Condition Based Monitoring of Gas Turbine Combustion Components

Program Review

SIEMENS

DoE Funding Opportunity No. DE-PS26-08NT00440-1B
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Gas Turbine Combustion Section Online Condition Monitoring Needs

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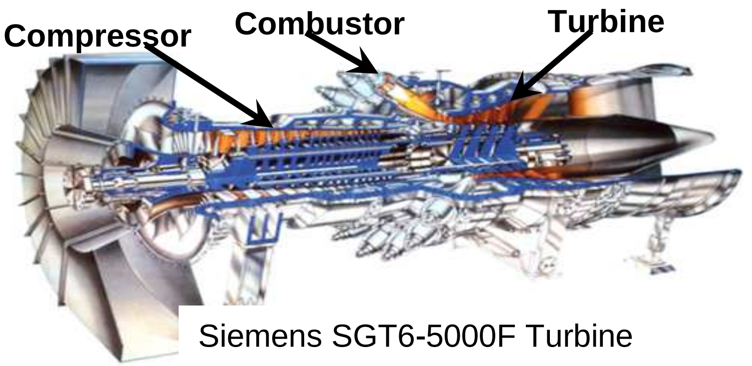
- Hot section combustion components of gas turbine engine are exposed to harsh operating conditions and high temperatures. As a result, combustion parts have shorter design lives and more frequent maintenance inspection interval requirements than other parts of the turbine engine.
- Frequent maintenance inspection outages affect engine availability and reliability.
- Use of sensor technology that directly detect and monitor hardware life online can help to optimize maintenance outage intervals. At present, there are no proven high temperature sensors available to continuously monitor the two primary life-limiting issues of combustion parts: cracking and wearing.



Siemens SGT6-5000F Turbine

Project Overview

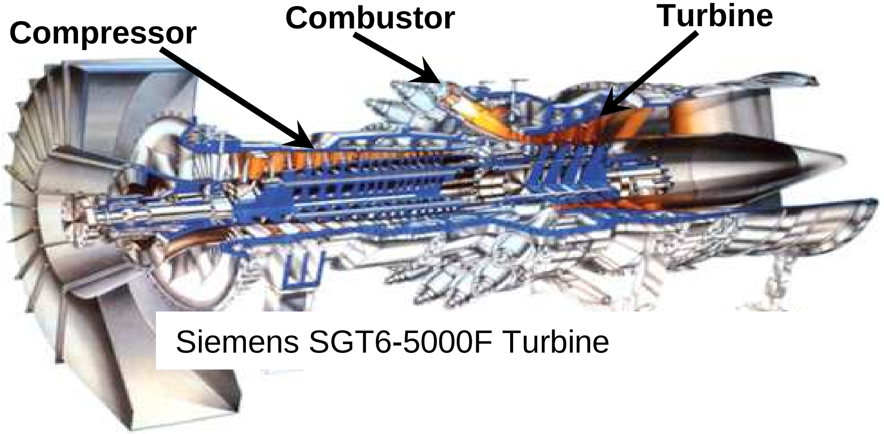
Project Goal:

The project goal is to develop wear and crack monitoring technologies to enable real-time condition monitoring and assessment of critical hot section combustion parts. The project develops hot component sensors and an integrated system to use the sensors to enhance plant and component reliability with a robust condition monitoring network.

Project Objectives:

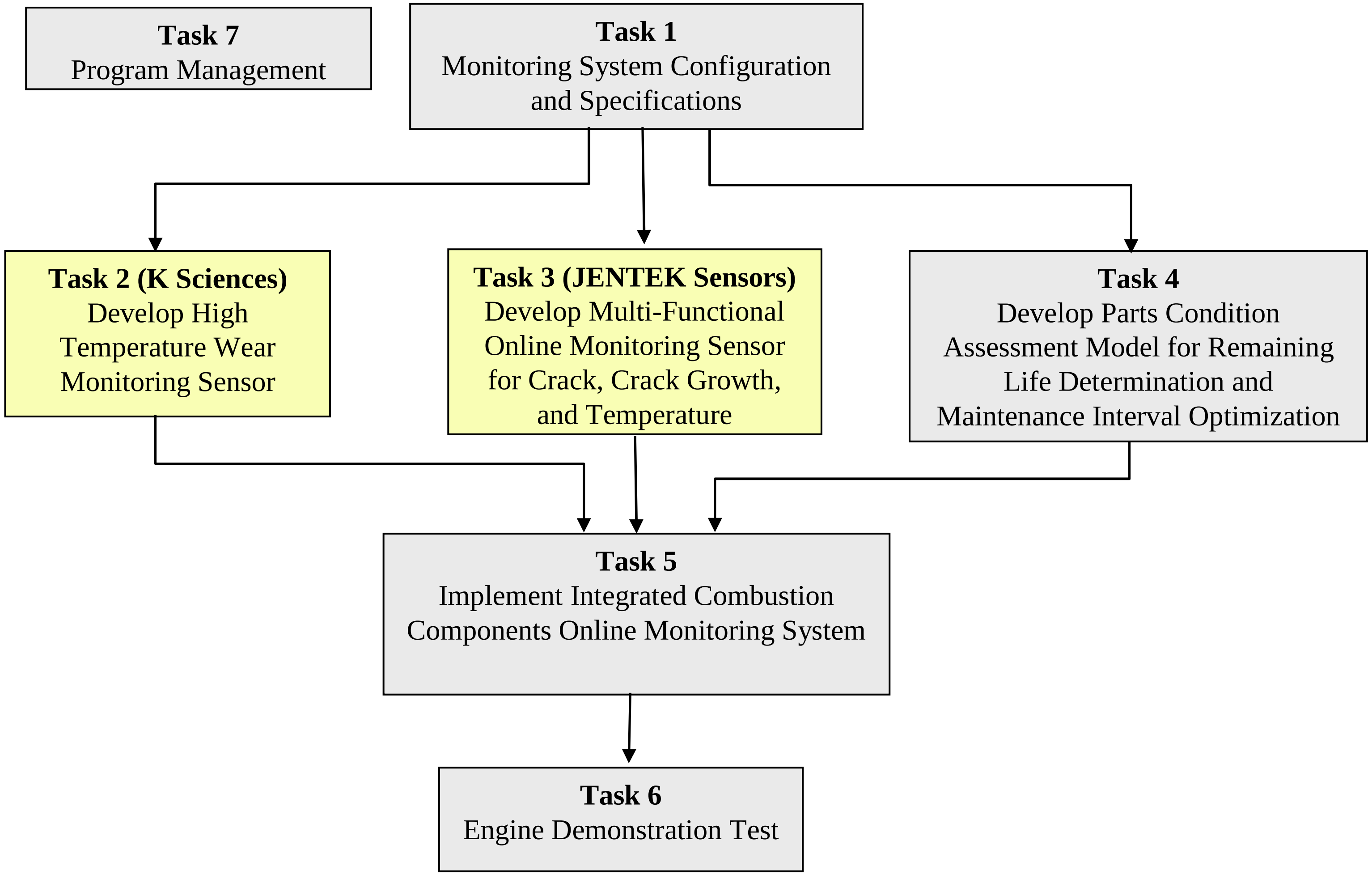
1) Develop a Magnetic Crack Sensor: Design, develop, and demonstrate a high temperature multifunction magnetic sensor to monitor cracking and temperature in hot section combustion components

2) Develop a Fiber Optic Wear Sensor: Design, develop, and demonstrate a high temperature sensor to monitor wear of hot section combustion components



Siemens SGT6-5000F Turbine

Program Tasks



Participants and Roles

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Added Vendor

Added Scope

Participants	Role of Participants
Siemens Energy, Inc.	• Program Management • Combustion Monitoring System Specification • Design Integrated Combustion Condition Based Monitoring System • Prototype Sensor System Tests in Simulated Engine Environment • System Validation Testing in Demonstration Engine • **Laboratory Proof of Concept Tests** • **Sensor Redesigns**
Philtec Inc. **K Sciences GP, LLC**	• Design High Temperature Wear Sensor • Fabricate Wear Sensor and Electronics • Laboratory Proof of Concept Tests and Prototype Tests
JENTEK Sensors, Inc.	• Design Multifunction Magnetic Crack and Temperature Sensor • Fabricate Multifunction Sensor and Electronics • Laboratory Proof of Concept Tests and Prototype Tests

Development Status:
Key Milestones and Deliverables

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- Sensors passed two formal R2 conceptual design reviews.
- Wear sensor passed a final R5 engine design review
- Wear sensor approved for engine installation in March to April Outage

Milestones Status

Technical Progress Milestone	Go / No-Go Milestone	Task	Description	Status
M1		1.4	Develop Online Combustion Monitoring System Specification for the Wear and Crack Sensors	Completed
M2		2.2	Concept Design of Wear Sensor	Completed
	M3	2.5	Lab Proof of Concept Wear Sensor Test	Completed
M4		3.2	Concept Design of Crack and Crack Growth Monitoring Sensor	Completed
M5		3.3	Concept Design of Temperature Monitoring Sensor	Completed
M6		3.4	Integrate Crack and Temperature Monitoring Capabilities within a Single Sensor	Completed
	M7	3.7	Lab Proof of Concept Crack Detection Test	Completed
M8		4.4	Develop Crack and Wear Monitoring Algorithms for Online Monitoring	Completed
M9		5.4	Wear and Crack Condition Monitoring Software Prototype	Completed
M10		6.1	Identify Engine Unit for the Prototype System Demonstration Test	Completed
	M11	6.3	Design Review of Integrated System Specification	Completed
M12		6.6	Perform Demonstration Test	Installation March-April 2012
M13		6.6	Final Report - Test Results	Sep-2012

Develop Specifications for Sensors

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Fuel Nozzles/Basket Swirler Bore Assembly Interface

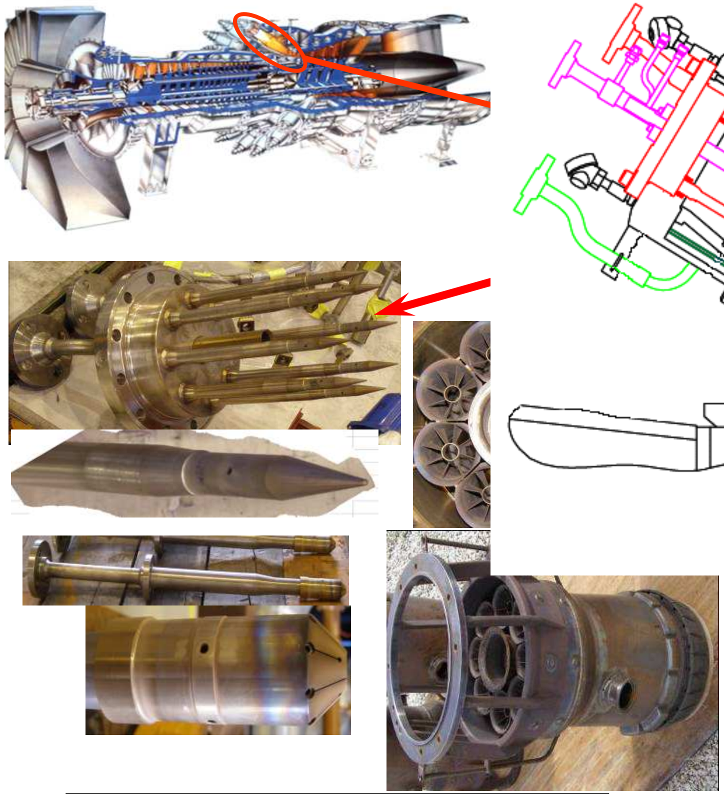
- *Fuel Nozzle Stem and Basket Swirler Bore contact surfaces*

