Project title: “Accurate High Temperature Engine Aero-Thermal Measurements for Gas-Turbine Life Optimization, Performance and Condition Monitoring”

Project acronym: “HEATTOP”

Contract number: AST5-CT-2006- 030696

Type of Instrument: STREP

# Publishable Final Activity Report

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**List of contractors:**

| **No** | **Role** | **Country** | **Partner name** | **Acronym** |
|---|---|---|---|---|
| 1 | Coordinator,<br>WP Lead | Germany | Siemens | SIE |
| 2 | WP Lead | U.K. | Rolls Royce | R-R |
| 3 | WP Lead | Sweden | Volvo Aero | VAC |
| 4 | | Switzerland | Vibro-Meter CH | VM-CH |
| 5 | | U.K | Vibro-Meter UK | VM-UK |
| 6 | WP Lead | Netherlands | KEMA | KEMA |
| 7 | | Italy | CESI RICERCA | CESI-R |
| 8 | | Ireland | Farran | FARR |
| 9 | WP Lead | Belgium | Von-Karman Institute for Fluid Dynamics | VKI |
| 10 | | U.K. | Oxsensis | OXS |
| 11 | | Germany | Advanced Optical Solutions | AOS |
| 12 | | France | Auxitrol | AUX |
| 13 | | Germany | Institute of Photonic Technology | IPHT |
| 14 | | U.K. | Univ. Cambridge (2 depts : MAT & DENG) | UCAM |
| 15 | | Sweden | Univ. Lund | ULUND |
| 16 | | France | Onera | ONERA |
| 17 | | U.K. | Univ. Oxford | UOXF |

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# 1 Executive Summary

HEATTOP is a FP6 STREP project and stands for Accurate High Temperature Engine Aero-Thermal Measurements for Gas-Turbine Life Optimization, Performance and Condition Monitoring. Project costs are 8.8 M€ with an EU contribution of 5.2 M€ and 17 partners are involved.

The project addresses the need for improved instrumentation to be used in development, design evaluation and performance monitoring of aero engines and industrial gas turbines for power generation. In the middle of interest are the hottest regions of engines, the combustors and HP turbines where temperatures reach 2000K. The temperatures affect directly engine efficiency and life time of components. As current sensors cannot be placed in the hottest regions, knowledge of conditions inside the turbine is gathered from outside measurements which are then extrapolated by using models and assumptions. Turbine parts and other hot gas components are very expensive, have a shorter life time due to heavy mechanical and thermal loads and are critical for engine reliability. Accurate knowledge of temperatures would be very beneficial in predicting their life time and verify the performance of a design. Other aerodynamic parameters as dynamic and static pressure and clearances affect efficiency, operation and health of an engine. Clearances between blade tips and inner turbine housing contribute to efficiency losses over the turbine and therefore are kept to be as small as possible while at the same time rubbing of blades with subsequent turbine failure must be avoided. Dynamic pressures need to be accurately measured to assure the mechanical integrity of the engine.

The objective of the HEATTOP project was to develop accurate high temperature sensors for measurement of pressure, temperature and tip clearances. The consortium consists of 17 partners of different type, size and legal status and is led by Siemens:

- Original Equipment Manufactures (OEM): Siemens, Rolls-Royce, Volvo Aero
- Industrial Partners: Vibro-Meter CH, Auxitrol, KEMA, Vibro-Meter UK, Onera
- Research Institutes and Academia: VKI, IPHT, ERSE and the Universities of Cambridge, Oxford and Lund
- Small and Medium sized Enterprises: Oxsensis, AOS and Farran

The new sensors will reduce the uncertainty und reduced reliability of measurements with conventional thermocouples and pyrometry surface measurement techniques or enable measurement where currently no practical technique exists. A more accurate knowledge of temperatures may help to reduce consumption of cooling air and deliver a better prediction of life time and replacement needs. Clearances could be optimized when gaps are know accurately, leading to increased efficiency and reduced risk of damages.

Volvo, Vibro-Meter, Auxitrol, Onera and Cambridge University worked on understanding the degradation mechanisms of thermocouples, manufacturing process improvements, and extension of temperature ranges towards 1500°C, thin film thermocouples and the development of fast response thermocouples. KEMA, Auxitrol and Vibro-Meter worked on pyrometer techniques and error correction methods for surface temperature measurement, University Lund investigated thermographic phosphors for measurement in an afterburner and Siemens together with IPHT and AOS developed fiber optic sensors (Fibre Bragg Gratings, Fabry Perot interferometer and Black Body Radiators) for temperatures up to 1200°C. Developed techniques for gas path temperature and pressure measurements included Oxsensis' high temperature optic fiber dynamic pressure sensor, a total pressure and temperature probe by Oxford University, an aspirated probe for measurement of stagnation pressure and temperature by Cambridge University, a cooled probe for pressure measurement by VKI and finally an IR probe for TIT measurement by ERSE. An mm-wave tip clearance sensor utilises radio frequency technologies and was developed by Vibrometer, Siemens and Farran.

All partners delivered new sensors and techniques which were tested and validated in the partner’s lab, in rigs and finally real production engines of Rolls-Royce, Siemens and Volvo up to varying Technology Readiness Levels (TRL). The most advanced technique in respect to achieved TRL are the dynamic pressure sensor by Oxsensis which was validated in BTB engine and up to 1000°C at a Rolls-Royce rig and a fast response thermocouple by Auxitrol.

This report summarizes the progress and achievements over the project duration of ~3.5 years.

## 1.1 Purpose of this document

This document is part of the “final reporting” in HEATTOP. It introduces the HEATTOP Consortium, presents the objectives, summarizes the project activities and work performed to achieve the objectives, and finally discusses the main project results.

## 1.2 Relationship to Project Objectives

This “Publishable Final Activity Report” is required by contract to the project and FP6 reporting rules. The report is compiled with the target to provide an expanded summary of objectives and achievements of HEATTOP.

In HEATTOP, all the material required for this report has already been provided in form of deliverable reports and in activity reports for the last 3 reporting periods.

Therefore, this document provides high level technical information based on those detailed technical reports provided over the project duration. It cumulates and summarizes the results and put them in perspective to the objectives and the state of the art.

## 1.3 Intended Audience

Target of this report are mainly officials and reviewers of the EU commission and the interested general reader. The report may used by technical managers interested in obtaining a quick overview about instrumentation developments before stepping into technical details.

## 1.4 Summary and Structure of the Document

This report is structured into the following sections:

- Section 1 contains the “executive summary”, explaining the structure and contents of the document and providing an abstract of the report
- Section 2 summarizes the project objectives, presents the HEATTOP consortium and its structure and shows the development approach
- Section 3 describes the performed work, methods and approaches.
- Section 4 provides an overview of the “publishable results”
- Section 5 lists the dissemination activities
- Section 6 summarizes the HEATTOP achievements and provides recommendations for post-HEATTOP and future R&D activities

# 2 HEATTOP Project Scope and Objectives

## 2.1 Background

The development of aero engines and stationary heavy duty gas turbines for power generation is characterized by the need for products with higher efficiency, higher power outputs and with lower emissions. At the same time first time costs and life cycle costs must be minimized.

Improving engine efficiency, reliability and costs are the key demands on the European engine industry when creating new competitive products, distinguished to existing gas turbines by higher efficiencies, reduced environmental impact and reduced cost of ownership. Only by realization of these demands the Original Equipment Manufactures (OEM) are able to secure their market shares, protect the European employment and at the same time help to support European efforts in reducing emissions and fight against climate change.

Overall, the common goals needed to be addressed in the European gas turbine industry are:

- Reduced emissions and increased engine efficiency through improved understanding of High Pressure (HP) compressor, combustor and turbine behaviour.
- Reduced product development time and cost through more effective experimental processes.
- Reduced costs of ownership from improved performance and better component life prediction.
- Improved competitiveness of European products in global markets as a result of the above.

One key technology to cope with the demands and achieve the objectives is seen in gas turbine instrumentation and diagnostics of the very hot components. However, at the time being, significant gaps exist between required instrumentation for measurement of temperatures, pressures and clearances in gas turbines and the state of the art technology. That impairs with the capability of the OEMs to develop more advanced gas turbines. It is understood that the current technologies need to be further developed to allow achieving the aforementioned objectives. In a previous FP5 project EVI-GTI has identified in their ‘Lab Gap Matrix’ areas of deficiencies in current sensor technologies that are holding back engine development. These are:

- Current sensors are not applicable to the very hot components of our gas turbines or they do not survive the time of a test
- Current sensors are not applicable to the hot components of our gas turbines for long-time monitoring purposes.

- Current sensors in hot components of our gas turbines are not accurate enough.

To close those gaps the project HEATTOP "Accurate High Temperature Engine Aero-Thermal Measurements for Gas-Turbine Life Optimization, Performance and Condition Monitoring" was initiated.

## 2.2 Summary of Project Objectives

Looking at those gaps and common goals of European gas turbine industry the development goals of HEATTOP were defined:

- Reduced measurement uncertainty for design validation, enabling improved engine performance in new products;
- New instruments for validation of design in parts of engines which are inaccessible with current state-of-the-art instruments;
- Reduced engine development costs through more direct measurements of key component performance, reducing the amount of special testing required;
- Reduced cost of product ownership through reduced component life prediction uncertainty and therefore reduced parts consumption, and improved product performance giving reduced fuel burn;
- Sensors enabling better engine control and monitoring;
- Validation of all technology developments within the project in representative environments to provide instruments suitable for utilisation within three years.

To achieve these goals within a period of 45 months, a work programme was set up to develop measurement technologies for high temperatures in four areas with specific development objectives:

**1. Advanced tthermocouple technology**

- Understanding aging, drifting and degradation mechanisms of type K thermocouples
- Improvements in attachment techniques for high frequency measurements
- Thin Film Thermocouples
- A new thermocouple type as a result of a Design of Experiment
- Fast response thermocouples
- Thermocouple for temperatures >1500°C

**2. Measurement of surface temperatures**

- Embedded fiber optic sensors
- Pyrometers with corrections for fouling, with decreased degradation and with longer wavelengths
- Thermographic Phosphors for 2D measurements

**3. Gas path aerodynamic measurements**

- Fast response measurements at high pressure (HP) turbine exit with a cooled pressure probe
- An optical fibre multiplexable pressure sensor
- An intermittent choked nozzle probe for total pressure and temperature
- A non-intrusive IR sensor for turbine inlet gas temperature measurements
- Fast response pressure and Dual Thin Film temperature probes for traversable measurements in the turbine section

**4. Tip clearance measurement system**

- a mm-wave blade tip clearance sensor capable for use in long-time monitoring (10,000 hrs) under high temperatures

**5. Testing and validation** of all developed techniques in rigs and engines.

**6. Dissemination of technology** developments by the developers

## 2.3 Consortium

A consortium was formed to achieve the aforementioned project objectives. The consortium consists of 17 partners from 9 European countries, see Table 1. Partners in the consortium are OEMS of aero-engines and gas turbines, other Industrial Partners, University and Academia and Small and Medium sized Enterprises

| **No** | **Role** | **Country** | **Partner name** | **Acronym** |
|---|---|---|---|---|
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| 15 | | Sweden | Univ. Lund | ULUND |
| 16 | | France | Onera | ONERA |
| 17 | | U.K. | Univ. Oxford | UOXF |

*Table 1: Consortium partners in HEATTOP*

The coordinator of the consortium is

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The consortium formed a General Assembly which is acting on the terms of a Consortium Agreement and the EU contract to the project.

## 2.4 Project Organization and Development Approach

To organize the relatively large consortium of 17 partners with a work scope of 17 different sensor developments, the responsibilities and work were structured in three main areas and nine work packages:

- Specification and Validation,
    - Containing Work Package 1 - Definitions, and two work packages for sensor validation in test facilities; WP 6 - Sensor rig tests and WP7 - Sensor engine tests.
- Sensor Design and Development,
    - Containing four technical development work packages
- Coordination and Dissemination
    - Dedicated to coordination and project management (WP0) and dissemination of results (WP8).

At the project Kick-off meeting the three OEMs Siemens, Rolls Royce and Volvo formed a Lead Committee. Siemens headed the coordination and project management work. Further purpose of the Lead Committee was to steer technical and organizational responsibilities of all partners towards the main project objective which is solving the main technical challenges to provide prototype instruments for in-engine use within the project duration. The Lead Committee defined the specifications and requirements on the sensor technologies and coordinated validation testing. The four technical work packages were led by engine OEMs or by experienced industries or research institutes.

Meetings of all consortium partners were held twice a year to keep all partners up to date with the technical progress and ensure a common understanding and direction of the consortium. Additionally separate meetings for each work package group were held as required.

After the requirements and specifications were defined in WP1 and submitted to the partners, the four developmental work packages were performed in parallel. Interfaces between the tasks of each partner were clearly defined and a timetable for milestones and deliverables was developed.

The development work was followed by validation testing in rigs and production engines. Once the prototype delivered satisfying results during rig testing, the sensor was prepared and installed for final engine tests on production aircraft engines and power gas turbines.

The flow chart in Figure 1 depicts the organization of work.

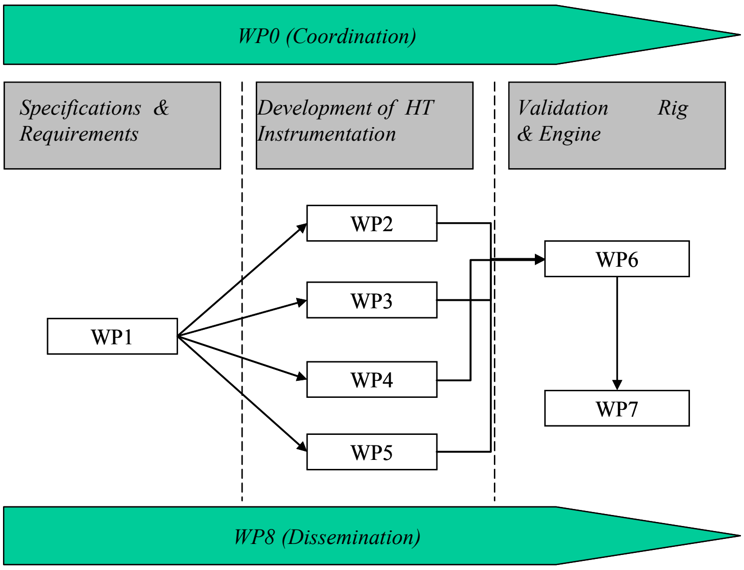


*Figure 1: The Work Package Flow Chart*

# 3 Performed Activities

## 3.1 Definitions and Specifications, WP1

The objective in Work Package 1 was for the OEMs to evaluate limitations of existing state of the art measurement techniques, its impact on gas turbine development and to formulate performance requirements and set target specifications for new technologies. During the first phase of the project the OEMs - Rolls Royce, Volvo and Siemens – worked on this objective.

The current state of art was defined by drawing on the results of work already carried out during the establishment of the EVI-GTI Lab Gap Matrix (WP2 of Framework 5 Thematic Network 'EVI-GTI'), with additional input provided from the three gas turbine OEMs and users of instrumentation within the consortium.

The engine environment requirements were gathered from the gas turbine OEMs and end users. The projected capabilities of the measurement technologies to be developed were gathered from the researchers and instrumentation supply chain.

This information has been combined to

I. Produce specifications for the technologies to be developed in the project
II. Determine the optimum validation approach for each technology for the later phases of the project.
III. Define ultimate targets for the technologies beyond the scope and timescales of the HEATTOP project

As a result the OEMS issued a Definition and Specification Document in which the state of the art with current sensors and the issues faced by engine OEMs because of these limitations were defined and captured. A second document defined for each technology target specifications, performance requirements and operating environment. Both documents D1.1 and D1.2 were issued by Rolls Royce.

With these documents, the OEMs gave clear directions to the consortium partners for their technology development and set the requirements for technology validation and demonstration later in the project.

At the conclusion of the project, the technology deliverable achievements were compared to the initial targets to assess the advancement of the state of the art achieved by the project. The results of these assessment and improved prediction of the long term ultimate potential of the deliverable technologies was reported in D6.3/7.4.

