-14, 2025

Format and content under development

Registration opens Spring 2026!

Send questions, comments, suggestions to asktgug@epri.com

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Summer 2025 TGUG Week at a Glance

TGUG Summer August 11-15, 2025 Hyatt Regency Minneapolis, Minneapolis, MN

Monday 1/12/26		Tuesday 1/13/26		Wednesday 1/14/26	Thursday 1/15/26	Friday 1/16/26
7:00 Breakfast/Registration →						
Technical Sessions - Generator Track	Technical Sessions - Turbine Track	Technical Sessions - Generator Track	Technical Sessions - Turbine Track	OEM Day In person only	TGUG DAY - Member Experience	Subject Matter Expert Training
8:00 →						
Stator Endwinding Bracing	Main Steam Valves - Operational Risk	AVR, CTs, PTs, Circuit Breakers	Special Repairs / Equipment Upgrades	Toshiba (1 hour) Generator Topics ~ 8:00 - 8:25; Bulletin Review ~ 8:25 - 8:35; Turbine Topics ~ 8:35 - 9:00	Roundtable Discussions	Topic: Generator Rotor Removal, Transit, Receipt, and Installation
10:00 Break →						
Case Histories - Generators	Steam Turbine Investigations	Case Histories: AVR & Bushings	STG Testing and Advanced NDE Technologies	Siemens Energy Generator Topics ~ 9:00 - 10:15; Bulletin Review ~ 10:15 - 10:45; Turbine Topics ~ 10:45 - 12:00	Roundtable Discussions	Steam Turbine and Generator Engineer and Operator Walkdown Best Practices Discussion
12:00 Lunch Break →						TRAVEL HOME
Isolated Phase Bus	Steam Turbine Operation and Control System Tuning	Generator Stator Core Horizontal Restack Development and its Execution	Nuclear ST Challenges	Mitsubishi (1 hour) Generator Topics ~ 1:00 - 1:25; Bulletin Review ~ 1:25 - 1:35; Turbine Topics ~ 1:35 - 2:00	TGUG Tools	
2:30 Break →						
Generator Rotors	Steam Turbine Operation Challenges	Auxiliaries or GRID	Recent Outage Experience & Best Practices	GE Vernova (2.5 hours) Generator Topics ~ 2:00 - 3:15; Bulletin Review ~ 3:15 - 3:45; Turbine Topics ~ 3:45 - 5:00	Operating Experience	
TGUG Technology Fair 4:30 - 6:30 pm		TGUG Technology Fair 4:30 - 6:30 pm		Working Group 5:30 - 7:30 pm Topic: Development of New Engineers	Optional Offsite Tour 5:30 - 7:30 WEG Electric Machinery	

Open to the Public
OEMs and Funders
Funders Only

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2025 Webcast Schedule – Programs 219 and 220

Program	Topic	EPRI Lead	Date (10:00am EDT U.S. unless noted)
219	Piping Support Inspection & Maintenance	Sambor	**November 11**
220	Residual Magnetism	Cochon	**November 13**
219	2025 Year End Review	Prescott	**December 9**
220	2025 Year End Review	Prescott	**December 11**

We welcome all suggestions for webcast technical topics. Contact Eric Prescott to submit ideas…



Program Area Lead
Program Manager

Eric Prescott
eprescott@epri.com

VIEW ALL PAST PROGRAM RECORDINGS AND CONTENT HERE:

Program 220: Generators and Auxiliary Systems | Events

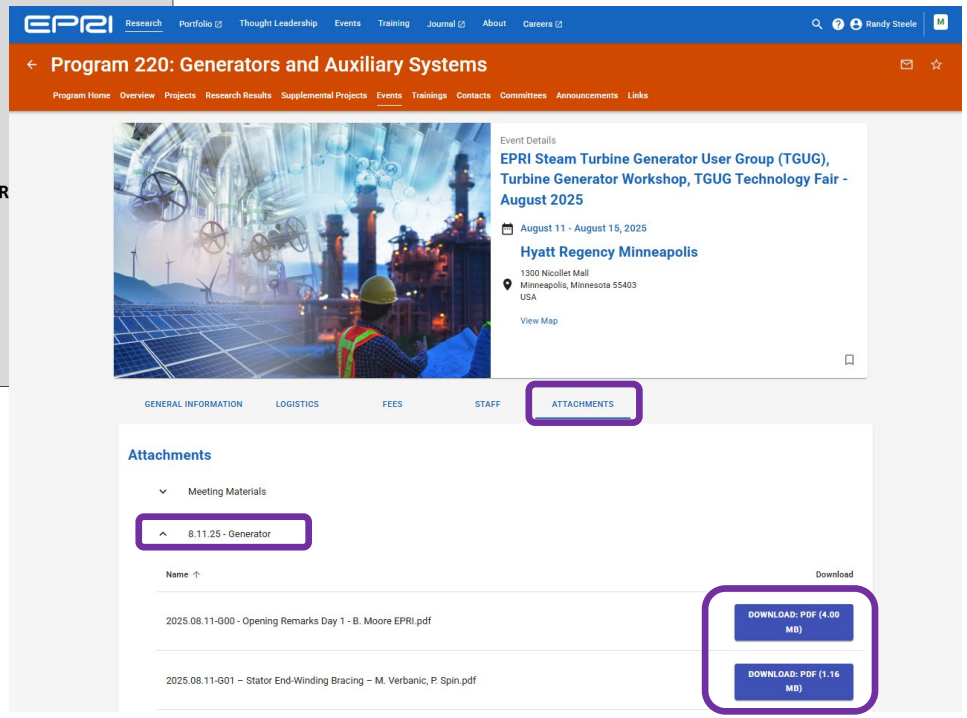
Program 219: Steam Turbines and Auxiliary Systems | Events

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Summer 2025 Event Schedule

TGUG Summer August 11-15, 2025 Hyatt Regency Minneapolis, Minneapolis, MN

Monday		Tuesday		Wednesday	Thursday	Friday
1/12/26		1/13/26		1/14/26	1/15/26	1/16/26
7:00 Breakfast/Registration						
Technical Sessions - Generator Track	Technical Sessions - Turbine Track	Technical Sessions - Generator Track	Technical Sessions - Turbine Track	OEM Day In person only	TGUG DAY - Member Experience	Subject Matter Expert Training
8:00						
Stator Endwinding Bracing	Main Steam Valves - Operational Risk	AVR, CTs, PTs, Circuit Breakers	Special Repairs / Equipment Upgrades	Toshiba (1 hour) Generator Topics ~ 8:00 - 8:25; Bulletin Review ~ 8:25 - 8:35; Turbine Topics ~ 8:35 - 9:00	Roundtable Discussions	Topic: Generator Rotor Removal, Transit, Receipt, and Installation
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12:00 Lunch Break						
Isolated Phase Bus	Steam Turbine Operation and Control System Tuning	Generator Stator Core Horizontal Restack Development and its Execution	Nuclear ST Challenges	Mitsubishi (1 hour) Generator Topics ~ 1:00 - 1:25; Bulletin Review ~ 1:25 - 1:35; Turbine Topics ~ 1:35 - 2:00	TGUG Tools	TR
2:30 Break						
Generator Rotors	Steam Turbine Operation Challenges	Auxiliaries or GRID	Recent Outage Experience & Best Practices	GE Vernova (2.5 hours) Generator Topics ~ 2:00 - 3:15; Bulletin Review ~ 3:15 - 3:45; Turbine Topics ~ 3:45 - 5:00	Operating Experience	
TGUG Technology Fair 4:30 - 6:30 pm		TGUG Technology Fair 4:30 - 6:30 pm		Working Group 5:30 - 7:30 pm Topic: Development of New Engineers	Optional Offsite Tour 5:30 - 7:30 WEG Electric Machinery	



[Summer 2025 TGUG | Event Details (epri.com)]

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TGUG Data Management

Objective

- Improve accessibility of Turbine Generator Users Group (TGUG) meeting content
- Create hierarchy and structure to allow facilitate event navigation and search

Research Value

- Current methods to access legacy meeting materials is cumbersome and flawed
- Search capability is limited, cannot effectively search underlying content

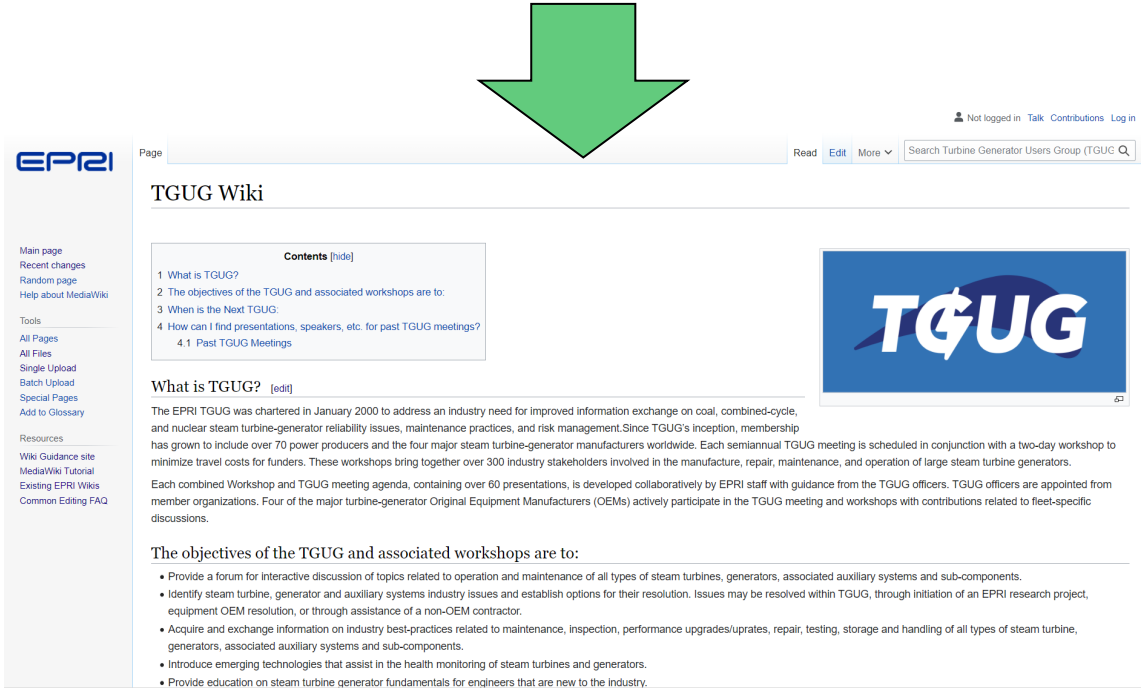
Project Approach

- Build TGUG website to capture and store TGUG content
- Enable functional search (including embedded files) of historical content
- Possibility exists to expand functionality of site
  - Add forum for engagement
  - Development of future meetings
  - Expand to program activities

tgug.epri.com

TGUG Winter January 13-17, 2025 Rosen Centre Hotel, Orlando, FL

	Monday	Tuesday		Wednesday	Thursday	Friday
	1/13/25	1/14/25		1/15/25	1/16/25	1/17/25
7:00	Breakfast/Registration					
	Technical Sessions - Generator Track	Technical Sessions - Turbine Track	Technical Sessions - Generator Track	Technical Sessions - Turbine Track	OEM Day	TGUG DAY - Member Experience	Subject Matter Expert Training
8:00						
	Generator Auxiliary Systems	Technical Tutorials	Inspection and Testing	Novel Steam Turbine Technologies and Maintenance Practices	Toshiba (1 hour) Generator Topics ~ 8:00 - 8:25; Bulletin Review ~ 8:25 - 8:35; Turbine Topics ~ 8:35 - 9:00	Roundtable Discussions	Offsite Tour(s) Siemens Energy Innovation Center Mitsubishi Power - Orlando Manufacturing Center
10:00	Break						
	Generator Rotors	EHC Fluid Analysis and System Maintenance	Inspection and Testing	LP Turbine Integrity Risk Management	Siemens Energy (2.5 hours) Generator Topics ~ 9:00 - 10:15; Buleltin Review ~ 10:15 - 10:45; Turbine Topics ~ 10:45 - 12:00	Roundtable Discussions	
12:00	Lunch Break						
	Generator Rotors	Steam Turbine Retrofits and Plant Conversions	Case Histories	Rotor Dynamics Issues	Mitsubishi (1 hour) Generator Topics ~ 1:00 - 1:25; Bulletin Review ~ 1:25 - 1:35; Turbine Topics ~ 1:35 - 2:00	Operating Experience	TRAVEL HOME
2:30	Break						
	Monitoring	Recent Outage Experience	Stator Winding / IsoPhase Bus / Bushing	Equipment Condition Assessment	GE Vernova (2.5 hours) Generator Topics ~ 2:00 - 3:15; Bulletin Review ~ 3:15 - 3:45; Turbine Topics ~ 3:45 - 5:00	Operating Experience	
	TGUG Technology Fair 4:30-6:30 pm	TGUG Technology Fair 4:30-6:30 pm			Working Group 5:30 - 7:30 pm Topic: Long Term Asset Management - Major Component Refurbishment-Replacement		



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Generator Workshop Presentations



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TGUG

Stator End-Winding Bracing

Michael Verbanic / Philipp Spin

2025 EPRI TGUG | August 2025



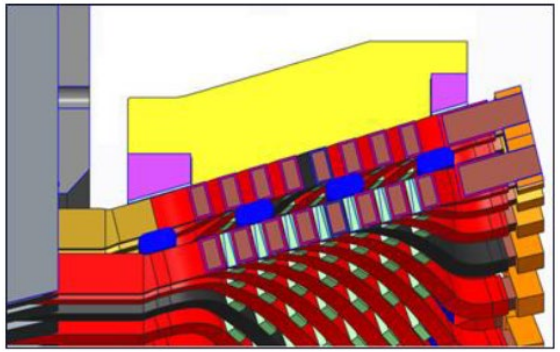
Siemens Energy is a trademark licensed by Siemens AG.

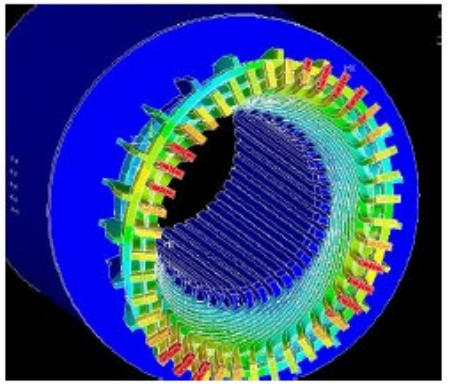
Confidential © Siemens Energy, 2025

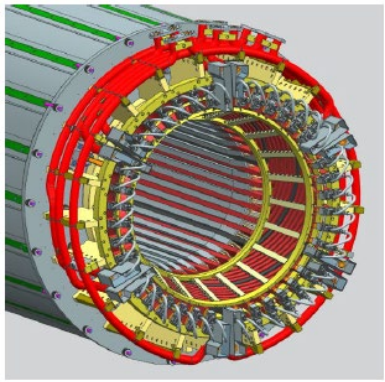
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Overview

- Overview of stator end-winding bracing design, verification, testing, and continuous improvement
- Key design parameters
  - Coil design
  - Cooling type
  - Core details
  - Insulation
  - Electrical connections



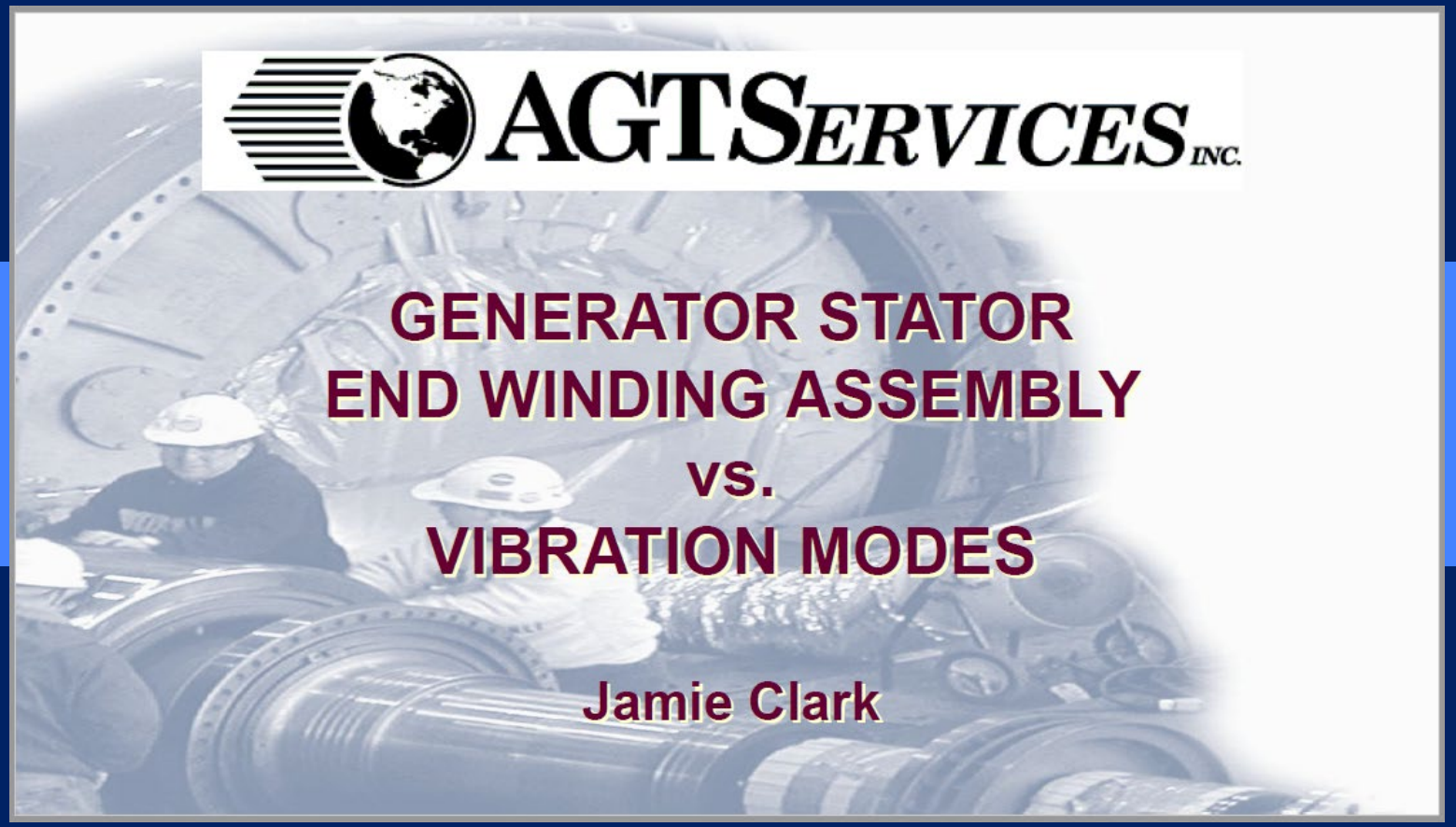




- Mechanical verification using FEA for strain, vibration, natural frequencies, and thermo-mechanical loading
- In-house testing includes bump tests, modal analysis, vibration monitoring, and strain gauges
- Fleet monitoring through online sensors, visual inspections, and trending to detect aging effects
- Continuous improvement via new materials, manufacturing methods, and enhanced calculation tools
- Evolutionary design development highlighted by Rigi-Flex technology and significant advances in 2000P/3000W models

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TCUG



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Overview

- Generator stator end windings have resonant frequencies typically +10%/-5% away from operating frequencies, resulting in relatively low vibration amplitudes.
- End windings function as an integrated system and should move together
- Tuning end windings is analogous to tuning a guitar: larger mass or longer overhang leads to lower resonant frequency (low pitch), while smaller mass or shorter overhang results in higher resonant frequency (high pitch).
- Connection types affect end winding behavior:
  - Strand-to-strand series connections
  - Cap-cap blocks
  - Nose rings
  - Surge rings/binding bands
- Early signs of movement can lead to mechanical failure
- Visual tools help analyze end winding activity before and after interventions.





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TCUG

PRAIRIE STATE
Generating Company

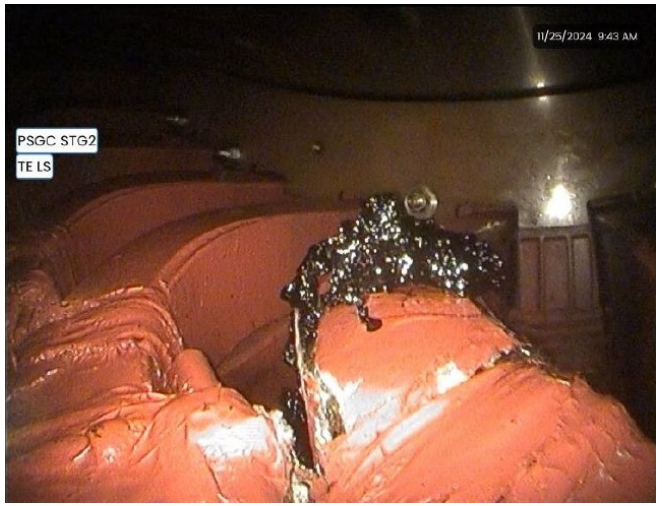
Generator Stator Fault and Partial Rewind Experience

Mehran Mustafa, Ph.D

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EPRI

Overview

- Prairie State Unit 2 experienced a generator stator fault shortly after reaching full load in November 2024.
- Initial inspection revealed burnt insulation smell and C-phase winding failure; borescope identified damage inside the stator.
- OEM team mobilized for rotor removal and detailed damage assessment; multiple electrical and flow tests conducted.
- Damaged top bar #36 removed and replaced using spare bars from previous repairs; extensive testing (IR, PI, DC overvoltage) confirmed integrity of remaining windings.
- Cooling system flushed and tested thoroughly with ultrasonic flow and thermal response tests to ensure no obstructions.
- Final assembly completed with updated protection relays and enhanced alarm systems.
- Lessons learned include improved foreign material exclusion, drying procedures for Glyptal paint, and recommendations for spare parts inventory.





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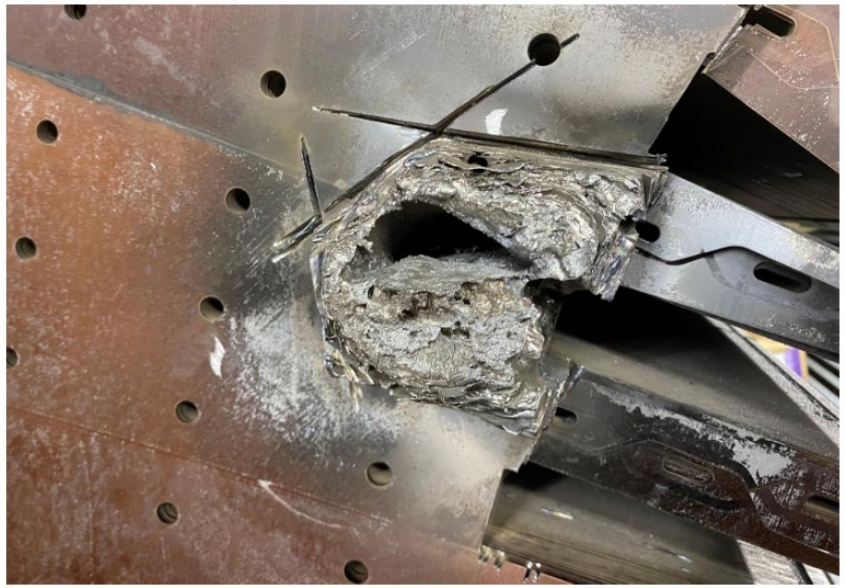
TGUG



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Overview

- Generator tripped on July 18 due to stator ground fault and rotor ground fault indications
- Initial inspections showed phase A ground fault; visual signs of core damage including melted steel and burn marks
- Borescope inspection confirmed additional core damage in cooling passages
- Fault localized to individual coils, asbestos safety procedures applied during coil removal
- Early decision made for full rewind, saving significant repair time
- Core failure area approximately 3 feet long; supply chain delays influenced repair strategy
- Horizontal re-stack and rewind performed by MPS and MD&A during 2024 outage
- Successful core loop and El-CID testing completed before rewind
- Stator wedging and dual crane lift executed for installation
- Challenges with Alstom end winding bolt system resolved with custom tooling
- Rotor air restriction baffle modified onsite to fit properly due to stepped ends





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T&UG



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Overview

- Overview of Isolated Phase Bus (IPB) designs and common overheating issues
- Standards referenced: ANSI/IEEE C37.23, NEC, NEMA, IEC
- IPB conductor temperature limits: 105°C max; enclosure limits: 80°C max
- Causes of conductor overheating:
  - Degraded components
  - Improper installation/maintenance
  - Radiated heat
  - Circulating currents
- Types of circulating currents: expected (design-related) vs unexpected (damage/degradation)
- Continuous vs non-continuous IPB designs and their impact on enclosure currents and shielding
- Importance of proper grounding to avoid ground loops and stray currents
- Mitigation strategies
  - Correct design
  - Installation
  - Maintenance
  - Grounding
  - Expansion joint integrity
- Overheating risks from associated plant equipment, especially transformers and GSU units
- Emphasis on preventative maintenance by qualified technicians to prevent overheating and ensure system reliability

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T&UG



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Overview

- Overview of Isolated Phase Bus (IPB) design, standards (IEEE C37.23), and OEM considerations
- Key design and production tests:
  - Power frequency withstand
  - Continuous current
  - Momentary and short-time withstand
  - Weather resistance
- Important materials and construction guidelines:
  - Aluminum and copper conductors
  - Insulation thickness
  - Stainless steel hardware with Belleville washers
- Maintenance focus: keep bus duct dry, clean, and cool to prevent failures
- Critical components for maintenance:
  - Flex/bolted connections
  - Insulators
  - Seal off bushings
  - Expansion/rubber bellows
  - Gaskets
  - Grounding/isolation
  - Heaters
  - Forced air systems







- Common failure causes:
  - Moisture ingress
  - Corrosion
  - Cracked insulators
  - Damaged bellows/gaskets
  - Debris accumulation
- Supporting systems:
  - Heater operation
  - Air pressurization
  - Forced air cooling for moisture control and temperature management



- Maintenance planning during outages includes cleaning, inspection, component replacement, repair welding, and hipot testing
- Refurbishment techniques: cryogenic cleaning, silver plating of contacts
- Online monitoring tools:
  - Temperature sensors
  - Humidity sensors
  - Heater circuit
  - Partial discharge monitoring for condition-based maintenance
- Case studies highlight costly failures from firestop barrier faults and prolonged moisture issues leading to insulation deterioration and bus replacement
- Emphasis on proactive maintenance planning to avoid unexpected failures and downtime

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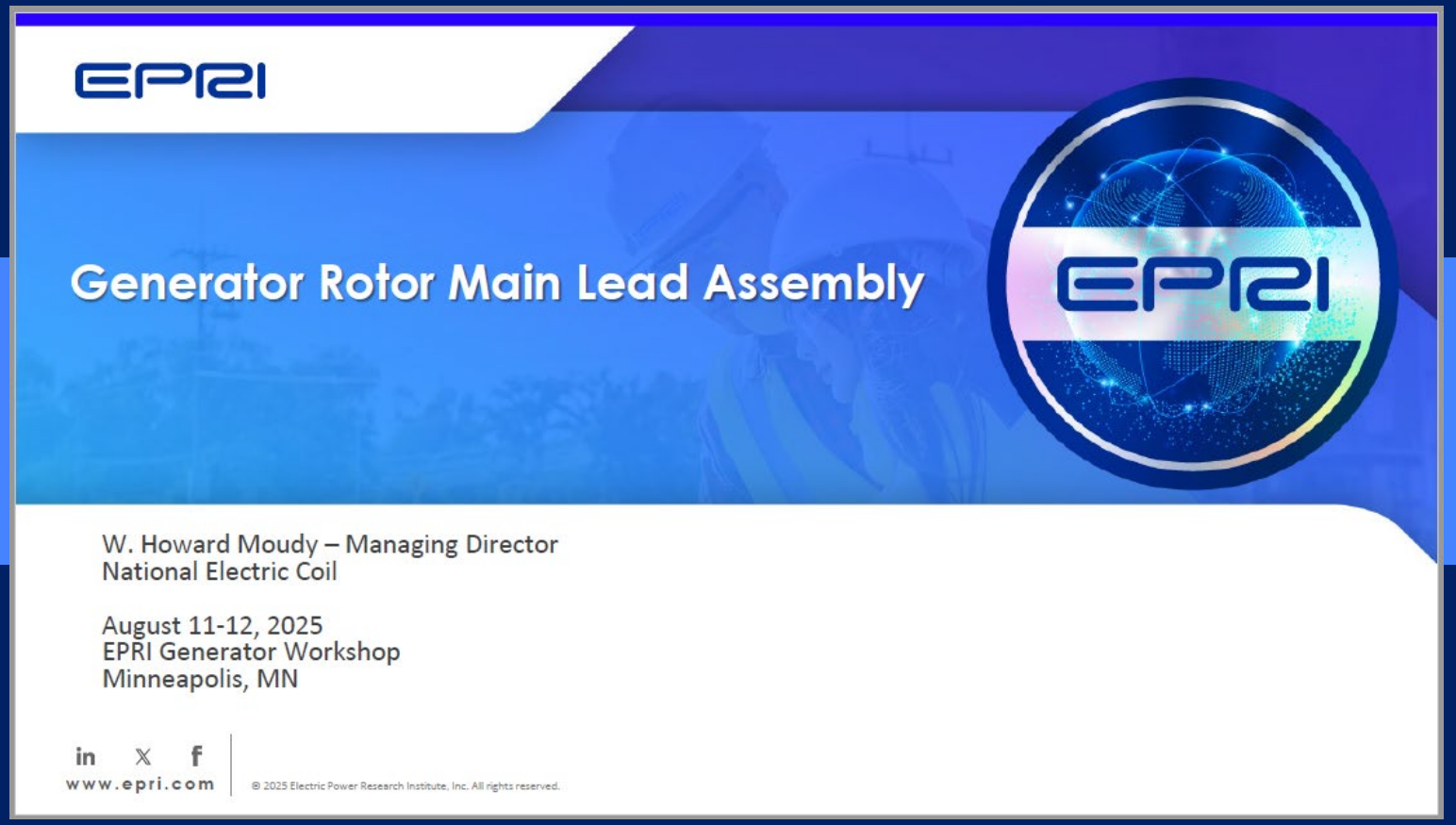
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Overview

- Overview of thermal expansion challenges in generator rotors, especially in cyclic, long, and air-cooled units
- Importance of low friction surfaces to reduce wear, binding, and insulation damage
- Common materials used for low friction surfaces, with emphasis on Teflon (PTFE) for its thermal stability and low coefficient of friction
- EPA regulations impacting PFAS chemicals like those in Teflon manufacturing, driving the need for non-PFAS alternatives
- Test results showing Teflon's superior friction reduction at room and elevated temperatures
- Future focus on developing effective non-PFAS low friction surface solutions compliant with evolving regulations

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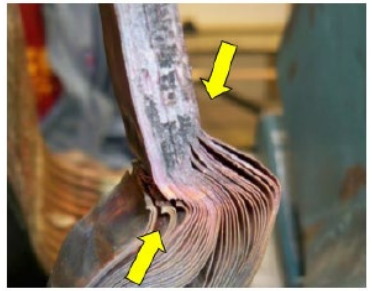
Overview

- Purpose of Rotor Main Lead Assembly: electrical connection to rotor winding with various configurations
- Key components include:
  - Collector rings
  - Bore plugs
  - Radial and axial leads
  - J-straps
  - Flexible connectors





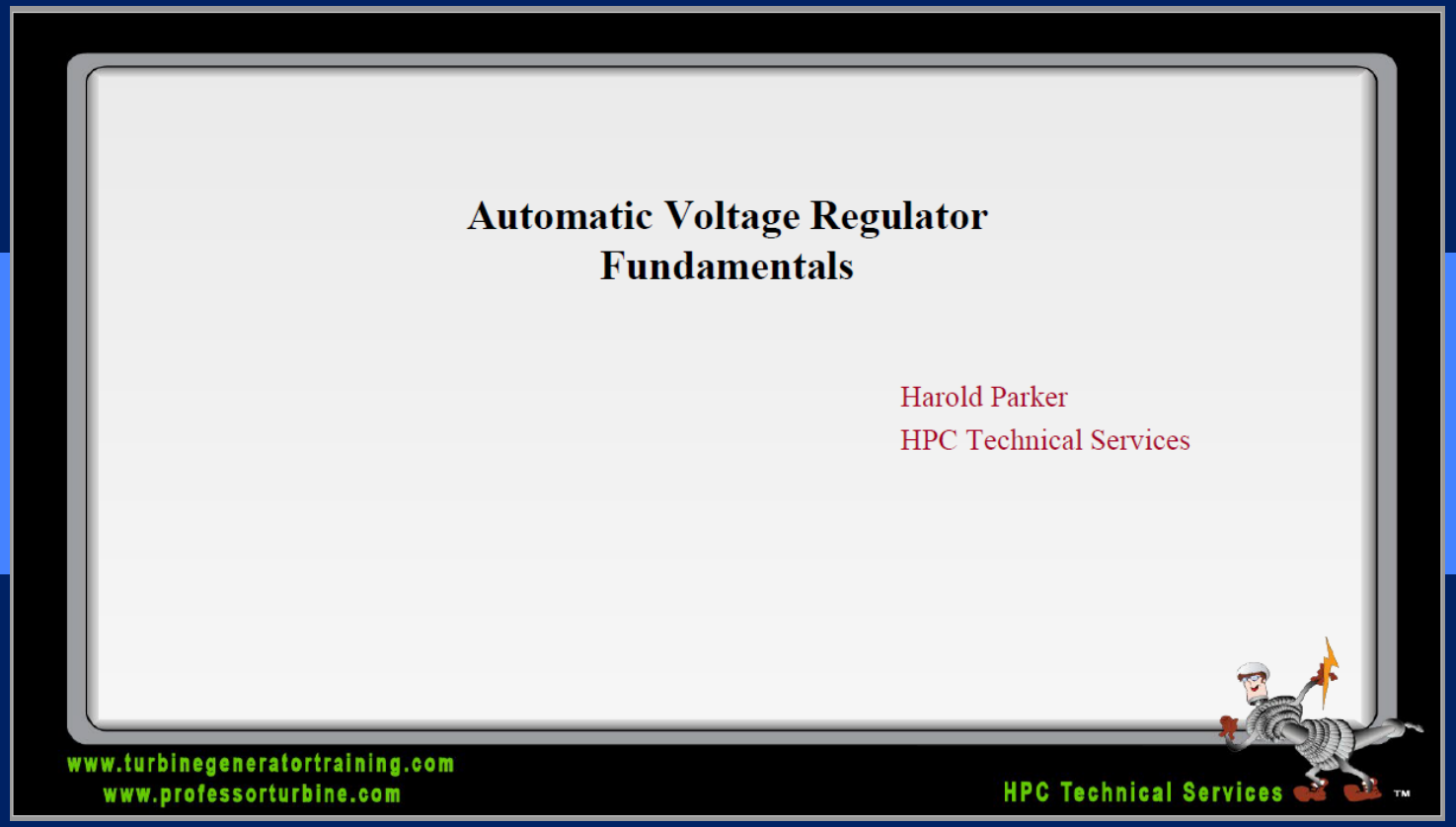

- Common configurations: collector ring types, brushless exciter, through coupling connections
- Typical issues:
  - Mechanical wear
  - Seal failures
  - Insulation cracking
  - Lead distortion
  - Hydrogen leaks


- Upgrades focus on improved materials, design geometry, and enhanced flexibility to reduce stress
- Maintenance essentials: inspection (boresonic, visual, NDE), cleaning, testing, and timely replacement of damaged parts
- Proper maintenance and upgrades ensure long-term reliable rotor operation; neglect can cause severe rotor damage

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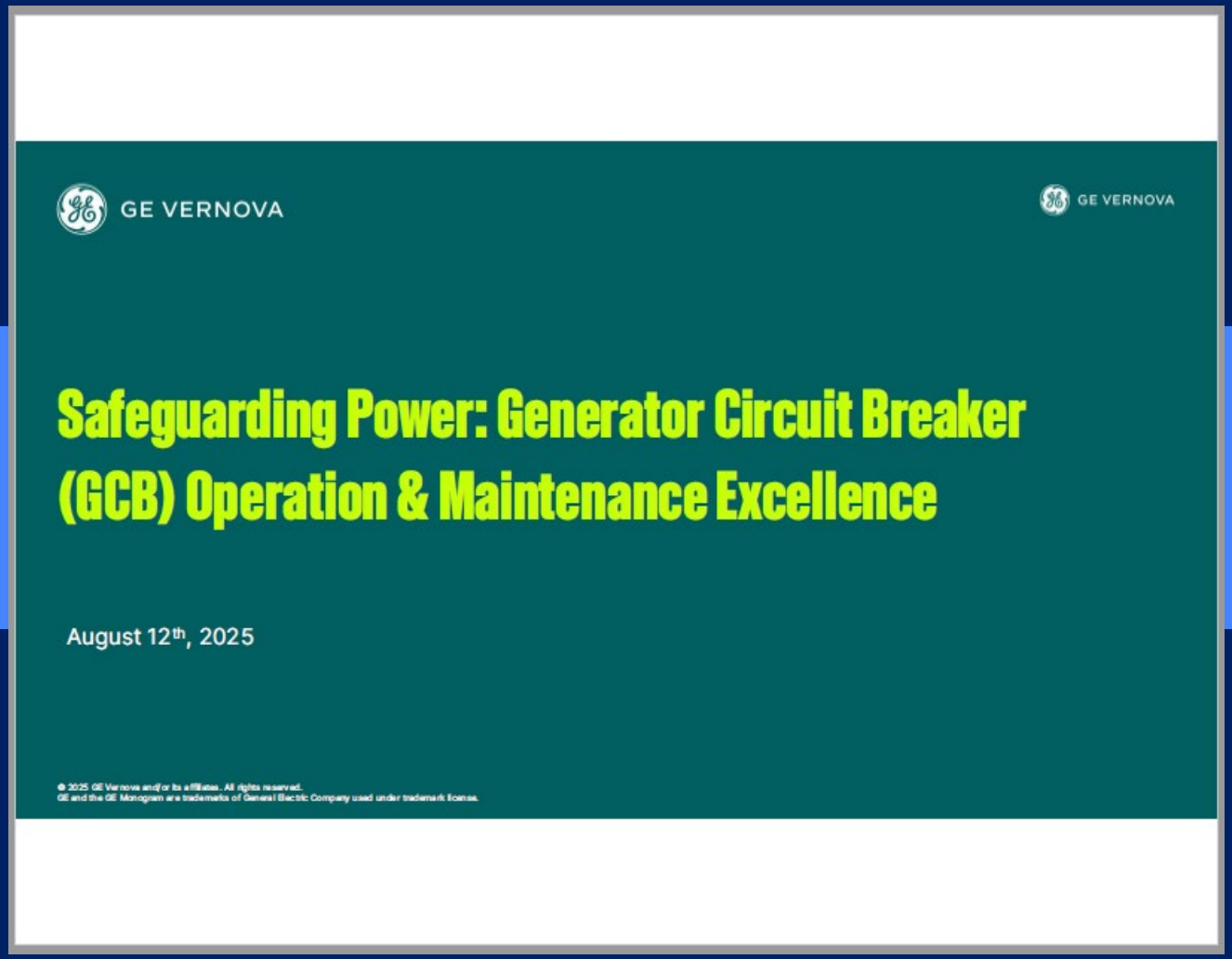
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Overview

- Purpose of AVR: Ensure reliable power delivery by controlling generator voltage
- AVR operation modes: Off-line controls terminal voltage; On-line controls reactive power flow
- Reactive power flow depends on voltage difference between generator and system (EG vs ES)
- Modern excitation systems vary field voltage/current to control generator voltage and MVARs
- Key components:
  - Current Transformers (CT)
  - Potential Transformers (PT)
  - Feedback loops
- Droop (RCC) characteristic enables load sharing among generators; AVR must be in Auto mode
- Manual voltage regulators allow voltage decay under load, risking loss of synchronism
- Protective features include Under-Excited Reactive Ampere Limit (URAL) to prevent instability and overheating
- Power System Stabilizer maintains synchronous operation by balancing mechanical and electrical power
- Brushless and static excitation systems improve reliability and control accuracy

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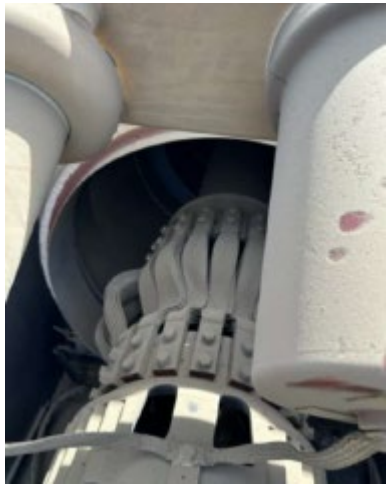


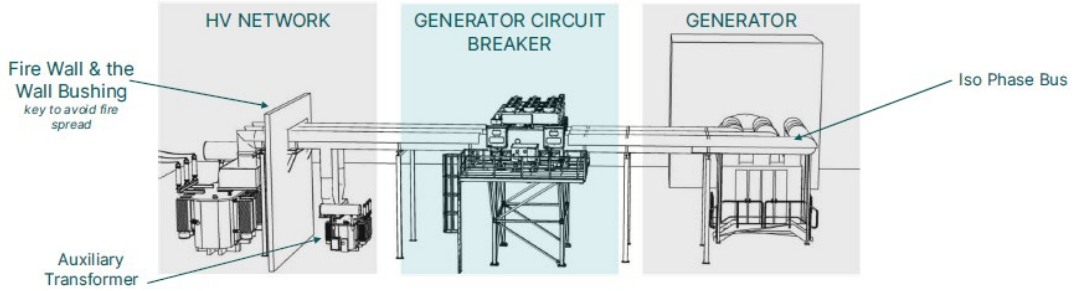
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Overview

- Introduction to Generator Circuit Breakers (GCB): purpose and key benefits
- Comparison of power system layouts with and without GCBs, highlighting improved safety, reduced faults, and cost savings
- Overview of GE Vernova's GCB product portfolio and mechanism evolution
- Storage and maintenance best practices for GCBs, including SF6 gas handling and shelf life considerations
- Importance of condition assessment through non-intrusive inspections and Dynamic Contact Resistance Measurement (DCRM)
- Benefits of digital monitoring (CBWATCH-3) for early fault detection and proactive maintenance
- Risks and costs associated with reactive maintenance versus advantages of a proactive strategy with OEM parts and training
- Emphasis on interlock systems and robust protection to prevent failures and outages
- Final recommendations:
  - Strategic spares
  - Preventive maintenance
  - Training
  - Heaters
  - Forced air systems
  - Real-time monitoring for operational excellence







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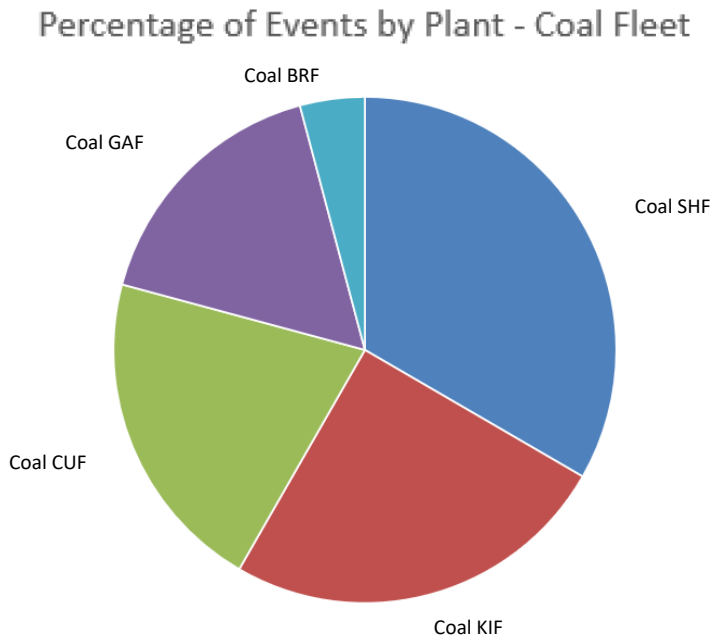
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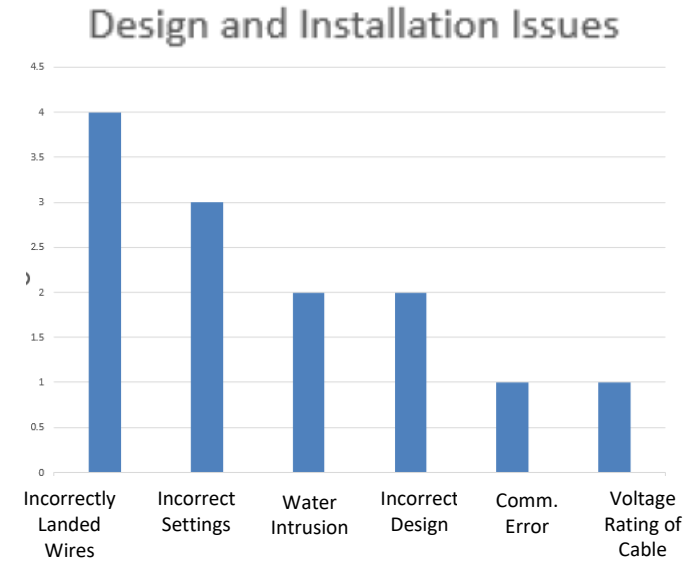


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Overview

- Collected and analyzed 1,991 corrective reports (CRs) related to exciters through FY19; refined to 141 key events
- Identified common failure modes:
  - End of Life (EOL)
  - Inadequate Preventive Maintenance (PM)
  - Refurbishment issues
  - Design & Installation problems
  - Electrical failures beyond maintenance
  - Human performance
  - Procedural gaps
- Fleet overview: Coal (25 units, mostly DC exciters), Gas (121 units, mix of static and brushless), Hydro (113 units, mostly static and pilot exciters)
- EOL is the leading cause of failures, especially obsolete control components like AVRs and power components such as Kato exciters
- PM inconsistencies noted across fleets, with cooling fan failures in Hydro and irregular brush inspections in Gas fleet
- Refurbishment lacks standardized specifications causing downtime and spare part issues
- Design and installation failures addressed via updated standards and checklists
- Engineering actions underway:
  - AHI score updates
  - PM standardization
  - Refurbishment specs
  - Relay standards
  - Brush optimization
  - Fan evaluation
- Emphasis on programmatic maintenance over tribal knowledge and improved tracking tools for overdue PMs





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Overview

- AEP Northeastern Unit 2 replaced its original GE analog voltage regulator due to end-of-life issues with the unique oiled-cooled Power Potential Transformer (PPT).
- The old PPT was abandoned in place, and a used UNITROL 5000 AVR from Conesville U6 was installed along with supplemental dry-type PPTs.
- The existing GE AVR cabinet was repurposed as a marshalling cabinet connecting the new AVR to the generator and control room.
- Vendor scope included extensive isophase bus modifications both indoors and outdoors, involving demolition, welding, conduit and cable installation, insulator mounting, and final testing per IEEE standards.
- Lessons learned emphasized the importance of having finalized drawings before fieldwork, checking phase rotation, and understanding unique equipment design details.
- Despite post-COVID cost increases, the project was successful with plans for further upgrades within five years.

Old AVR Cabinet

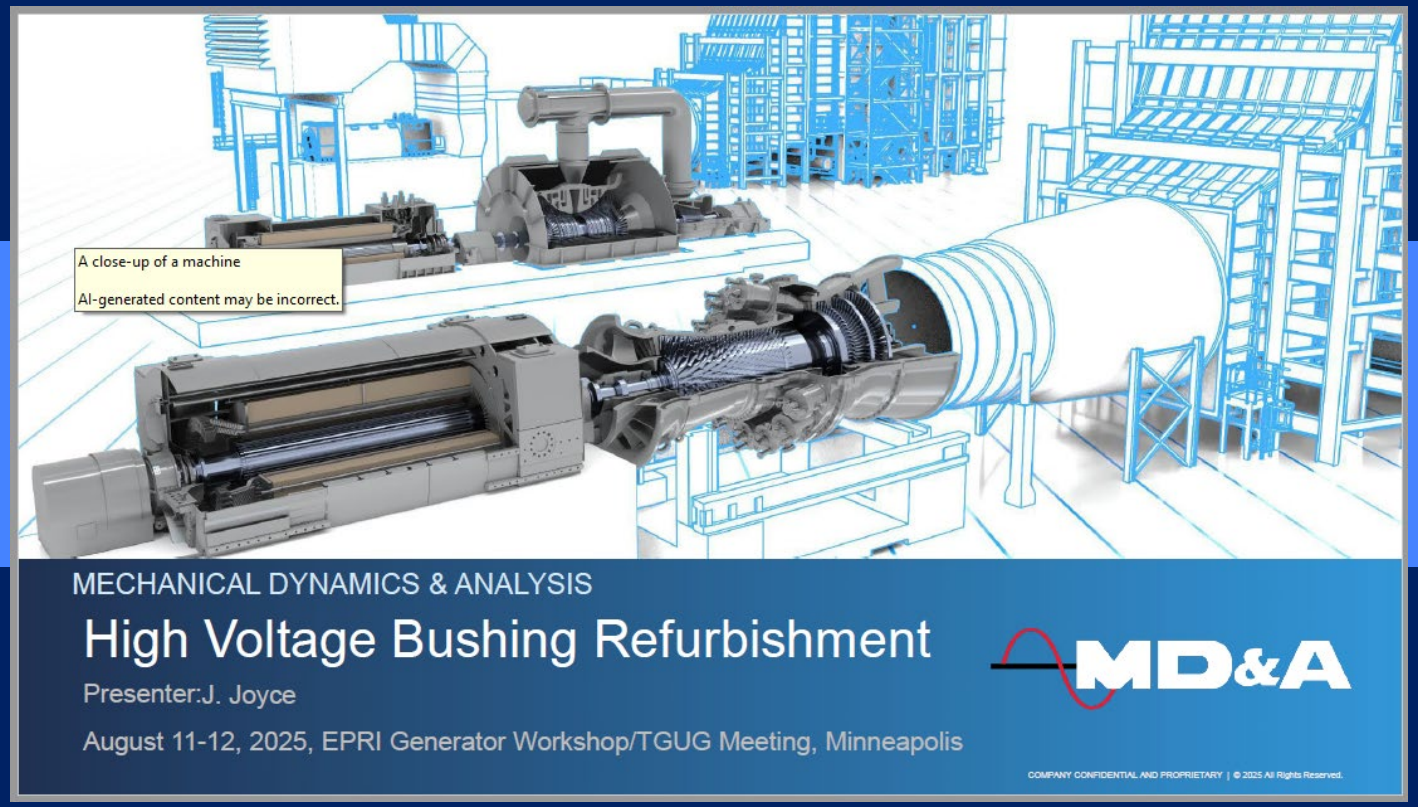


Completed AVR Install



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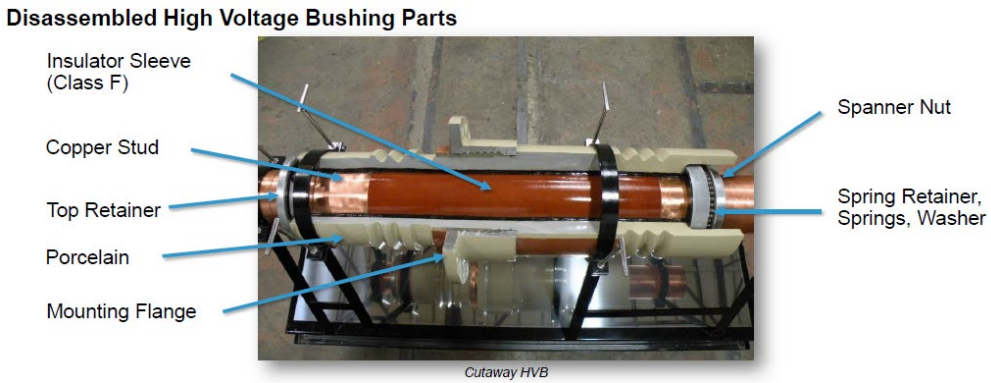
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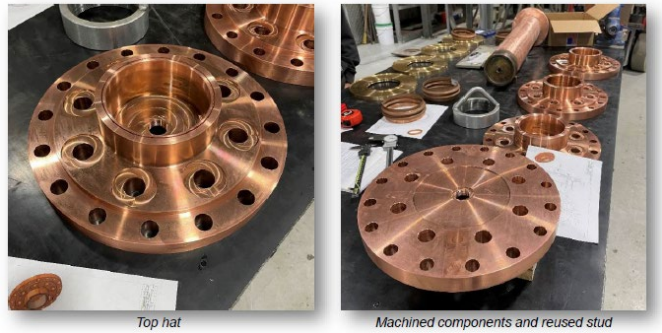


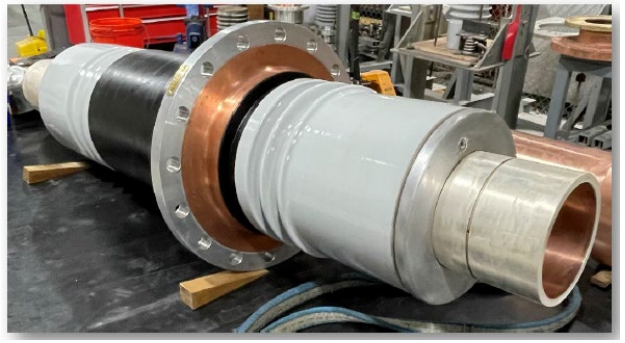
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Overview

- Overview of Mechanical Dynamics & Analysis (MD&A) history and expertise
- Definition and function of High Voltage Bushings (HVBs) in generators
- Typical HVB configurations and mounting orientations
- Cooling methods for HVBs: water, hydrogen, or air cooled
- Common mechanical, electrical, and thermal stresses causing HVB damage
- Key components of installed and disassembled HVBs
- Incoming inspection procedures: visual, pressure, and electrical testing
- Disassembly and refurbishment process including replacement of internals and parts
- Assembly steps: installation of insulator, copper stud, springs, O-rings, and sealing
- Final testing, silver plating, painting, tagging, and packaging before shipment







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Southern Nuclear

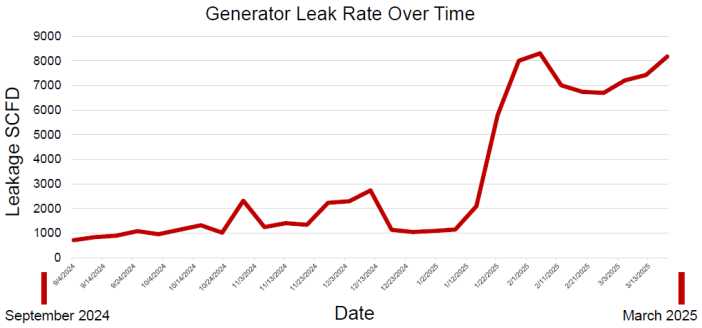
Vogtle 3&4 Elevated Hydrogen Consumption

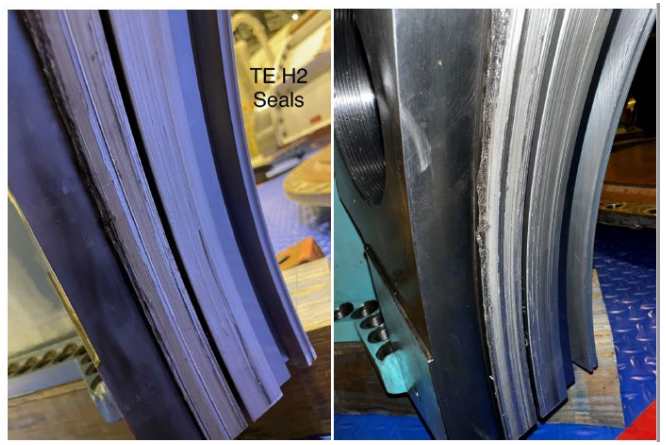
Rebekah Schooley
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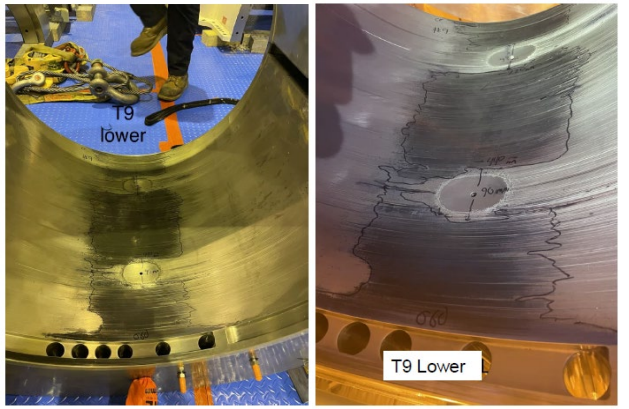
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Overview

- Overview of Vogtle Units 3 & 4, Toshiba PWR generators producing ~1,200 MWe each
- Unit 4 experienced elevated hydrogen consumption starting Sept 2024, peaking at ~8,300 SCFD by early 2025 due to a leak near bushing box flange
- Leak detection methods included sniffing, acoustic imaging; repair involved sealing with RTV and Viscasil dams
- Unit 3 showed excessive hydrogen seal oil flow in May 2023 linked to damaged hydrogen seals and debris in oil systems
- Repairs on Unit 3 included re-babbitting seals, machining shafts, and flushing seal oil system
- Post-repair vibration issues observed on collector ring brushes led to detailed vibration analysis
- Engineering recommends bearing repairs to restore geometry and address sensitivity of collector ring vibrations
- Enhanced monitoring and operational controls implemented during troubleshooting and repairs







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Overview

- Focus on risk-based, prescriptive maintenance using anomaly detection, diagnostics, risk assessment, and actionable recommendations
- Utilizes electromagnetic interference (EMI) data combined with process data, integrated into dashboards and common BI/CMMS tools
- EMI monitoring history from early radio interference detection to modern continuous online systems developed by Duke Energy and acquired by Cutsforth
- Production Risk Dashboard converts multiple diagnostic indicators into a prioritized risk and urgency framework based on severity, likelihood, and potential outage duration
- Customizable thresholds trigger alerts for maintenance actions with detailed diagnostic information and troubleshooting guidance
- Overall equipment health visualized through asset risk screens and trend analysis to support proactive asset performance management

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Generator Stator Core Horizontal Restack
-Development and its Execution-

EPRI Generator Workshop TGUG Meeting

Minneapolis

2025/8/11

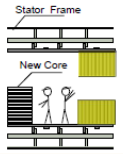
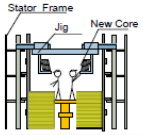
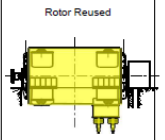
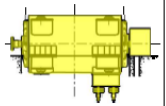
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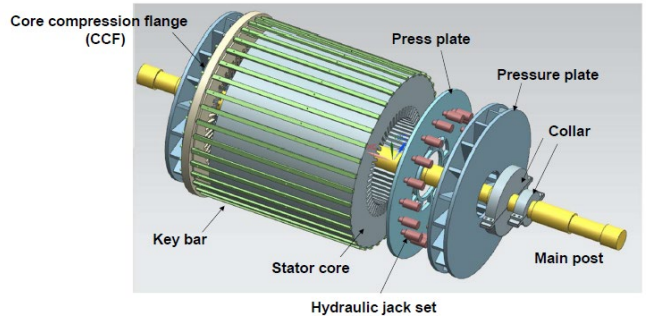
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Overview

- Background: Addressed issues with generator stator core damage and restacking, focusing on a 1985 Mitsubishi generator model.
- Challenges: Complex ventilation paths, unclear original core configuration, and lack of experience with horizontal onsite restacking (previously only vertical).
- Investigation: Detailed study of original design's ventilation network, key bars, core condition, and cooling paths; conducted mock-up tests to verify ventilation model accuracy.
- Development: Created calculation models matching measured airflow and temperature rises; designed special tooling and procedures for horizontal core restack.
- Execution: Disassembled new stock generator for trial, developed slot keepers and hydraulic jacks, performed multiple horizontal restack trials at site with specialists and local support.
- Outcome: Successfully completed horizontal core restack onsite, restored generator to operation, demonstrating Mitsubishi's capability to handle unfamiliar OEM designs and complex restacking projects.

	1. Horizontal restack	2. Vertical restack	3. Stator replace	4. Generator replace
Repair options	Core Restack 	Core Restack 	Stator Replace 	Generator Replace 
Outage duration	2-3 Months (full restack)	3-4 Months (full restack)	1-2 Months	1-2 Months
Price	$	$$	$$$	$$$$
Loss for outage	$$	$$$	$	$
Remark	On-base-repair is possible	/Stiff ground/ Stator support/ Required	No aged parts in stator Long delivery	No aged parts Long delivery

Conceptual design of horizontal restacking




Heating & finial core completion


Dimension check


Varnishing


ELCID & Core loop test

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Motors | Automation | Energy | Transmission & Distribution | Coatings

E+M WEG Group

Brushless Excitation System Overview & Redundancy, Series Vs. Parallel Rectifier Wheels

2025 EPRI Generator Workshop



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Overview

- Overview of brushless excitation systems for two-pole generators (265 kW to 700 kW, 3,000–3,600 RPM) by Electric Machinery
- Brushless exciter operation: PMG supplies AC → AVR controls DC excitation → exciter stator induces AC in rotor → diode wheel rectifies AC to DC for main rotor field
- Design considerations include main field current/voltage, ceiling current/voltage, AVR capability, and diode redundancy (series vs. parallel)
- Parallel redundancy: multiple diodes with fuses; series redundancy: potted diode modules in series—each with pros and cons related to current capacity, space, cooling, and retrofit ease
- Construction methods cover laminated rotor cores, form wound armature coils, field poles, vacuum pressure impregnation (VPI), and diode wheel assembly
- Common failure modes: diode/fuse failures, insulation faults, ground fault detection issues, electrical imbalances causing mechanical stress and heat buildup
- Testing protocols for exciter windings and diode bridges emphasized
- Retrofits from static to brushless excitation improve maintenance, efficiency, safety, and reduce power consumption; applicable across turbine types and generator models
- EM's brushless designs focus on compactness, robustness, and serviceability with proven OEM compatibility

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TGRA / PAW

NEIL

August 2025

Minneapolis, Minnesota
Kevin Martin, Principal LPE

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Overview

- TGRA Revision issued in 2022; all units assessed by end of 2023
- Updates driven by lessons learned from Callaway 2020 event, recent claims, operating experience, and future conditions
- New grading criteria include turbine valve testing intervals, condenser back pressure, full speed no load hours, blade vibration monitoring, and foreign material exclusion programs
- Problem Area Worksheets (PAWs) updated: Retaining Ring Failure removed, Pedestal Degradation added
- Significant increases in risk ratings for LP last stage blade cracking, rotor blade attachment missile generation, stator core thermal failure, and overspeed protection failures due to new probability factors and aging equipment
- Industry SMEs actively communicating risks and OEMs releasing technical information letters (TILs) for mitigation
- PAW examples highlight probability rating criteria and recommended loss prevention and reduction actions such as inspections, core restacking, preventive maintenance, and fire safety measures

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Recollections of My Career

John Baker, Prairie State

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Overview

- Emphasizes the importance of self-study, hands-on experience, teamwork, consistency, and formal education throughout his career.
- Highlights key experiences including generator repairs, protective relay system design, and handling major equipment failures due to human error.
- Stresses investing in personnel training, industry group participation, and professional development for sustained success.
- Shares lessons learned from incidents such as mis-wired PTs, auxiliary relay failure causing extended faults, and transformer bushing replacement under aggressive schedules.
- Values mentoring interns and supporting their career growth despite challenges attracting talent to remote locations.
- Advocates for open communication and parts sharing between utilities to foster collaboration and problem-solving.
- Expresses gratitude for career opportunities and support received along the way.

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Steam Turbine Workshop Presentations



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TCUG

Steam Valves & Turbine Security

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Overview

- Provides an Overview of steam valve types and purposes on Nuclear, Fossil, and Combined Cycle Steam Turbine Generators (STG)
- Main Stop Valve (MSV) & Intermediate Stop Valve (ISV/RSV): emergency steam shutoff
- Control Valves (CV): regulate steam flow to control speed, load, or pressure
- Intercept Valves (IV): regulate steam flow during overspeed scenarios after CV closure
- Bypass valves manage pressure when CVs are unavailable (BWR specific)
- Examples of steam flow rates at full load and full load rejection scenarios
- MSV design features: unbalanced valve, internal bypass for pressure equalization, hydraulic actuator mechanism
- Control valve operation and sequencing, including combined intercept valve test sequences
- Servovalve control signals and 2oo3 voting logic for reliability
- Valve testing purpose: exercise valves, lubricate components, detect operational issues
- Testing procedures differ by valve type and unit configuration

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TOUG

PSEG | NUCLEAR

Salem Unit 1 HP Turbine Stop Valve Mechanical Failure

Presenter: Jessica Maame Wiredu-Poli

Contributors: William Sitarik, Brian Moses, Maintenance & Operations

7/14/2025

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Overview

- Salem Unit 1 experienced a mechanical failure of the High Pressure (HP) Turbine Stop Valve on April 8, 2025.
- The transient event involved pressure changes in turbine stages and main steam headers, causing turbine bearing temperature increases.
- Investigation revealed valve damage due to legacy maintenance practices, including missing retaining pins and steam erosion.
- Valve maintenance history showed multiple rebuilds and repairs, with recent procedures lacking hot retorque operations.
- OEM and industry experts were engaged for inspection, repair, and guidance during outage.
- Repairs included welding steam damage, pinning per OEM instructions, and reassembly with correct parts.
- Corrective actions focus on updating maintenance procedures, supervisor hold points, BOM updates, gap analysis of bulletins, and design improvements to prevent recurrence.



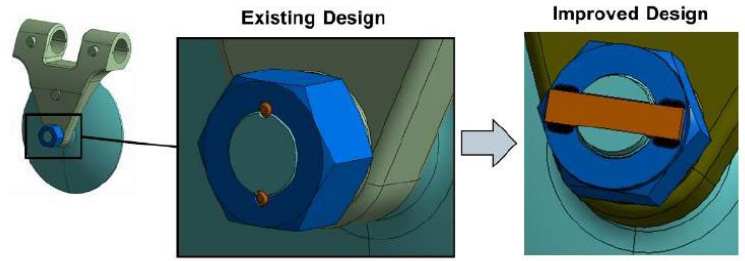


Figure 4: Illustration of Disc to Nut Modification

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TCUG

Ameren

EHC Fluid Leaks

Presenter: Luke Maichel

1

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Overview

- Case study: Governor Valve Actuator bolt failure at Labadie Energy Center Unit 1 in March 2023 caused by fatigue cracks and over-torque, leading to fire and unit shutdown
- Investigation revealed multiple broken bolts; repairs included bolt replacement and torque specification enforcement
- Common causes of fluid leaks identified:
  - wrong or missing O-rings
  - improper torque
  - pinched O-rings
  - foreign material
  - misaligned tubing
  - defective hoses
- Leak locations mostly on actuator manifold fittings and accumulator supply inlets due to alignment issues, loose bolts, or aging components
- Recommendations for preventing leaks:
  - never reuse O-rings
  - use proper Viton O-rings
  - apply correct torque with crow's foot and torque wrench
  - align fittings carefully
  - inspect and clean O-rings before installation
  - pressure test system after assembly
- Emphasis on maintenance best practices to ensure reliability and safety of turbine control systems

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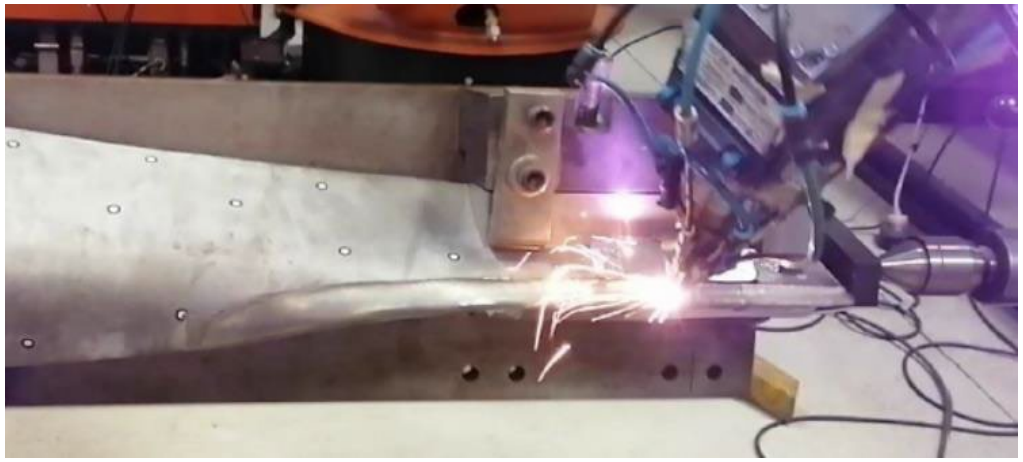


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EPRI

Overview

- Overview of Eskom’s steam turbine life assessment and repair strategies
- HP turbine rotor life management using material sampling and friction hydro pillar processing (FHPP)
- Case studies on aging turbines: Plant A showing creep damage and life extension options, Plant B with no significant damage
- LP turbine blade tenon repairs using laser welding to restore damaged understraps in-situ, avoiding costly full re-blading
- Laser welding procedure qualification, mechanical testing, and non-destructive evaluation methods
- Successful implementation with multiple rotors repaired and ongoing R&D for further turbine component repairs
- Collaboration between Eskom engineering teams, research institutions, and industry partners





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Overview

- Case study on turbine bearing vibration issues at Calvert Cliffs Unit 2, a large Westinghouse turbogenerator.
- Elevated vibrations detected on bearings 5, 7, and 8 after a 2024 unit trip; Absolute (seismic) vibration increased while Relative vibration remained low.
- Cause identified as structural weakening of the rotor support pedestal, shifting the 2nd lateral critical speed downward to operating speed, amplifying vibrations (“springboard effect”).
- Initial mitigation included monitoring with vendor trip limits and plans for rotor balancing; balance shot successfully reduced Absolute vibration from ~13 mils pk-pk to 7–8 mils pk-pk.
- Final elimination achieved by installing a Siemens-designed cone strut during 2025 refuel outage, stiffening the structure and reducing vibrations below 5 mils pk-pk.
- Lessons learned:
  - importance of understanding vibration fundamentals (Absolute vs. Relative)
  - trusting vendor expertise
  - avoiding confirmation bias
  - investing in turbine-specific vibration training for utility engineers.

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MOVE THE WORLD FORWARD MITSUBISHI HEAVY INDUSTRIES GROUP

Steam Turbine Off Design Operation – An OEM Perspective

EPRI Workshop

Muhammad Riaz, Ph.D.
Mitsubishi Power Americas, Inc.