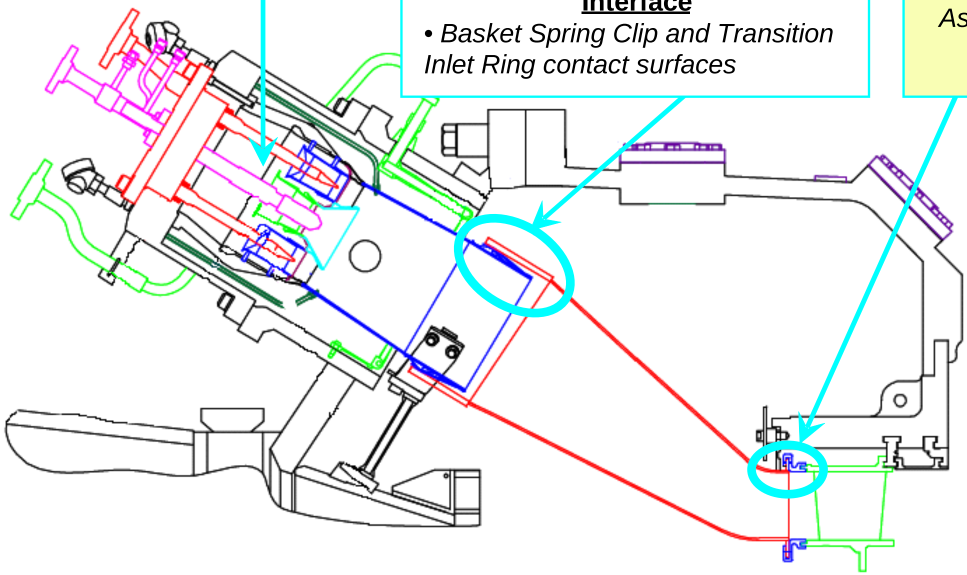
Basket/Transition Assembly Interface

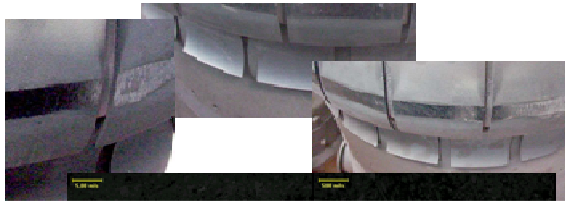
- *Basket Spring Clip and Transition Inlet Ring contact surfaces*

Transition/Stage-1 Vane Assembly Interface

- *Transition Floating Seal and Vane Assembly Interface*







Identify Critical Combustion Parts for Monitoring
- Identify locations
- Define monitoring needs

→ Driving factors and operating conditions contributing to wearing and cracking

→ Develop online combustion monitoring system specification for the wear and crack monitoring (Milestone 1)

Wear Sensor Development Specification

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Requirements	Target	Note
Sensor Maximum Operating Temperature	1000°C (1832°F)	* Very high target for a new sensor development.
Fiber Optic Transmission Cable Operating Temperature	500°C (932°F)	* Transmission cable used from the sensor location to outside of engine casing.
Wear Measurement Resolution	+/-0.025 mm (0.001 inch)	* Very high resolution target , information valuable if resolution is 0.25mm
Wear Measurement Range	0 to 10 mm	* Prototype sensor target
Sensor System Operating Life	Minimum of 2000 hrs for prototype sensor demonstration test	* Ultimate goal is to have a sensor with design life equal to combustion parts inspection interval cycle measured in thousands of hours.

Magnetic Sensor Development Specification

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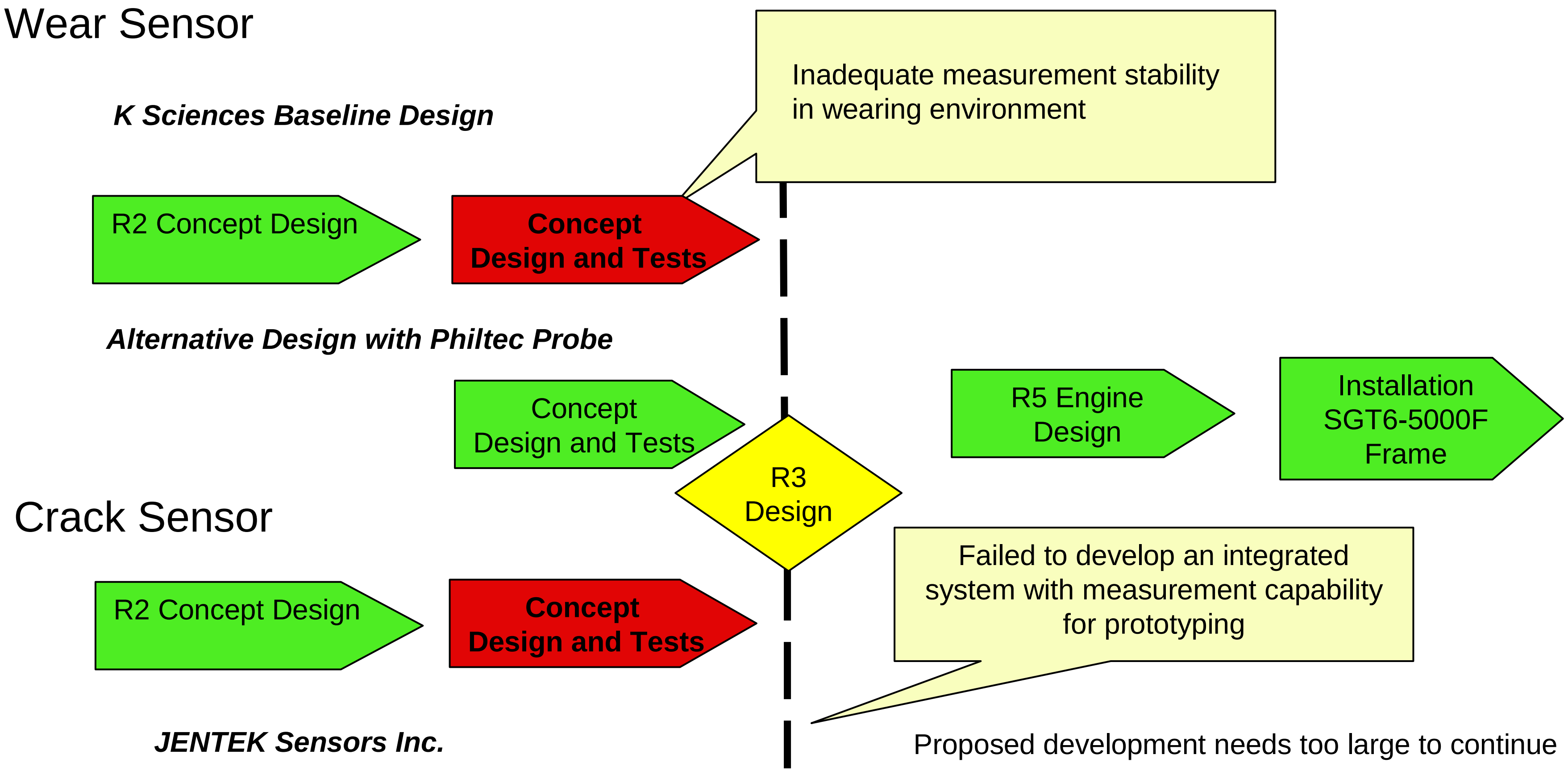
Requirements	Target	Note
Sensor Maximum Operating Temperature	1000°C (1832°F)	* Very high target for a new sensor development.
Transmission Cable Operating Temperature	500°C (932°F)	* Transmission cable used from the sensor location to outside of engine casing.
Crack Detection Resolution	Minimum of 0.50mm crack length by 0.25mm crack depth	
Crack Growth Monitoring Range (max crack length)	0 to 30 mm	* Prototype sensor target
Temperature Measurement Accuracy	+/-15°C (27°F)	* Secondary objective to use the sensor for dual use (temperature and crack monitoring).
Sensor System Operating Life	Minimum of 2000 hrs for prototype sensor demonstration test	* Ultimate goal is to have a sensor with design life equal to combustion parts inspection interval cycle measured in thousands of hours.

Sensor Development Progress



Validation Tests: Key Success Factors Obtained from Various Testing Levels

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Key Success Factor	Vender Test	Siemens Lab Tests	Engine Test
Measurement resolution and accurcy			NA
Measurement in actual materials and reflection environment of an engine	NA	NA	
Measurement repeatability			NA
Wears with contacting part			NA
Temperature cabability, short term			
Temperatuer capability, long term	NA	NA	
Engine robustness	NA	NA	
Installation capability	NA	NA	
Engine impact acceptable	NA	NA	

R2 Concept Design → R3 Design → R5 Final Design Details

Siemens developed specialized laboratory tests to go beyond vendor capabilities

Develop High Temperature Wear Monitoring Sensor (Baseline Sensor)

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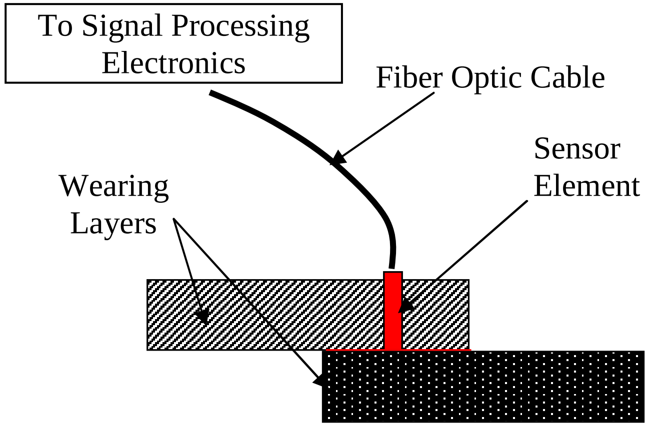
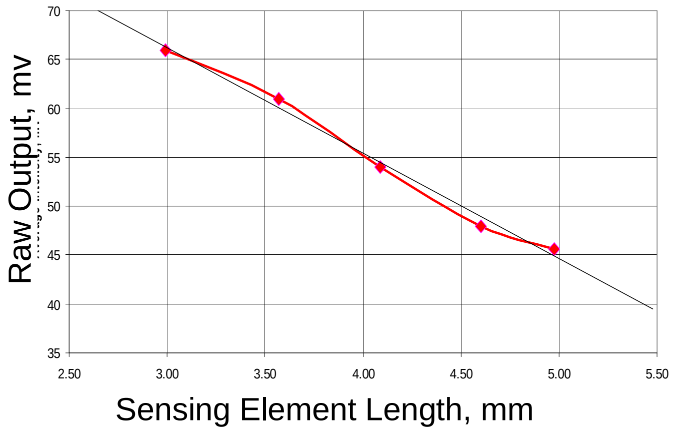
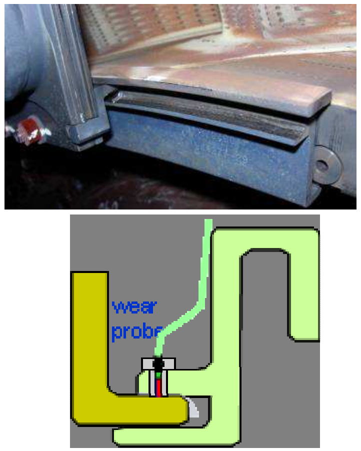
- Fiber optic sensor technology, initially developed by K-Sciences, monitored wear by determining sensor length directly as the sensor tip erodes with the wearing layer.
- Sensor development target: operating temperature of up to 1000C, and wear rate measurement resolution of +/-0.025mm (0.001inch).