## 3.2 Technology Developments in WP2-WP5

In work packages 2 to 5 the partners worked on the technical developments in the areas of thermocouple improvements (WP2), temperature measurement of surfaces and solid structures (WP3), techniques for aerodynamic measurements of hot gas flows (WP4) and tip clearance measurement. Each of the work packages, except WP5, contained the development of several sensors. In the following paragraphs the approaches and methods employed in the individual work packages are described and the achievements are related to the state-of-the-art. Some diagrams and photos are presented for illustration of the work and achievements.

### 3.2.1 Life and accuracy optimization of current instrumentation for high temperature measurement, WP2

The most common way for measuring temperature in aero engines is using thermocouples. Thermocouples have to withstand very harsh conditions regarding temperature, pressure, vibration levels and pollutions, and have to keep their long term accuracy. Therefore objective of work under WP2 is to improve existing techniques by understanding mechanisms of drift, aging and degradation, develop better attachment techniques and develop new thermocouples for higher temperatures, with reduced drift and fast response times.

#### 3.2.1.1 Improved fast response thermocouples and improved attachment techniques for high frequency measurements

The main objective of this part of the project was to study, design, manufacture and test a new concept of thermocouples for component temperature measurement. In fact the idea was to produce a new more accurate and more rugged thermocouple able to measure at high temperatures and high flow rates.

The work started with a theoretical study of new design solutions. The study was actually a heat transfer analysis consisting of problem considerations, creating the calculation models, CFD-calculations on chosen models, synthesis of the results and report writing.

In all used models it was type K thermocouple materials with Inconell 600 metal sheath and Magnesium-oxide as insulation material.

Traditionally used thermocouples for surface temperature measurement consisting of two “naked” wires spot welded onto the measurement object, are very weak.

Our approach was to study an encapsulated design as it is bought from a supplier and directly installed onto measurement object. This should increase the ruggedness of the thermocouple significantly as the wires are protected by the metal sheath.

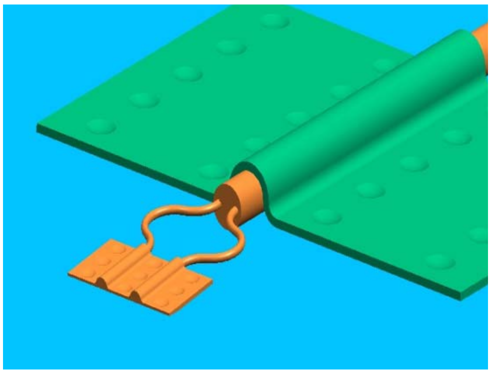


***Figure 2**: Traditional concept for measuring surface temperature*

Initially the idea was to study a grounded thermocouple with a “flattened” (encapsulated) junction. This solution should give more accurate measurement as the heat transfer between the thermocouple junction and measurement object would be improved. Both 2D and 3D study were performed taking into account stagnation effect and limited heat transfer as dominating parameters in affecting measurement accuracy. However stagnation effect was too high and an alternative design was needed.

In order to eliminate the effect of the stagnation problems “wedge” design was introduced. A study of the “wedge” design was also performed showing that stagnation effect is much lower and thereby the accuracy was improved.

From a heat transfer point of view both alternatives show good potential in improving accuracy, but generally the “wedge” design shows better potential. We also recommend further studies regarding 3D effects as they has not been treated completely taking into account the scope of this work.

This study was a recommendation and a guideline to the partners in this work package how to continue studying of new solution and try to find out a reliable method for manufacturing of a new thermocouple solution. Vibrometer UK developed two different type of thermocouples (recessed junction and flattened type)

Several thermocouples of both types were supplied by to Volvo for high temperature vibration tests. The other partner Auxitrol continued the development further in order to produce new thermocouples for engine test.

Vibration testing of new designed thermocouples has been performed at Volvo Aero high temperature shaker rig. The test thermocouples (both flattened and recessed junction type) and reference thermocouples were installed onto the top of the fixture extender.

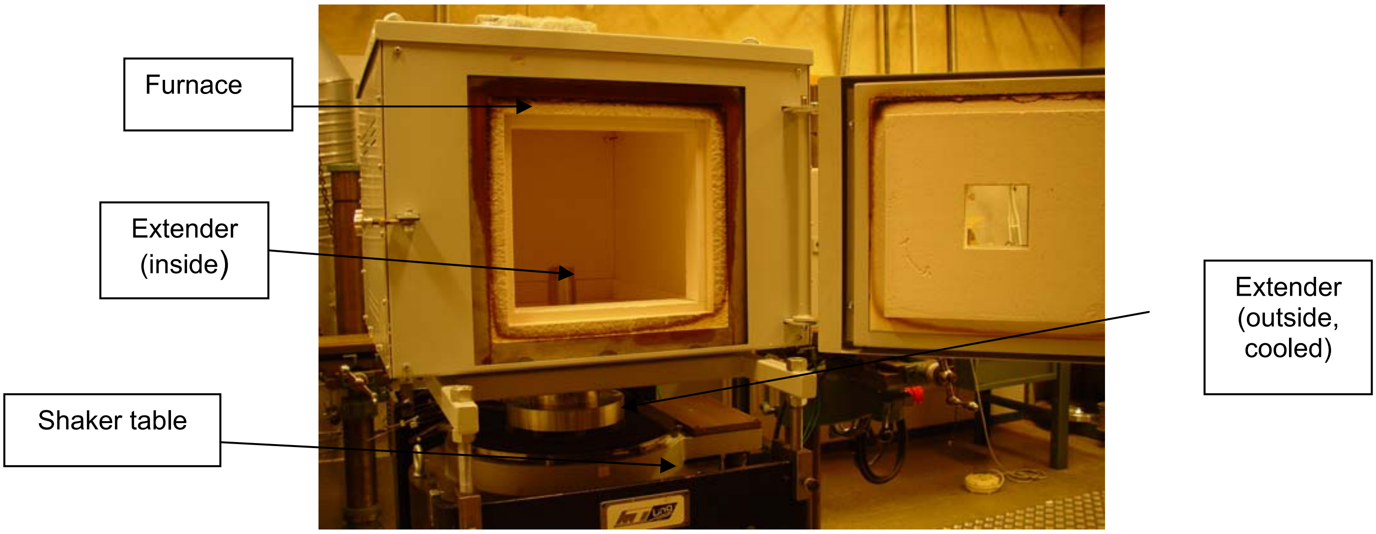


***Figure 3***: **High temperature shaker rig**

The thermocouples were tested at four different temperature levels (20ºC, 500ºC, 750ºC and 1000ºC) and four different acceleration load levels (1G, 5G, 10G and 20G). A frequency sweep 50-2000 Hz (up and down) at each combination acceleration/temperature was applied. Finally a 10 million cycles test at 1000ºC and 10G was performed.

This test was a durability test and below is an extract of the results showing temperatures measured by all thermocouples at 10G and 1000°C tested for 10 million cycles.

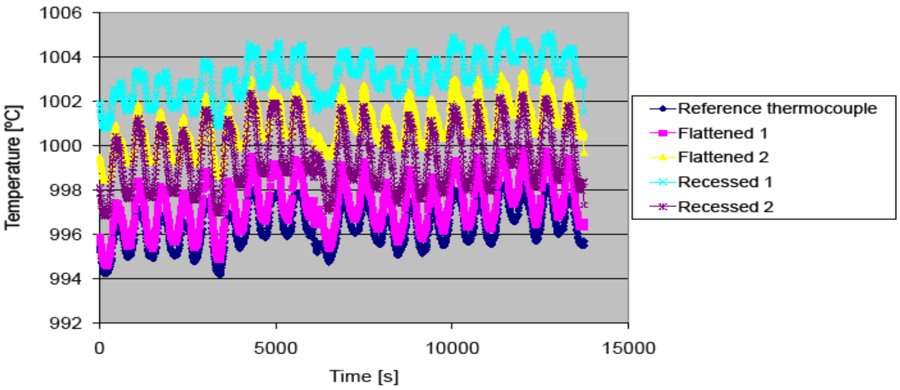


***Figure 4**: Temperatures measured by all thermocouples at 10G and 1000°C tested for 10 million cycles.*

All thermocouples survived the tests and we can be convinced that a step forward has been made. The results show that an improvement of the accuracy (measuring in environment with high speed hot flows) can be achieved with retained ruggedness of installations.

However the flattened type shows higher potential to be developed more. It is more rugged, the junction is in good contact with the metal surface and thereby it should be better for this type of applications.

The recessed junction type is more fragile and the junction is in poor contact with the metal surface. Generally it is difficult to find out a reliable manufacturing method that is quality assured with reasonable costs.

Complete results have been presented in D 2.2 issued by Volvo Aero

More tests with thermocouples from Auxitrol were performed on a calibration furnace in WP6 and on the RM12 engine within WP7.

The chosen test object was a “dummy” temperature rake that has been instrumented with 3 new thermocouples and 3 conventional thermocouples for measurement of surface temperature (i.e. open wires spot welded onto the surface), as reference thermocouples. The reasons for choosing a dummy rake as test object is easy assembling into the hot flow of the engine and easy installation and cable routing out of the engine, without time consuming and expensive engine modification. The installed thermocouples were K-type thermocouples. The thermocouples were installed at three radial positions; one new thermocouple and one reference thermocouple at each radial position, as close as possible to each other, see the picture below. The installation was done by making only one weld spot through the thermocouples tip.

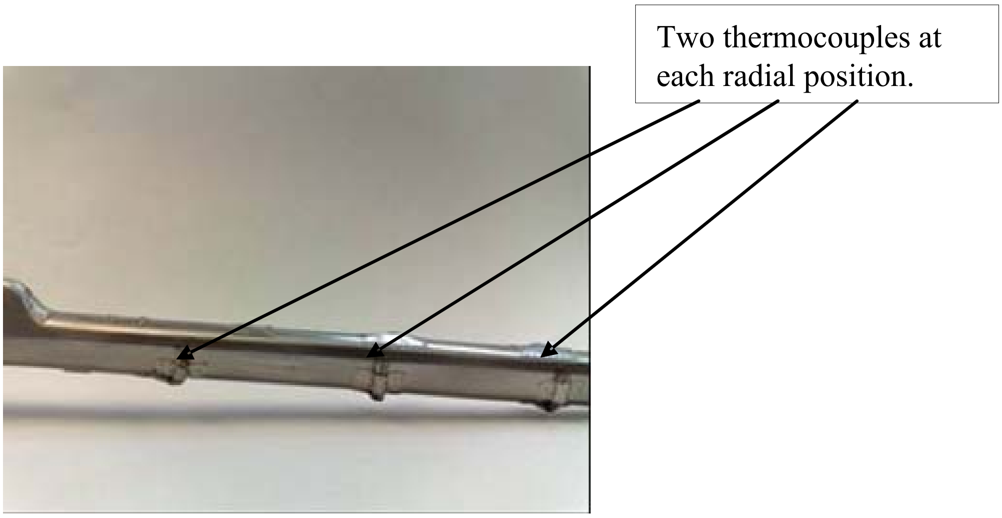


Figure 5: Fast response TC at engine rake

All thermocouples were connected to rig measurement system that is capable to register steady state and transient readings. The readings were mainly done at stable, steady state conditions, but a few transient readings were done as well.

All thermocouples survived the test and still functional afterwards. The new thermocouple installation seemed very rugged, despite the only one weld spot.

Figure 6 shows the difference between the reference thermocouples and new designed thermocouples.

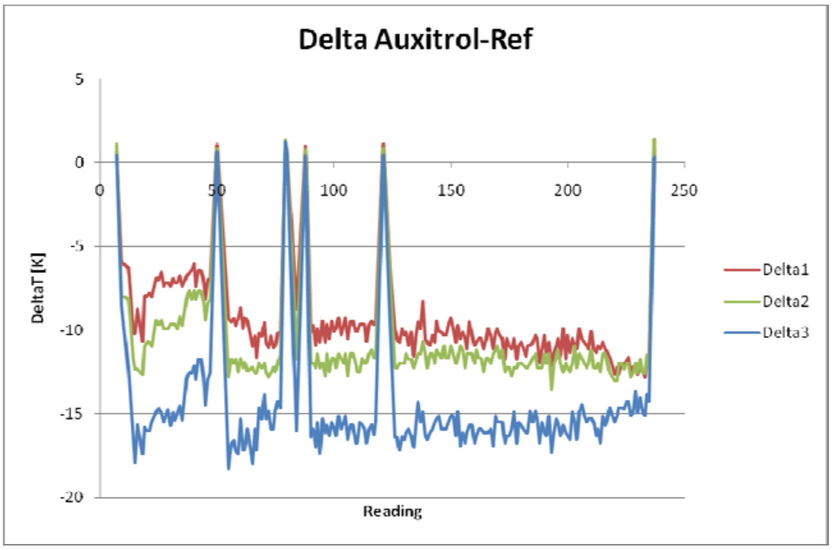


Figure 6: Difference between each pair of Auxitrol and conventional TC

The new thermocouples were expected to indicate a lower temperature because of reduced stagnation effect. Several other factors may affect the result though:

- Localization of the hot junction, within the sheath and on the dummy rake.
- Stagnation effect
- Mechanical and thermal work on the new thermocouple This results in changed measurement properties, typical for type K thermocouples.

We can also state that the difference is approximately 10-15K after for all three thermocouples. This allows us to say that the difference is approximately 1% at these temperature levels, which is fully acceptable.

However the biggest benefit, seen from an OEM perspective, is the reduced installation time and ruggedness that is achieved with new thermocouples.

Any comparisons in terms of time response could not be performed as no reference was available.

### 3.2.1.2 Drift and error of thermocouples, ageing of materials, high temperature effect, measurement errors

Some improvements have been done by Auxitrol on current K-type thermocouples in order to meet higher measurement performances:

- A development of fast response time thermocouples has been done for an accurate engine wall temperature measurement: a new design of grounded thermocouple with specific flat and thin shape at its extremity has been successfully manufactured and validated in laboratory and on the RM12 military engine from VOLVO. The TRL7 has been reached on this thermocouple.
- An analysis of error affecting current K-type thermocouples has been done, and laboratory testing have been performed to quantify the long term effect of high temperature on the thermocouples accuracy; it has been demonstrated that our manufacturing processes and our materials selection allow to keep a class One tolerance after high temperature exposure and temperature; this result has been validated by controlling some thermocouples coming from After sales services after several thousand of hours of engine running.

### 3.2.1.3 The Effect of Materials and Temperature on the Operational Drift Life of Thermocouples

The primary objective of this task was to understand how materials, temperatures, and manufacturing methods affected the rate at which thermocouples drift, overall accuracy, and reliability. The premise was to see if it was possible to produce an optimized thermocouple system by using Taguchi robust design methods (a "top-down" approach). The work was undertaken in parallel with Cambridge University who were looking at ways of increasing the temperature of operation of aerospace grade thermocouples.

The work involved testing a wide range of thermocouples using different combinations of sheath materials, element materials, and manufacturing processes on the basis of Taguchi Orthogonal Arrays. Testing was performed using thermal cycling tube furnaces developed specifically for the project (see Figure 7). These could insert and extract the thermocouples from the furnaces at the desired intervals to better-replicate the conditions the thermocouples will experience in service. Most previous studies on thermocouple drift have only used isothermal (constant) heating.

The thermocouples were tested for 2000 hours and 4000 cycles (i.e. 30 minute cycles) at temperatures between 700°C and 1050°C. Their output was compared to an in-situ platinum reference. The test data showed excellent grouping for each batch indicating that each thermocouple system had its own unique drift characteristic (see Figure 8). The testing was also severe enough to reveal failure mechanisms within the thermocouples.

The data were reduced (using Taguchi methods) on the basis of optimization functions of lowest drift, best accuracy, and lowest failure rate. The result had to be a compromise between the three objective functions. However, the selected combination of parameters produced a thermocouple with exceptional robustness, very low drift rates (<1°C), and accuracy to within 0.2%.

