MONITORING OF HIGH-TEMPERATURE MATERIALS CONDITION

INTRODUCTION

- In many cases characterization of material properties as well as detection of defects require the use of nondestructive methods of evaluation.
- Materials can be tested in room temperature conditions by means of one or several Nondestructive Evaluation (NDE) methods or Health Monitoring (HM) methods can be applied at high temperatures.
- Health Monitoring method is extremely important to obtain designed life time and reliability of the construction or device.

NONDESTRUCTIVE EVALUATION METHODS (NDE)

- Acousto - Ultrasonics
- Modal Acoustic Emission
- Electrical Resistance Monitoring
- Impedance-based Structural Health Monitoring
- Pulsed Thermography Technique
- Thermoelastic Stress Analysis
- Dielectric Measurement
- Fiber Optics and Fluorescence Method
- Ultrasonic Method, and more…

HEALTH MONITORING SYSTEM

Controlling all the parameters requires health-monitoring systems consisting of:

- a net of sensors,
- data acquisition system
- setup for processing and control
- the unit that analyzes the data and provides real-time informations.

Sensing components (sensors itself, packaging and wiring) of the system are made of materials that can withstand high temperature conditions and thermal cycles.

INTRODUCTION

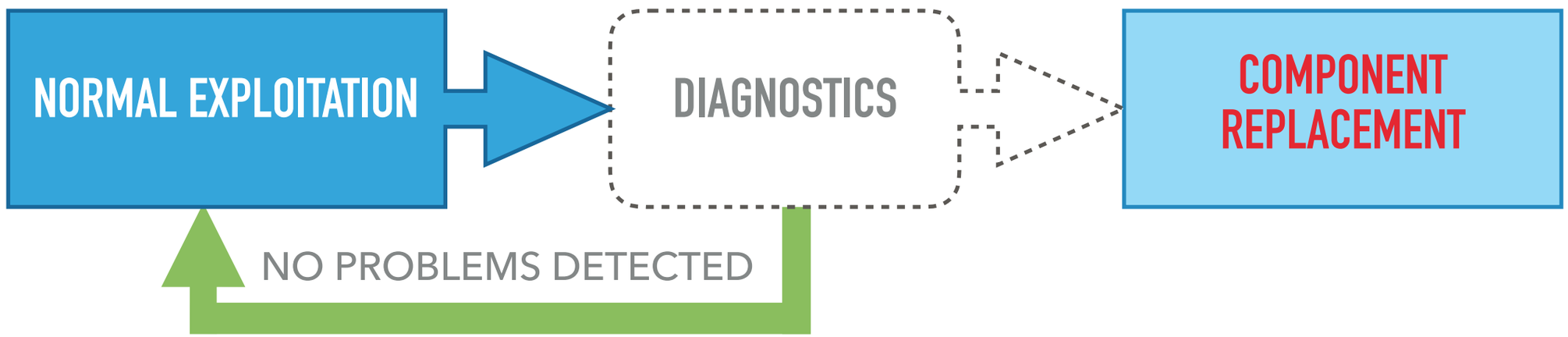
Monitoring of the health state of the aircraft engine is an example of utilization of different types of high-temperature sensors

- Microwave blade condition sensor
- Fiber optic temperature sensor
- Smart sensors
- Emission monitoring sensor