Aug 11th, 2025

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MITSUBISHI POWER

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Overview

- Overview of steam turbine off-design operations and associated risks from an OEM perspective
- Key off-design conditions covered
  - Full Speed No Load (FSNL)
  - Bypass Operation
  - Feedwater Heater Cut Off
  - Moisture Separator Reheater Cut Off
  - Off Frequency
  - Vacuum Breaking
  - Low Load Operation
- FSNL involves rotor at full speed with minimal steam flow; limited to 120 minutes due to thermal and vibration risks
- Bypass operation affects condenser vacuum and blade vibrations; requires proper drain maintenance and monitoring
- Feedwater heater cut-off increases turbine load and stresses; must follow O&M guidelines and monitor key parameters
- Moisture separator reheaters prevent blade erosion and efficiency loss; cutting off MSRs increases erosion risk
- Vacuum breaking introduces air causing thermal shock and corrosion risks; inspection recommended after use
- Off frequency operation causes overspeed and resonance stresses; alarms and inspections critical
- Low load operation impacts steam quality, blade erosion, and thrust loading; careful monitoring and inspections advised
- Emphasis on:
  - Following OEM guidelines
  - Monitoring operational parameters
  - Consulting OEM for out-of-limit conditions to ensure safe turbine operation

MITSUBISHI POWER

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Control System Tuning & Lessons Learned

EPRI TGUG Summer 2025, Steam Turbine Workshop

Shelby Munds, CASE RMC

August 11, 2025

Wunderlich-Malec

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EPRI

Overview

- Overview of Proportional-Integral-Derivative (PID) controllers: components (P, I, D), inputs/outputs, and evolution from mechanical to digital systems
- Explanation of PID control algorithms including time-domain and s-domain equations
- Common tuning methods: Cohen-Coon, Lambda, Ziegler-Nichols, and Trial-and-Error with pros and cons
- Importance of understanding tuning parameter representations (gain vs. proportional band, integral/reset rate, derivative time/gain)
- Complexity of control loops from simple single-loop to cascaded and multi-layered regulatory logic
- Impact of overall loop dynamics, valve characteristics, and field device conditions on turbine control performance
- Challenges in tuning due to system nonlinearities, operational constraints, and “tolerance stacking” effects
- Practical case study illustrating real-world issues caused by interactions between frequency regulation logic and valve behavior
- Emphasis on comprehensive approach beyond just PID parameters for effective turbine control tuning

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FirstEnergy

Steam Turbine Steam Chest Vibration

Elizabeth Schneider

2025 Summer EPRI TGUG Conference

August 11, 2025

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Overview

- Shares a case study of the steam chest vibration issue at Fort Martin Unit 1 coal-fired turbine
- Problem: high-pitched noise (1260 Hz, 120 dB) and flow-induced vibration in valve chest and piping between 65-85% load (390-515 MW)
- Background: vibrations and control valve failures began post-2017 outage; thermocouples and valve restoring arms also failed
- Maintenance history includes upgrades in 2007 (hydraulic system), 2014 (HP turbine upgrade), and 2017 (stop valve replacements, piping repairs)
- Troubleshooting focused on piping support adjustments reducing vibration amplitude but noise persists
- Control valves investigated for position accuracy and stroke settings; some valves converted from unbalanced to balanced design without stroke adjustment
- Next steps: review valve maintenance, verify mechanical positions vs. control system, install monitoring instrumentation, compare with sister unit, consider tuning valve curves
- Seeking input on similar experiences, alternative causes, additional data, and troubleshooting methods

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LP Turbine Operation Challenges and Findings

Company: Dominion Energy
Presenter: Jason Teichert
EPRI TGUG 2025 Summer

1

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Overview

- Plant commissioned in 2016; 3x 501GAC turbines on 1 CC totaling 1500+ MW
- Key issues: alignment problems between GEN and LP2 coupling corrected in 2019, increasing bearing #6 load
- Major spring 2023 outage included full inspection, rebabbitting T3-T6, and significant alignment adjustments
- Post-major challenges with hot starts, bearing trips (T5, T6), lube oil temperature management
- Fall 2024 anchor point inspections revealed casing shifts and clearance modifications to improve stability
- Spring 2025 planned outage focused on hood spray system upgrades and curtain control logic improvements based on sister plant Warren's design
- Detailed T6 pinch checks showed excessive interference potentially causing bearing issues; shim adjustments made
- Ongoing monitoring of shaft line orbit and exhaust temperatures to optimize operation and prevent trips
- Collaborative troubleshooting with OEM and historical data review prioritized for reliability improvements

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CLEAN ENERGY OF TOMORROW

Temelin Turbine Issues

2025 Summer EPRI Steam Turbine Generator Workshops

Jan Havelka
CEZ NPP Temelin

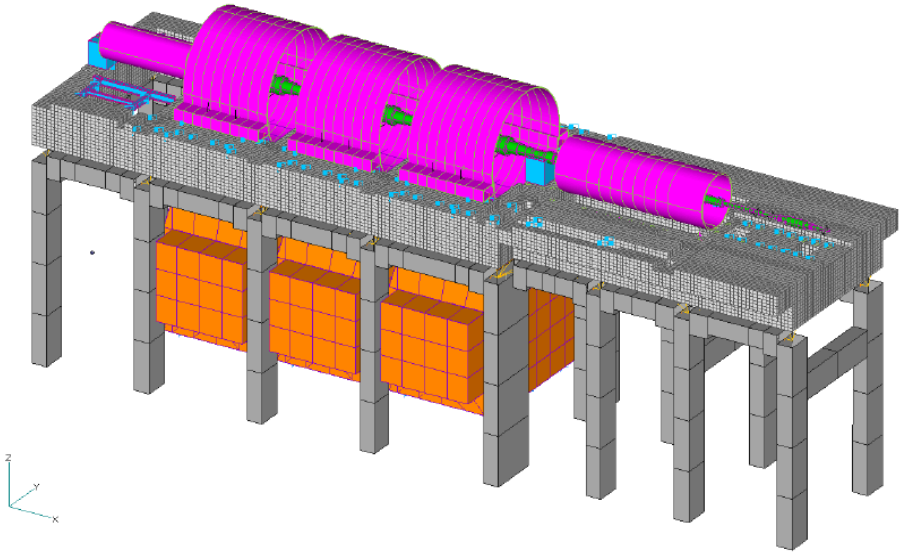
www.cez.cz/en

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EPRI

Overview

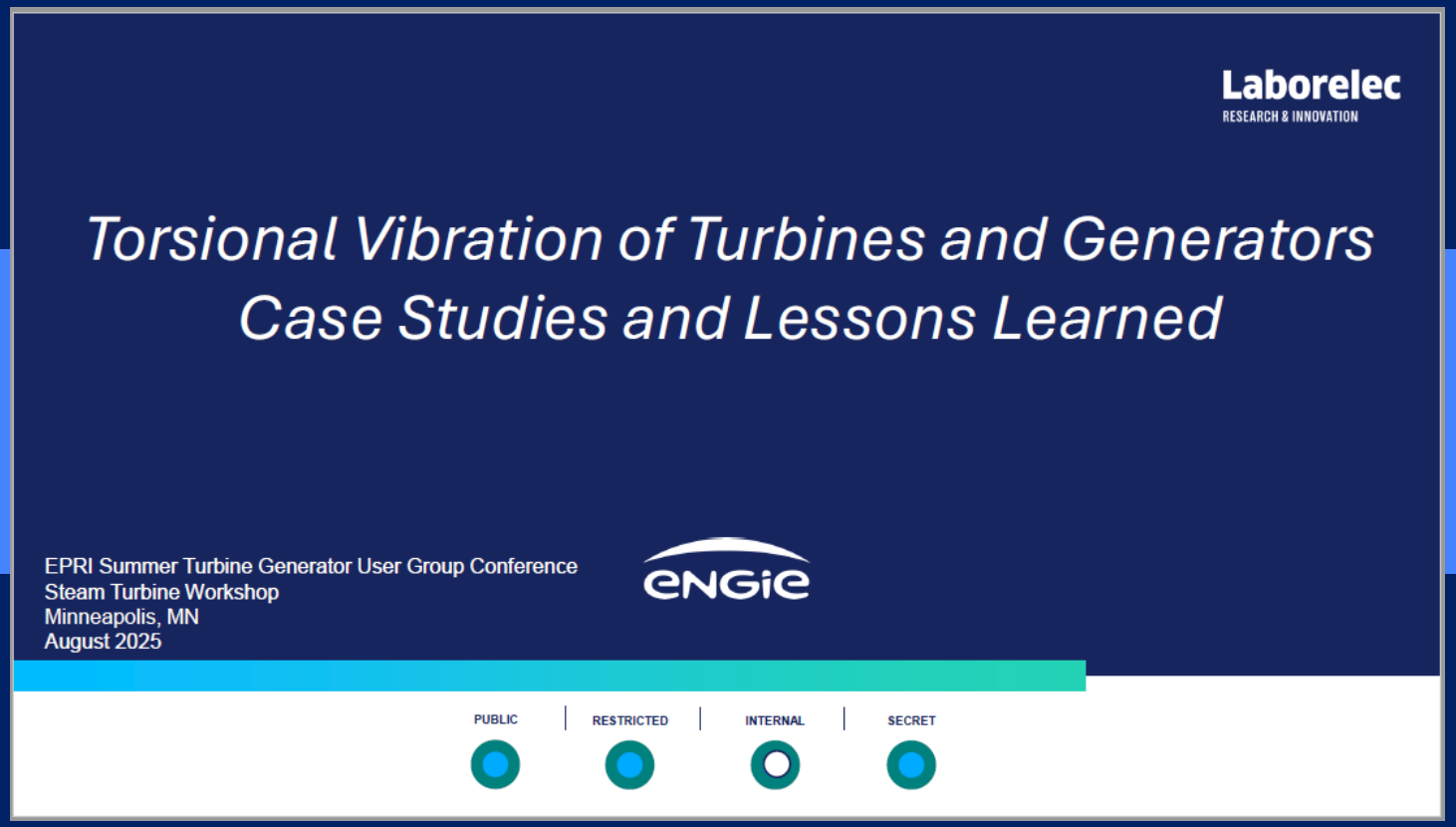
- Provides an overview of Temelin turbine issues focusing on HP and LP parts, vibration problems, and hydraulic system failures
- Key turbine specs: SKODA K1000-5.88, 3000 rpm, max throughput 1553 kg/s, nominal power increased ~85.7 MWe
- HP part leak discovered April 2024; damage to bolts and sealing surface identified
- Repair approach: cold spray technology qualified and applied
- High vibrations caused multiple shutdowns linked to blocked lateral line due to material incompatibility in guiding wedges
- Geometry changes made to wedges to increase clearance and prevent jamming
- Multiple outages for adjustments including radial gap tuning and installation of dynamic vibration absorbers (two installed by mid-2025)
- High pressure hydraulics experienced pump failures in 2024 due to wear and cavitation; fluid replaced and system modified
- Continuous monitoring and corrective actions ongoing to improve turbine reliability and performance at Temelin NPP





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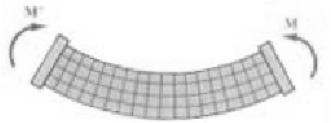


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Overview

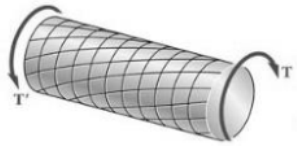
- Torsional vibrations in turbines and generators are hidden, lightly damped, and often unmonitored risks causing fatigue and catastrophic failures.
- Torsional vibrations are *externally* excited by grid interactions with no clear monitoring standards.
- Case studies show rotor cracking caused by grid disturbances, control instabilities, and series capacitor banks.
- Mitigation includes shaft line modifications to detune eigenfrequencies and electrical grid adjustments.
- Continuous monitoring, modeling, and data analysis are essential for assessing severity and protecting equipment amid evolving grid conditions.

Radial vibrations



- Vibration is felt on casing
- Usually sufficiently damped
- Internal excitation (unbalance)
- Criteria/standards advanced
- Closely monitored

Torsional vibrations



- 'Hidden' vibration
- Very lightly damped
- External excitation (grid)
- No clear criteria/standards
- Typically not monitored

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Using 3D scanning and ECA to detect cracks and corrosion pits on blades

Pavel Mares, Jan Patera
Research Centre Rez

CVŘ Research Centre Řež



UJV Group
PEOPLE | INNOVATION | TECHNOLOGY

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EPRI

Overview

- Motivation: Address turbine blade failures caused by corrosion pits leading to fatigue cracks and forced shutdowns.
- Utilized EPRI methodology linking corrosion pit dimensions to crack initiation using Kitagawa-Takahashi diagram.
- Research project objectives: develop diagnostics for corrosion pit monitoring, apply NDE for crack detection, assess operating conditions' impact.
- Project stages included corrosion pit monitoring (3D scanning), crack detection (Eddy Current Array - ECA), material testing, stress analysis, chemical regime study, vibration monitoring, and final summary.
- 3D laser scanning with high accuracy used for in situ corrosion pit measurement; surface treatment methods applied to minimize oxide layers.
- ECA employed for non-destructive crack and corrosion pit detection with flexible probes and qualified procedures per SÚJB, ENIQ, IAEA standards.
- Successful detection of cracks and corrosion pits on operational blades, with qualification tests ensuring reliability.
- Outcomes: refined methodologies for corrosion pit diagnosis and critical size determination, enhancing turbine blade service life management and failure prevention.

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EPRI

3D Scanning of Droplet Erosion Damage on Blades and Eddy Current Array Inspection of Crack Defects

Jay Richardson
Sr. Technical Leader, NDE
Plant Support Services

EPRI Summer Turbine Generator Users Group Conference
August 12, 2025

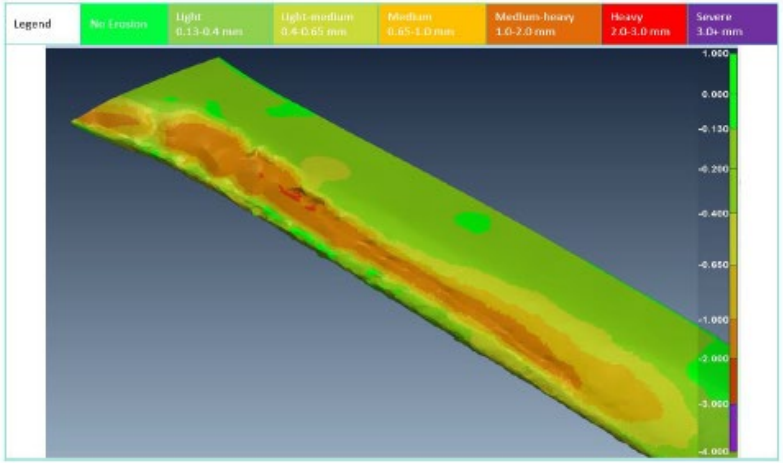
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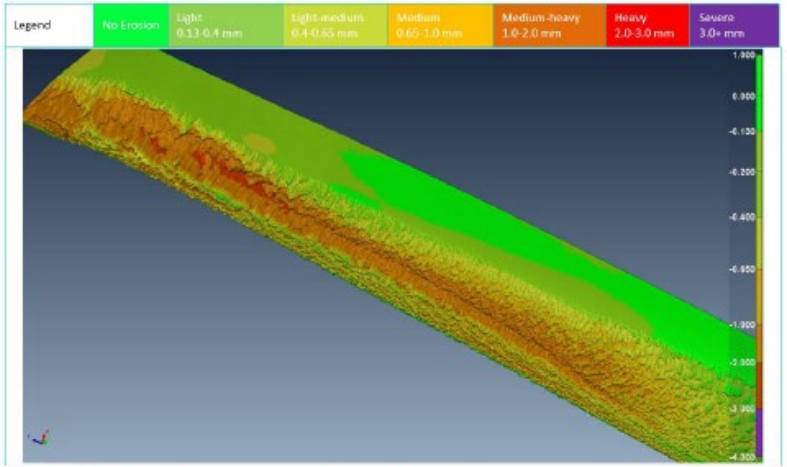
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Overview

- Overview of L-0 blade leading edge erosion damage characteristics and variability
- Evaluation of handheld 3D scanning technologies for accurate in-situ erosion measurement
- Comparison of multiple portable 3D scanners including laser, structured light, and photogrammetry
- Use of 3D color plots for visualizing material loss and volume accuracy analysis
- Eddy Current Array (ECA) technology applied for detecting surface cracks in eroded airfoils
- Investigation using implanted EDM notches and fatigue-induced real cracks for ECA signal differentiation
- Cyclic loading methods to generate and confirm cracks on suction and pressure sides of blades
- Phased Array Ultrasonic Testing (PAUT) used for near-surface crack depth sizing
- Summary: Metrology-grade 3D scanners suitable for gross erosion measurement; ECA probe design recommendations for improved crack detection in turbine blades



3D color plot from low resolution scanner



3D color plot from high resolution scanner

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MPR

Turbine Valve and Overspeed Protection System Test Interval Extensions and Electro-Hydraulic Control Systems Operating Experience

August 12, 2025

Phillip Rush (prush@mpr.com)
Cade Mottice (cmottice@mpr.com)
MPR Associates
Turbine Generator Users Group



PROPRIETARY

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EPRI

Overview

- Purpose of turbine valve and overspeed protection system (OPS) testing: ensure proper function to prevent overspeed events and meet regulatory requirements
- Benefits of extending test intervals: reduce unplanned trips, lower O&M costs, avoid downpowering, optimize resources
- Turbine missile probability (P4) depends on missile generation (P1), strike probability (P2), and impact on safety functions (P3)
- P1 increases with longer test intervals due to higher failure probability of valves and OPS components
- Reliability models quantify impact of test interval extensions and degraded components on missile risk
- Industry and site-specific data critical for accurate failure rate assessments and risk evaluation
- Examples of test interval extensions and specific component failure analyses provided
- Electro-Hydraulic Control (EHC) systems face reliability issues from thermal degradation, fluid quality, and maintenance practices
- Recommended EHC improvements: insulation repair, fluid sampling near valves, fluid changeouts, preventative maintenance, and vulnerability analysis (FMEA)
- Conclusions emphasize feasibility of test extensions with margin, importance of monitoring EHC system health, and use of FMEA for mitigation strategies

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Constellation

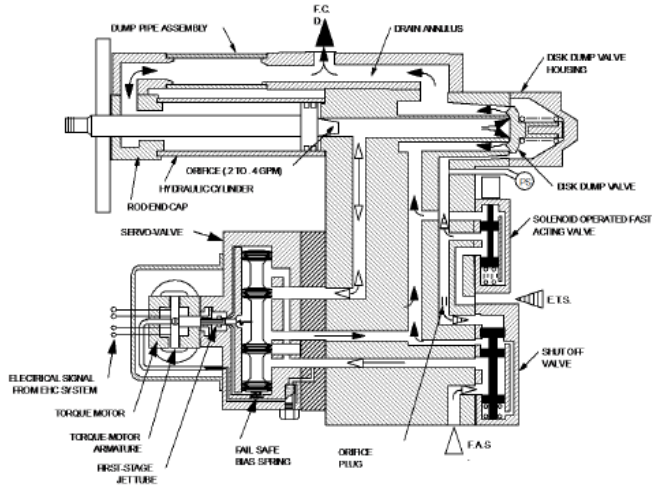
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EPRI Summer 2025 TGUG

EHC Fluid Quality and Extended Maintenance Impacts on Solenoids and Servos



Steve Myers – Constellation

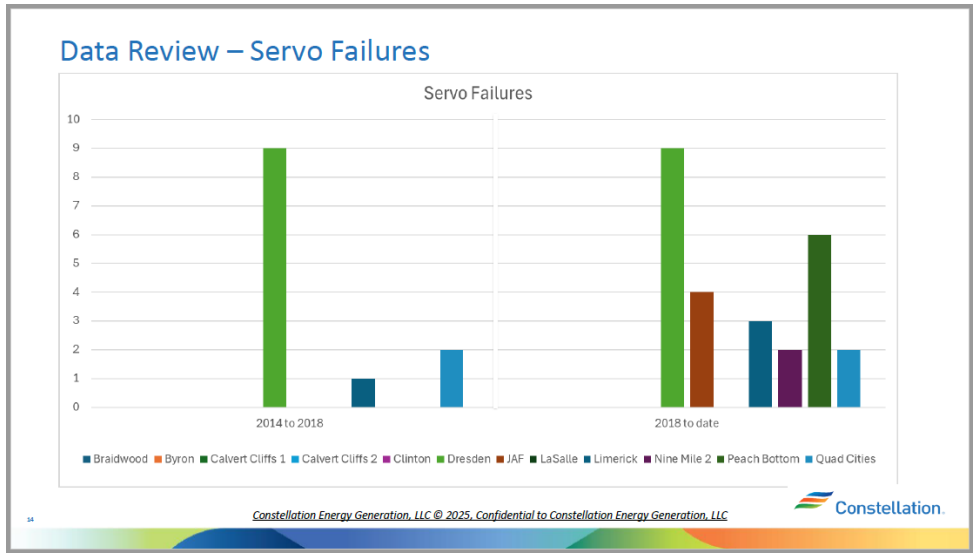
Mike Anderson – TG Advisors (Entrust)

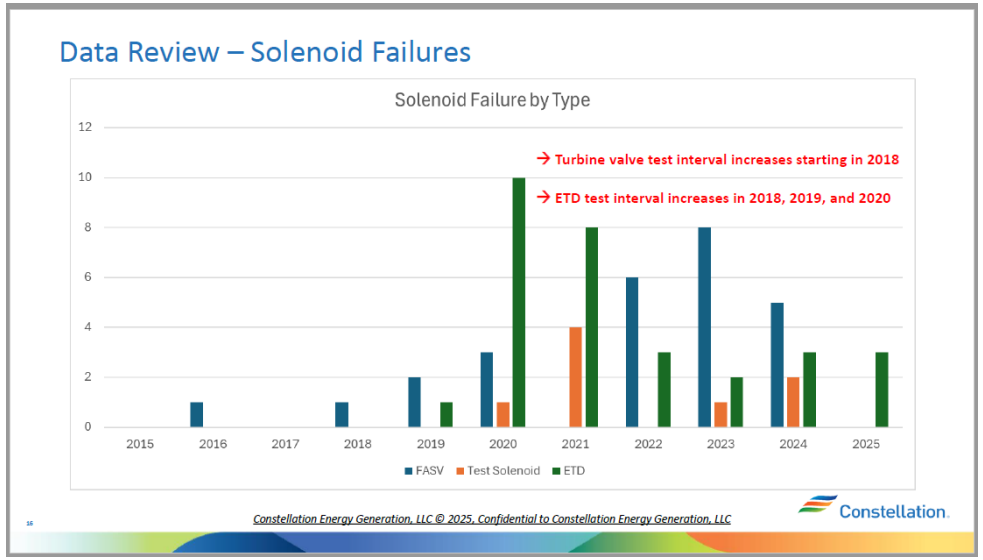
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EPRI

Overview

- Overview of EHC fluid quality and maintenance impacts on solenoids and servos in turbine systems
- Increasing actuator component failures observed over the past 5 years causing operational challenges and lost generation
- Key components reviewed:
  - Servos
  - Solenoids
  - Shutoff valves
  - Check valves
  - Dump valves
  - LVDTs
  - Trip switches
- Suspected causes include poor fluid quality, extended test and replacement intervals, and reduced manufacturing quality
- Case studies from Calvert Cliffs Unit 2, James A. Fitzpatrick, Nine Mile Point 2, Limerick, and others highlight varnish buildup, failed components, and operational risks
- Fluid varnish persists despite fluid changes and affects valve performance and reliability
- Recommendations: challenge PM strategies, replace servos/solenoids every 4-6 years, increase test frequencies if failures occur, conduct null-bias testing, maintain fluid cleanliness with flushing, and evaluate system design for fluid degradation risks
- Emphasis on fluid quality's critical role in preventing actuator failures and ensuring turbine reliability





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Turbine Generator Problem Areas

NEIL

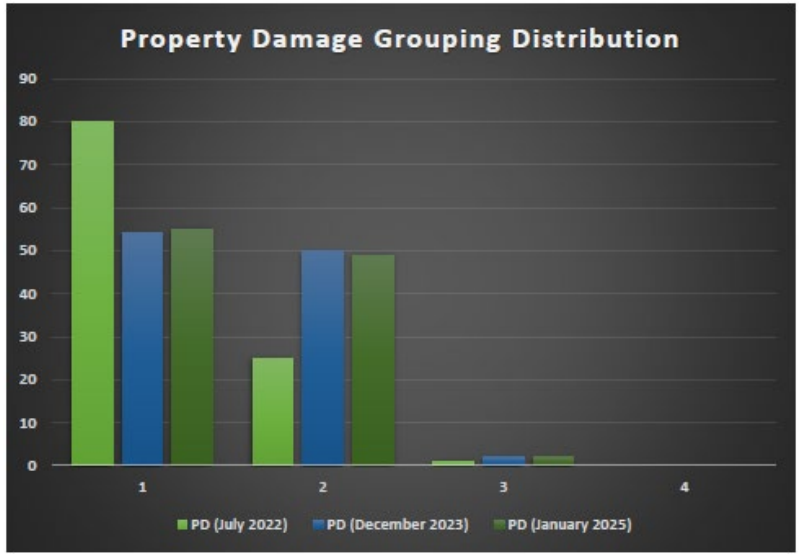
August 2025

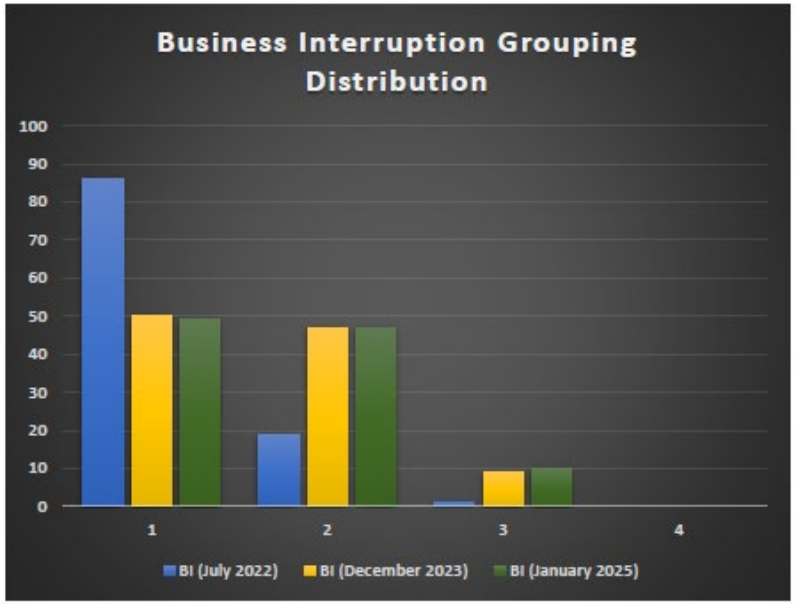
Minneapolis, Minnesota
Kevin Martin, Principal LPE

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Overview

- NEIL updated Turbine Generator Risk Assessment (TGRA) in 2022; all units assessed by end of 2023
- Updates driven by lessons learned from Callaway 2020 event, recent claims, operating experience, and future conditions like load cycling
- Problem Area Worksheets (PAWs) revised with new grading criteria including turbine valve testing intervals, condenser back pressure, full speed no load hours, blade vibration monitoring, and foreign material exclusion
- From July 2022 to January 2025, significant unit group migrations occurred in Property Damage (PD) and Business Interruption (BI) risk categories, stabilizing by 2025
- Notable increases in PAWs for LP last stage blade cracking, rotor blade attachment corrosion cracks, stator core thermal failure, and overspeed protection failures due to added probability factors and aging equipment
- Industry experts actively communicating risks related to full speed no load operation and turbine valve testing intervals
- OEMs responding with technical information letters (TILs) and design transitions to mitigate identified risks





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Overview

- Importance of collaborative outage preparation between service providers and site teams
- Key focus areas:
  - Scheduling
  - Communication
  - Work package review
  - Mobilization
  - Emergent work planning
- Emphasis on safety practices, tooling readiness, and risk mitigation through FMEAs and action tracking
- Case study: Steam turbine major outage with known vibration issues requiring adaptive scope changes
- Successful project outcome driven by contingency planning, daily communication, and leadership coordination

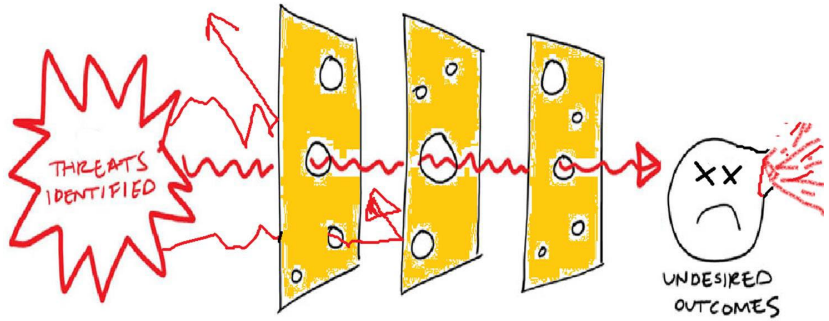
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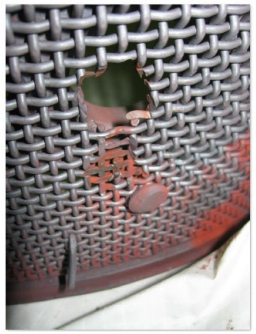
Overview

- Importance of Foreign Material Exclusion (FME) in plant safety and equipment reliability
- Definition of FME, Foreign Material, and Foreign Material Exclusion Area (FMEA)
- Core components of an effective FME program: procedures, plans, training, and material accountability logs
- Case studies illustrating the costly consequences of FME failures, including equipment damage, outages, and lost generation
- Examples of common foreign materials found and their sources
- The Swiss Cheese Model highlighting how multiple small failures can align to cause major incidents
- Emphasis on continuous awareness, proper practices, and cultural commitment to prevent FME-related issues and enhance overall site safety and performance











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TGUG

asktgug@epri.com

Turbine Generator Users Group Summer 2025

August 11-15, 2025

Minneapolis, MN
(virtual option available)

Turbine Generator Users Group Winter 2026

January 12-16, 2025

Tampa, FL

Turbine Generator Users Group Summer 2026

August 10-14, 2025

Kansas City, MO
(virtual option available)

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Final Remarks…

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Workshop Day 2

Program 219: Steam Turbines & Auxiliary Systems
Program 220: Generators & Auxiliary Systems

Eric Prescott
Area Manager, Senior Program Manager, Program Lead

2025 WANO Steam Turbine & Generator Workshop
Shanghai, China
3-6 November 2025

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Meeting Agenda

TOPIC
DAY 1: Experience Sharing *Monday, November 3rd*
DAY 2: Steam Turbine Focus *Tuesday, November 4th*
DAY 3: Generator Focus *Wednesday, November 5th*
DAY 4: Huaneng Advanced Cycle Working Session *Thursday, November 6th*

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Today's Discussions



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Randy Steele
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Mobile: 689.263.0242

DAY 2 - WORKSHOP TOPICS

Tuesday, November 4, 2025

Time	Topic	Lead
9:00a	• Opening Remarks	E. Prescott, EPRI
9:15a	Summary of Steam Turbine Fleet Experiences • *Industry Issues & Trends in 2025* • *Common Maintenance Findings*	R. Steele, EPRI
10:15a	Break	All
10:30a	Introduction to Blade Erosion • *Sources of Droplets* • *Effects from Erosion* • *Detection of Erosion* • *Mitigation of Erosion*	E. Prescott, EPRI
12:00p	Lunch	
1:00p	US Experience Managing Electro-Hydraulic Fluid Systems • *Fluid Sampling Program* • *Equipment Condition-based Maintenance*	R. Steele, EPRI
3:00p	Break	
3:15p	Monitoring & Diagnostic Technologies • *Technologies or tools that can be used for operation and maintenance optimization, overhaul optimization, and economic improvement, or best practices.* • *Application of AI and advanced analytics*	E. Prescott, EPRI
4:00p	Proposed 2025 Steam Turbine Research	R. Steele, EPRI
5:00p	Adjourn	All

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Steam Turbine Fleet Experiences

Industry Issues, Trends, and Maintenance Findings

Randall Steele
Senior Technical Leader

2025 WANO Steam Turbine & Generator Workshop
Shanghai, China
3-6 November 2025

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Steam Turbine Recent Experience Summary 2025

Loss of Fluid System Functionality

15 EHC SYSTEM EVENTS
3 LUBE OIL SYSTEM EVENTS

Management of Turbine Component Integrity

Operating Aging Equipment More Flexibly

3 STEAM TURBINE O&M CATEGORIZED EVENTS

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Loss of Fluid System Functionality

EHC Fluid System

- Loss of control fluid results in Turbine Trip
- Common sources…
  - Supply line failure due to vibration wear and unsatisfactory joint connections
  - Loss of signal from control system due to contact and wire wear
  - Sticking and sporadic movement of solenoid/servo/proportional valve from wear and fluid byproduct deposition
  - Position feedback response due to electrical connections, damaged positioners, or control system calibration
  - Fluid system with poor performance and unable to supply pressure

Related Experience

650723	Electro Hydraulic Control Fluid Leak At Intercept Valve Shut Off Valve
650026	Electro-hydraulic Control Leak From Main Turbine Control Valve System
649274	Unplanned Power Decrease Due To Main Turbine Governor Valve Oscillations
648700	Incorrect Valve Manipulated Resulting In Two Valves Being In The Incorrect Position
646473	Rapid Down Power Due To Electro-hydro Fluid Leak
645809	Control Valve High Pressure Turbine Main Steam Supply Line Going Closed
642866	Electro- Hydraulic Control System Leak Results In Manual Reactor Shutdown
637744	Electro-hydraulic Control Leak From Main Turbine Control Valve System
635610	Closure of Moisture Separator Reheater Steam Supply Valve Requires Load Drop
635410	Broken Turbine Control Valve Liner Variable Differential Transformer Rod Replaced During Exempt Down Power
633837	Automatic Actuation of Containment Isolation Valves During Turbine Valve Tightness Testing
632840	Main Steam Throttle Valve Failure to Open During Online Testing Results in Downpower
627692	Electro-hydraulic System Leak Results In Manual Reactor Trip
623776	Reactor Manual Scram due to Electro Hydraulic Control System Oil Leak
647769	Main Steam Temperature Control Valve Closure

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EHC System Supporting Information

RESOURCES

- **TR-104885** Introduction to Nuclear Plant Steam Turbine Control Systems
- **TR-108146** General Electric Electrohydraulic Controls (EHC) Electronics Maintenance Guide
- **1009072** Life Cycle Management Sourcebooks - Volume 9: Main Turbine Electro-Hydraulic Controls
- **3002003594** Electrohydraulic Control (EHC) Fluid Maintenance Guide
- **1011823** Electrohydraulic Control Fluid and Elastomer Compatibility Guide
- **1000935** EHC Tubing/Fittings and Air Piping Applications and Maintenance Guide
- **3002021551** EHC System Sensor Gap Analysis Workbook
- **3002021594** Electrohydraulic Control System Sensor Gap Analysis: Identification of Sensors for Fluid and System Components

Turbine Generator Outage Guidelines

3002013931 - EXE

https://turbineoutageguide.epri.com

WIKI coming soon…

Lube Notes

https://nmac.epri.com/index.php/NMAC/CBM/Lubrication

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Loss of Fluid System Functionality

Lube Oil System

- Turbine Trip when supply pressure not achieved
  - Fluid system with poor performance and unable to supply pressure
- Failure of EBOP/ESOP leading to damage event during shutdown
  - Mechanical System Reliability
  - DC Power supply
  - DC Power relays, fuses, logic & system integration

Related Experience

642867	Bearing Failure Resulted In Manual Unit Shutdown
633835	Lube Oil Pump Lockout Resulted in a Non-Functional Station Blackout Generator
631638	Lube Oil Drain Valve Found Open Instead of Closed

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Lube Oil System Supporting Information

RESOURCES

- **1025331** **Turbine** Generator Auxiliary Systems Volume 1: **Turbine** Generator Lubrication System Maintenance Guide-2012 Update
- **1004384** **Lube Oil** Predictive Maintenance, Handling, and Quality Assurance Guideline
- **3002003593** Backup **Oil** System Maintenance Guide
- **3002031196** **Turbine**-Generator Backup **Lube Oil** System DC UPS: Operating and Maintenance Guide
- **3002005576** Remediation of Lost Demulsibility in **Turbine Oil**
- **TR-111413** **Lube Oil** System Leakage Mitigation
- **3002024125** **Lube Oil** System Sensor Gap Analysis Workbook
- **3002024123** **Lube Oil** System Sensor Gap Analysis: Identification of Sensors for Fluid and System Components

Turbine Generator Outage Guidelines

3002013931 - EXE

https://turbineoutageguide.epri.com

WIKI coming soon…

Lube Notes

https://nmac.epri.com/index.php/NMAC/CBM/Lubrication

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Steam Turbine Integrity

Key Aspects of Integrity

- System Isolation and Testing
- PM/CM Scope and Quality of Execution
- Online Monitoring and Interpretation of Plant Data (Troubleshooting)

Related Experience

649265	External Leakage In Two Control Valves Of The Steam Reheater System
645363	Turbine Generator High Temperature Fasteners Exceeded Lifetime Limit
627694	Control Valve Failed to Control Gland Steam Pressure

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Defining Today's Challenges and Research Needs

Steam Turbine Issues:

1. Turbine Mechanical Integrity & Component Damage

- Running with cracked blades/attachments
- Rotor disk cracking
- Blade FOD
- LP blading pin cracks
- Blade shield HAZ cracking
- Journal repair from heavy rub at oil seal
- Journal/Bearing electrolysis damage
- Bearing noise
- Bearing oil leaks
- Valve casing cracks
- Valve casing fixation and pipe loads on turbine
- Horizontal joint steam leakage
- Cross over pipe compensator failure
- Axial movement of train during operation
- BFPT rotor flaws
- Loose spring blade replacement
- Shaft grounding

MAINTENANCE

SCRAM RISK/OPERATIONAL RELIABILITY

2. Valve Systems & Controls

- Valve inspection and test frequency
- Valve hunting
- Unifying/Improving EOH factors
- Overspeed energy calculation
- Loss of EHC fluid causing turbine trip
- Back up oil pump testing

3. Lubrication & Hydraulic Systems (EHC)

- EHC hose material selection
- Too much air in EHC fluid
- EHC fluid degradation

4. Vibration, Monitoring & Diagnostics

- Cyclic bearing vibration
- Torsional monitoring to manage grid interaction risk
- Unexplained turbine noise during operation

MONITORING

5. Steam Path & Chemistry

- Steam chemistry upsets and humidity control
- ST ELEP moisture requirement

6. Repair, Maintenance & Materials

- Coated airfoil repairs (diffusion and HVOF)
- Scrapping removed parts
- Blast media selection for cleaning turbines

7. Operational Risk & Assessment

- Fleet risk assessment
- Nuclear part load operation

8. Alignment & Assembly

- Coupling alignment cycle/accuracy improvement

Related P219 Member Assists in 2025

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TGUG Roundtable

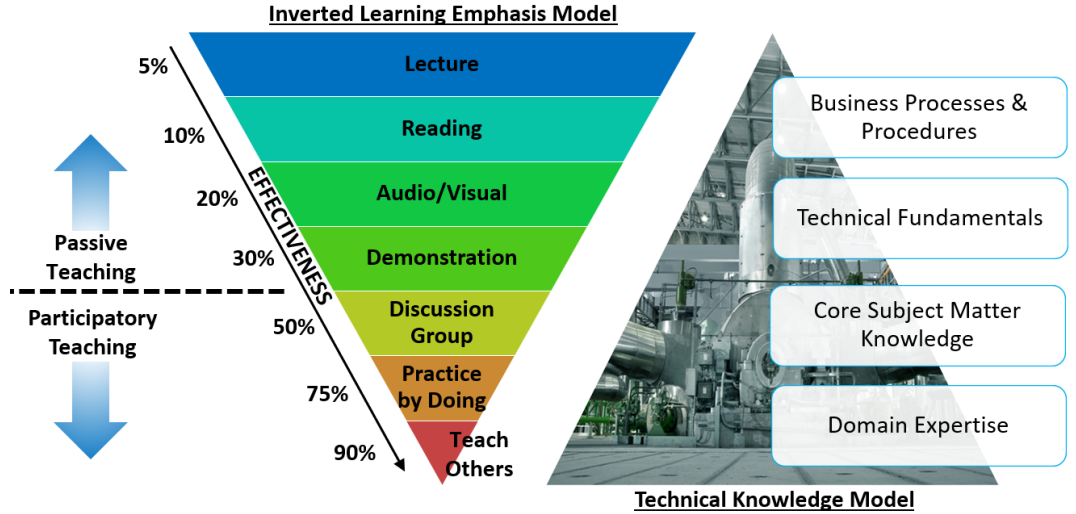


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Summary

- Historically, EPRI has been tasked to address specific technical challenges.
- Today, issue recurrence due to equipment degradation and operating practice is more prevalent.
- Equipment Aging, Workforce Transitions, or a little bit of both?

Participatory teaching leads to highest learning outcomes…



Discussion Groups



TCUG

Active Participation this is a Forum to Learn

Leverage EPRI and other industry working groups

Practice & Teach



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Break

Steam Turbine Blade Erosion

Sources, Effects, Detection, and Mitigation

Eric Prescott
Area Manager, Senior Program Manager, Program Lead

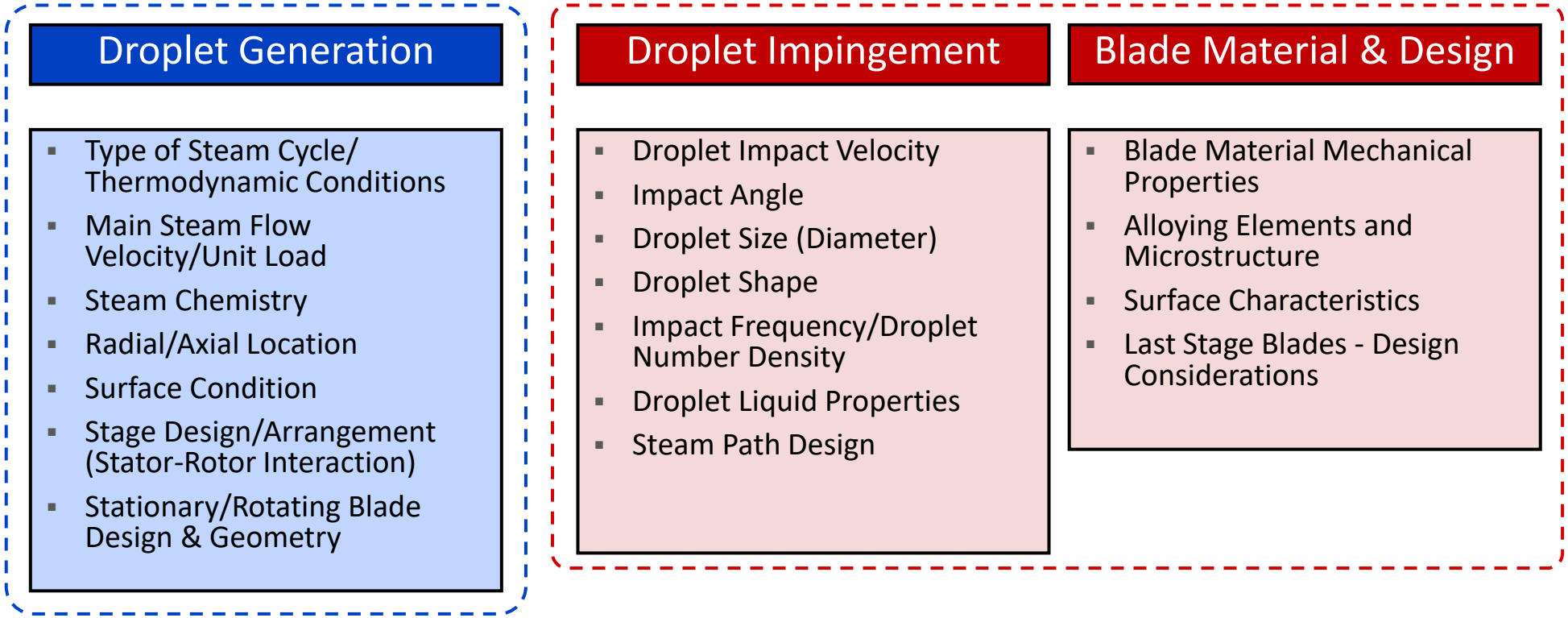
2025 WANO Steam Turbine & Generator Workshop
Shanghai, China
3-6 November 2025

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Droplet Erosion Damage Mechanism

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Factors Influencing Droplet Erosion Damage Mechanism

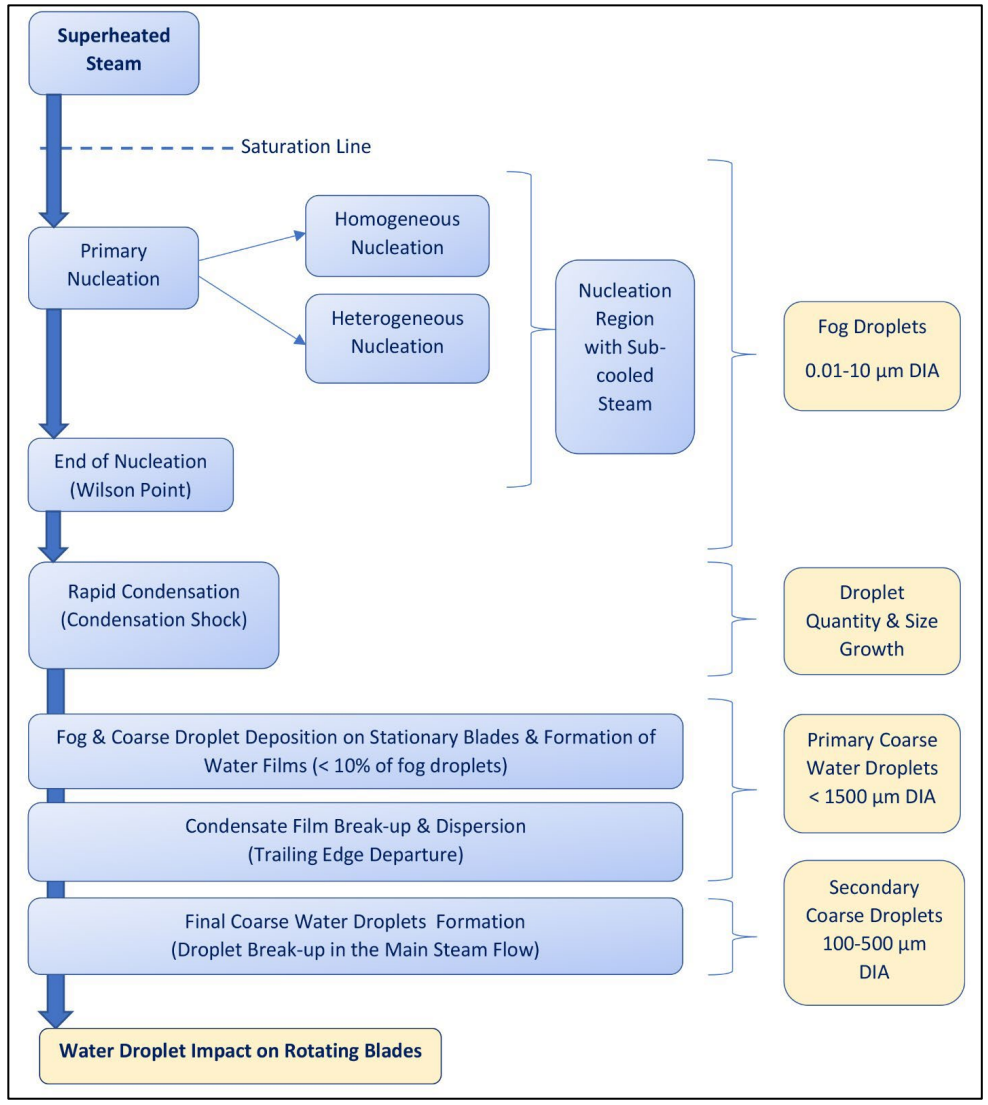


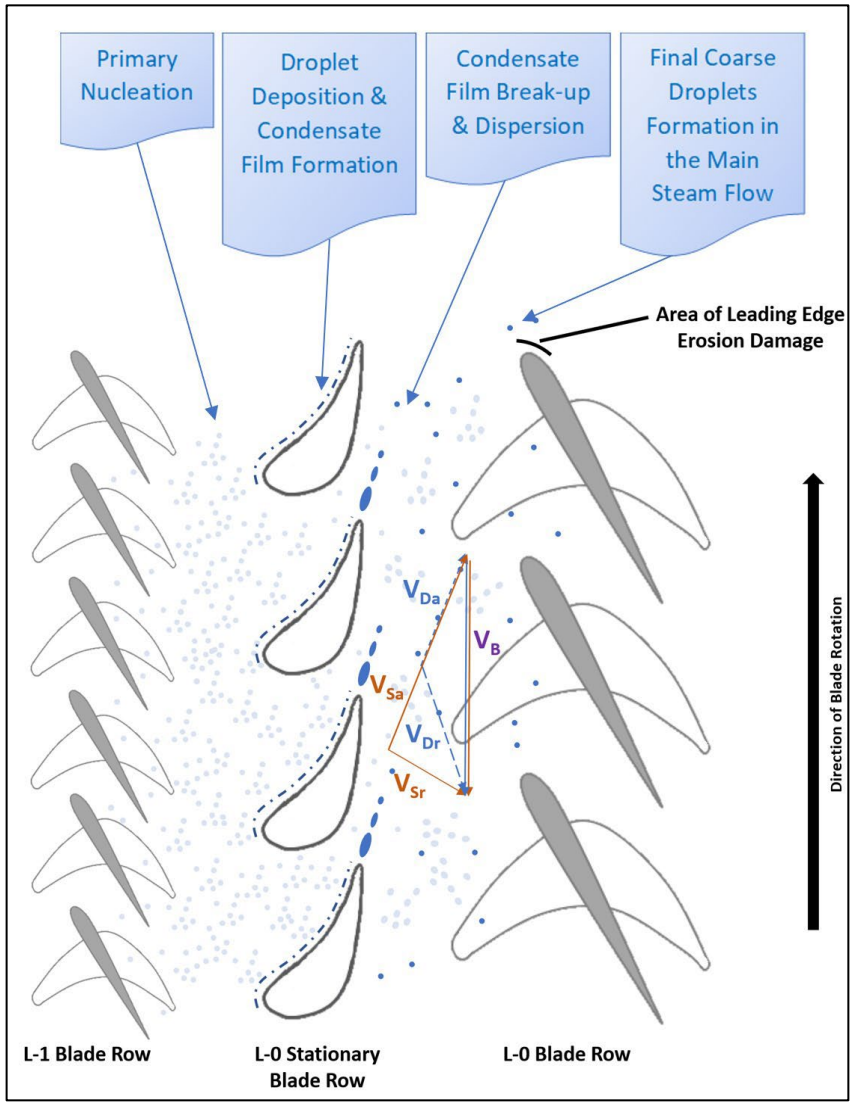
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Factors Influencing Droplet Erosion Damage

Moisture Generation and Growth

LEADING EDGE EROSION





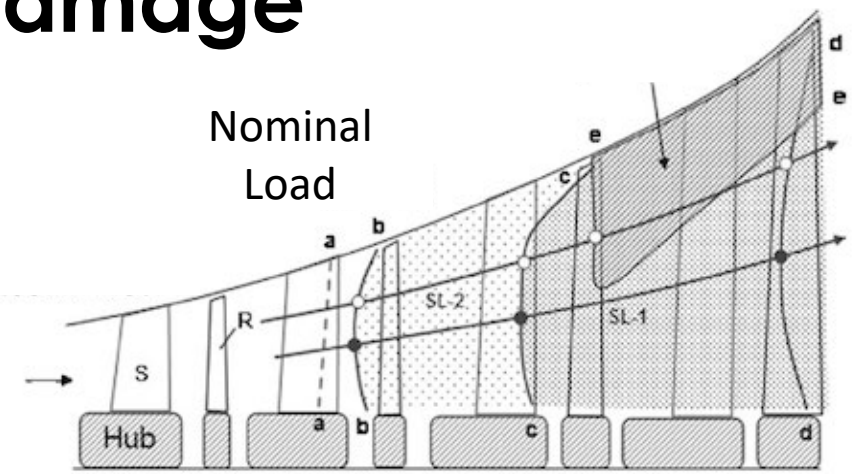
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Factors Influencing Droplet Erosion Damage

Moisture Generation and Growth

LEADING EDGE EROSION

- Droplet generation and growth – influenced by the steam thermodynamic conditions and flow patterns at various loads
- Lower reheat steam temperatures => higher moisture level
- Low mass steam flow – lower steam velocities (constant blade velocities)
- Same LP inlet steam temperature and condenser pressure, lower mass flow (lab tests) =>
  - **coarse droplet size increase** due to reduction in shear forces between droplets and steam flow
  - coarse droplet relative **velocity increases** => erosion damage potential increases
  - coarse water droplets suffer from a deficit in absolute velocity at the stator exit => impact on L-0 leading edge **suction side**
  - high **variation of droplet mass rate** due to unsteady steam flow field



Source: I. Bosdas, "Time Resolved Flow Field and Droplet Measurements in Wet Steam Turbine Flows" 2016.

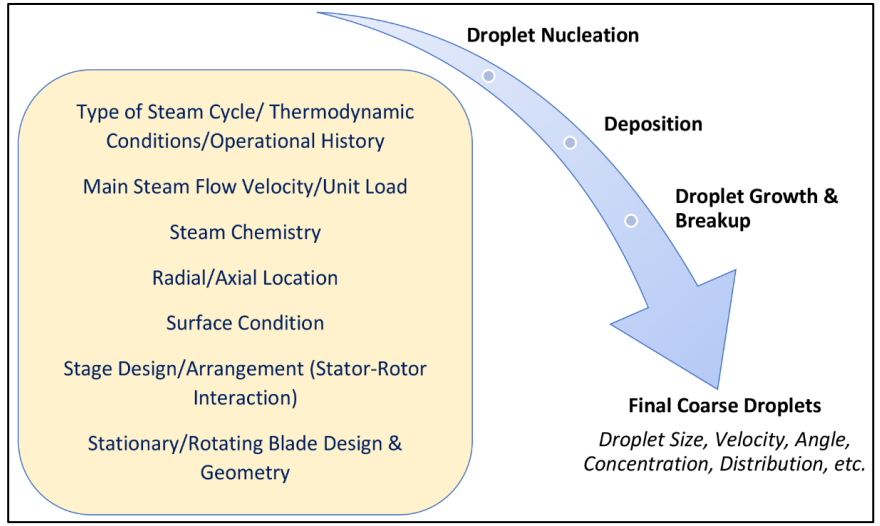
a-a: Saturation line

b-b: Heterogeneous nucleation transition (Dd: 0.01-0.1μm)

c-c: Primary homogeneous nucleation transition (Dd: 0.001-0.01μm)

d-d: Secondary primary homogeneous nucleation transition

e-e: Secondary droplet region originating from trailing edges of rotating blades (Dd: 0.01-300μm)



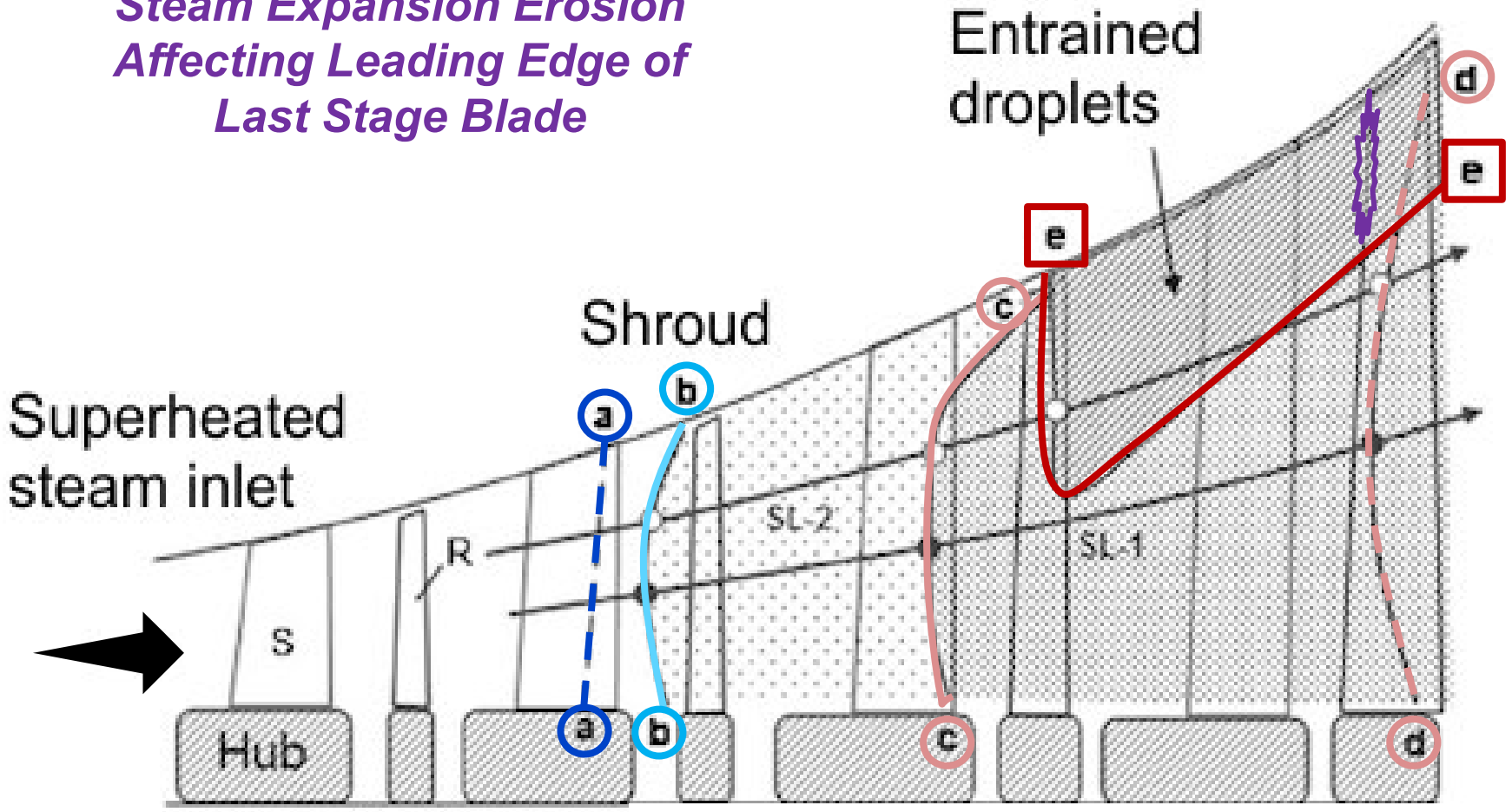
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Factors Influencing Droplet Erosion Damage

Moisture Generation and Growth

LEADING EDGE EROSION

Steam Expansion Erosion Affecting Leading Edge of Last Stage Blade



Source: I. Bosdas, "Time Resolved Flow Field and Droplet Measurements in Wet Steam Turbine Flows" 2016.

Nominal Load

a-a: Saturation line

b-b: Heterogeneous nucleation transition

(Dd: 0.01-0.1µm)

c-c: Primary homogeneous nucleation transition

(Dd: 0.001-0.01µm)

d-d: Secondary primary homogeneous nucleation transition

e-e: Secondary droplet region originating from trailing edges of rotating blades

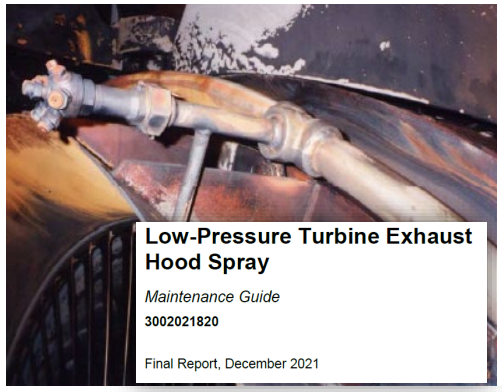
(Dd: 0.01-300µm)

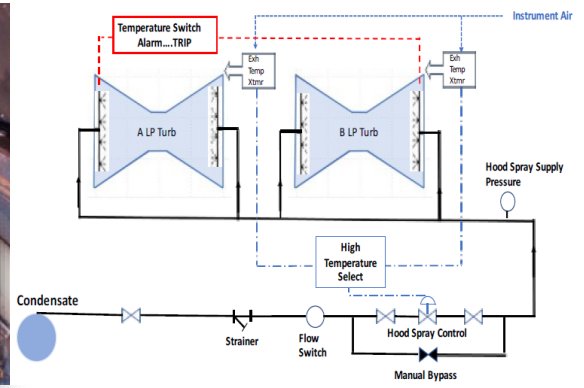
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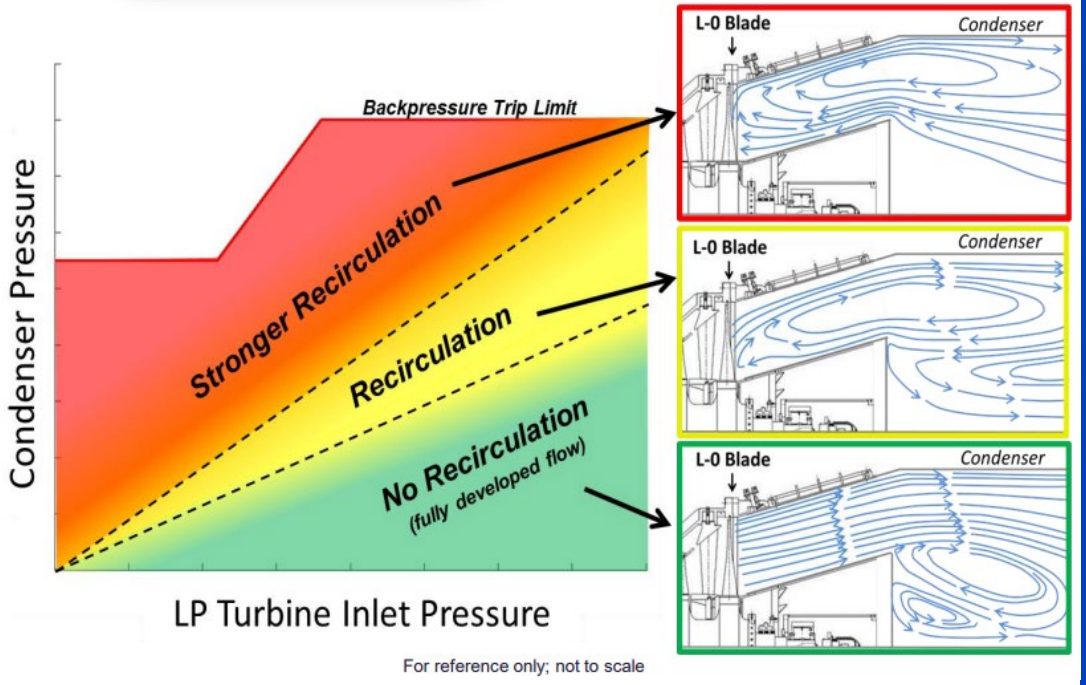
Factors Influencing Droplet Erosion Damage

Moisture Generation and Growth

- Low mass steam flow – recirculating flow field
- High exhaust steam temperatures => introduce water spray to cool back end, or resultant of other process effects (e.g. sparging)
- Droplet evaporation efficiency – influenced by the steam thermodynamic conditions and flow patterns with entry of exhaust-side droplet characteristics
  - Large droplets will not evaporate during the path of recirculation to the trailing edge
  - Too many droplets will lead to saturation condition where droplets will not evaporate
- **Initial droplet size increase** due to deviations in spray flow (including leakage) and nozzle/orifice size







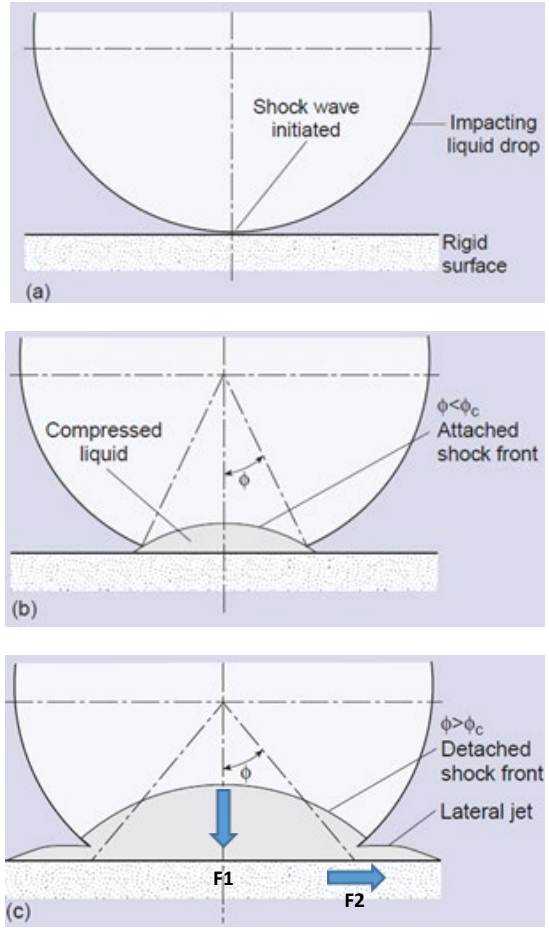
Source: Siemens Energy, "Jan 2022 TGUG OEM SESSION".

TRAILING EDGE EROSION

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Factors Influencing Droplet Erosion Damage

Droplet Impact - Simplified Liquid Dynamics onto a Solid Surface



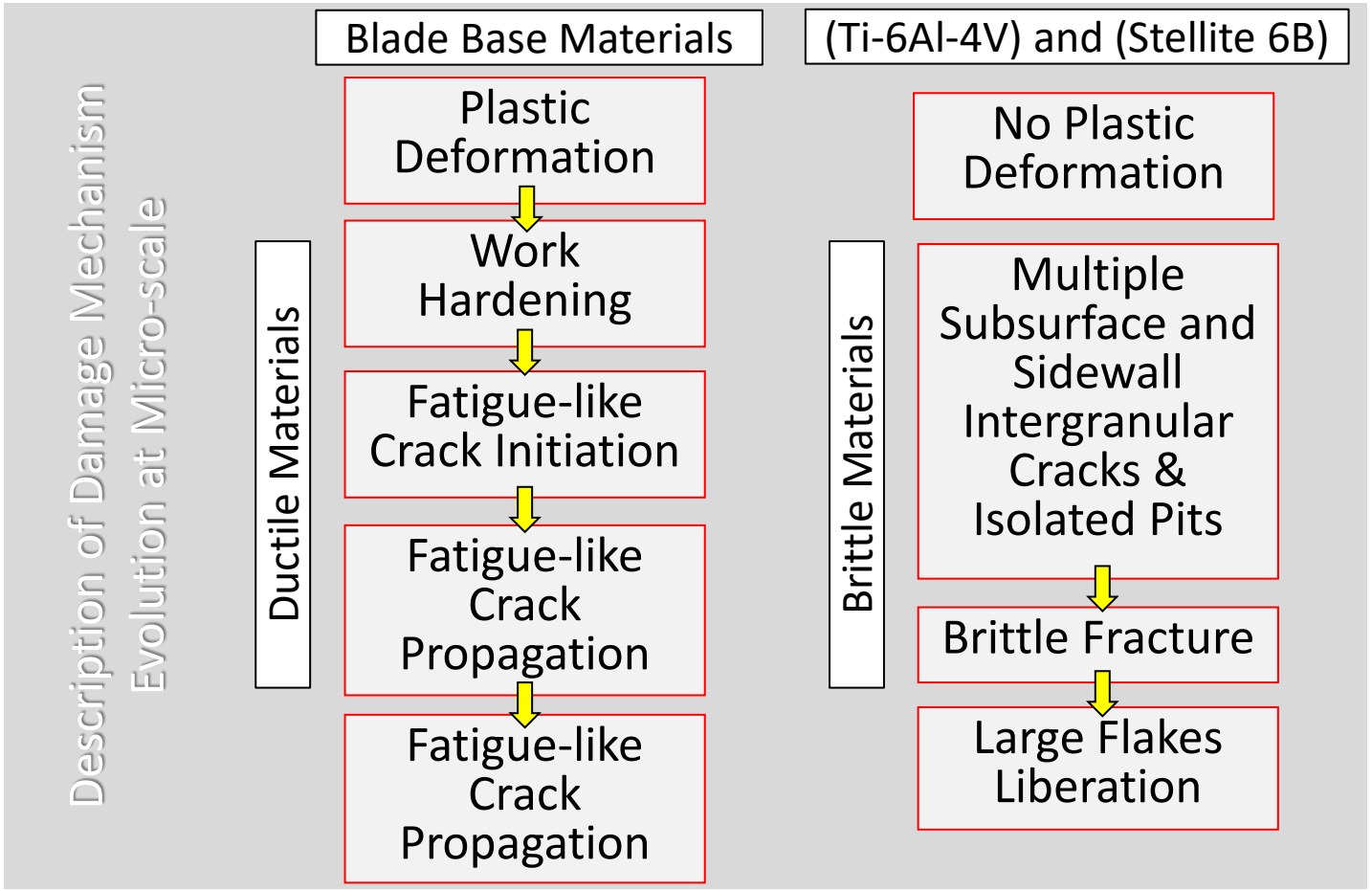
- (a) The initial impact between the liquid droplet with a curved surface and a rigid flat surface results in high pressure shockwaves (water-hammer)
- (b) The contact periphery spreads out with a velocity greater than the shockwave resulting in a compressed liquid in the shock envelope and a maximum pressure
- (c) When the contact angle reaches a critical value, the pressure built in the compressed fluid is released through lateral jet along the surface
- The major drivers to the surface damage are the high pressure shock on the solid surface (**F1**) generated at the initial impact, the shear forces (**F2**) because of a high-velocity lateral jet, and, in some cases, cavitation phenomenon.

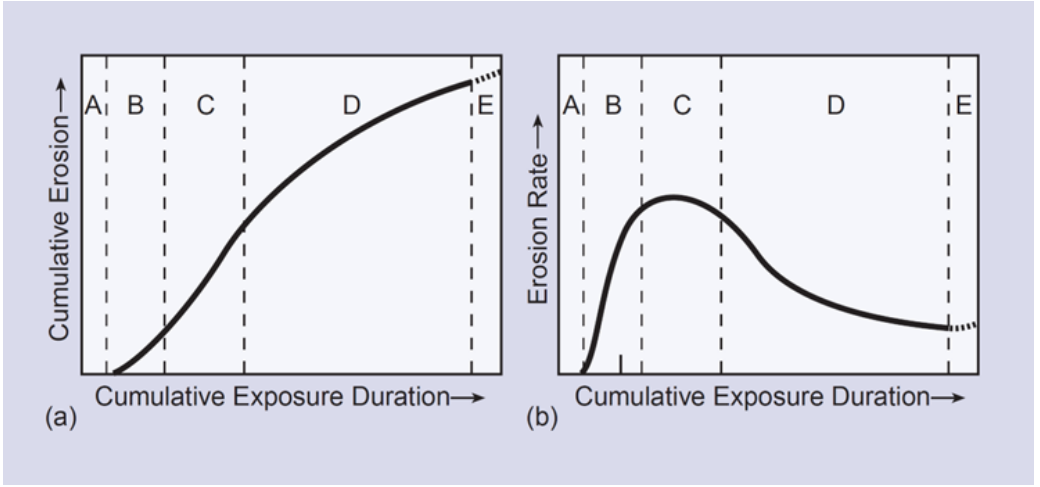
- Coarse droplet - 200 µm DIA diameter and a velocity of 500 m/s => impact pressure for a typical 12Cr SS steam turbine blade material ~ 1160 MPa
- Newer longer L-0 blades – 750 m/s at the blade tip for 3600 rpm units
- L-0 trailing edge area – 200 m/s
- Nuclear HP turbine blade tip velocities – 100-200 m/s (half-speed)

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Factors Influencing Droplet Erosion Damage

Droplet Erosion Damage Mechanism





- A. Incubation stage
- B. Acceleration stage
- C. Maximum rate state (sometimes called first steady-state stage)
- D. Deceleration stage
- E. Terminal or final steady

Droplet erosion damage mechanism is a special form of erosion produced by repetitive impingement of high-velocity liquid droplets on a solid surface

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Factors Influencing Droplet Erosion Damage

Droplet Impingement

- Factors:
  - Droplet Impact Velocity
  - Impact Angle
  - Droplet Size (Diameter)
  - Droplet Shape
  - Impact Frequency/Droplet Number Density
  - Droplet Liquid Properties
  - Steam Path Design

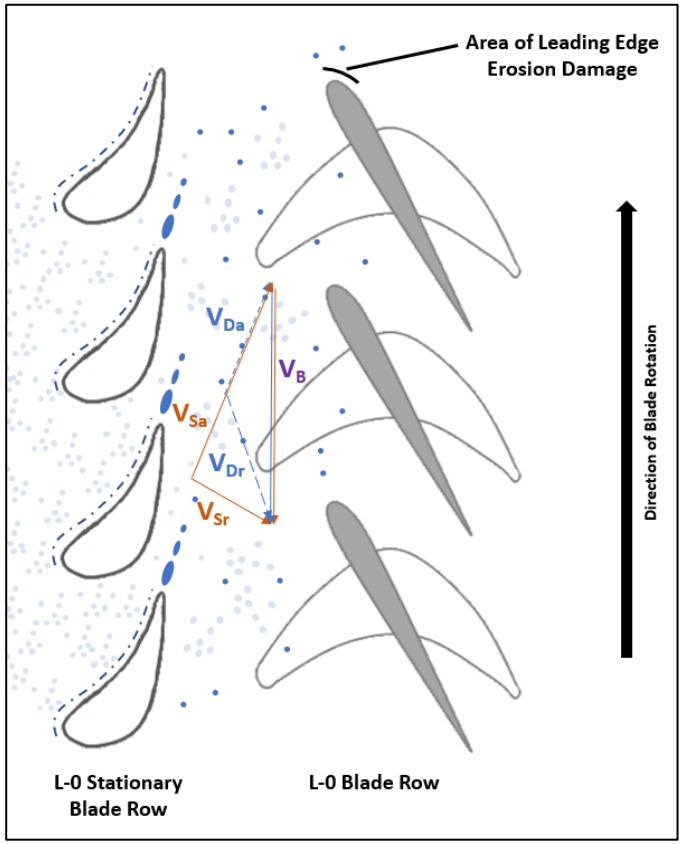
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Factors Influencing Droplet Erosion Damage

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  - **Droplet Impact Velocity**
  - Impact Angle
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  - Impact Frequency/Droplet Number Density
  - Droplet Liquid Properties
  - Steam Path Design

- Impact velocity not the same as droplet velocity
- Function of circumferential velocity of the blade at the radial location of the impact
- Influences the amount of energy transferred to the blade material
- **Erosion Rate ~ V^x**
- x = 3.5 - 5 (ductile materials)
- x = 6 – 9 (brittle materials)



V_{Sr} - steam relative/impact) velocity
V_{Sa} - steam absolute velocity
V_{Dr} – droplet relative/impact velocity
V_{Da} – droplet absolute velocity
V_B – blade velocity

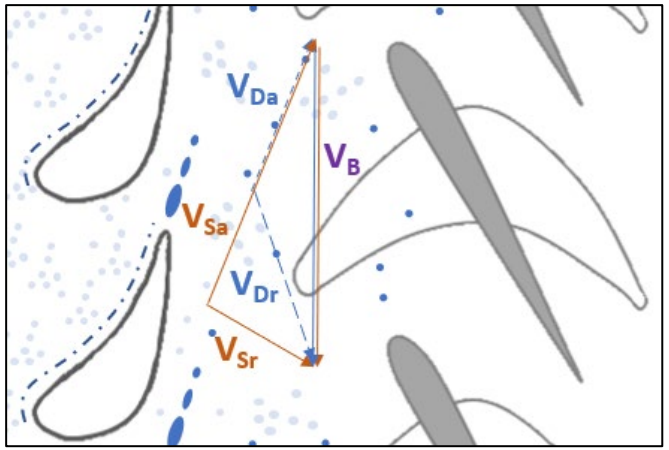
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Factors Influencing Droplet Erosion Damage

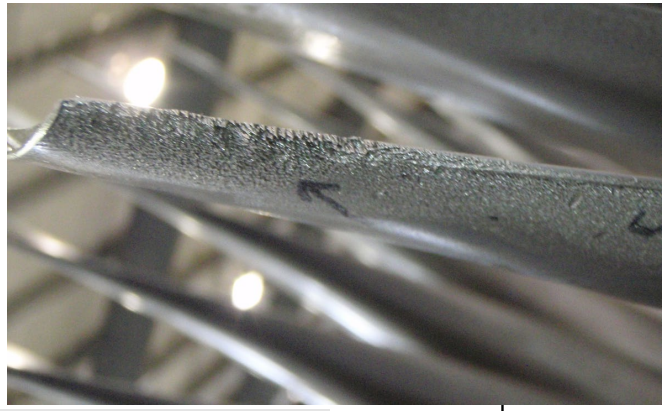
Droplet Impingement

- Factors:
  - Droplet Impact Velocity
  - **Impact Angle**
  - Droplet Size (Diameter)
  - Droplet Shape
  - Impact Frequency/Droplet Number Density
  - Droplet Liquid Properties
  - Steam Path Design

- Flat surfaces - normal component of the impact velocity causes maximum damage
- If the impact angle changes from 90° => normal component is reduced and less damaging
- 50° impact angle => erosion damage is reduced to 40% of the erosion at 90°
- Tangential component => potentially damaging to the asperities on roughened surfaces



V_{Sr} - steam relative/impact) velocity
V_{Sa} - steam absolute velocity
V_{Dr} – droplet relative/impact velocity
V_{Da} – droplet absolute velocity
V_B – blade velocity



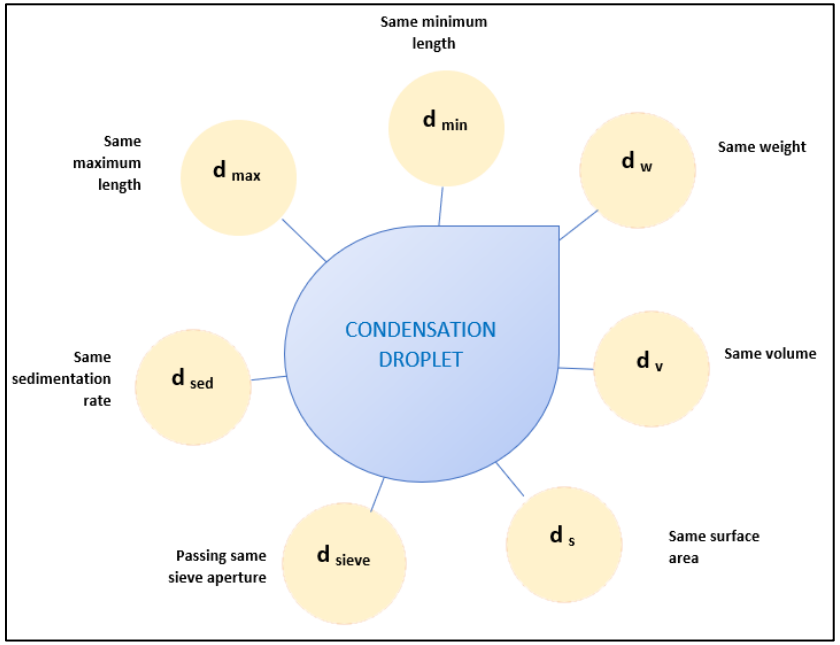
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Factors Influencing Droplet Erosion Damage

Droplet Impingement

- Factors:
  - Droplet Impact Velocity
  - Impact Angle
  - **Droplet Size (Diameter)**
  - Droplet Shape
  - Impact Frequency/Droplet Number Density
  - Droplet Liquid Properties
  - Steam Path Design

- Main impingement parameter along with droplet velocity
- It influences the area affected by the impact, time duration of the impact pressure wave, impact pressure distribution and the amount of transferred kinetic energy
- Same quantity of water larger droplets had a higher damaging effect (more and faster damage) than the smaller droplets with a larger number of impacts
- **Erosion Rate ~ D^x** where x = 3.2 – 3.5 (ductile materials)



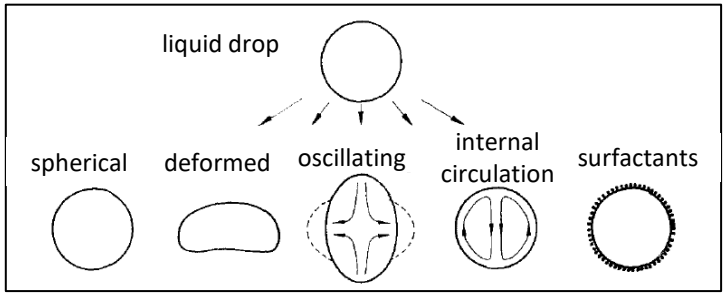
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Factors Influencing Droplet Erosion Damage

Droplet Impingement

- Factors:
  - Droplet Impact Velocity
  - Impact Angle
  - Droplet Size (Diameter)
  - **Droplet Shape**
  - Impact Frequency/Droplet Number Density
  - Droplet Liquid Properties
  - Steam Path Design

- Distorted droplets having radii larger than the initial diameter in the contact area => higher erosion potential
- Limited understanding on:
  - the distortion magnitude affecting the water droplets
  - kinetic energy transferred by a distorted droplet to the target material and
  - the quantification of the droplet shape influence to the erosion potential