Schematic of wear sensor instrumentation



Raw output correlation to sensing element length



Application Example

Concept Design of Fiber Optic Wear Sensor (Baseline Design)

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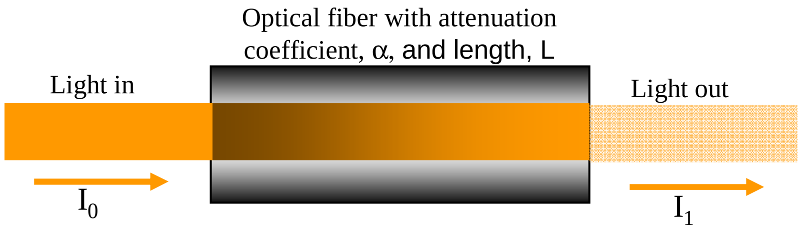
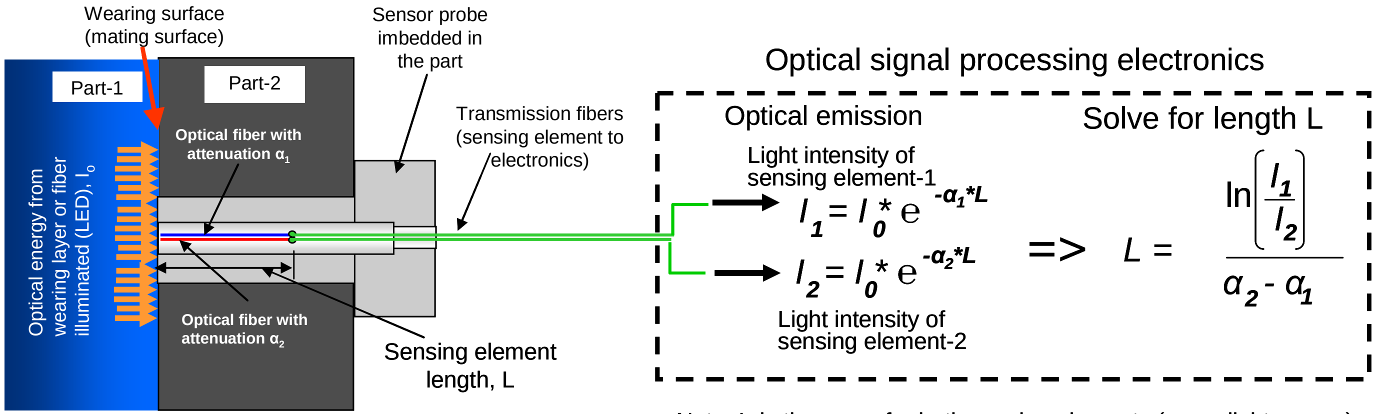
- The fiber optic wear sensor works using optical light transmission principle governed by Beer-Lambert Law. The optical light transmission intensity through a fiber can be related to the fiber length as shown below.



$$I_1 = I_0 e^{-\alpha L}$$

Beer–Lambert Transmissivity of Light as It Travels through an Optical Fiber

- Using dual fiber optic elements with different attenuation coefficients allows the monitoring of sensor length or wear



Note: I_0 is the same for both sensing elements (same light source)

Laboratory Proof of Concept Tests
K Science Wear Sensor

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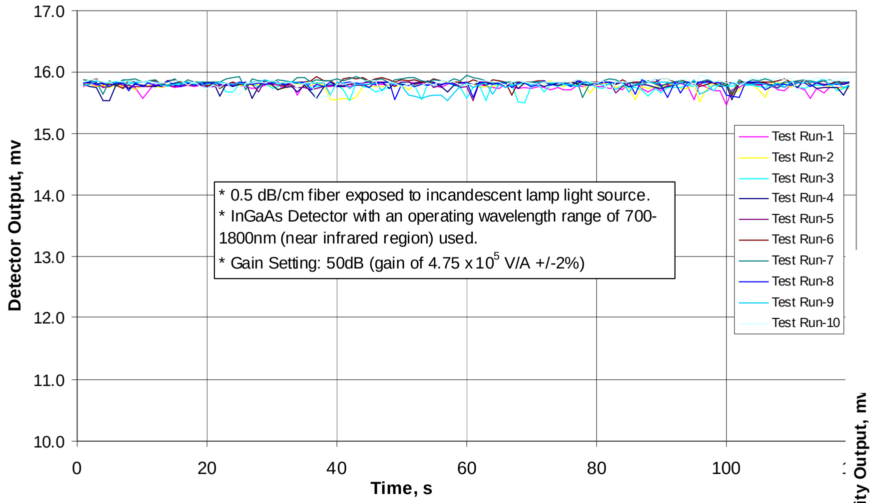
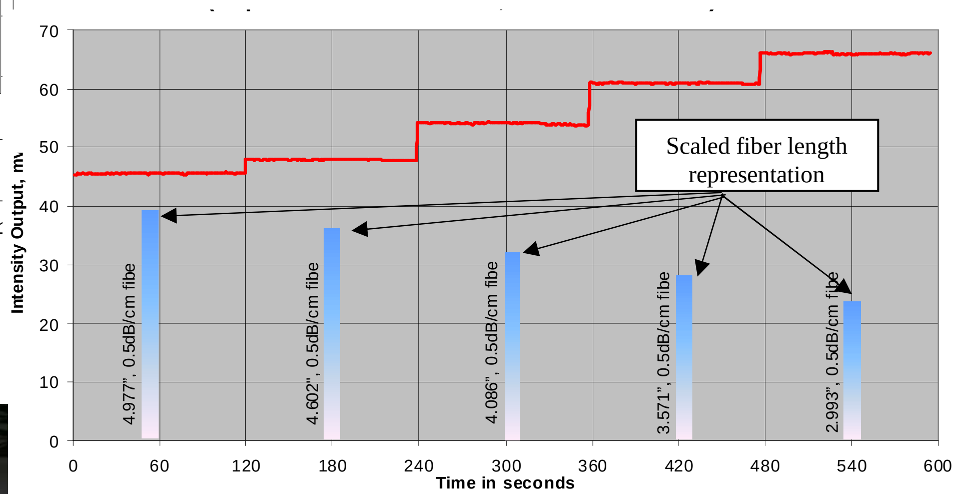
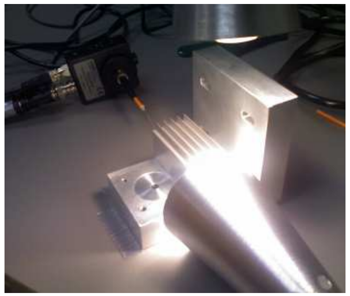
Signal Repeatability and Sensing Element Length Determination Experiments



Measurement Stability and Repeatability Tests

K Sciences and Siemens conducted initial lab proof of concept tests





Detector Output versus Sensing Element Length Test

Laboratory Proof of Concept Tests

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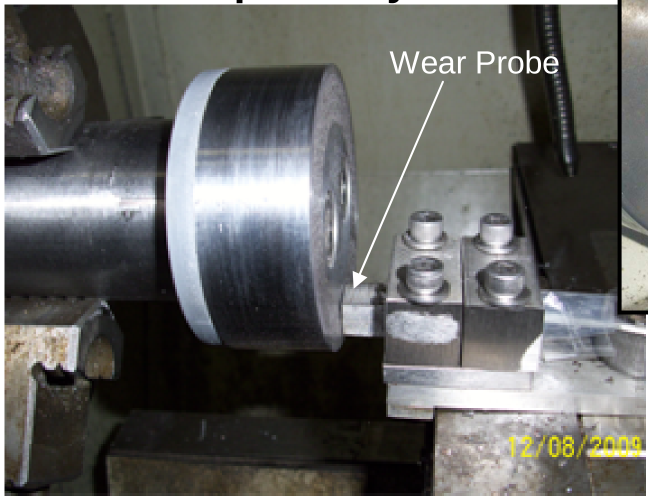
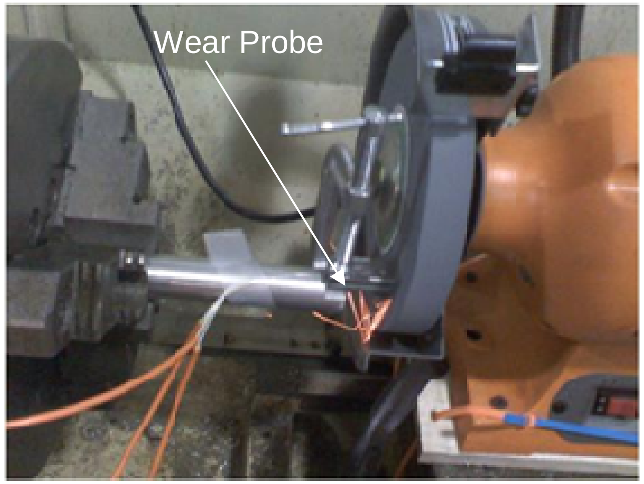
Wear Compatibility Test

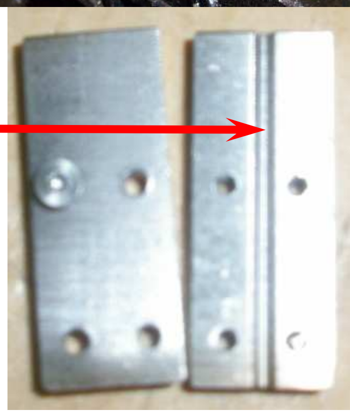


High speed wear simulation test on a lathe (wear probe rubbing against spinning metallic surface).



High speed wear simulation test on a grinder (wear probe rubbing against spinning abrasive surface).