DIFFERENT EXPLOITATION PHILOSOPHIES

Safe Life maintain philosophy

Retirement-for-cause maintain philosophy



MONITORING OF HIGH TEMPERATURE MATERIALS CONDITION

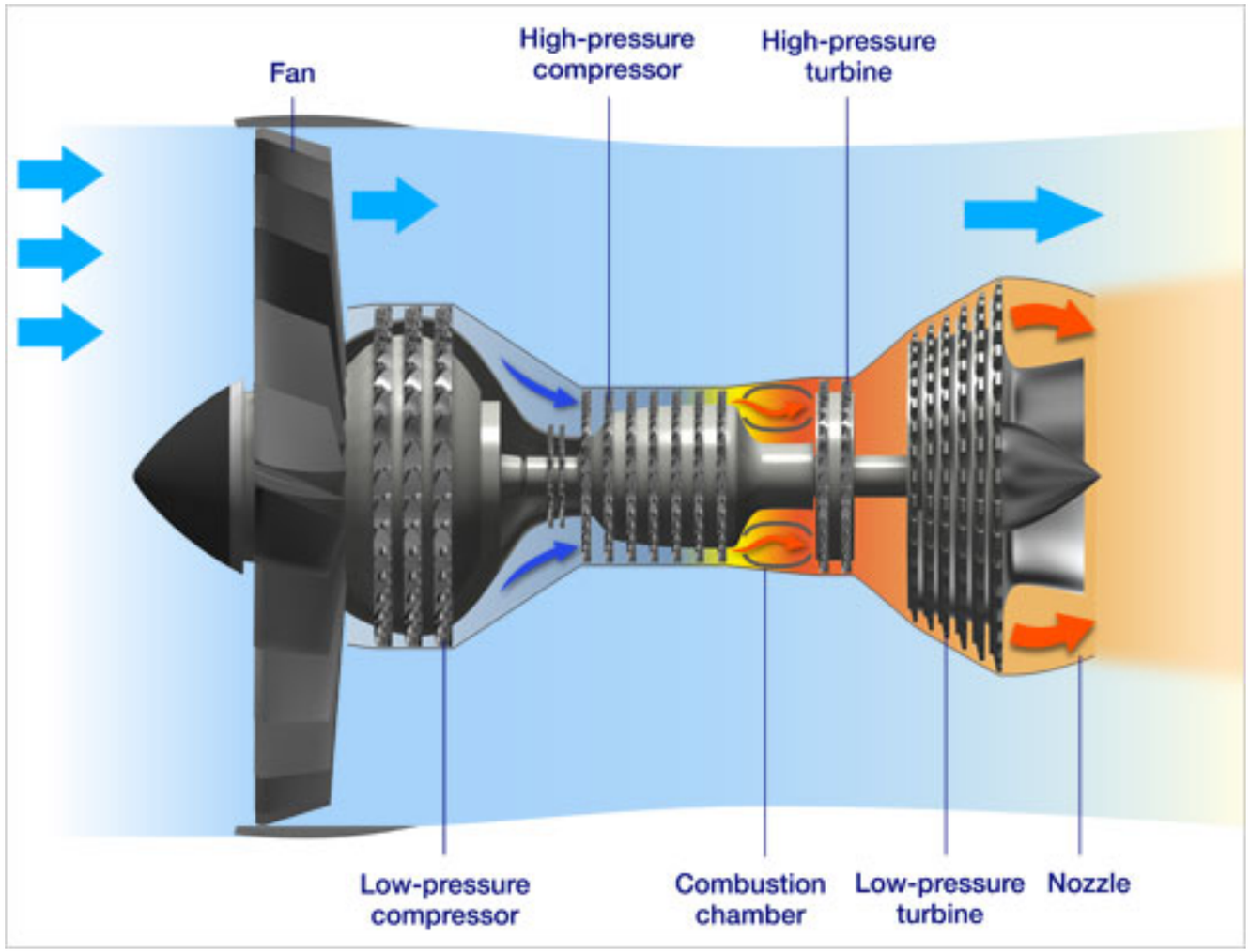
MICROWAVE BLADE TIP CLEARANCE/TIP TIMING SENSOR

MICROWAVE BLADE CONDITION SENSOR

- Severe environmental conditions in modern gas turbine engines
- Engine elements exposed to high thermal and mechanical loads
- Limitations of current periodic inspection methods results in unplanned shutdowns
- New methods of in situ monitoring of gas turbine health

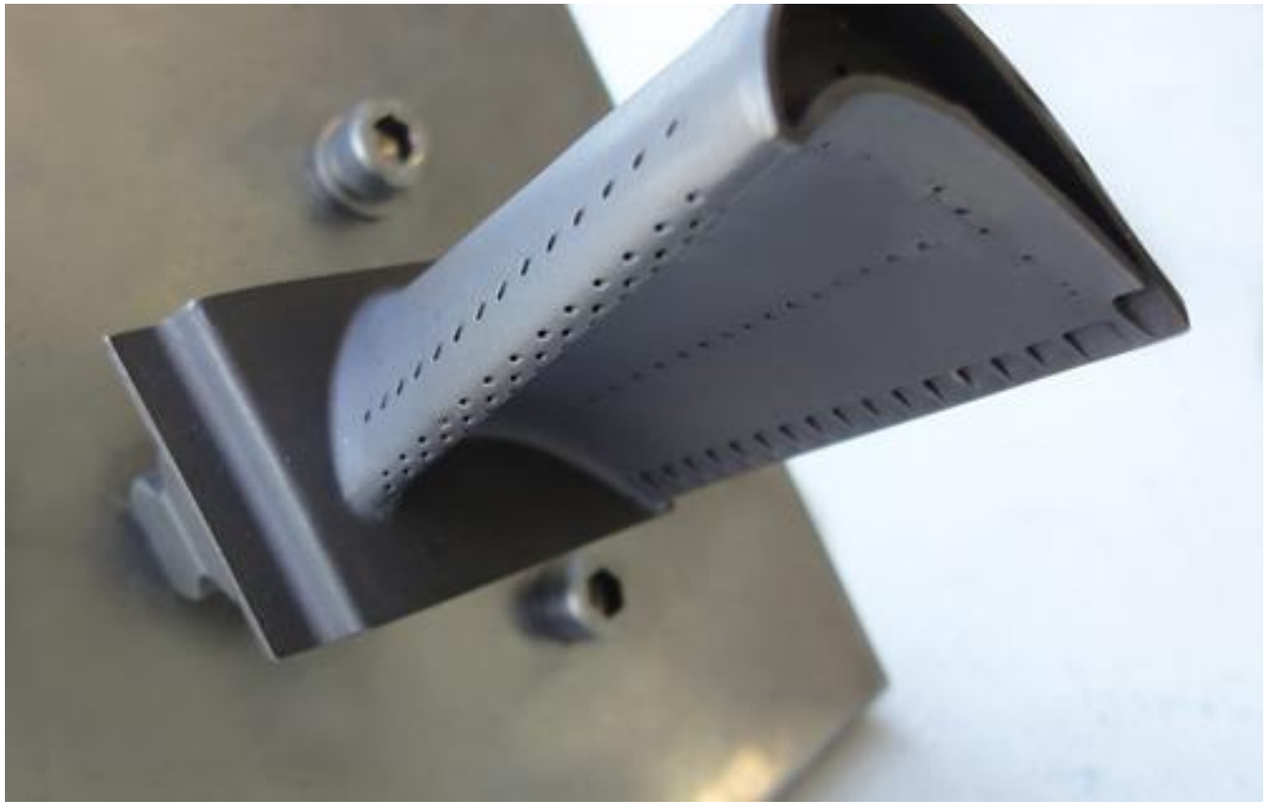
MICROWAVE BLADE CONDITION SENSOR

Schematic cross-section of a turbofan jet engine



Source: https://images.duckduckgo.com/iu/?u=http%3A%2F%2Fstatic1.olympus-ims.com%2Fdata%2FImage%2Fappnotes%2FBasic_structure_tuebofun_engine.jpg%3Frev%3D8FAC&f=1