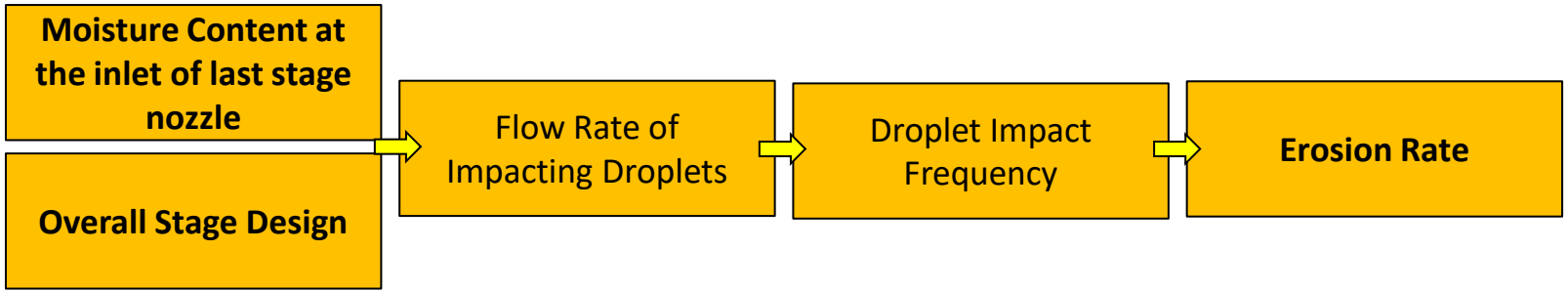


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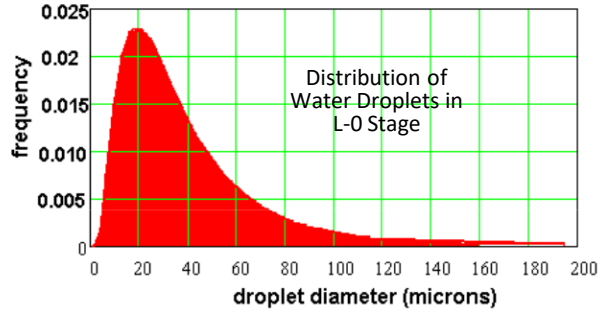
Factors Influencing Droplet Erosion Damage

Droplet Impingement

- Factors:
  - Droplet Impact Velocity
  - Impact Angle
  - Droplet Size (Diameter)
  - Droplet Shape
  - **Impact Frequency/Droplet Number Density**
  - Droplet Liquid Properties
  - Steam Path Design



Probabilistic approaches used in the past to correlate the erosion rates with the frequency of impacts



Relation between the erosion rate and impact frequency is not linear:
- complex pattern of impacting water droplets with different characteristics
- simultaneous impacts or at different intervals and
- the collision between incident droplets and rebounded droplets

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Factors Influencing Droplet Erosion Damage

Droplet Impingement

- Factors:
  - Droplet Impact Velocity
  - Impact Angle
  - Droplet Size (Diameter)
  - Droplet Shape
  - Impact Frequency/Droplet Number Density
  - **Droplet Liquid Properties**
  - Steam Path Design

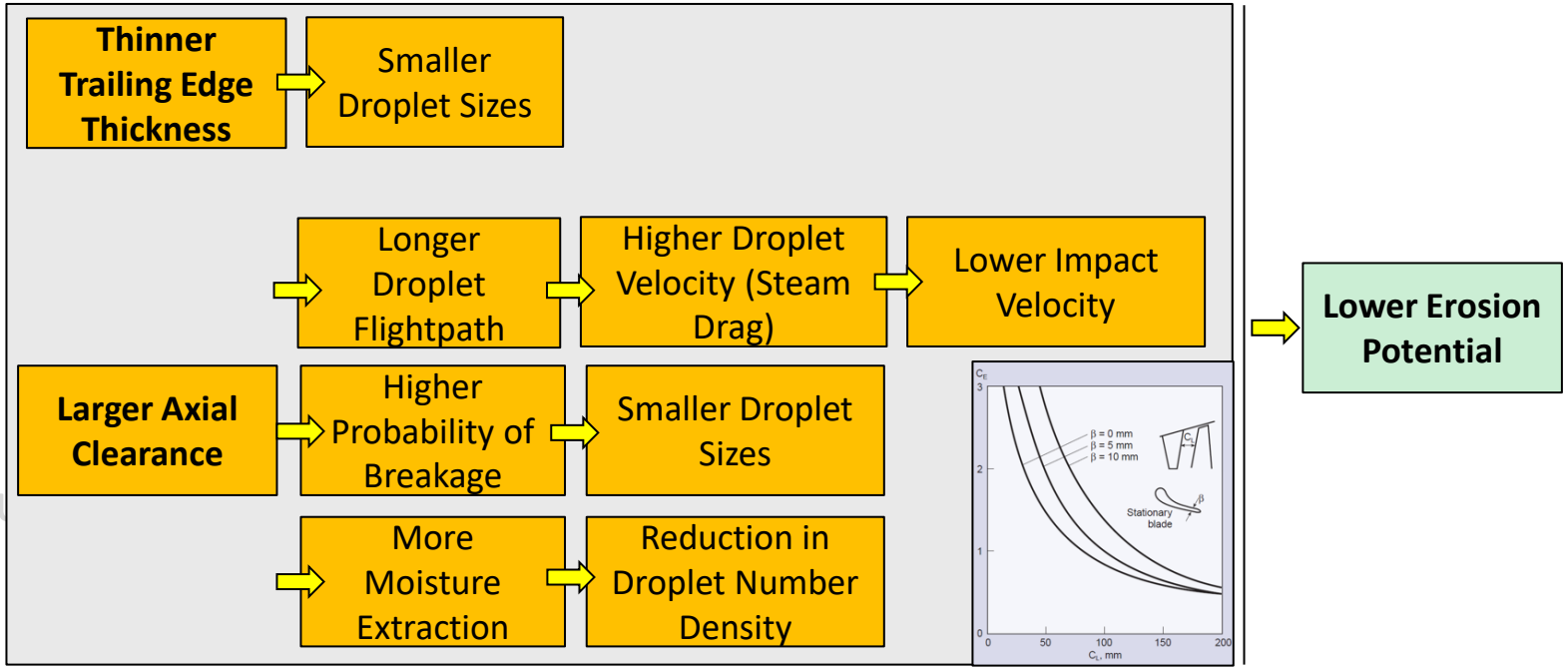
- Liquid density **Erosion Rate ~ ρ^x ; x = 2 - 2.5 (lab, atm press)**
- Liquid viscosity **Erosion Rate ~ η^x ; x = 0.5 – 0.25 (lab, atm press)**
- Other influencing liquid properties: impacting bulk modulus, specific acoustic velocity and temperature - influence on pressure shock waves and lateral jet flows
- Calculation of erosion rates for operating units requires the inclusion of operation specific liquid properties

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Factors Influencing Droplet Erosion Damage

Droplet Impingement

- Factors:
  - Droplet Impact Velocity
  - Impact Angle
  - Droplet Size (Diameter)
  - Droplet Shape
  - Impact Frequency/Droplet Number Density
  - Droplet Liquid Properties
  - **Steam Path Design**



Steam turbine stage design and operational modes have important roles in the water droplet formation and their specific characteristics **throughout** the turbine steam path prior to the impacting the L-0 rotating blades

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Factors Influencing Droplet Erosion Damage

Blade Target Material & Design Characteristics

- Factors:
  - Blade Material Mechanical Properties
  - Alloying Elements and Microstructure
  - Surface Characteristics
  - Last Stage Blades - Design Considerations

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Factors Influencing Droplet Erosion Damage

Blade Target Material & Design Characteristics

- Factors:
  - **Blade Material Mechanical Properties**
  - Alloying Elements and Microstructure
  - Surface Characteristics
  - Last Stage Blades - Design Considerations

- **Hardness**: **Erosion Resistance ~ HV^x ; x = 2.3 - 2.5 (steel)**
- **Yield strength** – good linear correlation
- Ultimate strength
- **Modulus of elasticity** – good linear correlation
- Ultimate resilience
- Toughness
- Hardenability
- Fracture toughness
- Strain energy

Independent macroscopic material property - Impact Erosion Resistance Parameter

$$\underbrace{R_{E,50}\sqrt{\frac{p_{impact}}{\rho_l}}}_{\text{reduced erosion resistance}} = f\left(\underbrace{\alpha, \frac{A_{target}}{D_{Sauter}^2}, \frac{p_{impact}}{K}}_{\text{liquid droplet characteristics}}, \underbrace{\frac{P_t + R_t}{D_{Sauter}}, \frac{p_{impact}}{H_V}, \frac{E}{K}, \frac{\rho_s}{\rho_l}}_{\text{liquid solid interaction}}, \underbrace{\frac{H_V}{U_r^*}, \frac{U_t}{U_r^*}}_{\text{solid characteristics}}\right)$$

Erosion Resistance Assessment - relative erosion resistance to a reference material (normalized erosion resistance) - ASTM G73

Crack Initiation
Crack Propagation
→ **Material elongation** + **Area Reduction** + **Impact Toughness**

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Factors Influencing Droplet Erosion Damage

Blade Target Material & Design Characteristics

- Factors:
  - Blade Material Mechanical Properties
  - **Alloying Elements and Microstructure**
  - Surface Characteristics
  - Last Stage Blades - Design Considerations

- Base material erosion resistance increases with are **chromium**, **manganese**, and **cobalt**.
  - *The effect of nickel was found inconclusive by test results reviewed but notionally increases strength and hardness without sacrificing ductility and toughness.*
- **Material microstructure** - fine microstructure has higher erosion resistance (such as of Stellite - small hard carbide particles in a strong but more ductile matrix)
  - *Erosion target material microstructure is also subject to transformation during the droplet impact process. At certain impact velocities, local water drop peening effect and surface hardening occurs with beneficial results in erosion resistance.*

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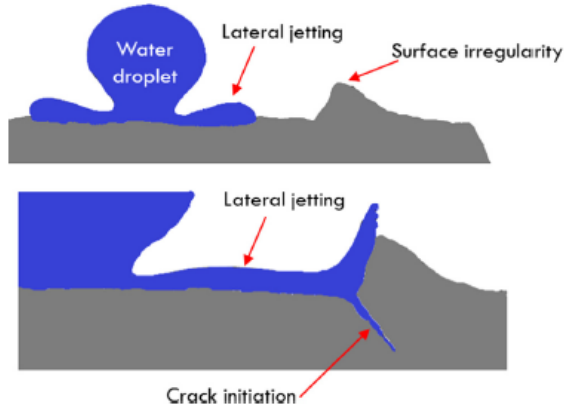
Factors Influencing Droplet Erosion Damage

Blade Target Material & Design Characteristics

- Factors:
  - Blade Material Mechanical Properties
  - Alloying Elements and Microstructure
  - **Surface Characteristics**
  - Last Stage Blades - Design Considerations

- Important role during the **incubation** period

Material	Impact Velocity	Droplet Diameters	Change in incubation period between original and polished surface
12% Cr SS	300 m/s	603 µm	+ 70%
Ti-6Al-4V	350 m/s	460 µm	+ 100 %



Important role during the **erosion progression**:

Surface condition determines the time required for the droplets to create roughened surfaces prior to the formation of erosion pits through the action of lateral jet flows

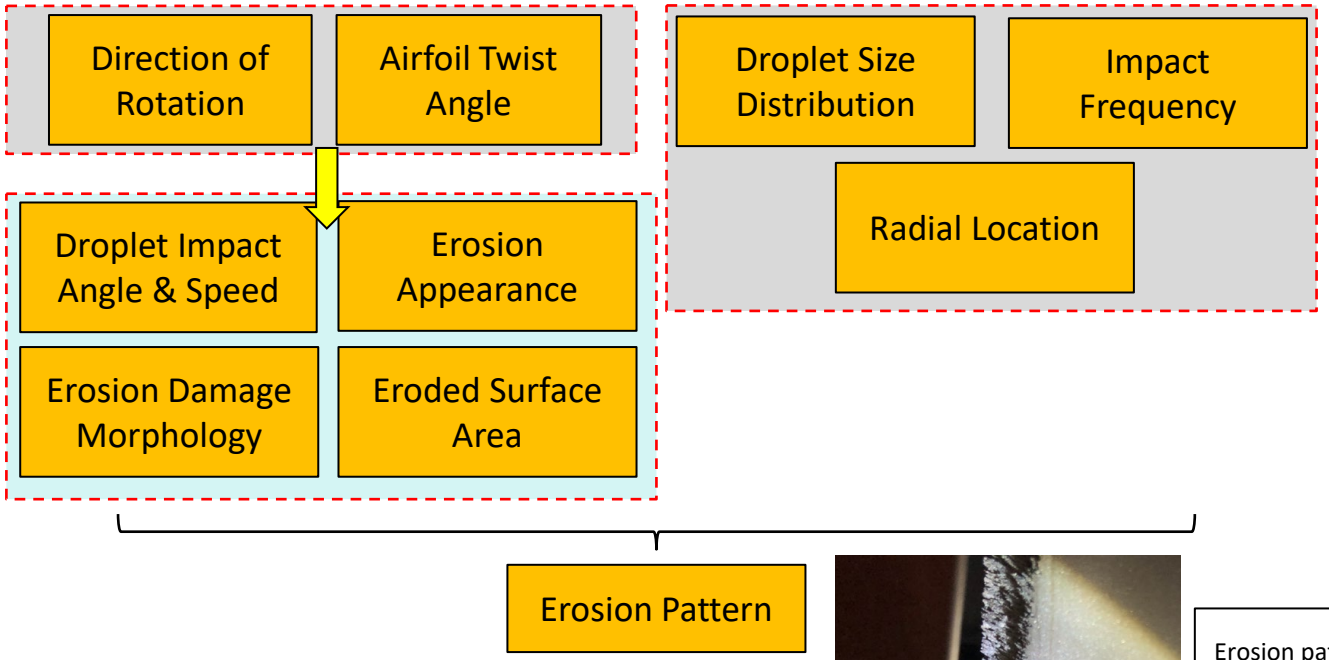
Simple mechanical polishing could significantly prolong the **incubation stage** and delay the erosion process

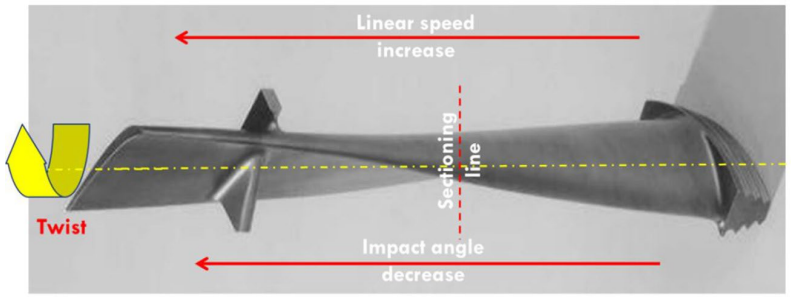
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Factors Influencing Droplet Erosion Damage

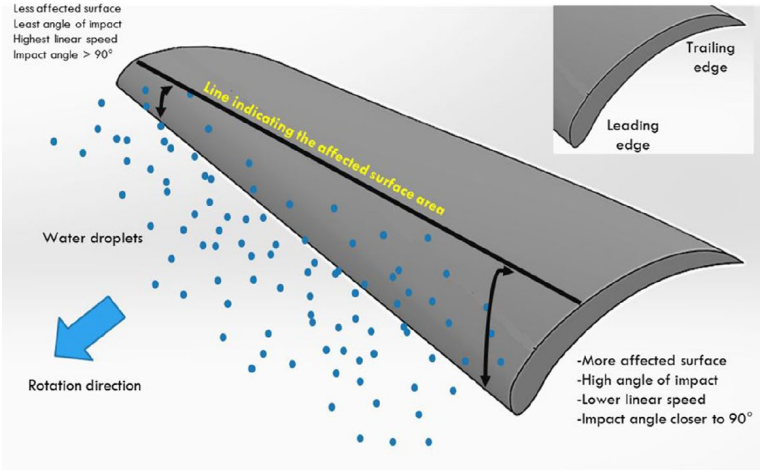
Blade Target Material & Design Characteristics

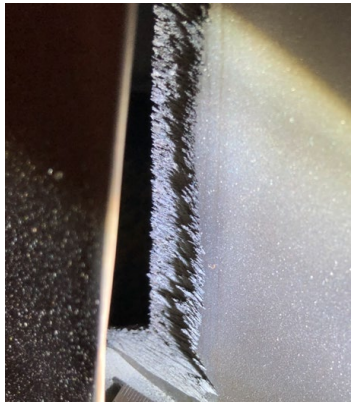
- Factors:
  - Blade Material Mechanical Properties
  - Alloying Elements and Microstructure
  - Surface Characteristics
  - **Last Stage Blades - Design Considerations**



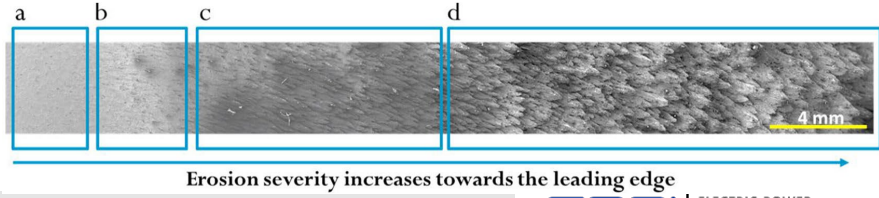


Source: Water droplet erosion of stainless-steel steam turbine blades, H S Kirols, 2017





Erosion pattern aligned with the direction of droplet impact angles and the direction of blade tip rotation



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Factors Influencing Droplet Erosion Damage

EPRI References

- Last Stage Blade Erosion Investigation_3002018670
- Low Pressure Turbine Last Stage Blades—Roadmap for Managing Erosion Damage_3002021593

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Risk Management

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Last Stage Blade Risk Management

Source & Influences	Mechanism	Location	Failure	Consequence

Leading Edge & Erosion – Steam expansion and drop accumulation

Trailing Edge & Erosion – Cooling spray recirculation at low flow conditions (highly variable between designs)

Corrosion – Wet steam expansion and layup humidity.

SCC – Steam Chemistry, Blade/Rotor Material, and Nominal Stress State.

Fretting – Contact Pressure, Contact Friction/Features, Vibratory Stresses

LCF – Start/Stop Cycles at geometric/assembly stress concentrations. Often originates at stress concentrations from other mechanisms.

HCF – Vibratory Stresses from overload and flutter conditions (Load vs Back Pressure). Often originates at stress concentrations from other mechanisms. Turning Gear Damages prevalent on loose/spring-loaded attachments

X

1. Erosion
2. Corrosion
3. Fretting
4. HCF

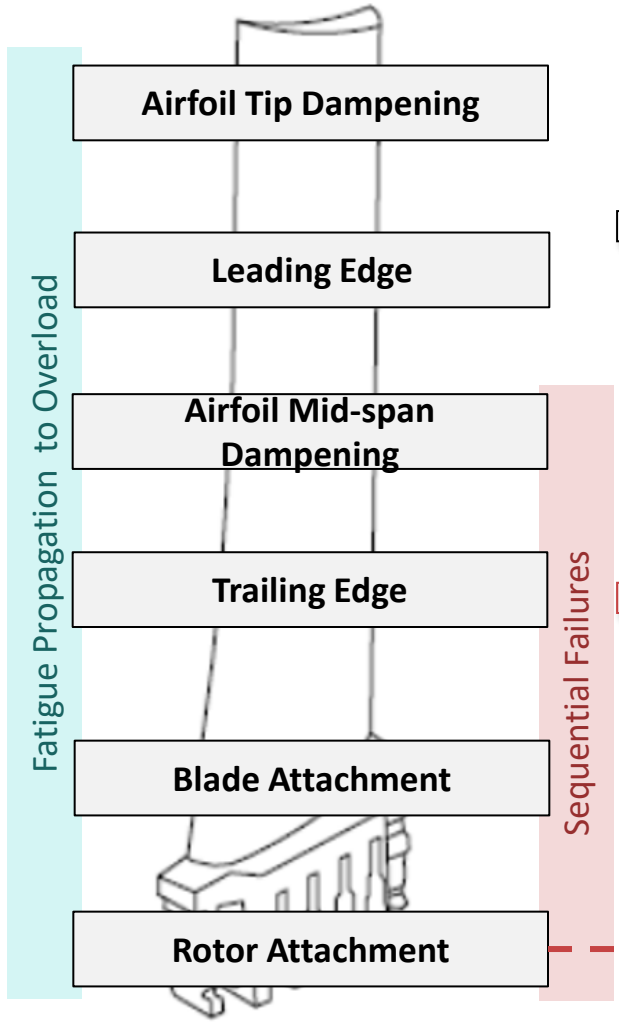
1. Erosion
2. Corrosion/SCC
3. HCF

1. Erosion
2. Corrosion
3. Fretting
4. HCF

1. Erosion
2. Corrosion/SCC
3. HCF

1. Corrosion/SCC
2. LCF
3. HCF

1. Corrosion/SCC
2. LCF
3. HCF



Last Stage Blade Failure **Manageable Loss of Mass**

Last Stage Blade Failure **Major Loss of Mass**

System Failure

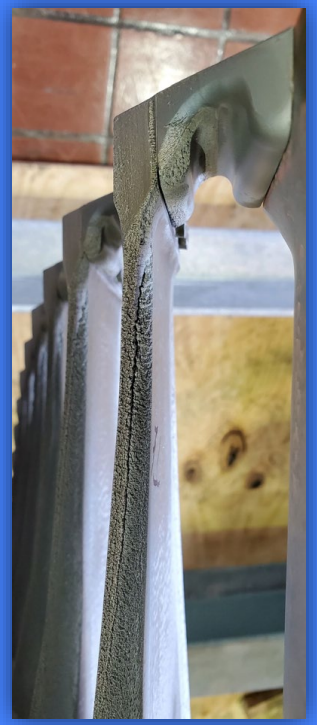
Impact to Safety, Availability, Reliability, Affordability

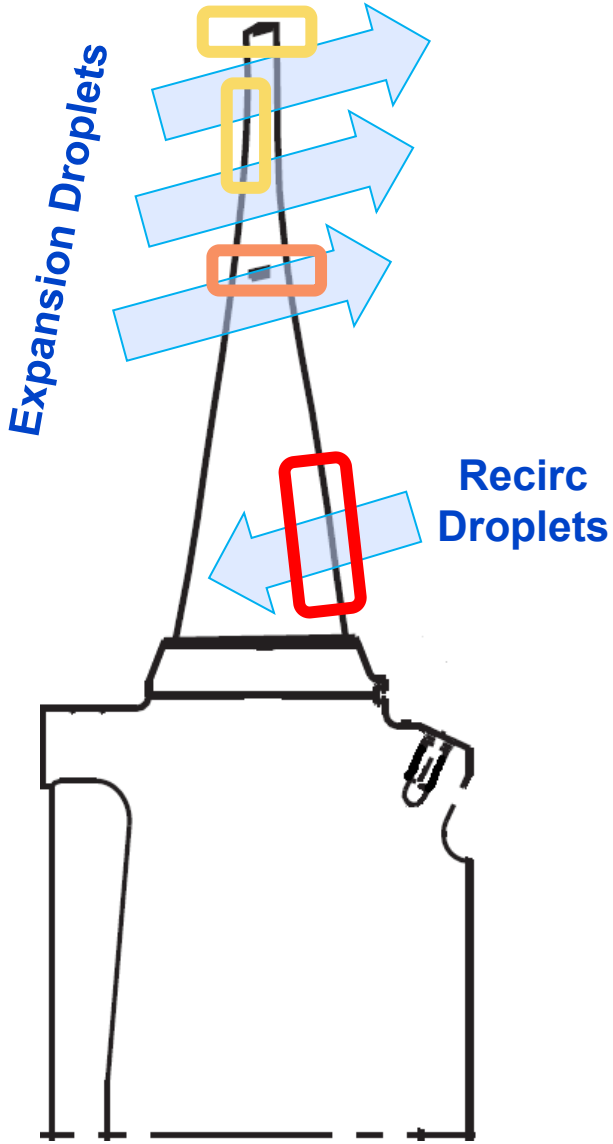
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Risk Management

Expansion Erosion

- ***Design*** – velocities, passage area, stage wetness, moisture removal, surface treatment
- ***Operation*** – load/steam cycle, moisture removal





Recirc Erosion

- ***Design*** – cooling spray system (nozzle & logic)
- ***Operation*** – load/steam cycle, moisture removal, evaporation efficiency



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Frequent Last Stage Blade Damages

Liquid Droplet Erosion

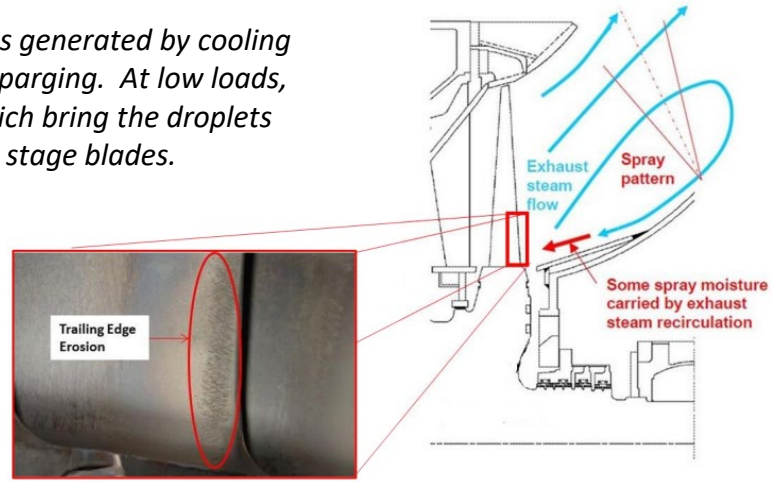
Steam Expansion

Development of water droplets through natural steam expansion in condensing turbines. Droplet migrate outwards and collide with rotating blades.



Recirculation

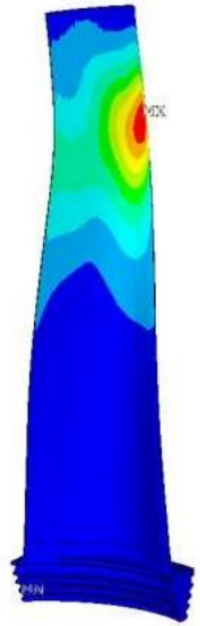
Backflow of water droplets generated by cooling sprays, condensation, or sparging. At low loads, eddy-currents develop which bring the droplets back into the rotating last stage blades.



High Cycle Fatigue

Resonance

Instability of the blade leading to large strain amplitudes. Occurs when natural frequencies align with a forcing frequency at a given rotational speed and nozzle passing frequency.

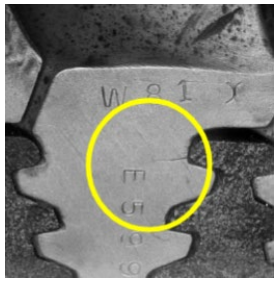


Flutter/Self-Excitation

Aeroelastic instability leading to a self-feeding oscillation. Occurs at load and flow conditions for a given blade and exhaust configuration design where sufficient damping does not exist.

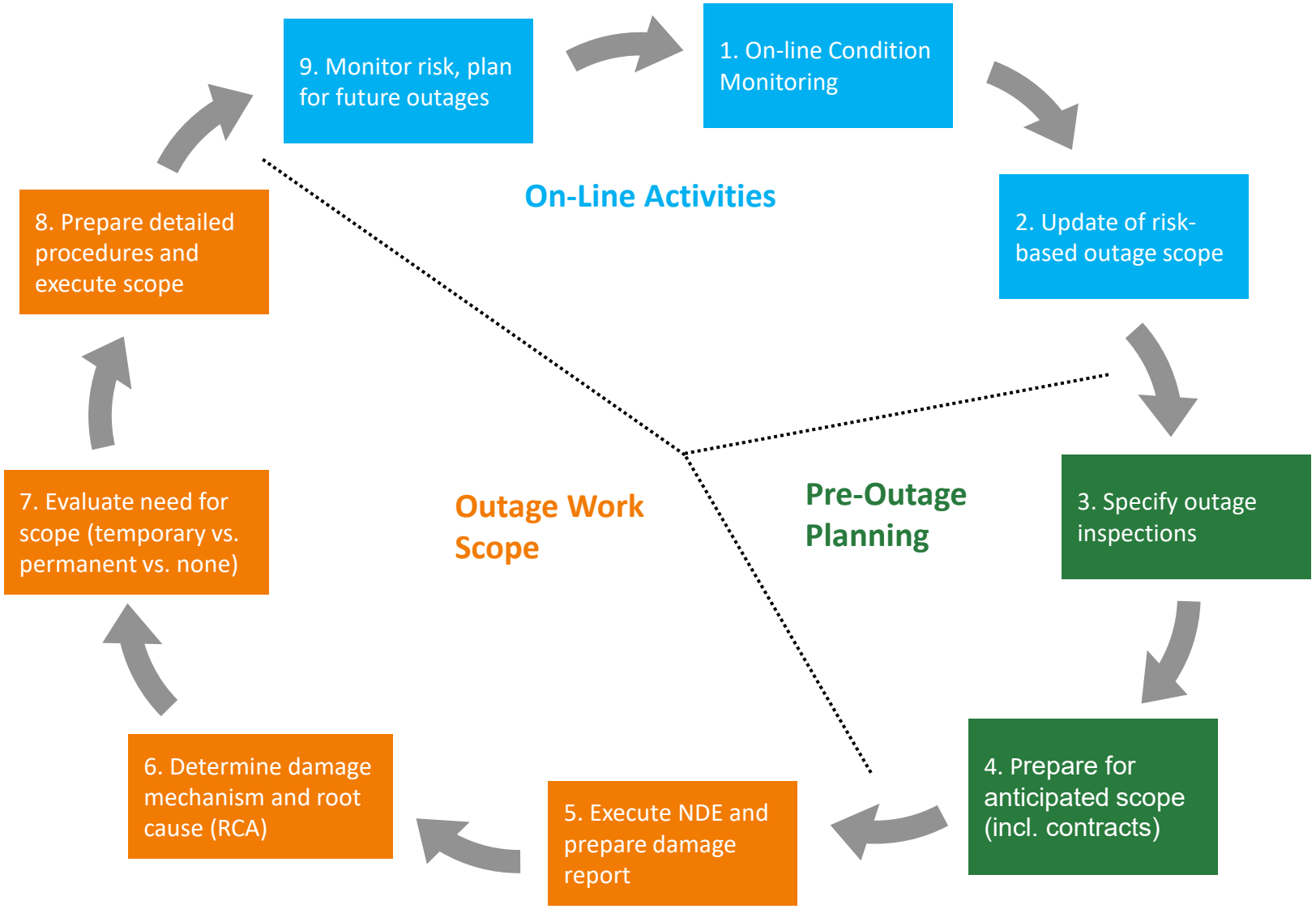
Dynamic Load

The accumulation of damage where the blade experiences elevated dynamic stress during operation. The magnitude of dynamic stress is often correlated to the back pressure at flow rates. Concerning damages are often associated to FSNL and part-speed operation when vacuum is lost.



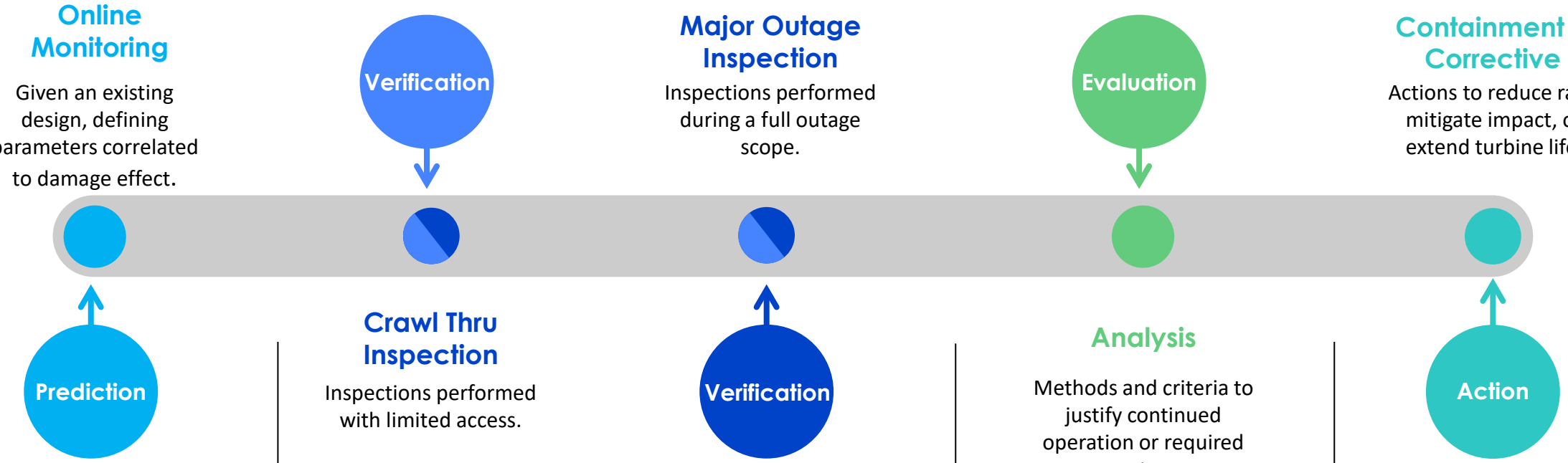
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Traditional Risk Management Lifecycle Framework



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LSB Erosion Risk Management



- ❑ Utility data sharing
- ❑ Sensors available
- ❑ Indirect parameters
- ❑ Correlation strength

- ❑ Feature Access
- ❑ Measurement technology
- ❑ Measurement relevance
- ❑ Stage of erosion
- ❑ Section thickness reduction
- ❑ Geometric stress riser

- ❑ Blade stresses
- ❑ Material strength
- ❑ Stress intensity

- ❑ Rework
- ❑ Repair
- ❑ Replace
- ❑ Design upgrades
- ❑ Operational enhancement

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Industry Approaches to Today's LSB Erosion Challenge

OEM Driven Decision Making

Damage Assessment

- *Damage limit based on OEM measurement method and assessment approach*
- *Method accuracy often limited*
- *Safety letters may be issued due to liberation risk*

Disposition

- *Repair not a widely accepted option for blades*
- *Stage removal or pressure plate with cycle derate until new blades can be manufactured*

EPRI Supporting Role

- **Transparency & Simplification**
- **Develop Technologies**
- **Articulate Risks**
- **Objectively Explore Risks and Inform Repair Processes**

Independent Decision Making

Damage Assessment

- *Damage limit based on judgement*
- *Method accuracy often limited*

Disposition

- *Accept failure risk and monitor damage*
- *Stage removal or pressure plate with cycle derate until new blades can be manufactured*
- *Repair by 3rd Party/Independent service providers*

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Managing Failure Risks

Liquid Droplet Erosion

Inspect

- ✓ *Visual and NDE examination for unacceptable damage*
- ✓ **3002032525** – *Crack detection using ECT to improve feature-flaw differentiation*

Measure

- ✓ *Measurement of damage feature and magnitude of material loss*
- ✓ **3002032523** – *3D scanning technologies*

Assess

- ✗ *Determination of acceptance and life limitations*
- ✗ *Varies by material, design, and operation (difficult to standardize)*

Tune Operation

- ✗ *May be limited by cycle design and mission profile*
- ✗ *Operators required to prioritize and establish new procedures*

High Cycle Fatigue

Inspect

- ✓ *Standard visual and NDE examination for unacceptable damage*

Measure

- ✓ *Measurement of blade vibration frequency and amplitude*
- ✗ *May be limited by design type*
- ✗ *Extended outage, added cost, and uncertainty for sensor installation and operational analysis (specialized skills to interpret)*

Avoid

- ✗ *May be limited by cycle design, wear and mission profile requirements*
- ✗ *Operators required to prioritize and establish new procedures*

Redesign

- ✗ *FOAK risks of 'unproven' design*
- ✗ *Cost and lead time to produce*

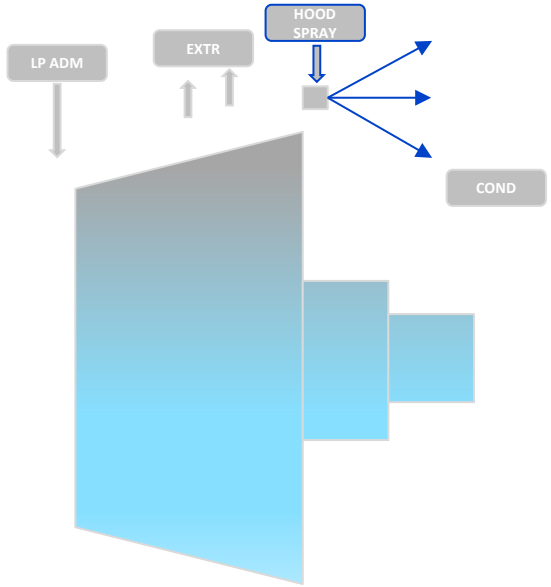
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Prediction

Online Monitoring

Measurable Parameters:

flow, pressure, temperature, time, speed



Potential Derived Parameters:

wetness, droplet size, P/T distribution, flow vectors

- Big data solution
  - Poorly refined data
  - Historical archived information
  - Difficult to obtain from member utilities
  - Context for arrangement (unless proven otherwise)
  - Requires alignment to inspection findings
- Theoretical model solution
  - Relies on configuration-specific CFD
  - Only as good as the model assumptions
    - Loads
    - Solver
    - Scenarios
  - Need fundamental understanding of damage qualification (i.e., what stage is the erosion in – defines the growth rate?

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Measurement & Inspection

Measurement

Section Reduction

- Sectional thickness increasing nominal and dynamic stress distribution
- Impact to blade natural frequencies – resonance/dampening

- Manual measurements with accuracy challenges and human error factors.
- Optical measurement technologies available but requires disassembly.

But then, what does it mean? Needs to be correlated to a stress distribution.

Feature Stress Concentration

- Feature appearance at stages of deterioration
- Establish influence on stress intensity

- Manual depth measurements and reproduction mold method available
- Both time consuming and imprecise.

But then, what does it mean? Needs to be correlated to a stress intensity factor.

Fatigue Cracks in Damage Feature

- Potentially undetected crack growth

- Common NDT, no well-defined methodology

But then, what does it mean? At what crack depth is tolerable? How can you apply a fracture mechanics calculation?

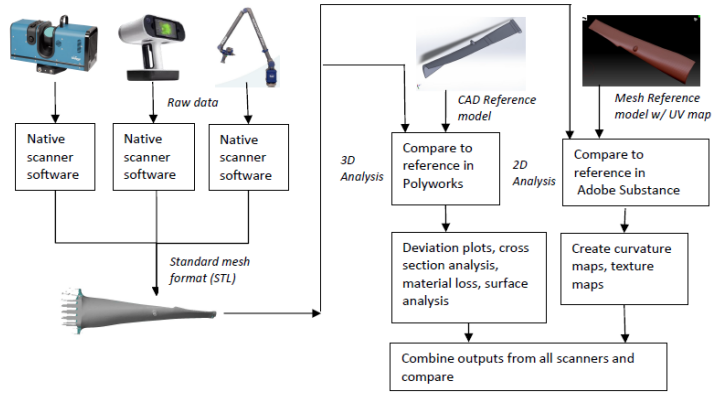
Opportunities to develop improved technology & method.

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L-0 In-situ Erosion Measurement - 3D Scanning Technologies

Project Objectives

- Assess advanced surface scanning techniques available on the market using hand-held devices that could be used for accurate in-situ erosion damage measurement - laser, infrared light, structured light, and photogrammetry
- Review data acquisition systems and software compatibility that are critical for long term erosion damage monitoring and evaluation
- Provide a technical guide and best practices for erosion damage scanning of last stage blade leading edges and erosion damage rate calculations

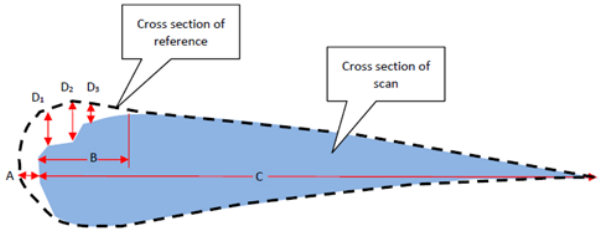


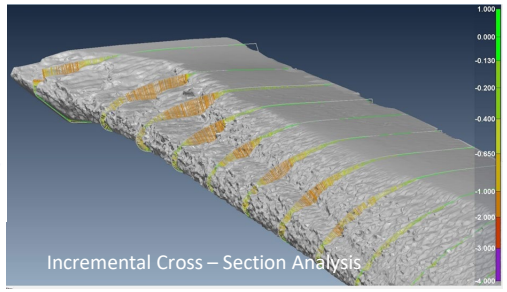


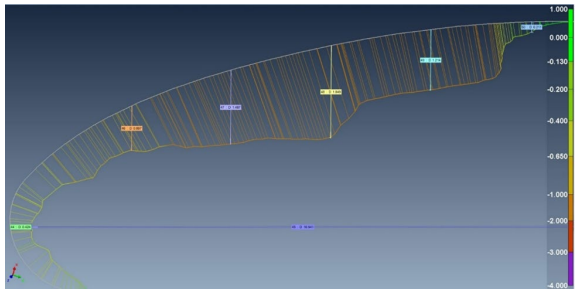
Creaform HandySCAN 3D (laser)

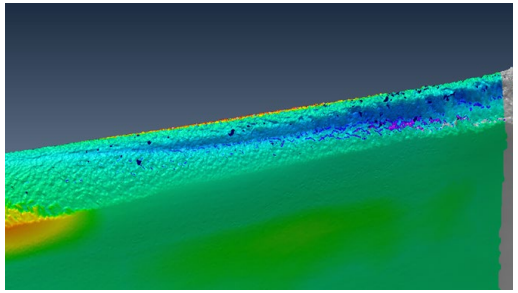
Key Findings:

- 3D scanning - mature technology, powerful inspection analysis and reporting software
- Hand-held 3D scanners (structured light, laser and photogrammetry) have shown promise in mapping erosion damage while capturing geometric and depth information on inspected surfaces
- Repeatable and more accurate measurements (than manual procedure), better blade erosion severity characterization, erosion rate may be determined more efficiently and accurately and can be automatically generated
- Common scan analysis software can be used to create standard reporting templates, including measurements taken in the exact same locations over time
- 3D analysis and 2D visualization software provide advanced image analysis toolset – color deviation plots, spatial frequency filtering and machine-learning capabilities





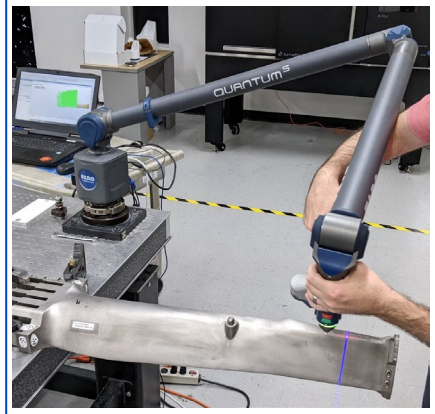


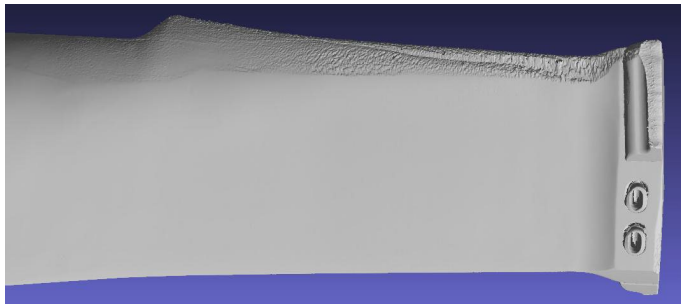


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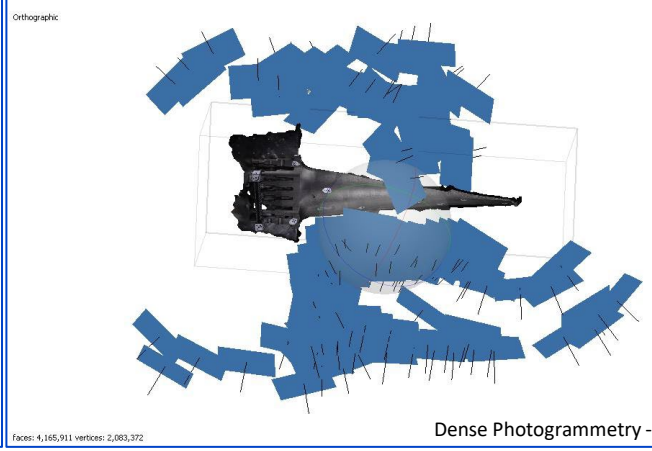
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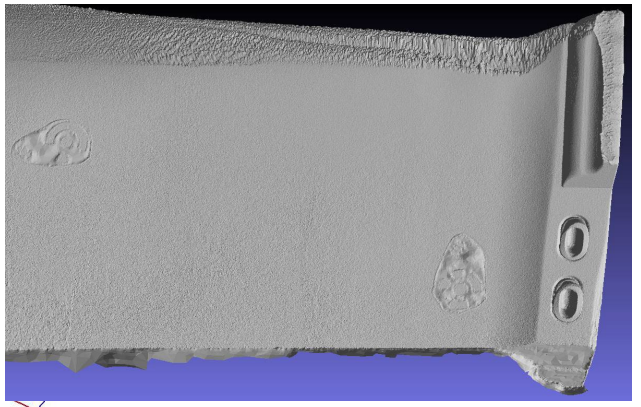
L-0 In-situ Erosion Measurement - 3D Scanning Technologies





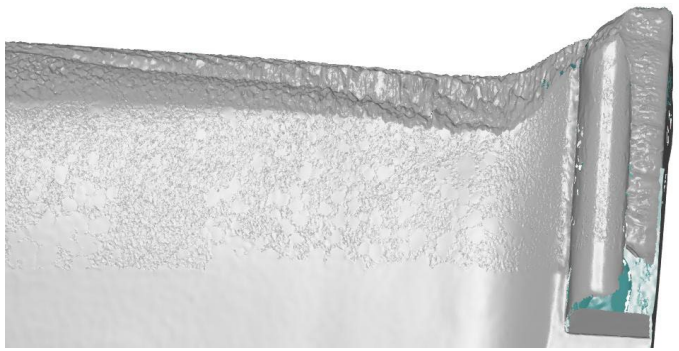
FARO ScanArm (with laser line scanner)



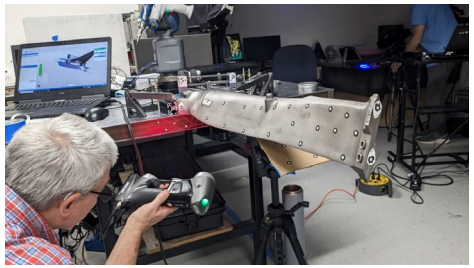


Dense Photogrammetry - model as constructed using Metashape software

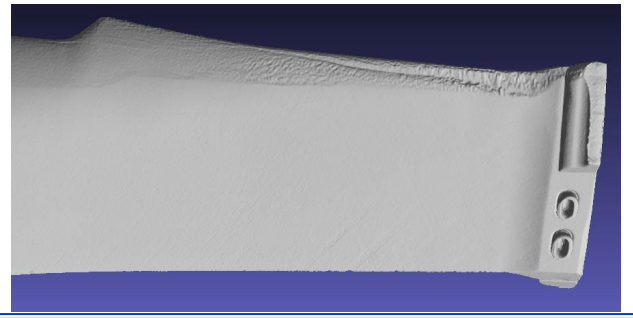


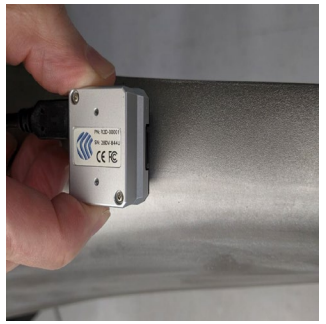


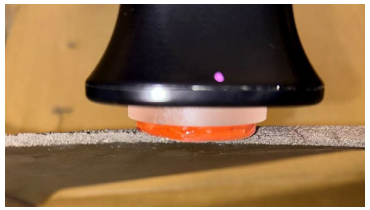
Zeiss Scan 1 (structured light)



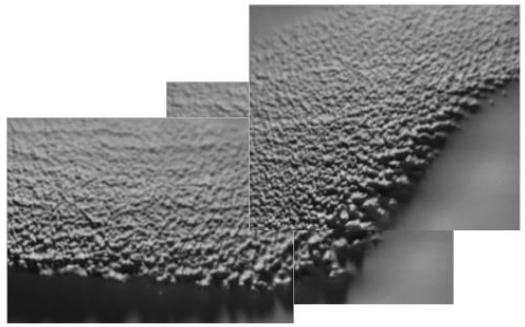
Creaform HandySCAN 700 (handheld crossed laser lines)







GelSight Mobile - optical tactile imaging using photometric stereo (same viewpoints, different lights)



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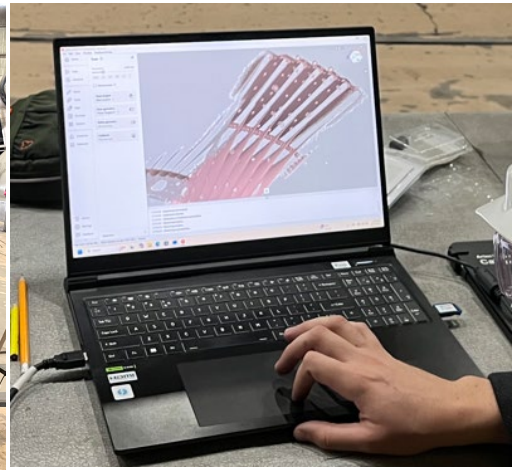
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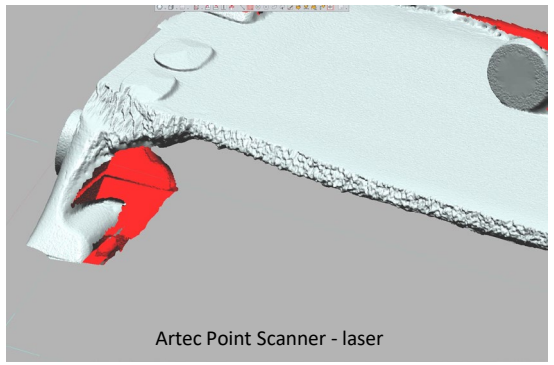
L-0 In-situ Erosion Measurement - 3D Scanning Technologies

On-going Research

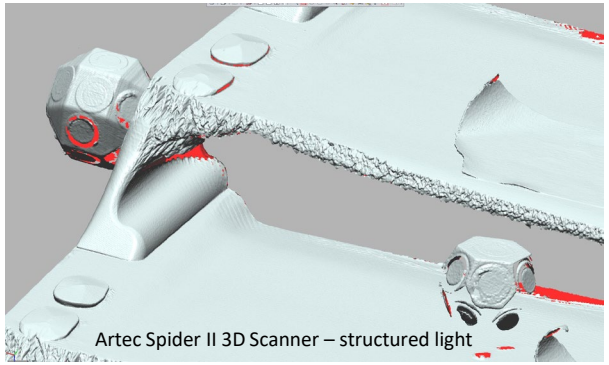




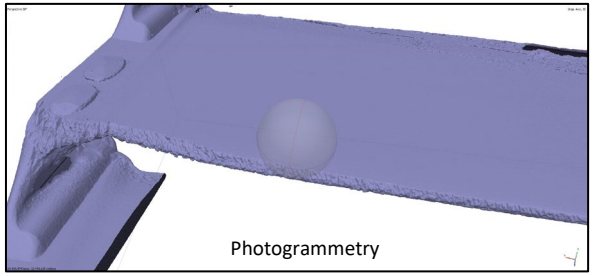




Artec Point Scanner - laser



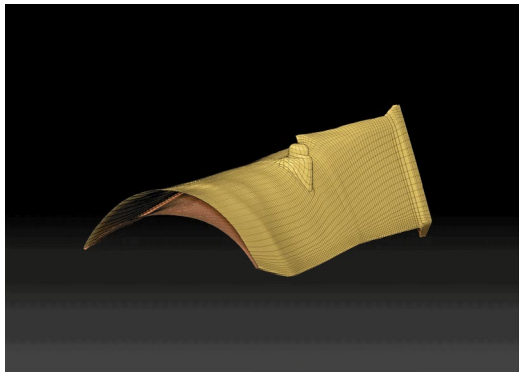
Artec Spider II 3D Scanner – structured light



Photogrammetry

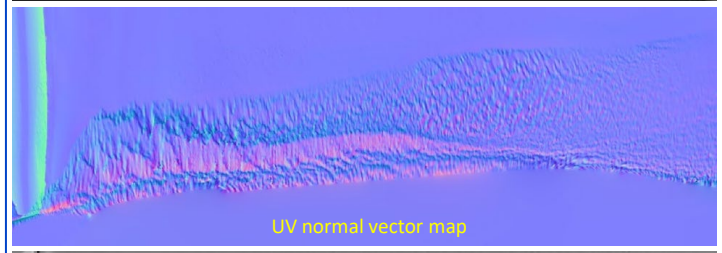
Raw data collected by three scanning systems (on-going project)

Erosion damage analysis using unwrapped 2D surfaces and UV maps (computer graphics methodology - Adobe™ Substance 3D)

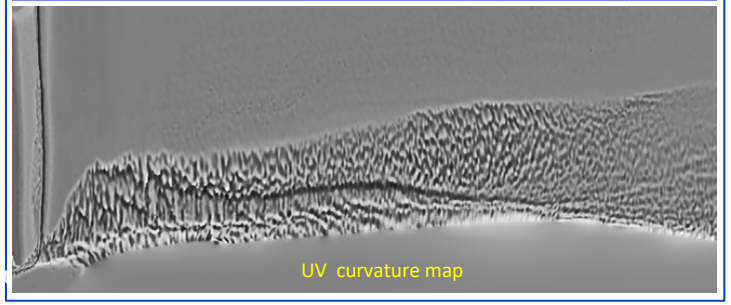




UV map – as scanned model



UV normal vector map



UV curvature map

Exploring new methods for droplet erosion damage measurements that can provide more comprehensive inspection data (**erosion maps**) and advanced analysis capabilities (**erosion rate**)

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Last Stage Blade Erosion In-Situ Crack Detection Method

Project Objectives

- Assess advanced crack inspection technique such as Eddy Current Array using Flex Probe on a turbine blade sample with significant erosion damage and induced cracks to determine detection capability

Project Approach & Findings

- Eddy Current Array using Flexible Probes – fast, real time mapping of indication, no surface preparation, applicable to (non)ferromagnetic materials;
- I-Flex (hard wound coils) and P-Flex (printed coils) probes were tested
- Eight EDM's were implanted along the leading edge of the airfoil containing light to heavy erosion using a 0.006-in thick electrode
- ECA signal responses from the implanted EDM notches produce a distinct signal response because of notch width
- In addition, real cracks in the leading edge area were created on another sample blade with erosion damage by cyclic loading in a three-point fixture
- CIVA simulations were performed to further explore capabilities of the inspection method

Flexible Probe



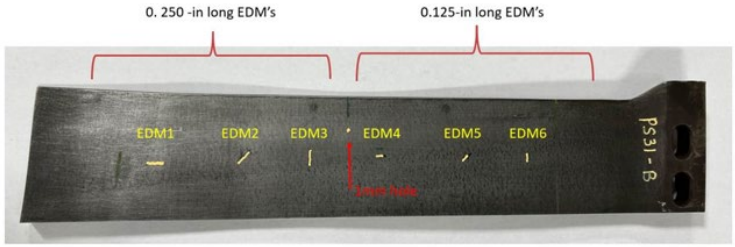
Hard Wound coils

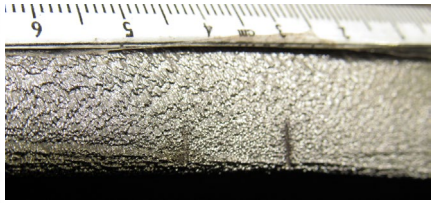


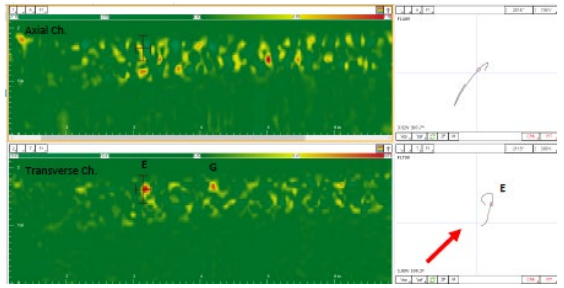
Printed coils



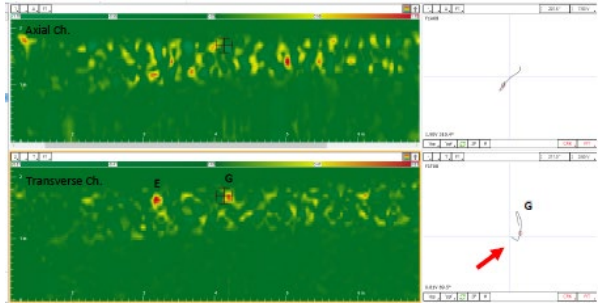








Transverse channel ECA results for defect E (EDM notch)

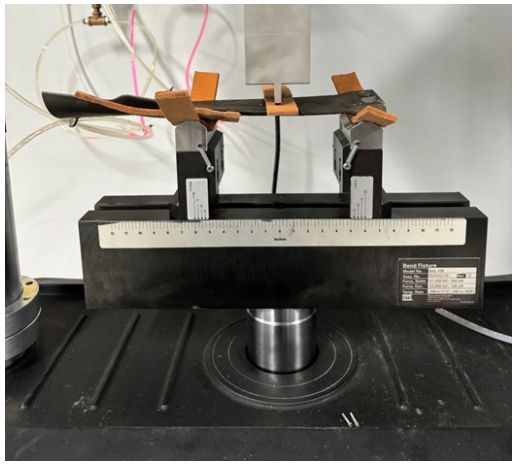


Transverse channel ECA results for defect G (EDM notch)

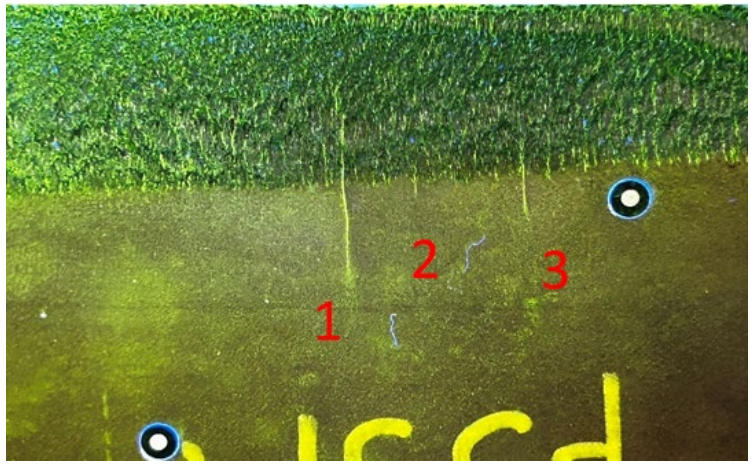
3002032525 ***Published***

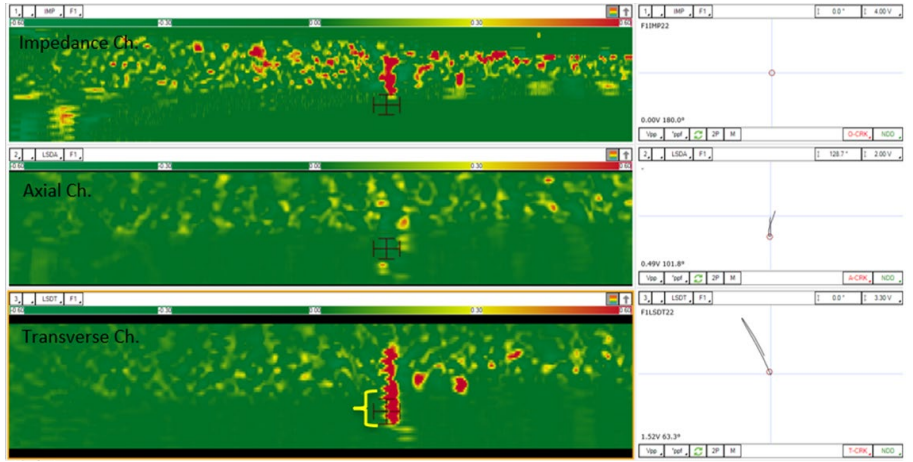
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Last Stage Blade Erosion In-Situ Crack Detection Method



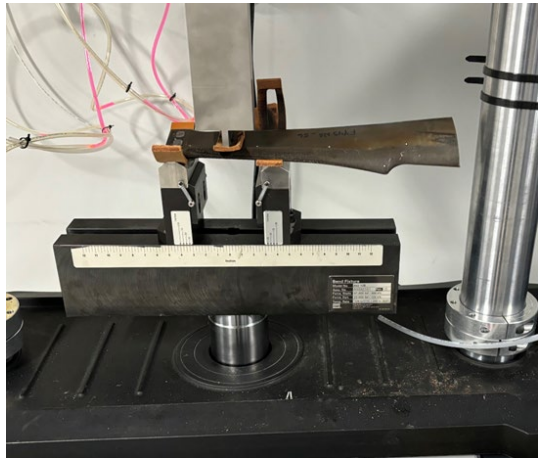
Blade sample in fatigue loading fixture to induce cracking along the suction-side leading edge



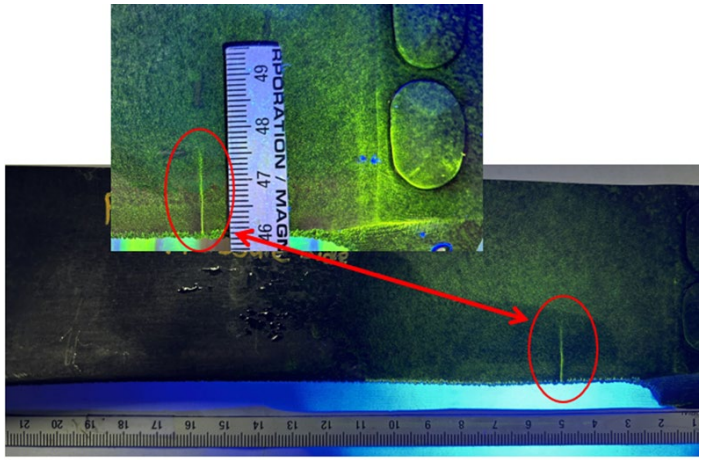


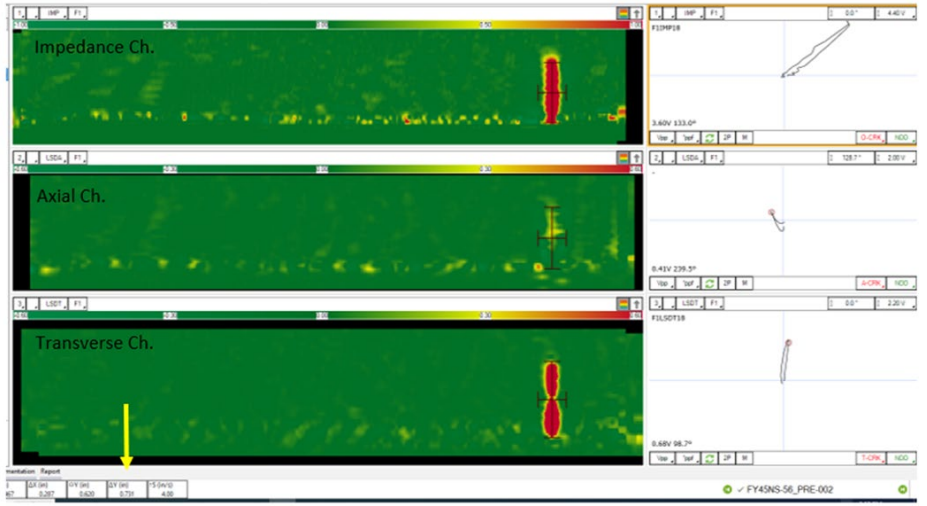
Fatigue crack #1 – eroded and non-eroded area of the blade airfoil

Fatigue cracks #2 and #3 were also detected



Blade sample in fatigue loading fixture to induce cracking along the pressure-side leading edge





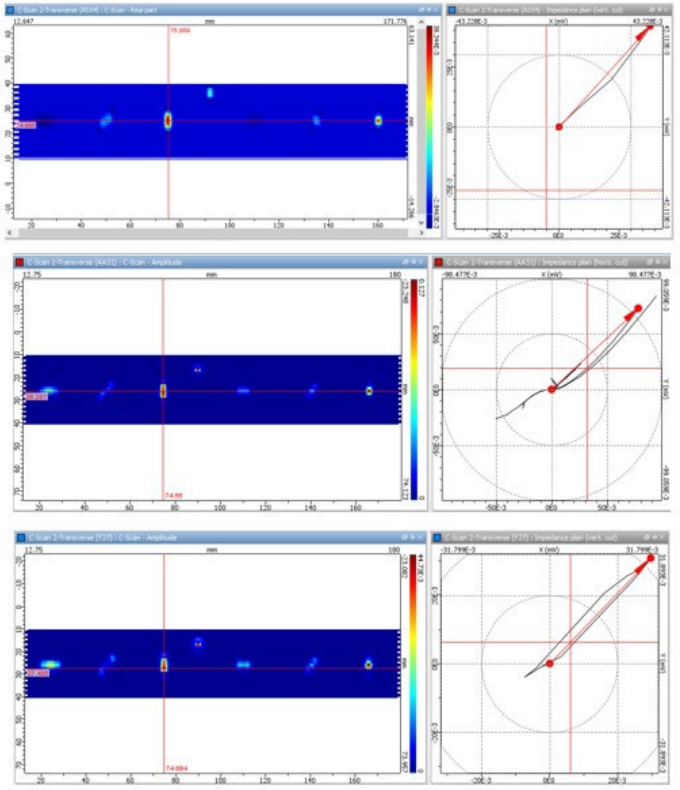
C-scan showing measured fatigue crack length (18.57 mm) in pressure side sample

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Last Stage Blade Erosion In-Situ Crack Detection Method

Key Findings

- The ECA probe technology detects fatigue-induced surface-breaking cracks in the eroded and noneroded regions of the turbine blade specimens.
- When using the flexible ECA probes for defect detection, there is a significant difference in the electronic signature between the fatigue-induced cracks and electrical discharged machined (EDM) notches in regions of erosion, with the former providing a far greater ECA response.
- The I-Flex ECA probe using the long single driver ECA coil topology demonstrated improved detection of surface-breaking cracks in a comparative study.
- Flexible ECA probe design may be customized to allow for improved data quality and resolution when inspecting for surface-breaking cracks on turbine blades with droplet erosion damage.
- CIVA modeling showed good correlation with physical examination results, including flaw length measurements, as well as probe lift-off results. CIVA modeling could assist with further development and customization of the ECA method.



View of CIVA simulation 2.0-mm coil across the test blade (DD-SPU topology) with a 0.4-mm (top), 0.8-mm (middle), and 1.2-mm (bottom) probe lift-off showing detection of both transverse EDMs at 800 kHz on the transverse channel.

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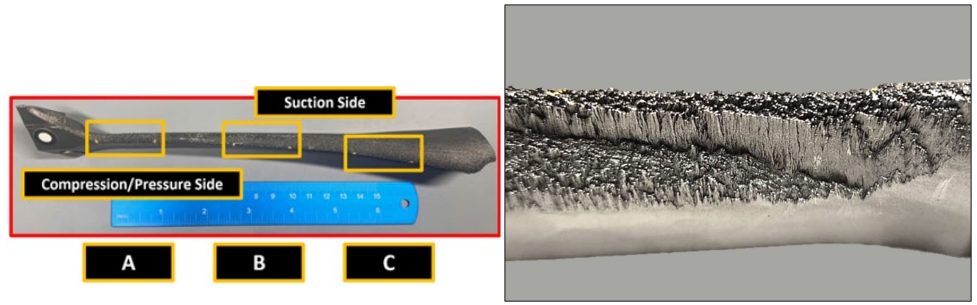
Last Stage Blade Erosion – Damage Feature Characterization

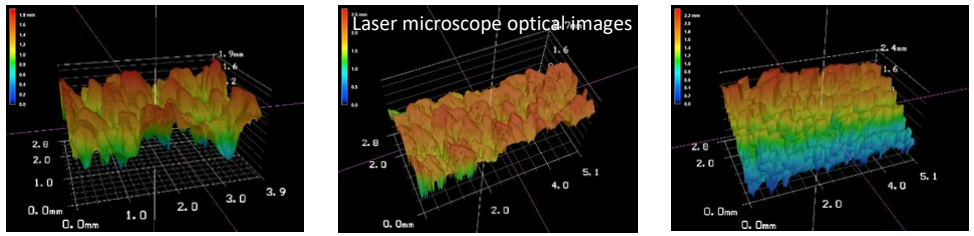
Project Objective & Approach

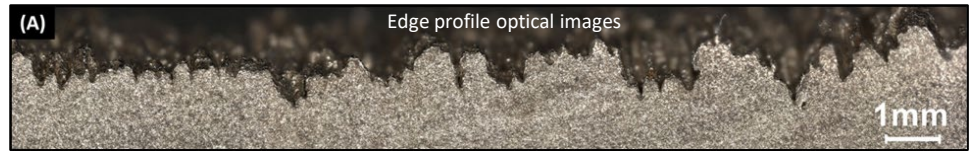
- Analyze surface topography and erosion damage feature appearance at various stages of deterioration on L-0 blade leading edge by using advanced 3D profile measuring microscopes – LED (structured light), digital optical, and laser technologies
- Characterize micro-scale morphology of erosion damage that could be important for the evaluation of geometric stress concentrators that could enhance the structural analysis of damaged blades.

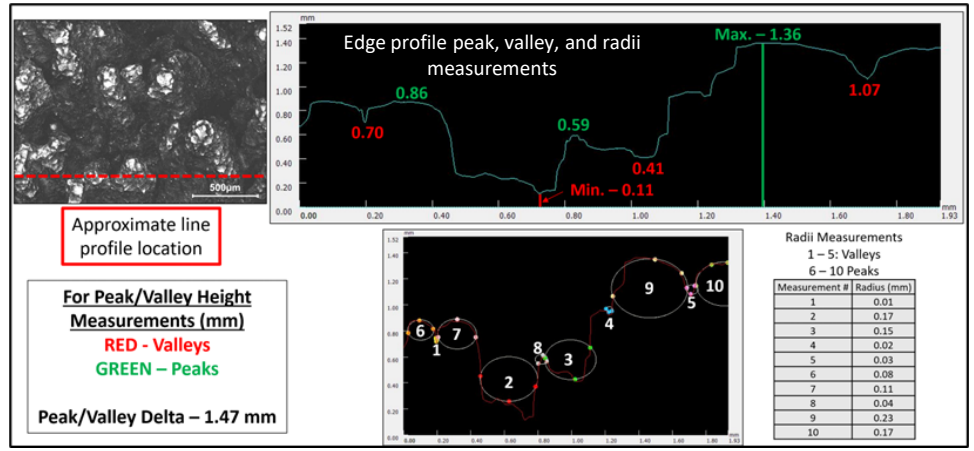
Key Findings

- The initial testing of all microscopes on the small patches of eroded surface has shown significant limitations to successfully acquire information from deeply recessed areas at higher magnification due to the curvature of the blade. The laser confocal microscope was able to capture surface height data with higher accuracy; however, the scanned sample area was small because of data acquisition constraints.
- The analysis of microscope test results using standard roughness parameters showed differences in surface morphology characteristics among the three examined regions, however the methodology revealed inconsistencies in the data obtained across the different microscopy techniques.
- An alternative assessment method of surface damage morphology was used by analyzing the edge features of the erosion damage which allowed the determination of linear density of peaks and valleys of the eroded surface and their dimensional characteristics such as width of peaks and radii of valleys.
- The relationship between the extracted standard roughness parameters and the corresponding stress concentration features remained unclear, complicating efforts to establish a direct link between surface morphology and mechanical performance.
- Next steps – determining the appropriate parameters for erosion assessment by getting a better understanding of how surface irregularities from erosion lead to fatigue crack initiation









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Evaluation

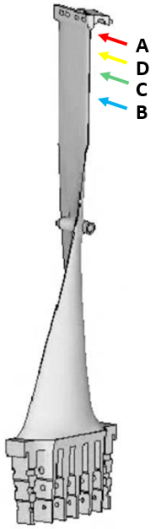
Research Opportunity – Analysis Tools

Analysis Result

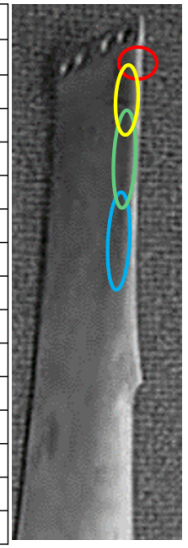
Stress Amplification		Design Stress	Material Capability
Geometric Change	Stress Intensity	LSB Analysis	Material Testing
Mass and Stiffness Impact	Geometric Factor a_{actual}	Geometric RE	Material Procurement
Section Profile Measurement	Damage Feature Measurement		

- Stresses derived from contour plots developed for T-G Guidelines Volume 7 (Section 2)
- Blade material:
  - σ_{ult} = 135ksi
  - $\sigma_{0.2\%\ yield}$ = 110ksi
- Resonant Frequencies reported to represent worse case in low load/unsteady behavior
- Detuned system effect can be approximated:

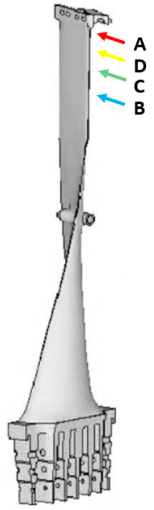
$$\sigma_d = \frac{2 \cdot \xi \cdot \sigma_R}{\sqrt{\left(1-\mu^2\right)^2 + \left(2 \cdot \mu \cdot \xi\right)^2}}$$



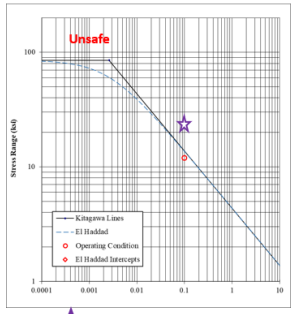
Stresstimate		ZONE			
		A	B	C	D
Static	MPa	55.1	276	241	138
	psi	8000	40000	35000	20000
Dynamic Resonant (A,3@157hz)	MPa	82.7	1.38	1.38	36.7
	psi	12000	200	200	5333
	SR	0.4	0.98	0.98	0.6
Dynamic Resonant (B,5@321hz)	MPa	29.9	29.9	26.3	13.8
	psi	4345	4345	3810	2000
	SR	0.65	0.65	0.68	0.8
Dynamic Resonant (C,9@538hz)	MPa	-6.2	5.17	6.2	1.24
	psi	-900	750	900	180
	SR	1.13	0.91	0.9	0.98
Dynamic Resonant (D,11@673hz)	MPa	1.72	0.69	0.28	1.72
	psi	250	100	40	250
	SR	0.97	0.99	1	0.97



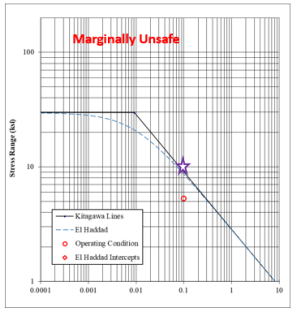
FATIGUE ANALYSIS USING RESONANT VIBRATION & BEAM EDGE CRACK



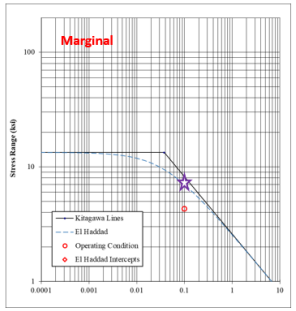
MODE A
Zone A – Fillet Transition



MODE A
Zone D – Upper Leading Edge



MODE B
Zone B – Lower Leading Edge



☆ Safety Diagrams with Stress Intensity v. Defect depth 'a' = 0.1 inches [2.5mm]

$$\Delta K \equiv Y \Delta \sigma \sqrt{\pi a} \qquad (Y_{f(a/w,0.1)} = 1)$$

Degradation Defect may not be Unfavorably Oriented in Stress Field

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Containment Correction

Pathways to Manage Erosion

In-situ Refurbishment	• Reset potential during **incubation stage – how do you define?**
Repair	• EPRI has started research in this area – currently in 5yr plan
Replacement & Upgrades	• Is there a need for **new design features or quality insights?**
Operational Mitigation	• Is research needed for **cycle optimization?** There is no one size fits all prescriptive solution envisioned, **expect only a framework** for defining analysis approach.