Sensing fibers assembled in this grove using high temperature cement glue



Baseline Sensor Wear Demonstration Test

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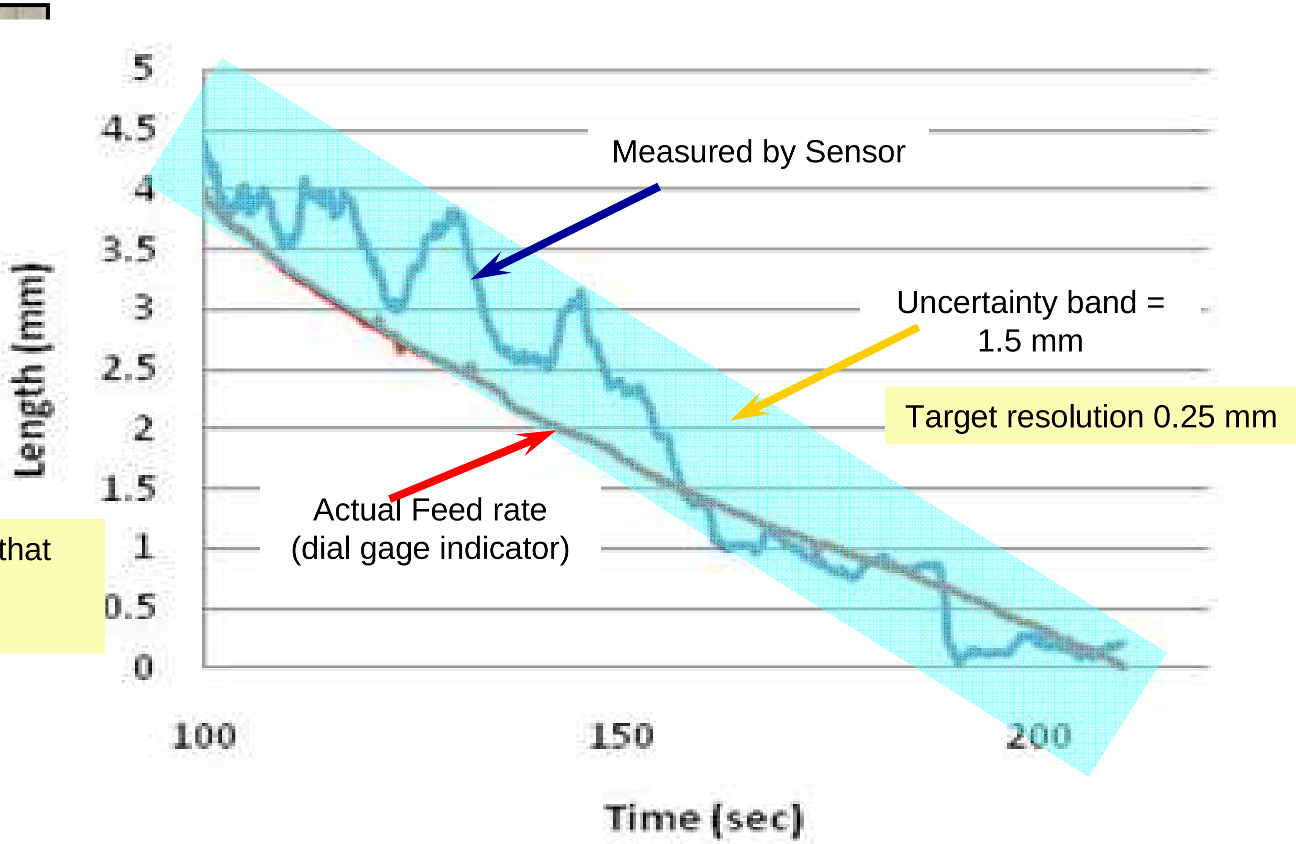
Metal-to-Metal Wear Simulation Test: created wide uncertainty band in measurement

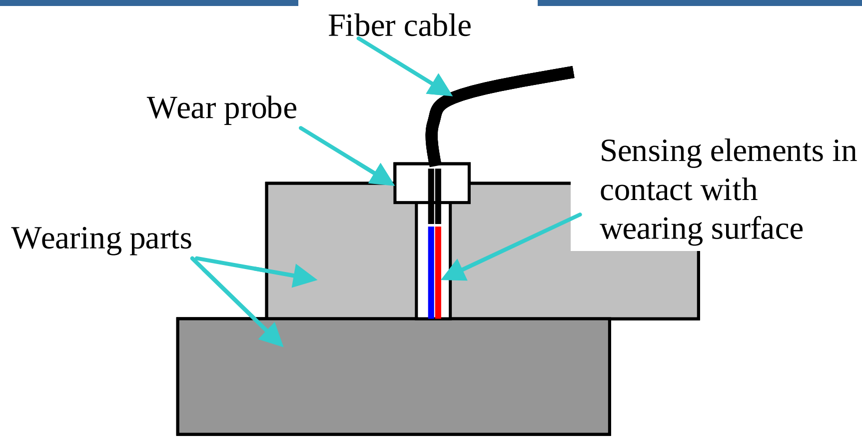


Wearing the fiber created cracks that reflected light and made the measurement very noisy

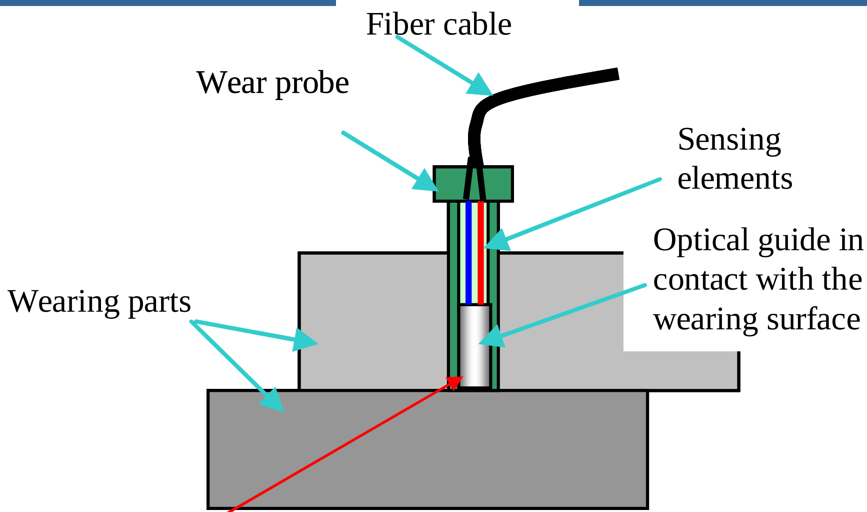
Siemens and K Sciences spent a great deal of effort to resolve issues

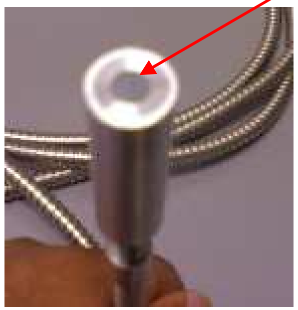
- Fiber bundle designs
- Data averaging

Baseline Wear Sensor Replaced with an Alternate Wear Sensor Concept



Baseline Fiber Optic Wear Sensor Design (K Sciences)





Alternate Optical Wear Sensor Design (Siemens)

- ➢ The Baseline Sensor performed marginally in static tests.
- ➢ When the fibers were exposed to wear, the measurements became unusable

Philtec Gap Measurement Technology Integrated with a Siemens Wear Probe Concept

- Performs better in aggressive wear environment
- Closer to practical demonstration than the K Sciences concept

Sensor Design: Alternative Wear Sensor

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Mating part reflects light through Plug back to Probe

Sensor Probe

Emits light into Plug and receives reflected light

Transmission Line

Transmit light through hot zone, up to 500C (high temperature fiber cable)

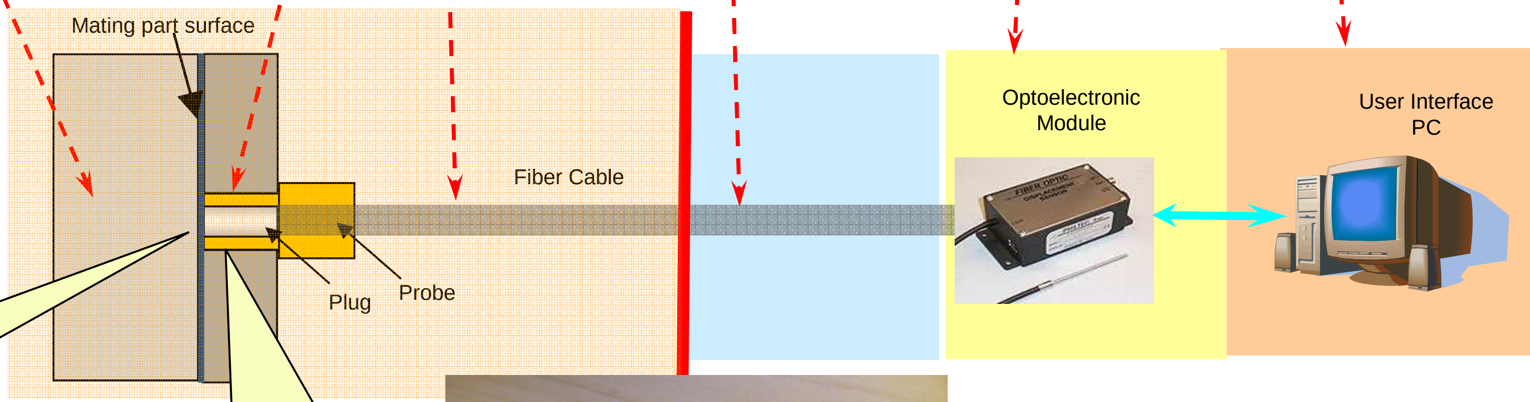
Transmit light outside of engine (low temperature fiber cable)

Optoelectronic Module

- Generates probing light (880nm diode)
- Receives reflected light and converts it into electrical signals.
- Digitizes and pre-processes signals

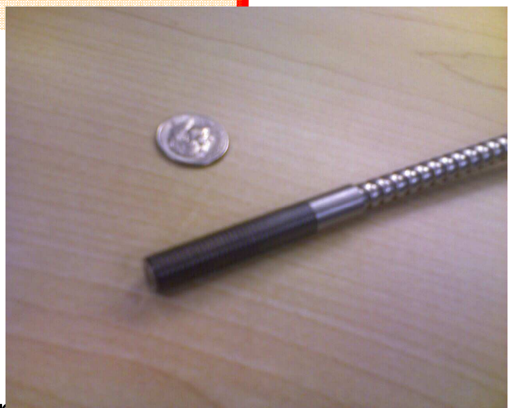
Data Analyzer Result Display

Data Processing and Storage System



Background reflection measured with no light source

Ratiometric method used to measure distance from fiber end to wearing part



Alternate Sensor Wear Simulation Test

Separating the optical fiber with an optical wear plug greatly improved the measurement stability