HIGH-PRESSURE TURBINE CONSTRUCTION



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Source: https://images.duckduckgo.com/iu/?u=http%3A%2F%2Fstatic1.olympus-ims.com%2Fdata%2FImage%2Fappnotes%2FBasic_structure_tuebofun_engine.jpg%3Frev%3D8FAC&f=1

DEGRADATION OF HIGH-PRESSURE TURBINE BLADES

Source: https://images.duckduckgo.com/iu/?u=https%3A%2F%2Ftse3.mm.bing.net%2Fth%3Fid%3DOIP.D4L7Ga52zMCkEQ6SJIwmCQEsDe%26pid%3D15.1&f=1

THE SENSOR

- Microwave blade tip clearance sensor
- Based on highly accurate microwave technology that can be applied in high-temperature environments
- Operates as field disturbance sensor (non-contact work)
- Probe is both transmitting and receiving antenna
- Sensor emits constant microwave signal and measures the signal reflected off a rotating blade
- Sensor measures the changes in microwave field due to the blade passing trough the field

THE SENSOR

- The motion of the blade phase modulates the reflected signal
- Reflected signal is compared to an internal reference data set
- Changes in amplitude and phase of the signal directly correspond to the distance to the blade
- The time intervals of passing blades are measured to provide blade tip timing

THE SENSOR

- Two generations of microwave sensors are available
- Both generations are made of high temperature materials that can withstand temperatures up to 900°C without cooling or up to 1200°C with cooling air

THE SENSOR

I generation sensor

- Operates at frequency 5.8 GHz
- Designed for large rotating machinery, e.g. land-based power turbines
- Can measure distances up to 25 mm

THE SENSOR

II generation sensor

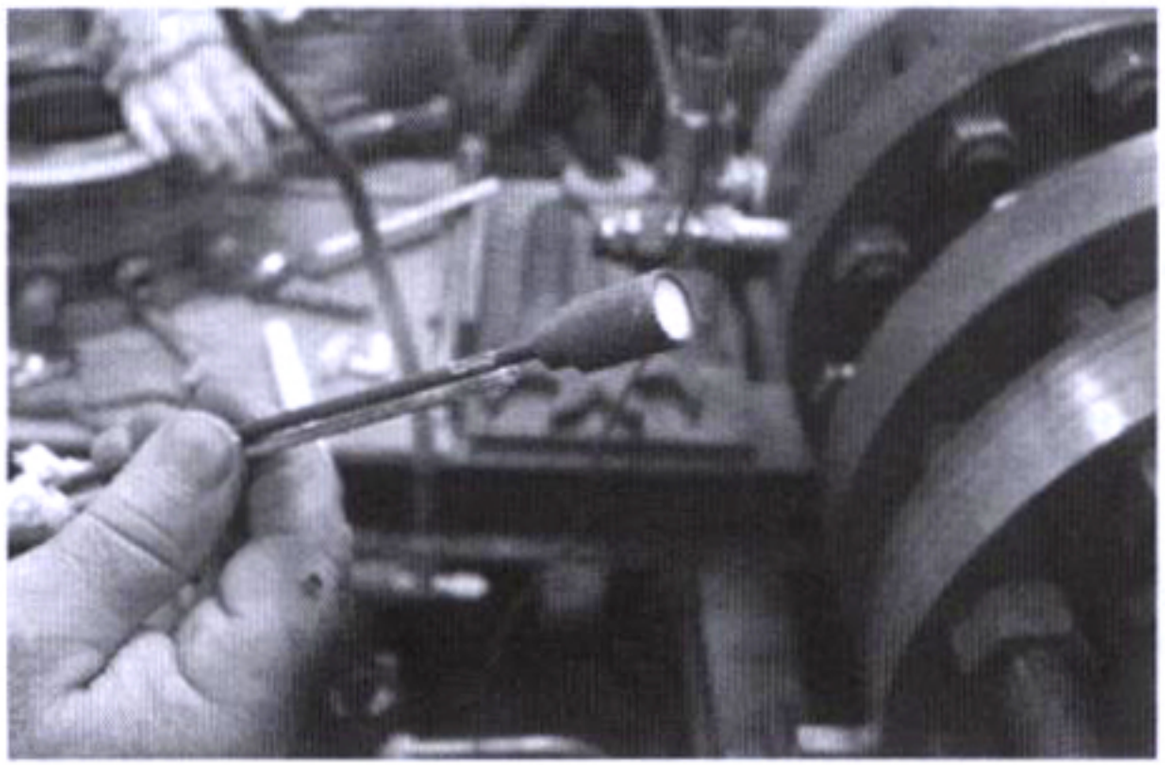
- Operates at 24 GHz
- Designed for small machinery such as turbines and compressor sections of aero engines
- Can measure distances up to 6 mm