The thermocouple was also tested in a combustion rig where temperatures were in excess of 1000°C. Due to the short duration of the test it was not possible to assess drift characteristics. However, the thermocouple displayed excellent performance and robustness. It was not possible to make an assessment of accuracy during the combustion rig trial due to absence of a calibrated reference in the same location as the VMUK thermocouple.

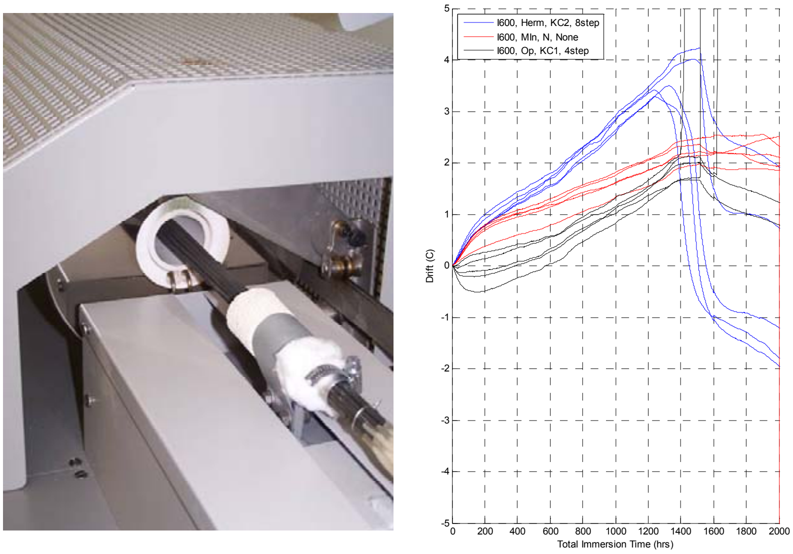


Figure 7: thermal cycling tube furnaces

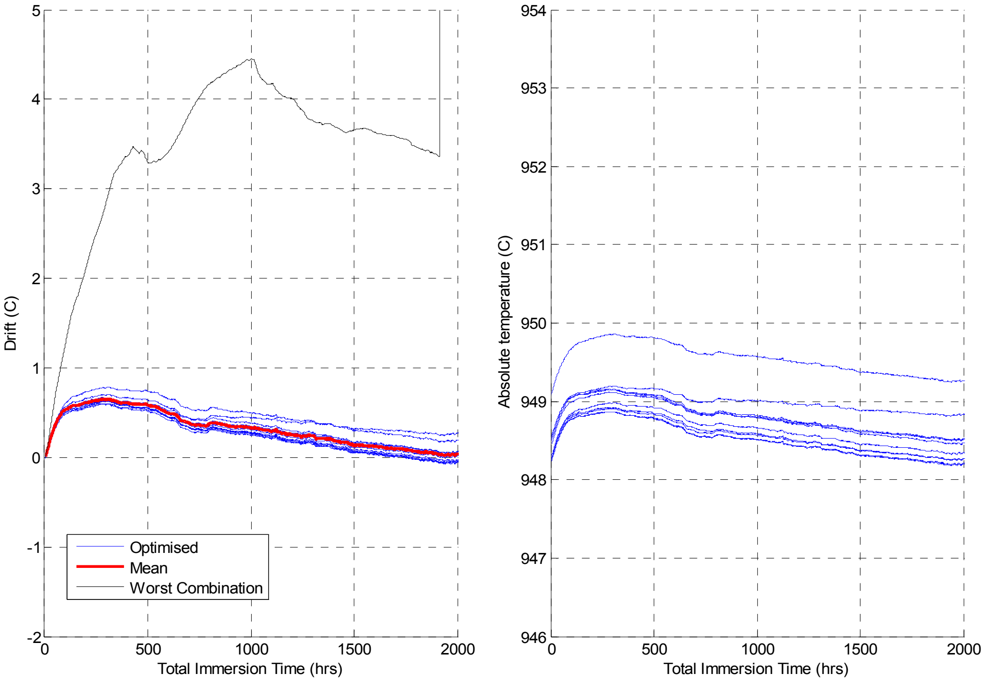


***Figure 8: thermocouple system drift characteristic***

Substantial materials analysis was also undertaken to get a better understanding of the degradation mechanisms and why the optimal combination worked so well. A range of optical, scanning electron microscopy, and energy dispersive x-ray analyses were undertaken on some of the thermocouples tested (e.g. see examples in Figure 9).

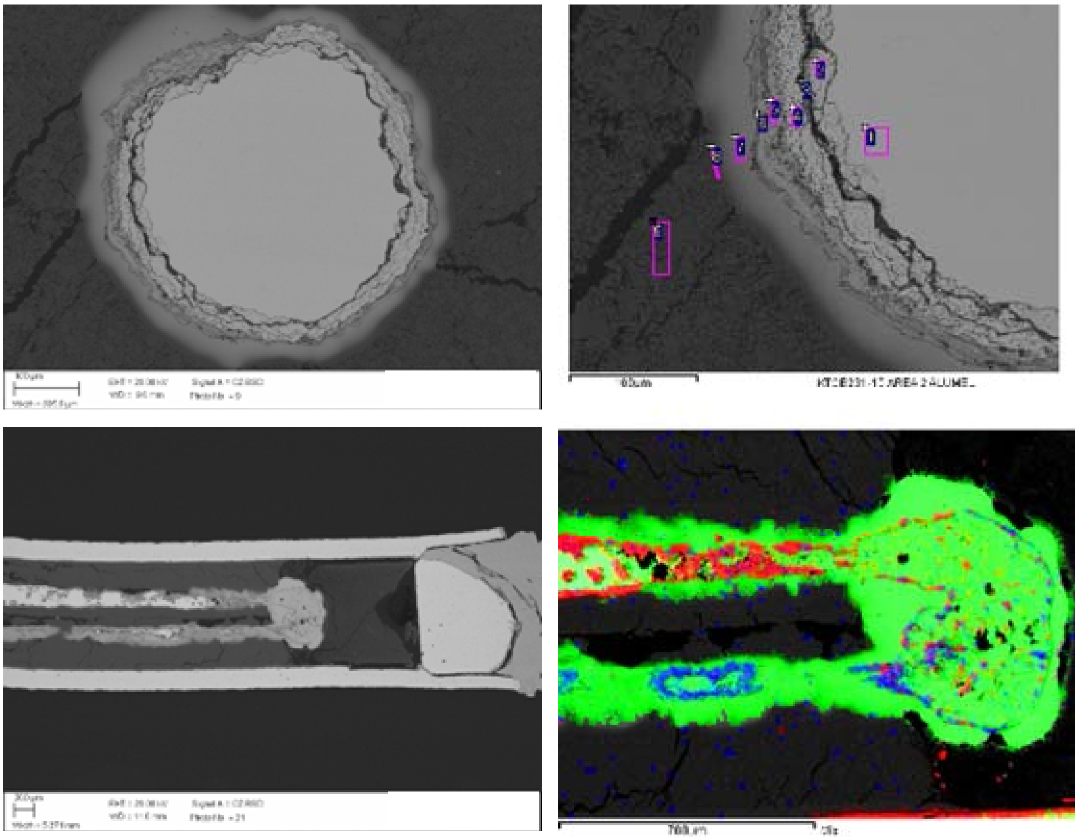


***Figure 9: materials analysis***

It was determined that the optimised system worked so well because the element material had exceptional oxidation resistance, had better short-range ordering characteristics and the selected sheath alloy was also very well matched to the thermoelectric material leading to minimal contamination. Maintaining hermeticity was found to be absolutely critical in maximising the performance and life of the thermocouple.

The optimised thermocouple was able to demonstrate performance that is substantially better than typical aerospace industry requirements (e.g. +/- 1% accuracy over life) and for temperatures up to 1050°C. The result should be improved certainty in exhaust gas temperature (EGT) measurements, leading to improved engine efficiency and better estimation of engine ageing via EGT margin erosion.

## Novel Thermocouple Development (UCAM)

During HEATTOP project a deep understanding of drift in Nickel based type K thermocouples has been achieved for both bare wire and MIMS (Mineral Insulated Metal Sheathed) configurations mainly in the temperature range 1000-1200°C.

Thermocouple drift does not allow MIMS type K thermocouple to be used above 1000ºC, because of the resulting loss of accuracy above this temperature.

As a result of this investigation a new strategy has been chosen to minimise drift in MIMS configuration: the resulting new thermocouple is based on a new configuration and new materials which remove the main cause of drift, allowing temperature as high as 1200ºC to be measured with lower uncertainty (0.2%). At the same time the new thermocouple has a better oxidation resistance and as a result longer life than the conventional Nickel based thermocouple.

The adopted strategy has been filed with the UK Patent Office and a prototype is currently being built and will be tested extensively.

#### 3.2.1.4 Thermocouples for very high temperature

A feasibility study has been done by Auxitrol for very high temperature measurement (up to 1500°C) in engine environment, using thermocouple technology. This level of temperature induces the use of new materials, for the thermocouple wires, the insulation and the sheath, as well as an arrangement of all manufacturing processes. The concept developed in HEATTOP was the following:

- development of specific thermocouple extremity, able to withstand very high temperature, Laboratory tests including high temperature, heat shock resistance, thermo-mechanical characterisation allowed to select a technology based on technical ceramic sheath;
- Assembly of the extremity onto a conventional thermocouple in lower temperature area. A brazing technology is being developed for this application in partnership with a soldering expert company.

The development of ceramic extremity for high temperature measurement is on-going; testing phase on ceramic extremities and on ceramic to metal brazing are underway; a status on the feasibility of developing ceramic thermocouple extremity for turbine application will be made within the next 6 months. The TRL3 has been reached on this ceramic thermocouple development.

#### 3.2.1.5 Thin Film Thermo couples for surface temperature and heat flux measurements

**Background**

Thin Film thermocouples offer great advantages compared to conventional instrumentation (small size, low mass, ability to not disrupt gas flow, to withstand high centrifugal acceleration and to be incorporated in components with minimum machining).

Thin Film thermocouples (TFTC) developed by Onera can be directly sputtered onto metallic aircraft engine/stationary gas turbine components (combustor, vanes, blades) made of nickel-base alloy, for example. These sensors are designed to be used for temperature measurements in development test rigs. They implement a multilayer coating prepared by radiofrequency cathodic sputtering (PVD, physical vapor deposition process).

### Objectives

The main objective is to meet the need of jet engine/gas turbine manufacturers regarding temperature measurement and heat transfer evaluation at the interface between metallic components (combustor, vanes and blades) and Thermal Barrier Coating (TBC), commonly used to protect materials constituting these components against high temperatures. Onera, in cooperation with Rolls Royce and Volvo Aero studied the innovative concept of Thin Film thermocouples inserted between TBC and metallic parts and performed validation tests of TBC coated TFTCs deposited on test pieces (sensor calibration, vibration test) and component (combustion test).

### Work performed

- From the state of the art of Onera, a preliminary study has been conducted on Laboratory test pieces to evaluate the feasibility of multilayer coatings involving TFTCs and TBCs.
- Following the preliminary study, manufacturing of TBC coated TFTCs on a combustor component , evaluation and validation works (thermal sensitivity versus temperature, aging, vibration testing, combustion testing) were conducted

### Main results

Feasibility of TBC coated TFTCs deposited on nickel-base alloy pieces and combustor components have been demonstrated:

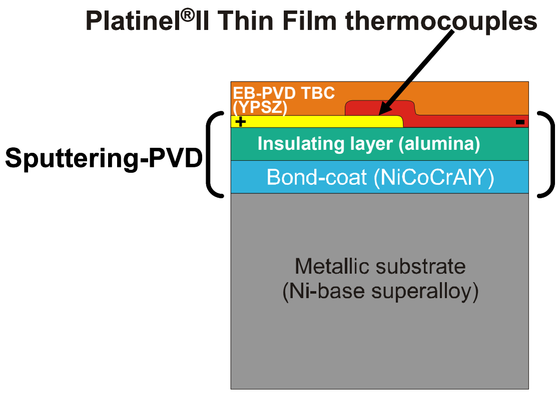


***Figure 10 Multilayer coating on Ni-based superalloy substrate***

Evaluation of TFTCs characteristics verified

- Adherence of TFTC films on alumina insulating layer.
- No cracking, no delaminating on nickel base superalloy substrates after aging.
- Calibration of thermal sensitivity versus temperature from ambient temperature to 1000°C.
- Electrical isolation of sensors relative to the metallic nickel base superalloy substrates.
- Relative variation of thermal sensitivity with time.

A combustor component (representative of flame tube wall) instrumented with TFTCs and coated with EB-PVD TBC was produced and was validated in Rolls Royce IP Combustion Rig.

→ The results demonstrate that Thin Film thermocouples can operate in a realistic combustion environment (maximum wall temperature of 860°C, bulk flame temperature of 1346°C) and give measurements consistent with those of conventional sensors.

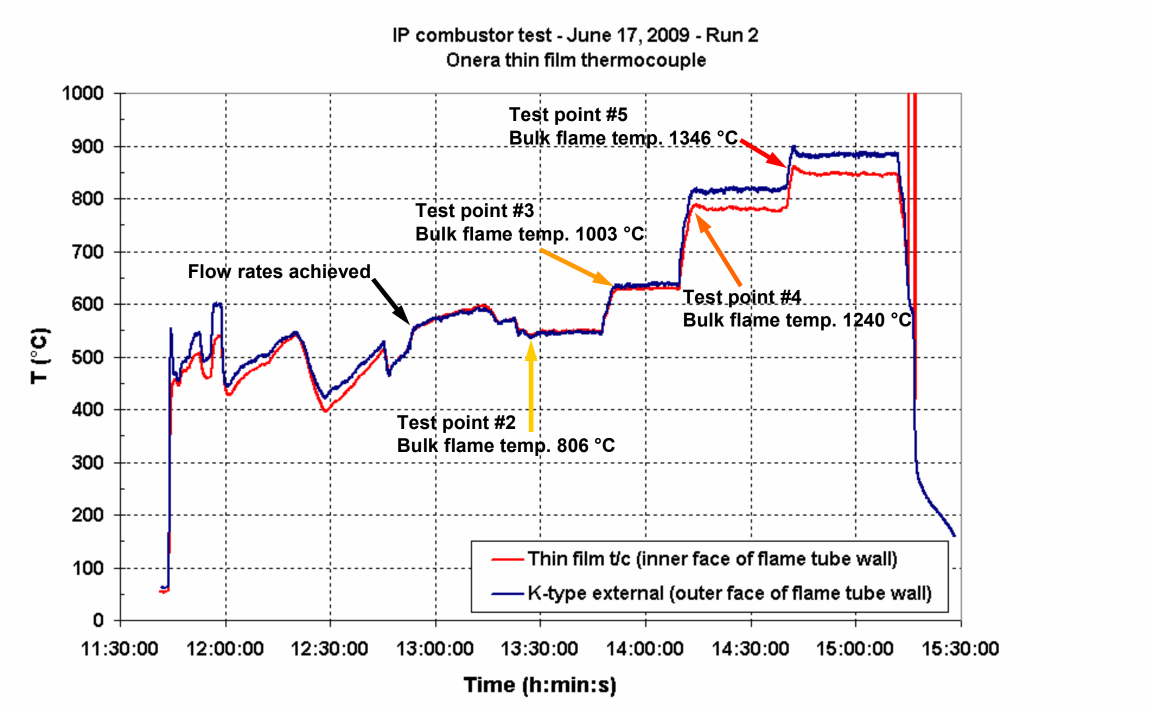


***Figure 11: IP Combustor test: TFTC & reference type K TC temperature responses (f=1 Hz)***

Performance requirements have been largely achieved. Feasibility of TBC/metal interface temperature measurement with Thin Film thermocouples is demonstrated. However, thermal sensitivity drift of Thin Film thermocouples at high temperature must be reduced to decrease temperature measurement uncertainty. Environment requirements have been partially reached depending on the combustion test conditions applied to the sensor (temperature, pressure, gas flow velocity). Requirements concerning sensor size, substrate material and sensor ability to survive and give measurement after TBC coating have been exceeded.

On the basis of those satisfactory results, further development of Thin Film thermal sensors by Onera in cooperation with industrial partners would increase the performances of Thin Film thermocouples and promote the application of thin film technology to other types of sensors such as heat fluxmeters.