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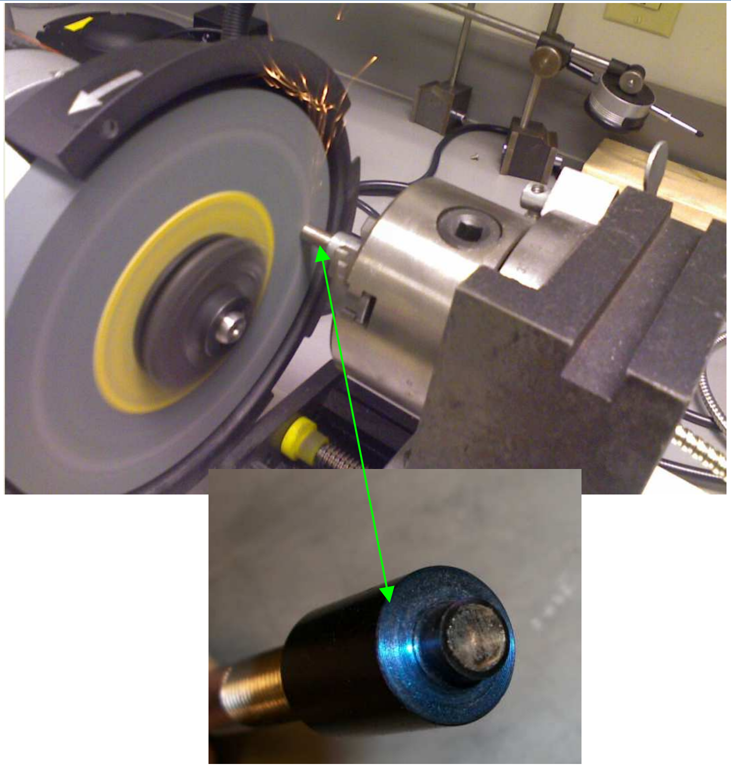
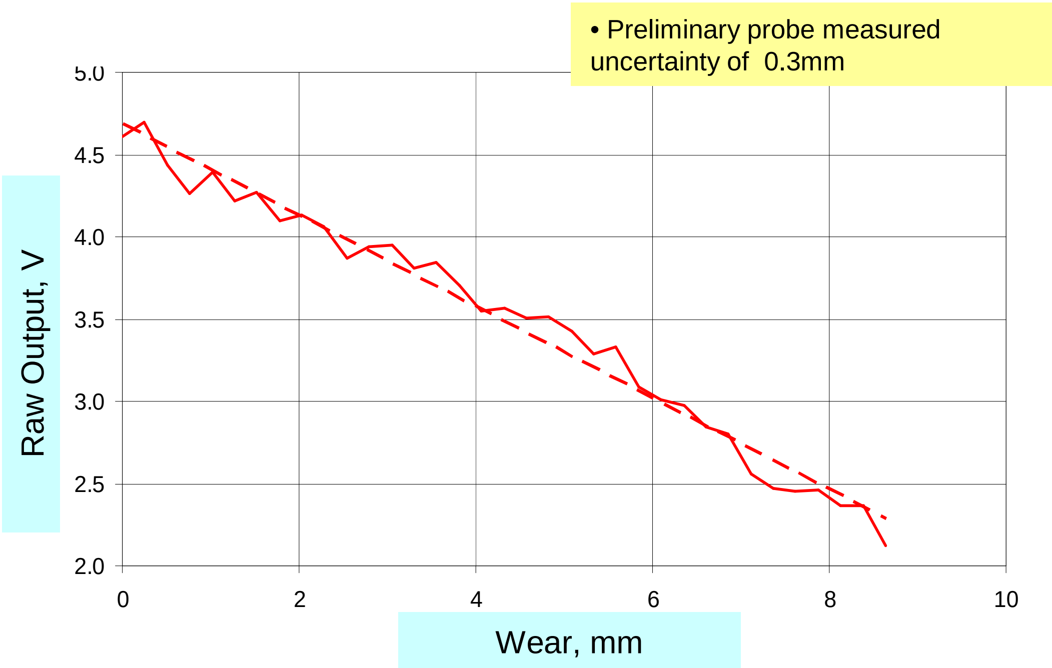


Wear simulation test using bench grinding machine



(b) Sensor output correlation to probe tip wear progression

Alternate sensor design improved wear monitoring capability over the Baseline (K Sciences) design in a dynamic wear simulation environment

Uncertainty achieved = +/-0.3mm.

Alternative Wear Probe Improvement

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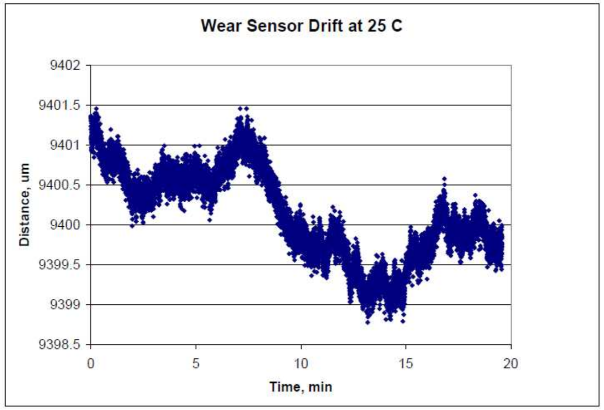
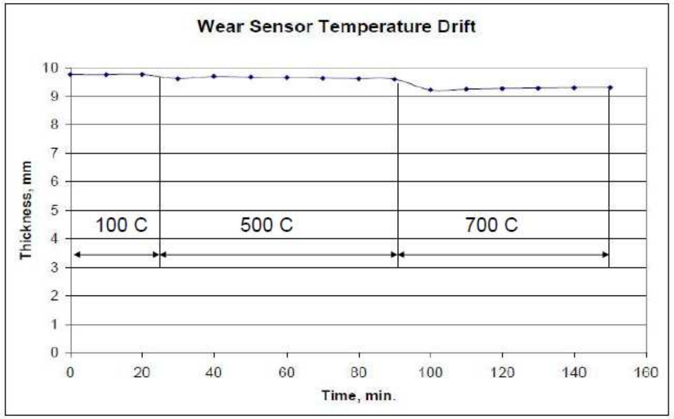
Criteria	Specifictions	Baseline/ K Science	Alternative/ Philtec
Distance operating range, mm	0 - 10	0 - 10	0.2 -12.7
Maximum operating temperature, C	1000	1000	800
Instability, room temperature, um	25-250	740	2
Instability, operating temperature, um	25-250	XX	30
Uncertainty during wear, um	25-250	1500	300



At room temperature the sensor output drifted less than 2 um during 48 hours.



Optical properties of the quartz media and reflective surfaces are temperature dependent; so calibration at operating temperatures is needed.

Alternative Wear Probe High Temperature Tests

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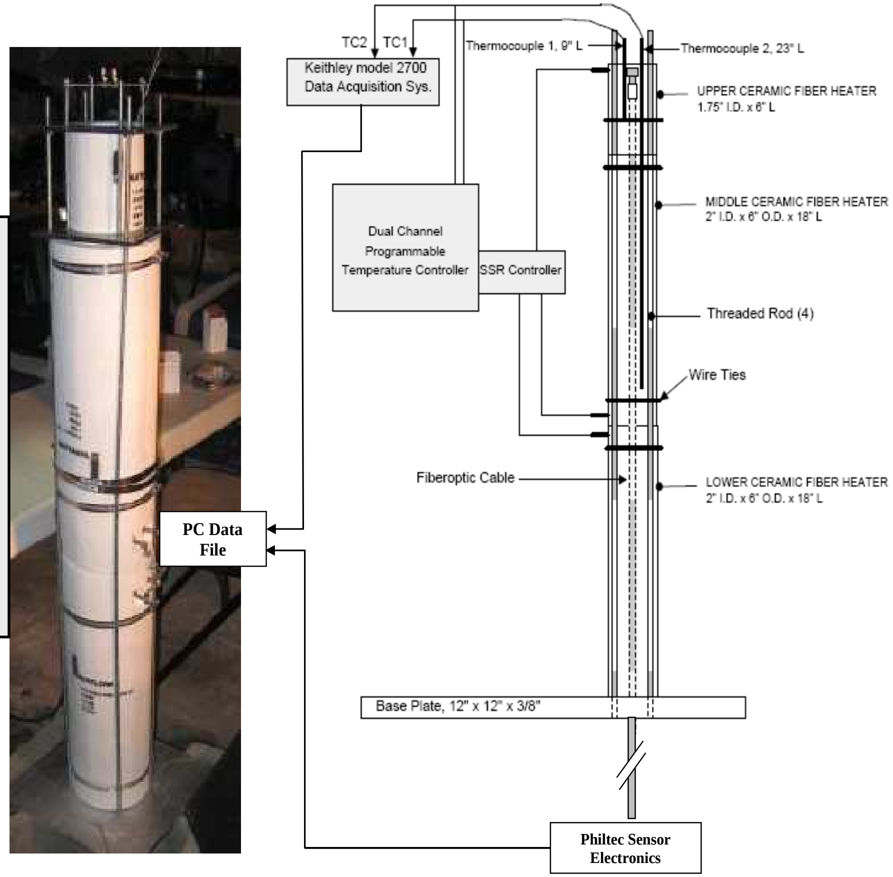
Test Objective: Evaluate sensor response and integrity in high temperature environment

Philtec Test Results:

1. Probe materials (fused silica fiber, optical guide, ceramic cement, and Hast-x probe housing) are capable to operate up to 1000C.
2. Probe performance stable for up to 600C.
3. Small drift observed at 800C and up due to thermal radiation noises and other setup issues.



A vertical stack of heaters used to heat the sensor tip plus one meter of cable length.

Alternative Wear Probe:

High Temperature Test - Probe tip exposed to 450C for 12 hrs

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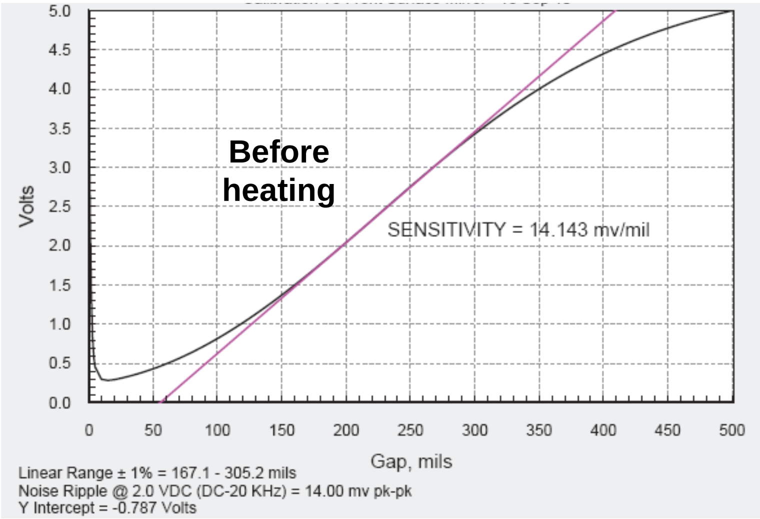
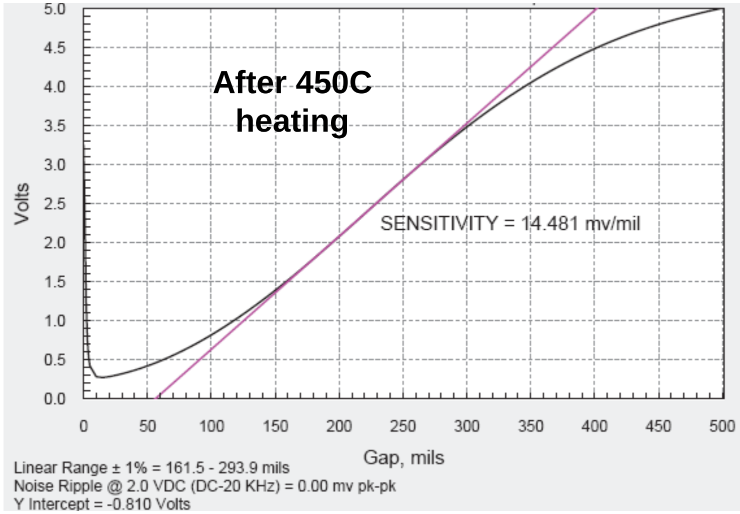


Sensor response before exposed to high temperature test



Sensor response after heated to 450^{o}C for more than 12 hours

The calibration curve before and after heating remained the same and the response during heating was as expected.