THE SENSOR

Source: Woike, M.R., Abdul-Aziz, A.,Bendic, T.J., A microwave blade tip clearance sensor for propulsin healt monitoring, NASA/TM-2010-216736, AIAA-2010-3308

THE SENSOR

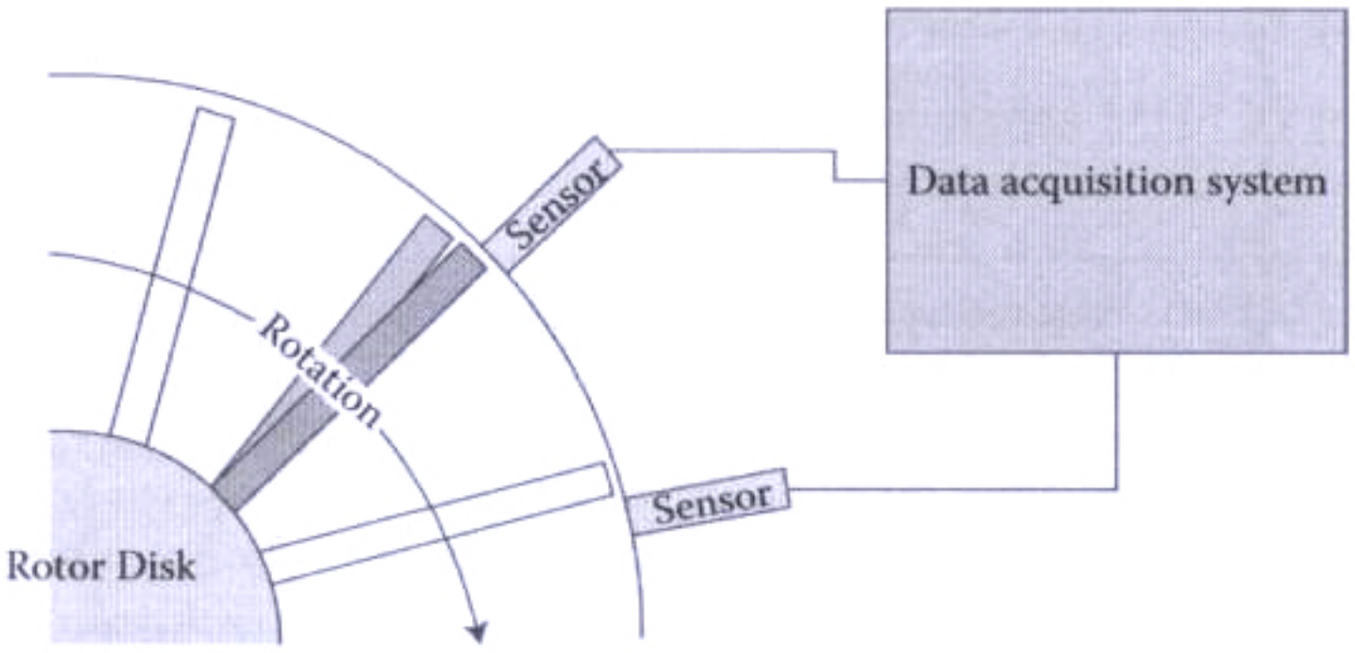
First-generation microwave blade tip clearance/timing sensor tested to 1200°C in high-pressure burner rig surviving three heat/cool cycles.



Source:Bar-Cohen, Y., 2014, High temperature materials and mechanisms,CRC Press, Taylor & Francis Group

PRINCIPLE OF THE OPERATION

Operational scheme of a pair of tip timing sensors during turbine rotor blade vibration detection procedure.



Source: Bar-Cohen, Y., 2014, High temperature materials and mechanisms,CRC Press, Taylor & Francis Group

1. The blade passes each sensor
2. The time of arrival is recorded.
3. Differences in between the time of arrival between the two sensors give:
   - blade vibration deflection
   - frequency informations.