### Validation of TRLs

TRL3 (Laboratory tests) is validated according tests results obtained in the evaluation of characteristics.

TRL4 is validated according results obtained in the Combustion test.

## 3.2.2 Advanced Solid Temperature Measurements, WP3

### 3.2.2.1 Fiber optical solid temperature measurement, WP3.1

**Background**

The efficiency of gas turbines is increasing with operation temperature. Therefore, gas turbines operate close to the thermal limit of their materials. However, 10 degree of temperature increase above the limit corresponds to a life time reduction of about 50 percent. In order to avoid fast degradation of materials the temperature of blades and vanes has to be known very accurately. Usually models are being used to estimate the material temperature out of other engine parameters. The accurate measurement of blades and vanes is very difficult.

Fiber optical temperature sensors have some potential to be more appropriate than conventional thermo couples for measurements in the extreme environment of gas turbines. Due to the high elasticity of silica and sapphire glass fibres the life time is expected to be higher than for thermo couples. Fiber sensors can be built extremely small for exact positioning at hot surfaces and reducing the averaging effect of the sensor. Using Fiber Bragg gratings, several sensor elements could be interrogated with one single fiber rather than routing bundles of thermo couple wires through and out of the turbine.

**Objectives**

The main objective of the work package is the development of high temperature fiber optical sensors for the measurement of gas turbine metal temperatures such as vanes and combustor walls. To reach this goal several steps had to be done:

- survey of materials such as fibers, packaging and connectors usable high temperature measurement
- down selection of promising technology approaches and materials
- development and investigation of sensor element
- development of appropriate high temperature packaging
- building of demonstrators
- validation testing of sensor in harsh environment

**Partners involved and their tasks:**

There have been three partners involved into sub work package 3.1.

IPHT Jena , Germany (Institute of Photonic Technologies)

- Task was mainly the technology survey and the development and characterization of sensor elements in the lab.

AOS GmbH, Dresden (Germany)

- As manufacturer of fiber optical sensors and equipment AOS tasks were the development of the sensor packaging, integration of the IPHT developed sensor heads and the transfer from the basic sensor technology into an appropriate sensor design.

Siemens AG, (Germany)

- Siemens tasks were the coordination of work and partners in sub work package 3.1., defining test specifications, developing design options for integration of fibres into gas turbine components and performing validation tests. In the project, Siemens provided the specification of the sensors, participated in the development of the sensor design and performed major parts of the sensor testing.

## Technical approaches and results

### Blackbody Radiation Sensors

The fiber optical Blackbody radiation sensor (BBR) has a thin layer as sensor element which emits thermal radiation corresponding to Planks radiation law. The emitted light is collected with a large core fiber of low aperture inside the tube and guided to a detector. Therefore the sensor setup is rather simple. However there are several effects which can influence the measurement and reduce the achievable accuracy. The emissivity of the Blackbody layer can change with time due to material degradation effects and chemical reactions at elevated temperatures and in the presence of dust and reactive gases. For the tests very thin layers of Pt, Pd and Ir were Laser welded onto the end of thin Inconel600 tubes of typically 1.0mm in diameter. The small thickness of the sensing layer allows measuring much closer to the hot surface of turbine vanes and tiles than the common thermo couples. Stable operation at 800°C over several months could be demonstrated with a 20um thick Pd-foil and 100/125um Multimode fiber after 500h at 800°C

In our chosen approach, the emitting material is applied in front of an optical fibre's surface, by a pre-package that will be attached during the application of the reactive layer.

Laser welded Inconel capillary

The fibre had to be fixed inside the protective tubing with appropriate high temperature glue. Alternatively, Au-coated fiber and a high temperature soldering technique can be applied.

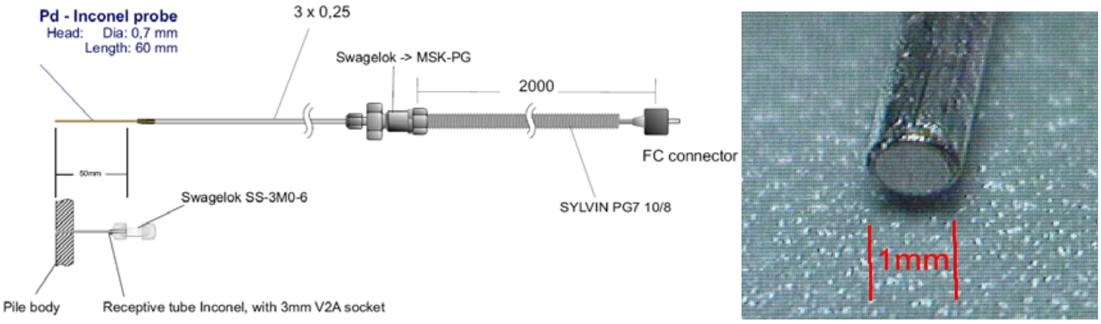


*Figure 12: BBR-Pd sensor with receptor on the pile body.*

### Silica FBG sensors

Several types of FBG in SM Silica fiber have been tested for their use for high temperature sensing. Drawing tower FBG were bleaching out at about 250°C, standard Excimer Laser FBG around 450°C, strong Power inscribed FBG type I around 700°C, FBG type II around 900°C, Femto-Second Laser inscribed FBG around 1000°C. However, fused Silica starts softening at temperatures around 850°C. This implies that no stable FBG temperature sensor operation can be guaranteed above 800°C. While short-term measurements using fs-FBG could be demonstrated up to 1000°C long term measurements were only stable up to 800°C. The bare FBG arrays where placed in thin Inconel tubes for testing. For embedding the FBG sensors for practical applications very thin and long holes can be eroded directly in the test object.

A type IIa FBG - array was manufactured, containing 3 FBGs multiplexed in one fiber.

The fs-FBGs could be realized only with a single measurement point in the probe, because fs-FBGs were not available as arrays.

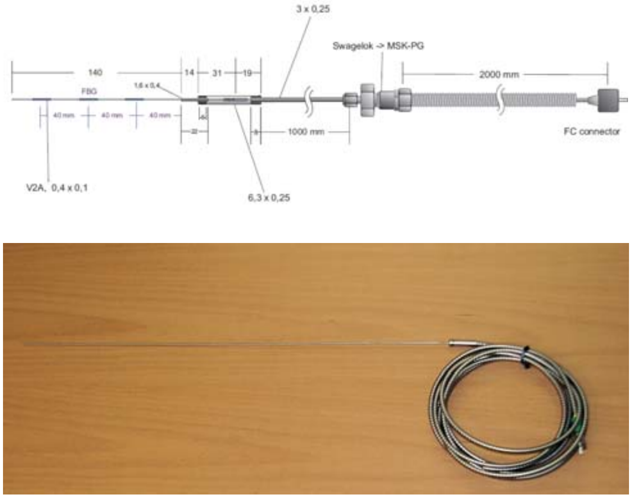


***Figure 13: High Temperature FBG sensor. 3 measurement points are sequentially arranged in the probe.***

Furthermore, a miniaturized FBG sensor packaging was developed. We focused on to achieve a similar mechanical robustness as for the RIG test design. One of the advantages of this miniaturized design is the possibility of calibrating the probe in a standardized calibration furnace.

### Sapphire FBG sensors

Sapphire fiber FBG can be produced using high power Femto Second Laser inscription. Due to the multimode character of the fiber the FBG spectrum has multiple fine lines which sum up to an envelope spectrum. In order to get an accurate Bragg wavelength signal out of the envelope spectrum it is necessary to equally illuminate these modes. Using a long large aperture multimode fiber before coupling into the sapphire fiber or can do this either by doing mode scrambling. There are several effects which disturbed the interrogation of a sapphire FBG. Pollution of the fiber can cause intensity loss due to the missing fiber gladding. So far this problem can be solved by using very clean ceramic capillaries as a housing of the sapphire FBG. The IPHT sapphire FBG were tested up to 1750°C. Above 1500°C the intensity of the thermal radiation had to be considered. The use of a high power light source and a correction of the effect by switching the light source off could reduce this effect.

The sapphire material is significantly different from fused silica. That leads to a couple of restrictions that appear when developing a packaging for the sapphire FBG:

- The sapphire fibre can only work as a wave guide (in terms of transporting the optical sensor signal) when surrounded by materials with lower refractive index. That means, no metal can be used for encapsulating and protecting the sensor.
- The sapphire fibre cannot be spliced to silica fibres. However, connections must be established because sapphire fibres are of short lengths. Those connections require a uneconomic effort and are not reliable.

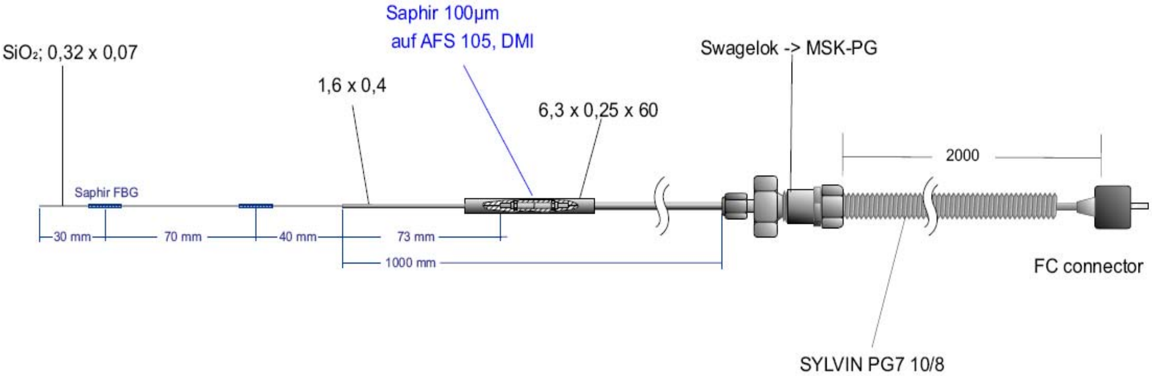


*Figure 14: Sapphire FBG sensor. The sapphire fiber contains 2 multi-mode FBGs*

### Tests performed on prototypes

Numerous laboratory tests were performed continuously by IPHT and Siemens. Tests included sensitivity measurements, aging and drift measurements by temperature cycling, vibration and bending impact and cross sensitivity checks.

The objective of validation tests at the HP combustion rig at DLR in Cologne was to:

- apply a realistic environmental conditions to sensor (heat, vibrations)
- test sensor and sensor packaging for robustness
- compare TC and optical sensor readings

For a test period of about 2 weeks the prepared tile with the embedded sensors was installed at the combustion test rig. In total, 8 combustion test runs of several hours each were performed during that time. The measurements were recorded continuously during the whole test period with a data rate of about 10Hz and evaluated afterwards. The test was successful.

The BBR sensors were interrogated with InGaAs foto receivers and recorded with an analogue data recorder with about 10Hz sampling rate. The FBG sensors were interrogated with an 1550nm Polychromator from IPHT and recorded with about 10Hz sampling on a PC

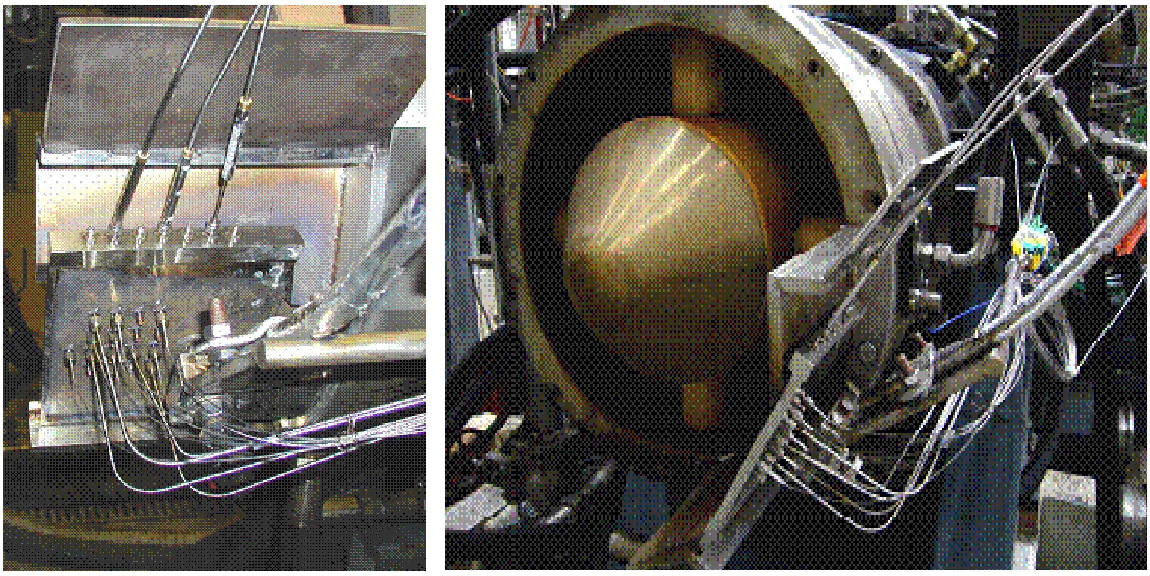


*Figure 15: Fully instrumented sensor tile.*

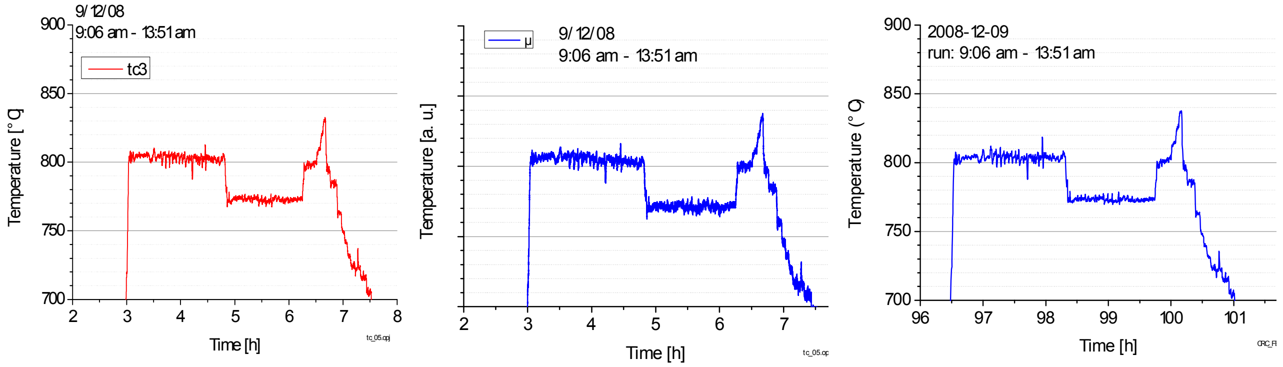


***Figure 16: results at rig at DLR, thermo couple, Blackbody sensor (BBR), fs-FBG sensor***

The fs-FBG had shown best performance of all tested FBG sensors, no drift occurred during the test period. The tested sapphire FBG still showed instabilities probably be caused at least partially by the adapted interrogation system, the total measured drift was about 30K. The Pd foil BBR sensor confirmed the good results from lab tests and was also in the rig the best choice, no drift occurred during the rig test at DLR.

## Achievements in relation to the state-of-the-art, impact on industry or research sector

At the beginning of HEATTOP the technology of fiber optic sensors, especially for high temperatures and harsh conditions of gas turbine environments, was quite low developed.

Development work on optical fibres for temperature measurement is increasingly done at academia and manufactures. Several suppliers have developed sensors for high temperature measurement of ~1100°C. However, these sensors are either too large, have a poor spatial resolution or are not available for use in harsh environments. Here is one of the big achievements of the work of HEATTOP: The temperature range and life time of sensing elements were pushed beyond existing limits and a package was developed that resulted in robust sensors.