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Actions EPRI is taking to support the industry…

P219 Steam Turbine Program

- Research results articulating the damage mechanisms and risks
- Inspection techniques to improve visual interpretation uncertainty
- Roadmap to effective management of erosion
  - Erosion prediction
  - Integrity assessment
  - Degradation forecasting
- Exploration of design options to reduce prevalence of erosion damage

P219 Steam Turbine & P229 Materials Collaboration

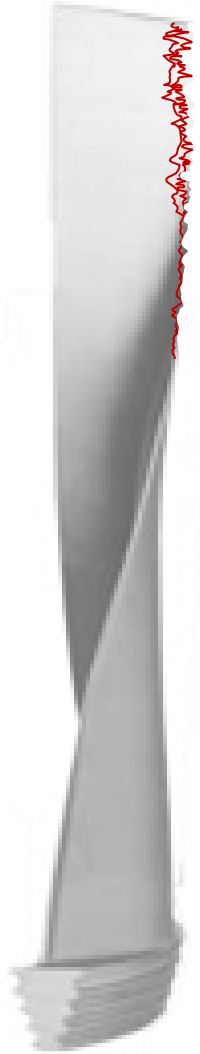
Life Extension thru Repair

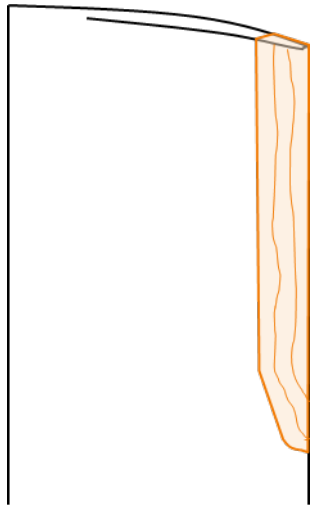
Establish practices and procedures to improve quality of blade restoration

- Define the base material properties for blades used in the industry
- Understand the design basis and protection measures
- Evaluate deposit properties and process control requirements
- Identify vulnerabilities associated with repair applications
- Establish repair guidelines
- Communicate repair scenarios and how to effectively manage process risk

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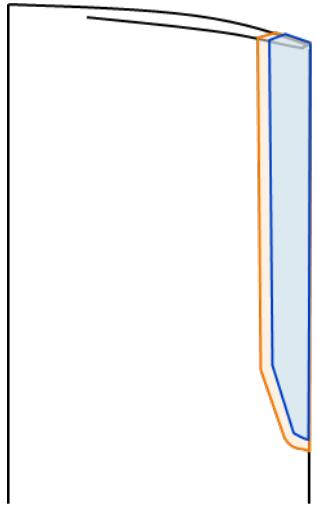
Comparison of Repair & Replacement Options





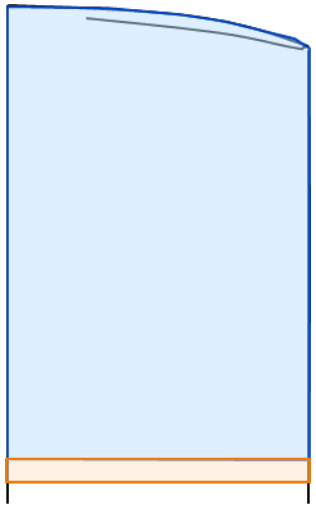
Weld Build-up

- \+ Design Cycle
- \+ Materials Availability
- \+ Process Adaptability
- \- Deposit Risk
- \- Protection Application Risk
- \- Profile Finishing Cycle



Insert Welding

- \+ Deposit Risk
- \+ Profile Finishing Cycle
- -/+ Design Cycle
- -/+ Materials Availability
- -/+ Process Adaptability
- -/+ Protection Application Risk



Tip Replacement

- \+ Deposit Risk
- \+ Profile Finishing Cycle
- \+ Protection Application Risk
- -/+ Process Adaptability
- \- Design Cycle
- \- Materials Availability



Blade Replacement

If no Inventory…
New Blade Rows
Lead Time 1-5yrs,
competing with
New Equipment
Supply Demand



Additive

- -/+ Deposit Risk
- -/+ Protection Application Risk
- -/+ Process Adaptability
- \- Profile Finishing Cycle
- \- Design Cycle
- \- Materials Availability

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Trailing Edge Repair Challenge



Erosion at Part Load is Highly Variable

- Exhaust volume and geometry
- Load, flow, backpressure operation
- Droplet source and size

Airfoil Stress may be Highest at Location of Erosion

- Nominal stress from centrifugal load
- Principal Bending stress
- Erosion creates surface features that increase stress intensity

Low Damage Tolerance – High Failure Consequence

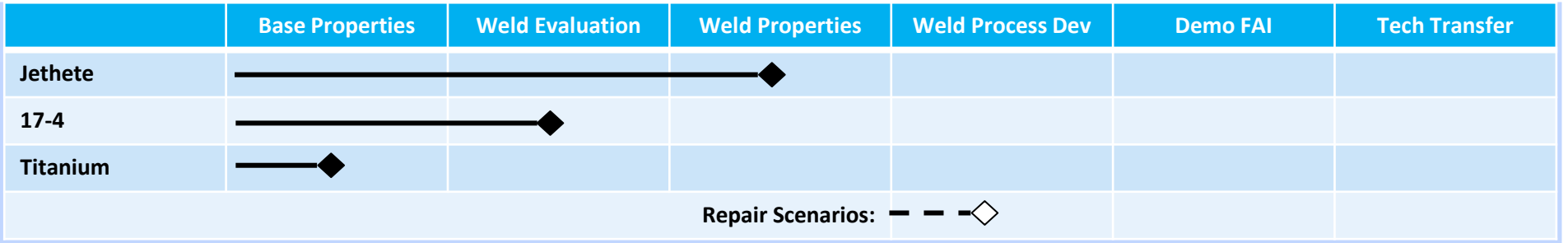
Critical to Success

- ✓ *Deposit meet or exceed strength and fatigue endurance requirements*
- ✓ *Deposit defect and metallurgical risk effectively managed*
- ✓ *Surface treatments to enhance strength and reduce erosion*
- ✓ *Mitigation through operation – managing the droplet sources throughout the recirculating flow operating range*

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Material Risks & Properties Development

Blade Repair



1

Base Properties

- Understanding material properties
- Establish structural design limits
- Define appropriate weld materials

2

Weld Evaluation

- Understand compatibility risks
- Define repair process options
- Determine baseline process parameters

3

Weld Properties

- Define repair process properties
- Further evaluate material and process risks
- Benchmark against base material properties

4

Weld Process Dev

- Define repair process equipment and procedures
- Further evaluate material and process risks
- Define quality measures
- Verify process performance

5

Demo FAI

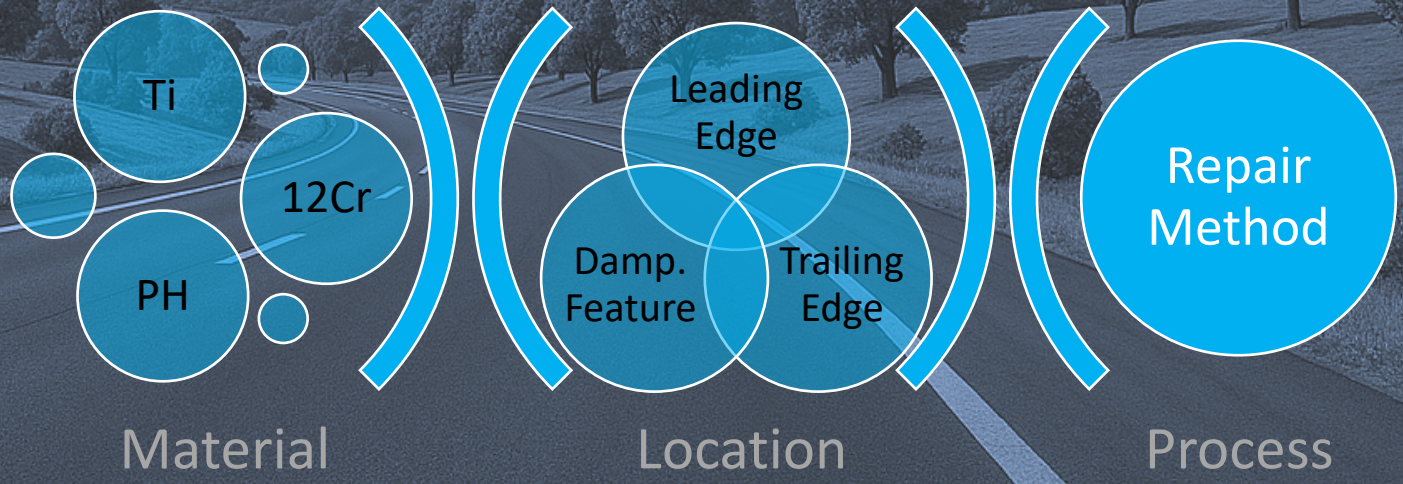
- Demonstrate process
- Establish best practices
- Verify quality requirements
- Build equipment, process, and quality specifications

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Key Challenges we Face

1) Urgency of the industry need

2) Variability of the scenario



3) Pathways to commercialization

Want to discuss more…?

P219 Steam Turbine

Tuesday 1-4p

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Lunch

Managing Electro-Hydraulic Fluid Systems

Fluid Sampling Programs, Condition-based Maintenance

Randall Steele
Senior Technical Leader

2025 WANO Steam Turbine & Generator Workshop
Shanghai, China
3-6 November 2025

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Agenda

- Intro to EHC Systems and Fluid
  - Getting to Know the System
  - Fluid Basics
  - Degradations
- Maintenance Tasks
  - System / Component Maintenance
  - Fluid Restoration
- Fluid Sampling
  - Why to do it?
  - What to look for?
- Troubleshooting and FMEA
- Recent User Experience



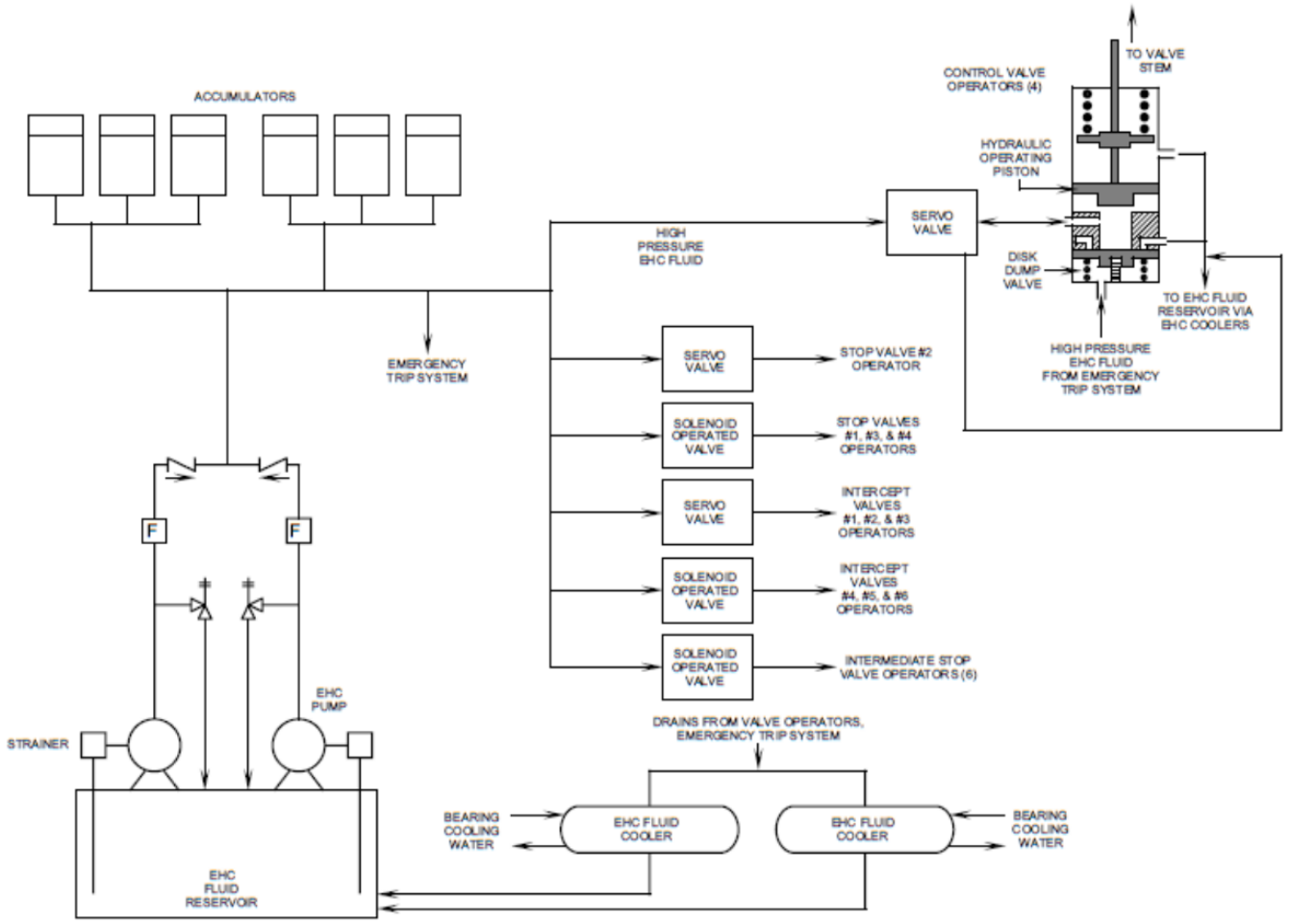
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Typical Electro-Hydraulic Control (EHC) System Components

- EHC System has 3 main sub-systems:
  - EHC Fluid System
  - Emergency Trip System
  - Electrical Control System

EHC Fluid System typically includes:

- Fluid Reservoir
- Strainer(s)
- Pump(s) and Motor(s)
- Heat Exchanger(s)
- Accumulators
- Interconnect Piping/Tubing
- Servo Valves
- Filtration/Purification System
- EHC Fluid



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Hydraulic Fluids

Four Basic Fluid Types

- Phosphate Ester
  - Usually consists of TXP “natural”, TBPP “synthetic”, or blends

Brand Name				Type	Desirable Features
Chemtura[1] Reolube		ICL[2] Fyrquel			
EHC[3]	HYD[3]	EHC[3]	HYD[3]		
Turbofluid 46XC and OMTI	220X	EHC-N (Stauffer EHC[3])	220N	Trixylenyl phosphate ester (TXP) “natural”	Lowest air-release times, best hydrolytic stability, and good overall.
Turbofluid 46B (Durad EHB)	HYD 46B	EHC-S	220	Butylated phenol phosphate ester (TBPP) “synthetic”	Best bulk oxidation resistance.
Turbofluid 46	HYD 46	-	-	Isopropyl phenol phosphate ester (IPPP) “synthetic”	Better hydrolytic stability than butylated synthetics.
-	-	EHC[4]	-	Blend of butylated phenol and trixylenyl phosphate ester	A compromise of the natural and synthetic.

- Polyalkylene Glycol (polyglycol)
- Polyol Ester
  - Synthetic organic ester base fluids
- Mineral Oil
  - API group 1-4 hydrocarbons

Table 2
Acceptable materials

	Seals, hoses and bladders	Wire and cable insulation	Paints	Sample bottles and caps*
Acrylic			U	
Alkyd paint			A	
Butyl rubber	R			
Cellulose **				A (liners)
EPR	R			
Epoxy paint (cured)			A	
Glass				A
Fluorocarbon (Viton, Kalrez, Fluroel)	R			
Natural rubber	U			
Neoprene	U			
Nitrocellulose lacquers			U	
Nitrile rubber	U			
Nylon	R	A		
Phenolic resins			U	
Polyethylene		A		A
Polypropylene		A		
Polyethylene terephthalate				A
Polyurethane paint			A	
PTFE, Teflon				
Polyvinyl chloride		U		
Silicone rubber	U	A		
Teflon	R	R		
Vinyl ester paint			A	
Viton rubber	R			

* For sample bottles, make sure that the cap and cap liner are also compatible.

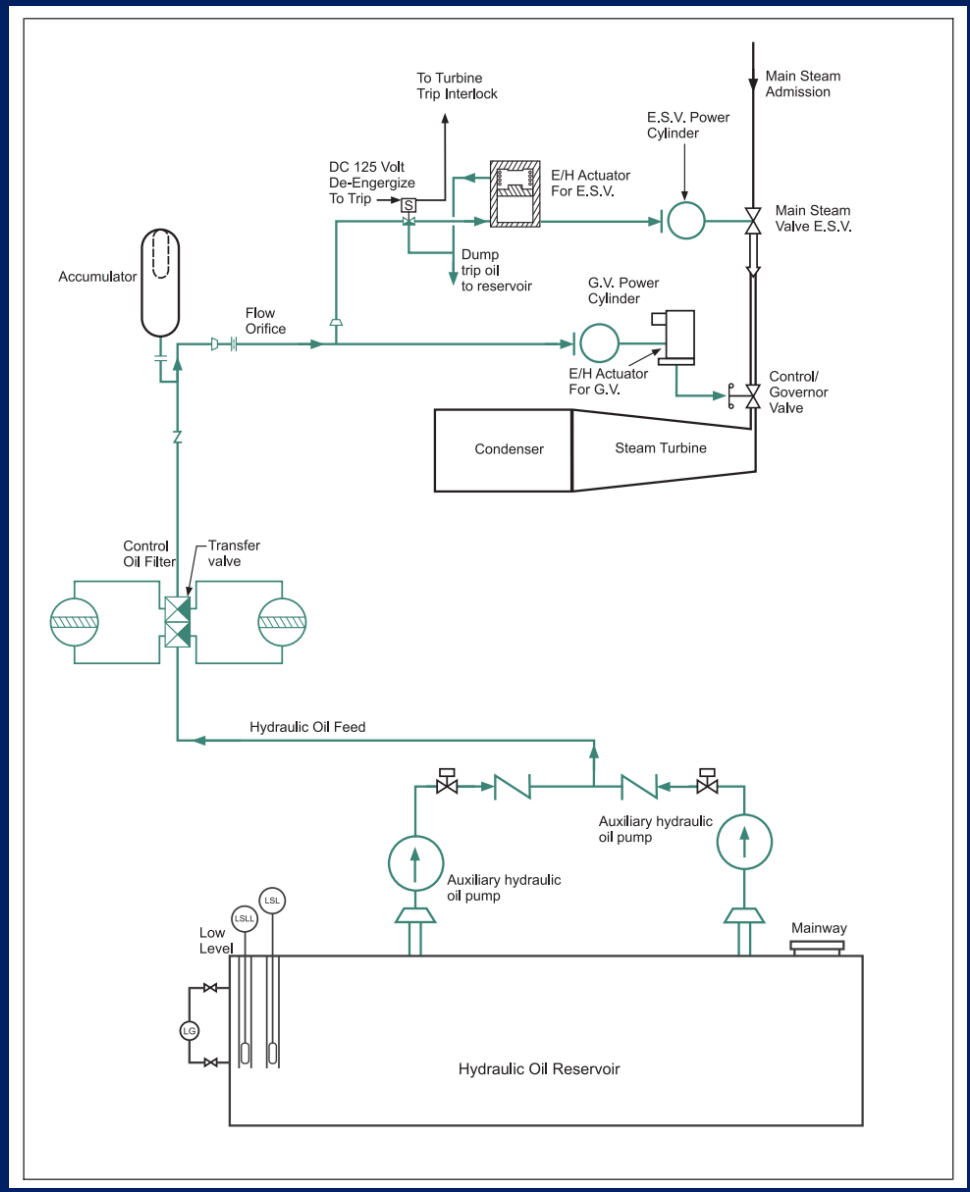
** Some types of cellulose might have binders to hold the fibers together, which must also be suitable.

R = recommended; A = acceptable; U = unsuitable

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Why Phosphate Ester?

- Vs. Mineral Oil, has:
  - Higher flash point
  - Higher fire point
  - Higher auto-ignition temperatures
  - Lower heats of combustion
  - Water more soluble (acid → varnish)
- Self-extinguishing
- May be biodegradable
- May, or may not, have additives
- More “sensitive” than mineral oil
- Common in Hydraulic Control Systems
  - Increasing Fossil use of PAG
  - Modernized control systems



Courtesy FM Global. Fig. 6 – Typical hydraulic control-oil supply system

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Phosphate Ester Fluid Degradations

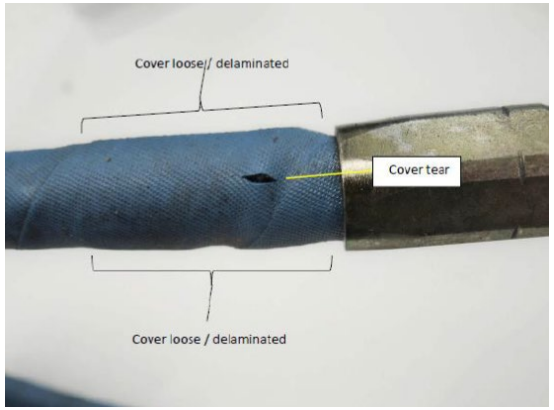
- High Temperature and/or High Water Content creates High Acid Number
  - Action typically required before values exceed 0.2 mg KOH/g
- High Particle Count
  - Affects operation of servo valves
  - Indicative of pump wear, contamination, fluid incompatibility, ineffective filtration
- High Water Content (Hydrolitic breakdown)
  - Rusting of ferrous components
  - Hydrolysis
- Low Resistivity
  - Electrokinetic wear of servo valve spools

NMAC – Lube Notes

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Beyond Fluid Failures – Fluid System Degradations

- (Check) Valve Failures
- Cooler Failure, Leaks
- Pump/Impeller Failure
- Seal/Gasket Failure
- Motor Failures
- Piping, Tubing, Hoses and Supports
- Heater
- Sticking Servo Valves
- Filter (gasket) failure
- Instrumentation











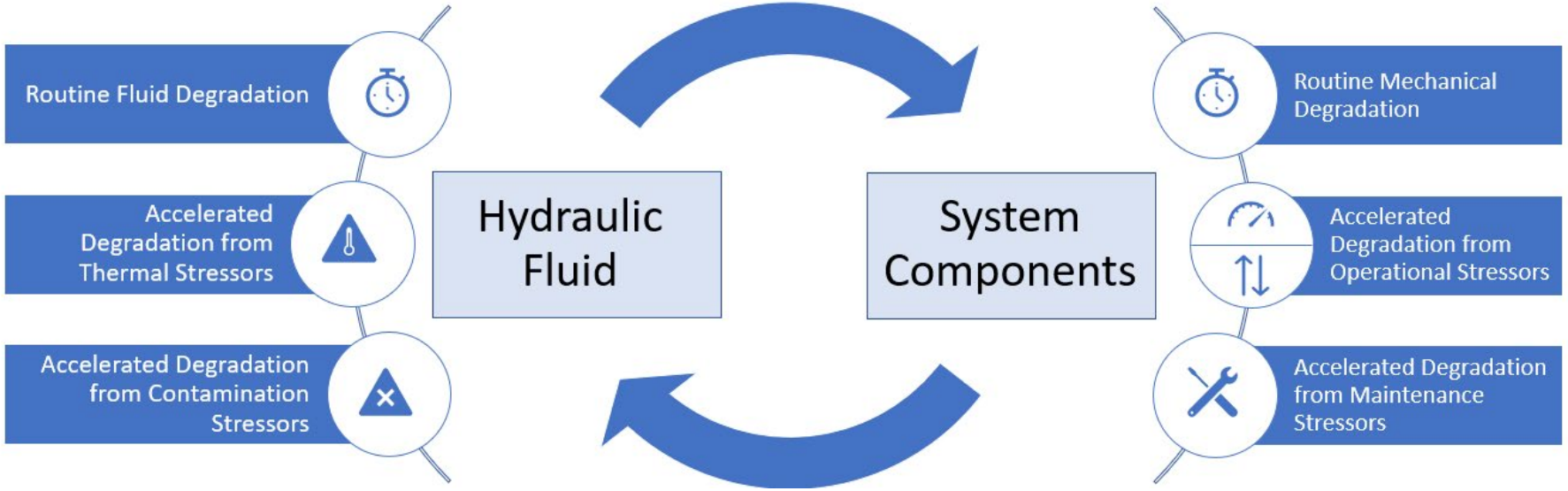


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Common Degradation Causes

- Purification Media Not Changed too Infrequently
- Purification Flowrate is Wrong
- Media is Too Wet, or Too Dry, and/or Fouled
- Change Procedure is Wrong or Not Followed
- Purification Housings Are Air Bound

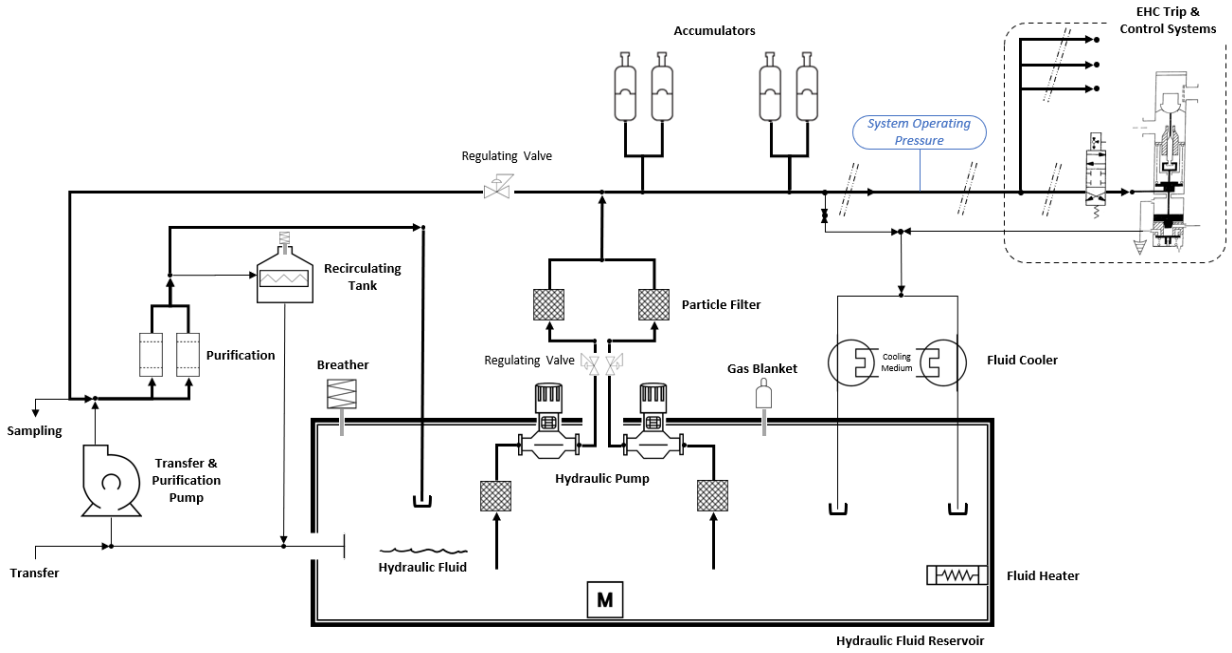
- Wrong Purification Media
- Wrong Fluid is Being Used
- Overstressed Fluid
- Material Incompatibility
- Unsuitable Substitutions
- Fluid and/or Media stored incorrectly



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Technical Walkdown / Operator Rounds

- Objective is to verify system operating parameters are within specifications, which includes:
  - Inspect for leaks and general tubing/piping condition
  - Listen for unusual noises (including vibrations) or unexpected pressure oscillations
  - Check for loose, damaged, or missing fasteners or hardware
  - Check color of desiccant
  - Check of heater fan operation
  - Verify operational parameters:
    - Fluid level
    - System pressure, temperature
    - Filter differential pressures
    - Etc.
  - Verify the reservoir is free of damage, external rust, and corrosion
  - Inspect actuators for evidence of wetting, leaks, looseness of bolting, cable and conduit



Preventive Maintenance Database – EHC Hydraulics

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Maintenance and Operations Best Practices

- Use the purification media continuously.
- Check and use the pressure gauges on purification system housings.
- Do not ignore the return line filter elements. Change them before they bypass.
- Keep the fluid level at full.
- Always filter makeup fluid. Purify new fluid as well if possible.
- Check the reservoir breather and keep it ‘wet’ with fluid.
- Change the purification media at least twice a year.
- Vent purification housings after changes
- Dry purification media if required.
- Check that heaters are really off when they are supposed to be off.
- Do not start with cold fluid.
- React to and correct the root cause of all high particle counts. Do not assume that it was sampling.
- Do a complete set of fluid tests, and look inside the reservoir port at least yearly.
- When getting Moog flapper-type servo-valves rebuilt, always either replace or at least inspect the torque motor.

EHC Systems can operate trouble free for decades

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Restoring Fluid Condition

- Bleed and Feed
  - Drain and refill slowly
  - Can be done online
  - Monitor fluid properties

- Replenish additive package
  - “Sweetener”
  - Prescribed by fluid manufacturer
  - Can be done online

- Replace and Flush
  - Take care to fully remove degraded fluid
  - Thoroughly clean system
  - Flush to remove contaminants
  - Requires outage

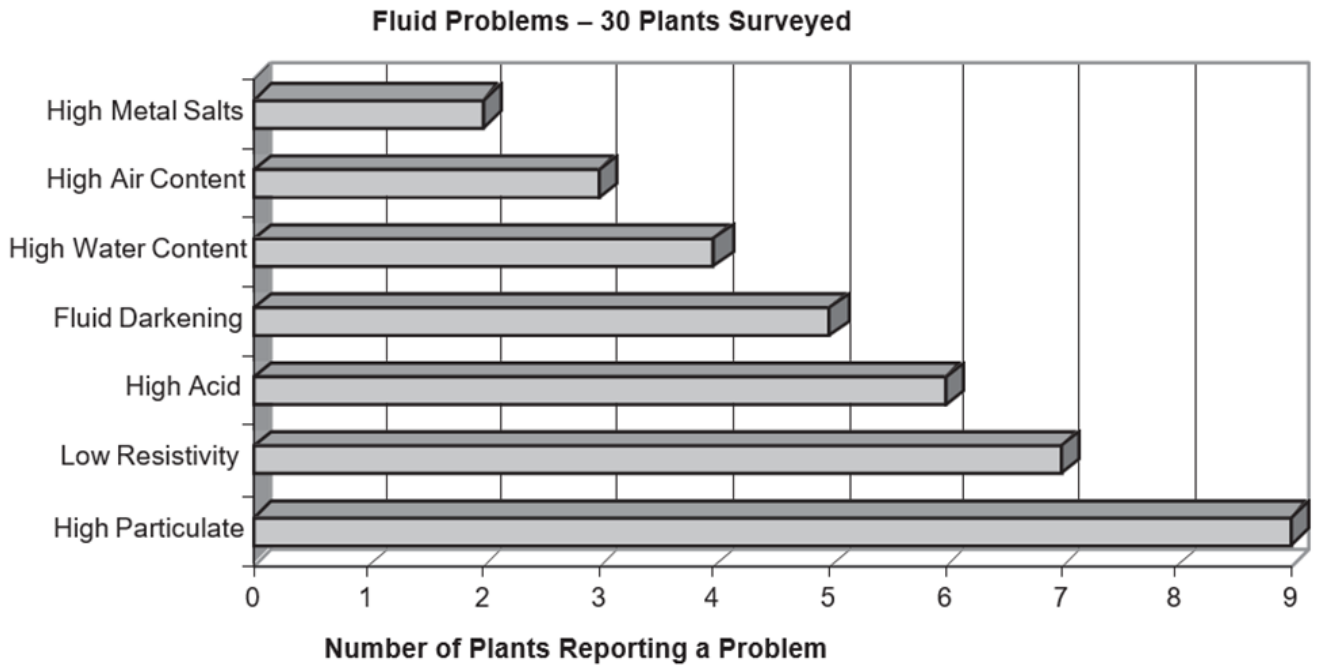
- Conditioning Equipment
  - Dehydration
  - Particulate
  - Heating/Cooling

Address the underlying cause(s)

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Phosphate Ester Testing – Fluid Quality Parameters

- Particulate Levels
- Volume Resistivity
- Acid Number (Neutralization Number)
- Appearance
- Water Content
- Air Release
- Metal Soaps
- Mineral Oil Content
- Inorganic Phosphate Content
- Chlorine Content
- Foaming
- Kinematic Viscosity



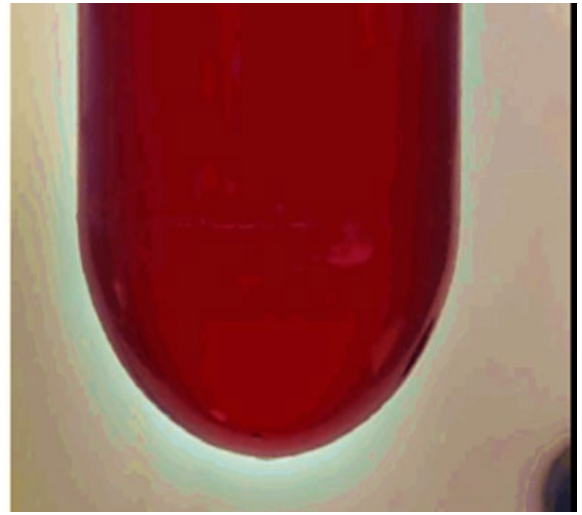
Applies to both new and operating fluids!

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Phosphate Ester Testing – Fluid Sampling

- Typically sample every 30-90 days:
  - Membrane Patch Colorimetry
  - Particle Count
  - Ultracentrifuge
  - RULER
  - Acid Number
  - Karl Fischer (Water Content)
  - Fourier-transfer Infrared Spectroscopy





Quality of Sampling Process and Lab are critical

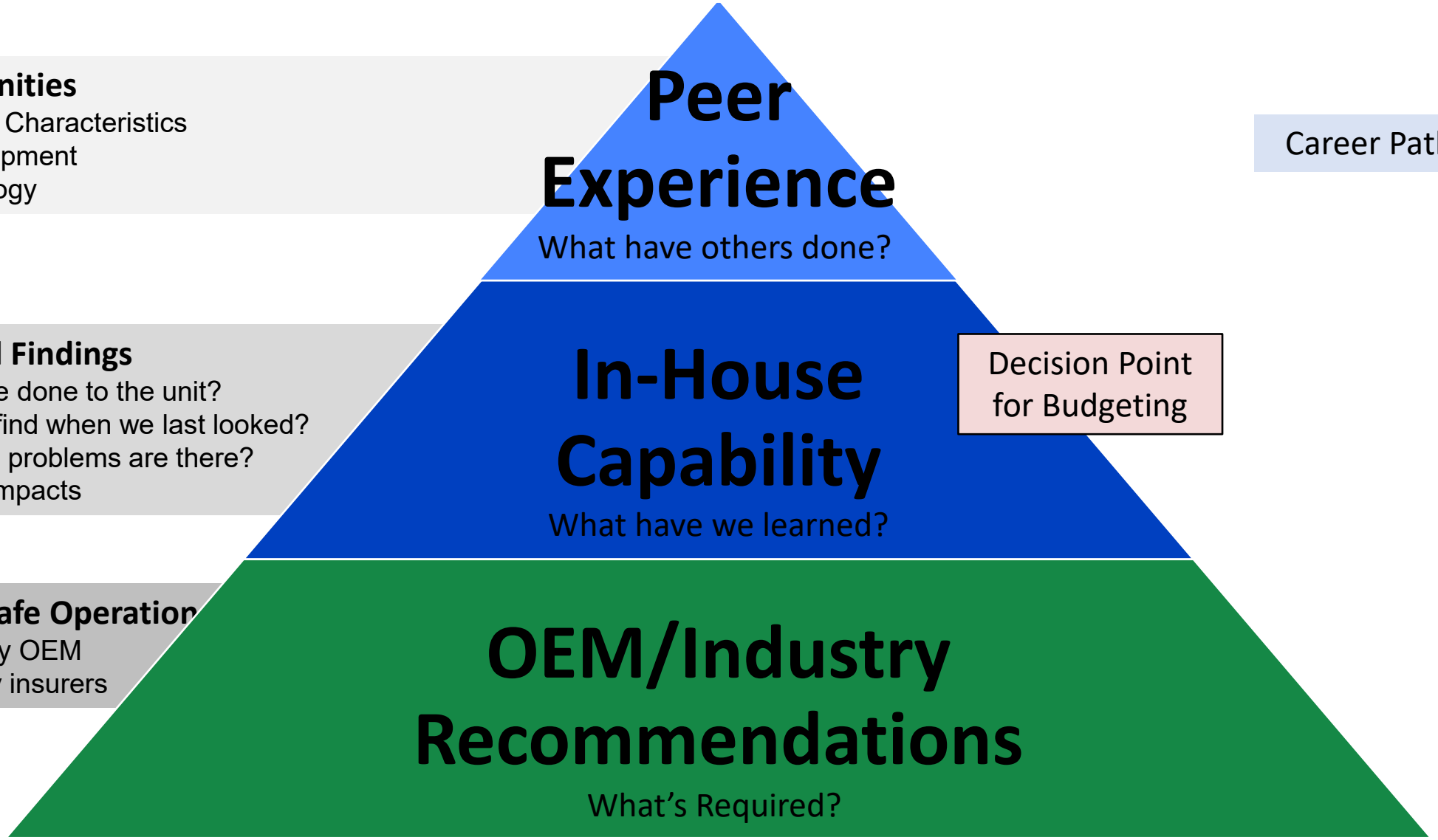
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Maintenance Scope Development

Fleet Opportunities
- Other Design Characteristics
- Optional Equipment
- New Technology

Operation and Findings
- What have we done to the unit?
- What did we find when we last looked?
- What existing problems are there?
- Operational Impacts

Required for Safe Operation
- Established by OEM
- Reinforced by insurers



Career Path

Decision Point for Budgeting

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Maintenance History

Build the Plan for maintenance at each opportunity

- Walkdown observations
- Open maintenance requests
- Last inspection report results
- OEM documentation
  - Instruction Books
  - Bulletins
  - Individual discussion
- Industry/peer knowledge sharing
- Establish outage objectives
- Document work/findings
- Rinse, repeat!



Steam Turbine Hydraulic Control System High-Pressure Unit Maintenance Guide – 3002010521

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Staying Ahead of Failures – FMEA & Sensor Gap Analysis

Summary Report, 3002021594

- Summary of degradation mechanisms and failure modes for components and hydraulic fluid
- Discussion of failure mode system interdependencies between fluid and equipment
- Fluid sensor package assessment based on today's state-of-technology understanding
- System sensor mapping plan that identifies sensors that may be considered for continuous monitoring or troubleshooting

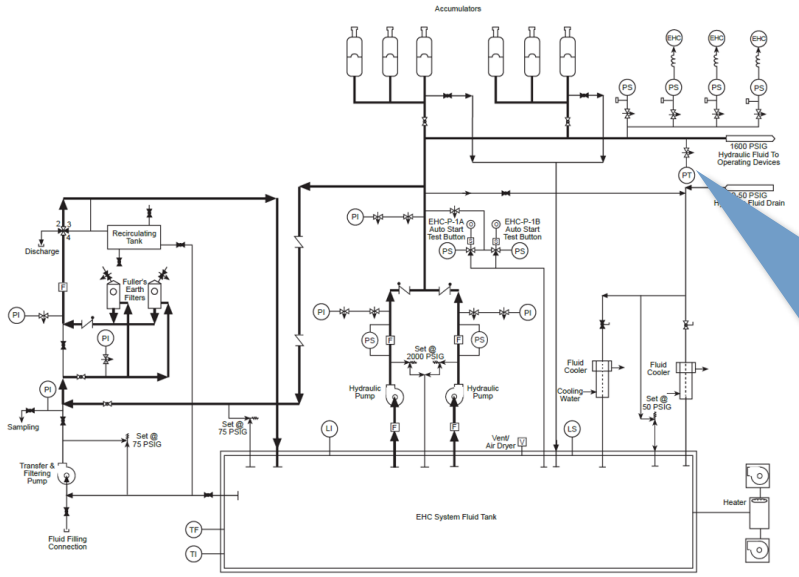
Excel Workbook, 3002021551

- Unlocked spreadsheet for plants to develop customized configurations and assessments of their system
- Failure locations with degradation mechanism, influence, leading indication, degradation detection, interdependencies and enhanced monitoring approaches
- Failure Modes Effects Analysis with modified detection scoring to rank and prioritize
- Fluid analysis tab that compares sample testing capability and sensor packages to detect and diagnose degradation
- System sensor parameter definitions that identifies sensors that may be considered for continuous monitoring or troubleshooting

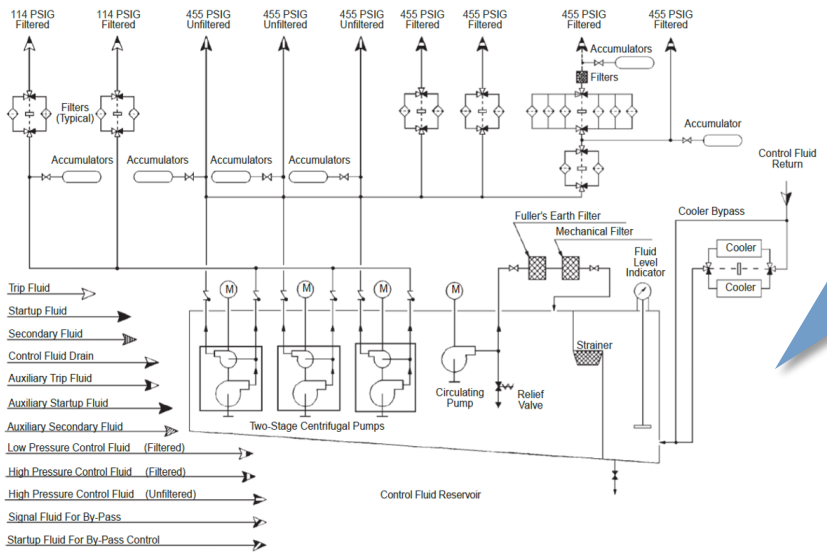
Two Deliverables, Two Formats, Many Use Cases

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Content Development

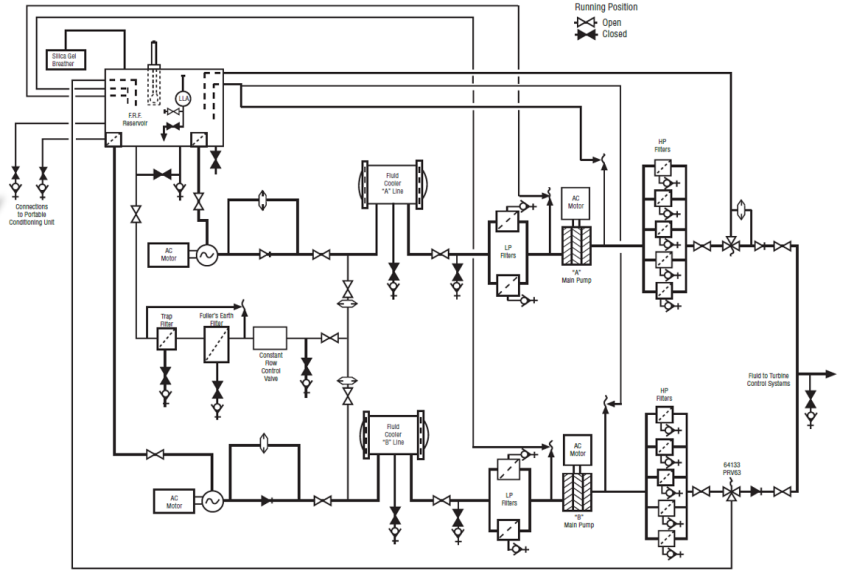


TR-107069 Figure 2-1. GE Typical EHC System

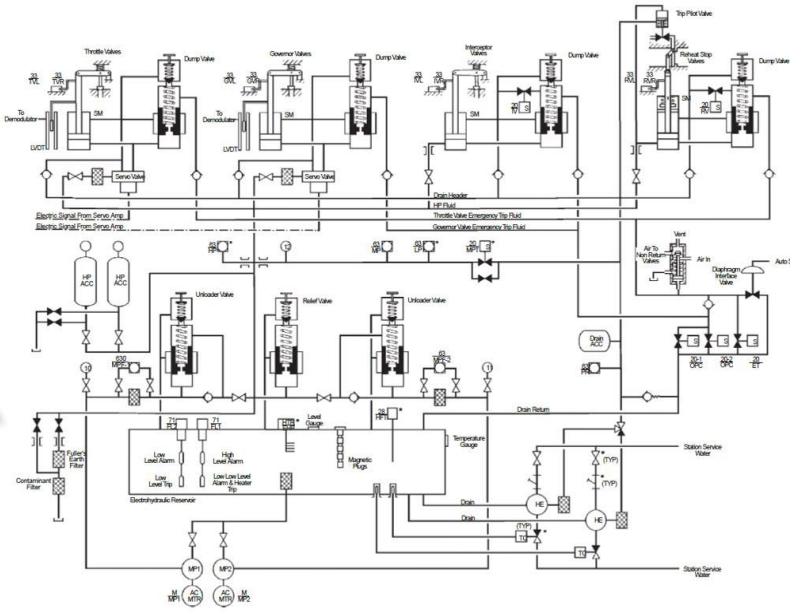


TR-107069 Figure 6-1. Siemens Typical EHC System (w/ MHC Backup)

Systems Vary:
OEM, Vintage, Fluid Application, SOA, etc.



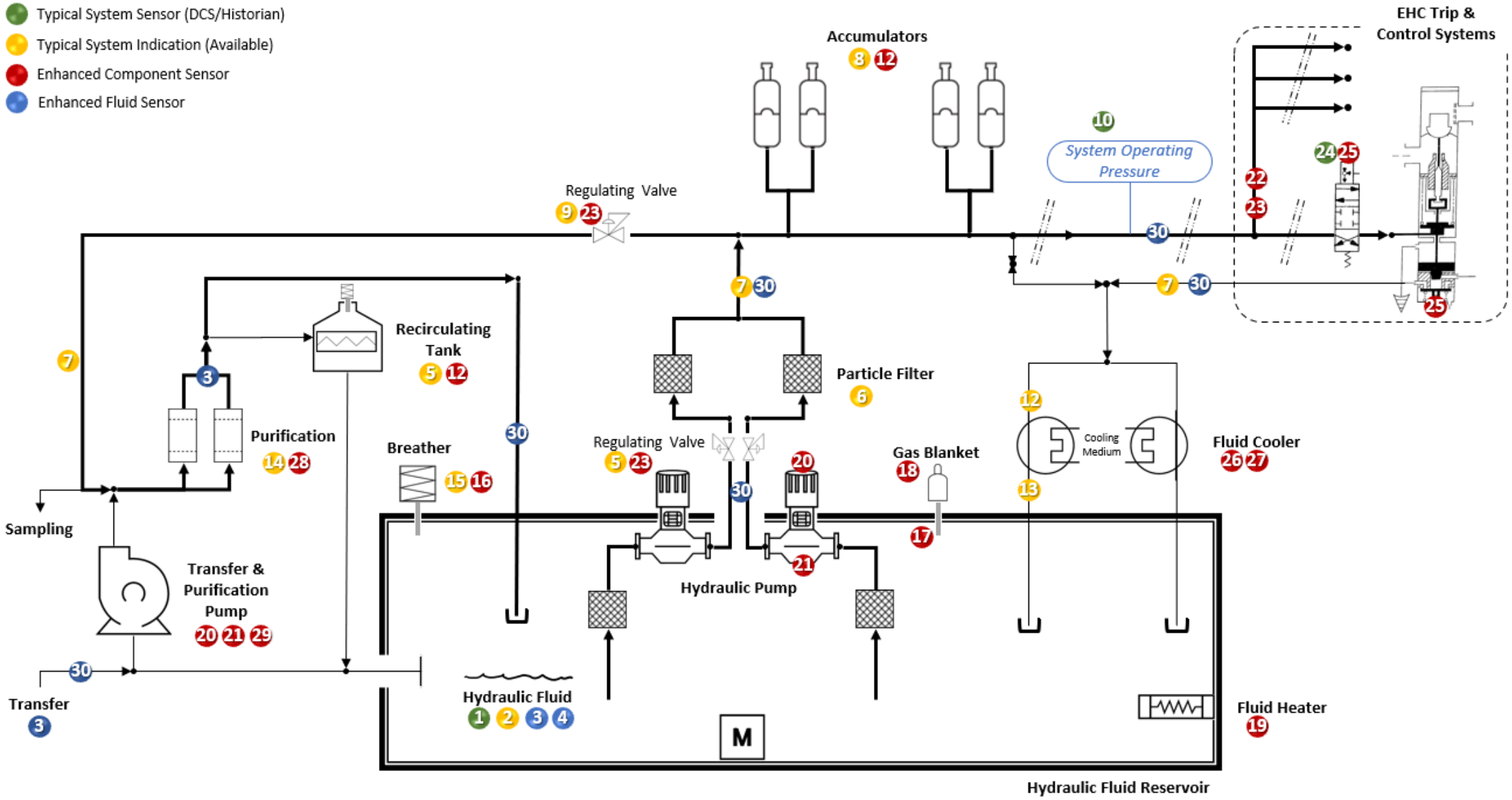
TR-107069 Figure 5-1. NEI Parsons EHG System



TR-107069 Figure 3-1. WH Typical [illegible]

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Creating a Comprehensive System Sensor Plan



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Overview

- Case study: Governor Valve Actuator bolt failure at Labadie Energy Center Unit 1 in March 2023 caused by fatigue cracks and over-torque, leading to fire and unit shutdown
- Investigation revealed multiple broken bolts; repairs included bolt replacement and torque specification enforcement
- Common causes of fluid leaks identified:
  - wrong or missing O-rings
  - improper torque
  - pinched O-rings
  - foreign material
  - misaligned tubing
  - defective hoses
- Leak locations mostly on actuator manifold fittings and accumulator supply inlets due to alignment issues, loose bolts, or aging components
- Recommendations for preventing leaks:
  - never reuse O-rings
  - use proper Viton O-rings
  - apply correct torque with crow's foot and torque wrench
  - align fittings carefully
  - inspect and clean O-rings before installation
  - pressure test system after assembly
- Emphasis on maintenance best practices to ensure reliability and safety of turbine control systems

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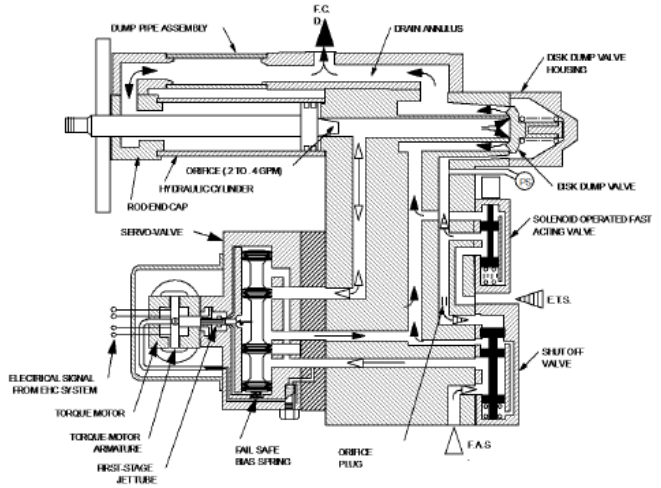
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EPRI Summer 2025 TGUG

EHC Fluid Quality and Extended Maintenance Impacts on Solenoids and Servos



Steve Myers – Constellation

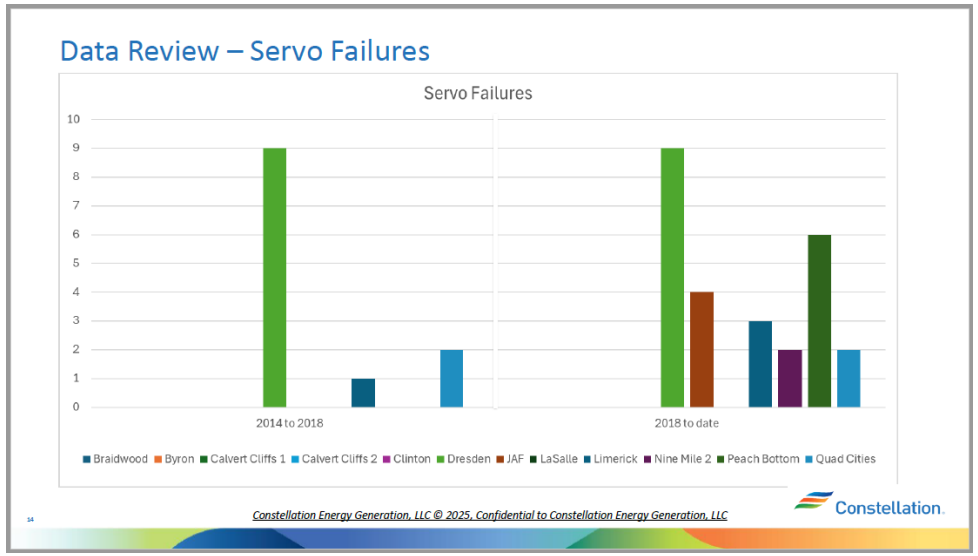
Mike Anderson – TG Advisors (Entrust)

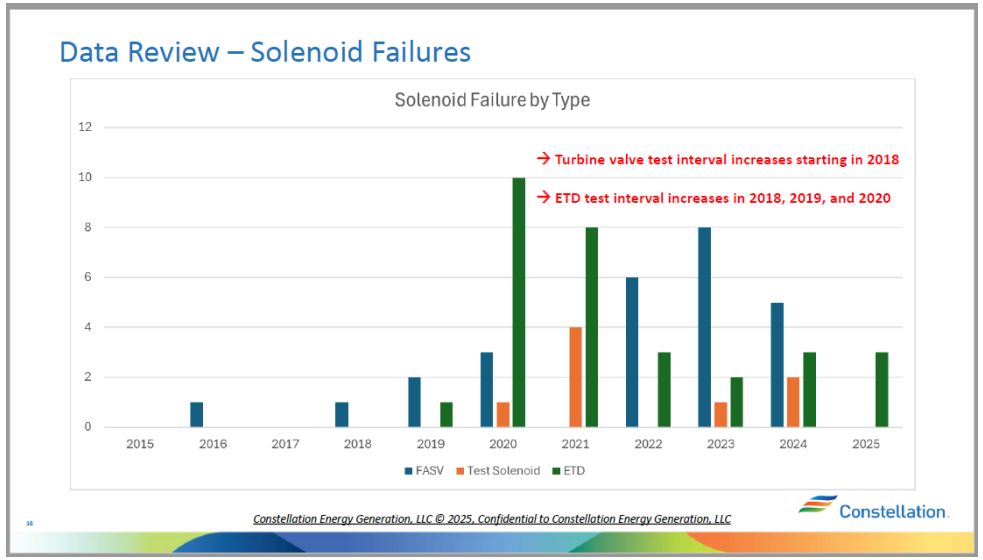
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Overview

- Overview of EHC fluid quality and maintenance impacts on solenoids and servos in turbine systems
- Increasing actuator component failures observed over the past 5 years causing operational challenges and lost generation
- Key components reviewed:
  - Servos
  - Solenoids
  - Shutoff valves
  - Check valves
  - Dump valves
  - LVDTs
  - Trip switches
- Suspected causes include poor fluid quality, extended test and replacement intervals, and reduced manufacturing quality
- Case studies from Calvert Cliffs Unit 2, James A. Fitzpatrick, Nine Mile Point 2, Limerick, and others highlight varnish buildup, failed components, and operational risks
- Fluid varnish persists despite fluid changes and affects valve performance and reliability
- Recommendations: challenge PM strategies, replace servos/solenoids every 4-6 years, increase test frequencies if failures occur, conduct null-bias testing, maintain fluid cleanliness with flushing, and evaluate system design for fluid degradation risks
- Emphasis on fluid quality's critical role in preventing actuator failures and ensuring turbine reliability

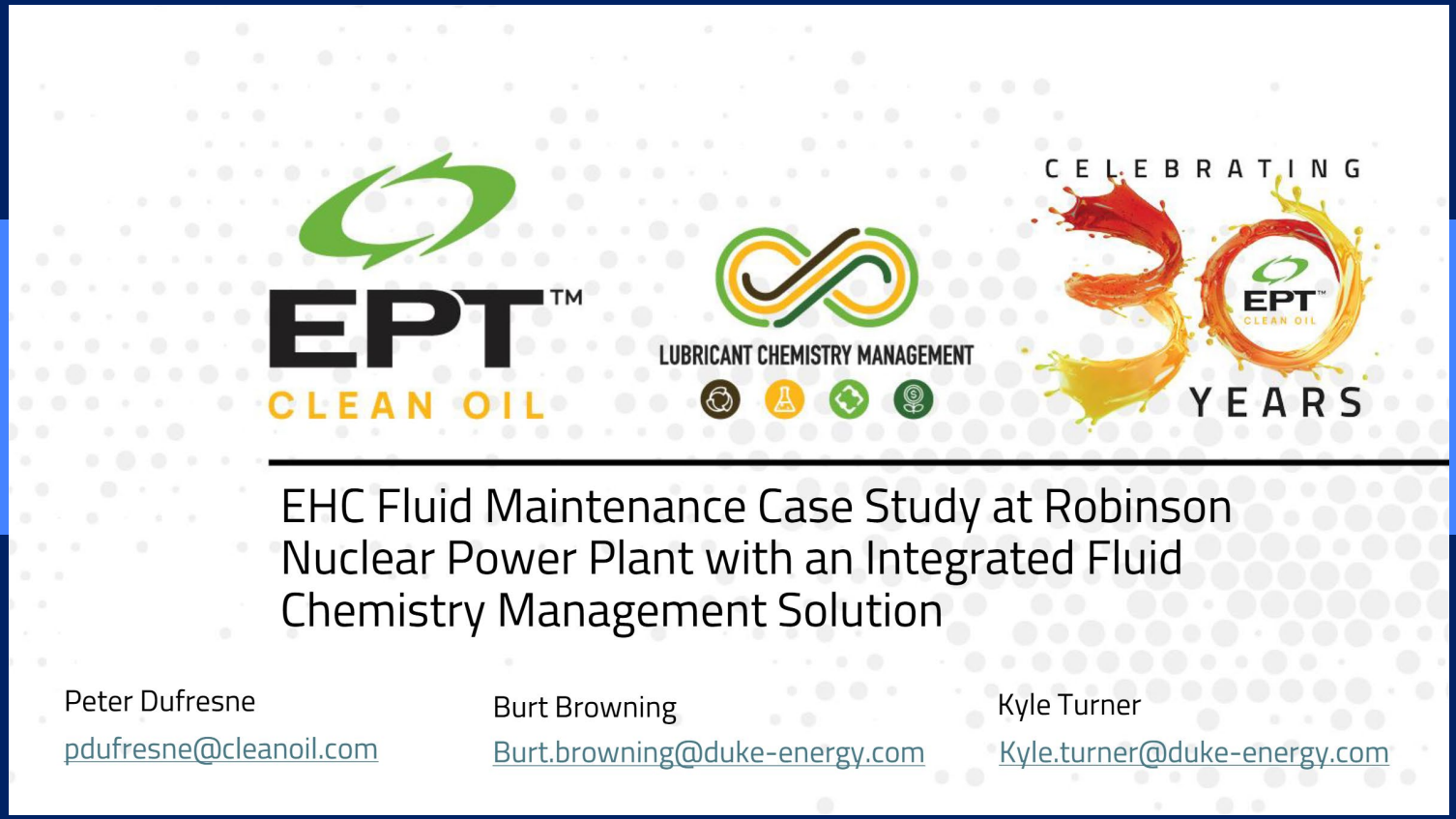




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Overview

- **Problem:** Post-2018 Quadvoter digital control install caused valve sticking, sluggish/failed actuation; fluid color darkened to black despite supplier tests reporting “within spec.”
- **Root-cause discovery:** Standard lab testing missed varnish/insoluble particulate issues; found EPRI guidance and adopted a detailed ACE™ test package.
- **ACE findings:** Very high MPC ΔL (66), patch weight 7.1 mg/50 mL, high sub-micron particulate, elevated dissolved metals, high foaming, overly dry fluid (<100 ppm).
- **Solution selected:** Install EPT ECR® 12000 fluid conditioning system (ICB® ion-exchange + ECR® + TMR® + 1 µm β1000 particulate filter and sensors).
- **Implementation notes:** Phased install using existing Fullers Earth skid in parallel, tank insulation/heating to maintain ~100 °F, N2 supply, SCADA control, factory acceptance testing with Duke team; completed Jan 2024.
- **Operational controls:** Automated self-isolating skid, DP auto-shutdown, leak and filter alarms, inline particle and water sensors, automated N2 flow.
- **Standards alignment:** Designed to meet ASTM D8323 and GEK46357K guidance; ICB® resin targets PE varnish removal (patented).
- **Maintenance actions:** Non-chemical system flush during 2024 fall outage to remove residual contaminants; continued monitoring.
- **Measured results (post-conditioning):** MPC (varnish) −99%, varnish precursors (phenols) −82%, patch weight −93%.
- **Key insight:** Chemistry-driven varnish/insolubles caused mechanical failures; improved testing (MPC ΔA/ΔB/ΔL, patch weight, phenols, strong acids) + ion-exchange-based conditioning are critical for FRF/EHC reliability.

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Winter 2025



EHC Laboratory Fluid Testing, Analysis and Data Interpretation

Evan Zabawski, CLS

Turbine Session, 13.01.2025

eurofins | TestOil

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Overview

- **Scope:** Overview of lubricant tests used to monitor fluid condition and equipment health.
- **Key tests:** *Elemental spectroscopy (ICP-AES), Viscosity (D445), Color (D1500), Acid Number (D974/D664), Resistivity (D1169), Particle Count (D7647 & pore blockage), Water by Karl Fischer (D6304), Membrane Patch Colorimetry (MPC D7843), Ultra-centrifuge (UC), Specific Gravity (D1298).*
- **Elemental spectroscopy:** Detects wear metals, additives, contaminants (0–5 µm best); large particles often missed.
- **Particle counting:** Optical counts ≥4 µm; useful for filtration/clean-up decisions but doesn't ID particle type and may not correlate with ICP.
- **Viscosity & Color:** Viscosity critical for equipment; contamination, oxidation, shear affect values. Color can indicate contamination but is limited.
- **Acid Number (AN):** Tracks oxidation/degradation; trends more valuable than single values; slow response in large reservoirs.
- **Water by KF:** Sensitive (10–25,000 ppm); doesn't distinguish dissolved/emulsified/free water; water accelerates corrosion and additive loss.
- **MPC & UC:** Quantify insolubles/varnish (ΔE or 1–8 scale); high fluid varnish ≠ system deposits; low result can hide plated-out varnish.
- **Resistivity & Specific Gravity:** Indicate conductive contamination and density/API; results temperature-sensitive.
- **Pitfalls & precision:** Many tests have notable repeatability/reproducibility limits; sample location, handling and test interferences strongly affect interpretation.
- **Takeaway:** Use multiple, correlative tests and trending (not single points) to diagnose contamination, wear, oxidation and varnish risk.

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Winter 2024

EHC FLUID QUALITY MANAGEMENT DURING STEAM TURBINE OUTAGES

TGUG, Houston, January 2024

Ken J. Brown, P.Eng, MASc, STLE CLS
Utility Service Associates
cell 416 458-4189
kenbrown@fluidcenter.com

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Overview

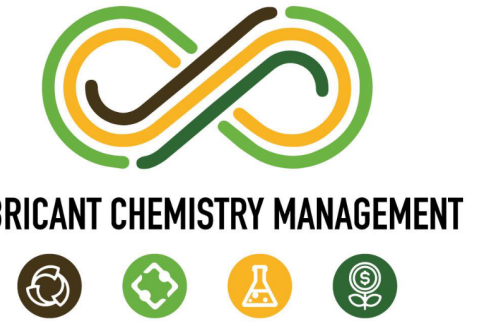
- **Goal:** Keep EHC systems healthy — identify current condition and target the desired state.
- **The "Right Stuff":** Right fluid, system, amount, parts, operation, maintenance, monitoring, resources & training.
- **Common causes of degradation:** incorrect purification (media, flow, housings), wrong fluid/substitutions, storage issues, thermal overstress, material incompatibility, procedural or inspection lapses.
- **Elastomer guidance:** *Use Viton/EPR; avoid Buna-N (nitrile).* Consider stainless hoses where appropriate.
- **Testing & limits (GEK 46357K):** Monitor acid number, water, resistivity, chlorine, particle count, MPC patch/phenols, viscosity, metals, air release — adjust sooner rather than later.
- **Pre-outage actions:** test fluid, inspect/store consumables, document system, assess pumps/accumulators/hoses/coolers, upgrade filtration if needed, verify new-drum quality.
- **During outage best practices:** protect/open equipment, witness key work, save replaced parts/samples, prefill & run purification, photograph and verify procedures.
- **Post-outage checks:** confirm fluid level/priming, monitor first starts, baseline pressures & fluid sample, inspect for leaks/noise, decide components for analysis.
- **Servo valve risks:** particle/varnish plugging, electrokinetic wear, material mismatches — inspect and analyze valves/screens.
- **Preventive program essentials:** current documentation, correct lab tests, proactive purification/filtration, proper storage, routine inspections, cross-team coordination.
- **Action emphasis:** Detect changes early, take corrective action before limits are exceeded, and preserve evidence for troubleshooting.

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Summer 2023





Phosphate Ester Lubricant Chemistry Management

EPRI TGUG August 2023

Peter Dufresne
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Matthew G. Hobbs, PhD
mhobbs@cleanoil.com

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Overview

- **Purpose:** Manage FRF (phosphate ester) chemistry to ensure EHC system performance and reliability.
- **Failure pathways:** Hydrolysis (water), Oxidation (oxygen), Thermolysis (high T) → acids, varnish, carbon/soot.
- **Standards & guidance:** Follow GEK46357K and ASTM D8323 for testing, limits, and corrective actions.
- **Routine vs. advanced monitoring:** Routine tests (AN, water, particle count, resistivity, viscosity) are necessary but insufficient — add MPC (micro-patch/ΔE, a+b, patch weight) to detect fines, varnish, and carbon not seen by ISO counts.
- **Key diagnostic thresholds:** AN > 0.20 mg KOH/g, resistivity minimums (commonly 5 GΩ·cm; D8323 often 10 GΩ·cm), MPC ΔE preferred <20.
- **Fluid-conditioning strategy:** Combine targeted technologies for comprehensive chemistry control:
  - **ICB® ion-exchange** — removes dissolved acids, varnish precursors, metals; shown best AN and resistivity improvement.
  - **ECR® electrostatic filtration** — removes ultrafine carbon/soot.
  - **TMR® N2 dry gas blanketing** — removes water and limits oxidation.
  - Plus high-efficiency particulate filtration and sensors.
- **Third-party comparison:** ICB® outperformed competing ion-exchange brands on AN, resistivity, MPC varnish removal, color, metals, and foaming.
- **Takeaway:** Use standards-aligned monitoring (including MPC) and combined conditioning (ICB + ECR + TMR + filtration) to keep FRF clean, dry, and low-acidity — preventing varnish/servo failures.

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Summer 2023

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Servo Failures Case Studies and Health Monitoring

Mike Anderson

August 14, 2023

EPRI Summer TGUG

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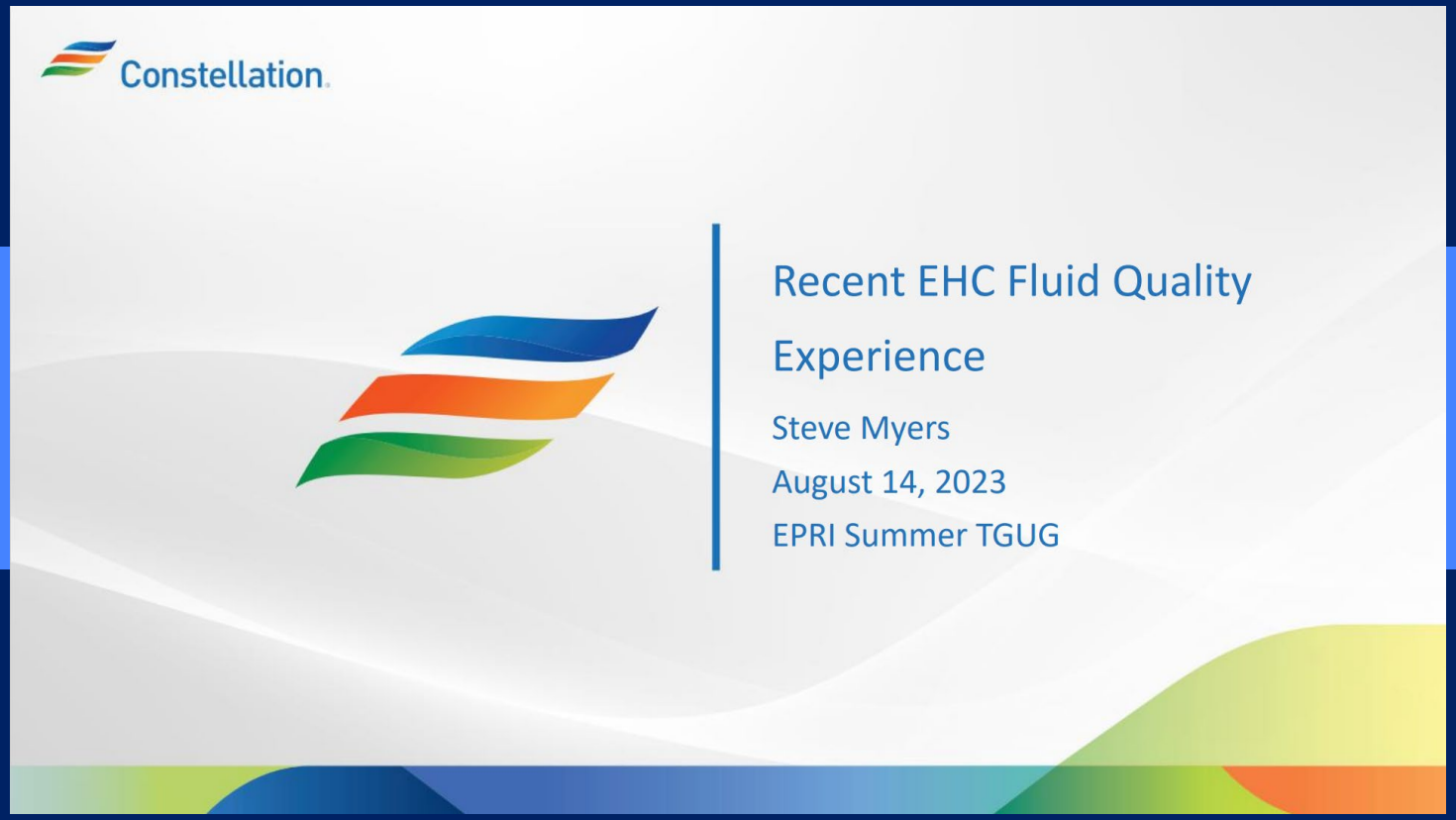
Overview

- **Incidents & Causes**
  - Limerick U1 (2022): O-ring damage from DEHC-driven aliasing/vibration and over-cycling; varnished EHC fluid found.
  - Nine Mile Point 1 (2014): “Crud burst” debris etched bushings → increased friction, hysteresis, reactor pressure fluctuations.
  - Multiple sites (NMP2, Ginna, FitzPatrick): silt/varnish, poor fluid quality, and missed null-bias setup caused long Loss-of-Power (LOP) closure times and stuck spools.
- **Failure Modes & Statistics**
  - Most common: unknown (52%), degraded cable/connection (17%), failed coil (12%), null bias issues (7%), varnish/etching/debris (7%), O-ring/parts (2%), poor calibration (2%).
  - Observed symptoms: valve drift/open, failure to respond, long bias closure, noise, oscillations, sluggishness.
- **Maintenance & Monitoring Recommendations**
  - Perform Null Bias/LOP timing at every refuel/major outage; average of 3 runs and trend over RFOs.
  - Consider emergent replacement if LOP times increase 50–100%.
  - Monitor servo performance online (pk-pk torque motor voltage for binding/hysteresis).
  - Control CV cycling aggressiveness in DEHC systems and maintain EHC fluid quality; no filter is perfect.
  - Suggested PM replacement frequency ≈ 4 years (adjust based on cycling and fluid quality).
- **Operational Actions**
  - Update procedures to include vendor null-bias setup on new servos.
  - Improve filtration, change operating procedures where debris/vibrations observed, and extend extent-of-condition replacements when failures found.

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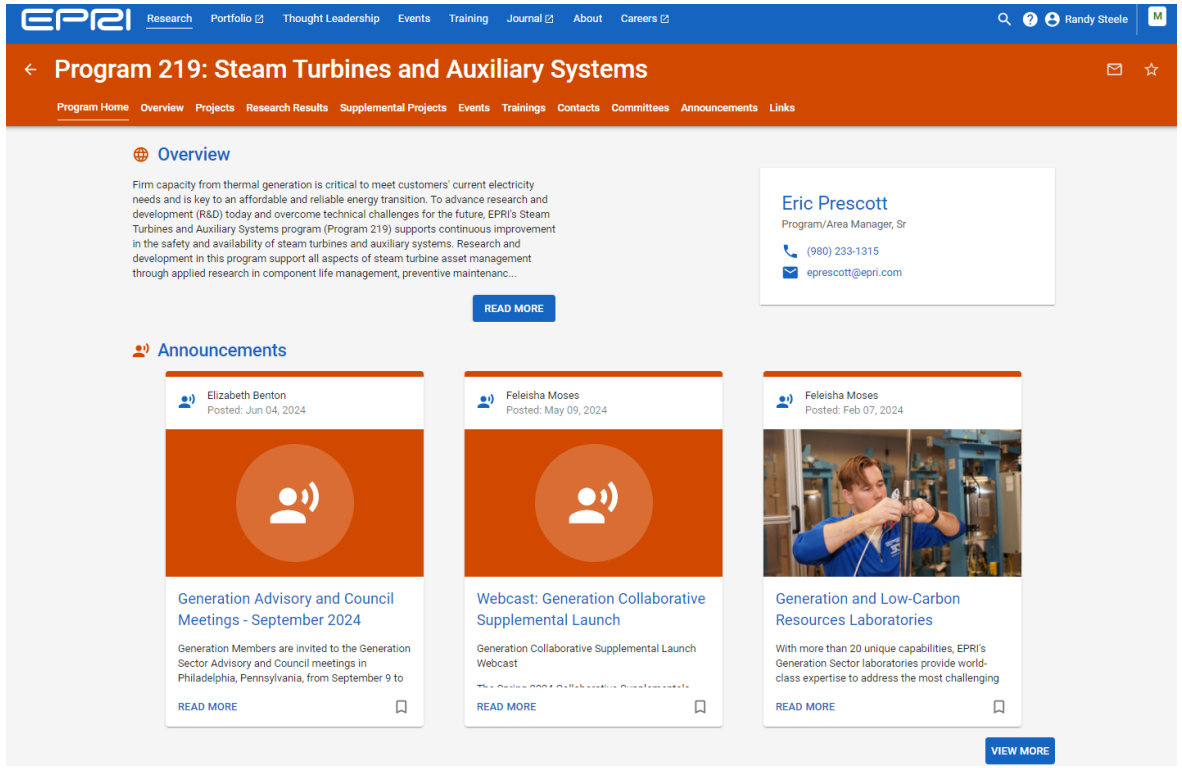
Overview

- **Scope:** Review of degraded EHC fluid events and responses at Braidwood, FitzPatrick, Calvert Cliffs, and Peach Bottom.
- **Braidwood:** Makeup barrels showed unexpectedly low resistivity (~23–24 GΩ·cm) near threshold.
- **FitzPatrick:** Metal particulate found in dump valves from installation debris; Mark I MTSV design (no bypass) allowed stagnant fluid to overheat and degrade.
- **Calvert Cliffs:** Runaway acidification (U1 acid 0.46 mgKOH/g, water 600 ppm, resistivity 7 GΩ·cm); vacuum dehydration, feed-and-bleed (12 drums), and FSA (ICB + N2 purge) + ECR installed; fluids returned to spec.
- **Peach Bottom:** Longstanding high acid, low resistivity, varnish/carbon; frequent replacements without flush leave ~200 gal residual fluid in actuators/lines.
- **Common contributors:** Low/uneven treatment flow, lack of bypass/dry-air purge, thermal stress/micro-dieseling, particulate contamination, and incomplete flushing.
- **Mitigations used:** ICB (replace Fullers Earth), ECR (electrostatic filtration), dry-air purge control, vacuum dehydration, feed-and-bleed, equipment inspections (hot-spot/drone), and considering side-stream skids.
- **Actionable takeaways:** Ensure proper makeup quality, add bypass/side-stream treatment or increase flow to cleaners, flush during replacements, install dry-air purge, and inspect for particulate/thermal stress sources.