MONITORING OF HIGH TEMPERATURE MATERIALS CONDITION

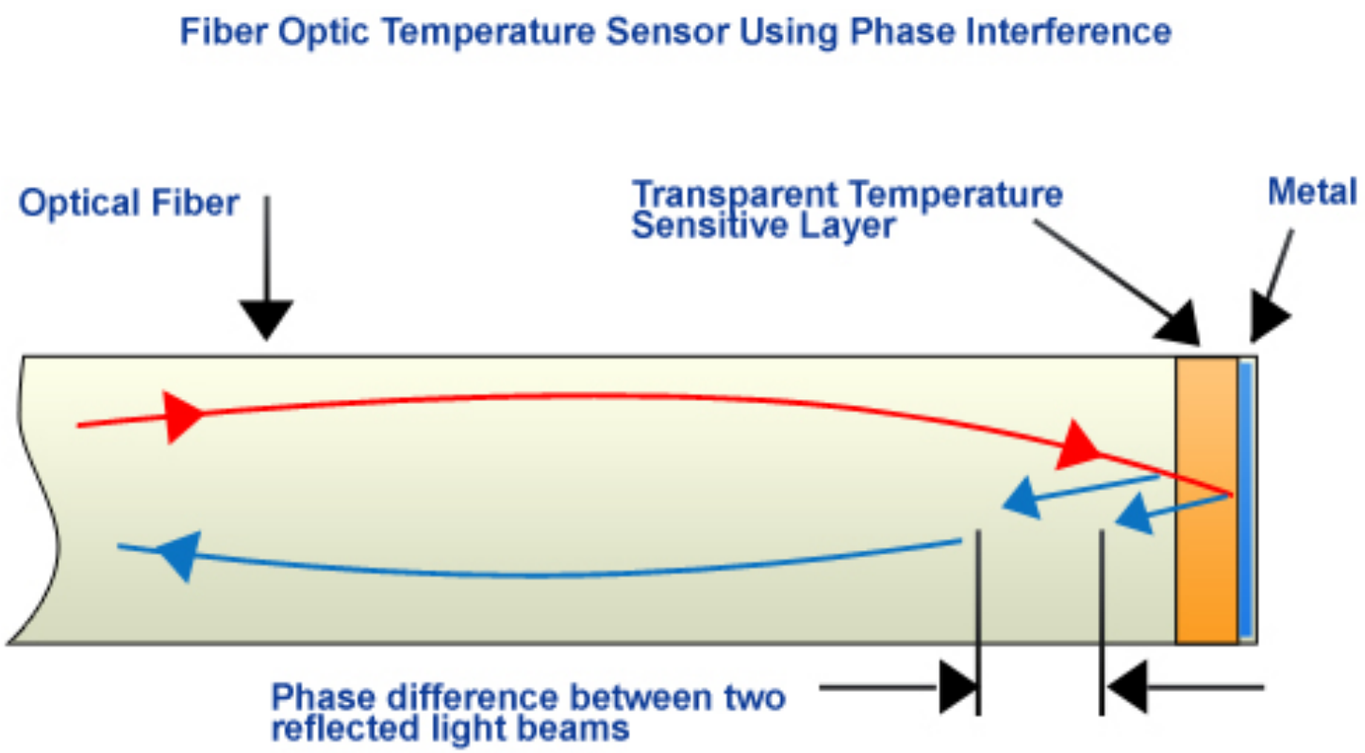
HIGH-TEMPERATURE FIBER OPTIC SENSORS

HIGH-TEMPERATURE FIBER OPTIC SENSORS

Features of the fiber optics sensors

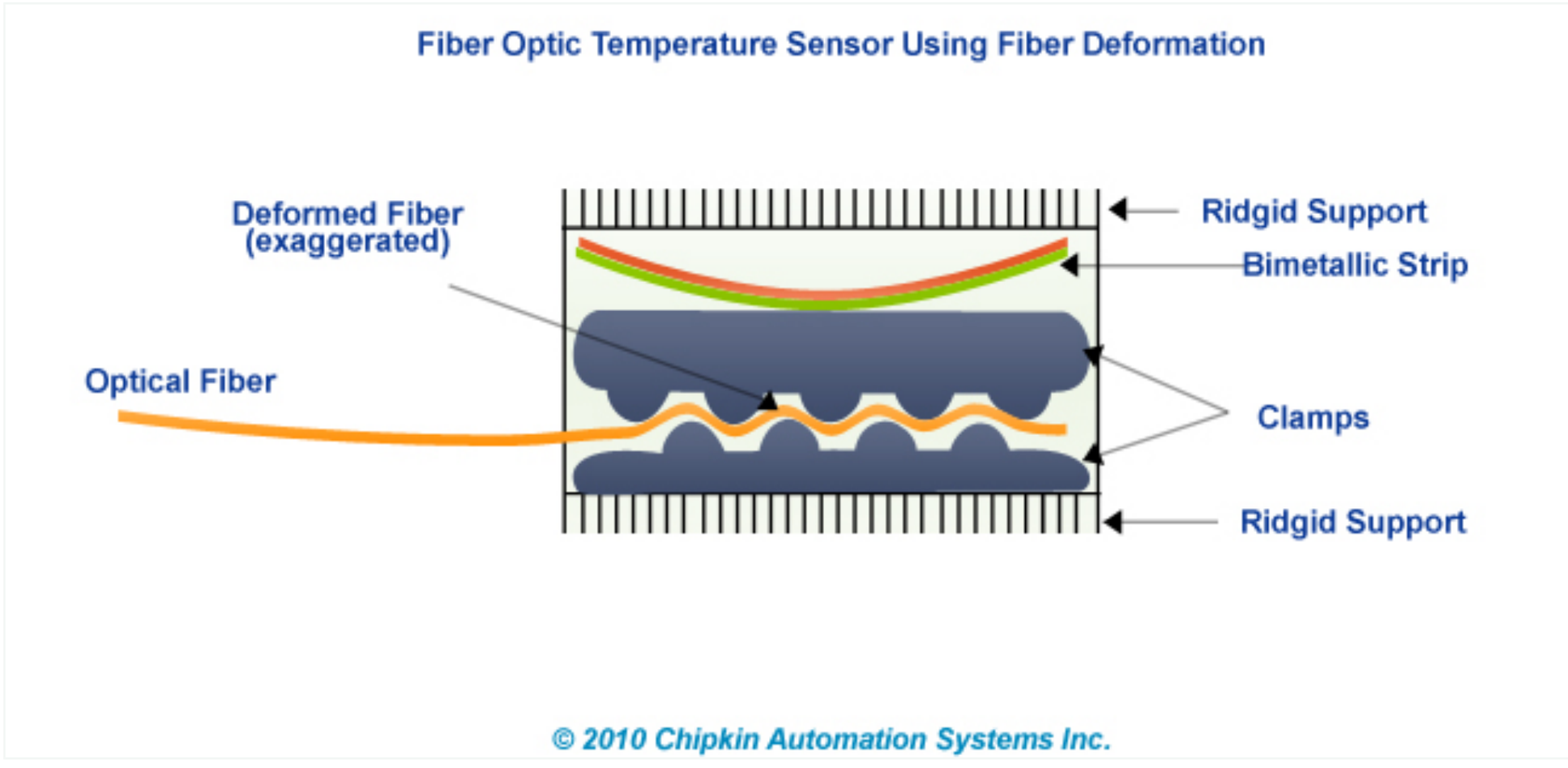
- Immune to the effects of electromagnetic interference
- Electrical insulation not needed
- Suitable to work in electrically charged environments or places where electric charge may be an issue
- Significant chemical resistance to harsh environments
- Small diameter allow for embedding fibers within a structure of engine (or any other installation)
- It is possible to fabricate multiple sensors on a single fiber
- There is no need for separate power wires