High Temperature Test:
Probe tip exposed to 780C for 4 hrs

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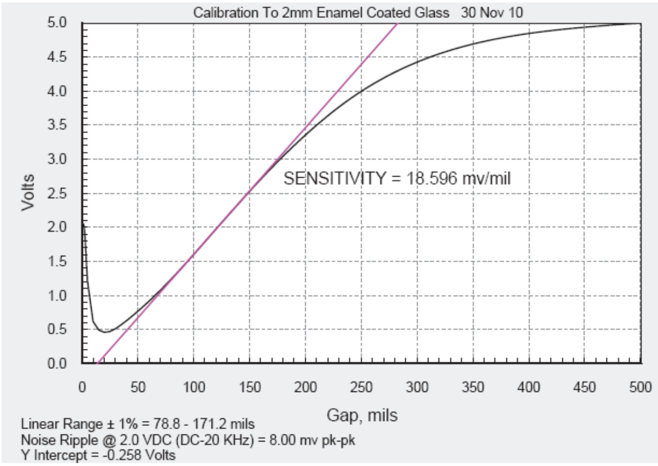
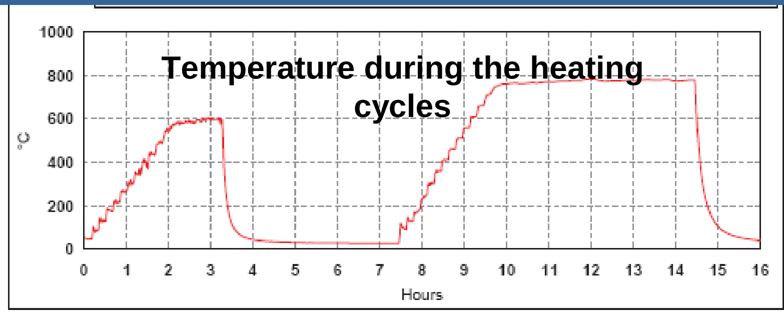
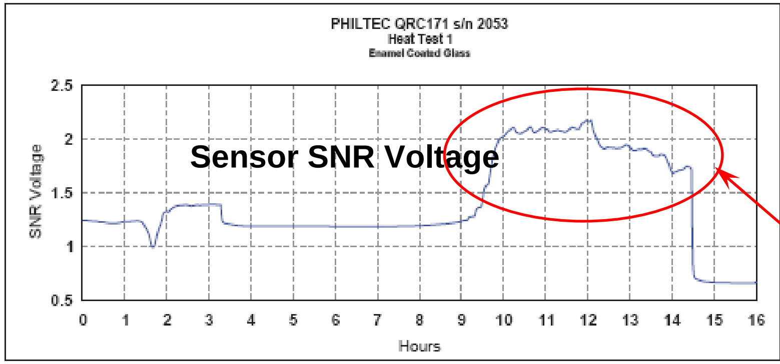
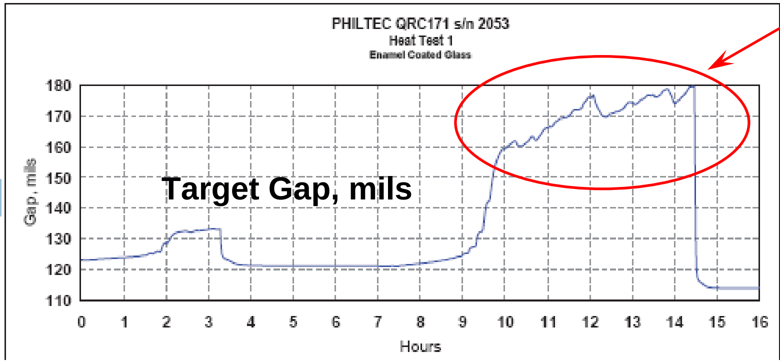


Sensor calibration curve before the high temperature test. The linear range spanned 78 to 171 mils (2mm to 4.3 mm)





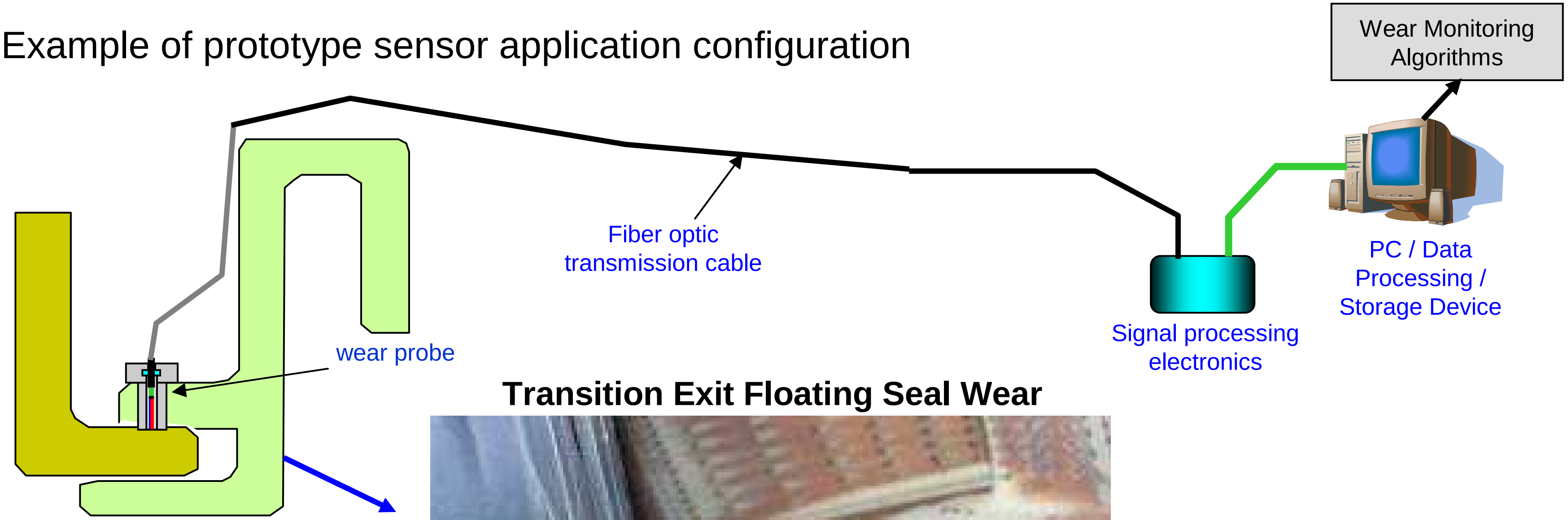


Sensor response shifted due to background radiation that is now compensated

Some drift observed at 800C and up due to thermal radiation noises and other setup issues. Work in progress to resolve the issues.

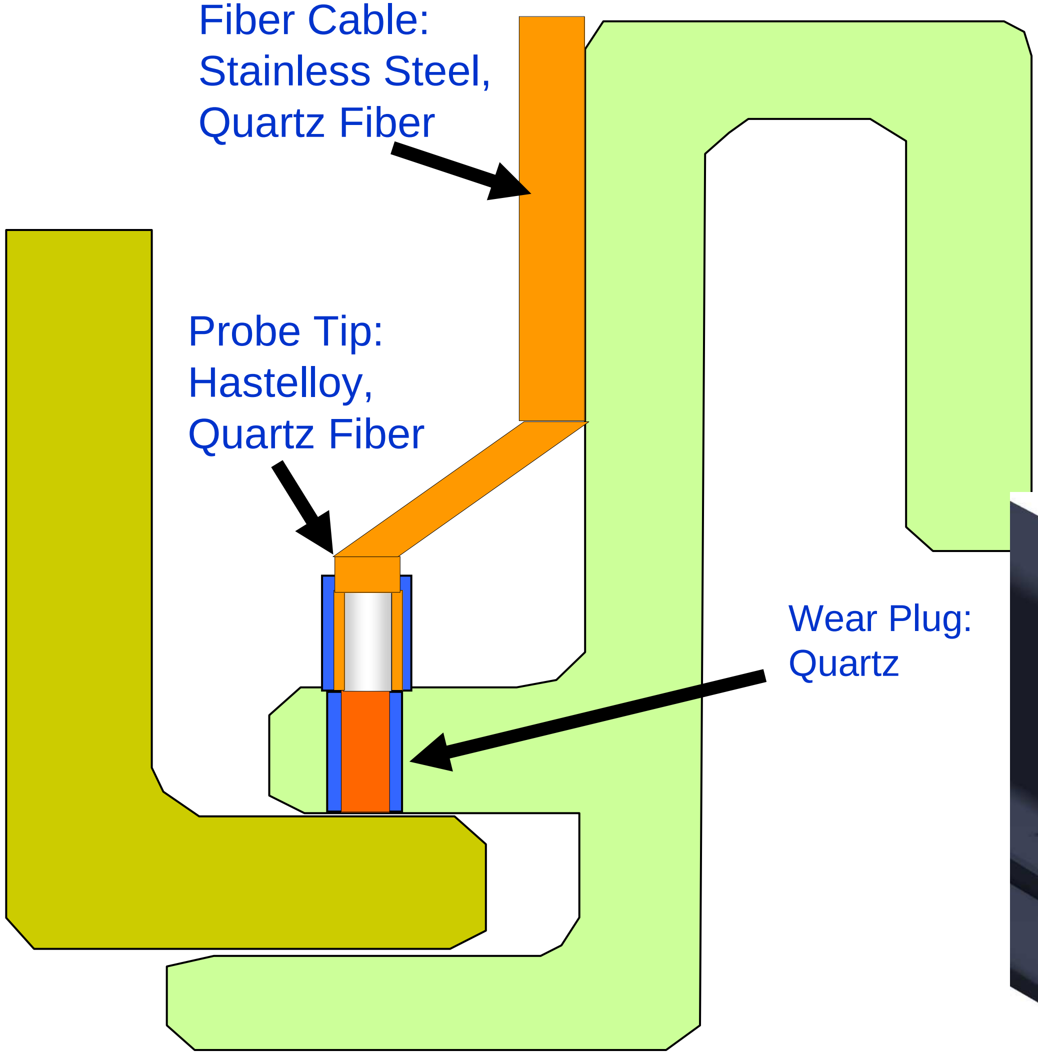
Transition Floating Seal Wear Monitoring Application

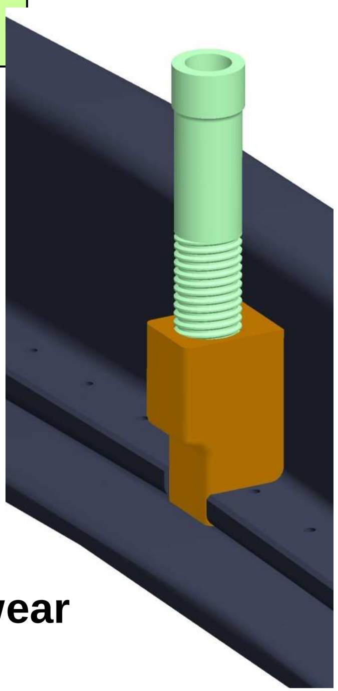
Example of prototype sensor application configuration