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Relevant EPRI Research

- Steam Turbine Mechanical Hydraulic Control System - Operation, Inspection, Setup, Troubleshooting, and Maintenance Guide, Revision 1 – 1019313
- Avoiding EHC Fluid Problems - NMAC (epri.com)
- Lube Note Publications - NMAC (epri.com)
- Steam Turbine Hydraulic Control System High-Pressure Unit Maintenance Guide – 3002010521
- Electrohydraulic Control Fluid and Elastomer Compatibility Guide – 1011823
- Electrohydraulic Control System Sensor Gap Analysis: Identification of Sensors for Fluid and System Components – 3002021594
- Electrohydraulic Control (EHC) Fluid Maintenance Guide – 3002003594
- tgug.epri.com



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Break

Monitoring and Diagnostics Technologies

Sensors, Technologies, and Application of AI

Eric Prescott
Area Manager, Senior Program Manager, Program Lead

2025 WANO Steam Turbine & Generator Workshop
Shanghai, China
3-6 November 2025

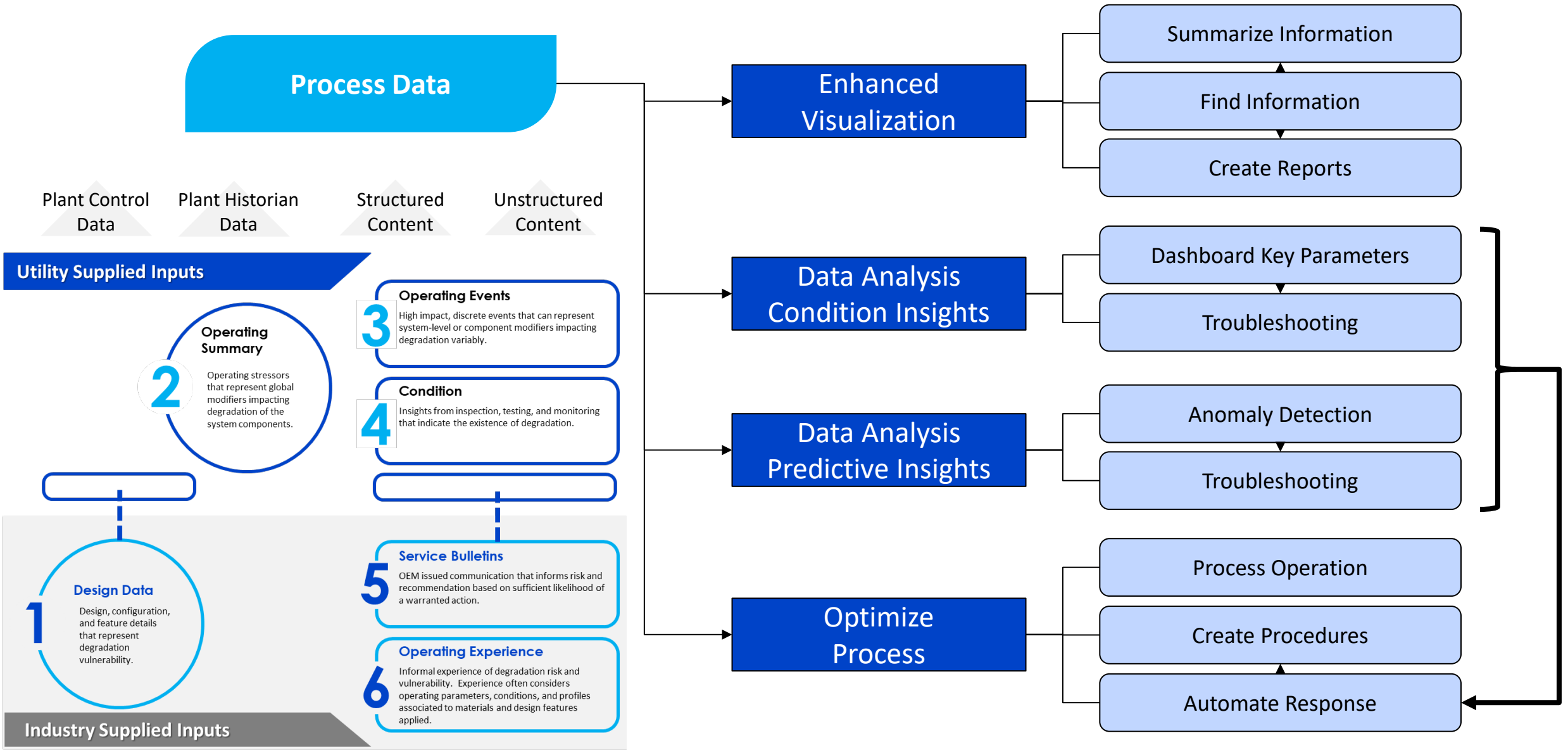
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User Feedback on AI Applications

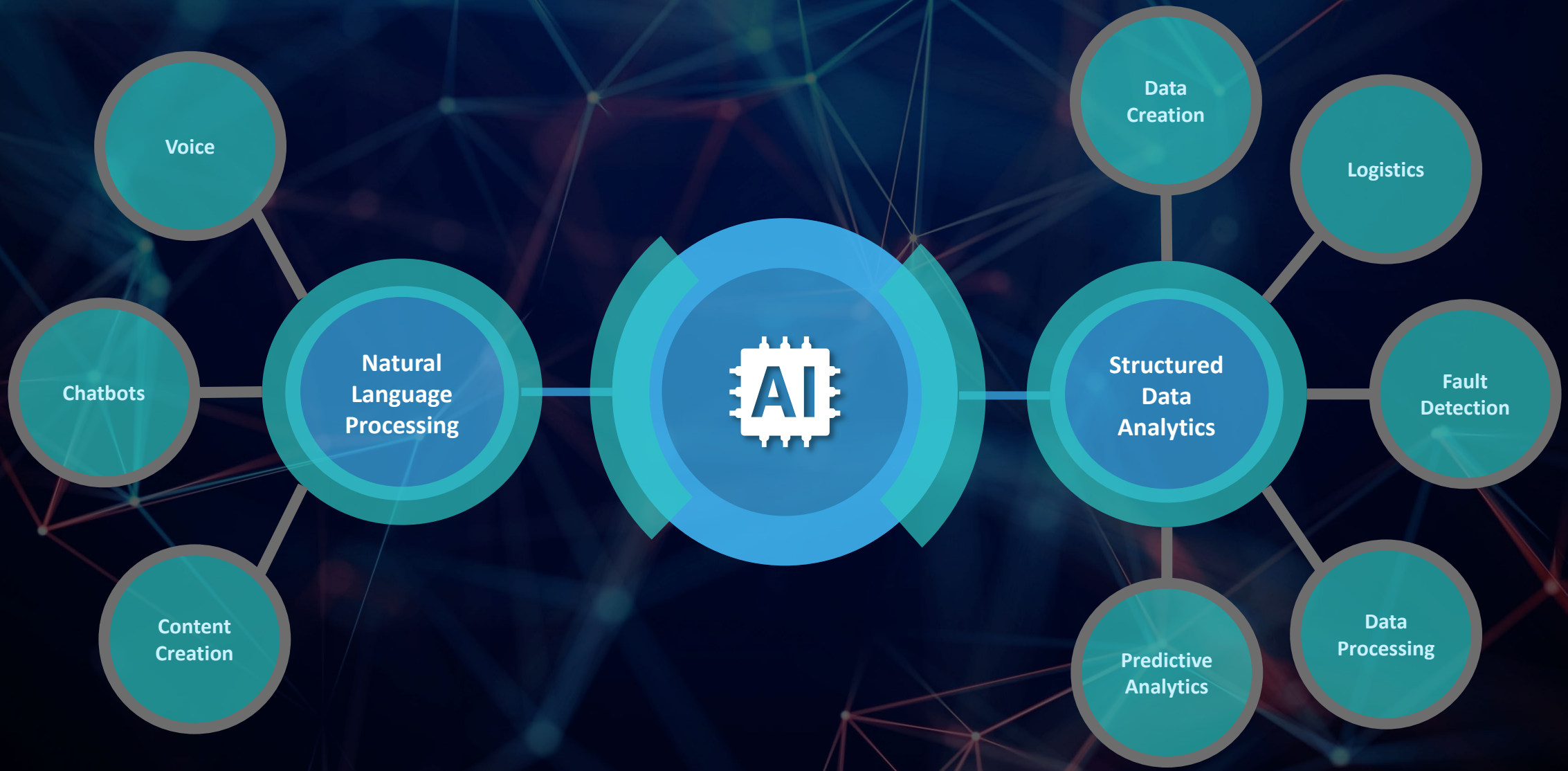
- **Performance Optimization**
- Make **quicker decisions**, and increase my productivity
- **Forecast with modeling to detect failures** or abnormalities to become more reliable.
- **Make it easier to find information**, help the complex problems process much better way to resolve the issues
- Integrate tools into operations that prompt **operator action and allow proactive maintenance**
- **Find trends in the machine data** and provide early warnings to operators / engineers.
- **Quickly analyze data**, summarize complex data, find patterns, write specs
- **Summarize data**.
- I would say since I am a feild engineer. Possibly **trouble shooting**.
- Optimization
- Taking lots of data from multiple sources , **refine data** to make decisions
- **Analyzing data Summarizing reports** Automating or speeding up mundane tasks
- **Simplify the report review processes** and extract the important information to produce a high level overview of work completed.
- Help **streamline and help create uniform procedures**
- The ability to **pull data from manuals, reports, and programs** faster to help make decisions.
- By gathering all of the complex data into actionable information to be given as recommendations to the field
- **Predictive monitoring, fault pattern recognition, data organization, search optimization**
- More **quickly find relevant references** from plant manuals

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User Feedback on AI Applications



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Voice

Chatbots

Content Creation

Natural Language Processing



Structured Data Analytics

Data Creation

Logistics

Fault Detection

Data Processing

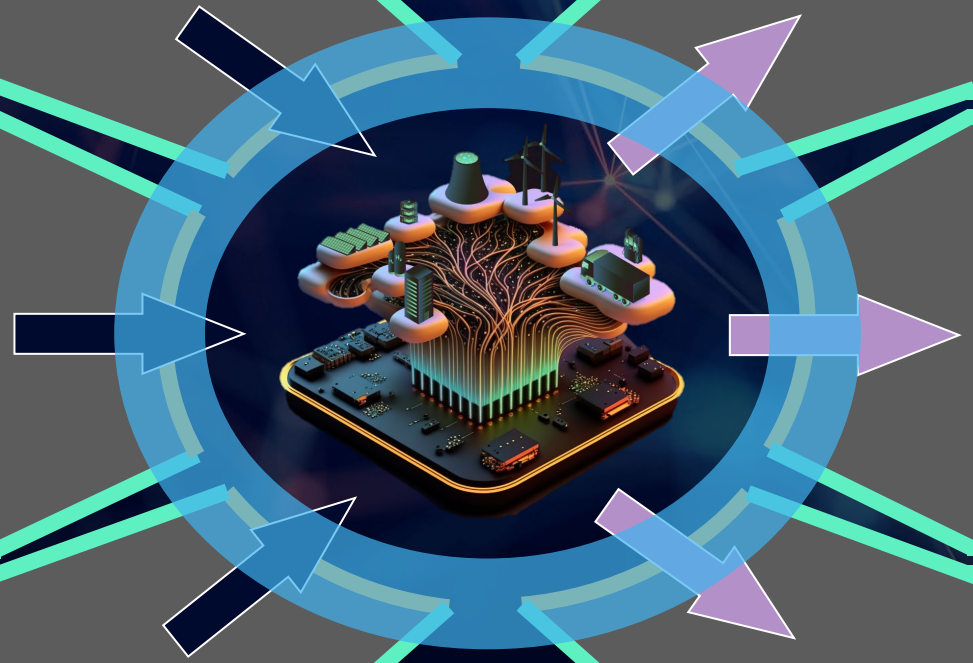
Predictive Analytics

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Data Sources

Logic Sources

Business Tools



Data Analytics & Visualization

Business Process Automation

System Automation

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Data Sources

Logic Sources

Business Tools

EXAMPLES…

Data Analytics & Visualization

Configuration Explorer
Cycle Performance
Equipment Behavior (Deviations and Anomalies)
Health and Risk Indices

- *Reliability Metrics*
- *Life Consumption*

Business Process Automation

Troubleshooting
Causal Analysis
Work Order Generation

- *Outage Planning*
- *Maintenance Dispatch*

System Automation (Generation Control)

Adaptive Control
Mission Regulation

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EXAMPLES…

Data Sources

Control System & Historian of Sensor Data
Remote Instrument Data
Inspection Findings
Maintenance Manual (OEM)
Technical Insights (OE & BP)

Logic Sources

Conditional Limits
Dependency Correlation Algorithms
Physics-based Virtual Sensors
Metrics/Decision Variables Calculation

Business Tools

Plant/Turbine Control System
CMMS
ERP

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Most practical applications for ST equipment…

Data Analytics & Visualization

Configuration Explorer

Cycle Performance

Equipment Behavior (Deviations and Anomalies)

Health and Risk Indices

- *Reliability Metrics*
- *Life Consumption*

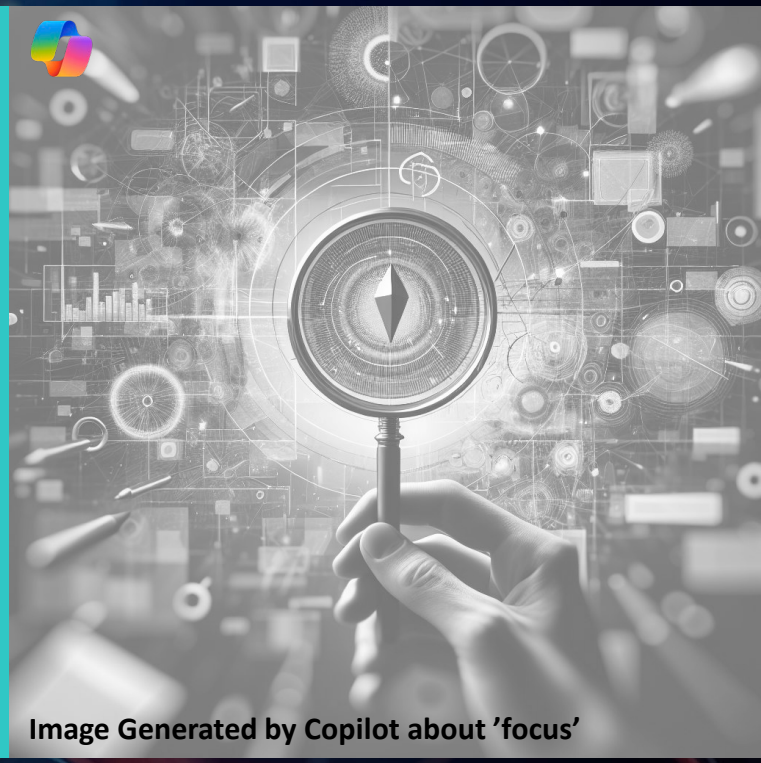
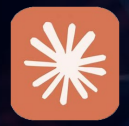


Image Generated by Copilot about 'focus'

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How do we get there?



Claude 3.7 Sonnet insights on “AI applications for steam turbines”

Predictive Maintenance

AI algorithms analyze vibration patterns, temperature fluctuations, and other sensor data to predict component failures before they occur
Machine learning models can detect subtle anomalies in turbine performance that might indicate developing issues
This reduces unplanned downtime and extends equipment lifespan

Performance Optimization

AI systems continuously monitor operating conditions and adjust parameters to maximize efficiency
Deep learning models can identify optimal steam flow rates, pressure settings, and load balancing
These optimizations can increase power output while reducing fuel consumption

Safety Enhancement

Computer vision systems monitor physical components for visual signs of deterioration
Anomaly detection algorithms identify potential safety issues in real-time
AI assists in analyzing complex interactions between turbine systems and nuclear reactor operations

Digital Twins

Virtual replicas of physical turbines allow for simulation and testing
Engineers can test scenarios and modifications without risking actual equipment
Helps in training operators and planning maintenance activities

Condition Monitoring

Real-time analysis of turbine health using multiple data streams
ML algorithms detect patterns that human operators might miss
Provides continuous assessment rather than periodic inspections

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How do we get there?

Claude 3.7 Sonnet insights on “AI applications for steam turbines”

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Digital Twins

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Helps in training operators and pla

Condition Monitoring

Real-time analysis of turbine healt
ML algorithms detect patterns tha
Provides continuous assessment ra

E how do i know if the vibration patterns are bad

“Compare current readings against historical "healthy" patterns”

E how do you know if changes are unhealthy

“Monitor rate of change over time (slope of deterioration)”

E how much rate of change is too much

“Standards provide starting points for rate-of-change thresholds:

- **ISO 20816:** Suggests alert at 25% increase from baseline and alarm at 40% for many components
- **EPRI guidelines:** For nuclear applications, often recommend investigating sustained increases of >15% over baseline”

E which epri guideline does this reference

For the most current and applicable guidelines, you should contact EPRI directly or access their document library through your organization's subscription, as their recommendations may have been updated since my last knowledge update.

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Input Data Critical Success Factors:

- *Clean*
- *Correct*
- *Consistent*
- *Concise*
- *Context*
- *Cleared IP*



Data-driven Numerical Models

Physics-based Models

Risk-Informed Models

Common Model Traps:

- *Assuming all units, cycles, machines are the same*
- *Relying solely on standard instrumentation to manage reliability risks*
- *Not understanding the constraints of the measurements/sensors*
- *Setting up APR/ML clusters with unrelated parameters*
- *Not including equipment interdependencies in models*
- *Defeaturing structural models*
- *Ignoring transient behavior*
- *Improper technical insight elicitation*

High Quality Information Resources Necessary for Development and Successful Deployment

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AI is a Generic and Inclusive Term Consisting of Many Technologies

The Possibilities are Endless…

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Practical Examples of Applied Technologies…

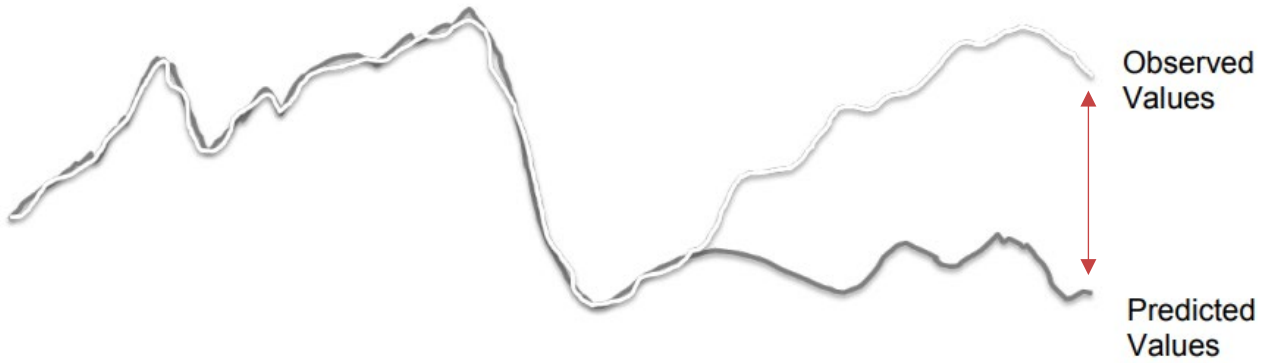
APR (Advanced Pattern Recognition) is the most frequently applied, and commercially viable technique available that falls under the Predictive Analytics branch of AI that use multivariate modeling techniques.

Algorithms and dashboards can be part of OEM APM (Asset Performance Management) platforms off-prem or stand-alone data analysis packages on-prem.

Today's commercially available technology focuses on steady-state analysis.

Critical Success Factors:

- **Relevance of parameter relationships**
- **Stability of parameter performance**
- **Quality of training data**
- **Knowledge base to troubleshoot deviations**



Predicted Values are generated by the trained relationship between associated parameters.

Observed Values are the real time measurement.

Deviation of the values represents a change in system performance that can be associated to damage, degradation, or other operational anomalies.

KEY CHALLENGE

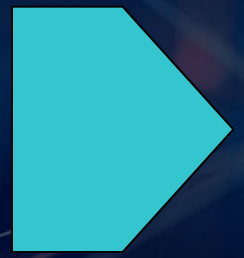
INCREASES DIAGNOSTIC COMPLEXITY (TIME & RESOURCES)
REQUIRES SME INPUT TO REVIEW DEVIATIONS, FALSE-POSITIVES, IMPACTFUL FAULT CONDITIONS AND IRRELEVANT FAULT CONDITIONS.

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Steady State vs Transient vs Offline APR

Steady State

Common use case due to stability of training data parameters.
Intelligent grouping of parameter clusters can inform response.



Cycle Parameters ($P,T,\dot{m}$)
Valve Position
MW Output
Lateral Vibration

Transient States

Less common use case for start up and shut down behaviors.
Both time and frequency domain data may be required to assess effectively



More vibration information
Differential Expansion
More…

Offline Operational Equipment

Not commonly applied.
Critical systems like turning gear, lube oil, and other standby services can drive degradation and start up reliability.

Helpful to alert, but require SME Input …may limit idealized efficiency gains

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Practical Examples of Applied Technologies…

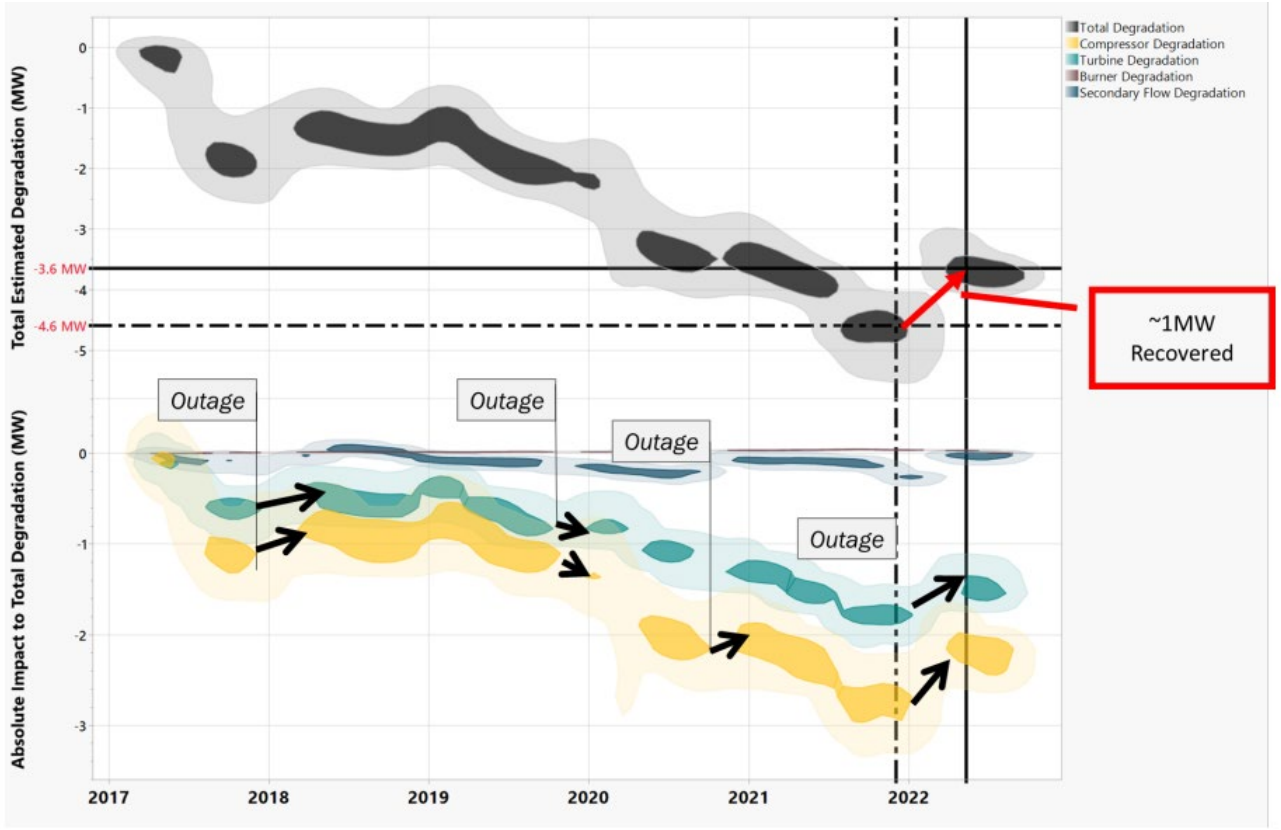
Physics-based 'Digital Twins' for machinery diagnostics are advanced tools that apply measured operating parameters to define extent of a damage mechanism that can be used for process control or maintenance planning.

Modelling and simulation is used to calculate a desired measurable point in the system. Often this are different from virtual sensors in application but share similar methodologies depending on complexity of the target insights.

Critical Success Factors:

- Quality of modelling method
- Adequacy of sensor data
- Accuracy of physical properties data and behaviors
- Understanding the limitations

Ex. Gas Turbine Performance Digital Twin



Key Challenge

Model development (Accuracy, Time & Resources)

Requires specialized engineering insights and computational methods to develop models

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Visualization of Indirect/Computed Information

Digital Twin – As a Virtual Sensor

Applying available data to calculate an un-sensored parameter

- *Heat Rate/Thermal Performance*
- *Discrete temperature of interest*
- *Critical stress*

Digital Twin – As a Metric Calculator

Applying available data to calculate key metrics

- *Material life consumption*
- *Degradation mechanism risk*
- *Health indices*

Variable and Highly Targeted

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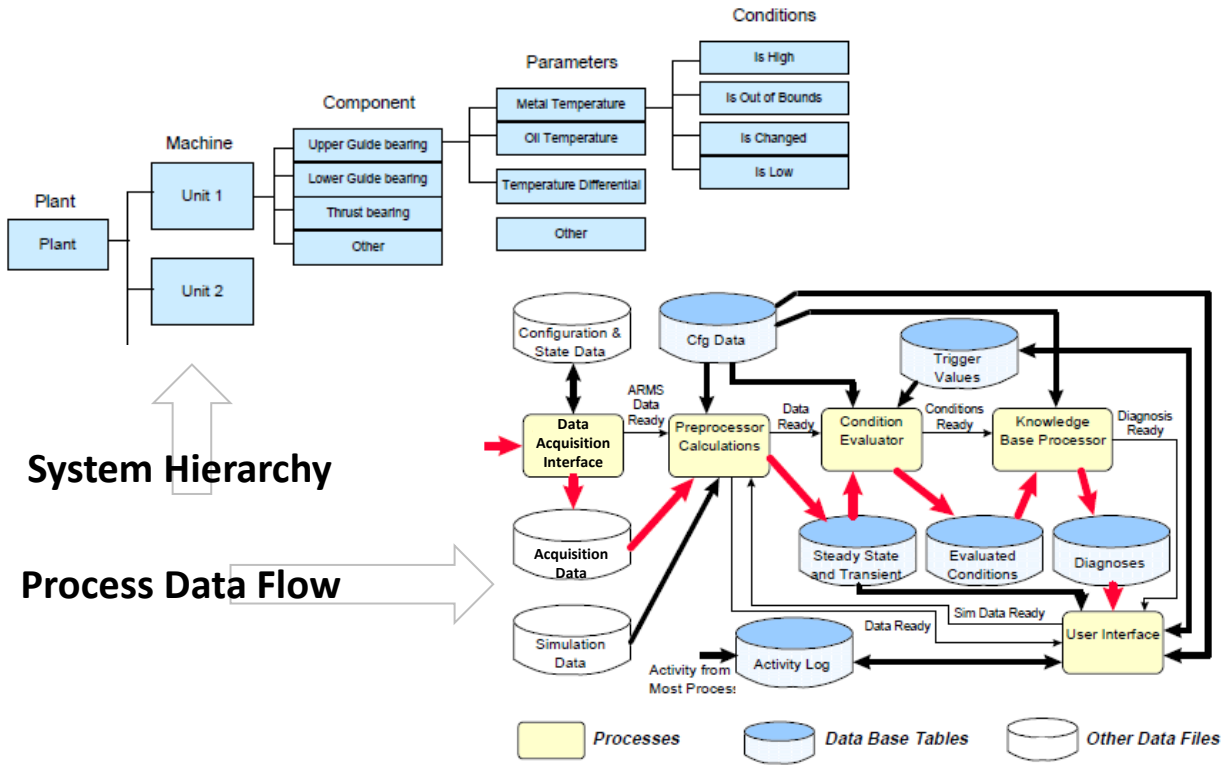
Practical Examples of Applied Technologies…

Expert Systems for machinery diagnostics are advanced tools that apply quantitative analysis and qualitative decision theory to provide real-time insights that support equipment troubleshooting and maintenance planning.

Inference Engine and rules base establish the diagnostic within the expert system.

Critical Success Factors:

- **Quality of knowledge base**
- **Adequacy of sensor data**
- **Relevance of parameters to the diagnostic reasoning**
- **Building the outputs for specific role**
- **Understanding the limitations**



Conditions are used to generate actionable insights.

KEY CHALLENGE

INCREASES DIAGNOSTIC DEVELOPMENT (TIME & RESOURCES)
REQUIRES SME INPUT TO ESTABLISH CAUSE-EFFECT RELATIONSHIPS IN TERMS OF THE END USE APPLICATION.

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‘System Expert’ Layers

Understanding the Failure Modes

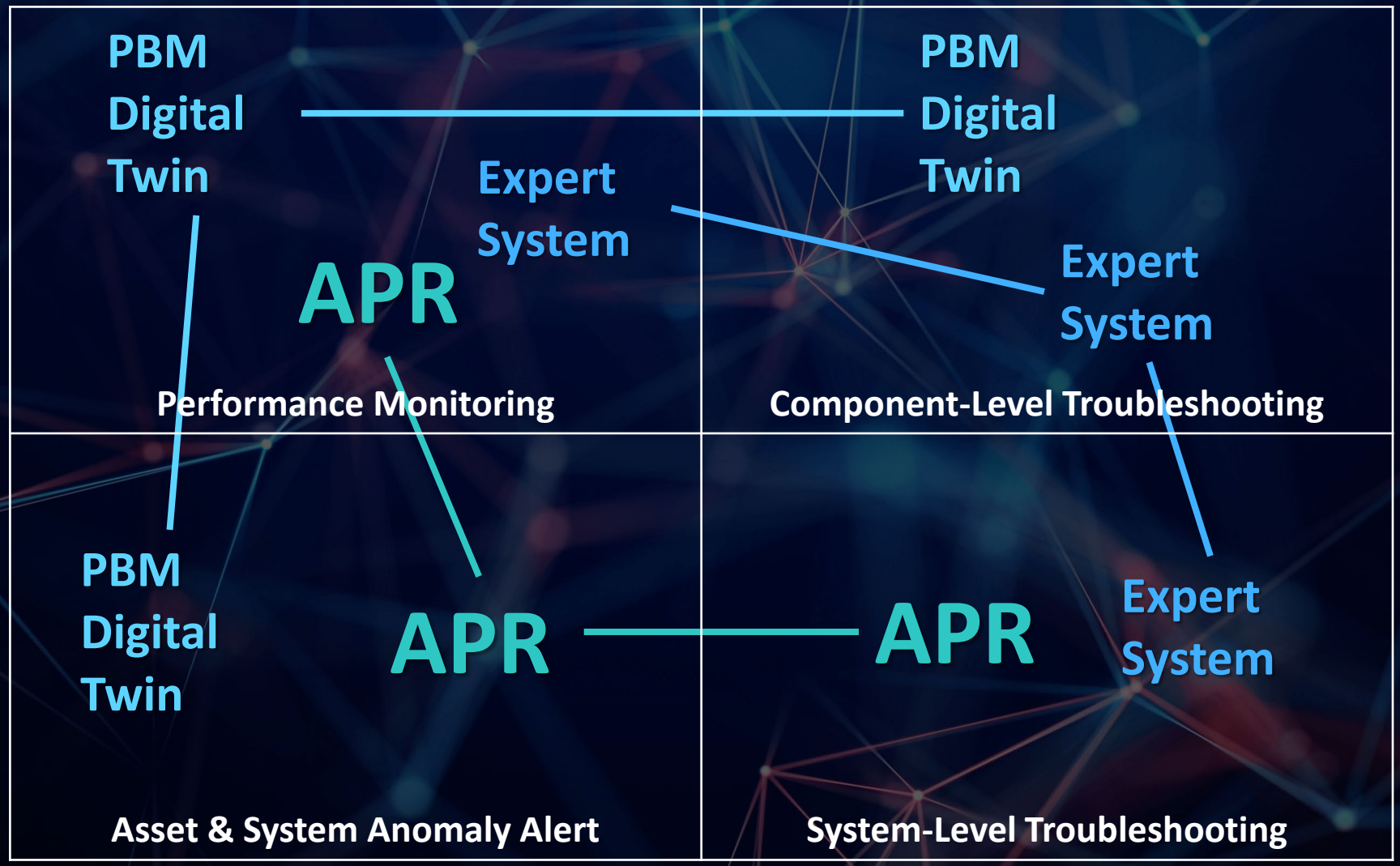
A detailed analysis is conducted to understand mechanism risk and detection capability.

HP Rotor Forging High Cycle Fatigue Detection

Correlation Strength	Indication Category	Indication Type	Sensor	Typical Fault Behavior	Sensor Readiness	Parameter	Parameter Location
Low	Leading Indicator	Indirect	Counter	NA	NA	Start Quantity	DCS/Historian
Low	Leading Indicator	Indirect	Counter	NA	NA	Event Quantity	DCS/Historian
Low	Leading Indicator	Indirect	Output (MW)	NA	NA	Event Quantity	DCS/Historian
Low	Leading Indicator	Direct/Indirect	Mass flow	↗ Gradual or ↗ Sudden	Standard Instrument	Mass Flow	Steam Generator Cluster
Low	Leading Indicator	Indirect	Proximity Probe (x/y)	↗ Gradual or ↗ Sudden	Standard Instrument	Vibration Amplitude	Bearings
Low	Leading Indicator	Indirect	Thermocouple	↗ Gradual or ↗ Sudden	Standard Instrument	Temperature	Casing (rotor calculated)
Low	Damage Detection	Indirect	Proximity Probe (x/y)	↗ Gradual or ↗ Sudden	Standard Instrument	Vibration Characteristic	Bearings
-	Leading Indicator/ Damage Detection	Indirect	Torsional Strain	↗ Gradual	Concept	Strain Amplitude	Shaft/Coupling
-	Leading Indicator/ Damage Detection	Indirect	Torsional Acceleration	↗ Gradual	Concept	Acceleration	Shaft/Coupling

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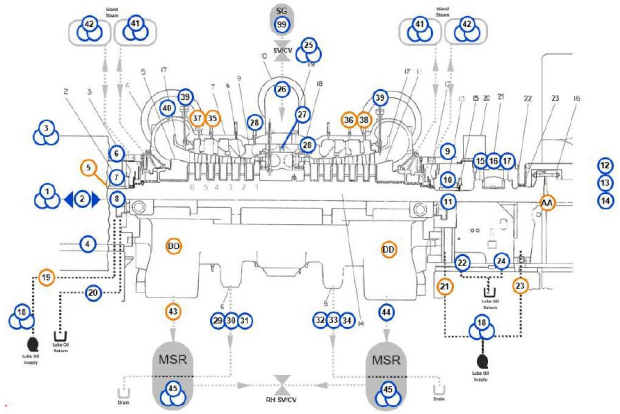
Technologies Fit for Purpose



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EPRI Steam Turbine Resource Development Examples…

Comprehensive FMEA with Sensor Gap Analysis



HP Rotor Forging Low Cycle Fatigue Detection

Correlation Strength	Indication Category	Indication Type	Sensor	Typical Fault Behavior	Sensor Readiness	Parameter	Parameter Location
Low	Leading Indicator	Indirect	Counter	NA	NA	Start Quantity	DCS/Historian
Low	Leading Indicator	Direct	Speed	↗ Gradual or ↗ Sudden	Standard Instrument	RPM Rate	Control Cluster
Low	Leading Indicator	Direct	Thermocouple	↗ Gradual or ↗ Sudden	Standard Instrument	Temperature Rate	
Low	Leading Indicator	Direct	Pressure Transmitter	↗ Gradual or ↗ Sudden	Standard Instrument	Pressure Rate	
Low	Leading Indicator	Direct	LVDT	↗ Gradual or ↗ Sudden	Standard Instrument	Valve Position Rate	
Low	Leading Indicator	Direct/Indirect	Mass flow	↗ Gradual or ↗ Sudden	Standard Instrument	Mass Flow	Steam Generator Cluster
Low	Leading Indicator	Direct	Proximity Probe (x/y)	↗ Gradual or ↗ Sudden	Standard Instrument	Differential Expansion	
Low	Damage Detection	Direct	Thermocouple	↗ Gradual	Standard Instrument	Temperature	
Med	Damage Detection	Indirect	Proximity Probe (x/y)	↗ Gradual or ↗ Sudden	Standard Instrument	Vibration Amplitude	
High	Damage Detection	Indirect	Proximity Probe (x/y)	↗/↘ Gradual or ↗/↘Sudden	Standard Instrument	Phase Angle Change (transient & steady state)	Calculated

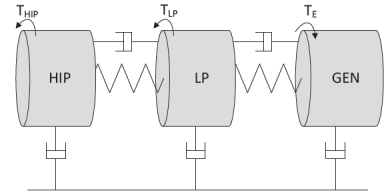
Prioritize sensor deployment, analytical requirement, and method development

Ex. Emerging Risks and 'Smart' Risk Management Solutions:

Torsional Stresses and Resonance from Increased VER/IED Penetration

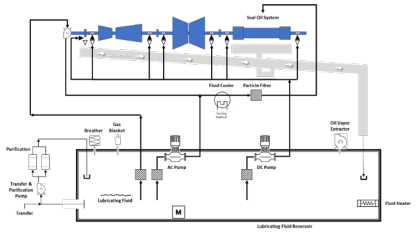


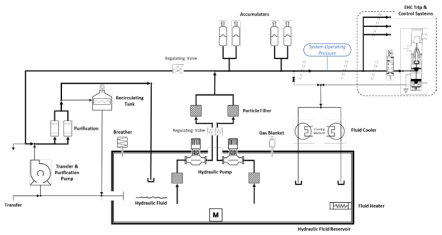
- *Grid-Induced Failures Reported on Steam Turbines & Generators*
- *Codes & Standards are emerging and may have deficiencies*
- *Risk Management. Technologies exist that measure the mechanical effect on the systems. Proven to reduce the margin of error in calculation.*



Enhancing Fluid System Monitoring for High Frequency Events

- *RAMS model development*
- *Fluid systems include both components and working fluid that drive system degradation*
- *Transforming periodic fluid sample testing*





More Data ♦ More Opportunities ♦ More Complexity ♦ More Challenge

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Practical Examples of Applied Technologies…

Model Predictive Control (MPC) is an advanced control technique that predicts future behavior of a system to optimize its target performance.

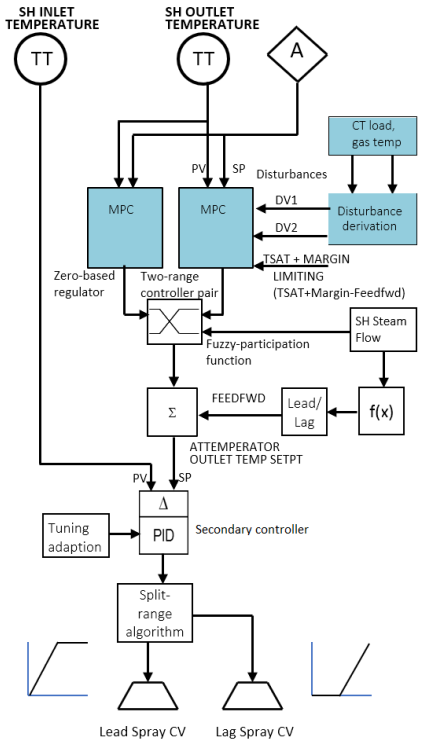
Sequence Automation Sequence automation co-ordinates other control functions to operate the controlled plant from a defined start state to a defined end state.

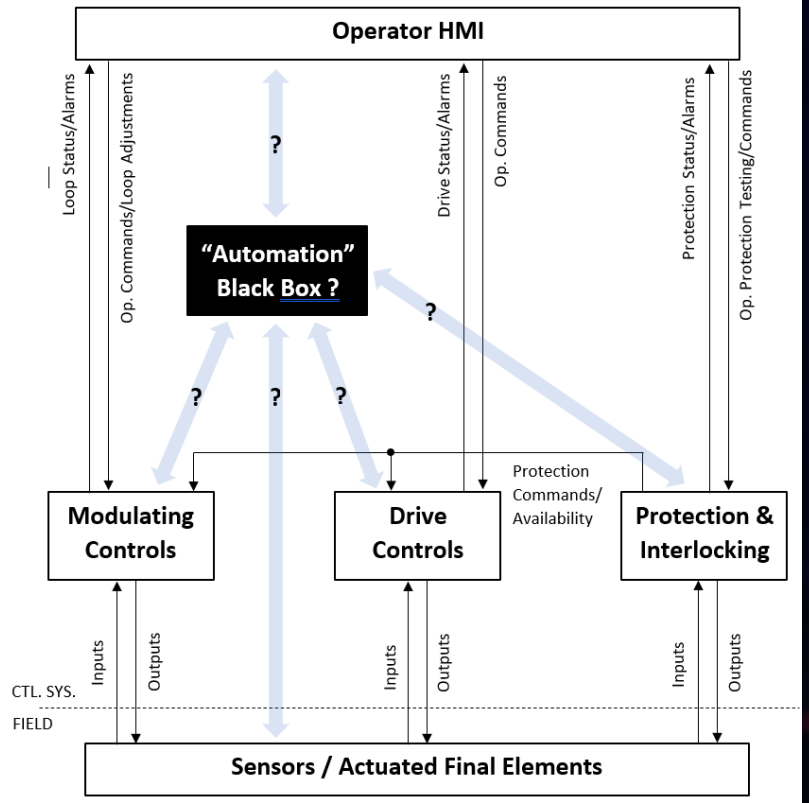
EPRI PROGRAM 227 – AUTOMATION & CONTROL

Critical Success Factors:

- **Quality of modelling method**
- **Adequacy of sensor data**
- **Accuracy of physical properties data and behaviors**
- **Understanding the limitations and evaluating upstream and downstream operational impacts**

Ex. HRSG Attemperator Optimization





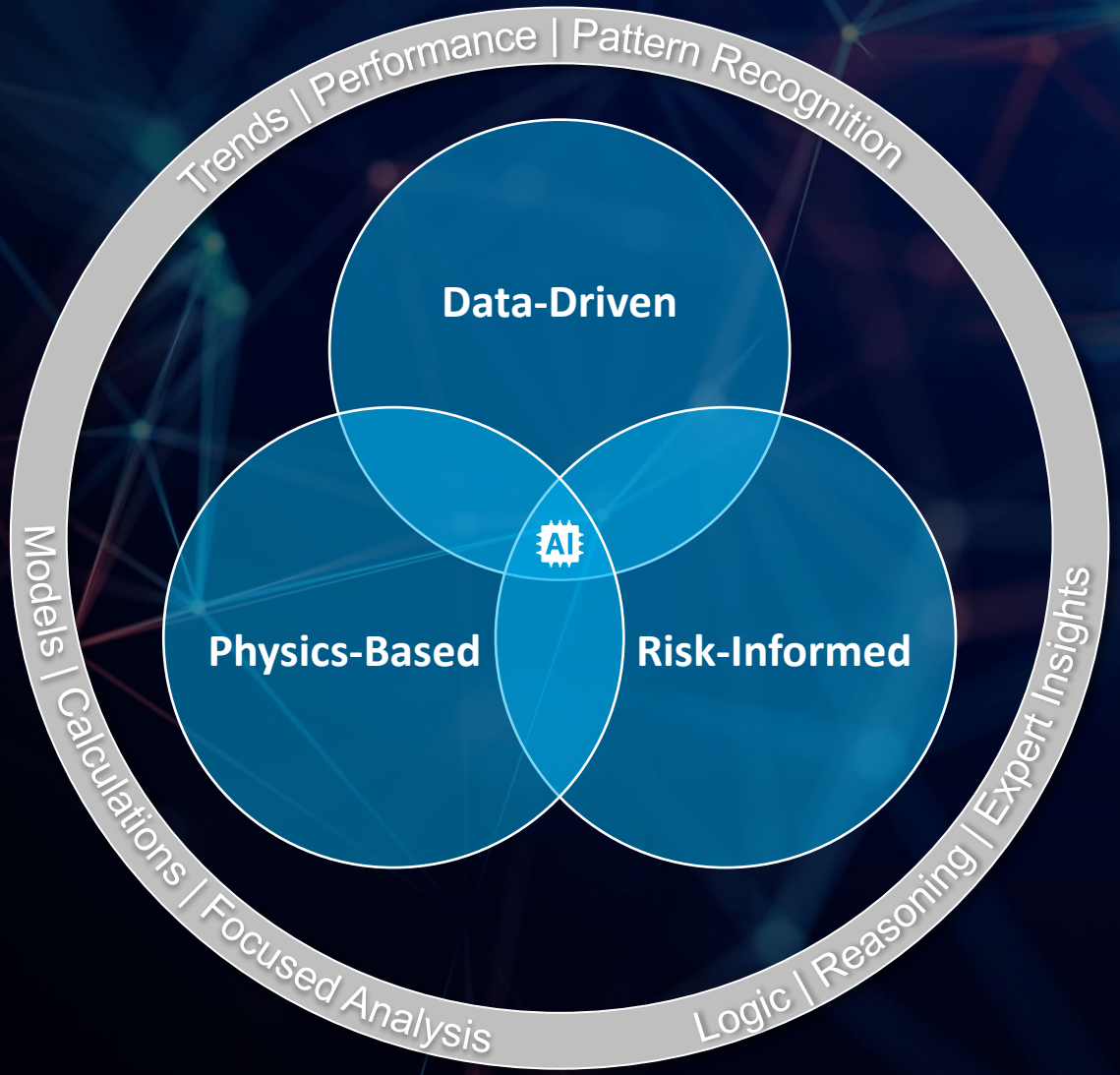
Key Challenge

Model development (Accuracy, Time & Resources)

Requires specialized engineering insights and computational methods and control process understanding to develop models

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Managing Expectations…



- Define the Scale of Project through Clear Objectives & Business Goal
- Right Size the Level of Investment
- Integrate the System / Analytics Team
- Understand / Simulate System Relationships
- Acknowledge the Limitations of Conventional Sensor and Proposed Analytic Packages
- Establish Mechanisms to Continue Learning

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2026 Research Plan

Program 219: Steam Turbines & Auxiliary Systems

Randall Steele
Senior Technical Leader

2025 WANO Steam Turbine & Generator Workshop
Shanghai, China
3-6 November 2025

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Enhanced Information Resources

2025

TGUG WIKI

ST&G OUTAGE *Guidelines* WIKI

2026 and Beyond…

- Build out ST&G Outage Guidelines WIKI
- Risk Management Site/Wiki
- Anonymized Member Assist Information Summaries
- Webcast Audio Information Transcripts
- Forum Information Summaries (re: TEN, IGTC)

- PMBD Update ???
- OPEX Database ???

Anything else to consider?

How do we effectively leverage decades of research and insights to inform engineering resources?

Developing Engineers

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TGUG Data Management

Objective

- Improve accessibility of Turbine Generator Users Group (TGUG) meeting content
- Create hierarchy and structure to allow facilitate event navigation and search

Research Value

- Current methods to access legacy meeting materials is cumbersome and flawed
- Search capability is limited, cannot effectively search underlying content

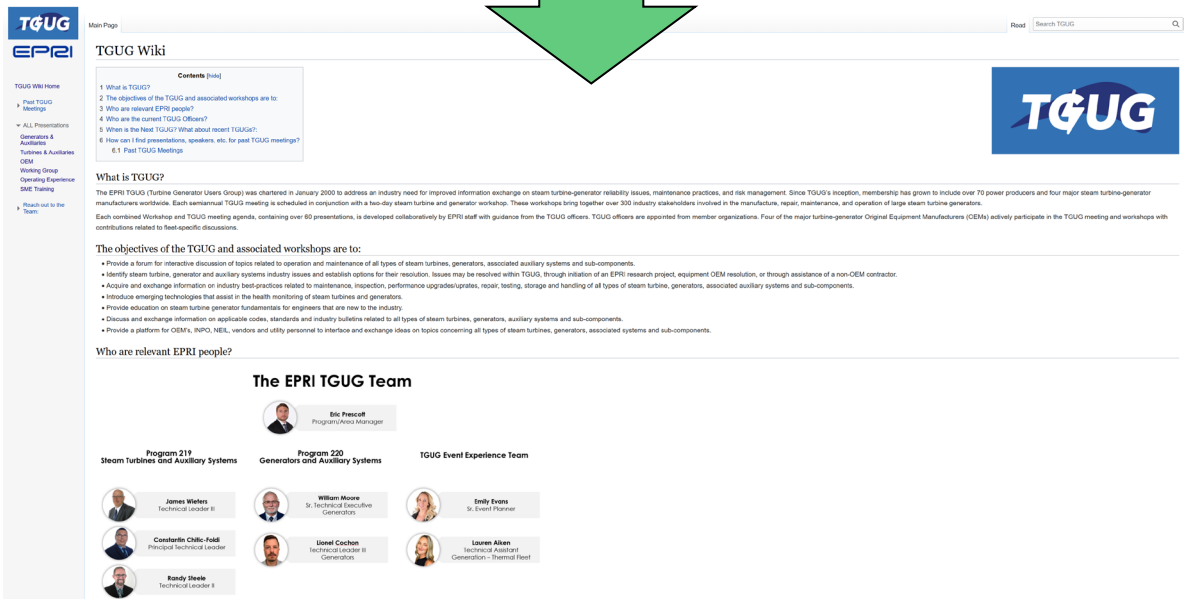
Project Approach

- Build TGUG Wiki site to capture and store TGUG content
- Enable functional search (including embedded files) of historical content
- Possibility exists to expand functionality of site
  - Add forum for engagement
  - Development of future meetings

TGUG Summer August 11-15, 2025 Hyatt Regency Minneapolis, Minneapolis, MN

	Monday	Tuesday		Wednesday	Thursday	Friday
	8/11/25	8/12/25		8/13/25	8/14/25	8/15/25
7:00 Breakfast/Registration						
	Technical Sessions - Generator Track	Technical Sessions - Turbine Track	Technical Sessions - Generator Track	Technical Sessions - Turbine Track	OEM Day In person only	TGUG DAY - Member Experience	Subject Matter Expert Training
8:00						
	Stator Endwinding Bracing	Main Steam Valves - Operational Risk	AVR, CTs, PTs, Circuit Breakers	Special Repairs / Equipment Upgrades	Toshiba (1 hour) Generator Topics ~ 8:00 - 8:25; Bulletin Review ~ 8:25 - 8:35; Turbine Topics ~ 8:35 - 9:00	Roundtable Discussions	Topic: Generator Rotor Removal, Transit, Receipt, and Installation
10:00 Break							
	Case Histories - Generators	Steam Turbine Investigations	Case Histories: AVR & Bushings	STG Testing and Advanced NDE Technologies	Siemens Energy (2.5 hours) Generator Topics ~ 9:00 - 10:15; Buleltin Review ~ 10:15 - 10:45; Turbine Topics ~ 10:45 - 12:00	Roundtable Discussions	Steam Turbine and Generator Engineer and Operator Walkdown Best Practices Discussion
12:00 Lunch Break							
	Isolated Phase Bus	Steam Turbine Operation and Control System Tuning	Generator Stator Core Horizontal Restack Development and its Execution	Nuclear ST Challenges	Mitsubishi (1 hour) Generator Topics ~ 1:00 - 1:25; Bulletin Review ~ 1:25 - 1:35; Turbine Topics ~ 1:35 - 2:00	TGUG Tools	
2:30 Break							
	Generator Rotors	Steam Turbine Operation Challenges	Auxiliairies or GRID	Recent Outage Experience & Best Practices	GE Vernova (2.5 hours) Generator Topics ~ 2:00 - 3:15; Bulletin Review ~ 3:15 - 3:45; Turbine Topics ~ 3:45 - 5:00	Operating Experience	TRAVEL HOME
	TGUG Technology Fair 4:30-6:30 pm	TGUG Technology Fair 4:30-6:30 pm			Working Group 5:30 - 7:30 pm Topic: Development of New Engineers	Optional Offsite Tour 5:30 ~ 7:00 WEG Electric Machinery	

Open to the Public
OEMs and Funders
Funders Only



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Re-Platform Outage Guidelines

Objective

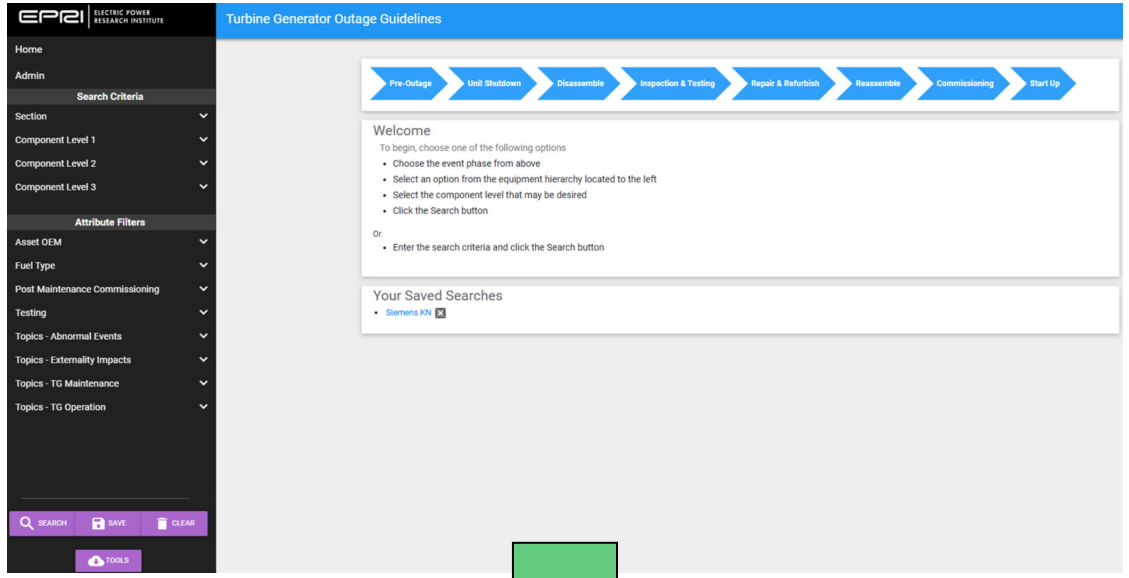
- Improve accessibility of Outage Guidelines
- Create hierarchy and structure to allow facilitate event navigation and search

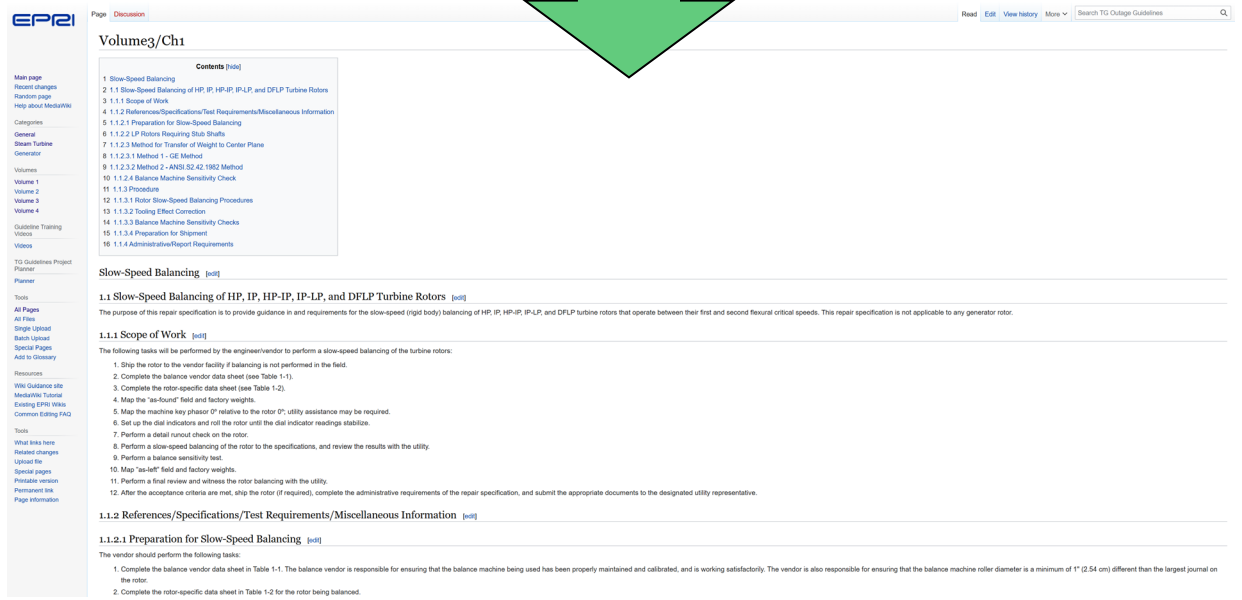
Research Value

- Current methods to access materials is cumbersome and flawed
- Search capability is limited, cannot easily access underlying content

Project Approach

- Build TG Outage Guidelines Wiki site to re-home .exe content
- Enable functional search (including embedded files) of historical content



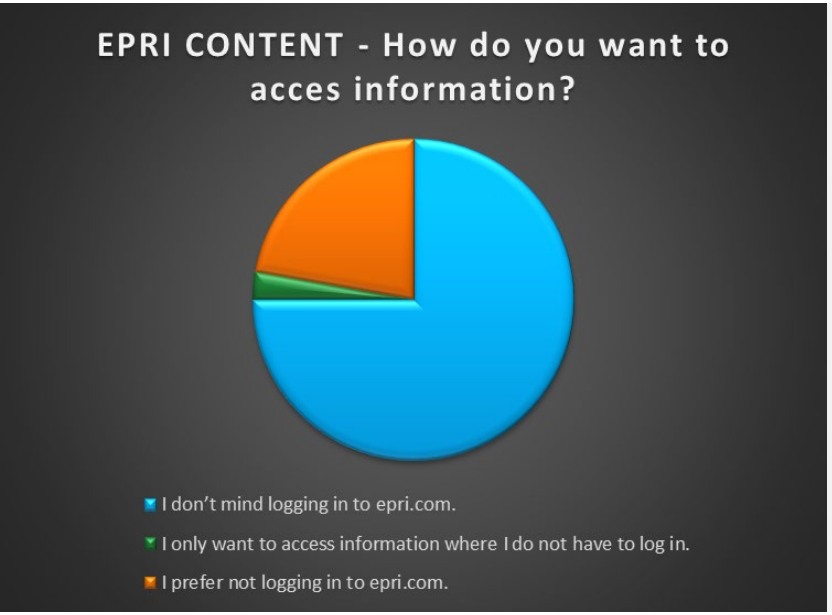


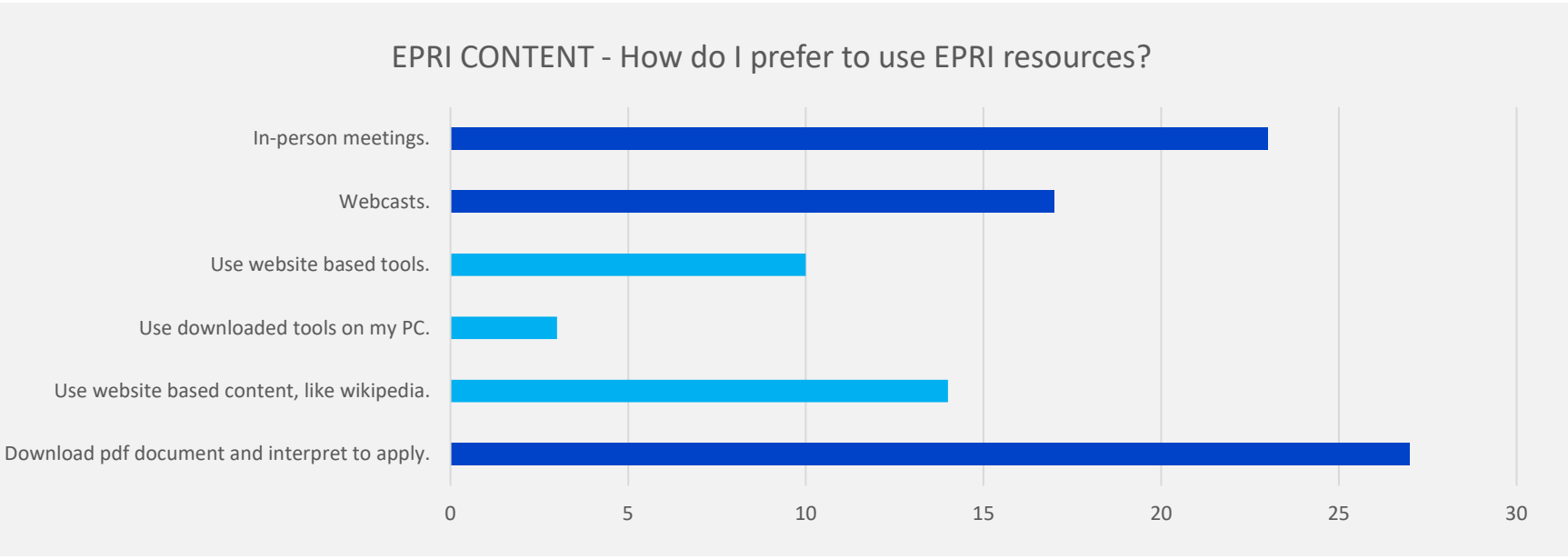
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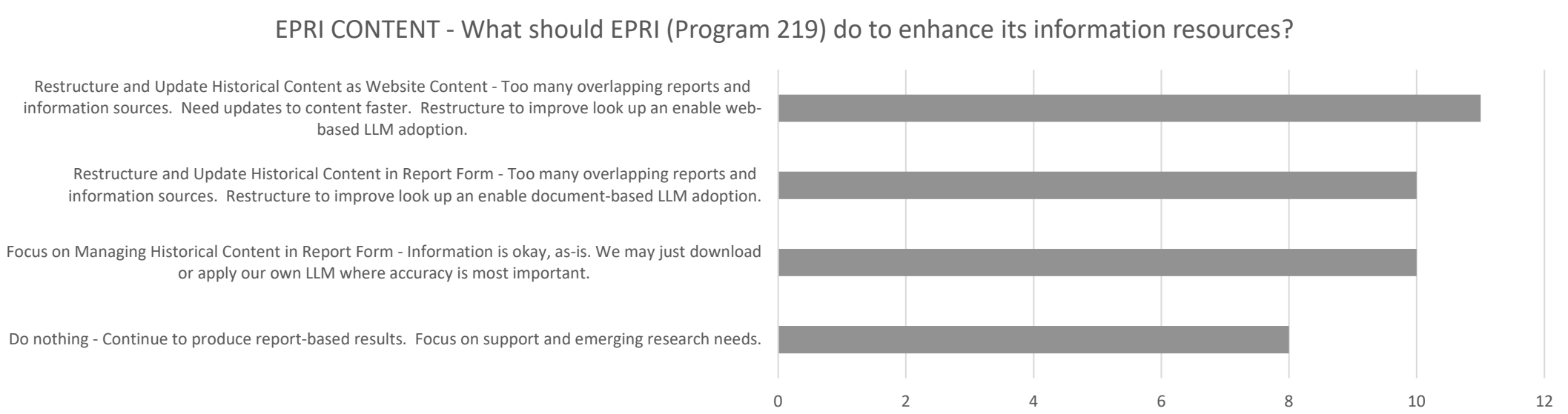
Research Feedback

2026 Project Survey Insights

EPRI Content



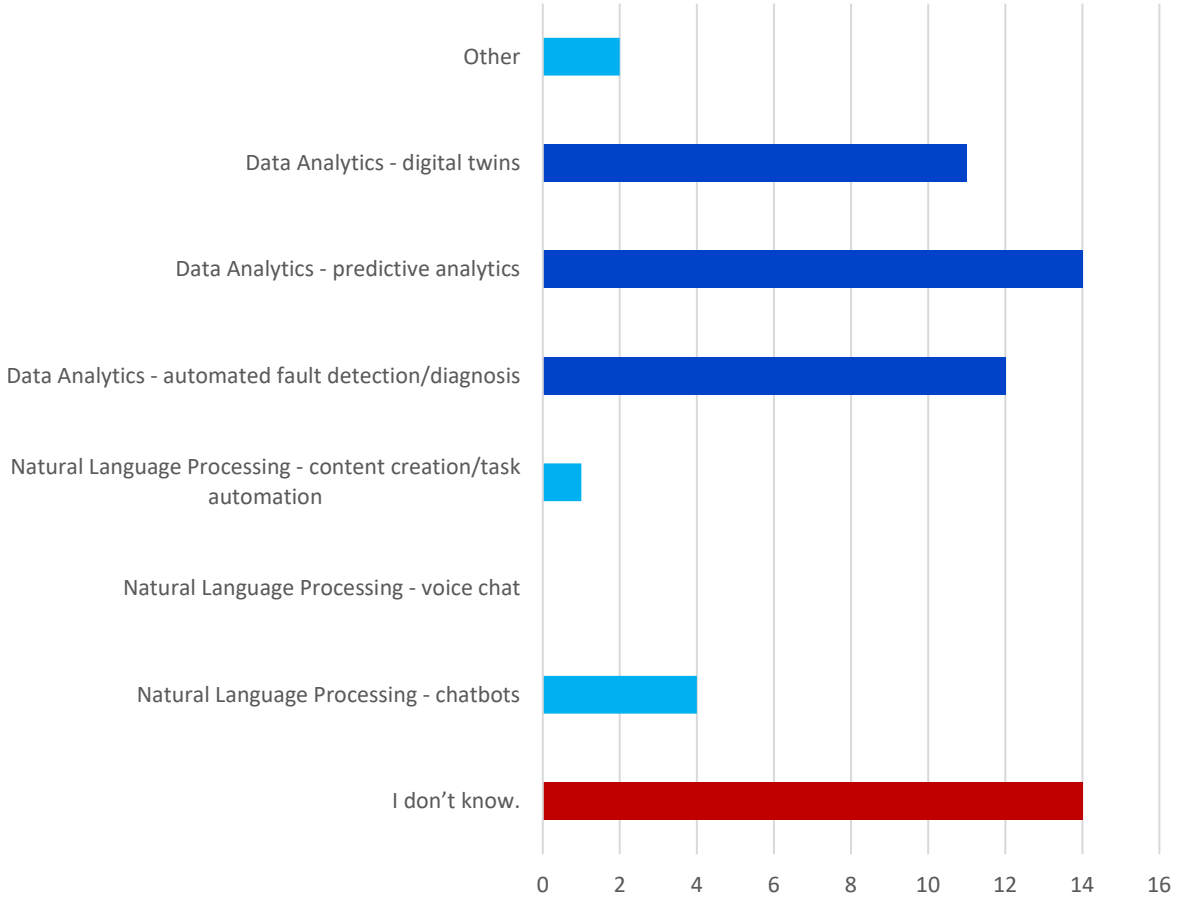




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2026 Project Survey Insights

DIGITALIZATION - What AI tools is your company actively developing, or planning to implement on ST and GEN systems? (check all that apply)



- → Leveraging remote monitoring for vibrations/instrumentation to perform predictive monitoring and any necessary actions to prevent an issue.
- → * Online monitoring of vibrations and other parameters, could be analyzed by AI to improve fault detection. * Digital twins are at an early stage of development for the Steam Turbines
- → Automatization of defects detection from visual inspections.
- → We hope that AI technology could assist us in turbine parameter condition monitoring by automatically identifying anomalous trends, performing preliminary root cause analysis, and providing maintenance priority suggestions during overhaul processes based on daily operational conditions of the units.
- → troubleshooting
- → Digital twin models envisioned for low pressure last stage turbine blade management including torsional vibration of turbogenerator drivetrain
- → We are really at the beginning stages of this. Nothing that seems useful at the moment.
- → Records searching, PI historian advanced pattern recognition
- → Currently using Asset 360 for monitoring and fault detection
- → Using LLM and RAG to search our internal databases just like for instance Chat GPT.

How can we help you?

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2026 Project Survey Insights

PROBLEMS YOU TOLD US

- Aging components and mitigation efforts as our units prepare for 60-80 year operation.
- Best practices for power update consideration.
- Preparing for Combined-cycle plant uprates

2026 Project to update existing results?

- bearing metal temperature high, shaft or bearing vibration high,
- HP valves degradation
- Main valves stroke stick,
- Repairs of main steam valves, erosion of internal sealing surfaces of valve housings are an increasing concern. Difficulties in finding repair methods at reasonable costs. Experience within the fleet is highly appreciated and/or help to develop repair methods.
- EH oil component leakage,

Historical Results

- Crack propagation in fixation.
- Damage on LP blade carrier with GGG40 casting repair options.

2026 Project?

- HP and IP turbine spindle thinning.
- LSB erosion repair options
- We have experienced Last Stage Bucket cracks

Ongoing Multiyear

- Mitigation of erosion on lo/hp castings, mitigation of lo deformation
- LP Turbine Rotor disc head cracking, SCC, high cycle fatigue
- SCC in the Last Stage Bucket Steeples.
- Nothing new, it seems that SCC issues are returning on the rotors that were retrofitted in the beginning of the 2000's. Knowledge on how to deal with the issues within the business has decreased (options, mitigating measures etc), spread the old knowledge to the new generations of engineers.

Historical Results

- Moisture Separator inefficiency leading to degradation of the reheater
- Compensator overpressure.
- How creep fatigue affects thick walled components
- Shell Creep (D11 Fleet), What methods would be best to identify this sub-surface creep.

Ongoing Multiyear

- How is load cycling contributing and how do we set an optimal low load setting that minimizes potential damage to last few stages of LP.

Historical Results

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2026 Project Survey Insights

Development focused…

- A close out checklist developed by experts at EPRI and the industry to walk down major outages before close up of steam turbine to ensure nothing is missed - To me this is a priority and something I am working on, we are seeing a loss of good skilled millwrights and the upcoming millwrights are just there to collect a paycheck.
- craft and OEM knowledge challenges. train Craft using steam turbine facilities
- Focus on the next generation of engineers.
- Refurbishment plannings and how big projects can be set up for success.
- Upgrading turbine control systems

Operator focused…

- Abnormal events and ability to diagnose quicker. Retrofit to extend life of aging assets that won't be replaced in near term. We'll past expected retirement but likely to run another 15 to 20 years.
- 5. Abnormal Events Troubleshooting

Flexible operation

- flexibility vs aging of steam turbine
- Flexible operation influence on life time.

Valve Actuators

- 1. On LVDT damage, perhaps include guidance to mitigate against high temperature exposure.

Materials

- turbine fitness for service and life extension evaluation process
- Aging management and mitigation best practices
- We need to understand shell creep better especially on the D11 fleet but also the A10 fleet
- I also believe it would be useful to have some sort of guide for predicting life of major parts like shells, Rotors, Valve bodies, etc.

Alignment Guidance

- Ways to take coupling alignment data more quickly with accuracy. Emphasizing the bearing elevation changes impact to internal alignments.
- 4. TG Alignment guides and improvement technologies
- Field Guide/Guidelines for TG Alignment.
- do like the idea of scanning technologies for alignment, this would be very useful as outage timelines are shrinking.

Inspection

- Eddy Current Array for Corrosion (Pitting) Characterization & in situ assessment/scanning.

Bolting Guidance

- Bolting (cylinder and valve bolting).
- 1. Bolting project
- 3. Case studies for use of Pilgrim bolts on casings.

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What we heard…

Enable AI

DT

LLM

- ST FMEA for Expert System Development
- ST Risk Content Website

Information to Manage Upgrades

- Nuclear
- Combined Cycle

- Technical Specification
- Design Review
- Quality/Execution Oversight
- Best Practices/Lessons Learned

Technology

- Alignment Optimization
- LSB Erosion Management
- Torsional Interactions

Materials

- LSB Assessment and Repair
- High Temperature Component Life
- Field Repair Quality

Develop Resources

- Training Material
- Webcasts

Focus on nuanced technical challenges and research tech transfer

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Final Remarks…

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www.epri.com

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Workshop Day 3

Program 219: Steam Turbines & Auxiliary Systems
Program 220: Generators & Auxiliary Systems

Eric Prescott
Area Manager, Senior Program Manager, Program Lead

2025 WANO Steam Turbine & Generator Workshop
Shanghai, China
3-6 November 2025

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Meeting Agenda

TOPIC
DAY 1: Experience Sharing *Monday, November 3rd*
DAY 2: Steam Turbine Focus *Tuesday, November 4th*
DAY 3: Generator Focus *Wednesday, November 5th*
DAY 4: Huaneng Advanced Cycle Working Session *Thursday, November 6th*

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Today's Discussions



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Mobile: 689.263.0242



Lionel Cochon
Technical Leader, Sr.
lcochon@epri.com
Mobile: 804.418.5237

DAY 3 - WORKSHOP TOPICS

Wednesday, November 5, 2025

Time	Topic	Lead
9:00a	Opening Remarks	E. Prescott, EPRI
9:15a	Summary of Generator Fleet Experiences • *Industry Issues & Trends in 2025* • *Common Maintenance Findings*	L. Cochon, EPRI
10:15a	Break	All
10:30a	Summary of Plant Robotic Inspection Research	R. Steele, EPRI
11:15a	Vine Robotics for Power Plant Applications	R. Steele, EPRI
12:00p	Lunch	All
1:00p	Overview of Generator Robotic Inspection Technologies	L. Cochon, EPRI
2:00p	Generator Inspection Robotics Development Update	CNNP
3:00p	Break	All
3:15p	Proposed 2026 Generator Research	L. Cochon, EPRI
4:00p	Open Discussion – Addressing Questions from Audience	All
4:45p	Final Remarks	E. Prescott, EPRI

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Generator Fleet Experiences

Industry Issues, Trends, and Maintenance Findings

Lionel Cochon
Senior Technical Leader

2025 WANO Steam Turbine & Generator Workshop
Shanghai, China
3-6 November 2025

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2025 Top Issues Discussion

1 Supply Chain & Workforce

Addressing the supply chain.

Fewer supplier resources and workforce skill/experience necessitating additional approaches to manage risk.

- ❑ *Life extension to meet supplier lead times*
- ❑ *Enhanced oversight and review guidance to assure quality*
- ❑ *New equipment specification insights*

People are critical resources.

Addressing loss and scale of growth required to operate and maintain the fleet of today and tomorrow.

- ❑ *EPRI results for subject matter roles & responsibilities*
- ❑ *Development plans and content for industry at-large*

2 Events from Aging and Maintenance Challenges

Aging of limited life and life-of-asset components (i.e., winding systems, stators, excitation systems)

Execution of maintenance programs to enhance the reliability of auxiliary systems (i.e., cooling, LO, grounding, excitation systems)

3 Coal Plant Retirement Deferrals

Managing the reliability risk of aged plants where resources are limited and maintenance activities may have been suspended.