Within this task 3.1, all sensor concepts were increased in terms of the technology readiness level.

| Sensor type | Range | Application (air and stationary) | TRL before | TRL after |
|---|---|---|---|---|
| Blackbody layer sensor | 900°C | Bond coat temperature | 2 | 5 |
| Sapphire Fabry Perot | 900°C | Solid part temperature | 1 | 3 |
| Silica FBG type II | 600°C | Solid temperature distributions | 3 | 5 |
| Sapphire FBG | 1200°C | Gas temperature | 1 | 4 |
| Silica fs-FBG | 800°C | Solid temperature distributions | 1 | 4 |

***Table 2: Comparison of TRL***

Related to the state of the art of fiber optic technology a big step was made with the Sapphire Fiber FBG that reached 1200°C as a packaged sensor. The sapphire fiber has the potential for even higher temperatures and for the first time temperatures of above 1700°C were measured with a fiber. To our knowledge this is a first time achievement. The demonstrated potential will trigger research and development to provide packaging concepts in order to produce a lasting sensor with the fiber. Further, investigation into new interrogation concepts and stabilisation of Sapphire fibers with multiple FBGs will be needed to make this technique available for long term monitoring.

The concept of BBR fibers enables an application for accurate point measurements. Potential for stretched goals are increasing the temperature range above 800°C as this is too low for the OEMs. In addition, concepts for calibration and temperature stabilisation of detectors must be developed.

Fabry- Perot elements reach high temperatures of 1100°C. This is state of the art. However, they are quite big, fragile and do not provide the incremental benefit of accuracy and resolution.

In respect to the choice of measurement technique when solid temperature measurements are required the industry shall still use thermocouples as the standard sensor. The fiber optic sensors are an option for special measurement tasks but still require a high level of specialist support for the analysis of data. More operation experience and long term measurements are needed.

The new multiplexable sensors offer attractive solutions for the industry when multiple points with a single sensor shall be measured in their engines. It reduces the efforts, the degree of intrusion and saves costs. With more life time experience the sensors could become an interesting alternative for condition based monitoring applications.

### 3.2.2.2 A pyrometer corrected / calibrated for transmission and fouling, WP3.2

**Objective**

Though temperature sensing of objects in aero engines and industrial turbines by radiation thermometry is a technology being applied for quite some time now, it suffers from a number of issues that limit its accuracy.

These are:

- Fouling of the optics
- Degradation of optical system transmission (through high temperatures)
- Unknown (and variable) emissivity of the object and reflected radiation
- Presence of Thermal Barrier Coatings (TBC) on blades

Besides, for (long-term) monitoring applications currently available systems are limited in versatility because an expensive turbine modification is often necessary and this results in a fixed line of sight.

The main objective of KEMA in this field of radiation thermometry is to make the application of radiation thermometers in heavy duty gas turbines easier and less susceptible to fouling and transmission losses.

**Work performed**

Based on the current prototype of a pyrometer that can be utilized in an existing boroscope hole of a GE Frame 6B turbine, design improvements have been studied, including the inclusion of a facility for on-line calibration for fouling and transmission losses, thus enhancing the instrument with self-inspection capability. Other objectives were a modular design in order to be able to interface easily with a wide range of turbines and ease of installation and maintenance of the system. Design parameters of importance are:

- Temperature resistance of optical fibres (state of the art high-temperature resistant fibres are used)
- Degradation of the optics. Special solutions are envisaged that limit optics degradation and that correct for degradation
- Air cooling of the probe

**Design of the mechanical construction**

The final design has been constructed and laboratory tested. It features a built-in thermocouple against which the radiation thermometer can be calibrated during operation.

In 2008, the KEMA boroscope hole pyrometer has been validation tested at the Siemens Berlin Testbed with excellent results. It could be proven that measurements errors of up to 140 ºC, caused by fouling and transmission losses of the optics, could be reduced to about 3 ºC. The probe design has been thoroughly reviewed by Siemens, to ensure the probe would not jeopardize the integrity of the turbine.

In a quest for further reduction of the size of the instrumentation, a probe with refractive optics has been designed and constructed, see Figure 17

***Figure 17: KEMA boroscope pyrometer with refractive optics***

Thermal Barrier Coatings, ceramic layers on metal turbine blades, cause difficulties with the interpretation of measurement signals, because of scattering and absorption characteristics. A mathematical model has been constructed and implemented to improve the understanding of measurement signals. The model has been successfully applied to existing measurement results. Future research in this field should be directed into the thermo-optical characteristics of the TBC.

### Achievements in relation to the state-of-the-art, impact on industry or research sector

The instrumentation objectives have been achieved, and instruments with TRL 6 have been delivered. As far as is known, the demonstration of the boroscope radiation thermometer with on-line calibration facility was the first of its kind. It is important to recognize however, that interpretation of radiation thermometer signals is also affected by emissivity and reflected radiation issues, to which the current development does not give an answer.

The utilization of borescope holes for radiation thermometry applications certainly enhances the applicability of the technology and could have great impact on its use for troubleshooting turbine problems, blade tests, blade life modelling and the like.

#### 3.2.2.3 Improved optical designs for Pyrometers (decreased degradation), VMUK, WP3.2

The primary objectives of these studies were to understand the most significant degradation and error mechanisms in radiation pyrometers and then look at ways of reducing these using new developments in technology. This is with a view to increasing the service interval of pyrometers such that they might be viable for civil aviation use, as opposed to their current exclusive military use.

The degradation tests comprised a range of accelerated thermal cycling, vibration, contamination, and other mechanical tests to determine the long-term stability of a pyrometer system. The main degradation mechanisms identified were signal attenuation due to lens fouling and a sensitivity of the bundle transmission to temperature. Variation in the surface emissivity was also found to be a major contribution to error. On the basis of the results from these tests, a dual wavelength system was developed. While dual-wavelength technology is not strictly new, it is believed that recent developments in detector and electronics technology coupled with VMUK's significant in-service experience with pyrometry will lend substantial benefits over previous incarnations of dual-wavelength systems.

A series of laboratory tests were undertaken to assess the effects of lens contamination on measured signal. These tests showed that the chosen dual-wavelength system was able to almost completely compensate for lens contamination when particles sizes were of the order >10um. However, smaller sub-micron particles were found to still cause errors even with the ratio method due to what is thought to be Rayleigh scattering effects (seeFigure 18). However, SEM analysis has shown that the air purge system incorporated in the current VMUK pyrometer is very effective in preventing very small particles from reaching the lens. In theory, therefore, it should only be the larger (> 10um) particles that can reach the lens, which have been shown to be compensated for by the dual-wavelength system. It is anticipated, therefore, that the combination of an effective purge system and a dual-wavelength detector will help to substantially minimize the effects of contamination and substantially increase the pyrometer service interval beyond current levels.

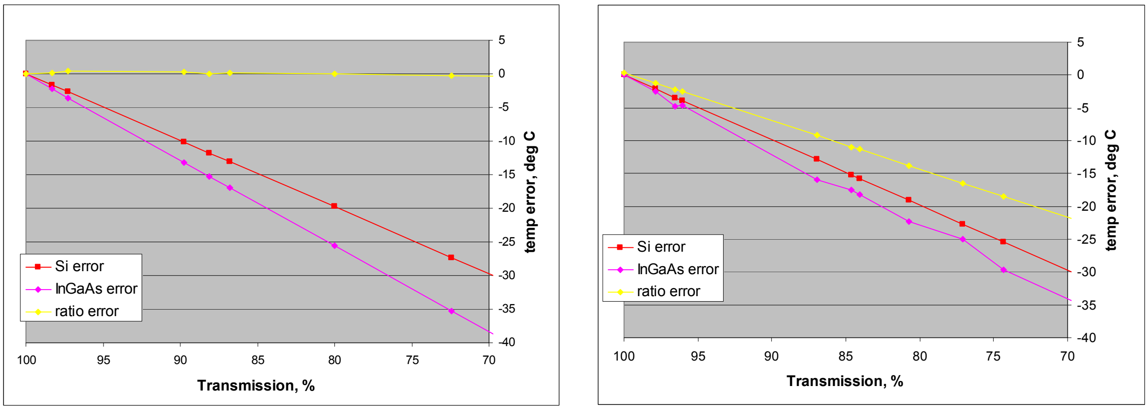


*Figure 18: effects of lens contamination*

The next step was to test the pyrometer within a real engine environment to understand its performance. A Rolls-Royce Viper 202 engine was used to perform these tests (see Figure 19). The pyrometer was positioned downstream of the single stage turbine and pointed upstream towards the low pressure side of the blades. Several of the blades had been coated with paints of different emissivity to provide a useful once-per-rev signal as well as provide understanding of the performance of the dual-wavelength system.

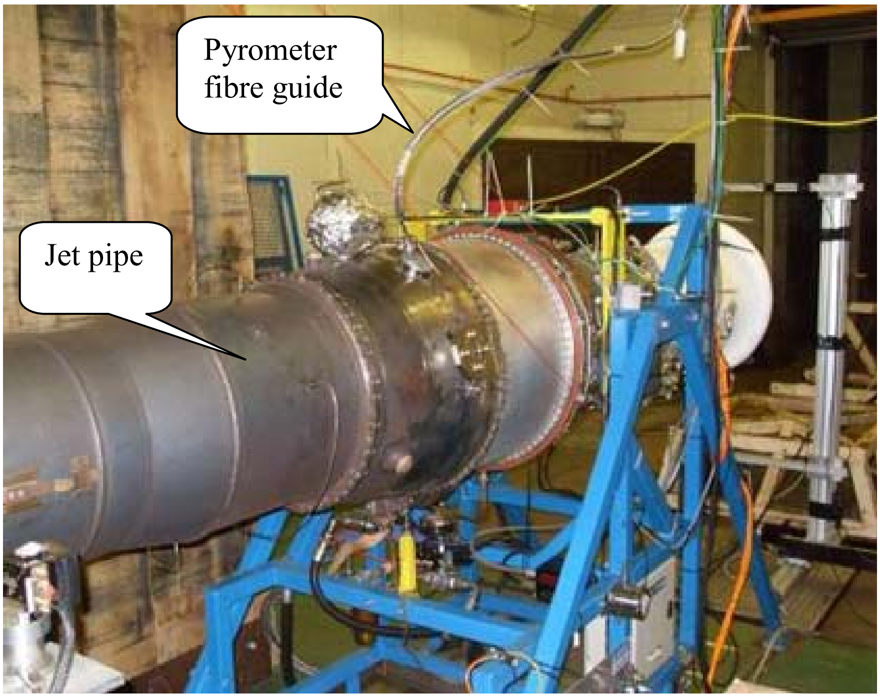


*Figure 19: Rolls-Royce Viper 202 engine*

The figure below shows a typical result for the longer wavelength channel, where the blades that had been coated with differing emissivity paints can be seen (33 & 35 are low and 29 & 31 are high).

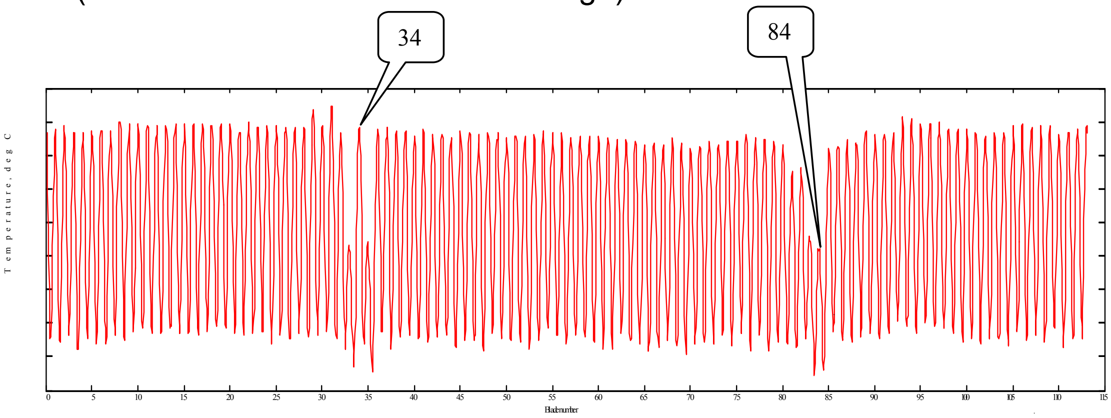


***Figure 20: typical result for the longer wavelength channel***

A further experiment on the viper engine was carried out where the pyrometer was directed to the right and where the blades overlap each other. The results display good agreement between the two channels and also the ratio result. A steel mesh was then positioned in front of the pyrometer to simulate lens fouling. This reduced the optical signal by approximately 43% corresponding to a temperature error of about 42ºC, shown in the figure below (Figure 21). The ratio measurement is, however, unchanged. This indicates, as expected, that the attenuation of the mesh is independent of wavelength.

It was expected; however, that the individual channels temperatures would be less than that of the ratio method by about 10ºC, due to the emissivity of the blades being less than unity, but this was not the case. The reason for this may be due to difficulty encountered in ascertaining the background (dark) level of the pyrometer. The background level was found to be much larger in the engine test station than in the laboratory. Particular care must be taken in future tests, therefore, in determining dark level offsets.

A further issue is with regards to the blade emissivity. Although the detectors were selected to be sufficiently close in waveband to minimize the effects of non-grey emission, in the figure below it can be seen that the blades painted with differing emissivity are affecting the output of each detector in a slightly different way, such that the ratio does not completely remove the influence of the emissivity variation. This is suggesting non-grey behaviour of the surface. Further research beyond HEATTOP is to be undertaken by VMUK to understand the effects of emissivity variation on the dual-wavelength system.

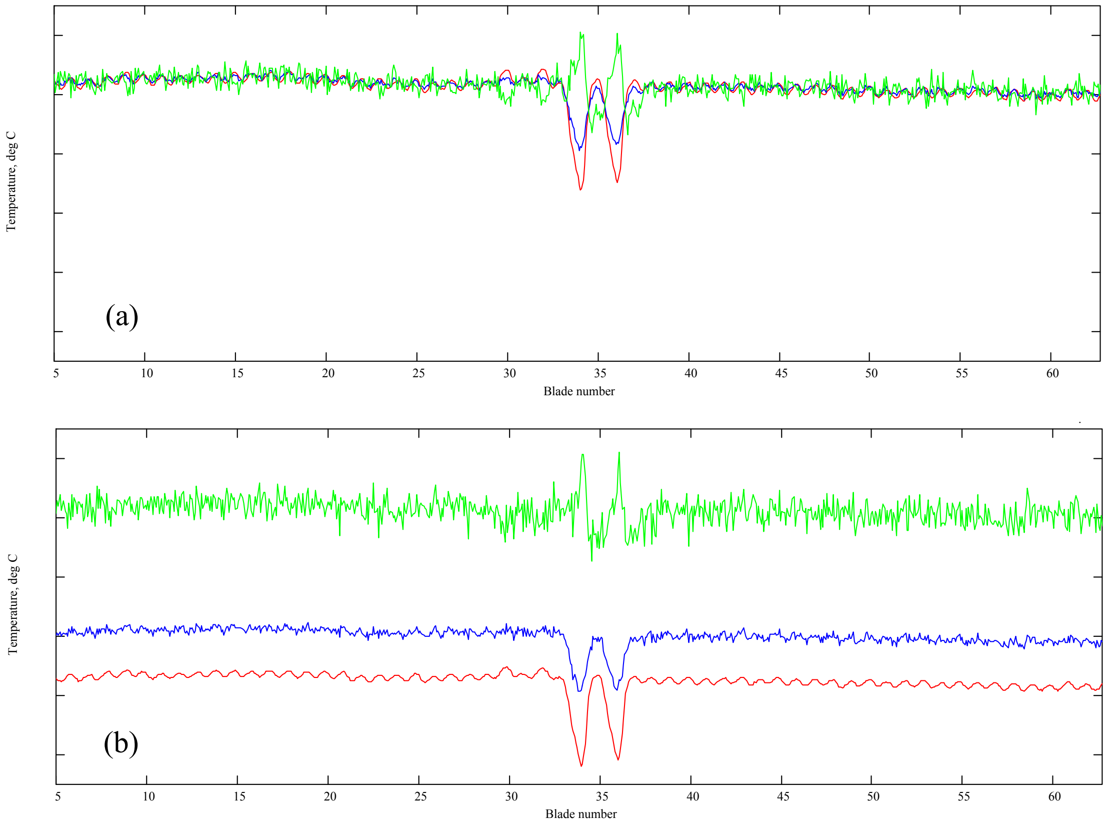


***Figure 21: Results of Viper testing***

Overall, the work has proved that the combination of the dual wavelength system and the current VMUK purge system should create a pyrometer that is largely insensitive to contamination as well as other phenomena that cause signal attenuation in equal amounts over both wavebands. This will make a significant contribution to the goal of VMUK to extent service intervals to many 1000's of hours. The main issues that still need to be resolved relate to accurate estimate of dark level offsets during when the pyrometer is on an engine, obtaining an accurate reference measurement to which to compare the pyrometer measurement, and issues relating to emissivity and non-grey behaviour. These will be undertaken as future studies by VMUK over the coming year.