Transition Exit Floating Seal Wear

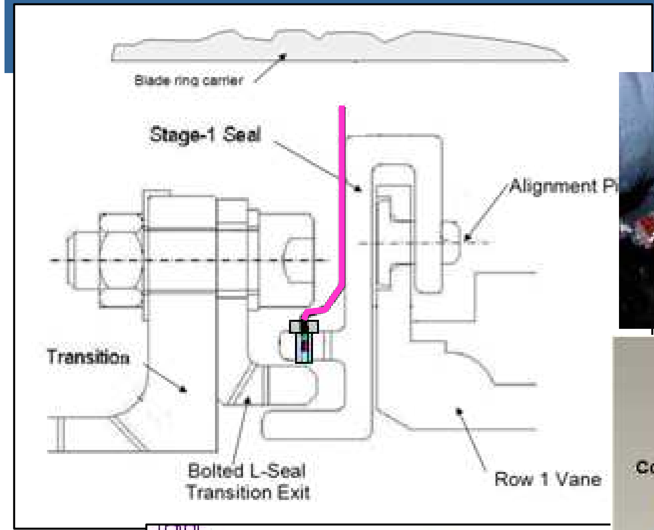
Materials and Installation

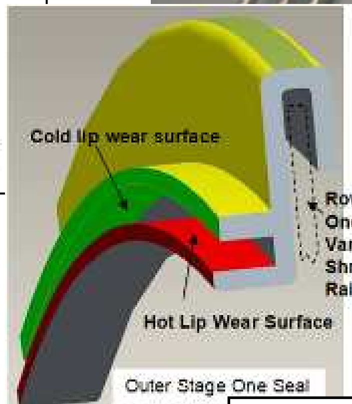


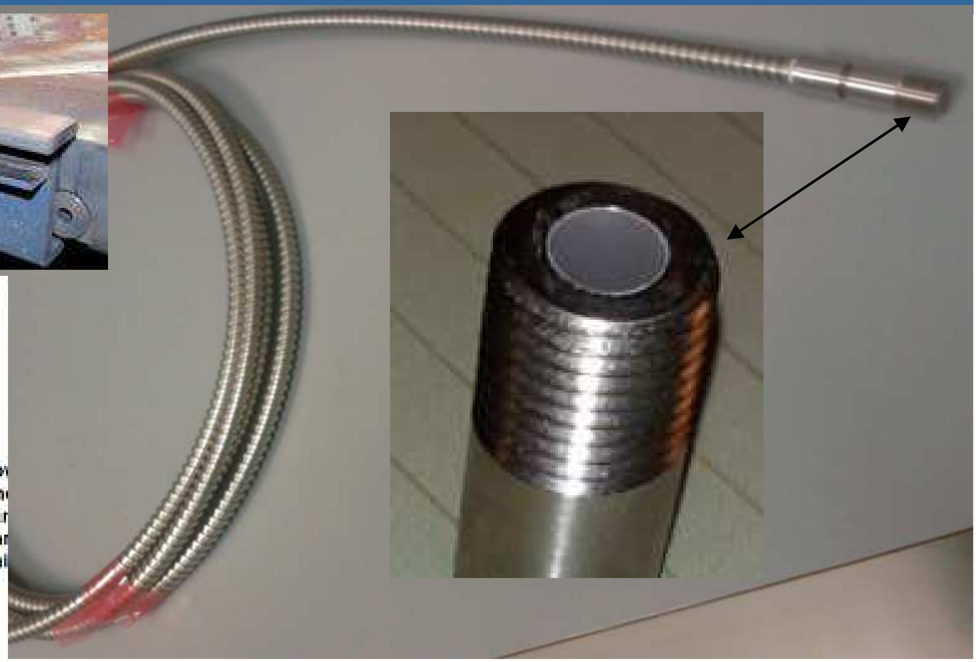


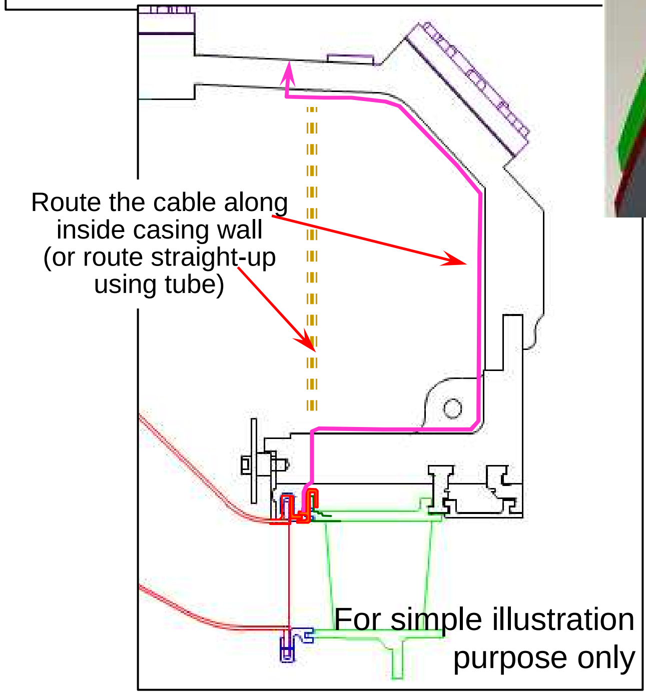
Measuring outer seal wear

Transition Floating Seal Wear Monitoring Application







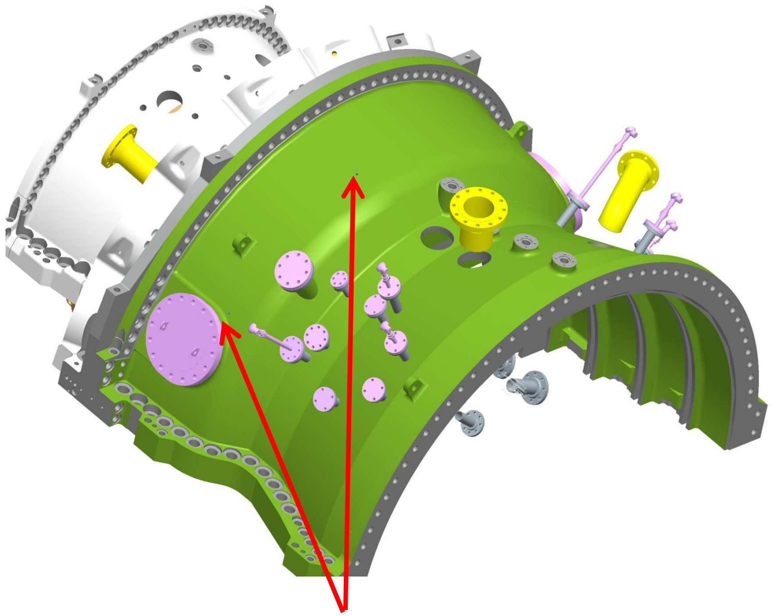


Probe can be mounted on the floating seal with the probe tip flesh against the wearing surface.

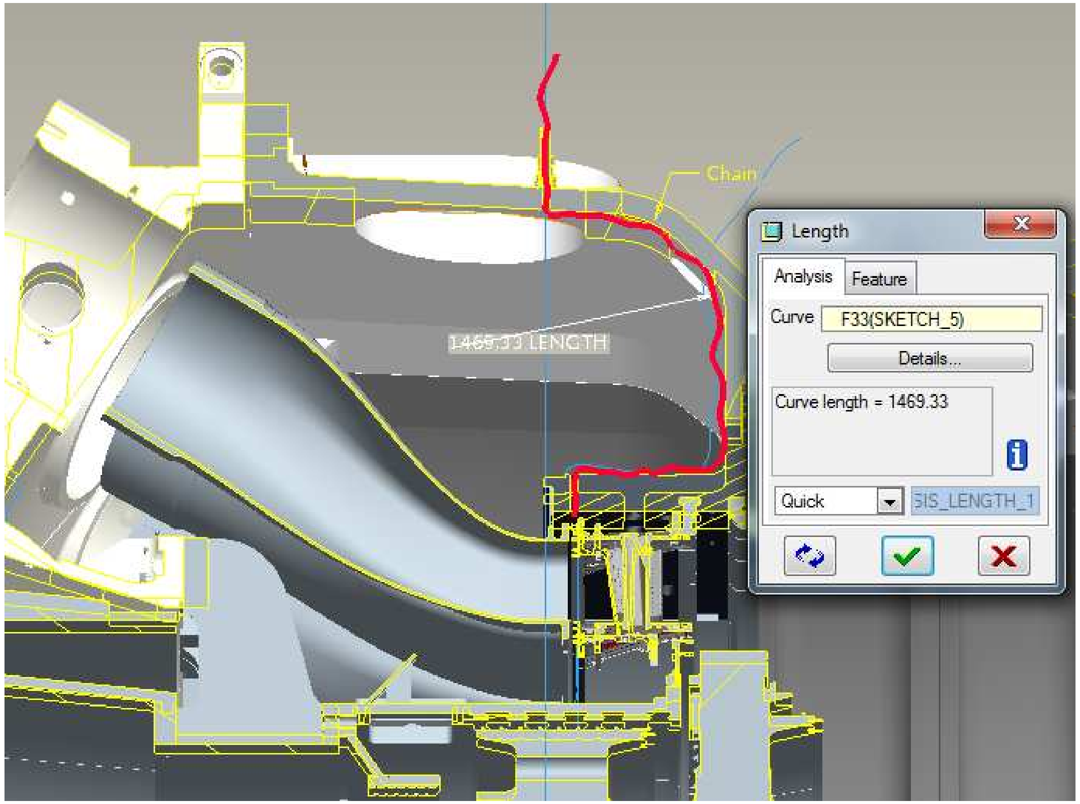
- Threaded probe tip, 0.375” diameter
- Flex hose cable, 0.25” diameter

The cable will be routed using a guide tube to the outside casing

Installation Design:
Optical Wear Sensor – Routing Access



Proposed routing to outer seal



Requested installation of 4 sensors, but only 2 sensors were approved by customer

Outer seal high-temperature cable length is 1.5 m

Risk Assessment:
FMEA Performed and Presented to Customer

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Design Feature or Attribute	Potential Failure Mode	Potential Effect(s) of Failure	SEV	Potential Causes	OCC	Current Controls	DET		RPN
Ability to measure wear in a way that is useful for Transition Exit Seals.	The system does not detect the worst wear location	Inability to make useful predictions.	3	There are not enough probes on each seals, or these are installed in areas that are not wear[illegible] of the seal in [illegible]	10	There is no control to predict what seal/s position/s will have the most significant wear on the engine. However, within each seal, [illegible] e studied to allocate areas of higher risk of [illegible]	10		300
	The system can not be installed	Inability to make useful predictions.	3	There is no e[illegible] manpower a[illegible] before the Tr[illegible] to continue w[illegible]	[illegible]	[illegible] PDP process?	3		27
	Wear measures are inaccurate and/or limited	Inability to make useful [illegible]	3	High local te[illegible] pinched during installation. Innacurate [illegible]	6	?	10		180
Probe	Probe threaded piece liberates	[illegible]	[illegible]	[illegible]	2	Secondary protection mechanisms. Tackweld probe to housing. Probe is then held by cable that stabilized by conduit.	10		160
	Probe (or pieces) liberates	FOD.	6	[illegible] vibrations.Probe gets ingested and travels downstream causing impact damage to other combustion components	1	?	10		60
	Probe (or pieces) breaks or liberates	higher local leakage. Nox	3	Open gap on the sealHigh dynamics. HCF. Engine vibrations.	3	?	10		90
	Probe breaks (cracks) but does not liberate	No readings	3	Probe contacts against the Vane carrier during operation and it brakes	1	?	10		30
Transition Seals	L-Seal or Floating Seal or pieces liberate	FOD	6	Too much removed material to install probe. Mechanical integrity affected	1	Provided sketch shows acceptable scheme.	10		60
	L-Seal or Floating Seal accelerated wear	Higher leakage. Nox	6	Weigth of probe affects seal dynamics. Added vibration. Cut changes the way the seal deforms at baseload conditions.	3	?	3		54
Instrumentation conduit (routing of instrument cables)	Conduit breaks and pieces liberate	Flashbacks. Forced outage	8	Conduit pieces get caught in basket swirlers.	2	There is an spec for proper instrumentation conduit installation. Spec is 8 to 12"between clips. Scheme SCH_0805 attachment spacing. SCC-0806 Routing and potting tunes	5		80
	Conduit breaks and pieces liberate	FOD.	6	Conduit pieces travel downstream causing impact damage to other combustion components	2	There is an spec for proper instrumentation conduit installation. Spec is 8 to 12"between clips. Scheme SCH_0805 attachment spacing. SCC-0806 Routing and potting tunes	5		60
Casing component	Crack	Increased leakage	8	drilling the casing to install instrumentation and route cabling from seal to outside	3	?	3		72
	Cement fails	Leakage. Also possible damage in the enclosure area. Personal damage?	10	Not properly installed. Sealing (potting) to the outside of the casing fails.	1	Look for leaks before engine startup?	3		30