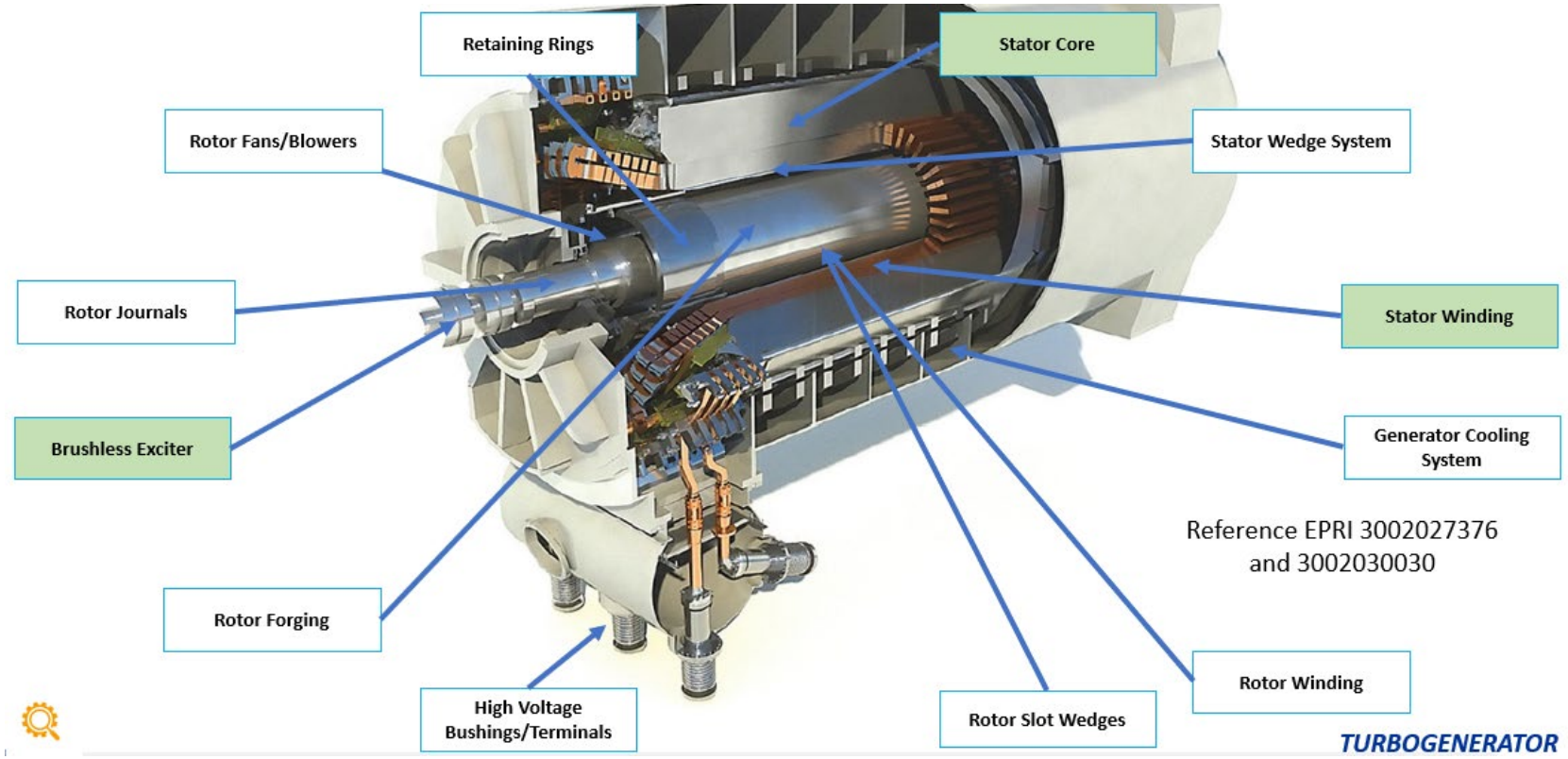
4 Emerging Grid Risks to Synchronous Generation

Understanding how the grid transformation affects the integrity of synchronous machines. This includes new generation and demand sources (datacenters).

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Where is the Weakest Link?

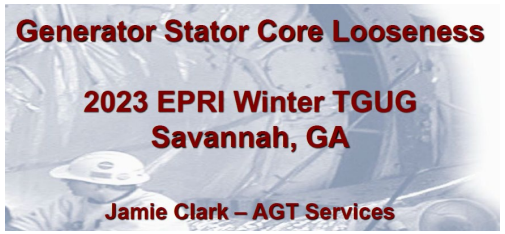
- The Generator and Exciter have many different components. Each one can be a “weak link” and lead to an unplanned outage.
- A dramatic increase in SCRAMs has occurred in the last year. 10 in last 365 days. There are varying reasons….
- In terms of the most significant impact (forced outage time and cost), three Main Generator components stand out from the rest.
  - Generator Stator Core
  - Generator Stator Winding including SCWS
  - Brushless Exciter
- We will discuss these three components, their reliability issues, and some new and old learnings



Due to the generator’s many components, a thorough health assessment of the complete unit is desirable. However, three major components stand out as having the most significant impact, year over year, with failures.

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Too Many Core Issues in Industry!



EPRI TGUG
Kansas City, MO
August 15-20, 2020

Non-GE Manufactured 7FH2 Generator Stator Core Failure Case Study

Jim Fogarty — *Generation Technology Consultants*
Dennis Ulery — *Generation Technology Consultants*
W. Howard Moudy — *Director of Operations National Electric Coil*



Emergency Stator Core Repairs
Partial and Full Restacks

Bill Moore, P.E.

EPRI, Savannah, 2013

EPRI Generator Workshop
Farley Unit 1 Stator Core
24 January 2023
Savannah, GA.

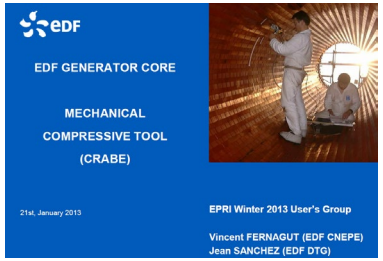
Rebekah Schooley
rschoole@southernco.com

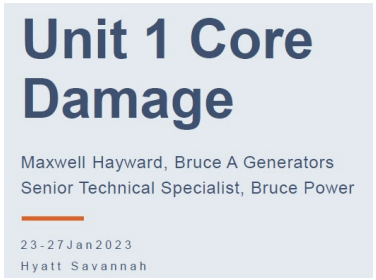
Generator Stator Core Life Expectancy

Nuclear Perspective

Kevin O'Dowd, CEG
Generator Fleet SME

August 13, 2024





LG&E KU
PPL companies

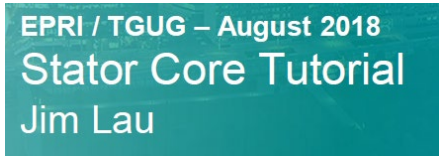
Stator Core Basics and Experiences
2015 EPRI TGUG Generator Workshop

Presented by Gus Dattilo, Sr. Electrical Engineer

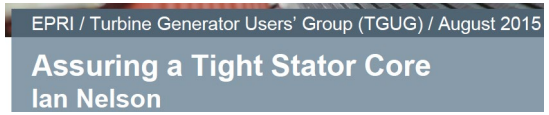
324 Model Generator Spacer Block Migration

Mike Young
Electrical Engineer
SRP
Delivering water and power®

EPRI TGUG Generator Workshop
August 19 and 20, 2019
Albuquerque, NM



TIL 2419 Potential Stator Core Looseness on TOPGAS* Generators and Service Recommendation





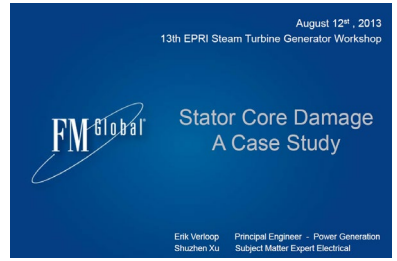


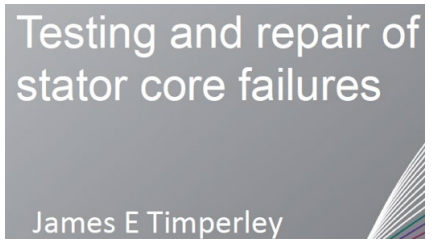
Generator Stator Core Inspection, Test, Repair & Replacement

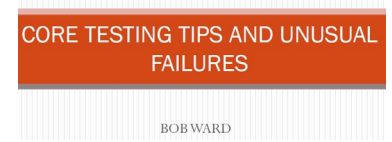
EPRI Report #3002024052

Bill Moore, P.E., EPRI
Sr. Technical Executive
bgmoore@epri.com
980.229.6308

Webcast via Webex
April 6, 2023









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Core Failures











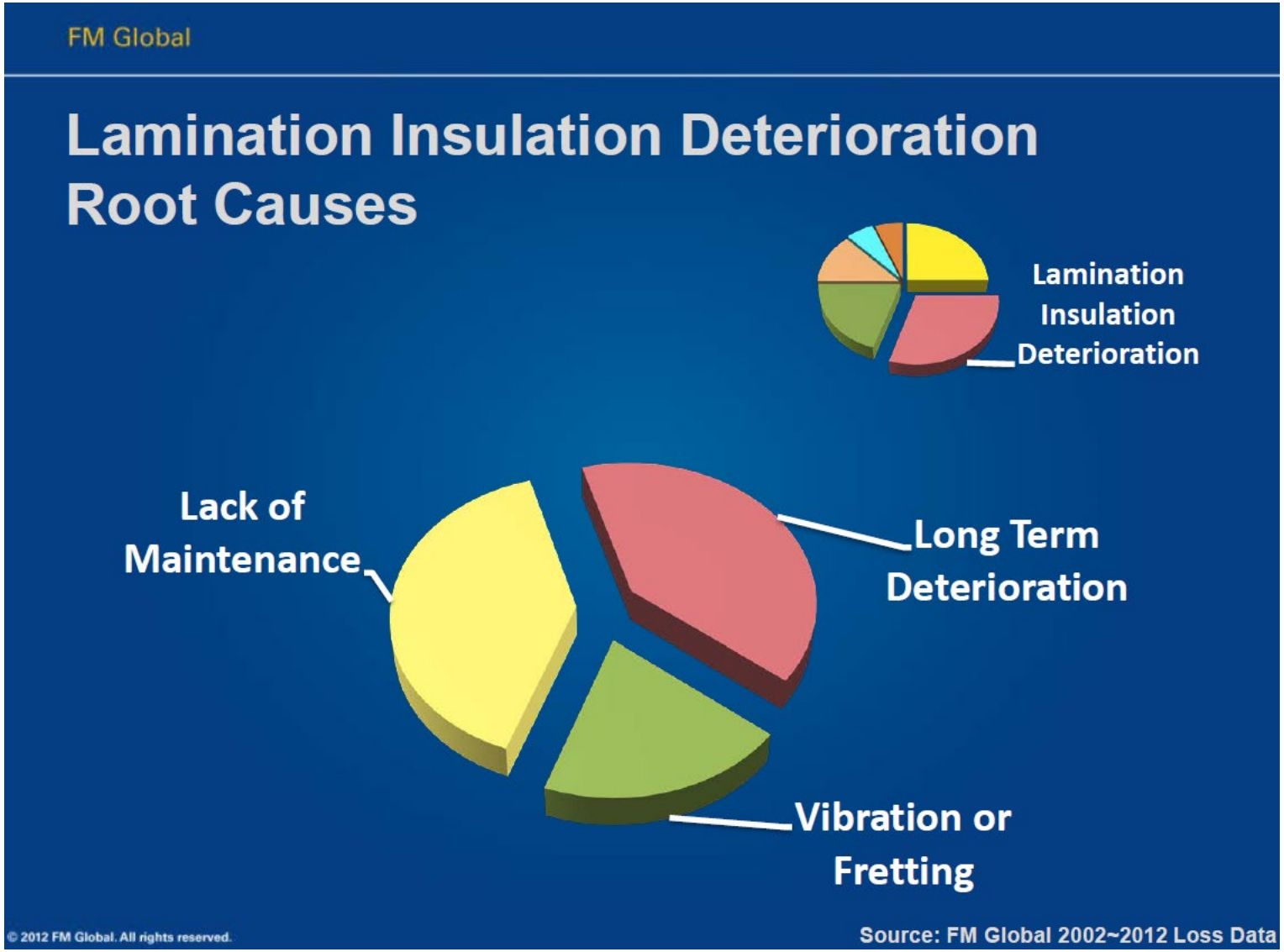




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Lamination Insulation Deterioration – Root Causes

- Lack of Maintenance, Vibration or Fretting and Long-Term Deterioration
- All three related
- Vibration/Fretting leads to lamination shorting and shorting leads to arcing/melting
- Keeping a core tight is the #1 maintenance item



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Stator Core Issues

Component	Year	Issue	Key Actions-Learnings	Source/Link (www.tgug.epri.com)	EPRI Resource
Stator Core	2025	Fatigue of cap screws resulting in stationary blade detachment and core damage.	Vibration. Acoustic Monitoring, Bump Testing, Tightness Checks	OE 624017 January 2025	https://tgug.epri.com/images/8/8b/2025.01.14_-_G02_-_Generator_Acoustic_and_Vibration_Testing_and_Analysis_-_J._Mihalic_-_ElectroMechanical_Engineering_Associates.pdf
Stator Core	2024	Significant core damage.	No root cause identified. Core replaced.	OE 604157 July 2024.	EPRI Reports: 3002024052, 1007441, 1008378, 1008378 &2025 report roadmap in progress on generator core aging, planned 2026 report on GCM, Acoustic Monitoring
Stator Core	2023	Core Replacement	Replace-AGE-Deterioration of Arrowheads tightening core	https://tgug.epri.com/images/e/e9/2023.01.24_G13aa_Schooley_Farley_Core_-_Panel_TGUG_2023.pdf	https://tgug.epri.com/images/6/67/2023.01.23_G05_Owner_Oversight_Of_Contracted_Activities_and_Quality_Assurance_Newell_FM_Global.pdf
Stator Core	2022	Core damage. Did not fail catastrophically.	Maintain tightness of core. Maintain/Upgrade Generator Condition Monitor with verified alarms, regular gas sampling, and actionable procedures.	OE 527132 August 2022	https://tgug.epri.com/images/1/1a/2025.01.14_-_G04_-_Stator_Core_Condition_Monitor_Update_-_C._Breslin_-_Environment_One.pdf
Stator Core	2022	Foreign Material	Replace-Factory Oversight	https://tgug.epri.com/images/8/85/2022.08.16_G05_18-Stefaniak2-DTE_Fermi_Update1.pdf	https://tgug.epri.com/images/b/ba/2024.08.13_-_G05_-_Generator_FME_-_B._Moore_and_M._Norman_-_EPRI_and_TVA.pdf

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Too Many Stator Winding Issues

Constellation

Calvert Cliffs Stator Water Cooling H2 Leak

Constellation Energy

Nick Trainer
Senior Engineer – Corporate Engineering

Stator Water Leak and H2 Leak OE

Ali Athar, Bruce B Generators
Responsible System ET, Bruce Power

GER-3751A

GE Power Systems

Understanding, Diagnosing, and Repairing Leaks in Water-Cooled Generator Stator Windings

EPRI

EPRI ELECTRIC POWER RESEARCH INSTITUTE

Stator Water Cooling System Chemistry

Sourcebook

EPRI ELECTRIC POWER RESEARCH INSTITUTE

LAYUP GUIDE FOR THE GENERATOR STATOR COOLING WATER SYSTEM

Southern Nuclear

Stator Connection Ring, SLMS and SCW Issues

Kevin O'Dowd
Exelon

Hatch Unit 1: Rewind to Rewind

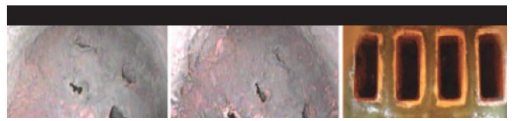
Rebekah Schooley

Suitability for Service Testing of Water Cooled Stator Windings

Mike Bresney
AGT Services

AGTServices, Inc.
Generating timely repair solutions

BEST PRACTICES FOR CHEMICAL CLEANING OF WATER-COOLED GENERATOR STATOR BARS





MD&A

HITACHI
Inspire the Next

Mechanical Dynamics & Analysis, Ltd

TIL 1098
Detecting Leaks in Water Cooled Stator Windings

Presented by: Jeff Caudell, Consulting Engineer

Water Cooled Generator Stator Winding Leaks EPRI Generator Workshop Denver, August, 2024

AGTServices, Inc.
Generating timely repair solutions

Stator Cooling Water (SCW) Operating Chemistry at EDF (France)

7th EPRI Turbine Generator Workshop – 08/2012

Michel Dijoux
EDF Ceidre

Water Cooled Generator Testing

Ron Halpern

EPRI

Guidelines for Detecting and Removing Flow Restrictions of Water-Cooled Stator Windings

EPRI

TECHNICAL BRIEF

Best Practices for Optimum Performance of Generator Stator Cooling Water Demineralizers

Southern Company Generation

one team • one future

STATOR WINDING CLIP TO STRAND LEAKS
EPRI 2007 TECHNICAL WORKSHOP
J. S. PHELPS

target ZERO
Every day, every job, safely.

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Stator Winding Issues





Figure 3 – Stator winding meltdown and failure suspected to be due to oxide plugging as a result of improper layup







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Stator Winding Issues

Component	Year	Issue	Key Actions-Learnings	Source/Link (www.tgug.epri.com)	EPRI Resource
Stator Winding	2025	H2 Leak - Elevated Values	Detection-Bushings, Seals	EPRI Generator Workshop 2025	Recently Presented August 2025
Stator Winding	2025	H2 Leak - Elevated Values	Detection Approaches	EPRI Generator Workshop 2026	
Stator Winding	2024	H2 Leak into SCWS	Detection Approach – smaller leaks but one major leak	https://tgug.epri.com/images/1/14/2024.08.12-G10-Calvert_Cliffs_Stator_Water_Cooling_H2_Leak-N._Trainer-Constellation.pdf	2025 EPRI Report in Progress - Leak Monitoring Guidance
Stator Winding	2024	Water leak	Repair-TIG Braze-Multiple Attempts	https://tgug.epri.com/images/2/27/2024.08.12-G03-Hatch_Unit_1_Rewind_to_Rewind-R._Schooley-Southern_Nuclear.pdf	EPRI Reorts: 3002000420, 3002030036, 3002021515, 3002019747, 3002016241, 3002003591
Stator Winding	2023	H2 and water leaks	ODS (Operating Deflection Shape)-Vibration	https://tgug.epri.com/images/5/58/2023.08.15_G05_U2_Main_Generator_Forced_Outages_Fiori-PGandE.pdf	Water Chemistry Sourcebook, Layup, Chemical Cleaning, Demineralizers
Stator Winding	2023	Connection ring water leak and H2 leak	Sealant re-injection. Fluke acoustic meter.	https://tgug.epri.com/images/c/c2/2023.08.14_G07_Stator_Water_Leak_and_H2_Leak_OE_Ali_Athar_Bruce_Power.pdf	

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Brushless Exciter – Number is Lower due to Alterrex & Static

ELETRONUCLEAR
ELETROBRAS TERMONUCLEAR S.A

Angra 1 Exciter Diode Wheel Refurbishment

Waldir Zimmermann Gomes
Systems and Reactor Performance Department
Angra 1 - Eletronuclear

Sequoyah 1 - Main Generator WTA Brushless Exciter Contamination and Recovery

Lisa Sinclair and John Keith Taylor
TVA Nuclear

January 2023 – EPRI Turbine-Generator Users Group

SIEMENS



Kansas City Power & Light

Refurbishment of the KCP&L LaCygne Hydrogen Cooled Brushless Exciter

Previously Presented August 23, 2005 EPRI Conference

Bill Moore – NEC

entergy

ANO-1 Exciter Failure & Foreign Material Event – Thanksgiving Day 2022

BRUSHLESS EXCITATION SYSTEMS

Presented at the EPRI Turbine Generator Workshop
Houston, Texas
January 18, 2011
by
J.A. Demcko, PE

Presented at EPRI Utility Generator Predictive Maintenance and Refurbishment Conference Phoenix, Arizona, December 3, 1998.

Preventive Maintenance and Overhaul Experience for Rotating Brushless Exciters and other Excitation Systems

by

Tom Figiel, Commonwealth Edison
Jim Bothwell, Consultant
William Moore, P.E., National Electric Coil

EPRI

GENERATOR EXCITER SYSTEM MAINTENANCE GUIDE

Constellation

Exciter Pole Failure Update

Constellation Energy

Nick Trainer
Senior Engineer – Corporate Engineering
Generator SME

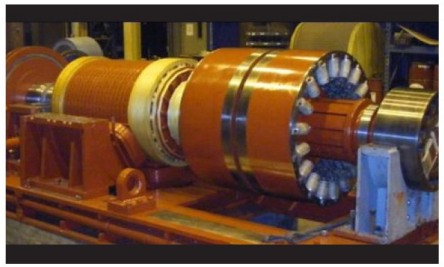
EPRI Generator Workshop
Orlando 2025

Brushless Exciter Conversion: Owner Case

Mechanical Considerations and AVR Protections

Rob Pascarella, Kai-Jei Yang
both of *Entergy Power Generation*

EPRI Winter TGUG
January 2020



October 2021

Brushless Exciter Flute Cracking Inspection and Repair

Joop Kraijesteijn, 3angles
Jason Sinkhorn, EME

EPRI TGUG Generator Workshop
January 19-21, 2021

Ground Detection System for Brushless Exciters

LG&E KU PPL companies

Gus Dattilo, Lead Engineer, LG&E and KU

Brushless Exciter Upgrade Case History

Craig Spencer

8/28/2023

EME
Powering Engineered Solutions

BRUSHLESS EXCITER CONVERSION TO STATIC - SUPPLIER PERSPECTIVE

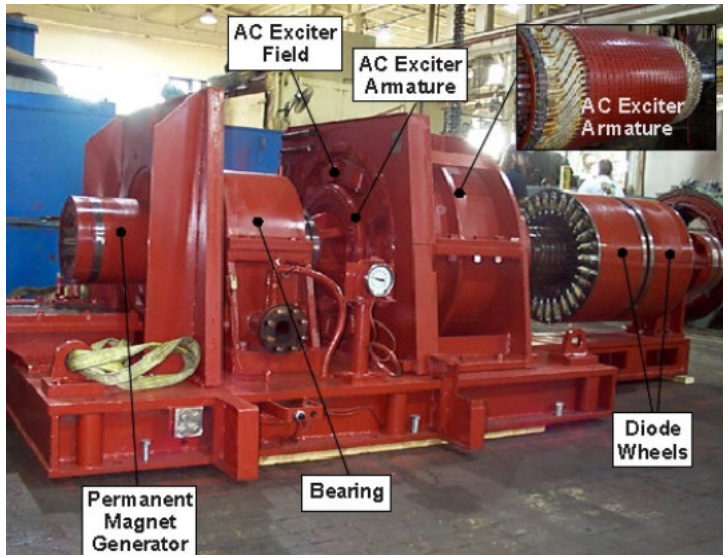
Chris Mascaro
EPRI 2020 TGUG, Amelia Island, Florida
January 14, 2019

Brushless Exciter Maintenance Repair and Overhaul

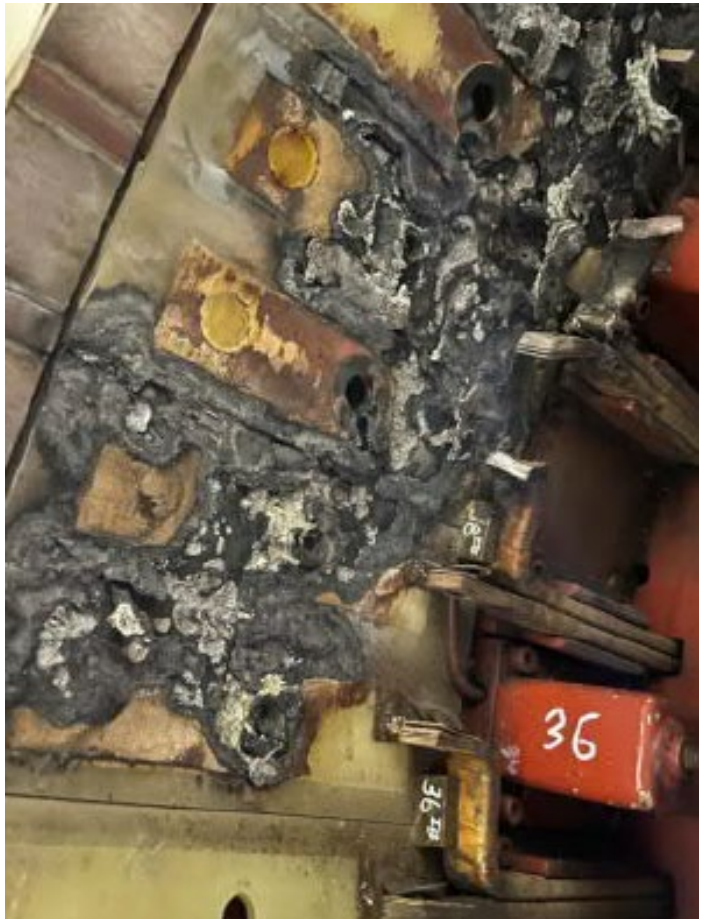
Presented by
National Electric Coil

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Brushless Exciter Issues







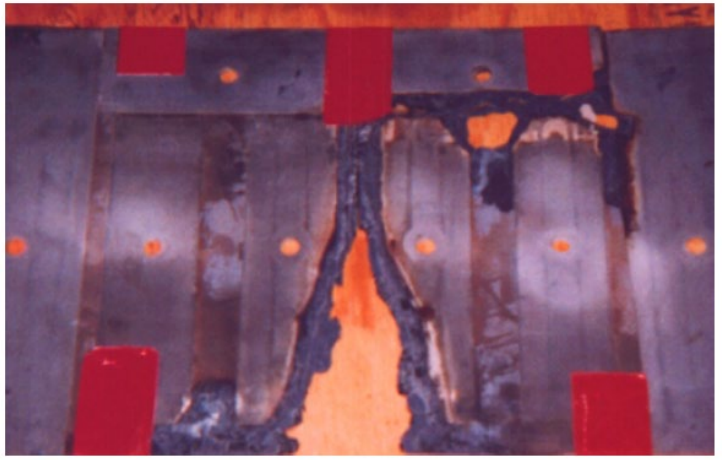


Figure 2: Burned remains of diode wheel insulation



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Recent Brushless Exciter Issues

Component	Year	Issue	Key Actions-Learnings	Source/Link (www.tgug.epri.com)	EPRI Resource
Brushless Exciter	2025	Vibration leading to stationary pole to pole connector crack	Motion Amplification	https://tgug.epri.com/images/0/04/2025.01.14_-_G06_-_Exciter_Pole_Failure_Update_-_N._Trainer_-_Constellation.pdf	EPRI Report 3002021510 Exciter System Maintenance Guide
Brushless Exciter	2025	Vibration leading to stationary pole to pole connector crack		Discussions at TGUG Gen Workshop	EPRI 2025 Report in Progress - Plant Engineer Walkdowns
Brushless Exciter	2022	Foreign Material in Diode Wheel.	Designate Exciter as FMZ	https://tgug.epri.com/images/0/04/2024.01.23_G03-Collier-Entergy-ANO-1_Exciter_Foreign_Material_Event_Thanksgiving_Day_2022_%28004%29.pdf	https://tgug.epri.com/images/b/ba/2024.08.13_-_G05_-_Generator_FME_-_B._Moore_and_M._Norman_-_EPRI_and_TVA.pdf

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Preventive Actions by Component

Component	Preventive Actions
Stator Core	Update the Generator Condition Monitor (replace if older than 2005). Identify procedural action if GCM alarm is verified. Reduce load/Vars 10% to see if alarm clears. Capture gas sample and send off prior to every major outage. Put in place procedures and POs for emergency gas sampling and analysis. Keep core tight. Check four building bolts and through bolts on older Westinghouse cores every major. Do not allow torque to go less than minimum recommended value by OEM. Check torque at start of outage to allow time to tighten. Loosen belly bands, if present, before tightening. Perform ELCID/SMCAS every major or if core hot spots are repaired.
Stator Winding	Assure a stator leak monitoring system is installed and working on all water-cooled units. Perform regular testing of stator winding including: Insulation Resistance, PI, Over voltage, pressure decay, vacuum, Helium tracer, capacitance on individual bars if needed. Monitor H2 leaking out of generator and into SCWS. Utilize H2 leak detection such as snoop, H2 detection tape, sniffer, Fluke Acoustic Meter and FLIR (CO2 or SF6). Maintain water chemistry within set limits. Full drain and dry on shutdown/layup for longer than 3 days.
Brushless Exciter	Overhaul brushless exciters every major outage (8 years) including removal of all diode wheel parts with individual component (diodes, fuses, heat sinks) and perform cleaning and testing. Replace diode wheel insulation on inner diameter. Perform engineering and operator walk down checks. If unusual vibration is detected, employ motion amplification, acoustic monitoring or ODS to identify source. Maintain stock of fuses and diodes. Replace as needed after testing. Verify hold down torque values on skid.

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Defining Today's Challenges and Research Needs

GENERATOR ISSUES:

1. Generator Electrical Health & Diagnostics

- Generator health assessment
- Rotor turn short
- Low insulation resistance
- Low PI and water leaks
- Capacitance mapping
- HIPOT testing
- Residual magnetism
- Stator fault contingency planning
- Rewind insights
- Field overheating damages after rewind/turbine upgrade (CT)
- Cyclic bearing vibration
- Rotor vibration anomaly
- Shaft voltage monitoring/action
- Torsional monitoring to manage grid interaction risk
- Core bolt torque requirements
- Core support plate megger
- 18-5 retaining rings
- Air test on turning gear

2. Cooling & Lubrication Systems

- Cooling water chemistry
- Stator cooling water runback and trip
- Stator cooling water system fouling
- Oil ingress
- Bearing oil leak

3. Excitation & Grounding Systems

- Exciter brush arcing
- Brushless exciter failure
- Exciter bearing alignment
- Ground detection
- Generator grounding requirements
- Phase ring arcing
- Flood resin in core
- Collector enclosure arc flash protection

4. High Voltage & Bus Systems

- HVB failure
- HVB hydrogen leak
- IPB failure
- IPB enclosure failure
- High IPB temperature
- New installation main lead failure

5. Operations, Planning & Oversight

- Synchronous condenser operation
- Outage intervals
- 3rd Party quality oversight for manufacturing
- Technical case for capital projects
- Synchronous generator model validation
- Rotor forging specification

Related P220 Member Assists in 2025

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Defining Today's Challenges and Research Needs

GENERATOR ISSUES:

1. Generator Electrical Health & Diagnostics
- Generator health assessment
- Rotor turn short
- Low insulation resistance
- Low PI and water leaks

2. Cooling & Lubrication Systems
- Cooling water chemistry

3. Excitation & Grounding Systems
- Exciter brush arcing

5. High Voltage & Bus Systems
- HVB failure

6. Operations, Planning & Oversight
- Synchronous condenser operation

EPRI research available on most topics.

Equipment design and risk tolerance plays a key role – requiring subjective decision making.

EPRI research available on most topics.

Future research opportunities exist.

Help us understand what is needed.

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Break

Plant Robotic Inspections

EPRI Research Summary

Randall Steele
Senior Technical Leader

2025 WANO Steam Turbine & Generator Workshop
Shanghai, China
3-6 November 2025

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Topics

More from Inside EPRI…

- Underground Transmission Vault Inspection Using Robotic Techniques – 2024 Update – 3002029495
- Robotic Inspection Technologies for Transformers: Laboratory and Field Assessments – 3002019141
- Topical Guide: Boston Dynamics Spot Robot – A Cyber Security Technical Assessment Methodology (TAM) Worked Example - 3002023859

SPECIFIC FOR STEAM TURBINES

- Drone Applications for LP Steam Turbines: Interactive Guide – 3002024049
- User Experience

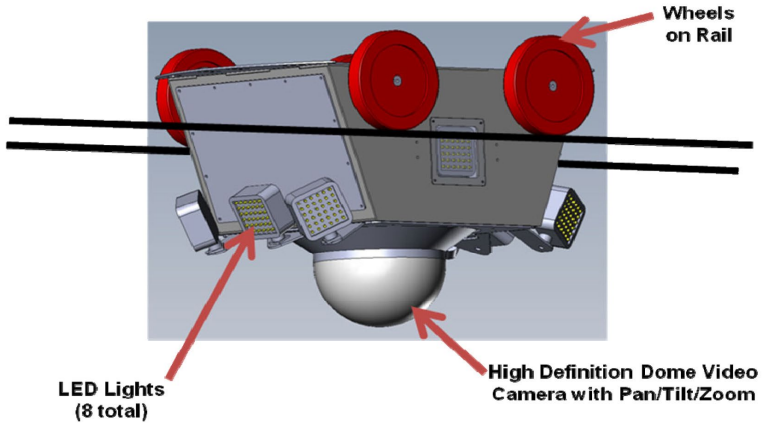


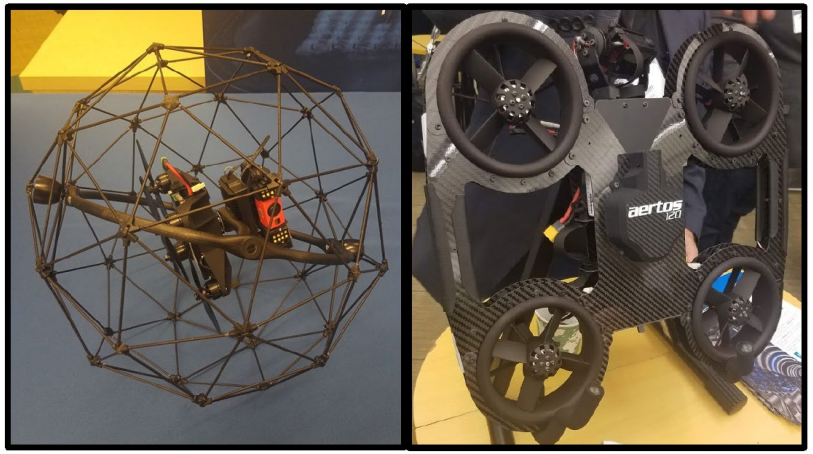
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Underground Transmission Vault Inspection Using Robotic Techniques – 2024 Update – 3002029495

Evaluates underground power transmission line inspection

- Robot-on-Rail Systems
- Unmanned Aerial Systems (UAS)
- Unmanned Underwater Vehicle Systems
- 360° camera and tripod systems (under development)









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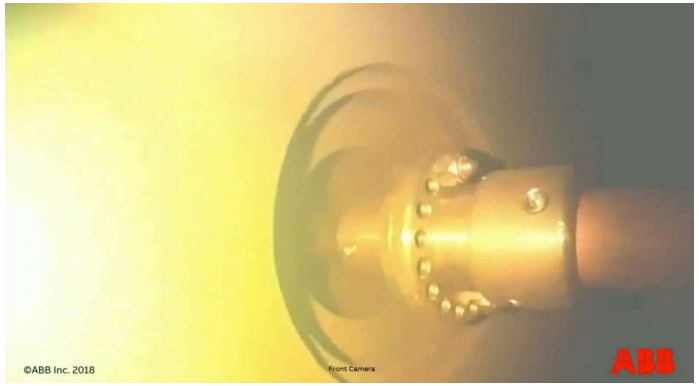
Robotic Inspection Technologies for Transformers: Laboratory and Field Assessments – 3002019141

Objective:

Identify and Demonstrate robotic technologies that are capable of performing an internal transformer inspection without the requirement to drain the oil.

- VideoRay
- ABB TXplore









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Topical Guide: Boston Dynamics Spot Robot – A Cyber Security Technical Assessment Methodology (TAM) Worked Example - 3002023859

Key Questions:

- What are the cyber security vulnerabilities associated with Spot?
- What are the recommendations for its safe usage by utility organizations at power generation facilities?

Challenges:

- Mobility and physical object manipulation
- Video streaming and recording capabilities inside sensitive areas of a facility
- Detect, respond and recovery functionality



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Drone Applications for LP Steam Turbines: Interactive Guide – 3002024049

- The Steam Turbine LP Exhaust Inspection Using Drones deliverable is designed to be a reference that will support system owners, engineers and unmanned aircraft system (UAS) pilots understanding of the potential damage mechanisms that may occur and details leading to effective inspection practices.

3002020913, Unmanned Aircraft System (UAS) User's Guide for Nuclear Power Plants

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LP Turbines - Opportunity

Locations

- Steam Path Integrity
- Cooling Spray Systems
- LP Casing Structure and Joint Integrity
- Condenser Neck and Flexible Joint Integrity
- Admission, Condenser, and Auxiliary Steam Piping Integrity
- Instrumentation

Damage Mechanisms

- Fatigue
- Deformation/Distortion
- Corrosion
- Erosion
- Wear
- Foreign Object Damage (FOD)
- Loose, Missing Components
- Generic Damages
- Manufacturing Quality

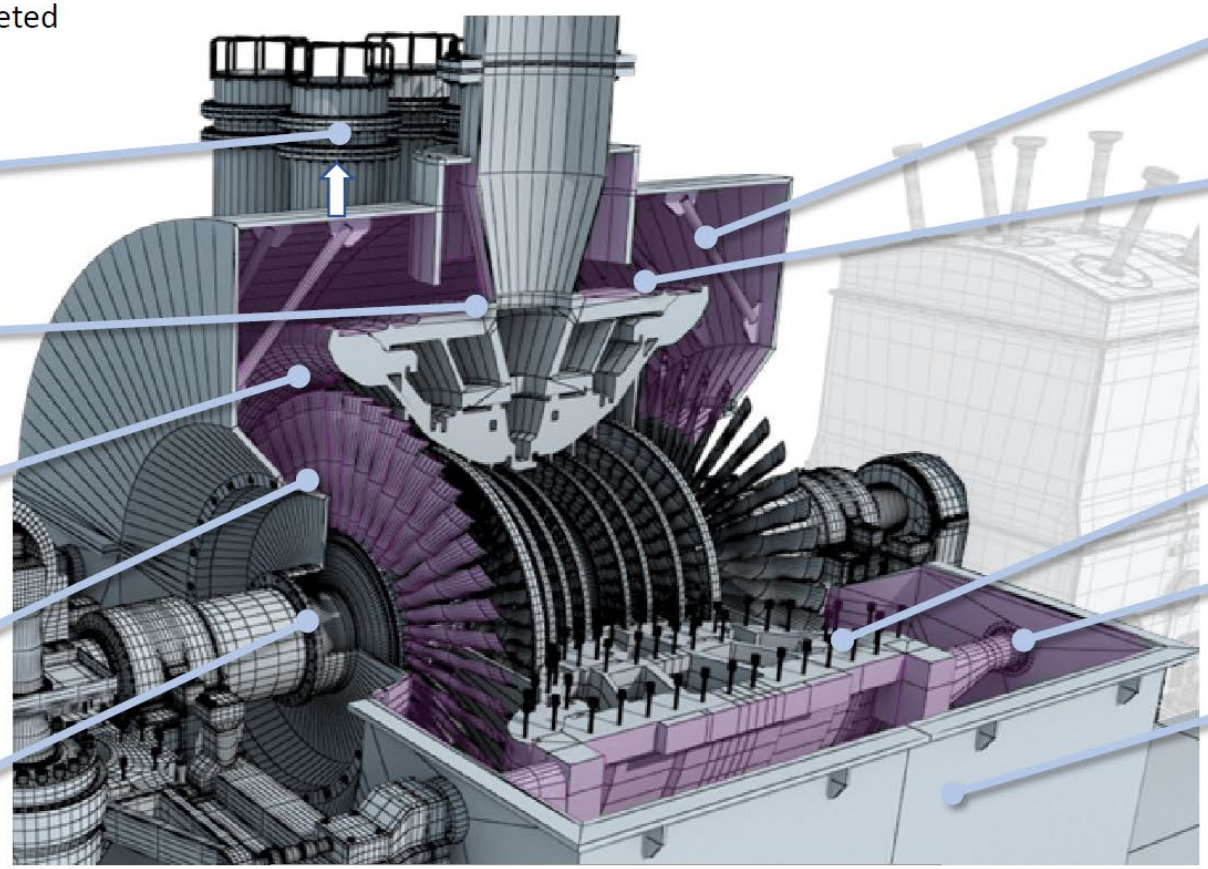
Known Challenges

- Confined space and limited access
- Working from elevation
- Hostile environmental conditions (temperature, humidity, etc.)
- Narrow investigation paths
- Obstacles

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Inspection Objectives

AREAS OF COVERAGE
Components that may be targeted for inspection.



- LP Rupture Diaphragms
- Admission Steam Connections
- Exhaust Flow Guide
- Last Stage Blade
- Exhaust Glands
- Structural Elements
- Outer Surface of Inner Casing, Inner Surface of Outer Casing
- Inner Casing Joint
- Structural Elements
- Condenser Neck Features

(Included, but not limited to; piping, flexible joints, instrumentation, pipe hangers)

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Drone Characteristics

- Size – Must fit access point
- Temperature – Can see elevated temperatures
- Battery - >30 minute flight time
- Safety – Propeller guards (FME)
- Control – GPS/SLAM (Simultaneous Location and Mapping) and obstacle avoidance)
- HD Camera
- Gimbal
- Illumination/Lighting
- 3D Scanners

Flyability Elios 2	
Digital Aerolus Aertos	
DJI Mavic 2 Pro	

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Axial Entry L-0 Blade Inspection

Exhaust Flow Guide Damage

FULL ACCESS

- Erosion (Depth, Length)
- Distortion (Radial Clearance)
- Corrosion Pitting (Pit Size, Density)
- Wear (Blade Rubbing)

Blade Tip Damage

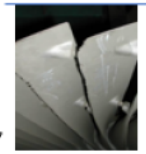
LIMITED INSPECTION



- Cracking Indication (Linear>1mm)
- Erosion (Seal, Connection, Rivet)
- Wear (Flow Guide/Connection Rubbing)
- Wear (Trailing Edge Tip)
- Distortion (Connection Clearance)

Leading Edge Damage

LIMITED INSPECTION



- Cracking Indication (Linear>1mm)
- Erosion (Depth, Length, Location, Width, Stage)
- Foreign Object Damage (Depth, Size, Location)
- Stellite Separation (Braze or Weld)

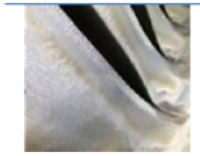
Mid-Span Connection Damage

LIMITED INSPECTION

- Cracking Indication (Linear>1mm)
- Erosion (Seal, Connection, Rivet)
- Wear (Connection Rubbing)
- Distortion (Connection Clearance)

Trailing Edge Damage

FULL ACCESS



- Cracking Indication (Linear>1mm)
- Erosion (Depth, Length, Location, Width, Stage)
- Foreign Object Damage

Blade Attachment Damage

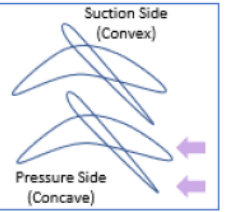
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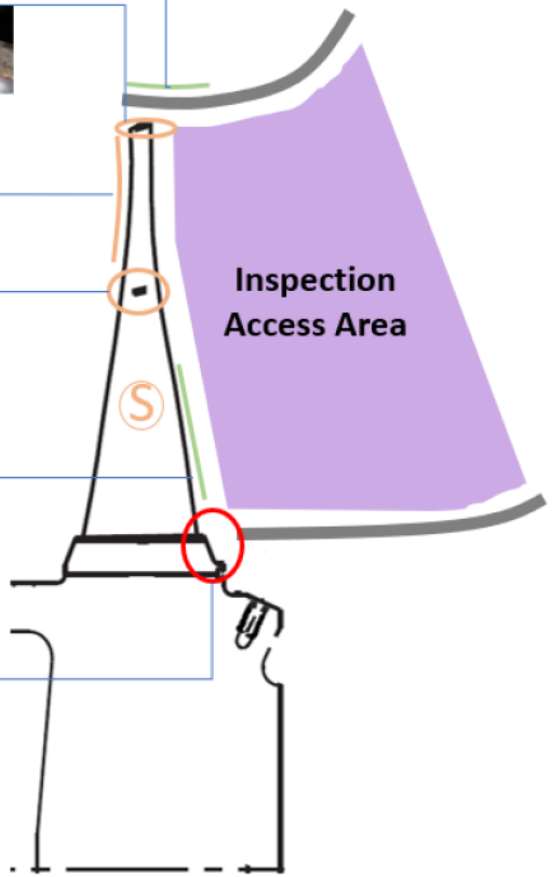


- Cracking Indication (Linear>1mm)
- Corrosion Pitting (Pit Size, Density,)
- Corrosion Deposit (Discoloration)
- Deformation (Lifting or Axial Offset)
- Erosion (Surface Depth or Discoloration)

Generic Surface Condition

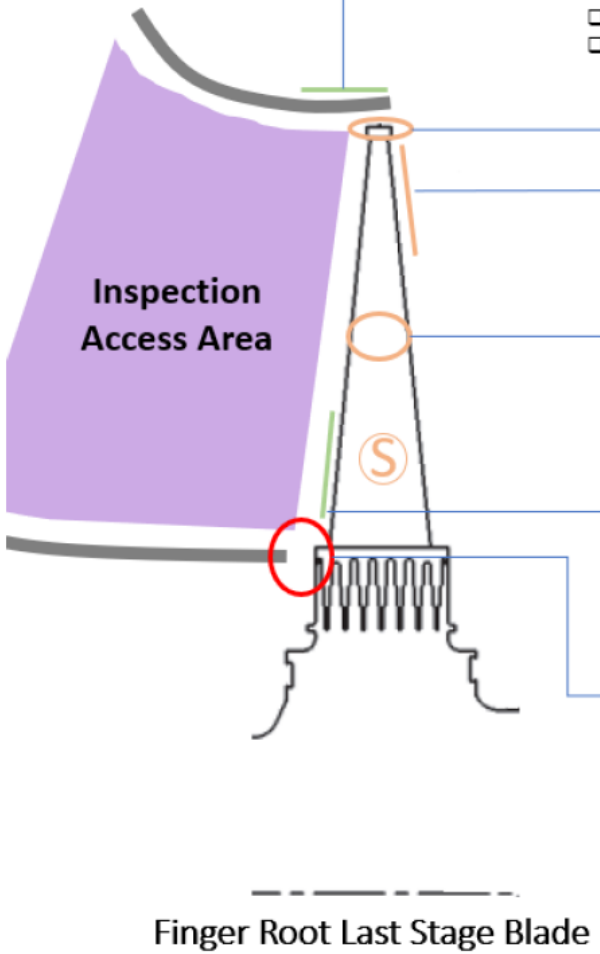
- Cracking Indication (Linear>1mm)
- Corrosion Pitting (Pit Size, Density,)
- Corrosion Deposit (Discoloration)
- Foreign Object Damage (Depth, Size, Location)
- Erosion (Surface Depth or Discoloration)





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Radial Entry L-0 Blade Inspection



FULL ACCESS

Exhaust Flow Guide Damage

- ❑ Erosion (Depth, Length)
- ❑ Distortion (Radial Clearance)
- ❑ Corrosion Pitting (Pit Size, Density)
- ❑ Wear (Blade Rubbing)

LIMITED INSPECTION



Blade Tip Damage

- ❑ Cracking Indication (Linear>1mm)
- ❑ Erosion (Seal, Connection, Rivet)
- ❑ Wear (Flow Guide/Connection Rubbing)
- ❑ Wear (Trailing Edge Tip)
- ❑ Distortion (Connection Clearance)

LIMITED INSPECTION



Leading Edge Damage

- ❑ Cracking Indication (Linear>1mm)
- ❑ Erosion (Depth, Length, Location, Width, Stage)
- ❑ Foreign Object Damage (Depth, Size, Location)
- ❑ Stellite Separation (Braze or Weld)

LIMITED INSPECTION

Mid-Span Connection Damage

- ❑ Cracking Indication (Linear>1mm)
- ❑ Erosion (Seal, Connection, Rivet)
- ❑ Wear (Connection Rubbing)
- ❑ Distortion (Connection Clearance)

FULL ACCESS



Trailing Edge Damage

- ❑ Cracking Indication (Linear>1mm)
- ❑ Erosion (Depth, Length, Location, Width, Stage)
- ❑ Foreign Object Damage

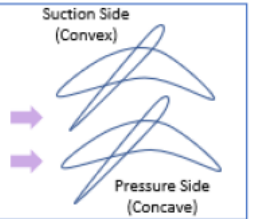
UNKNOWN ACCESS

Blade Attachment Damage

- ❑ Cracking Indication (Linear>1mm)
- ❑ Corrosion Pitting (Pit Size, Density,)
- ❑ Corrosion Deposit (Discoloration)
- ❑ Deformation (Lifting or Axial Offset)
- ❑ Erosion (Surface Depth or Discoloration)

Generic Surface Condition

- ❑ Cracking Indication (Linear>1mm)
- ❑ Corrosion Pitting (Pit Size, Density,)
- ❑ Corrosion Deposit (Discoloration)
- ❑ Foreign Object Damage (Depth, Size, Location)
- ❑ Erosion (Surface Depth or Discoloration)



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Structural Inspections

- Turbine Structure
  - Outer Casing Inner Surfaces, Struts, Gussets, Fabrication Welds, and Bolted Joints
  - LP Inner Casing Outer Surfaces, Fabrication Welds, and Bolted Joints
  - Exhaust Diffuser Cone Surfaces, Joints and Blade Attachment Platform Interface
  - Exhaust Diffuser Flow Guide Surfaces and Joints
  - Mid-Section Flow Guides and Struts
  - LP Alignment Features
  - LP Extraction Piping Outer Surfaces and Casing Interface
- Cooling Spray Systems
  - Hood Spray Nozzles, Manifold, and Pipe Routing
  - Curtain Spray Nozzles, Manifold, and Pipe Routing
- Condenser (Double-Flow Exhaust)
  - Condenser Run Gland Piping Outer Surfaces
  - Condenser Joint
  - Condenser Erosion Plate and/or Tube Bundle
- Condenser (Axial Exhaust)
  - Condenser Run Lube Oil Piping/Shield Outer Surfaces
  - Condenser Joint (Vertical Flange)
  - Condenser Erosion Plate and/or Sparging Pipe, Tube Bundle
- Other Areas
  - LP Admission Pipe Between Hood and Inner Casing
  - Inner Surface of Rupture Diaphragms

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Planning Inspections

- EMI/RFI – Electromagnetic- or Radiofrequency Interference can cause malfunction.
- Radio Relay – Used to extend or strengthen the link between drone and control
- FME – The drone (or pieces of the drone) can become foreign material. Develop a retrieval plan
- Navigation Path – Obstructions and Barriers may be in place making inspection difficult
- Dust – Propellers create prop wash that can agitate particulates into the air, impacting visibility/acuity or potentially spreading contamination

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Flight vs. Inspection Checklists

FLIGHT CHECKLIST

PRE FLIGHT	DURING FLIGHT	POST FLIGHT
At office	**After launch**	**After landing**
☐ Aircraft Documentation ☐ NOTAM ☐ Local regulations and permissions. ☐ Proximity to the airport. ☐ Weather condition permits flying. ☐ All Batteries Charged ☐ Flight Gear check	☐ Aircraft reached safe altitude. ☐ Confirm observer has the aircraft in sight. ☐ All systems green ☐ Satellite and GPS check ☐ Check Battery remaining	☐ Power down UAV ☐ Remove and safely store batteries ☐ Airframe inspection ☐ Check camera/ sensor to ensure data collected ☐ Transfer data and flight log ☐ Make logbook entry
In the field	**Before Landing**	**Back at office**
☐ Scan area for obstacles, e.g. take-off and landing area. ☐ Wind check ☐ Daily Flight Report filled. ☐ Assemble UAV, ensure screws are tight and propeller check ☐ Sensor/ Camera setting check ☐ Batteries securely mounted ☐ Ensure GPS fix ☐ Confirm Mission flight plan ☐ Operators checklist (Integrated) ☐ RC remote check (if used) ☐ Final airframe inspection ☐ Flight Crew briefings, e.g. flight mission and safety ☐ Wind check again for launch.	☐ Ensure UAV flight done according to mission plan. ☐ Scan landing area for obstacles. ☐ Wind check ☐ Observer briefing for landing ☐ All systems green	☐ Flight and Maintenance Report ☐ Charge Batteries ☐ SD card cleaned and ready to use ☐ Airframe checked ☐ Data processed

INSPECTION CHECKLIST

PRE FLIGHT	DURING FLIGHT	POST FLIGHT
At office	**After launch**	**After landing**
❑ LP Turbine sectional drawing ❑ Photos of the inspection volume ❑ Available reference geometry and measurements ❑ Photos of ideal inspection images/data ❑ Establish method for viewing live data collection ❑ Define data management requirements	➢ Action: Guide pilot to obtain desired inspection information	➢ Action: Perform cursory review of data collected to ensure scope is complete ➢ Action: Define areas of insufficient inspection, evaluate feasibility of capture plan
In the field	**Before landing**	**Back at office**
❑ LP Turbine sectional drawing ❑ Photos of the inspection volume ❑ Available reference geometry and measurements ❑ Photos of ideal inspection images/data ❑ Share detailed turbine inspection requirements		➢ Action: Review collected information ➢ Action: Report inspection findings and disposition ➢ Action: Record lessons learned

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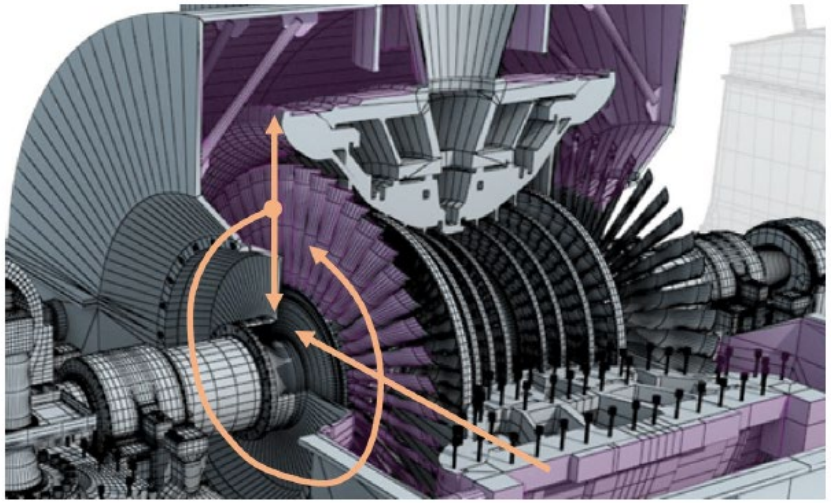
Westinghouse BB281 w/ Alstom LP 48 Retrofit



Site photograph of LP with Access Ports Open



Primary Inspection Navigation Zone (Drone Hood Entry)



Inspection Navigation Path

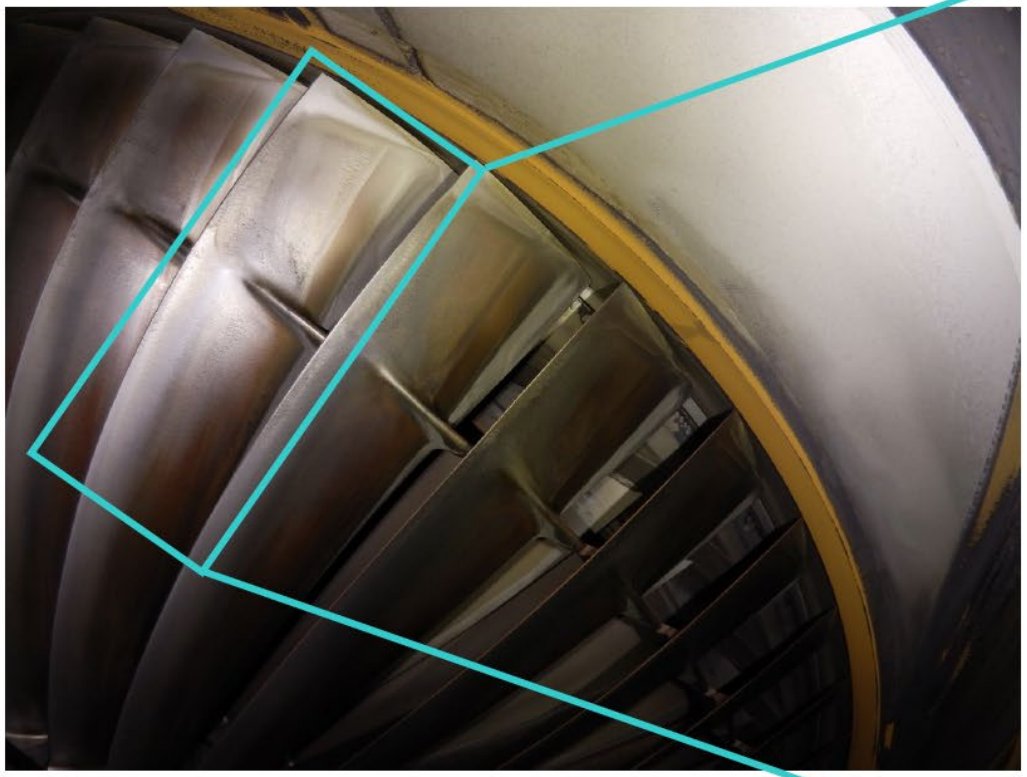


Drone Viewing LSB at Bottom Section of Turbine

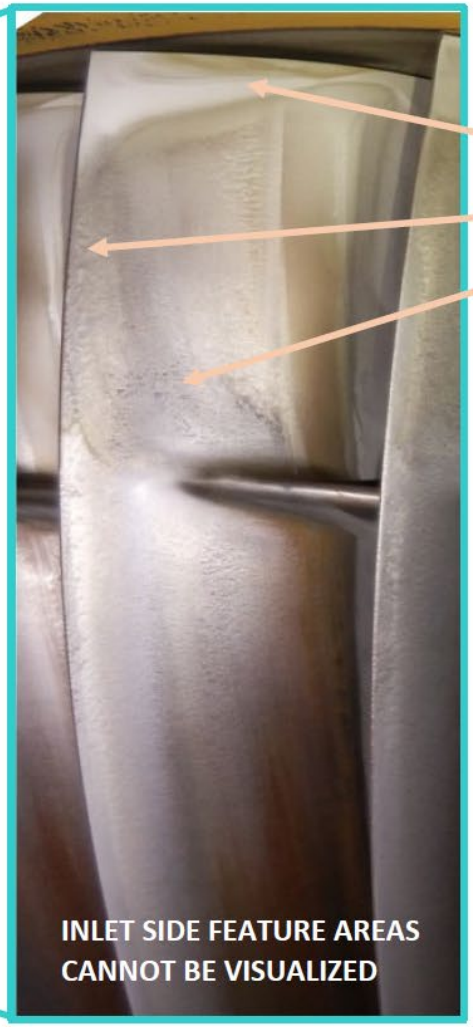
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Westinghouse BB281 w/ Alstom LP 48 Retrofit

INSPECTION SUMMARY – *Last Stage Blade General Condition*



- Sample Drone Photo of LSB sector
- Light intensity creates a narrow area of focus



FEATURE AREAS OF INTEREST CONSIDERED

- Erosion
- Cracking Indications at TE
- Corrosion Pitting
- Corrosion Deposit
- Foreign Object Damage

Acceptable for review of gross damages.

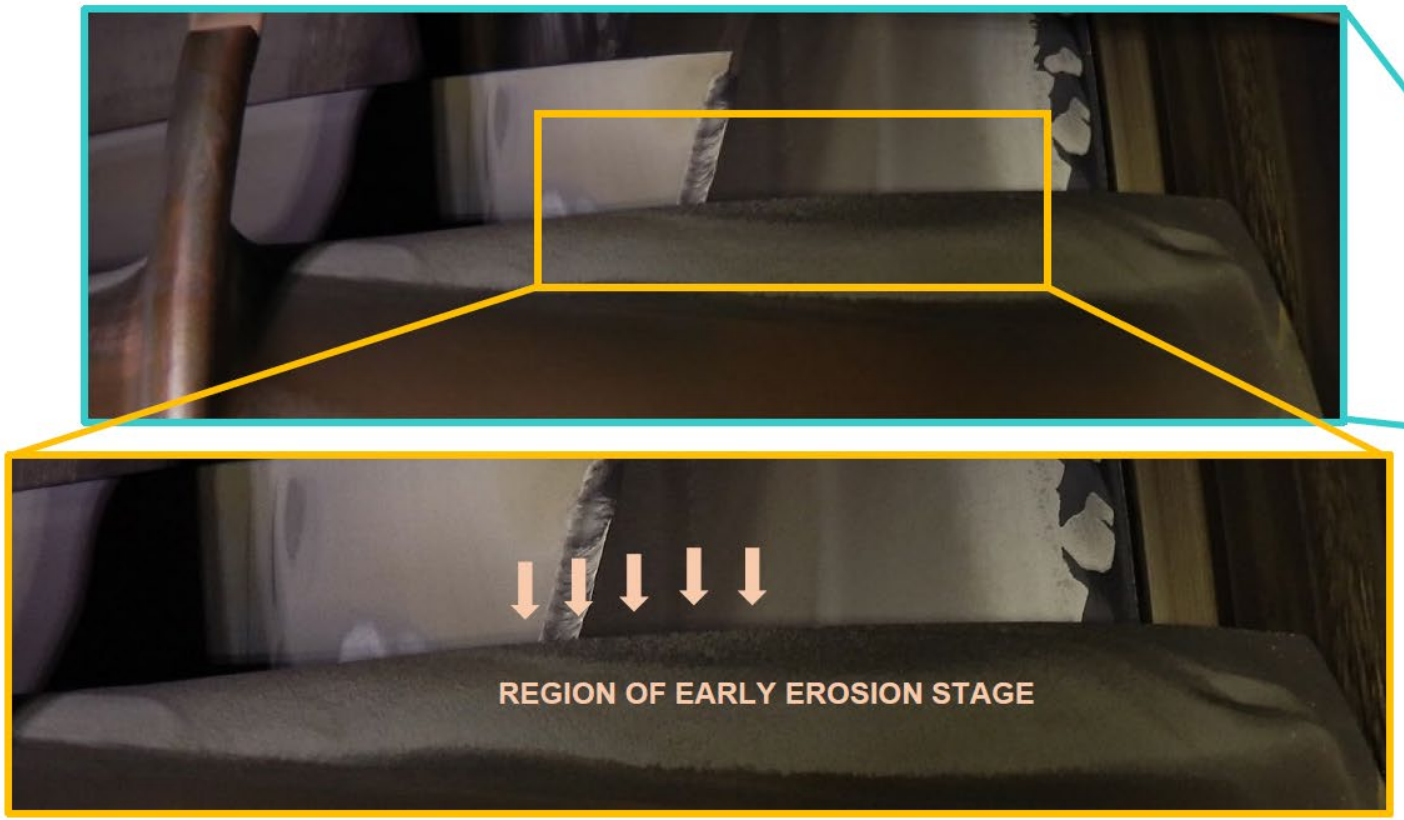
Is the imaging quality acceptable for detailed assessment?

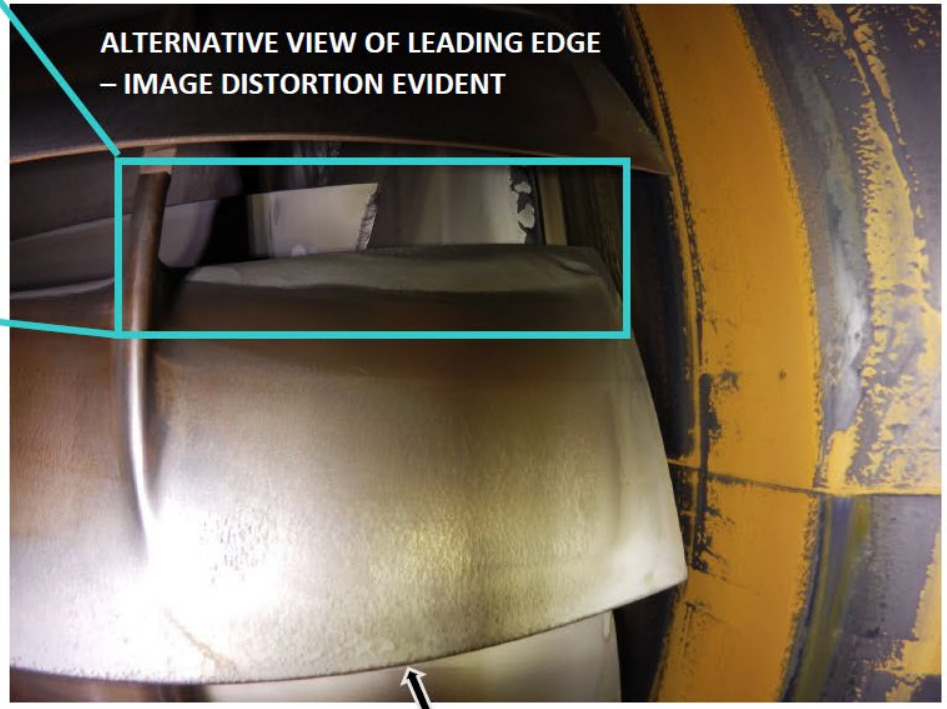
- Magnification required for proper evaluation
- Broad capture range impacts image quality
- Exfoliated oxides and discoloration observed

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Westinghouse BB281 w/ Alstom LP 48 Retrofit

INSPECTION SUMMARY – *Last Stage Blade Leading Edge Erosion (alternative view)*





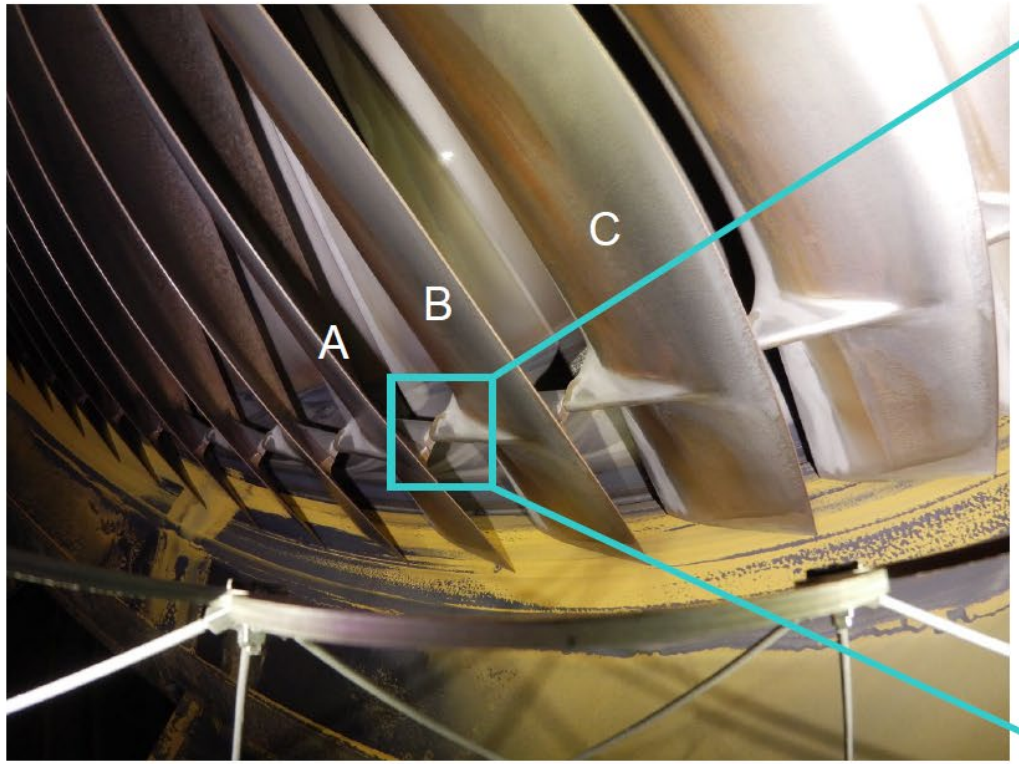
LEADING EDGE EROSION FEATURE AREAS

- Erosion damage is difficult to determine (erosion damage is generally consistent for all blades)

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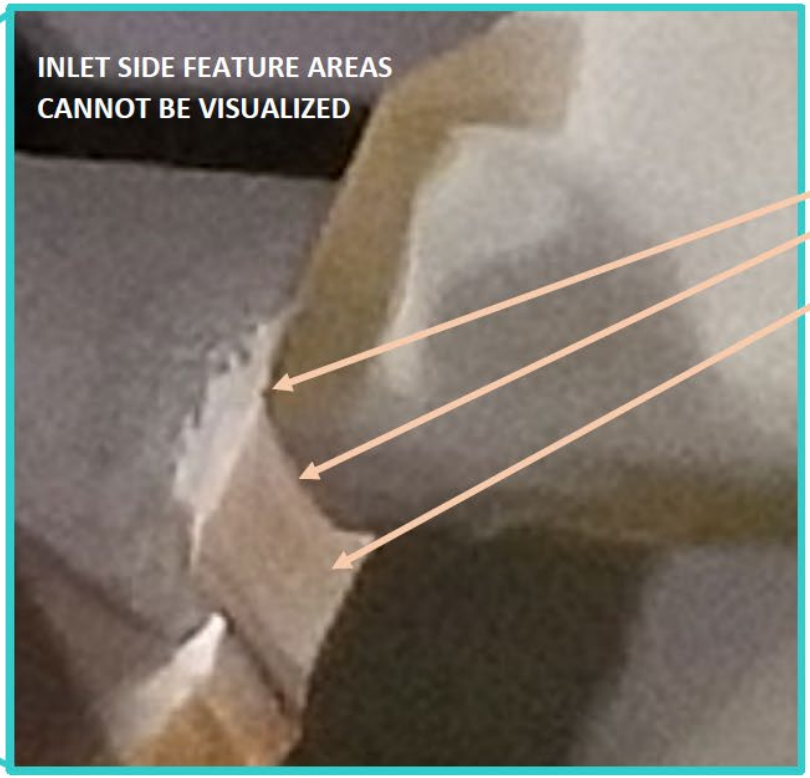
Westinghouse BB281 w/ Alstom LP 48 Retrofit

INSPECTION SUMMARY – *Last Stage Blade Leading Snubber*



- Sample Drone Photo of LSB sector
- Snubbers A-B and B-C can only be evaluated in this image

? Limited view orientation. Is a representative inspection acceptable?



- Magnification required for proper evaluation
- Broad capture range impacts image quality
- Exfoliated oxides and discoloration observed

FEATURE AREAS OF INTEREST CONSIDERED

- Cracking at snubber
- Cracking/Fretting at contact face
- Contact face deformed material
- Design Clearance/Seizure

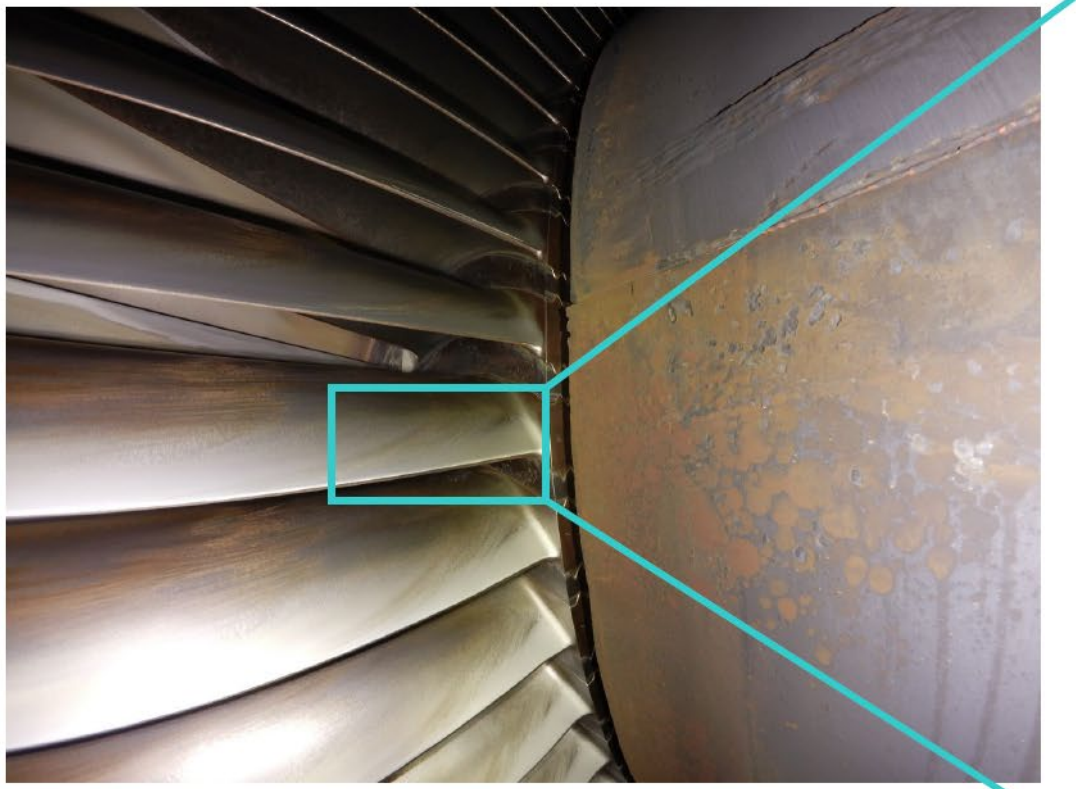
? Acceptable for review of gross damages.

Is the imaging quality acceptable for detailed assessment?

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Westinghouse BB281 w/ Alstom LP 48 Retrofit

INSPECTION EVALUATION – *Last Stage Blade Trailing Edge Erosion*



- Sample Drone Photo of LSB sector





- Magnification required for proper evaluation
- Exfoliated oxides and discoloration observed

FEATURE AREAS OF INTEREST CONSIDERED

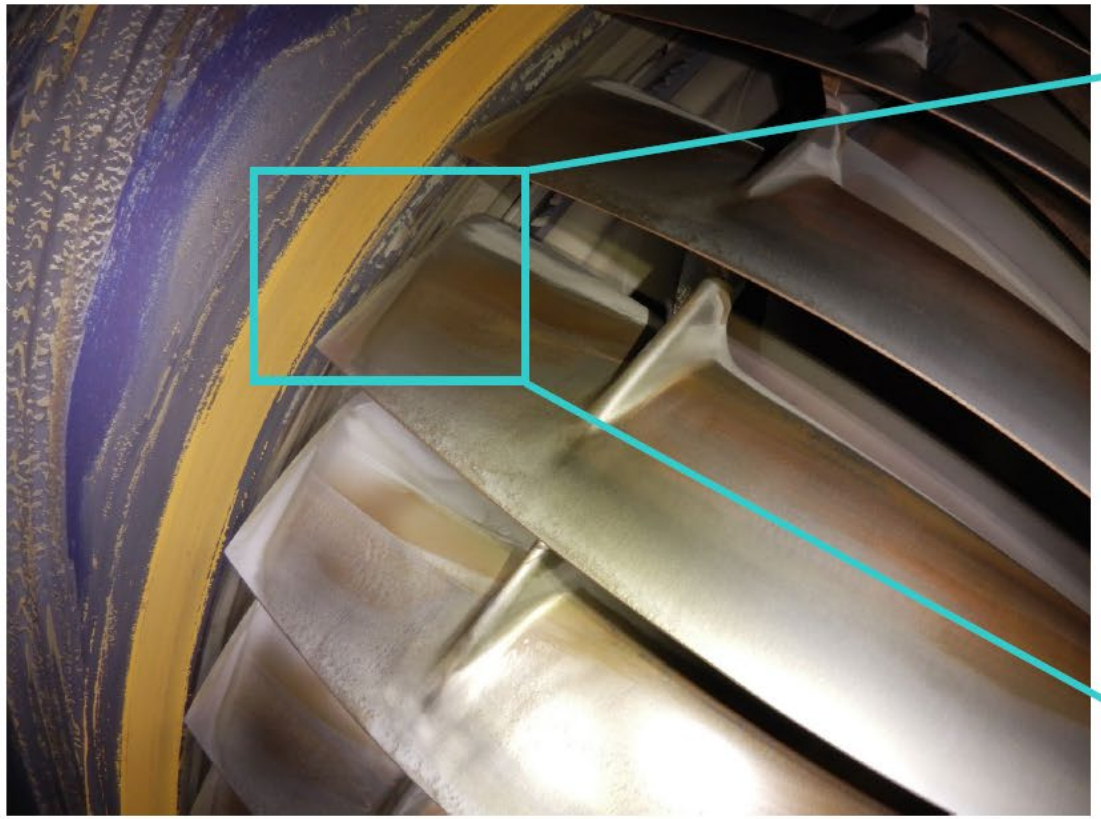
- Cracking
- Erosion
- Foreign Object damage

✓ Good image quality for damage evaluation

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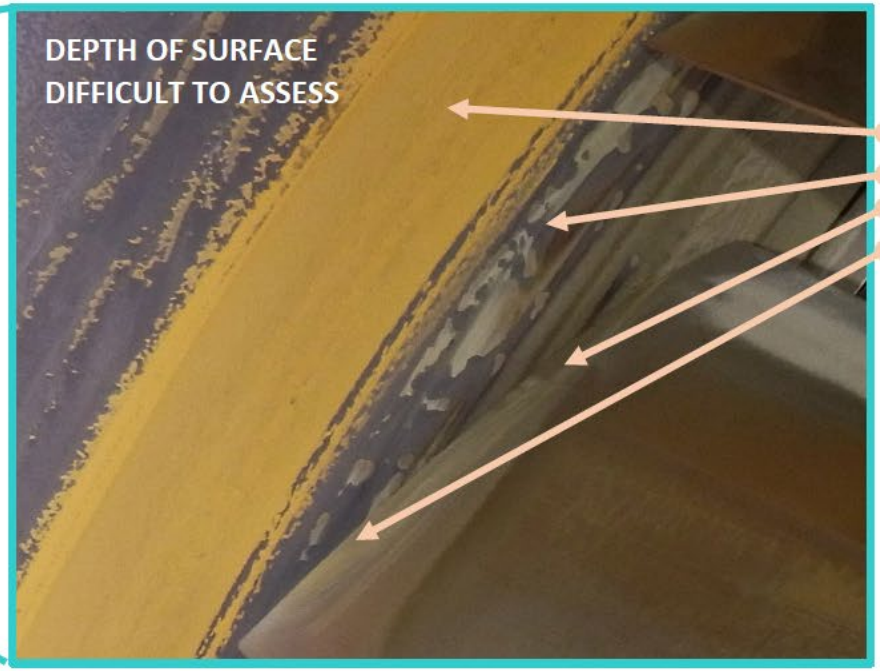
Westinghouse BB281 w/ Alstom LP 48 Retrofit

INSPECTION SUMMARY – *Last Stage Blade Tip*



- Sample Drone Photo of LSB sector
- Camera skew desired to view parallel to tip exhaust angle

? Limited view orientation. Is a representative inspection acceptable?