HIGH-TEMPERATURE FIBER OPTIC SENSORS



Source: http://automationwiki.com/images/4/47/Fiber_Optic_Temperature_Sensors_Using_Phase_Interference.jpg

HIGH-TEMPERATURE FIBER OPTIC SENSORS



Source: http://automationwiki.com/images/4/47/Fiber_Optic_Temperature_Sensors_Using_Fiber_Deformation.jpg

HIGH-TEMPERATURE FIBER OPTIC SENSORS

- High-temperature fiber optic sensors can operate at temperatures up to 1000°C
- They can withstand many thermal cycles, (e.g. 700 h of thermal cycling to 1000°C)
- Good accuracy (3 % in reference to S-type thermocouple)
- Very high costs of such kind of sensors

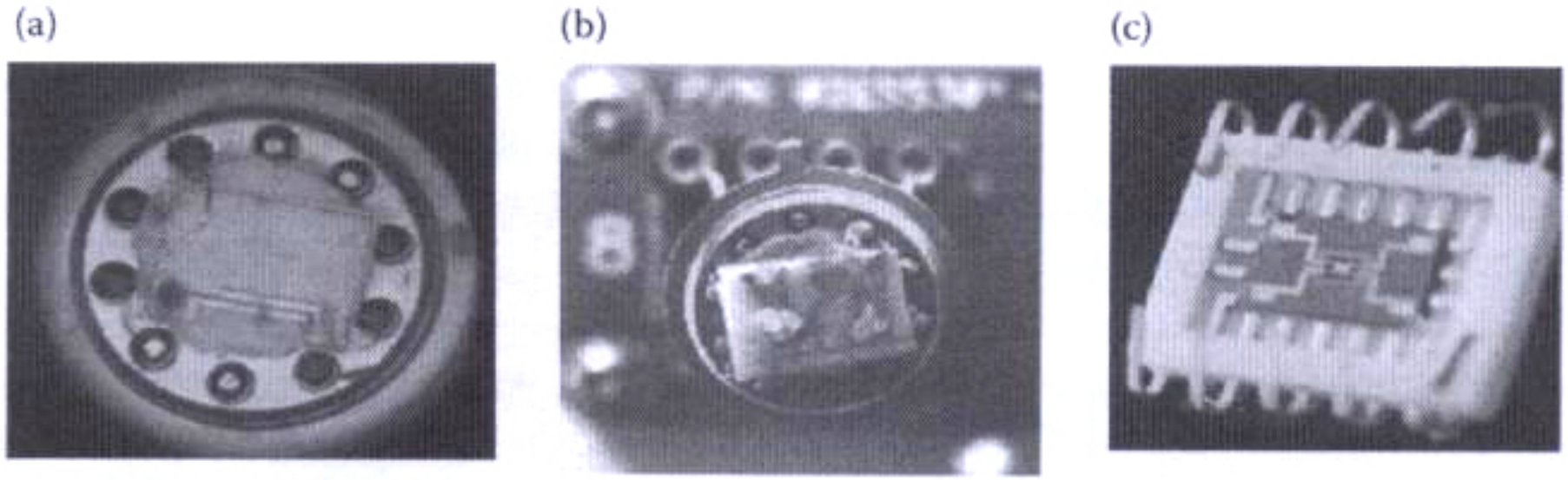
MONITORING OF HIGH TEMPERATURE MATERIALS CONDITION

ENGINE EMISSION MONITORING SENSOR (HIGH-TEMPERATURE ELECTRONIC NOSE)

ENGINE EMISSIONS MONITORING SYSTEM

- Sudden/rapid changes in emissions can indicate a state of health of an engine
- Turbine engine exhaust emission measurements are required during developing of new engine (combustion efficiency, optimization of fuel splits, etc.)
- For certification procedures

ENGINE EMISSIONS MONITORING SYSTEM



Basic sensors: (a) titanium oxide-based CO sensor, (b) lithium phosphate-based CO_2 sensor, (C) zirconia-based O_2 sensor

Source: Hunter et al. Smart sensor systems for spacecraft fire detection and air quality monitoring. In 40th International Conference on Environmental Systems, AIAA: Portland, Oregon, 2011d; Vol. AIAA 2011-5021

ENGINE EMISSIONS MONITORING SYSTEM

- Emission sensor technology based on gas micro sensor arrays
- Enable to quantify composition of constituents in turbine exhaust products (e.g. CO, CO_2, NO_X, unburned hydrocarbons)
- Different chemical sensing techniques for measuring different species
- Different materials need to be applied to fabricate sensor resistant to sever environment
- Sensor array formed by integration of a number of individual high-temperature gas sensors into a single platform