Highest Risk Item: wear location does not wear

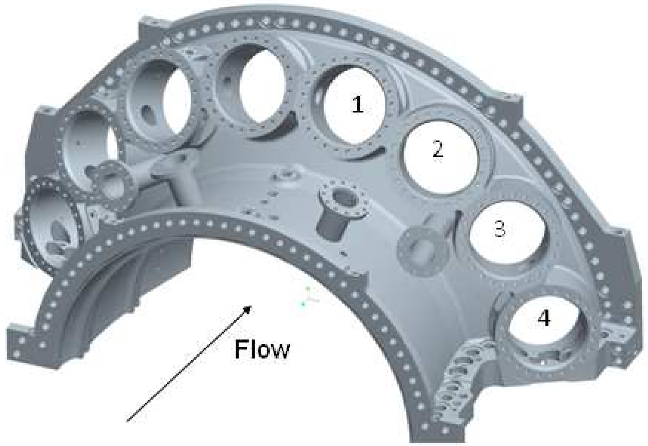
Moderate risk is sensor liberation, but it is mitigated by the cable holding onto the sensor

Demonstration Engine Sensor Validation

Tasks:

- Component instrumentation drawings (part modification, instrumentation routing, etc.)
- Risk assessment
- Design review for installation
- Customer acceptance - Level of Authority (LOA)
- Component and engine instrumentation installation
- Monitor and evaluate sensors performance
- Final test result report

Basket 2 is installation location

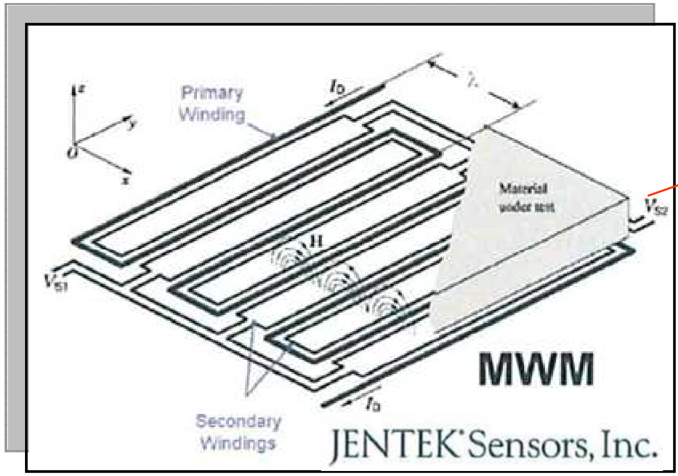


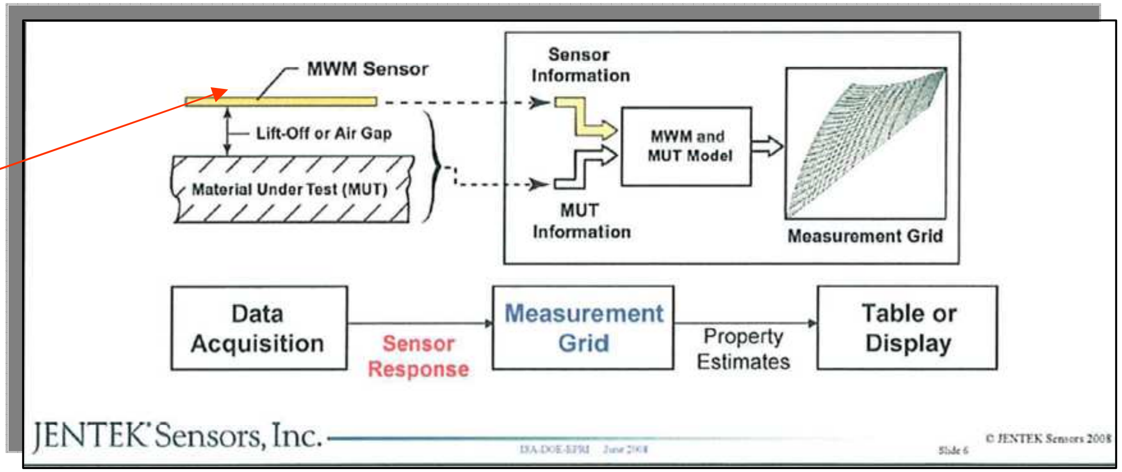
Wear Sensor Being Installed in a Siemens SGT6-5000F Turbine During Current March Outage (US Location)

Develop Multi-Function Crack and Temperature Monitoring Sensor (JENTEK)

SIEMENS

- The multifunction magnetic sensor is an eddy current sensor based on JENTEK's Meandering Winding Magnetometer (MWM-Array) technology that determines cracking and surface temperature by monitoring changes in the electrical conductivity of the material under the sensor. The MWM-Array technology has especially arranged conducting windings that consist of a drive winding to create a magnetic field and multiple sensing elements.
- To monitor cracks, a time varying magnetic field is created by applying a current at a prescribed frequency to the drive winding; the resulting material dependent response is processed using a multivariate inverse method and pre-computed sensor response database to allow the conductivity to be measured independently over a wide dynamic range of nonlinear sensor responses. The change in conductivity can be related to temperature or crack initiation.
- When a crack, corrosion damage, an inclusion, surface roughness, or an internal geometric feature alters the flow of the eddy currents, then the inductive sensing coils sense an absolute magnetic field that is altered locally by the presence of the crack or other flaw. The measured quantities are absolute, and they are automatically compensated for lift-off (proximity)





JENTEK Magnetic Sensor System

SIEMENS

High temperature transmission cable
Spec: ≥500C, ~2m long, ~5mm cable bundle diameter

Probe-to-Instrument Cable

Instrument-to-computer (USB) Cable

MWM-Array Sensor
Spec: ≥1000C, ~ 30mm x 30mm size, detects crack size of ~30mm long with a sensitivity of 0.5mm length by 0.25mm deep crack

Probe Electronics Unit
(can be placed next to the engine, from the outside)

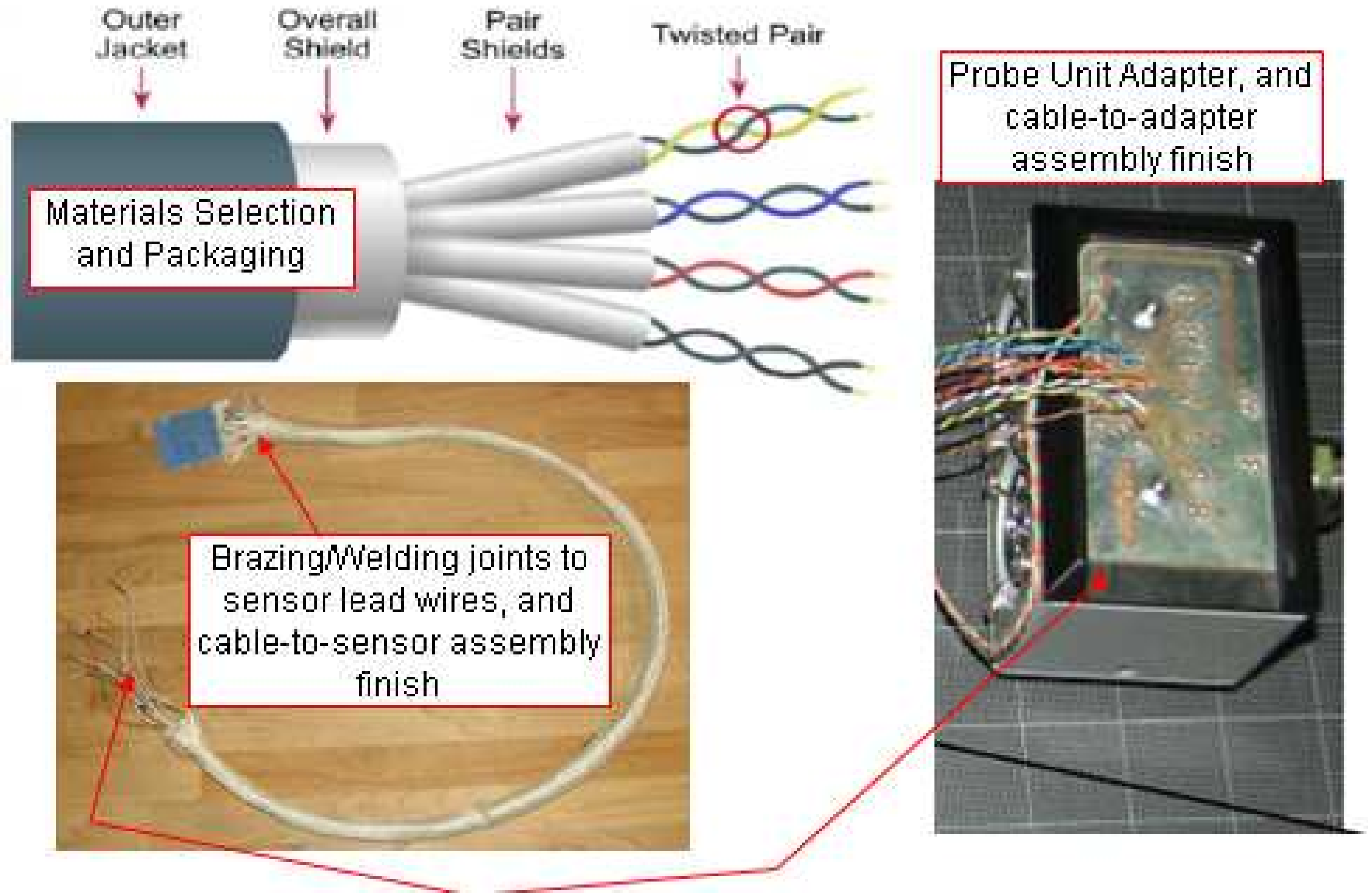
Impedance Instrument
(can be placed away from the engine, such as the control room)

Laptop with GridStation Software
(PC/laptop sensor data access can be arranged to be done remotely)

These system components did not require that much development work.
Directly adapted from existing system (prototype unit).

Challenges:
High temperature MWM array
High temperature cable and attachments
Signal to noise ratio in long (>1m) cable system

Crack Sensor Transmission Cable Fabrication



Cable material selection, twisted pair cable packaging, cable-to-probe unit adapter, and cable-to-sensor lead wire connection requires significant improvement.

Online Parts Condition Monitoring System