- Magnification required for deeper evaluation
- Exfoliated oxides, oxidation and discoloration observed
- Difficult to determine whether surface

FEATURE AREAS OF INTEREST CONSIDERED

- Flow Guide Erosion
- Tip Rubbing/Indentation
- Tip Wear
- Tip Clearance/Casing Deflection

? Acceptable for review of gross damages.

Is the imaging quality acceptable for detailed assessment?

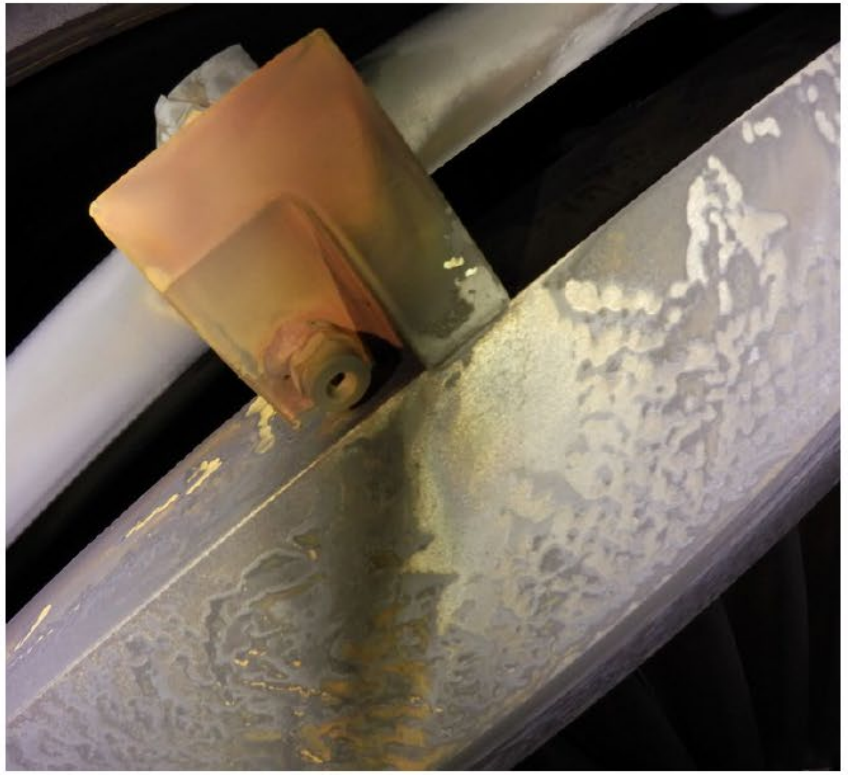
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Westinghouse BB281 w/ Alstom LP 48 Retrofit

INSPECTION SUMMARY– *Hood Spray System*



- Example of photo taken with nozzle locking tab in focus
- Difficult to indicate rigidity of feature.



- Example of photo taken with nozzle orifice in focus
- Difficult to indicate erosion, blockage or rigidity of feature.



- Example of photo taken while drone unstable.

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Lessons Learned

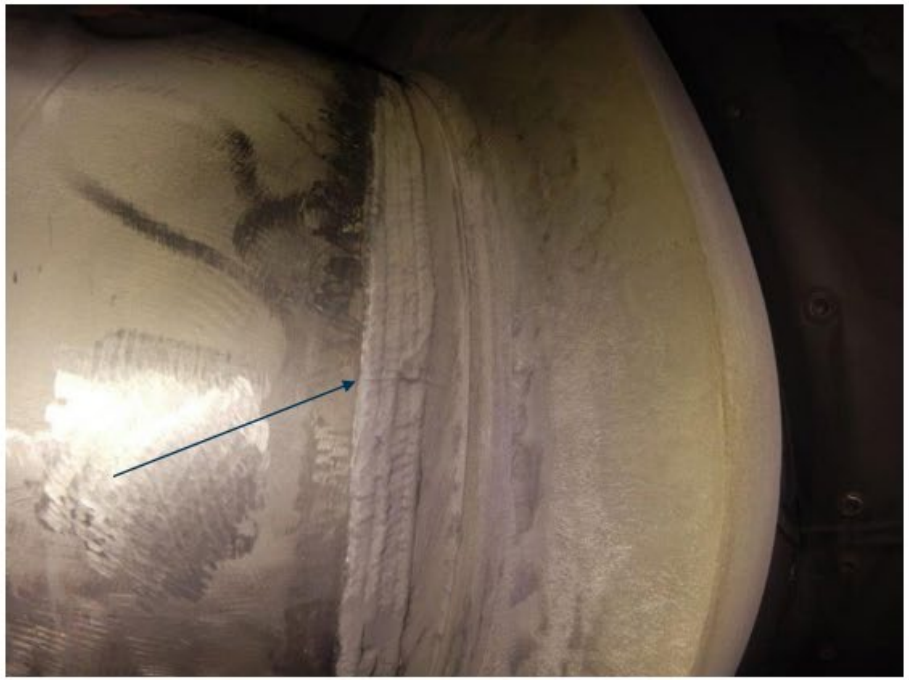
- Documentation provided by the OEM does not always depict the structural features of the exhaust area
- Plants may not have good information on the extraction and auxiliary system piping within the navigation volume.
- The camera is on one axis beyond the drone's orientation; therefore, the view perspective changes around the periphery of the part. Difficult to assess each independent feature using the same comparison.
- Features examined are small in comparison to the range of view. Very difficult for the technical lead to evaluate component features real time.
- Difficult to identify where the features are (blade no., peripheral position, etc.)
- The speed of inspection and repetition of features challenges the technical lead to evaluate component features in real time.
- For this size drone and LP configuration, navigation below the LP inner casing and between the hood was possible but limited. Tight clearances and obstacle variability (pipes, hangers, structural elements and other instruments) create increased risk when inspecting these areas. For full speed units with smaller exhaust sizes, the range of inspection may be limited to only the exhaust view of the last stage blades.
- The technical lead will be responsible for directing the pilot. There may be an opportunity to develop an improved process or procedure to use as guidance.

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User Experience – Wolf Creek Nuclear Station

Additional External Crack

- Used drone to visually inspect exterior weld conditions on inlet piping
  - Identified single indication on the #5 CIV
  - Confirmed crack via MT





8

evergy

Public

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EPRI

User Experience

- OPG Atikokan uses drone to inspect L-0 blades through condenser investigation vibration issues
- Constellation intends to perform drone inspections every outage
- OPG and Constellation have both experienced false positives and out-of-coverage damage findings
- TVA uses drones extensively for:
  - LP L-0 Inspections
  - LP Inner Manway Inspections
  - Turbine Building Crane Bus
  - Condenser Inspections
  - Main Steam Valve & EHC Inspections
  - Other Inspections and Considerations

Turbine Building Crane Bus



Condenser Inspections



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Vine Robotic Inspections

EPRI Technology Innovation Research

Randall Steele
Senior Technical Leader

2025 WANO Steam Turbine & Generator Workshop
Shanghai, China
3-6 November 2025

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Research Challenge

How do we visually inspect areas that traditional borescopes cannot access?

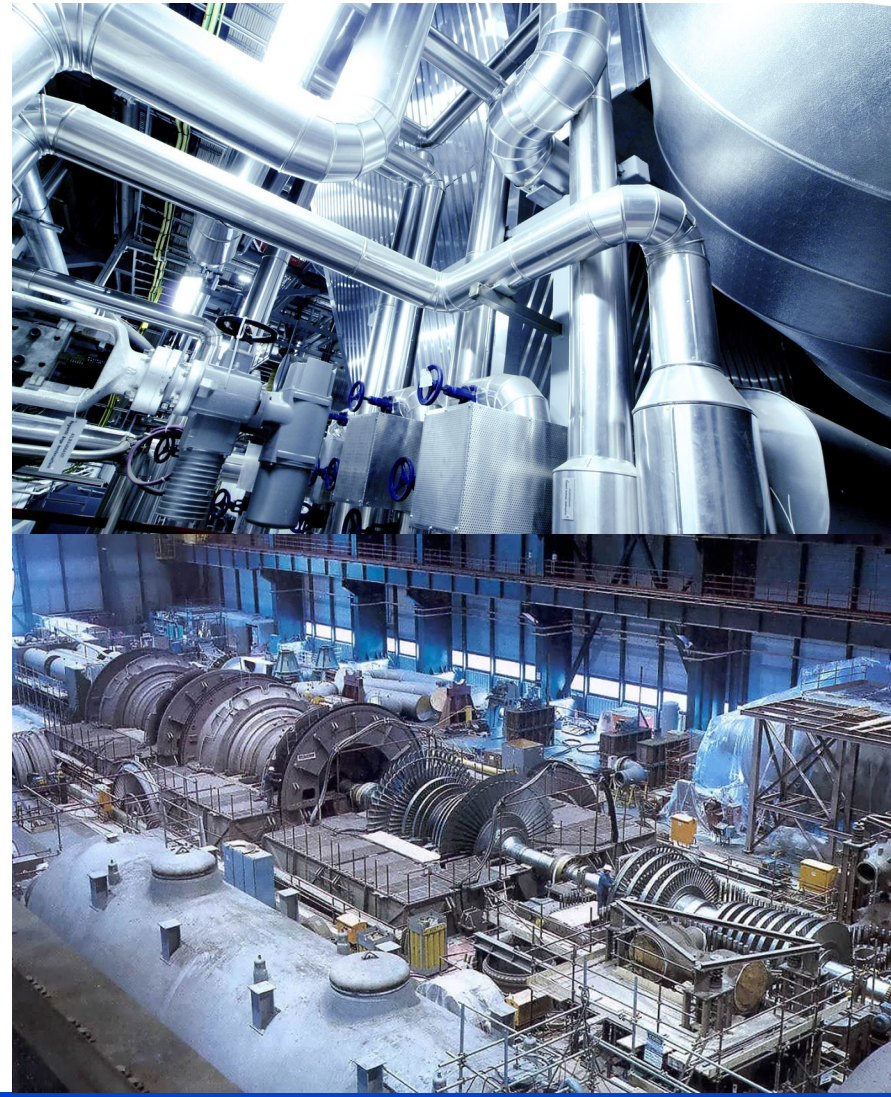
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Everting Vine Robots (EVR) for Steam Turbine Inspection

Technology Review and Feasibility Study

Brief Project Description

- The overall project goal is to build an improved inspection device or system based on the **pneumatic-everting-soft robot technology** that can be used in power plant applications on major equipment such as steam turbines. Additional applications for further consideration:
  - large turbogenerators
  - high energy piping
  - large pumps
  - heat exchangers
  - moisture separators (MSRs)
  - boilers
- Phase 1 of the project consist of the following activities:
  - EVR technology review
  - technology assessment and gap analysis for large equipment inspection
  - initial concept development for a customized EVR inspection system

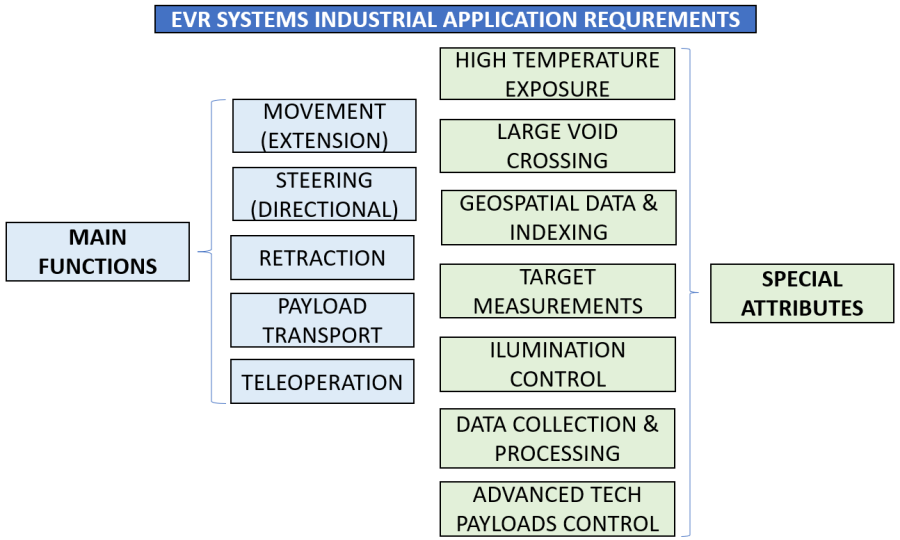


Goals: Improved inspection coverage, maneuverability and defect detection capabilities

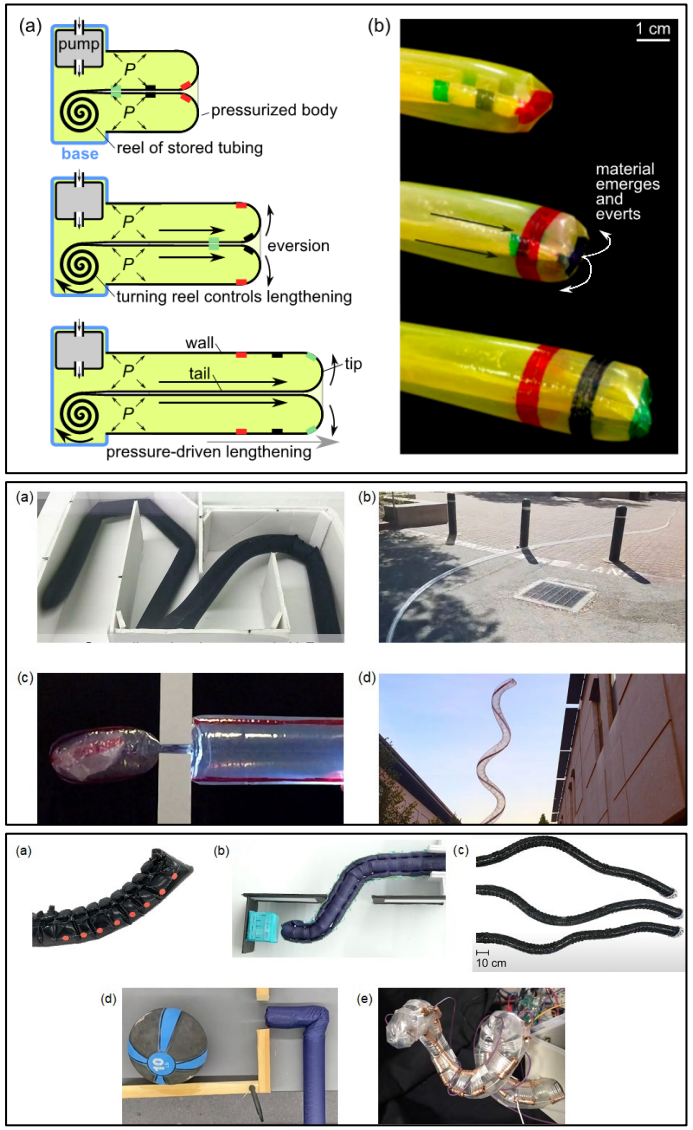
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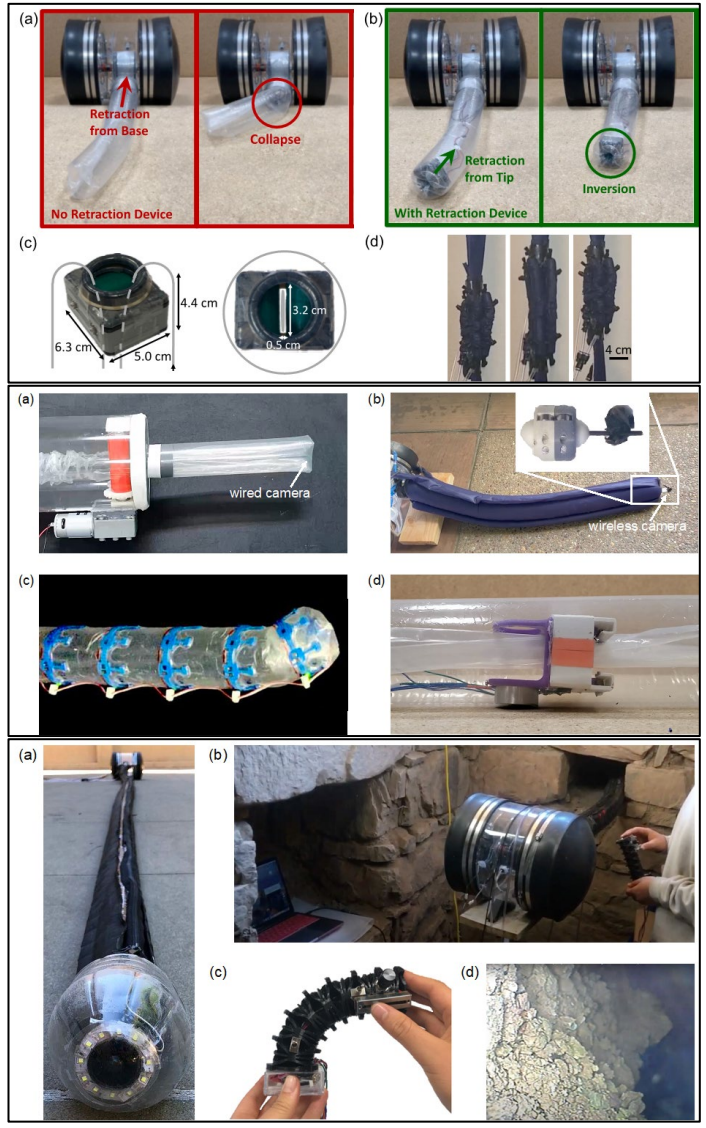
Everting Vine Robots (EVR) for Steam Turbine Inspection

Technology Review and Feasibility Study



- EVRs move through their environment by extending from their tip out of a fixed base *(similar to the growth of a natural vine from its tip out of its fixed roots)*
- The body of an EVR is fabricated from a tube of soft, fluid-tight material that is folded inside of itself *(similar to inverting a sock)*
- Internal fluid pressure applied inside the tube causes the material that has been folded inside to turn inside-out at the tip of the tube *(to "evert")* and extend the tube in length

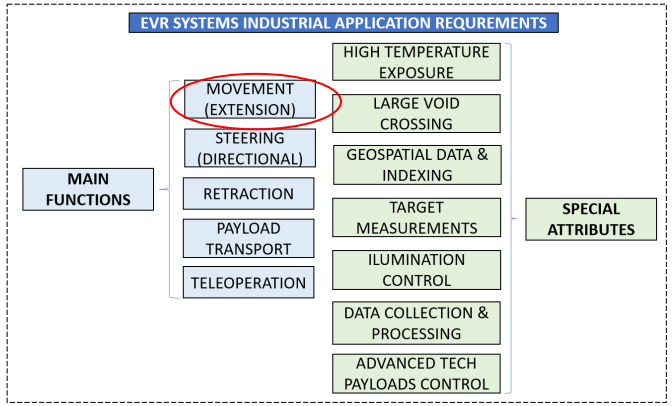


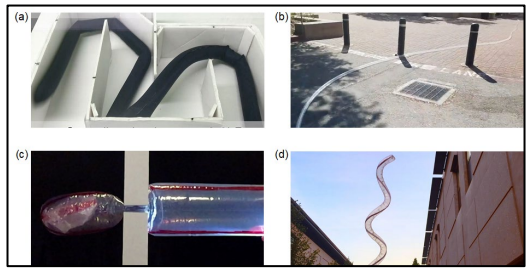


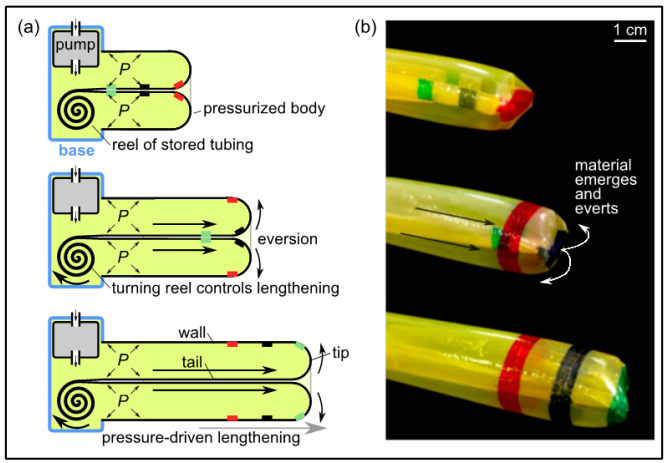
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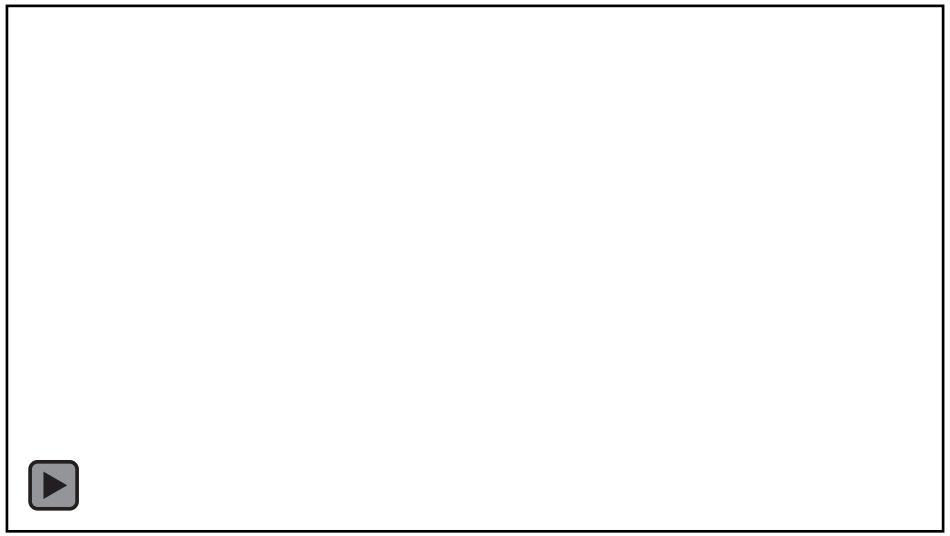
Everting Vine Robots (EVR) for Steam Turbine Inspection

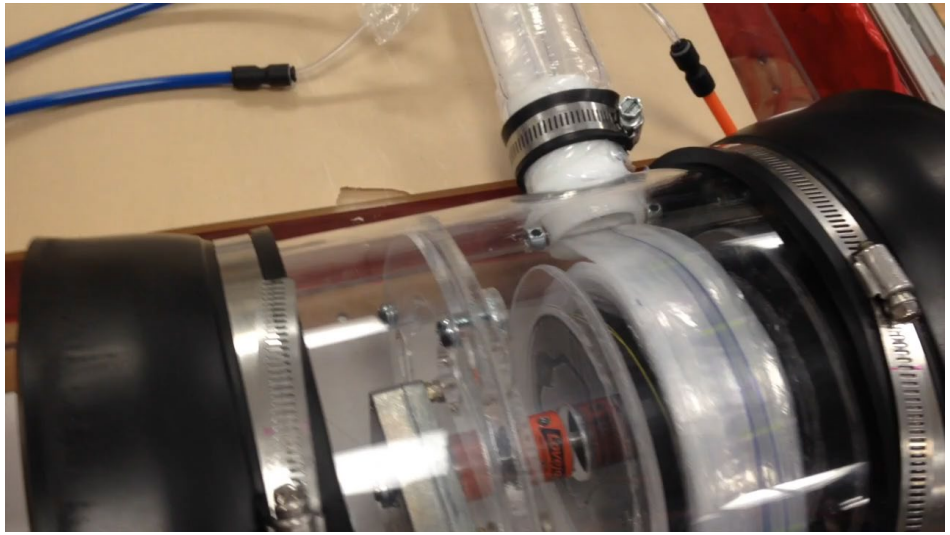
Movement











- Common materials that have been used so far:
  - low-density polyethylene (LDPE)
  - silicone-coated and thermoplastic polyurethane-coated LDPE
  - ripstop nylon
- For the internal fluid - air most common, but water also tested

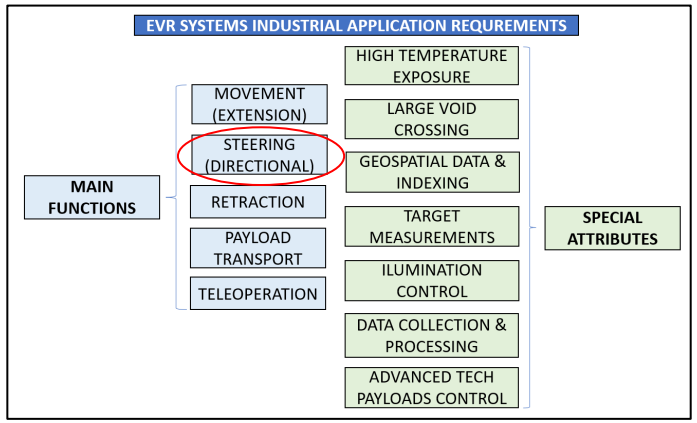
EVR Benefits

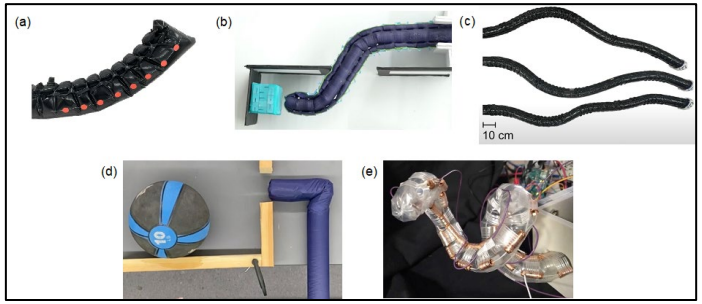
- It does not need to move their entire body through an environment to navigate it => EVR can navigate long and highly tortuous paths without concern for the frictional properties of its contact with its environment
- EVR can extend to very long lengths – 72 m tested, but longer lengths possible
- EVRs move via tip-extension => can navigate through apertures, even those smaller than their body diameter

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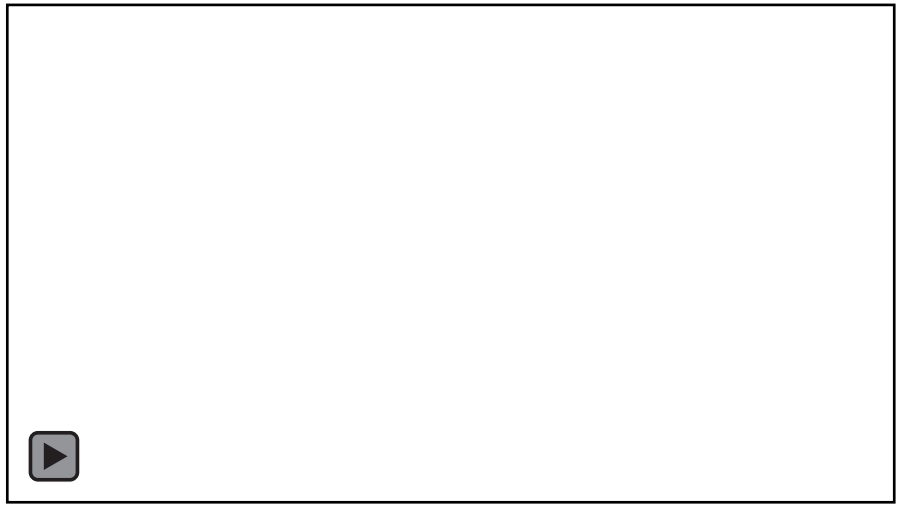
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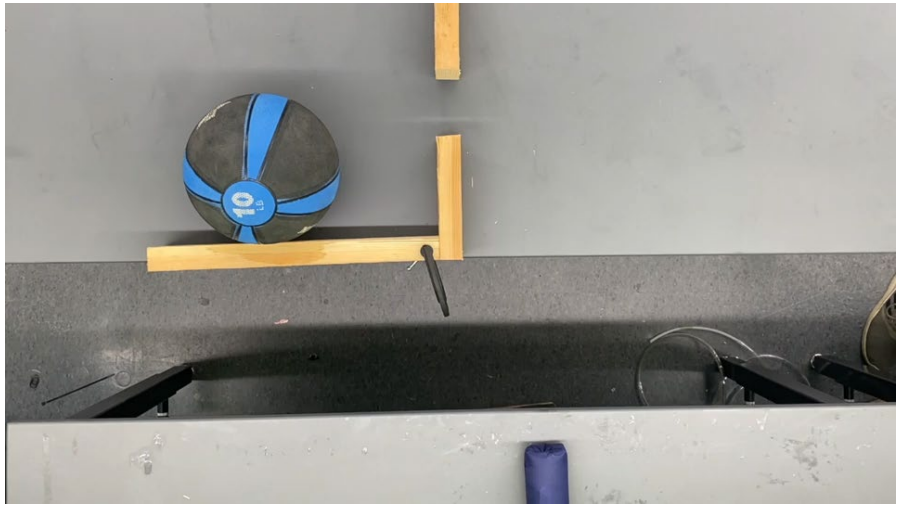
Steering





(a) A single curvature enabled by a single cylindrical pneumatic artificial muscle actuator attached on the top side of the robot body. **(b)** Multiple curvatures enabled by shape locking operating in conjunction with fabric pneumatic artificial muscle-based steering. **(c)** Multiple curvatures enabled by magnetically controlled valves operating in conjunction with cylindrical pneumatic artificial muscle-based steering. **(d)** A sharp bend enabled by a hinged steering device that travels inside the robot body. **(e)** High curvature actuation enabled by cable-based steering



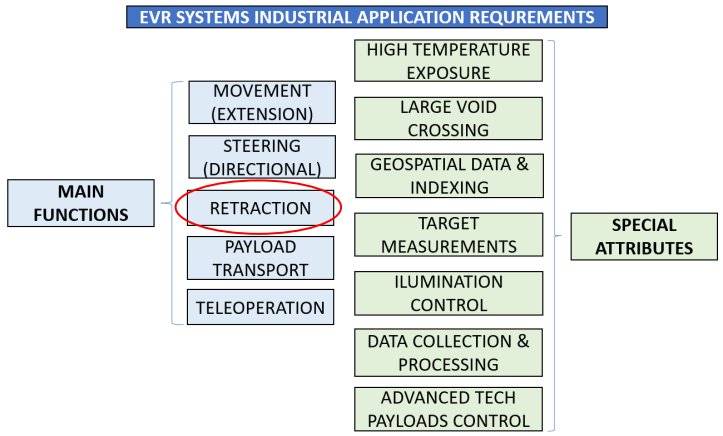


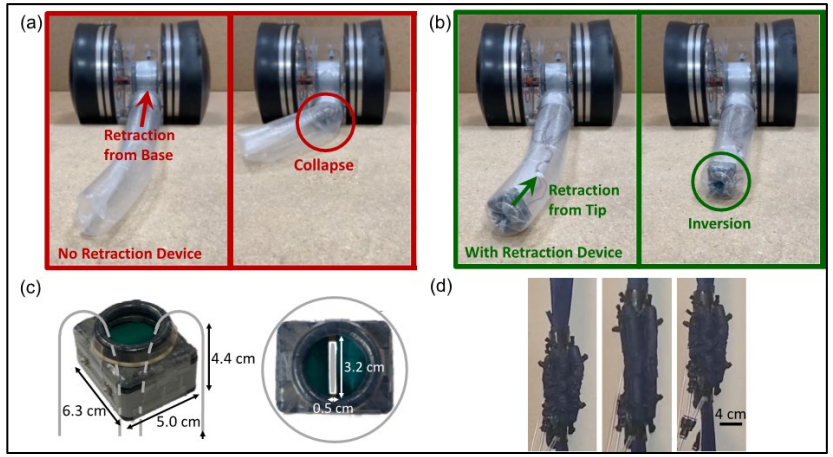
- All EVR steering mechanisms operate by either shortening or lengthening one side of the robot body compared to the other side, which causes the robot body to curve toward the shorter side pneumatic artificial muscle-based steering
- Sharp bends possible - use of a steering device that drives itself along the robot tail and uses an internal motor to bend a rigid hinge that forces the robot body into a sharp turn
- Other methods – cables, tape, latches, and magnets

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Everting Vine Robots (EVR) for Steam Turbine Inspection

Retraction





(a) Undesired collapse due to applying a force on the EVR tail from the robot base. **(b)** Successful retraction via inversion due to applying a force on the tail from the tip using a retraction device. **(c)** Retraction device using motorized rollers. **(d)** Retraction device using a pneumatic inchworm mechanism

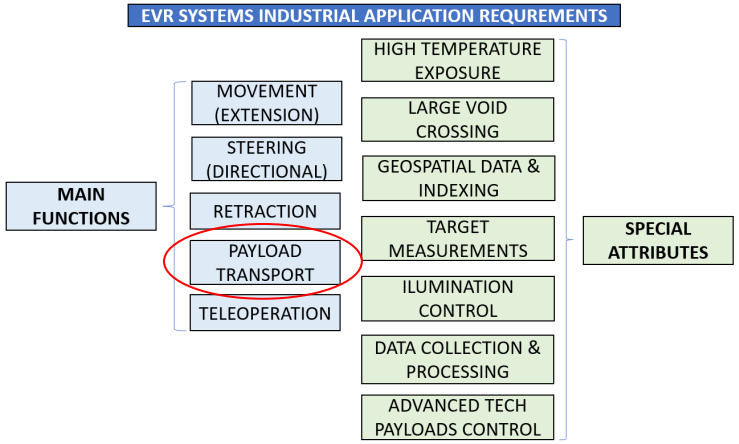


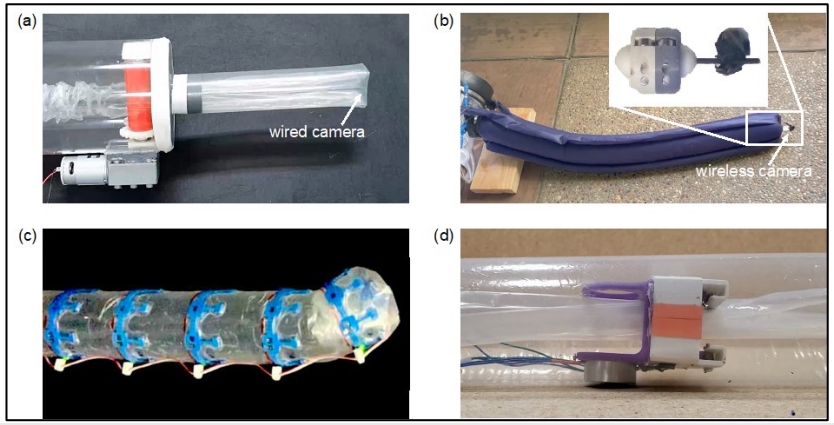
- EVRs can be retracted either by having their membrane pulled back from the base (ideally after draining their internal fluid to reduce their body stiffness and friction with the environment), or by “inverting” back into themselves
- Above certain lengths and curvatures of the robot body, the robot will “collapse” when retraction is attempted. Solutions: “retraction device” grounded to the robot tip (pair motor-driven rollers or pneumatically actuated inchworm-like mechanism)

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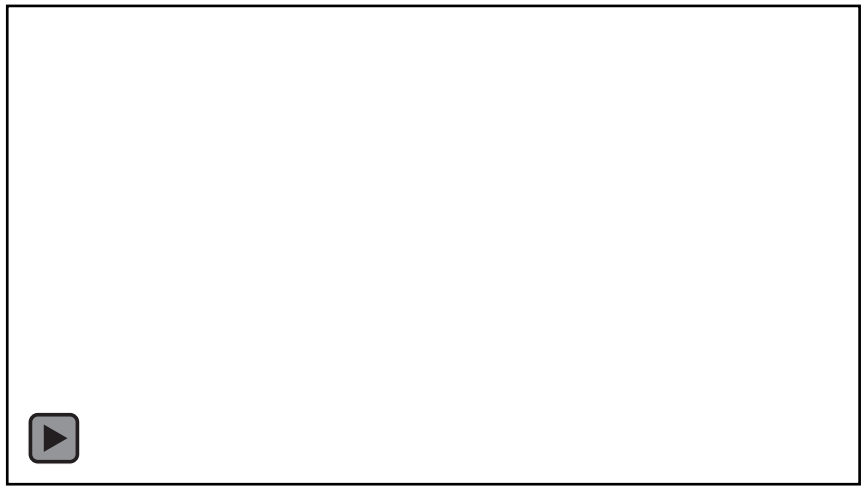
Everting Vine Robots (EVR) for Steam Turbine Inspection

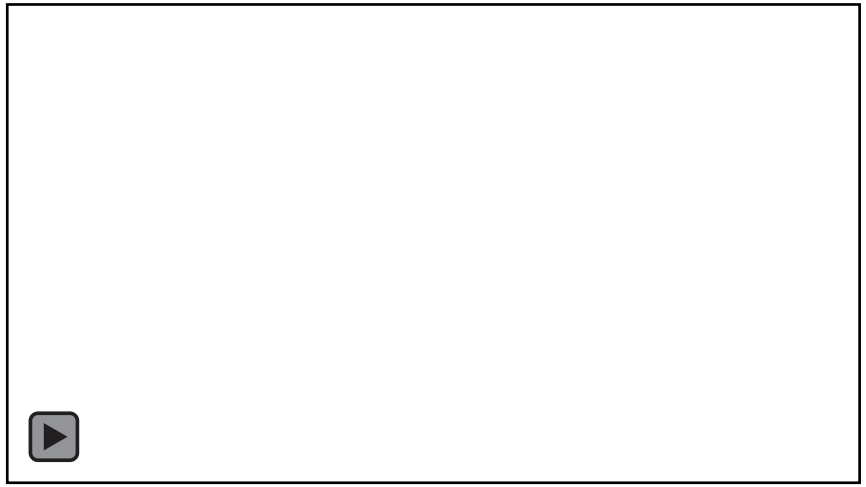
Payload Transport





(a) Wired camera at the robot tip, wire inside the tail, using motor-driven rollers and internal air pressure to modulate the friction between the wire and the tail. **(b)** Wireless camera at the robot tip using an interlocking mechanism that sits inside the robot tip, with one piece inside the tail and the other piece inside the pressurized part of the robot body. **(c)** Distributed sensors fixed to the robot body using flexible sensor bands **(d)** Electromagnet transported along the grown robot body by driving it along the tail using a motorized cart



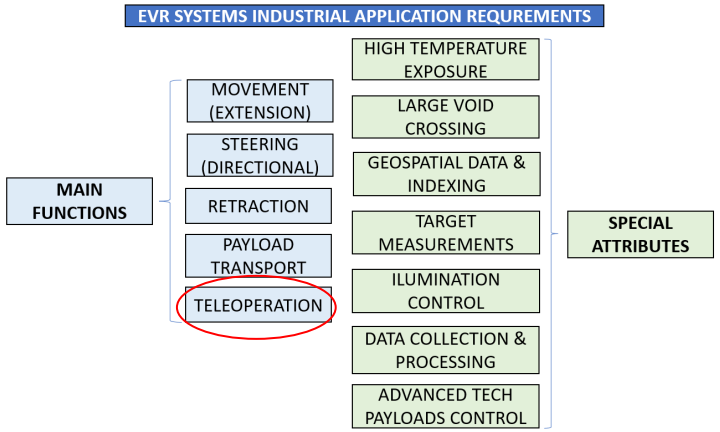


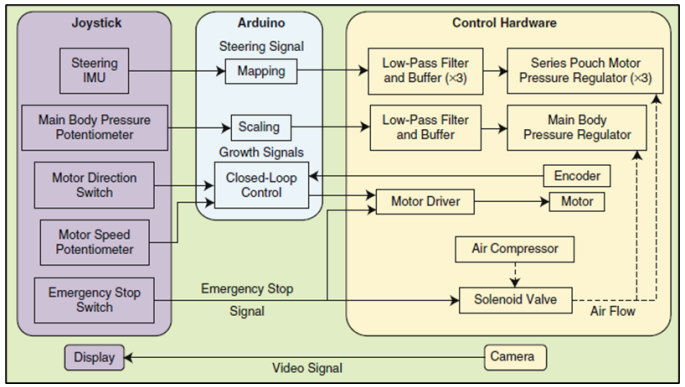
- Challenge: robot body material that is at the robot tip continually changes as an EVR grows and retracts
- *Method*: pass the wire inside the robot body tail and use a combination of motors and air pressure at the robot base to modulate the friction between the tail and the wire to prevent the camera from being ejected from the tip as the robot grows
- *Method*: interlocking mechanism - hourglass-shaped part sits inside the robot tail and protrudes from the robot tip to hold the payload, while a ring-shaped part sits inside the pressurized part of the robot body and interlocks with the hourglass-shaped part to keep it from falling out of the tip of the robot
- *Other applications* - distributed sensors fixed to the robot body using flexible sensor bands placed at regular intervals along the body or transporting an electromagnet along the grown robot body by driving it along the tail using a motorized cart

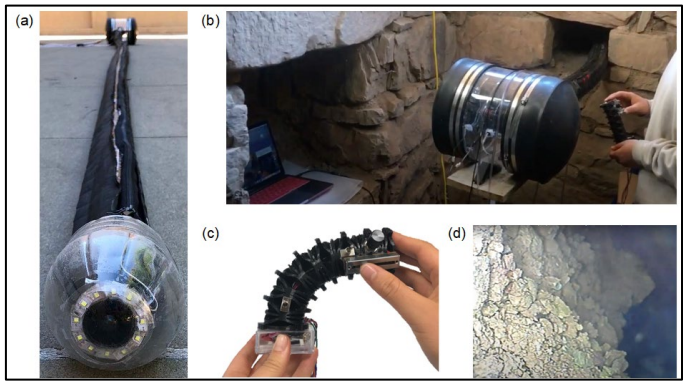
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Everting Vine Robots (EVR) for Steam Turbine Inspection

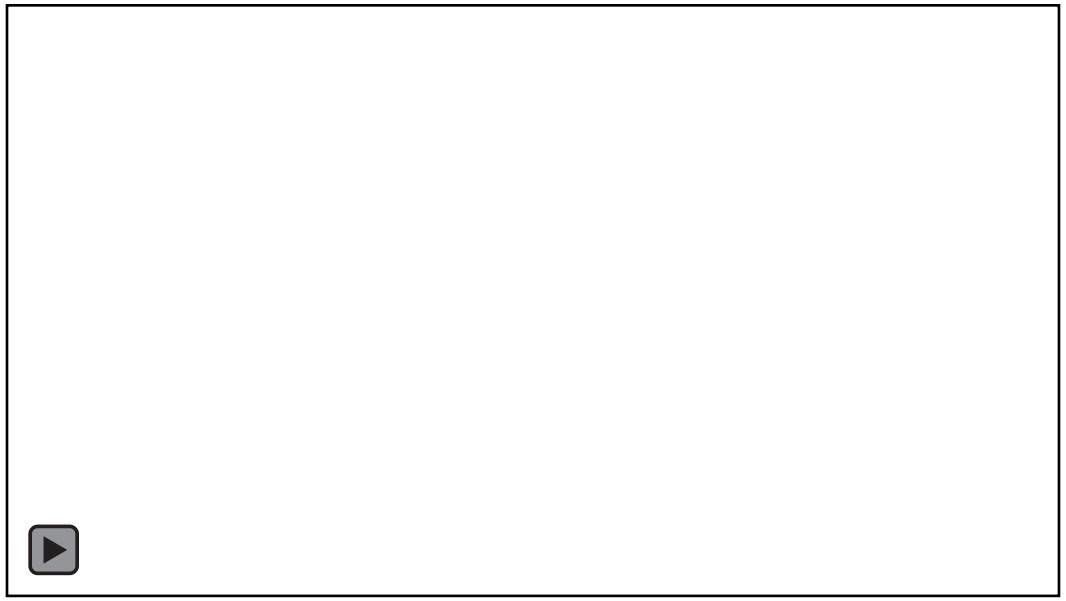
Technology Review and Feasibility Study







(a) 10-meter-long, 10-cm-diameter EVR steered with three series pouch motor actuators running along its length, with a wired camera at the tip. **(b)** Field deployment inside a small tunnel at an archeological site showing the robot base, flexible joystick, and visual display of the tip camera image. **(c)** Flexible joystick used to teleoperate the robot (d) Image from the camera at the robot tip while inside the tunnel



- Real-time teleoperation with a human operator
- A flexible joystick is used to control the direction of motion of the robot tip, where the 2D direction and amount of bending of the joystick corresponded to the direction and amount of bending of the robot body using a simple geometric model of the actuator placement around the circumference of the robot body
- Human operator had to rely solely on the camera image from the robot tip to know where the robot was - lack of situational awareness
- Potential solutions: add shape sensing method onto the robot body (for ex., using inertial measurement units) or optical fibers lining the robot length

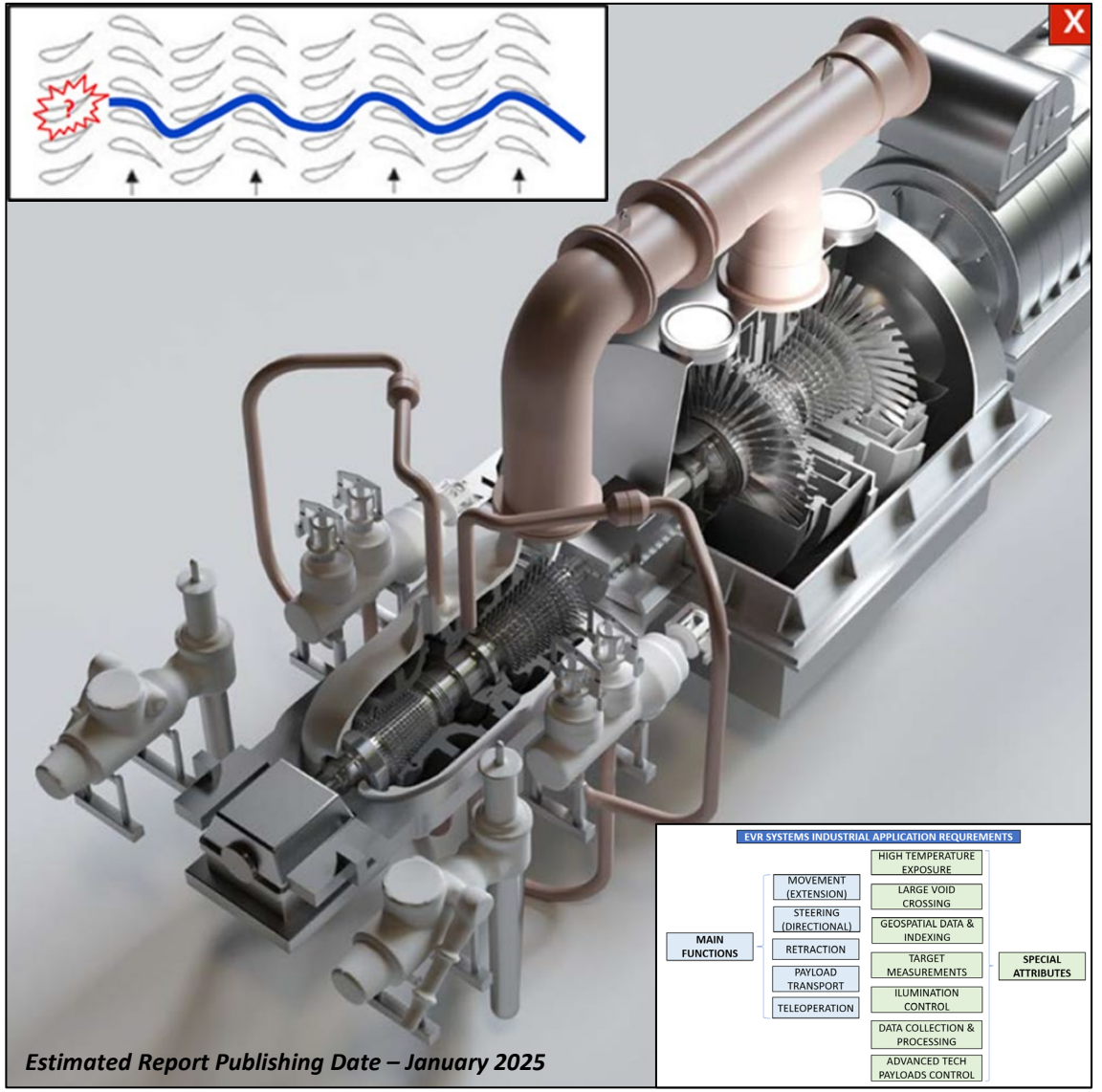
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Everting Vine Robots (EVR) for Steam Turbine Inspection

Technology Review and Feasibility Study

Desired Attributes (example)	Existing EVR Capability	GAP Analysis
Maximum Length from Entry Point to Transport Sensors (10 m)	17 m maximum length at large diameter (10 cm DIA EVR) with steering and sensors	
Maximum Width Void to Cross (3 m)	2.8 m wide void (3 cm DIA EVR)	
Maximum Curvature Turn to Traverse (1 cm)	4.4 cm radius of curvature (3 cm DIA EVR)	Further characterization and improvements needed considering the correlation between specific features and attributes
Largest/Heaviest Payload to Transport (2 kg)	2.75 kg maximum payload in transverse loading (6 cm DIA EVR body, 45 cm length) with additional stiffening	
Highest Operating Temperature (100°C)	Mylar-based EVR (3 cm DIA EVR) tested up to 50°C	
Accuracy of Sensor Localization (10 cm)	10 cm error over 1 m deployed length (7 cm diameter EVR) for IMU-based shape sensing	
Power and Signal Transmission (10 m)	17 m wired signal transmission (10 cm diameter EVR body)	

- Application of soft robot technology in industrial applications is a relatively new research area; tests and demonstrations performed by various universities around the world - in lab environment
- Prototype development and testing – will require collaboration with other industry stakeholders (NDE service, robot technology development companies) and a well-planned multi-year effort



Estimated Report Publishing Date – January 2025

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Lunch

Generator Robotic Inspection Technologies

Technology Overview

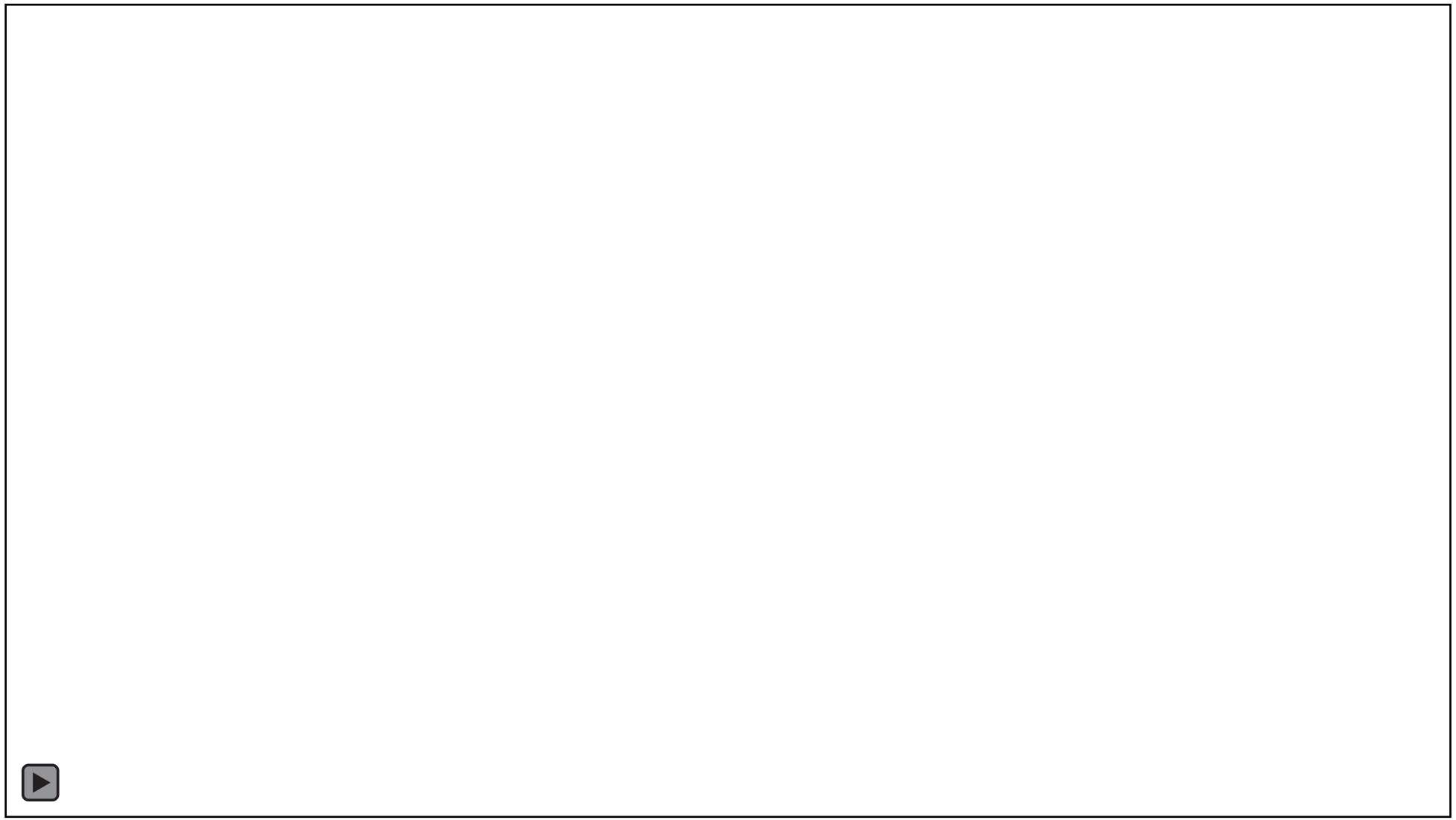
Lionel Cochon
Senior Technical Leader

2025 WANO Steam Turbine & Generator Workshop
Shanghai, China
3-6 November 2025

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Video of Robotic Inspection

Generator Robotic Inspection & Test Guidelines (3002013612)



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Generator Robotic Inspection Capabilities and Perception

- EPRI Report 1000100 ‘Experience with Limited Access Generator Inspections,’ pub. in 2000 established that Robotic Inspections (RI) were equivalent (and in some cases superior) to inspections with the rotor removed.

- Since 2000 - a number of developments occurred in the capabilities of robotic inspections:
  - Robots - smaller, can access smaller airgaps while still carrying all testing sensors.
  - Camera technology improved exponentially - developments for mobile phone and drones.
  - Wedge tightness methodologies

- In the 1990s there were only three main suppliers of Robotic Inspections, while in 2018 there were seven commonly used suppliers and several more technologies in development.

- Most insurance companies now accept RI as either a substitute for a rotor-out inspection or as providing valuable input to decisions on when to remove the rotor and what the scope of work will be.

- OEMs have updated their Maintenance policies to introduce rotor-in robotic inspections as an alternative to a rotor-out inspection (under conditions): common RI scope consists in **Visual inspection** (stator and rotor), **low flux (ELCID**) and **Wedge Tightness** test

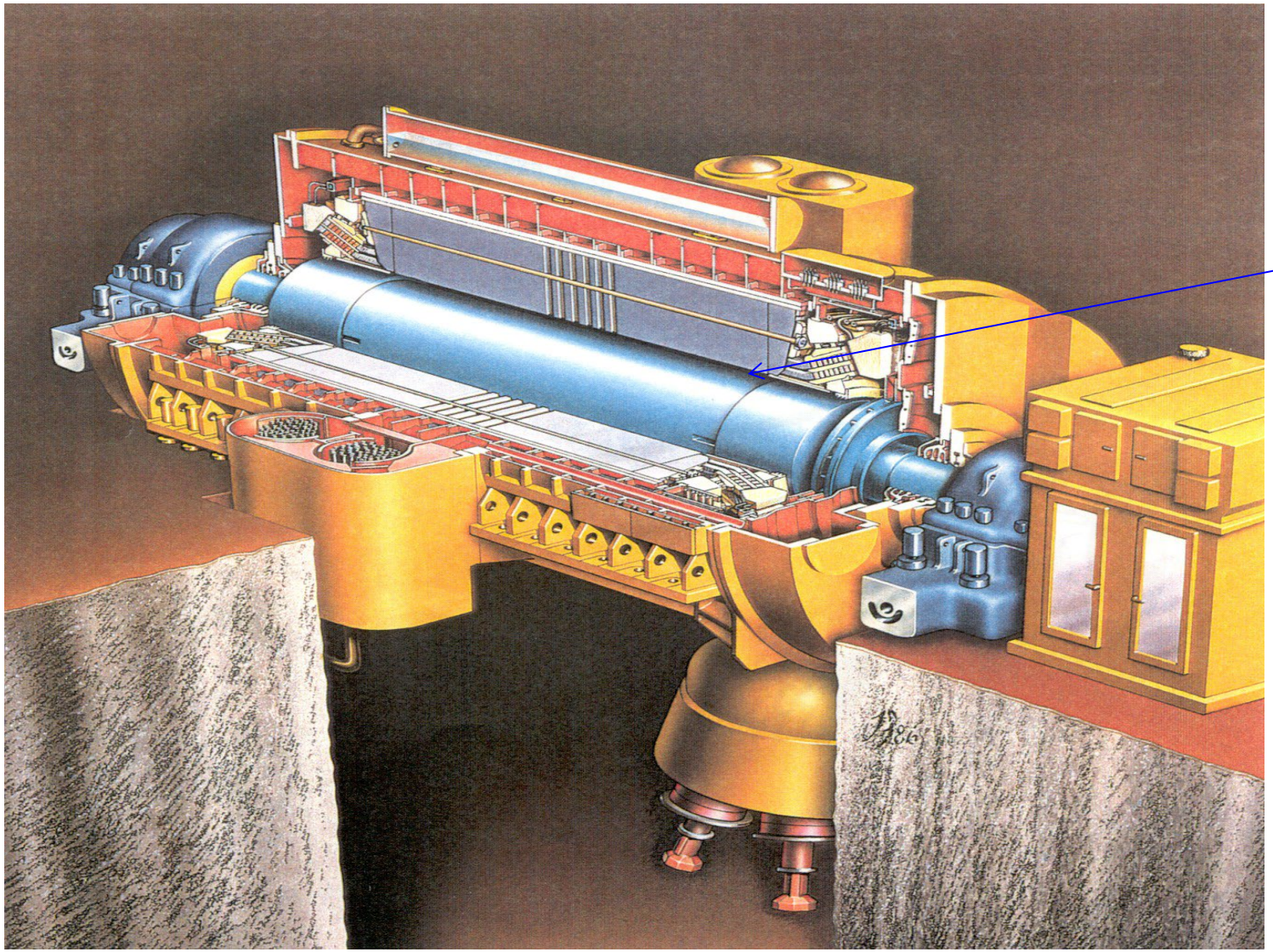
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Generator Robotic Inspection Capabilities and Perception

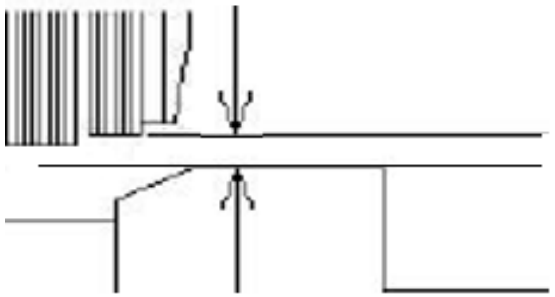
- The decision to do Robotic Inspection must take into account other information on the condition of the generator that may require removing the rotor to address.
- With recent developments in the technology, plant owners who previously couldn't take advantage of Robotic Inspections due to access restrictions may find that new technologies could now allow their machines to be inspected.
- Robotic Inspections can cut outage costs and durations while maintaining quality/reliability of information gained.
- Increasing trends in numbers of users and rate of technology development indicate that RI on large generators **will become the norm** rather than the exception in future.
- Some considerations are needed to assess if a RI is adequate for your generator / outage.

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Risk #1 – Robot Must Fit (Air Gap & Entrance Angle)







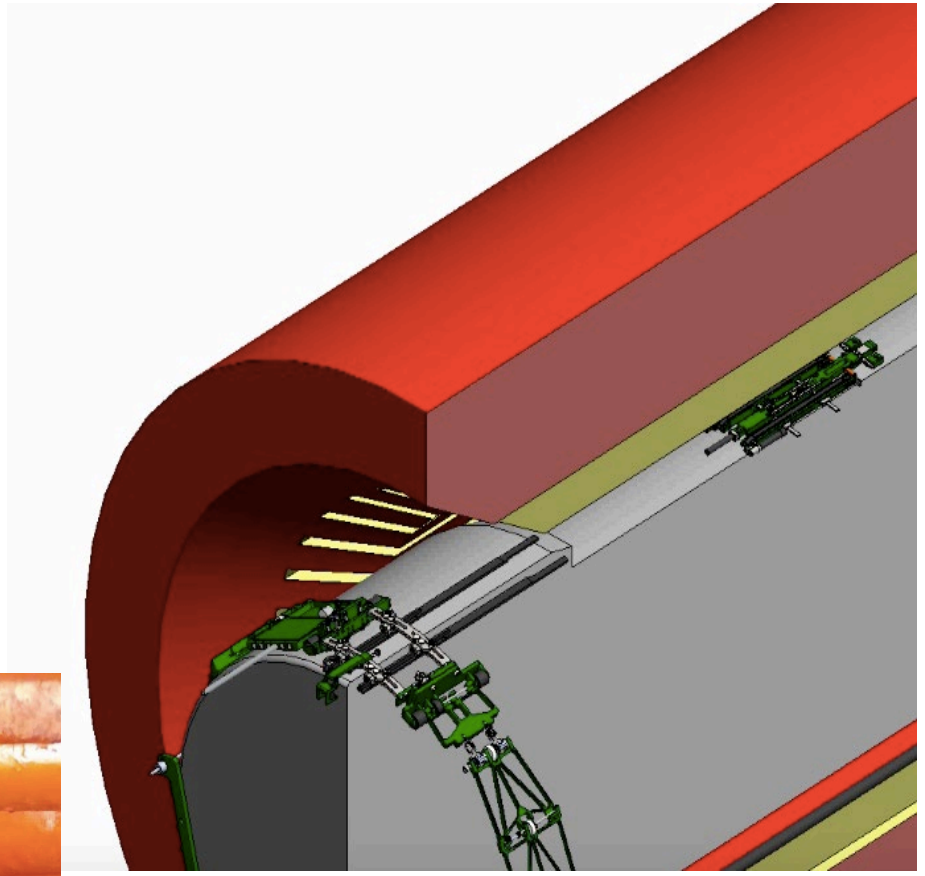
Thickness of Robot Critically Important

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Dekra/Brush/3 Angles – 17 mm







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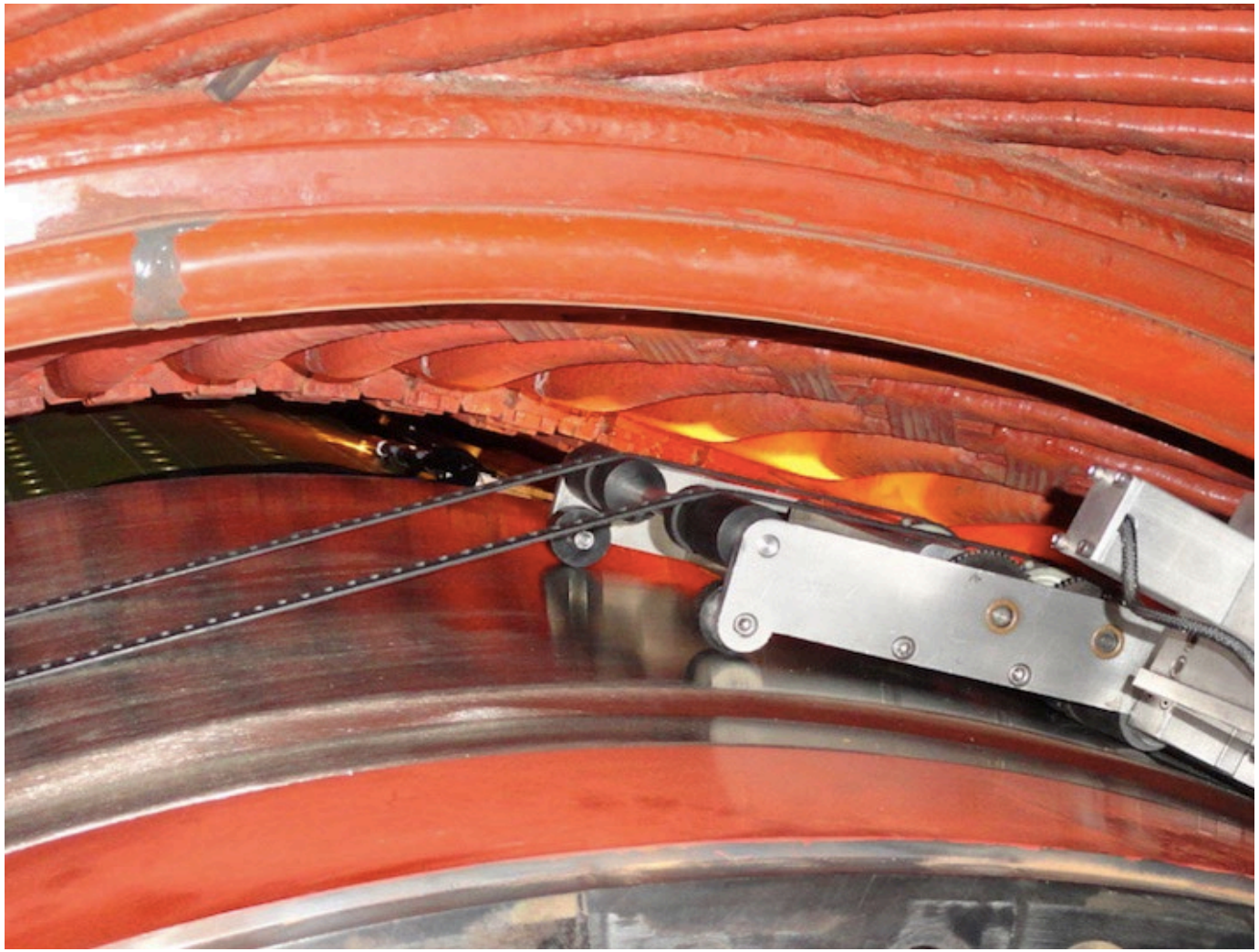
GE “Magic” Robot – 28.6 mm Thick (Height)

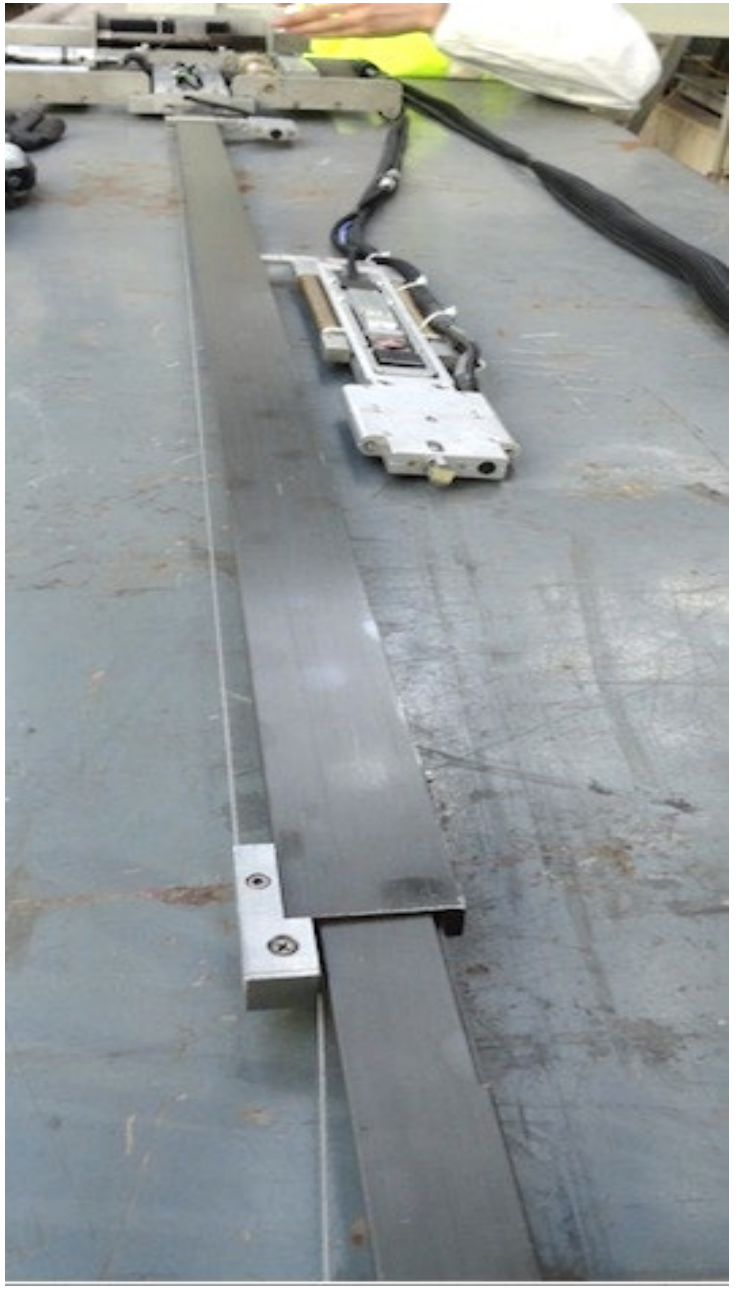




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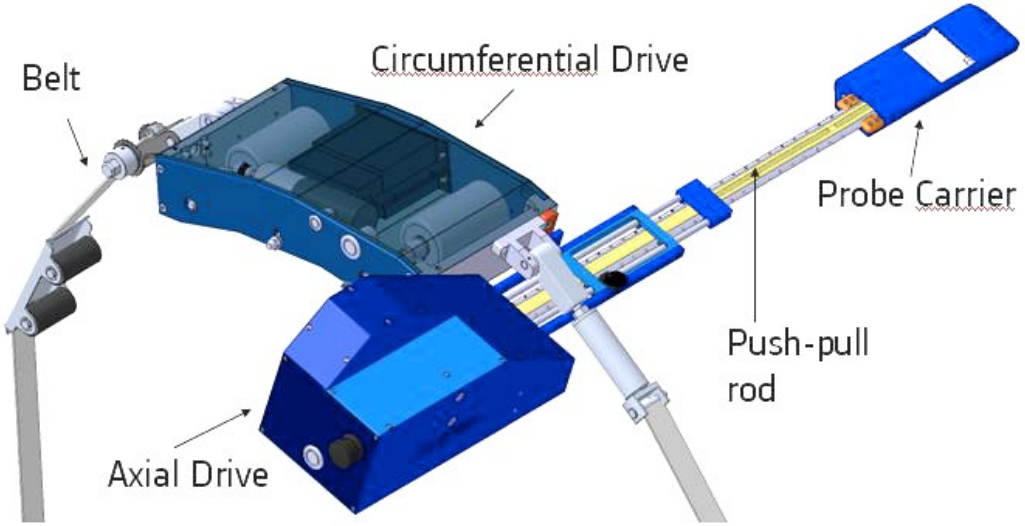
GE “Magic Jr.” Robot – 12.7 mm

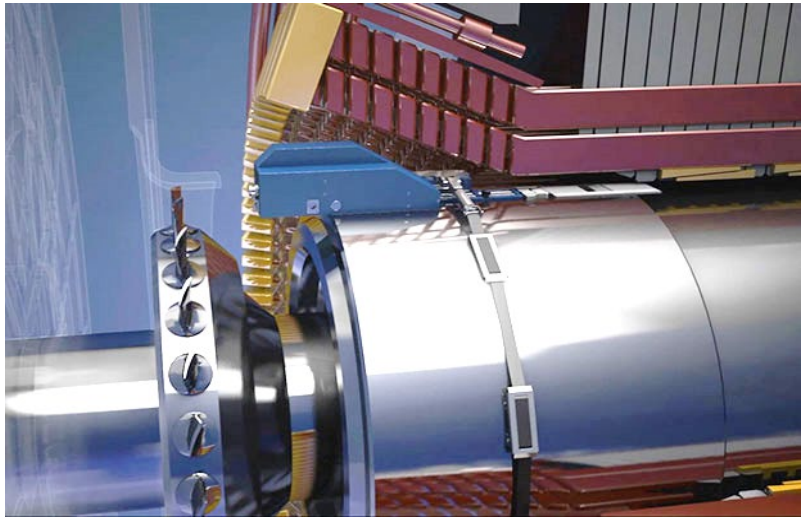


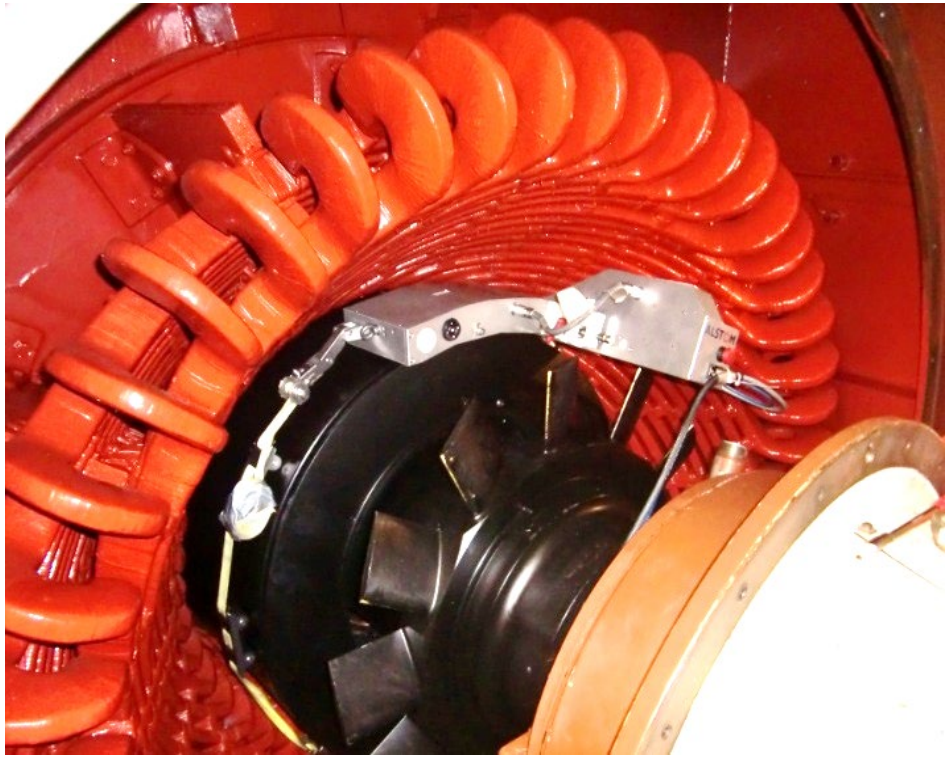


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Alstom (now GE) “Diris” – 12 mm