If the remaining issues with the system can be resolved, pyrometry has the potential to substantially improve certainty in the performance of the safety critical high pressure turbine rotor blades. This will allow the turbine to run as hot as possible with the smallest possible safety margin in order to maximize the efficiency of the engine and hence reduce fuel consumption and emissions. Moreover, accurate surface temperature measurement will improve the currently over-engineered blade cooling system designs and hence reduce secondary air usage, further improving overall engine efficiency.

### 3.2.2.4 Emissivity of metals and TBC modeling

Pyrometry is a method among others to measure temperature of moving parts – turbine blades in our case, by collecting the radiation emitted by the materials. One of the major sources of error in temperature measurement is inaccurate evaluation of the blade emissivity.

The emissivity of metals and TBC modelling was targeted by Auxitrol and KEMA in task 3.2.4 The activity for Auxitrol was to calculate the apparent emissivity of a blade, taking into account the blade itself but also the contribution from the other parts of the turbine that also emit radiations. In radiation thermometry, a measured optical signal is related to a blade temperature. The optical signal collected by a radiation thermometer is a function of the temperature of the viewed blade, but also of the emissivity of the material constituting the blade and of all reflected radiation coming from other parts of the turbine.

A model for turbine blade apparent emissivity calculation has been developed, and then implemented in a Matlab software.

The code allows calculating the apparent emissivity as well as the measured and the real temperature of a blade. The benefit is the determination of the real blade temperature, by emissivity correction.

### 3.2.2.5 Thermographic phosphors, WP3.3

The overall objective is to investigate and develop an 2D optical measurement techniques for gas turbine temperature diagnostics. In a gas turbine, metal surfaces temperatures are usually below 1200°C, whilst the thermal boundary layer, TBC, surface temperature might reach 1400°C. The most important aspect of a surface measurement is the precision, which should not differ by more than +/-1%, according to the aims described in D1.1 and D1.2. It is also stated that the absolute accuracy should be similar to that of thermal paint (+/-4%) or better. Peripheral velocities of rotor blades are in the order of 4-500 m/s.

The technique used is called Laser-Induced Phosphorescence, LIP, which utilizing thermographic phosphor powders. The use of thermographic phosphors for temperature measurements offers remote, close to non-intrusive, surface measurements with high precision. The phosphor powder is attached to a surface and is excited with a pulsed laser source. The afterglow, called phosphorescence, is being detected using a CCD camera and by examine the spectral intensity changes of the phosphorescence it is possible to determine temperature.

The technique of measuring temperature using thermographic phosphor is established since several decades. However, the technique still needs improvements when applied in very harsh environments, such as in gas turbine engines.

There are many different kinds of phosphors used for temperature applications, with different emission spectra and different lifetimes. The precision and the temperature range in which the phosphor is sensitive differ between different phosphors. When performing optical temperature measurements, black body radiation might interfere with the phosphorescence emission and become a problem at higher temperatures. Therefore phosphors that emit light in the blue region are preferable. Furthermore, in the case of measure on very fast moving targets, the emission must be short lived, in order of microseconds, in order to be able to use short exposure time and to avoid smearing of the detected image pixels.

Investigating blue emitting phosphors (purchased from Phosphor Technology, UK) with short emission lifetimes was the objectives of the work reported in D3.7 in WP3. Here it was concluded that the fast and blue emitting thermographic phosphor BaMg2Al16O27:Eu, or BAM, had short enough phosphorescence lifetime to be suitable for further investigation for measurements on fast moving targets.

The investigation of the feasibility of BAM was the objective of the work done in WP6. Measurements were done on a fast rotating target in a high pressure combustion facility rig at Lund University Combustion Centre, see Figure 22. This investigation is reported in D3.8.

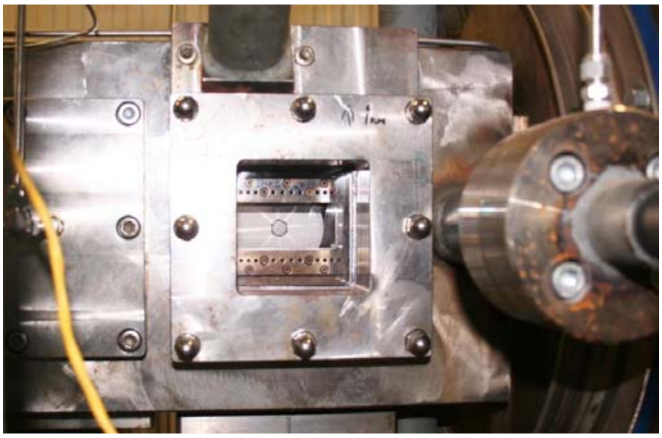


***Figure 22: View of the rotating target in the combustion chamber through the windows of the right side of the test section which allows optical access.***

Also included in D3.8 is a demonstration of the measurement technique using this investigated phosphor BAM on stationary targets in a product fighter jet engine RM12 at Volvo Aero Corporation at Trollhättan, see Figure 23, Sweden, which is the only contractor of the HEATTOP partners involved in this work. This investigation constitutes WP7.

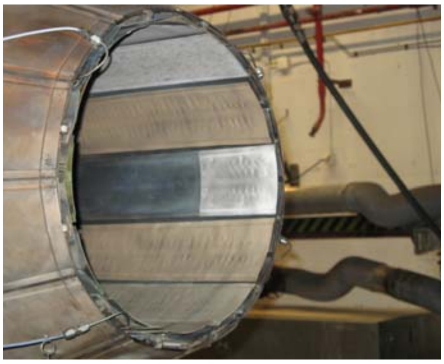


***Figure 23: BAM coated on a exhaust nozzle segment of the jet engine.***

## Final results

The thermographic phosphor BAM was reported in D3.7 to have a temperature sensitivity range up to about 1100°C, not fully reaching the target maximum temperature of 1400°C. Unfortunately, this maximum temperature has to be revised because of new findings regarding instability of BAM. The maximum temperature is probably about 400°C, but further investigation is needed. YAG:Dy is an alternative phosphor for the stationary measurements due to its high temperature sensitivity. However, it has a much longer phosphorescence lifetime than BAM making it unsuitable for high temporal resolved measurements.

Calibration measurements results show that the precision of BAM in temperature range up to 400°C is about 2%, whilst the precision of YAG:Dy is 0.6% as best, corresponding to a precision of +/-7 degrees at about 600°C. Thus, regarding the precision, the objective was reached regarding YAG:Dy, but not regarding BAM. The precision is dependent on the temperature sensitivity of the phosphor. Both

BAM and YAG:Dy shows quite a small temperature dependency compared to many other thermographic phosphors. Therefore, further investigation of other luminescent material is planned for.

Regarding the results from WP7, the accuracy results show a clear trend indicating the capability of the technique. However, because of various difficulties regarding signal detection, image processing and equipment limitations, target absolute measurement accuracy was unsatisfactory. Despite this setback, the technique looks promising and effort will be put into further development.

The results from the work done within WP6 shows that a phosphor with as short phosphorescence emission lifetime as BAM is well suitable for high temporal measurements, allowing temperature to be mapped on surfaces reaching speeds of 500 m/s, hence the objective was reached considering time resolution.

## 3.2.3 Gas path aerodynamic measurements, WP4

### 3.2.3.1 A New Fast Response Cooled Total Pressure Probe for Measurements in Very High Temperature Gas Turbine Environments

**Background**

The measurement of unsteady pressures within the hot components of gas turbine engines still remains a true challenge for test engineers. Several high temperature pressure sensors have been developed but so far their applications are restricted to unsteady wall static pressure measurements. Because of the severe flow conditions (turbine inlet temperatures of 2000 K and pressures of 50 bar or more in the most advanced aero-engine designs) little (if any) experimental techniques exist to measure the time-resolved flow total pressure inside the gas path.

**Concept and Objectives**

The present work proposes a concept for a high temperature unsteady total pressure probe, to be continuously immersed into the hot gas stream to obtain time series of pressure with a high bandwidth and therefore statistically representative average fluctuations at the blade passing frequency. This concept is based on the use of a conventional miniature piezo-resistive pressure sensor, located in the probe tip to achieve a bandwidth of at least 40 kHz. Due to the extremely harsh conditions, the probe and sensor must be heavily cooled. The short term objective of this design is to reach the capability to perform measurements at the temperature conditions found at HP turbine exit (1100 – 1400 K) and in the long term at combustor exit (2000 K or more).

**Methodology**

The first step in the methodology was focusing on the pre-design one- and two-dimensional calculations which were carried out to assess the cooling performance required in terms of heat transfer as a function of the environmental conditions. The heat balance is solved based on a given coolant mass flow rate, taking into account conduction and forced convection inside the probe against the heat absorbed by the probe by external forced convection and radiation. All relevant parameters such as flow temperature, speed, density, turbulence level are considered and studied as a function of probe diameter and probe immersion depth into the gas path. The mechanical aspects of the design are considered by calculating bending stresses and thermal stresses according to the prescribed probe geometry and material properties.

A first water-cooled design concept was then finalized, mainly dictated by the objective of keeping a minimal probe size and by the cooling requirements. All efforts were concentrated to achieve the most compact design which results into an 8 mm diameter probe tip (incorporating the sensor).

3D Navier-Stokes computations were carried out to determine the optimum cooling configuration in particular to detect flow separations or stagnation regions causing possibly a local heating of the probe or sensor. The mechanical design is validated by comparison to FEM calculations. The manufacturing of the probe is a highly complex process, combining modern machining and welding techniques of miniature parts. The first prototype is shown in Figure 24.

**Results**

The first experimental results were obtained after the probe was traversed at the turbine exit of a Rolls-Royce Viper turbojet engine, at exhaust temperatures around 750˚C and absolute pressure of 2.1 bar. The probe was able to resolve the high blade passing frequency (~23 kHz) and several harmonics up to 100 kHz. Besides the average total pressure distributions from the radial traverses, phase-locked averages and random unsteadiness are presented. Turbulence parameters are derived from the pressure signals.

The same probe was used for measurements in a Rolls-Royce intermediate pressure burner rig. Traverses were performed inside the flame tube of a kerosene burner at temperatures above 1600°C. The probe successfully measured the total pressure distribution in the flame tube and typical frequencies of combustion instabilities were identified during rumble conditions.

The cooling performance of the probe is compared to estimations at the design stage and found to be in good agreement. The frequency response of the probe is compared to cold shock tube results and a significant increase in the natural frequency of the line-cavity system formed by the conduction cooled screen in front of the miniature pressure sensor are observed due to the higher temperature.

These continuous recordings of unsteady total pressure in the gas path were not only performed for the first time at those elevated temperature levels in real gas turbine environments, but the probe may also be used in a “virtual” 3-hole probe mode, which allows the measurement of the periodic unsteady yaw angle. This allows also deriving other quantities like static pressure or flowing Mach number.

Other prototypes were built, based on the experience with the first probe, with improved manufacturing and instrumentation process. This second generation prototype was also used for measurements at the turbine exit of the military engine Volvo RM12, under conditions between 800°C and 900°C and 4 to 5 bar. Very high signal-to-noise ratios were obtained in the recordings at the scale of the blade passing frequency and the probe was proven to be robust and rugged considering the high mechanical excitations induced with afterburner on.

***Figure 24 Fast response cooled total pressure probe (left) and first engine measurements in a Rolls-Royce Viper gas turbine exhaust (right)***

**Achievements versus State-of-the-Art**

After almost 4 years of development and use in various environments like gas turbine engines or combustion chambers, the feasibility of the probe concept was proven both for the design and manufacturing phase as for the validation phase in experiments at extremely temperatures exceeding 1600°C.

The objectives were therefore fully met but the technology still requires a high level of specialist support when making measurements.

To the author's best knowledge, this cooled probe technology represents the only experimental technique currently available to provide steady and unsteady total pressure, flow angle, static pressure and flow Mach number at those extreme temperature conditions in turbo machinery applications.

**Impact on industry and research sector**

The availability of this new probe technology opens a totally new area of measurements formerly unavailable. For the industrial gas turbine industry as well as for the aero-engine industry, this will enable detailed flow field surveys both in combustion research as well as in turbine aerodynamics. This will enable further validation of combustion simulation codes and provide more realistic boundary conditions as an experimental input for turbine aero-thermal simulations.

This cooled probe technology may be used in other industrial sectors as well; anywhere high temperature processes are used, for example in steel or chemical industry.

## 3.2.3.2 Optical fibre multiplexable pressure sensor

### Introduction

Oxsensis role in HEATTOP was to develop prototype optical sensors primarily for the measurement of dynamic pressure in combustion control applications. Prior to the programme start, prototype sensors and interrogation electronics have been demonstrated both in lab and rig environments. HEATTOP provided a route to further develop the sensor system to higher degree of technology readiness as measured by the use of Technology Readiness Levels (TRLs) which are a recognised industry tool for gauging technology maturity.

### Project Objectives

A key area for development within the project was the high temperature packaging of the sensor element which, being made in single crystal sapphire (melting point 2053°C), is inherently high temperature capable. This addressed issues such as high temperature fibre and metallurgy. In addition developing accurate laboratory methods to measure the performance of the sensor for use in a range of extreme environments was a significant part of the project.

The objectives of the Oxsensis activity within HEATTOP are summarised in Table 3. Essentially the target was to produce a prototype sensor capable of surviving and operating in a combustion location and of producing measurements of pressure and temperature using a single fibre.

| **Requirement** | **HEATTOP Specification** |
|---|---|
| **Performance Requirements** | |
| Measured parameter(s) | Pressure (dyn/static), Temperature |
| Range(s) | P ≤ 50bar, T ≤ 1000C |
| Resolution Uncertainty | P: 1 in 100,000, T – 1K |
| Frequency response bandwidth or Sample rate | 40kHz P, 1 second T |
| Life time of sensor (hours) | 150 hours |
| **Environmental Requirements** | |
| Temp at measurement point | 1000°C |
| Pressure at measurement point | 50 Bar |
| Mach No at measurement point | 0.5 |
| 'Back end' temperature (if different from measurement) | 550°C |
| Lead-out temperature | Same for short distance then ref tables in § 4.1 |
| **Other Requirements** | |
| Multiple parameters - one fibre | P and T |
| Multi-channel interrogator unit | Portable bench equipment |

Table 3: HEATTOP Oxsensis objective targets

## Project Collaborators

Most of the development work within HEATTOP was carried out in-house by Oxsensis permanent staff. Testing of devices was done in collaboration with the engine and rig owners with Rolls-Royce and Siemens both providing significant testing opportunities within the project. In addition to these collaborations Oxsensis used subcontractors to provide a number of specialist services in the areas of metrology and modelling, particularly thermal modelling of the sensor package.

## Sensor Operating Principles

Oxsensis sensors are Fabry-Perot devices. An optical cavity is incorporated into the sensor the size of which varies in response to the parameter to be measured (in Oxsensis case either temperature or pressure. Figure 25 shows a schematic of the sapphire sensing element indicating the cavities used for pressure and temperature measurement.