CARBON MONOXIDE DETECTION

- CO content is an indicator of combustion efficiency and engine health
  - Detector based on semiconductor oxide resistor (conductance depends on CO concentration in the environment)
    - TiO_2-based sensors for higher concentrations of CO (above 10 ppm)
- Modified version of the sensor suitable for lower concentrations
- Combination of the two sensors can cover large range of concentration from 1 to 500 ppm

CARBON DIOXIDE DETECTION

- CO_2 is also considered as an indicator of combustion efficiency
- Detector based on electrochemical cell with lithium-based electrolyte
- The output voltage depends on CO_2 concentration
- Construction of the electrochemical cell
  - Li_3PO_4 electrolyte
  - Li_2CO_3 sensing electrode
  - Li_2TiO_3/TiO_2 reference electrode
- Sensing mechanism: sensing electrode potential changes depending on CO_2 concentration, reference electrode potential is inactive to CO_2.

OXYGEN DETECTIONS

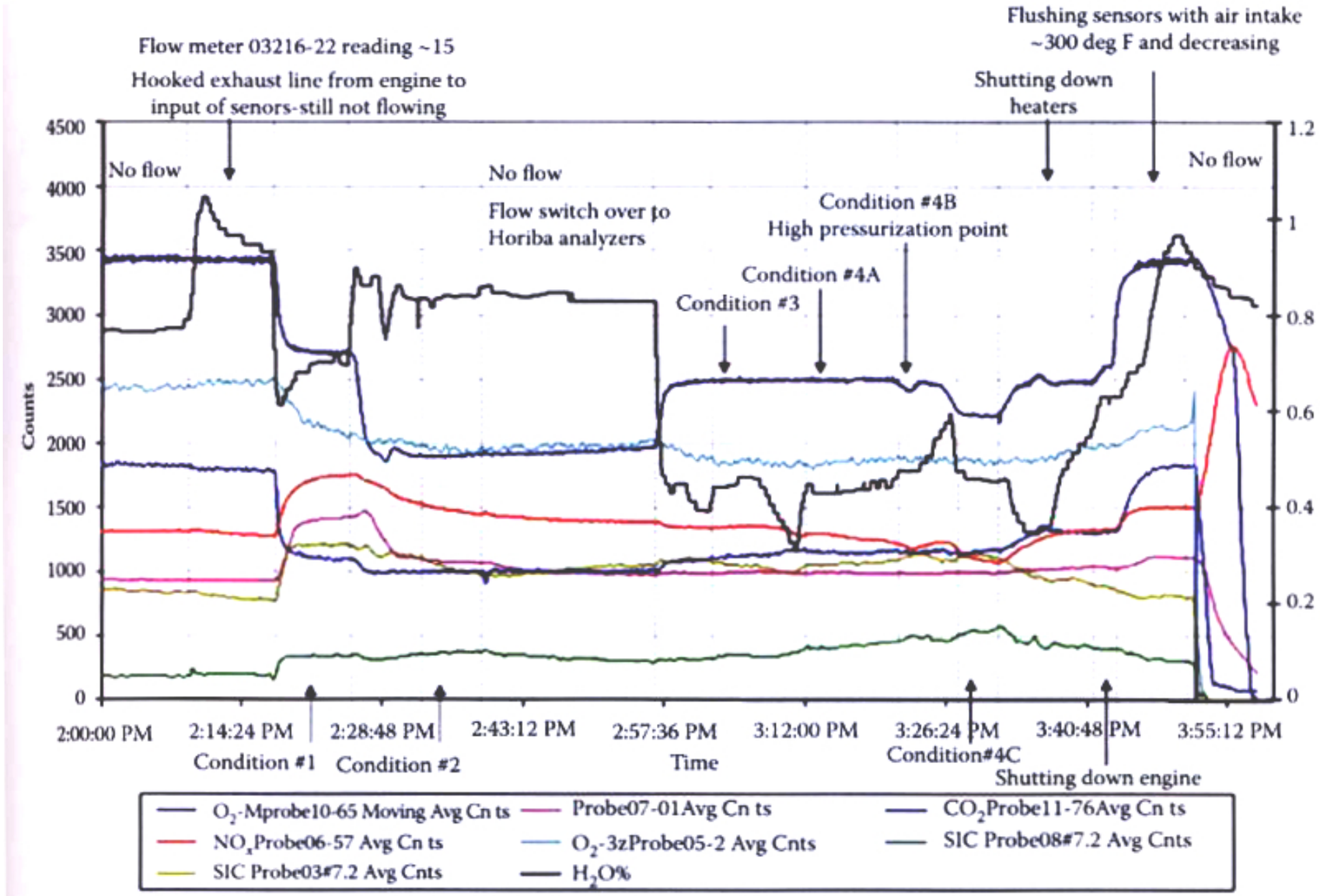
- Oxygen concentration acts as fuel/air ratio indicator as well as indicator of overall emission data quality
- Zirconia-based sensor using electrochemical cell technology
- Cell construction:
  - ZrO_2 solid electrolyte (ionic conductor in T>500°C)
  - Pt anode and cathode
- Electrochemical potential of the cell is proportional to the ambient oxygen concentration at high temperature
- Nearly linear response to various O_2 concentrations