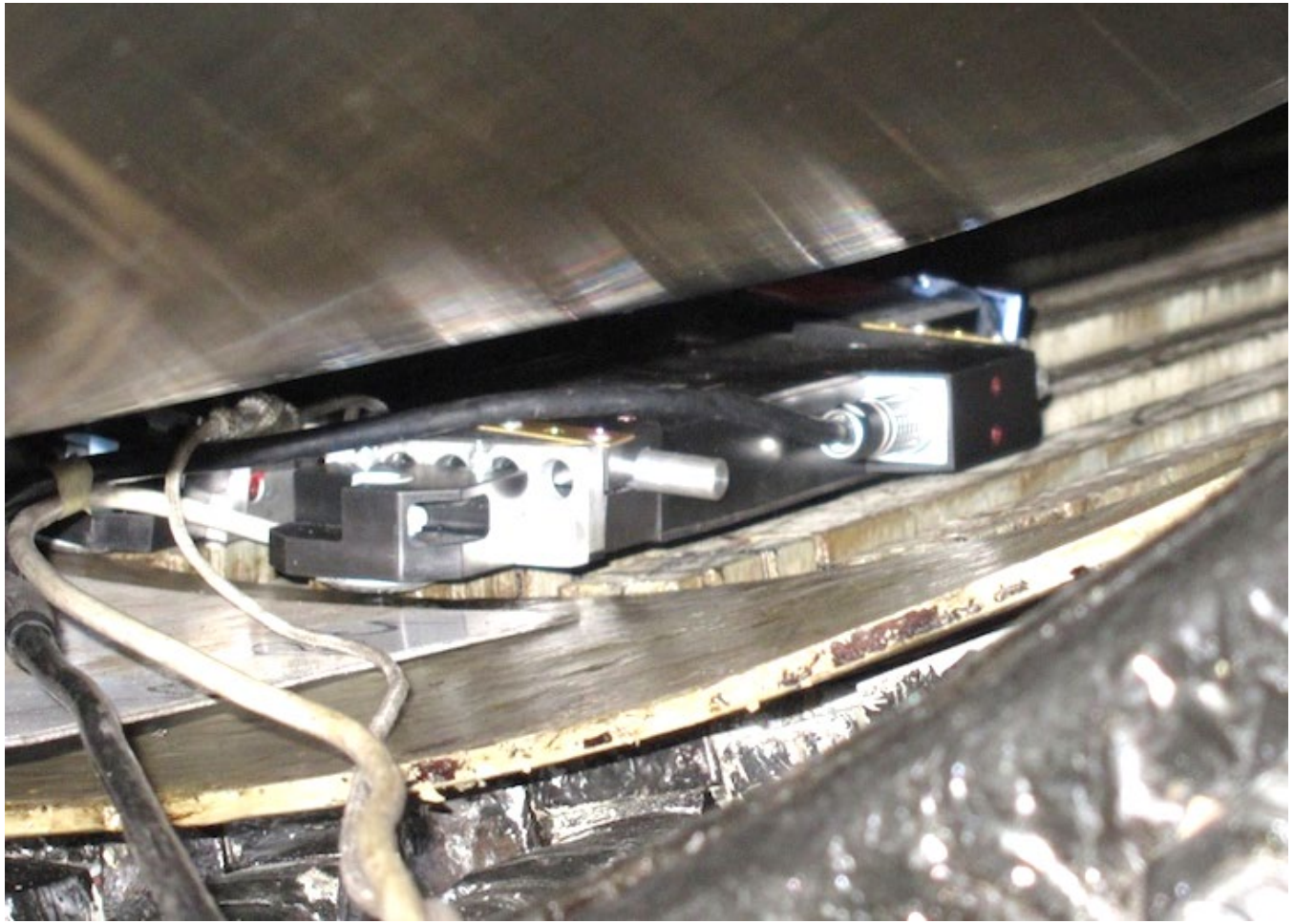


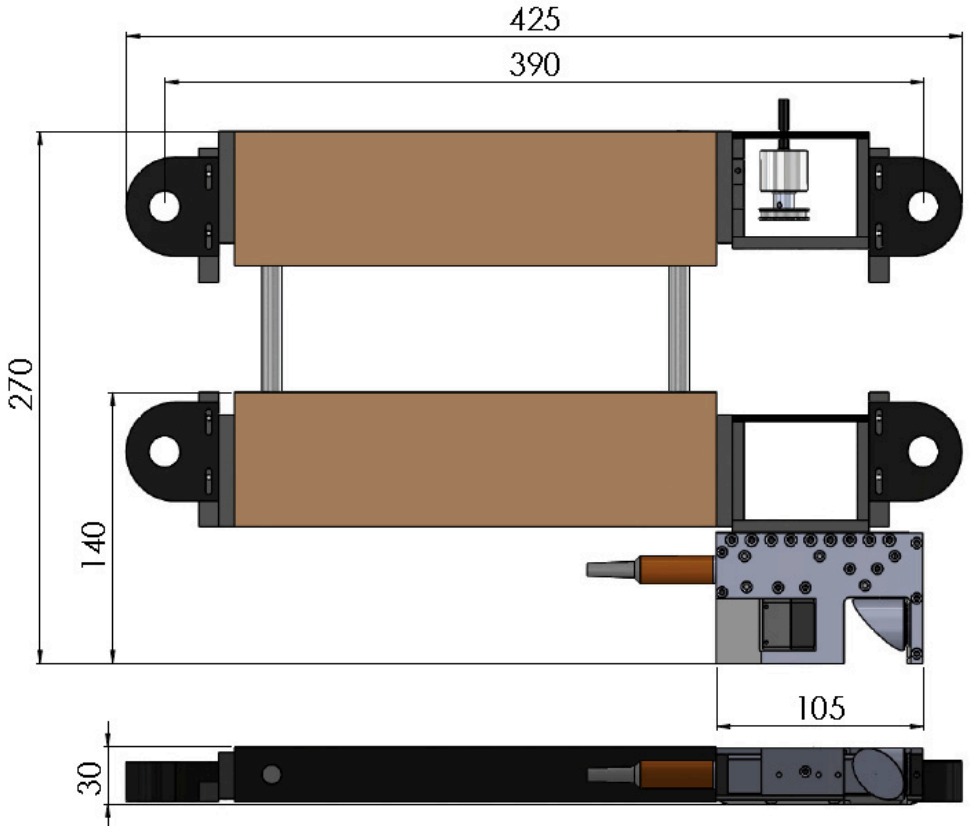




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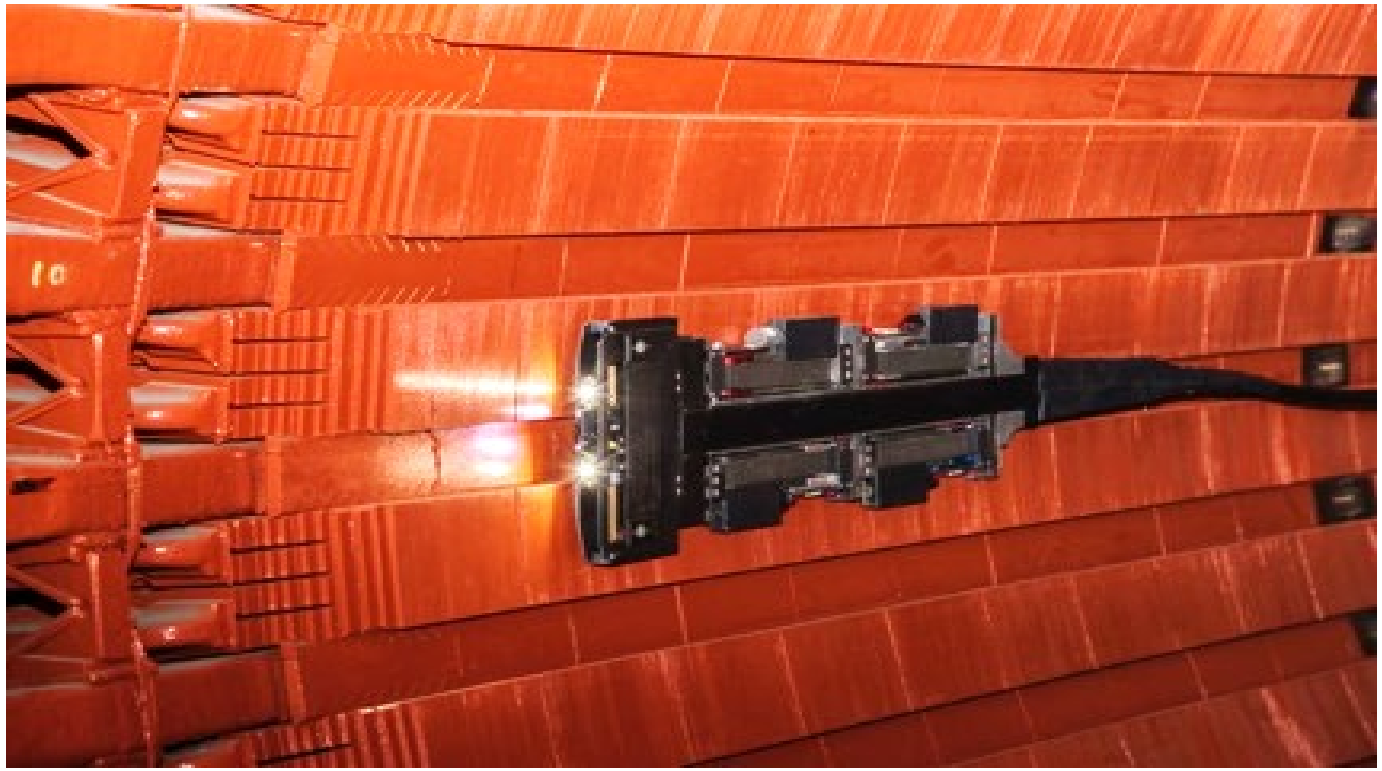
IRIS Power RIV (Remote Inspection Vehicle) – 30 mm

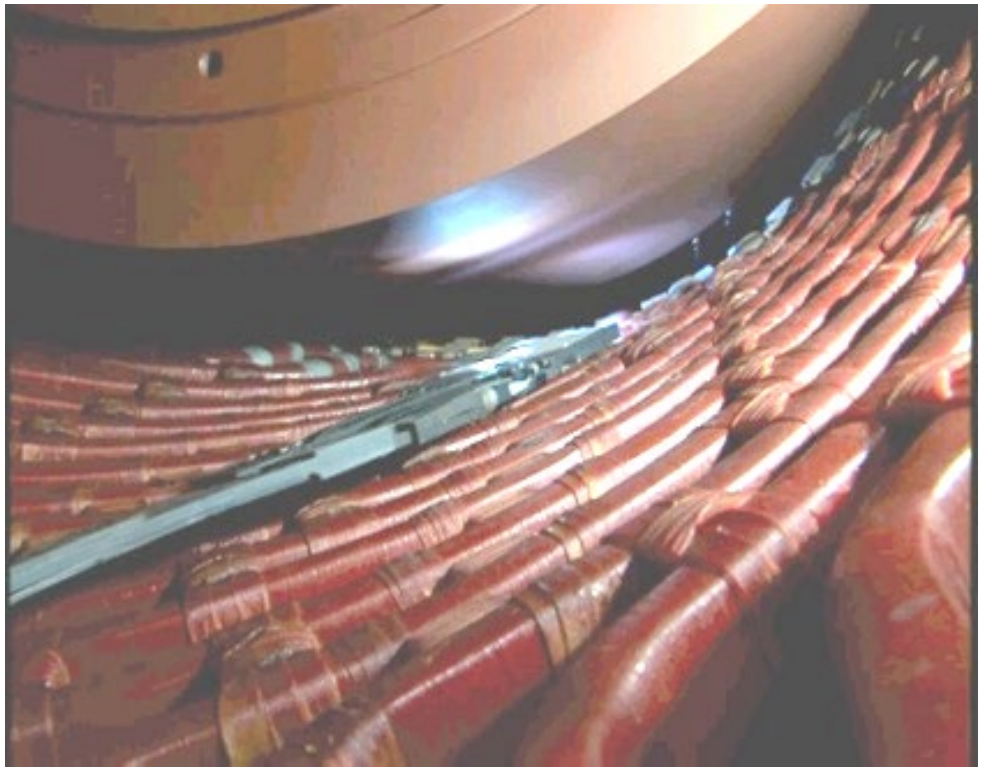




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Siemens Energy *Fast* Gen^{SM} – 22 mm

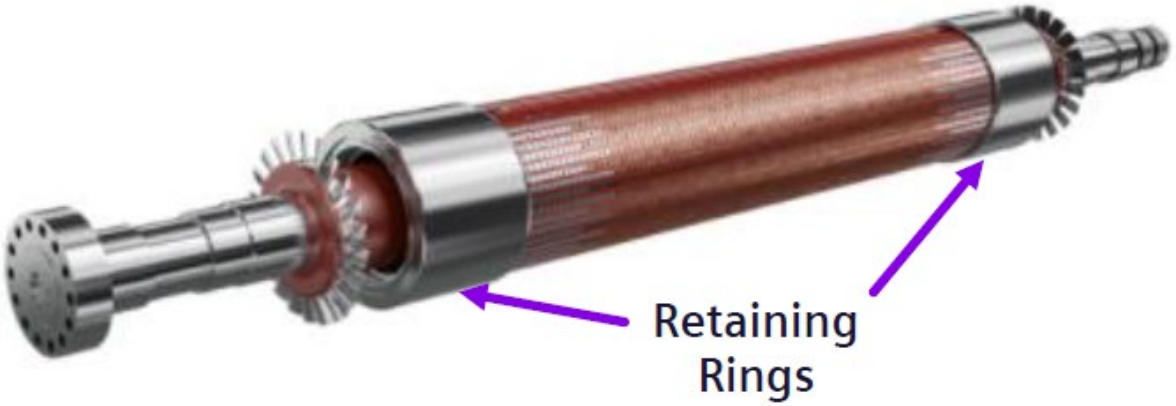


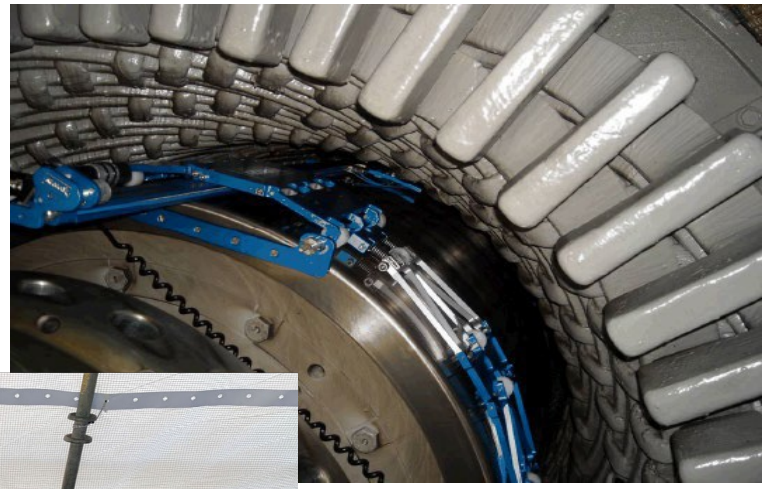


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Retaining Ring Inspection

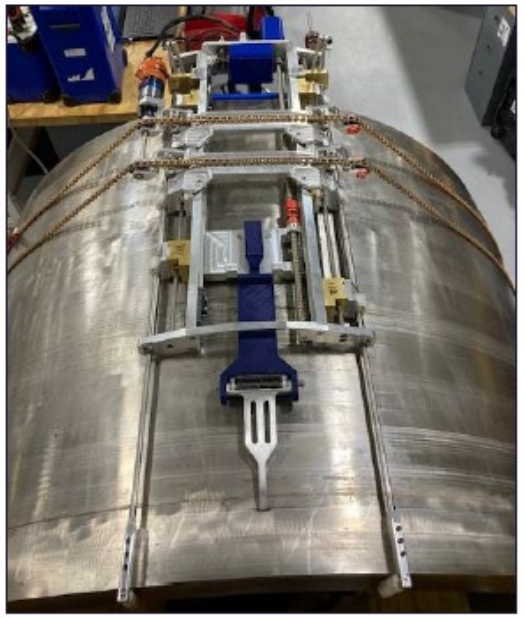
- Several OEMs (Siemens Energy, GE VERNOVA) and vendors (3 Angles) have developed retaining ring robotic inspection (rotor in or out)
- Eddy current and/or Ultrasonic test (UT)

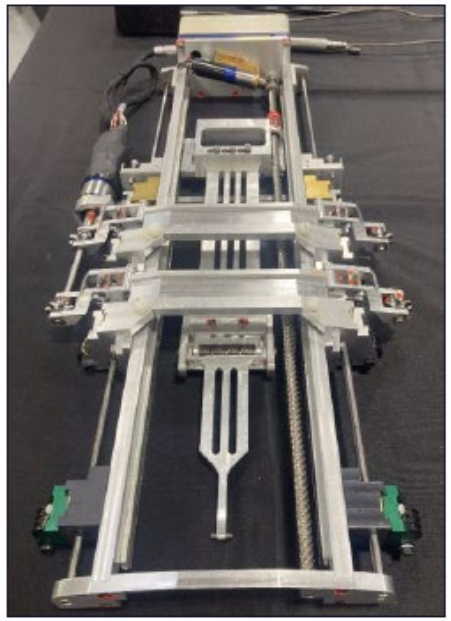






3 Angles robot





Siemens Energy robot

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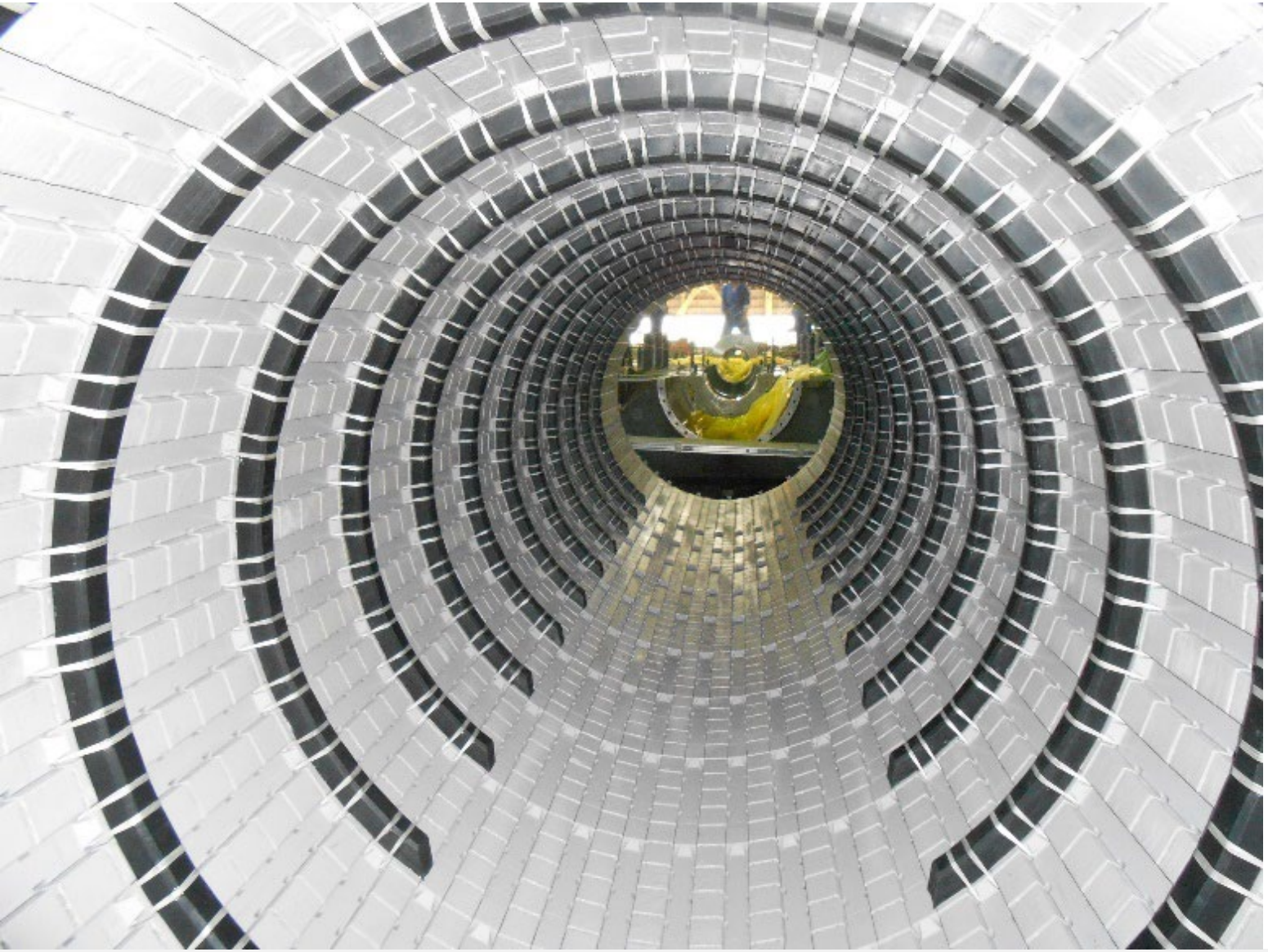
Table of Comparative Properties from EPRI Report*

	Type	Min Gap Size	Dis-assembly required (one or both ends)	Circum-ferential travel	No of cameras	No. of traverses to inspect rotor and stator	EL CID	Wedge Tapper	Experience	Can Purchase Kit
GE MAGIC	Crawler	28.6 mm (1.126")	One	Steers in air gap	2	2	Yes	Yes	>2600 inspections	No
GE MAGIC JNR	Telescopic boom	12.7 mm (0.5")	One	Rotates on CRR	2	2	Yes	Yes		No
ALSTOM DIRIS TOP	Cable car	25 mm (0.984")	Both	Rotates on CRR	N/A	N/A	Yes	Yes	N/A	No
ALSTOM DIRIS SMALL	Telescopic boom	12 mm (0.472)	One	Rotates on CRR	1	2	Yes	Yes	N/A	No
Iris Power RIV	Crawler	30 mm (1.181")	One	Manual removal and insertion	1 (rotating mirror)	2	Yes	Yes	N/A	Yes
DEKRA/ Brush ARGIS	Crawler	17 mm (0.669")	One	Rotates on CRR	4	1	Yes	Yes	N/A	No
Siemens FAST Gen^{SM}	Crawler	22 mm (0.866")	One	Manual removal and insertion	3	2	Yes SMCAS^{SM}	Yes	>2000 inspections	No

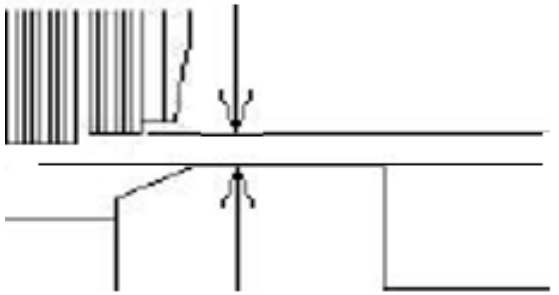
*As of 2018

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Risk #2 – Once robot is inserted, is it free to travel?



Does it travel axially, circumferentially, and are there restrictions such as air gap baffles or baffle rings?



Concerns with Robotic Inspection: "Obstacles Inside"

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List of Typical Generator Inspection Items:

Condition	Symptom	Claimed RI Capability	Traditional Inspection
Stator			
Oil/other contamination	Dust/grease/oil visible on core and wedges	Yes	Visual
Loose wedges	Greasing/ dusting	Yes	Wedge tapping
Misaligned wedges	Vent duct obscured	Yes	Visual
Bar movement	Black dust coming from vent ducts	Yes	Visual
Vibration sparking	White deposits seen down vent ducts	Yes	Online PD
Core laminations loose	Visible displacement of laminations	Yes	Physical/Visual
Vent spacers distorted	Visible distortion of vent duct spacers	Yes	Visual
Core interlaminar insulation defects – tooth	Discolouration, darkening of steel, blistering of paint	Yes	EL CID
Core interlaminar insulation defects – slot	None	No	El CID
Airgap baffles	Cracked stud welds, looseness	Yes	Visual
Foreign object in airgap	Impact damage to core/wedges, blocked vents, actual object/s visible	Yes	Visual
Flux probe	Physical damage to probe or wiring	Yes	Visual
Flux shield overheating	If visible, bluing of copper, discolouration	Possible	Endoscope
Bar fretting at exit from core	Greasing/dusting	Possible	Endoscope
End blocking cracking/loose	Visible cracks, greasing/dusting	Possible	Endoscope/visual externally
Corona at semicon/stress relief interface	White powder	Possible	Endoscope/visual externally
End winding vibrations	Greasing/dusting	No	Visual externally
Circular phase connections loose or corona	Dusting/greasing/white powder	No	Visual externally



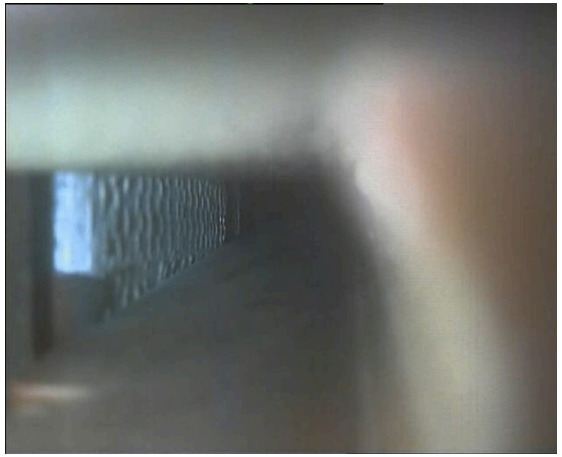
Top filler migration in rotor slot blocking ventilation.

AI or Artificial Intelligence may be applied to assist in generator inspection and test robots. An AI use case, for example, could tell if a rotor or stator vent duct was blocked. Eliminates required human viewing.

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List of Typical Generator Inspection Items:

Condition	Symptom	Claimed RI Capability	Traditional Inspection
Liquid-cooled stator winding leaks	Seldom visible symptoms	No	Online leak monitoring, vacuum/pneumatic testing
Winding insulation deterioration	Seldom visible symptoms	No	Online/offline PD
Poor connections ("Hot Joints")	End cap discoloration, paint flaking/blistering	No	Visual externally
Rotor			
Surface currents	Signs of overheating/arcing in body/wedges/inertia slits/CRRs	Yes	Removal of CRRs and visual, NDE
Wedge migration	Wedge out of position	Yes	Visual
Wedge cracking	Possible visible cracks	If visible, otherwise no	NDE
Balance weights locking	Punching not aligned to groove, broken off, weight partially out of threaded hole	Yes	Visual
CRR cracking/ movement	Possible visible indications, generally unlikely	Unlikely	NDE
Vent ducts blocked	Visible insulation/ foreign objects in vents, bluing of copper	Yes	Visual
Shorted turns	Seldom visible indications	No	Stray flux, RSO
End winding issues	Copper discoloration, blocking migration, copper distortion	No	Endoscope
Bearing problems	White metal damage, oil contamination, bearing alignment	No	Online monitoring of bearing/vibrations, oil flows, oil sampling



Slot discharges on side of bar seen down vent duct by ARGIS (DEKRA)

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Summary of Advantages and Disadvantages of Robotic Inspections

ADVANTAGES	DISADVANTAGES
Generally less disassembly required than for rotor removal	Not all machines can be accessed by the robot Gap or gas baffles or other unusual dimensional access restrictions
The duration is significantly less than for a rotor-out inspection	In some cases the time to disassemble the generator to where a robot can be inserted is such that there is very little advantage to doing RI
Rotor removal with its inherent risks is not required	RI may require the rotor to be pulled in any case (low risk)
The same tests and inspections as with the rotor removed can be done	No 'touch' involved in inspection and with close-up HD camera view more difficult to assess severity of findings
Systematic visual inspection with high definition cameras allows more consistent inspection and a valuable record of results	Specialist training/experience required to carry out RI and assess results
Wedge testing done correctly by robot is generally more consistent, less subjective and more reliable than by an operator using a hammer or spanner	

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Summary of Advantages vs Disadvantages

ADVANTAGES	DISADVANTAGES
If the RI is done properly, the trendable data that results allows better outage planning	
Insurance companies now accept RI as a substitute for rotor-out inspections if done properly and other information such as online monitoring data is taken into account	
The technology is constantly developing and improving, and developments in other fields such as Artificial Intelligence, mobile phone and drone technologies are being applied	
The cost is significantly less than the cost of removing a rotor	

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Risk #3 – What if Robot gets Stuck in Air Gap?

- Very Rare
- Robots have a “tether” line or power line that allows retrieval of the robot if it should drop to the bottom side of the air gap

Risk #4 – What if I find a Foreign Object and have to remove the rotor anyway?

- Rare
- GE has stated that this event only happens 5% of the time
- It is better to have found the object and likely prevented a failure, even though cost increases significantly



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Risk #5 – What if the robot does not function?

- Case presented at TGUG in 2024 from an inspection in 2022
- 3rd party robot vendor
- 1st robot failed to perform ELCID because of worn insulation and bare wires, resulting in current damage to several electrical components
- 2nd robot failed twice due to malfunctioning motor amplifier (different issue from the 1st robot)
- 3rd robot was used to perform the ELCID





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Risk #3 – What if I find a Foreign Object and have to remove the rotor anyway?

- Rare
- GE has stated that this event only happens 5% of the time
- It is better to have found the object and likely prevented a failure, even though cost increases significantly





Video snap shots of blocked cooling channels





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EPRI Robotic Inspection Report – Summary Points

- **Today's Robots**
  - **Smaller**, can access smaller airgaps while still carrying all testing sensors.
  - **Camera technology** improved exponentially – both the clarity and number of cameras
  - Improved **Wedge Tightness Testing** techniques
  - Limitations may still exist when performing **ELCID** towards end of core
  - **Industry perception** of Generator Robotic Inspection has improved significantly
- **Bottom Line**
  - They are a **good alternative** to rotor-out inspections.

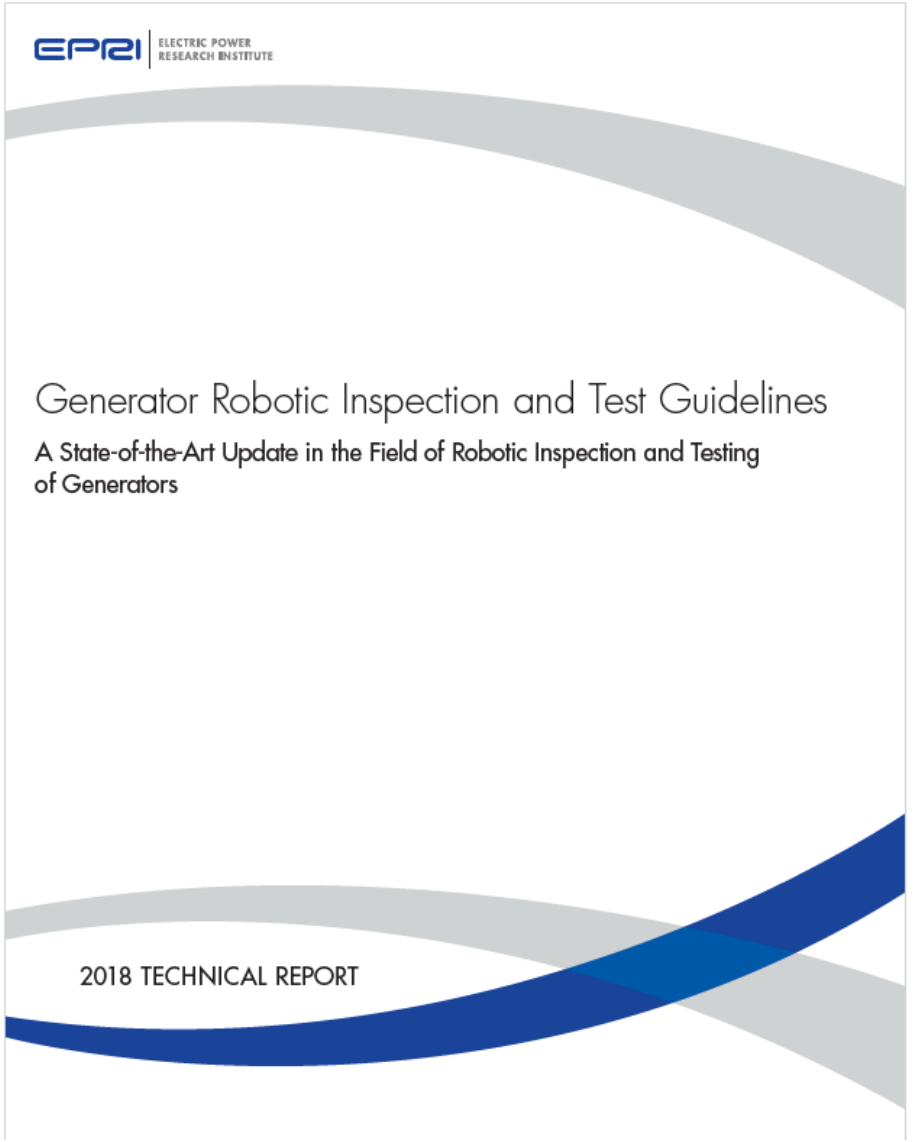
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Conclusions

- Top drivers in the industry today:

  - Reduce costs,
  - Shorten outage duration
  - Maintain Availability

- Robotic Inspection can satisfy all those criteria if done properly



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Break

2026 Research Plan

Program 220: Generators & Auxiliary Systems

Lionel Cochon
Senior Technical Leader

2025 WANO Steam Turbine & Generator Workshop
Shanghai, China
3-6 November 2025

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Vibration Sparking in Air-Cooled Generators

Industry Issue/Project Description

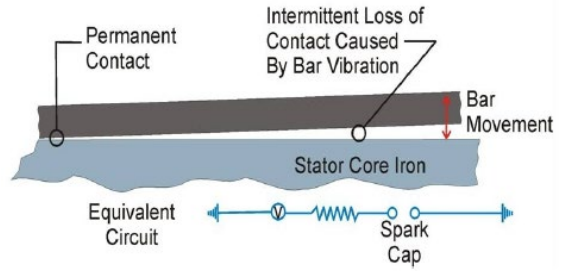
- Vibration sparking (VS) is a particularly “fast acting” failure mode, compromising the stator bar ground insulation, usually resulting in a ground fault. One of the first industry failures occurred in the 2007 time-frame. The problem has recently surfaced again on air-cooled Nuclear generators with water-cooled stator windings. Other instances in the industry have been reported.
- EMSA/EMI testing claims to have the ability to detect, online, vibration sparking also called Spark Erosion (SE). This claim is evaluated in this project.

Takeaways and Member Benefits

- The scope of this project focused on several key areas:
  - Determination if EMI testing can identify vibration sparking
  - Four, nuclear, air-cooled generators with a known history of VS/SE, were tested.
  - The ability to detect VS/SE, and also to evaluate the degradation level of the stator winding will be evaluated.

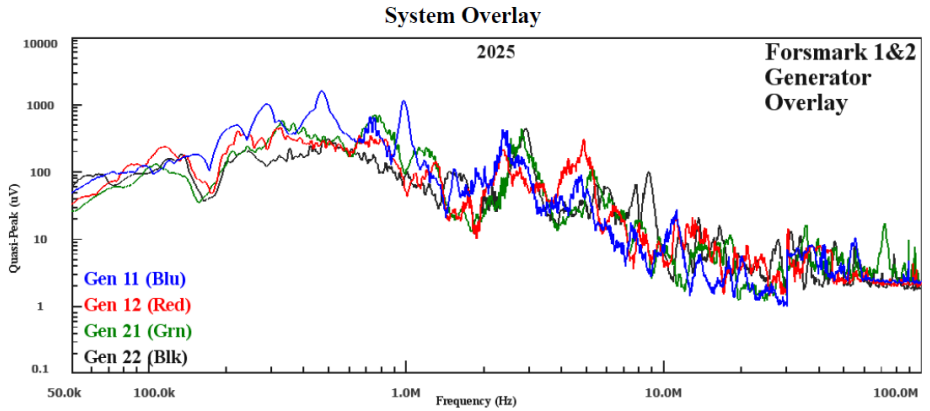
Deliverable Format

- Technical Update, Complete by March 2026





The image above shows how vibration occurs with loose bars. The graphs below is from recent testing done as part of this EPRI project.

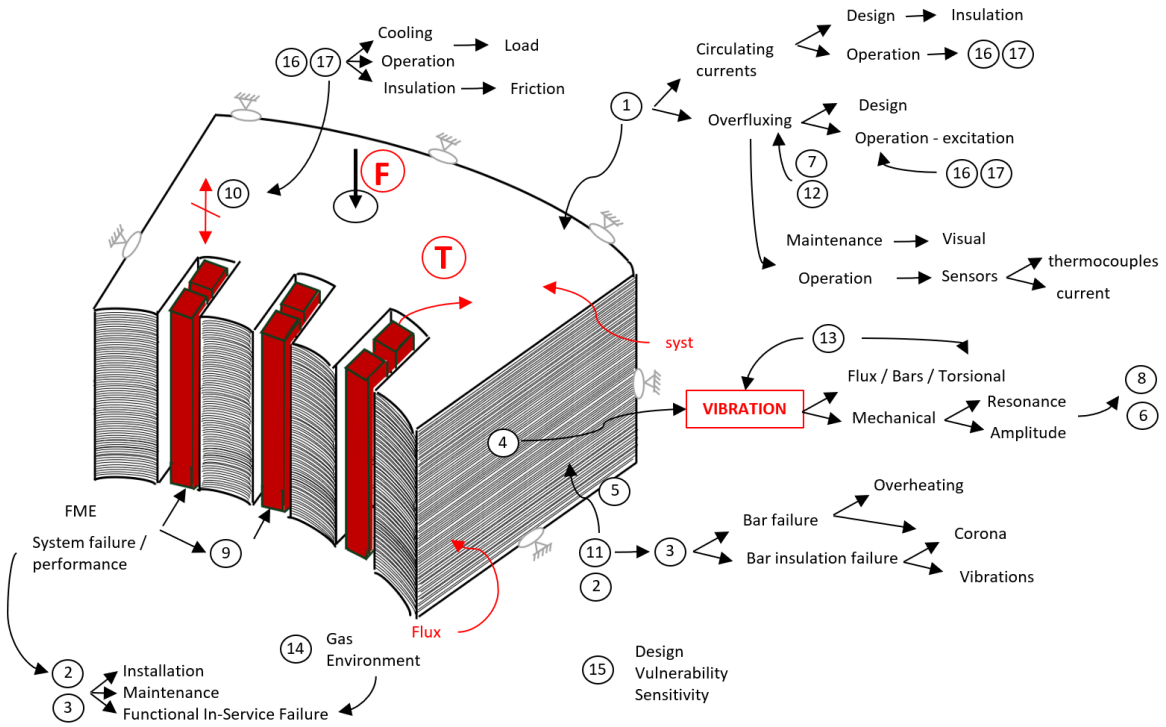


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Generator Core Remaining Useful Life

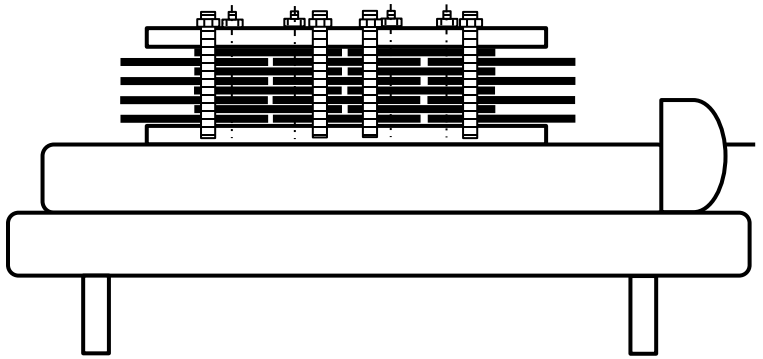
Phase I – Develop a Roadmap

- Describe the industry's understanding of damage mechanisms and life management approaches
- Apply FMEA techniques to inform degradation risk and test setup/loads
- To be published by end of 2025



Phase II – Conduct Experimental Testing and Assess Findings

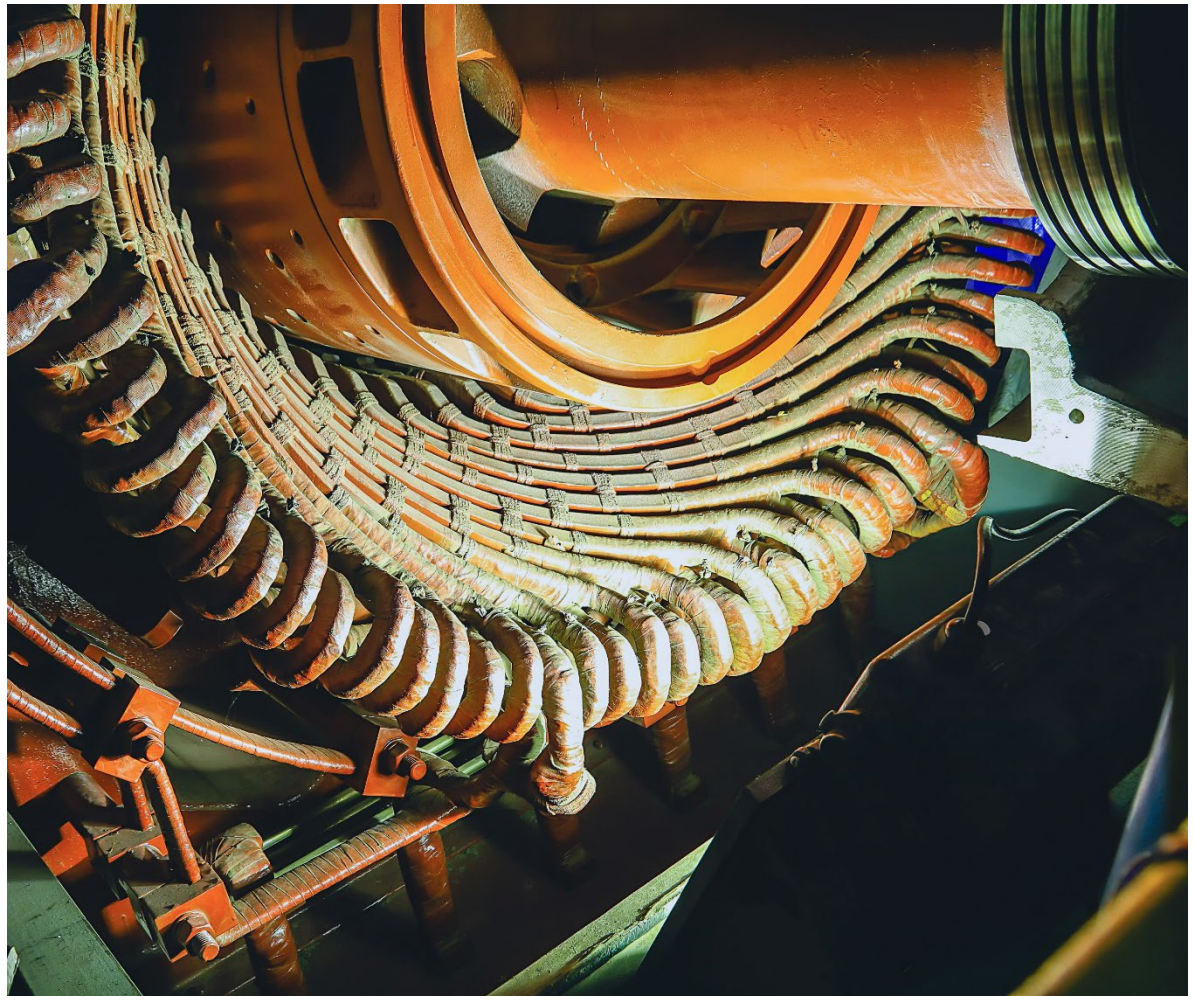
- Design a mock core assembly and test plan to accelerate the degradations that can be observed during operation
- Assess test data for actionable insights and opportunities to refine future testing



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2026 Project Proposals

Generators & Auxiliary Systems



- Generator Condition Monitor
- Generator H2 Coolers
- Acoustic Testing for Generators
- ODS Testing for Generators
- Sensor to Monitor Core End Heating from Stray Flux
- Generator Rotor Thermal Sensitivity
- Magnetic Termites in Generators & Importance of FME
- Protection Relays for Generators
- Generator Database for Program Members
- Stator Water Box Leaks and Repairs
- Generator Bushing Installation and Maintenance Guide- Update

Let us know what you think.

Generator Condition Monitor: Background, Use, Experience & Trends

Industry Issue/Background

- Stator core failures and other failures where insulation deteriorates, continue to occur throughout the industry. One tool for early indication of degradation and potential failure is the GCM (Generator Condition Monitor). But is it used properly? Are alarms believable? And what actions should be taken when it indicates a problem.

Member Benefits

- This document will benefit members by covering the GCM from soup to nuts including "how it works," best practices, case histories of "saves," and actions to take when an alarm is indicated.

Deliverable Format and Due Date

- Technical update expected by year end 2026.

Is My Insulation Degrading?



What Does the GCM-X Do?

Risk Mitigation → Generator Overheat Detection

- Immediate detection of overheat:
  - Thermal decomposition of organic materials such as epoxy paint, core lamination enamel, or other insulating materials used in the generator is detected by recognition of sub-micron particles emitted in the decomposition process.

GCM-X IS DESIGNED FOR USE ON ALL GENERATORS COOLED WITH HYDROGEN

Slide from January 2025 EPRI Generator Workshop "Stator Core Condition Monitor Update by Christopher Breslin

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Generator H2 Coolers: Inspection, Testing, Repair & Replacement

Industry Issue/Background

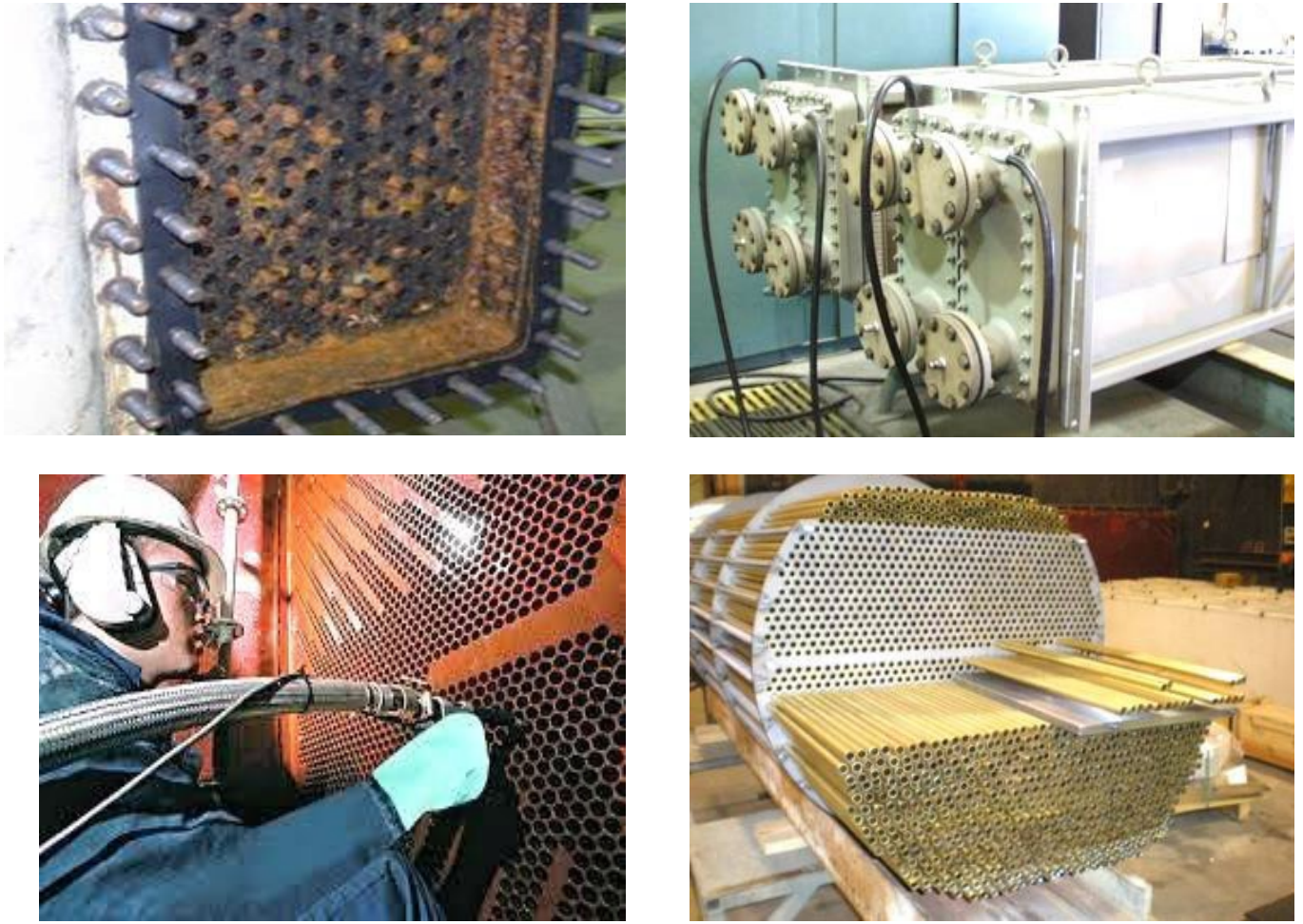
- Generator hydrogen coolers are aging like all power train equipment. However, due to several reasons, they could be one of the most forgotten and least inspected and tested components of the generator. Performing essential inspection, testing, repair and even replacement is essential for overall generator reliability.

Member Benefits

- Complete document covering all aspects of hydrogen cooler maintenance including estimates for remaining life.

Deliverable Format and Due Date

- Technical update expected by year end 2026.



Examples of generator cooler inspection, testing, cleaning and repair from EPRI 2025 Generator Workshop (B. Gonsholt).

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Acoustic Testing for Generators: Background, Approach & Benefits

Industry Issue/Background

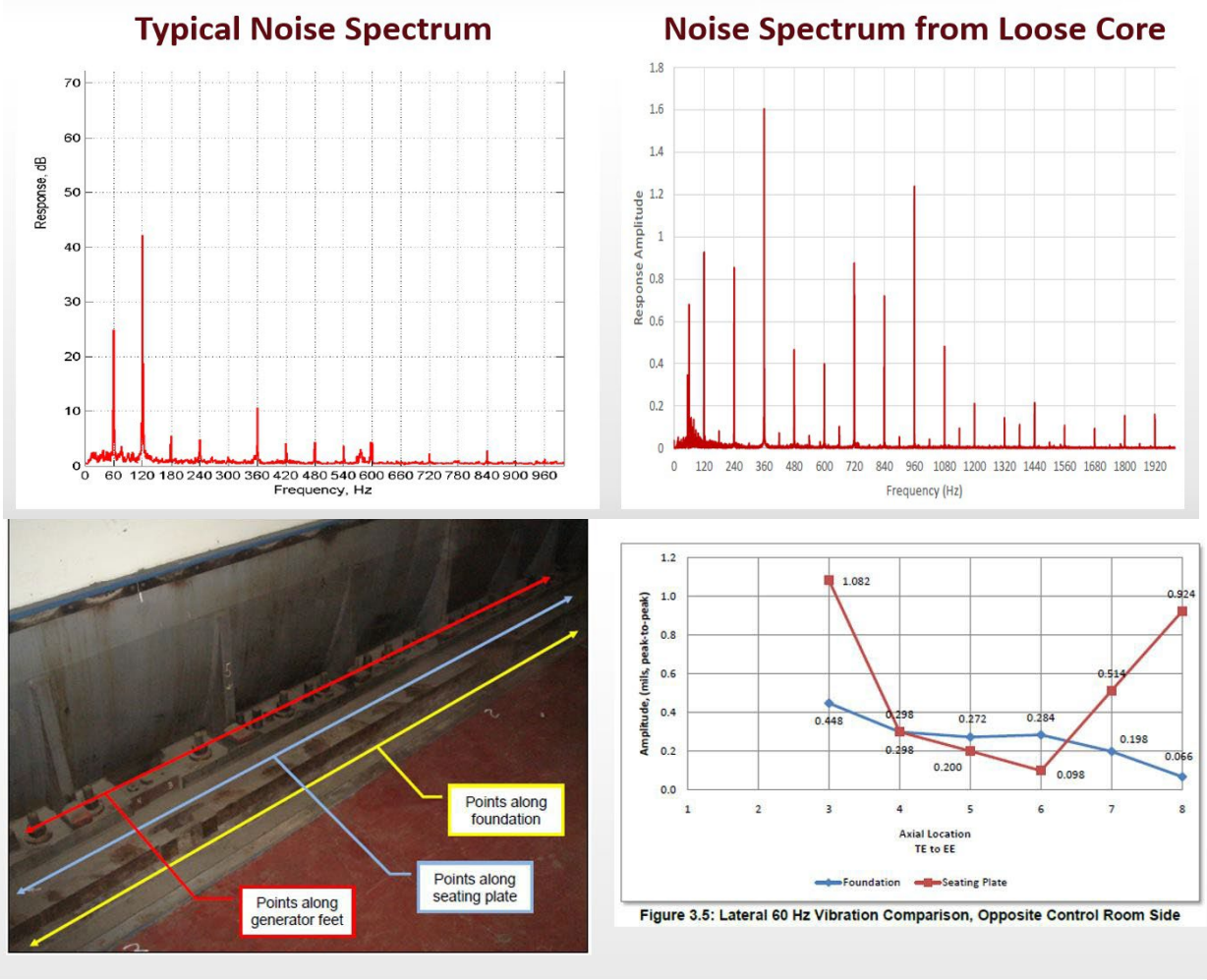
- Acoustic testing techniques may be underutilized in the power industry. This technique can help to properly analyze generator vibration problems.
- Acoustic analysis is non-intrusive and can give keen insight into such issues as key bar rattle, frame vibration and potentially a loose core while still in operation.

Member Benefits

- Detailed explanation of this technology, how it works, past case histories and potential future applications will be described. The report will be an additional tool in the toolkit for members and could provide the foundation for more research evaluating generator stator core looseness online

Deliverable Format and Due Date

- Technical Update or Technical Brief expected by year end 2026.



Examples of Acoustic (Top Image) and ODS (Bottom Image) Testing from 2025 EPRI Generator Workshop by J. Mihalic.

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ODS Testing for Generators: Background, Approach & Benefits

Industry Issue/Background

- ODS (Operational Deflection Shape) Method is a technique used to compare phase and amplitude of a part in vibration. It can be used as a measurement technique to analyze the motion of rotating equipment and structures during operation.

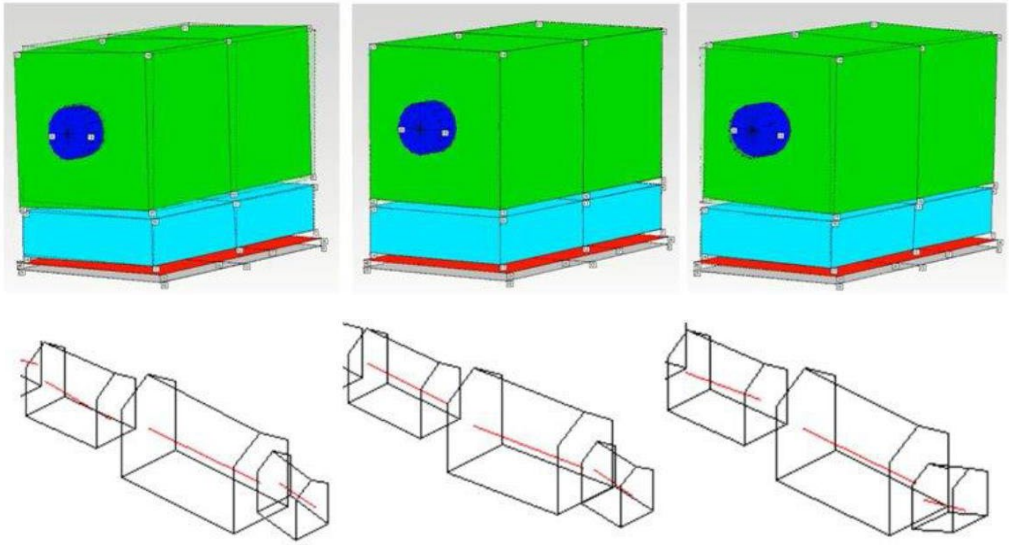
- This technique can identify a wide variety of mechanical faults and resonance issues such as looseness, soft foot, broken welds, misalignment, unbalance, bending or twisting from resonance, structural weakness, and foundation problems.

Member Benefits

- Detailed explanation of this technologies, how it works, past case histories and potential future applications. The report will be an additional tool in the tool kit for members and could provide the foundation for more research evaluating generator stator core looseness online.

Deliverable Format and Due Date

- Technical Update or Technical Brief expected by year end 2026.



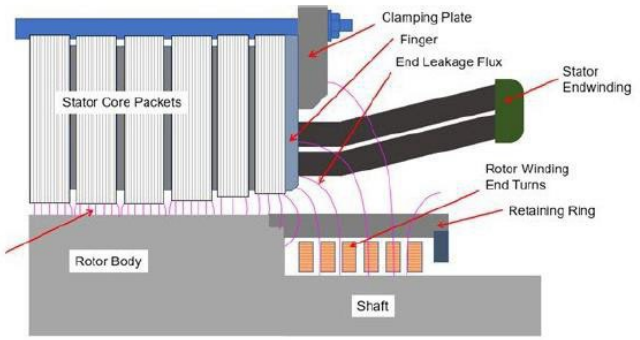
ODS evaluation of soft foot on Alterrex.

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Sensor to Monitor Core End Heating from Stray Flux

Industry Issue/Background

- Stator core failures in the industry occur with some regularity. Many failures occur from core looseness which leads to lamination shorting, overheating and melting. Core end heating, due to stray flux leaking out of the end of the machine, can cause a failure as well. Presently, there are not established methods to monitor stray end leakage flux.
  - Another project, focused on detection of arcing that can damage the retaining ring and rotor, along with back of core burning project, may be suitable for evaluating stray flux.
  - Coupled with direct temperature measurement, these sensors may provide important information, especially when operating in the core end heating area of the capability curve.



Sketch illustrating end leakage flux.





Sensor 1 - Multi-Turn Flux Probe

- Sensor 1 is a multi turn flux probe and has been previously evaluated as an arc sensor in EPRI Project #3002013650
- Sensor 1 was installed close to key bar number 11, at the 6 o'clock position looking from excitation end. This location was selected after discovery of recent damage in that core area.



Top left – sketch showing end leakage flux. Top right – core end overheating. Bottom left – graphic image illustration through bolt melting. Bottom right – back of core burning EPRI project.

Member Benefits

- Enhanced approach to monitor core end overheating.
- For units that run frequently with high negative VARS, this may provide added operation control to prevent core end overheating, melting and failure.

Deliverable Format and Due Date

- Technical Update including test data expected by year end 2026.

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Generator Rotor Thermal Sensitivity

Industry Issue/Background

- Generator rotor thermal sensitivity is an issue that surfaces regularly. Rotor vibration increases, sometimes to unacceptable levels and the root cause can be difficult to determine.
  - EPRI does not have specific guidance for this issue.
- This research would identify the common causes of thermal sensitivity and how it can be corrected. Heat run testing in the field and in the balance pit to identify thermally sensitive rotors would be discussed also.

Member Benefits

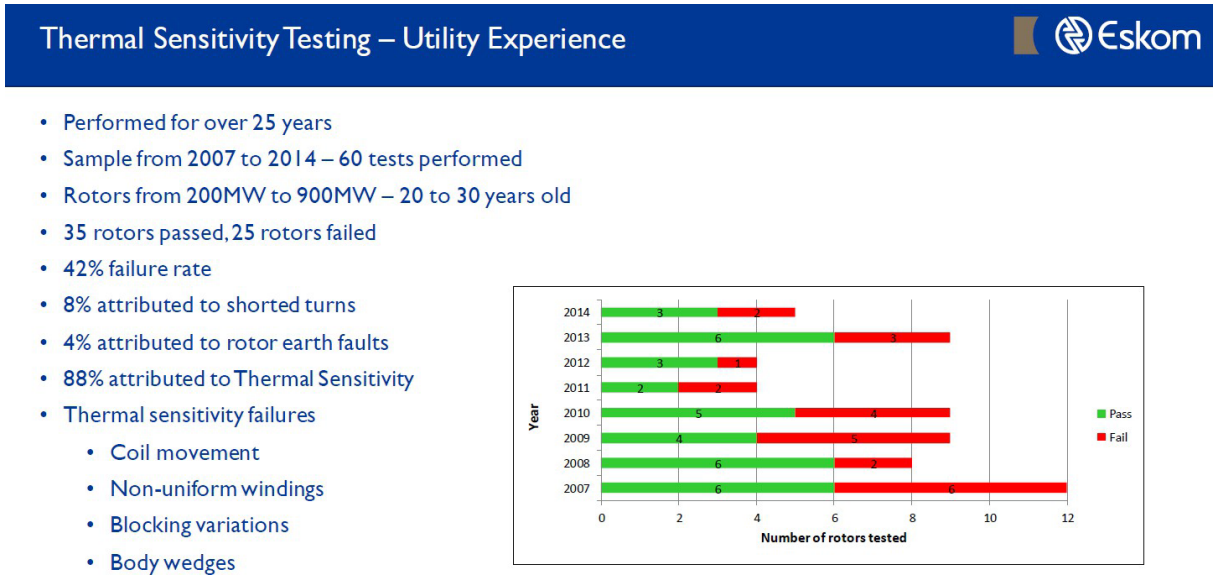
- This document would provide a specific reference and guidance for the issue of generator rotor thermal sensitivity. Details of heat run testing to identify thermal sensitivity would be included, along with specification of many of the reasons for this difficult problem.

Deliverable Format and Due Date

- Technical Brief, expected to be published by Year End 2026







Deformation of the top copper turn (top left), and insertion of balance weight too far (top right); both restricting normal expansion are two of many reasons for thermal sensitivity. Bottom image shows slide from EPRI Generator Workshop identifying a significant number of rotors (42%) suffer from thermal sensitivity.

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Magnetic Termites in Generators & Importance of FME

Industry Issue/Background

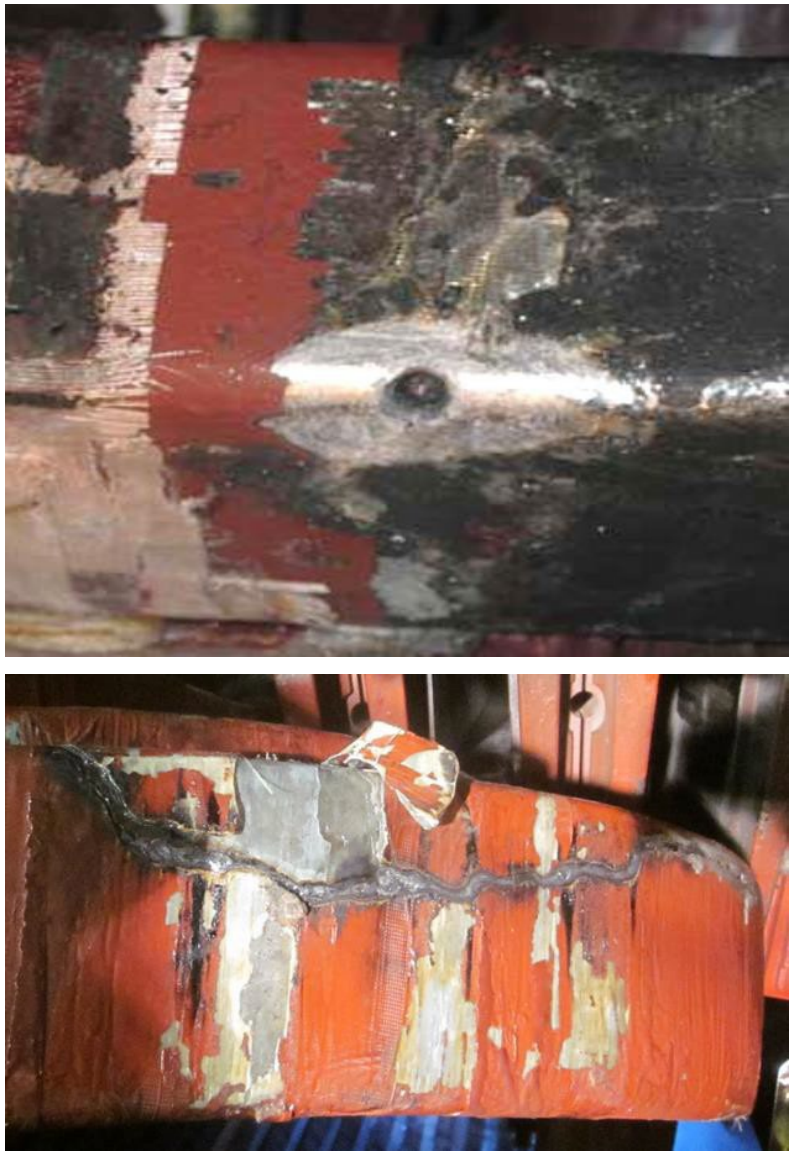
- Magnetic Termites in generators can cause significant failures. This term refers to a metal particle, of a minimum size, that enters the stator bar insulation, and is driven by magnetic fields to ground, causing a ground fault. Magnetic Termites can be avoided by proper FME.
  - In a 2023 presentation by FM Global, the generator ranked #2 in industry losses from foreign object damage.
  - Additionally, EPRI has been made aware of recent, multiple instances of foreign object intrusion resulting in contamination and magnetic termites.
  - FME (Foreign Material Exclusion) had been a significant problem that EPRI provided input on in the early 2,000's, but issues continue to occur.
  - Also, the popularity of 3rd party contractors in charge of FME for generator rewinds, has increased.
- This project will describe magnetic termites, where they come from and how the cause failures. Proper FME, including past EPRI documentation, will be covered.

Member Benefits

- A clearer understanding of magnetic termites and essential Foreign Material Exclusion (FME) practices will support effective isolation during generator maintenance. Best practices and past case histories, including details on magnetic termites, will be reviewed to reinforce efforts.

Deliverable Format and Due Date

- Technical Update or Technical Brief, expected to be published by Year End 2026



Magnetic termite penetration (above) and tracking (below) in stator bar insulation.

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Protection Relays for Generators

Fundamentals & Optimal Setting Guidance





Industry Issue/Project Description

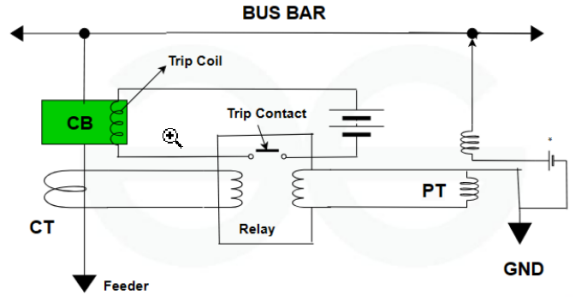
- Industry standards offer suggestions but lack strict rules
- Standardization is challenging due to site-specific factors and unit size
- How to estimate the damages if the protections are too sensitive or if they do not stop the incident on time or too late? Too sensitive (or restrictive) might mean unnecessary trip / unit shutdown
- Understanding the risks is important when tuning the protections
- This project will provide some guideline and methodology on how to set relay protection settings

Member Benefits

- Enhanced understanding of relay protection settings
- Guidance on standardization despite site-specific differences

Deliverable Format

- Technical Update listing the different protection relays, technologies, damage mechanisms and risk levels.



Generator Database for Program Members

Industry Issue/Project Description

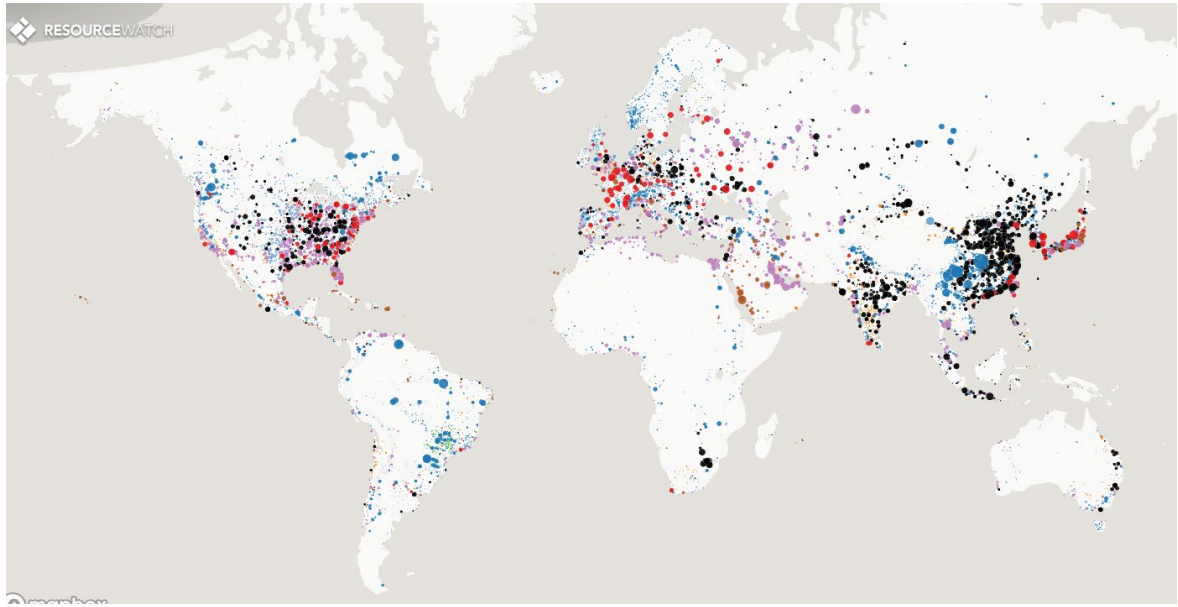
- Details regarding generators (models, including exciters) are usually not known or difficult to obtain
- This project will provide a list of power plants with some details about their generators to help identify where same units are, who can share OE and potentially spare parts
- **REQUIRES ACTIVE ENGAGEMENT FROM ALL MEMBERS**

Member Benefits

- Members will be able to identify other plants to share lessons learned and OE but as well understand who can have spare parts in case of need
- EPRI will be able to support Members with their fleet management as well as improve information and assistance (risks or best practices) from other plants experiences

Deliverable Format

- Excel spreadsheet or database subscriber website



World Map of Power Plants

Source: Resource Watch

Plant name	Unit Name	Unit Number	Company	Serial Number	OEM	Generator Model	Output (MW)	Output (MVA)

Commissioning Year	Made In	Fuel Type	Status	State/Country	Stator rewind date	Rotor rewind date

Generator Database

Stator Water Box Leaks and Repairs

Industry Issue/Project Description

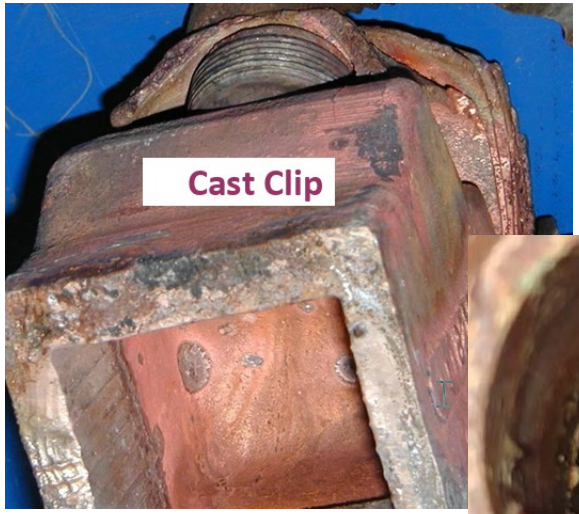
- H2 leaks in SCWS are ongoing challenges
- Lack of single-source document or guide listing the main repair solutions available, performed in the industry
- This project intends to provide comprehensive information about stator bar water box leaks, how to test and detect leaks and how to repair them (short- and long-term solutions)

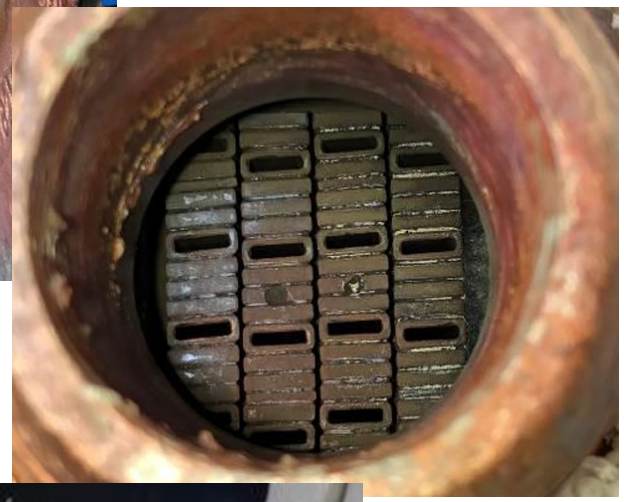
Member Benefits

- This will help Plant Personnel in testing stator bar water boxes to identify leaks as well as listing all current repair methodologies

Deliverable Format

- Technical Update, or Field Guide, complementary of 3002032553 regarding H2 leak monitoring







Generator Bushing Installation and Maintenance Guide- Update

Industry Issue/Project Description

- Listed references not reflecting current technology or industry standards
- Not included in previous technical report
  - Different HVB designs details (direct cooled – water cooled) and specificities
  - Repair / refurbishment methods
  - Mechanical or hydraulic testing
  - Bump tests
- This project intends to provide an update to the previously released technical report, with the addition of design differences and specificities, repairs methodology

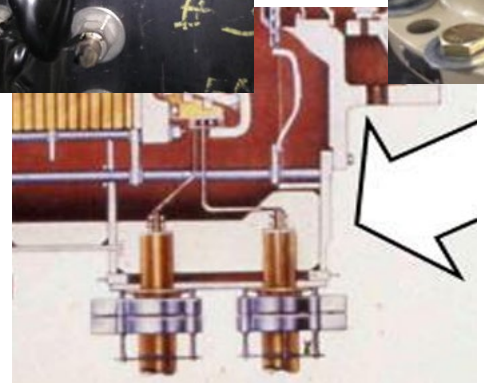
Member Benefits

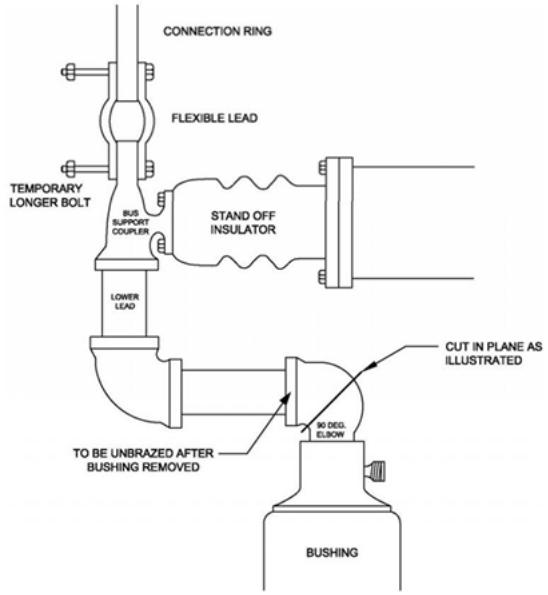
- Up-to-date installation and maintenance guide, including repair methodologies and mechanical/hydraulic testing
- Field guide format, more practical for Plant Personnel

Deliverable Format

- Field Guide format, update of **1016787** released in 2008, with addition of repair methodologies and additional installation testing











Open Discussion

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Final Remarks…

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