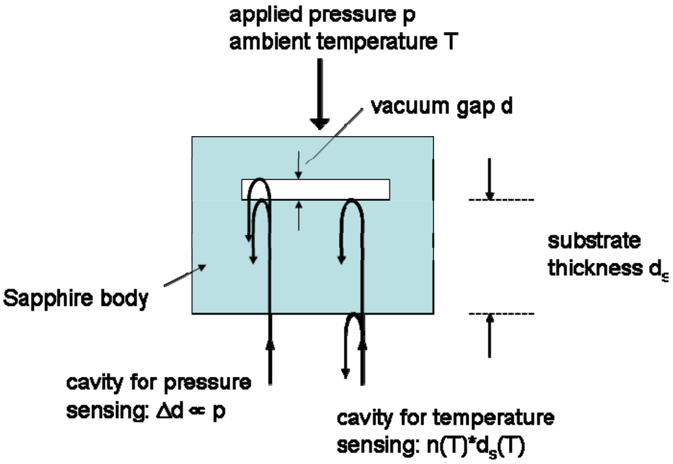


Figure 25: Schematic of Fabry-Perot optical sensor element

The sensor is paired with an optical interrogator which is used to measure the optical length of the Fabry-Perot cavity and provide an electrical output which indicates the value of the measured parameter. Within HEATTOP Oxsensis worked on two interrogator types – the Dual Wavelength Interrogator (DWI) and Multi-Parameter Interrogator (MPI).

The operation of the dual wavelength interrogator is shown in Figure 26 and involves ‘shining’ two separate wavelengths at the sensor head and measuring the returned signal. The returned signal varies with the size of the optical cavity (this is the x-axis on the graph in the figure) and is therefore proportional to applied pressure since the cavity length is a linear function of pressure. Two wavelengths are used so that first order errors due to optical losses can be corrected for by dividing the two signals. In a real system there is also a reference signal used to ensure variation in light output does not result in a measurement error.

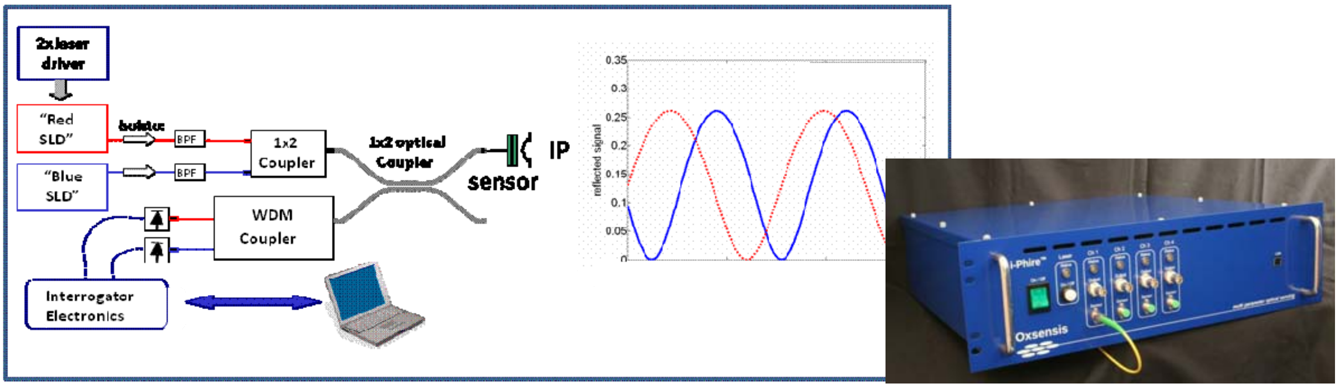


Figure 26: Dual Wavelength Interrogator operation and (inset) 4 channel model

The MPI operates on a different wavelength based principle. In essence an electrically controllable cavity (or slave cavity) is formed, in this case on a silicon optical chip, which nominally matches the sensing cavity. As the sensing cavity changes in response to the measured parameter(s) the slave cavity is kept matched to it and the drive required to maintain a match is related to the measured parameter. A schematic of the system is shown in Figure 27 alongside a photograph of a development prototype device.

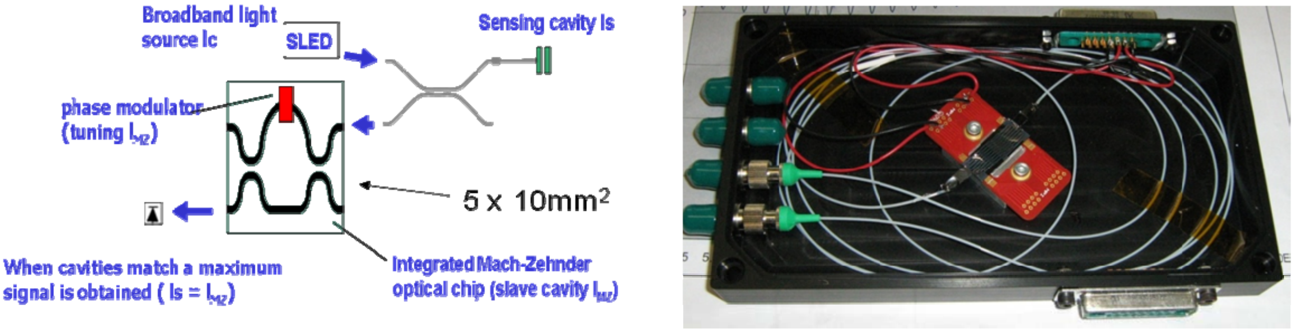


Figure 27: MPI schematic and early prototype

## Progress and Achievements towards Objectives

Oxsensis has successfully achieved the majority of the objectives set out at the start of the project. A brief summary of the overall progress is provided in Table 4 below.

| **Requirement** | **HEATTOP Specification** | **Tick list** |
|---|---|---|
| **Performance requirements** | | |
| Measured parameter(s) | Pressure (dyn/static), Gas Temperature | Demonstrated in laboratory, Field test due with hybrid interrogator |
| Range(s) | P ≤ 50bar, T ≤ 1000C | *Cal 600°C,* Test >1000°C |
| Resolution Uncertainty | P: 1 in 100,000, T – 1K | P: Achieved, T: 5K |
| Frequency response bandwidth or Sample rate | 40kHz P, 1 second T | DC – 20kHz – Electronics Limited |
| Life time of sensor (hours) | 150 hours | 150Hrs @1000 C in laboratory<br>>3000 hrs @ 550 C in engine |
| **Environment requirements** | | |
| Temp at measurement point | 1000°C | Spec Demonstrated |
| Pressure at measurement point | 50 Bar | Spec Achieved (Lab) |
| Mach No at measurement point | 0.5 | Spec Achieved |
| 'Back end' temperature (if different from measurement) | 550°C | Spec *Exceeded* (Lab) |
| Lead-out temperature | Same for short distance then ref tables in § 4.1 | Spec Achieved (Lab)<br>EXCEPT CONNECTOR |
| **Other requirements** | | |
| Multiple parameters - one fibre | P and T | Demonstrated (Lab) |
| Multi-channel interrogator unit | Portable bench equipment | *Ready for Trials* |

Table 4: Summary of Oxsensis achievements in HEATTOP

A more informative summary of the development made to the system during the HEATTOP project is to consider the status of testing at the start and end of the project. At the start of the project Oxsensis had carried out some testing on small engines but at a relatively low TRL level. By the completion of HEATTOP sufficient information on the performance of Oxsensis sensors had been gained to de-risk the product sufficiently to enable a number of sensors to be installed in a grid connected power station where they have now been running successfully for in excess of 5000 hours.

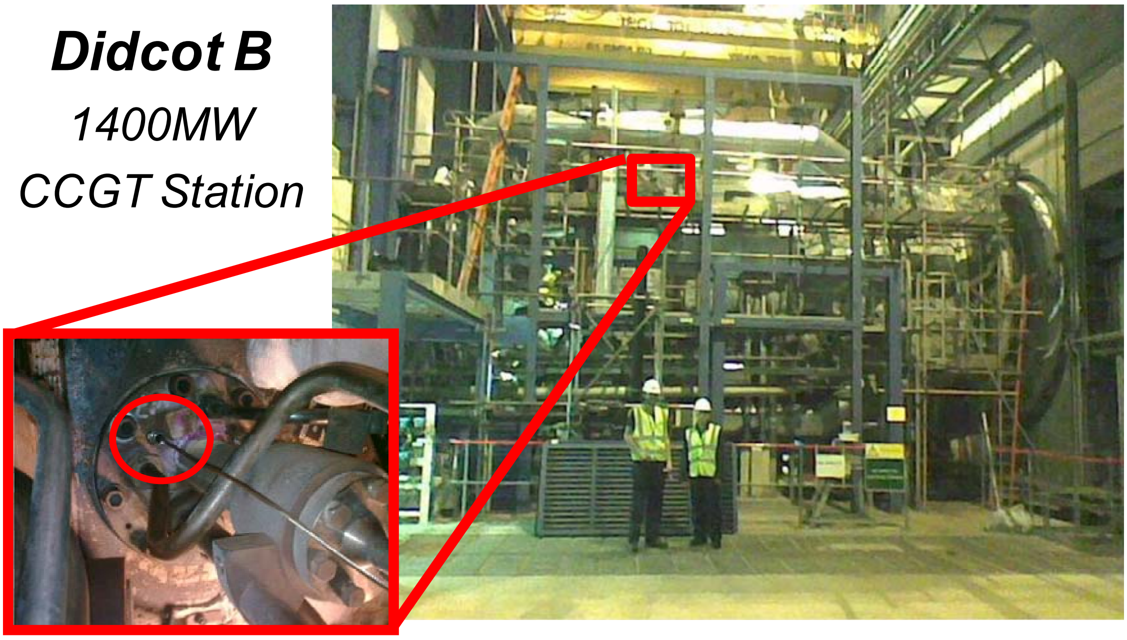


Figure 28: Oxsensis sensors installed in grid power station

The deployment of sensors in operational equipment (albeit only in a monitoring role) represents a step change in the maturity of the technology through HEATTOP. Sensors are now at TRL 6/7 with TRL 7 meaning sensors are in operational use. Given that Oxsensis stated aim is for the sensors to be used as part of the Gas Turbine control system then TRL 7 can only be fully achieved when the sensors are incorporated into the control function rather than providing a stand-alone monitoring function. Despite this limitation which requires further confidence to be developed in the sensor, the overall progress during HEATTOP has been significant representing at least two TRL levels during the 3-4 years the project has been running.

### Impact of HEATTOP Development Work

The full benefits of the work carried out in HEATTOP have yet to be realised due to the long product introduction cycle in the Gas Turbine industry. The potential of the sensors developed in HEATTOP is to improve both the design and operation of the hot sections of Gas Turbines for power generation and aero-engines. The target still being worked on is to enable closed loop control of fuelling and other engine functions by providing more accurate and reliable data. Following on from HEATTOP Oxsensis is continuing the development of the product through commercial interactions with major Gas Turbine and OEMs and through publicly funded collaborative projects.

### 3.2.3.3 Task 4.1.3 Intermittent choked nozzle probe for stagnation pressure and temperature - UCAM-DENG, RR.

The intermittent choked nozzle probe developed under HEATTOP project measures time averaged stagnation temperature and pressure in the gas path of combustor exits and first stages of the gas turbine.

The novelty of this measuring device is the method of measuring temperature, which is based on the theory for compressible gases passing through a choked nozzle. The probe measures intermittently stagnation pressure and temperature and, if a gas analyzer is added to the system, also gas composition.

The advantage of this technique over standard methods of measuring gas path quantities is that with one probe is possible to measure more quantities, thus reducing the instrumentation costs. Moreover the temperature measurements are directly related to the gas characteristics, without involving intermediate properties of the sensors. The errors are therefore reduced compared to the standard methods of measuring temperature, i.e. thermocouples. The thermocouples are affected by errors due to calibration drift and to radiation and conduction, which are due to the difference between the actual gas temperature and the temperature measured, which is the body temperature of the sensor itself. These errors could be in excess of 50K for thermocouples. In the intermittent choked nozzle probe, conduction and radiation errors and calibration changes during operation are of second order, often negligible. Moreover the most common thermocouples (K, N type) have a limited temperature operating range with an upper limit of approximately 1500K. The intermittent choked nozzle has been successfully tested up to 1900K.

The scope of the development of the probe within the HEATTOP project is validating the methodology in realistic environments, building a prototype and testing the probe in rigs and/or engines. The probe has been initially tested in laboratory environments at the Whittle Laboratory (University of Cambridge, UK) and the operating principle validated. Then the probe has been designed for realistic environments and the prototypes were built and tested in a small engine, downstream the LPT rotor (1000K, 2bar(a), Mach=0.5) and in a combustor rig at 4 bar and 1900K. The probe survived the tests and proved to be a reliable device to measure time averaged stagnation pressure, temperature and gas composition. According to the uncertainty analysis the accuracy for the temperature measurements is expected to be of the order of 0.6% (±10K at 1800K). The actual accuracy achieved during the tests wasn’t precisely assessed because of the higher uncertainty on the reference measurements during the tests. Stagnation pressure and gas composition have the same accuracy of the standard techniques normally used for such measurements, respectively pneumatic and aspirating probes, and they are related to the sensors connected to the probe.

### Project execution

The primary objectives for the project regarding the intermittent choked nozzle probe were:

1. Develop a full understanding of the technique, testing the probe in laboratory for different conditions.
2. Undertake computational simulations to define conduction and radiation effects at the nozzle and for structural analysis
3. Development of a robust packaging
4. Tests in realistic environments

When the project started, a preliminary probe had already been built and tested in laboratory environments at high temperature and the operating principle validated. New prototypes of an engine scale probe suitable for both laboratory and rig tests were designed, manufactured and tested within the HEATTOP project.

The probe is composed by a nozzle immersed in the hot gas, a heat exchanger to reduce the temperature of the aspirated gas, a mass flow measuring device and a pressure measuring device, a valve to switch the flow on and off. The probe operates in two phases. In the first phase the probe operates as a standard pneumatic pressure probe: the downstream valve is closed, the flow stagnates in the line and the time averaged stagnation pressure is measured by a remote pressure transducer. In the second phase the flow is aspirated in the probe: the downstream valve is open and the line is connected to a pressure lower than the one in the investigated environment. The back pressure at the nozzle is assured to be such that the upstream nozzle is choked. The characteristics of the gas composition and the mass flow rate flowing through the nozzle are measured respectively by the gas analyzer and by the mass flow measuring device. These quantities (mass flow rate, gas composition and stagnation pressure) are combined in the formula for non-dimensional mass flow rate in a choked nozzle and the stagnation temperature is computed.

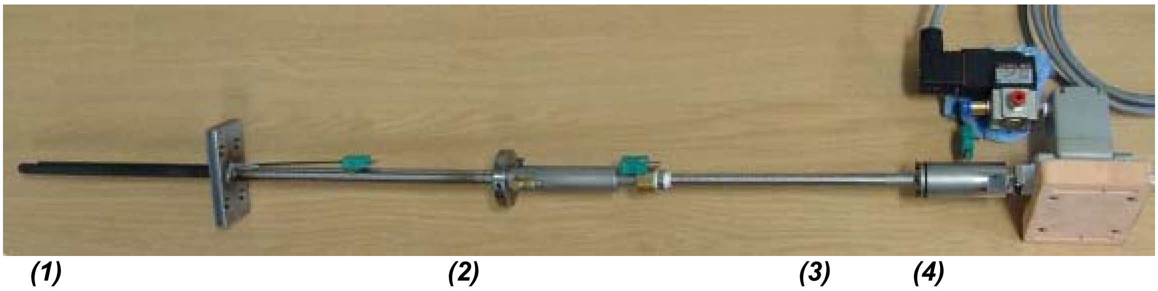


Figure 29: Picture of a probe prototype: (1) probe head, (2) cooling system, (3) mass flow meter, (4) on/off valve. Downstream the system – not depicted in the picture is the gas analyser.

The geometry of the probe head was optimized considering measurement accuracy and robustness requirements. A choice of materials and structural solutions had been selected for industrial applications. CFD simulations, including conjugate heat transfer analysis, and FEA had been used to this purpose. The CFD analysis was used to determine the effect of the probe presence on the flow and temperature field at the nozzle, therefore the effects on measurement accuracy. Conduction and radiation effects on the measurements were evaluated and the tip geometry optimized accordingly. The final material and design of the probe was determined considering the conditions of the environment where the probe was addressed to.