HYDROGEN DETECTION

- Hydrocarbons concentration indicates of fuel/air ratio
- Indicates an engine health issues (e.g. oil leaks)
- Development of sensor based on SiC-based Schottky diode (ability to operate as semiconductor at temperatures up to 600°C)
- Use of Schottky diode allows to obtain high sensitivity
- Sensors still under development – problems with long term stability

SMART SENSOR SYSTEME

Example data set from emission sensor array during an engine test stand run over a range of operational conditions



Source: Bar-Cohen, Y., 2014, High temperature materials and mechanisms,CRC Press, Taylor & Francis Group

MONITORING OF HIGH TEMPERATURE MATERIALS CONDITION

SMART SENSOR SYSTEMS

SMART SENSOR SYSTEM

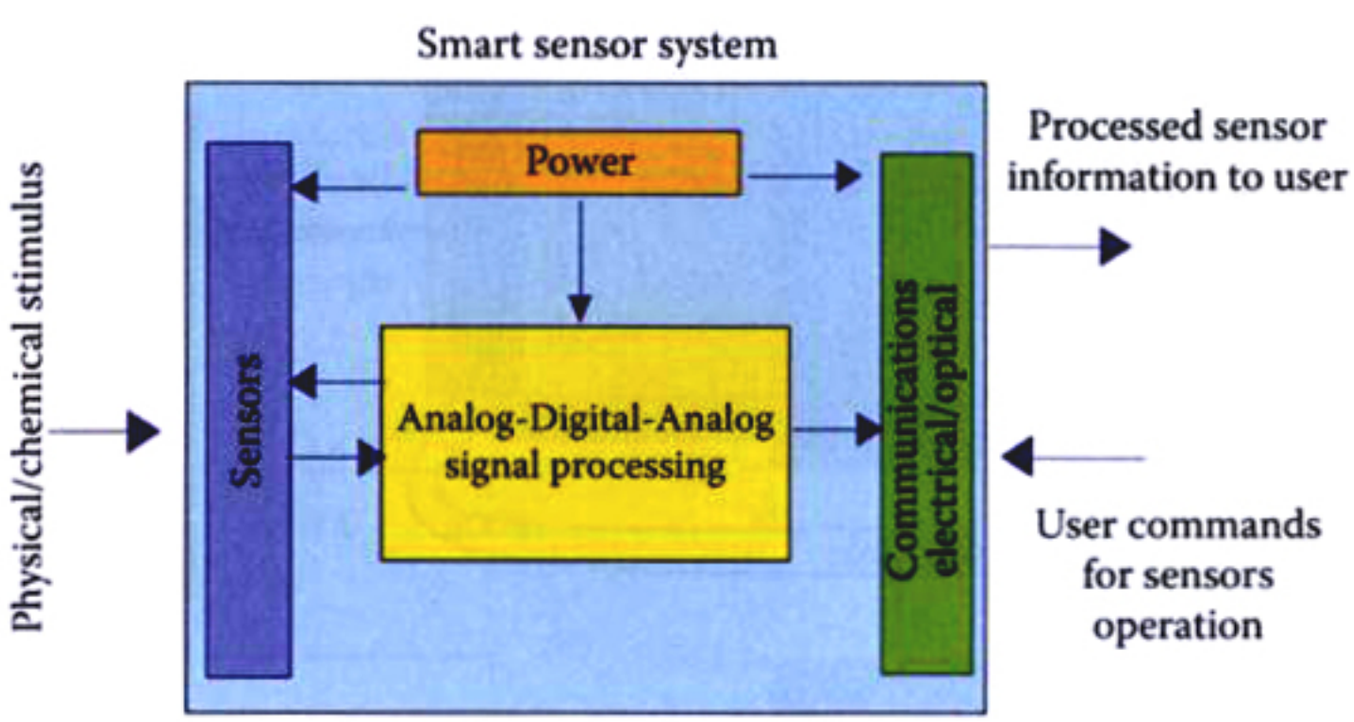
- A system that will be able to operate in harsh environments (in propulsion system) to provide improved information to intelligent engine system

- A propulsion system that can optimize parameters on basis of analysis of its internal conditions and surrounding environment could achieve a higher level of performance than a system which does not take into account changing conditions

- High-temperature sensors, electronics as well as wireless technology and proper power systems are needed to built a complex controlling system

SMART SENSOR SYSTEM

Smart sensor system – a combination of sensing element with processing capabilities provided by microprocessor. The sensor signal is processed to prepare output information for external user.



Source: Hunter, G.W. et al. Interface Magazine, Electrochemical Society Inc. 20(1), Winter, 2011b, 66-69

SMART SENSOR SYSTEM

- To introduce reliable high-temperature sensor system few elements need to be fully developed
- Silicon carbide electronics and packaging – complex electronic elements (ICs, RF transmitters A/D converters, etc.) are under development
- High-temperature wireless communications – high-temperature-compatible materials for electronic components are needed
- Power scavenging – thermoelectric and piezoelectric materials for collect thermal energy are under investigation

REFERENCES

1. Bar-Cohen, Y., 2014, High temperature materials and mechanisms,CRC Press, Taylor & Francis Group
2. Woike, M.R., Abdul-Aziz, A.,Bendic, T.J., A microwave blade tip clearance sensor for propulsion health monitoring, NASA/TM-2010-216736, AIAA-2010-3308
3. http://automationwiki.com/index.php?title=Fiber_Optic_Thermometers

THANK YOU FOR THE ATTENTION

THE END