In the first period of the project the technique had been validated in laboratory, showing good repeatability and agreement with theory. Full error analysis was used to estimate the achievable accuracy and the improvements to be made to the system to increase the probe accuracy. In the last year of the project two different probe prototypes were tested in a small engine and in a combustor rig.

The first probe prototype was made in Nickel superalloy (Haynes 230). This prototype was uncooled. It was successfully tested in the Rolls-Royce Viper engine. The probe was located downstream the rotor in the exhaust duct and radially traversed along the gas path. The stagnation pressure was 2 bar(a) and the peak stagnation temperature was 1000K. The maximum Mach number was 0.5. The aspirated probe measurements were compared with a series of reference measurements. In particular the profiles of temperature, pressure and yaw angles were compared with the same measurements taken by a water cooled wedge probe, having a thermocouple mounted in. The measurements were taken on the same position but during a different run of the engine. The comparison of the profiles of the stagnation pressure for the two probes is depicted in Figure 30. The agreement was very good and showed a good run to run repeatability.

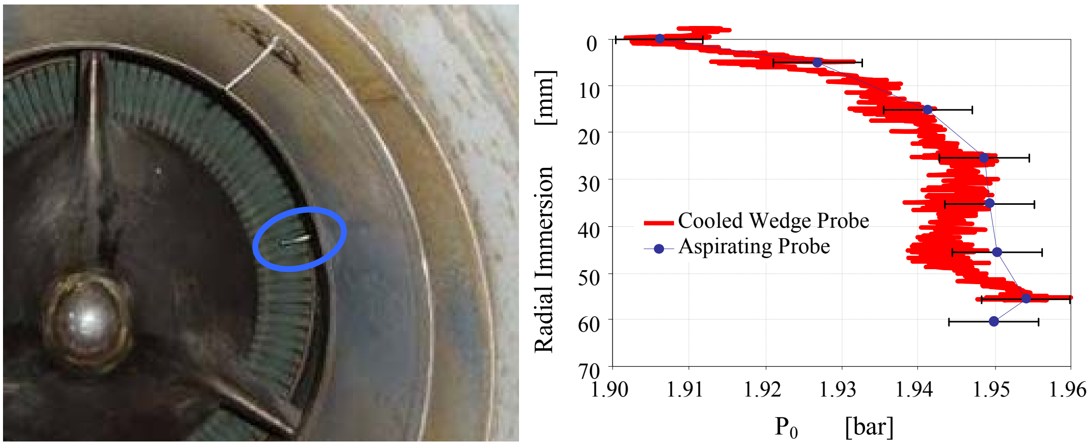


***Figure 30: Installation of the aspirated probe in the RR Viper engine and comparison of the profiles of total pressure for aspirated probe and wedge probe.***

The comparison of the two non-dimensional profiles of stagnation temperature showed a good agreement, within the expected error for this test. However the absolute value of temperature was shifted of +40K compared to the thermocouple mounted on the wedge probe (see Figure 3). However an analysis of the data of the thermocouple in the wedge probe show that the temperatures read by the thermocouple should be corrected for conduction errors. These errors are due to the low temperature of the tip of the probe, which is water cooled and to the heat transfer affecting the thermocouple temperature. The temperature of the thermocouple is lower than the real gas temperature of the external flow and thus the temperature readings. According to the guidelines of AGARD (AR 245) the error is of the order of 30K or more. If this correction and the repeatability of the measurement are considered the data of the two profiles agree within the uncertainty that was estimated for the intermittent aspirated probe in these tests.

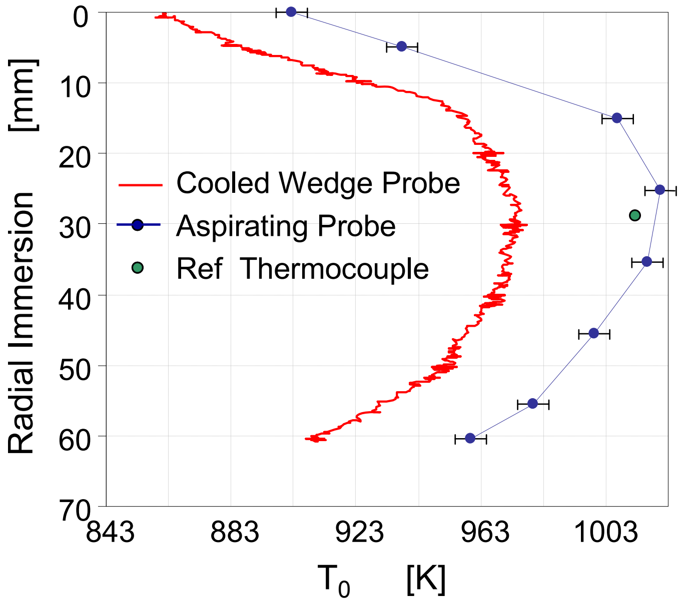
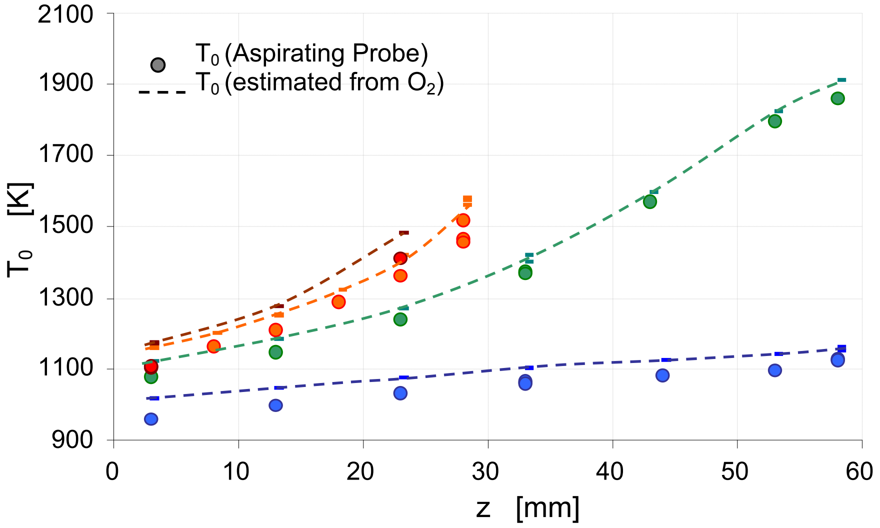


***Figure 31: Comparison of the profiles of temperature measured in the RR Viper engine for aspirated probe and Wedge probe.***

The second set of tests was performed in the Rolls-Royce IP combustor rig. In this case the conditions of pressure were set at 1.5bar and 4 bar. The temperature could be varied changing the AFR. Four temperatures were analysed for the 4 bar conditions. The maximum temperature measured was 1900K. The velocity of the flow was low in this case and approximately equal to Mach equal 0.1. The probe was located in the flame tube and traversed radially. The probe head was made in Silicon Carbide, which is a ceramic material able to withstand the peak temperatures expected in the rig. The profiles of stagnation pressure, temperature and %O2 content in the exhaust gases were measured for each AFR.

During these tests some thermocouples were located close to the wall and no other reference measurements were available in the core of the flame tube. Because of the high temperature no standard device could be used or give accurate measurements. The temperature measured for all the profiles showed to have an offset respect the reference thermocouples. This offset could be explained by the different position of the thermocouples and the uncertainty on the relative position of the two measurements. Since no reference measurements were available for the measurements inside the flame, it was decided that a reference temperature profile would be calculated from the gas composition measurements made by the probe. Thus the temperature profiles were computed from the measured oxygen content of the gas, using the relationship between the oxygen content and the adiabatic flame temperature (assuming full equilibrium of the reaction between the kerosene and the air). The derived temperatures were not expected to have high accuracy but the method is useful to determine temperature variation from point to point as the probe moves through the combustor. The mean computed temperatures were found to differ from those measured by the probe by approximately 40K in every case. That shows that the probe has a coherent behaviour and the non-dimensional profiles computed with independent method give the same results. Again the actual absolute temperature could not be compared with a reference accurate measurement.



At the end of the project the operating principle has been proved valid both in laboratory and in rig/engines. Four different prototypes were built and two of them, one uncooled metallic and the other uncooled ceramic were tested respectively in the Viper engine and in the RR combustor rig.

The probe has been proved to be reliable and robust for the tests in harsh environments and in real engine, up to 1900K degrees of temperature. The complete system and the installation in the engine have been demonstrated suitable for these environments. The achievable accuracy was defined by a detailed uncertainty analysis and it is estimated equal to ±0.6%,±5K @ 900K (verified in laboratory) or ±10K @ 1800K.

The effect of radiation and conduction errors have been analysed with CFD simulations and they have been proved to be ±2K. Calibration drift has not been observed during the performed tests; the calibration curve showed in fact to be the same before and after the tests.

The probe could be used in the hot section of gas turbines, both for in flight and power generation gas turbines or in rig. Tests planned for the near future will be done to simulate simple installation of the probe in standard instrumented vanes. The probe could be used as fixed or traversable reference instrumentation for time averaged stagnation temperature, stagnation pressure and sampling of gas composition. It could be also used as a reference temperature measurement to correct the errors, such as the calibration drift or conduction/radiation, on measurements of thermocouples, which have higher time resolution.

### 3.2.3.4 Time resolved total pressure and thin film gauge temperature probe measurements in engines (UOXF)

#### Project execution

#### Project execution

The objectives under HEATTOP were as follows:

To develop robust high bandwidth total temperature and pressure probes employing thin film gauges and Kulite transducers to measure hot gas path total temperature and total pressure respectively.

- To develop a reliable and robust fast insertion system used to inject the probes into the hot gas paths for immersion times of the order of 0.1s.
- To test and develop the above systems in progressively hotter and more hostile flows to build confidence in the technique with a view to testing in a real gas turbine.
- To demonstrate the system in a real gas turbine environment.
- The primary contractor was the University of Oxford, however both Rolls-Royce and Volvo Aero Corporation were heavily involved in their respective engine and rig tests.

#### Description of the measurement technique

Two types of fast response probes were developed at the University of Oxford under HEATTOP: a fast response pressure probe and a fast response temperature probe. The pressure probe uses commercially available Kulite piezo-resistive pressure transducers to measure the unsteady total pressure, whilst the temperature probe uses a custom made dual thickness dual thin film gauge tip to measure the unsteady total temperature. The fast response pressure probe is shown **Error! Not a valid bookmark self-reference.**.

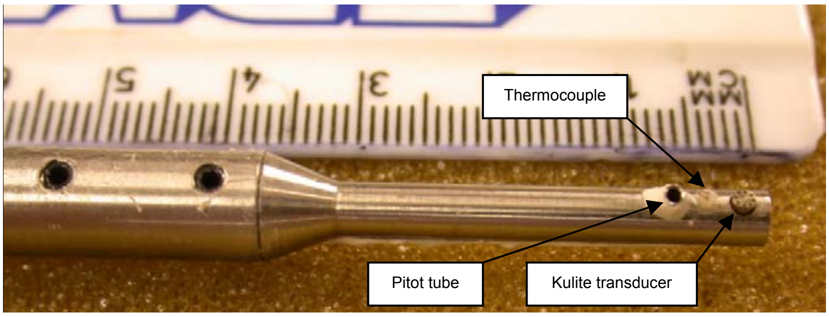


*Figure 32: The fast response Kulite pressure probe*

The probes are un-cooled whilst in the flow, therefore are inserted for short timescales of the order of 100 ms to prevent thermal damage. Between insertions, the probes are retracted and are then continuously immersed in cooling air fed into the traverse gear via a cooling adapter. The pneumatic traverse is actuated by four fast solenoid valves, two each for insertion and retraction. Typically air is fed to the probe from the facility shop air supply, as long as the pressure is above that inside the engine at the measurement plane. The fast-insertion traverse system is shown in Figure 33.

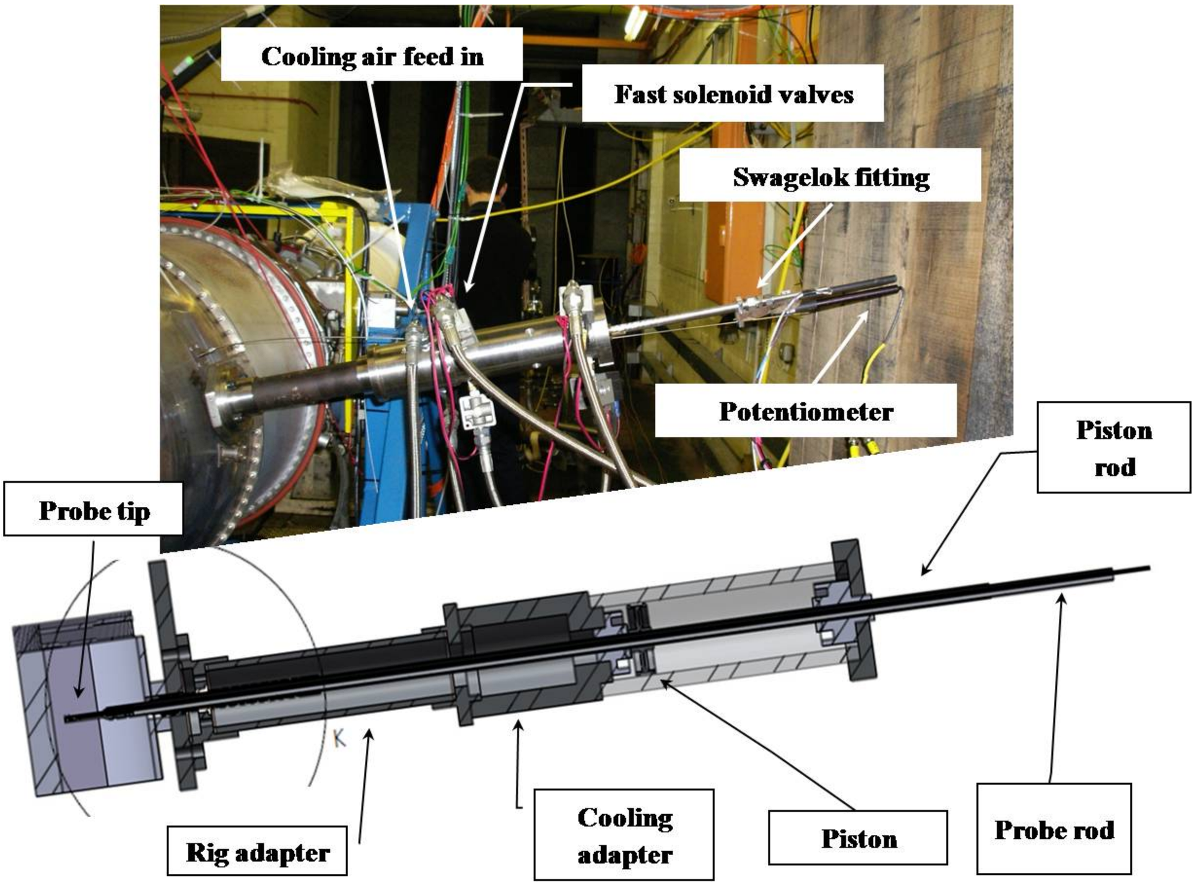


*Figure 33: The fast insertion system*

## HEATTOP Tests

The fast response probes developed under HEATTOP were tested on three different vehicles over the course of the project:

- The Rolls-Royce Viper turbojet at Rolls-Royce Ansty, UK.
- The Rolls-Royce IP (intermediate pressure) combustion rig at Rolls-Royce Derby, UK.
- The Volvo Aerospace RM12 military turbofan at Volvo, Trollhattan, Sweden.

### Results

Overall in the Viper turbojet tests the pressure and temperature probes performed 50-60 insertions each, 33 mm downstream of the turbine. The majority of these were at full power: 12800 RPM, 2 bar total pressure and 1000 K exhaust gas temperature. Temperature and pressure data was acquired at up to 200 kHz sampling rate.

In the RR IP combustor rig tests the probes again performed approximately 50 insertions each, 175 mm downstream of the combustor nozzle exit, at conditions up to 1950 K peak temperature and 6 bars pressure, i.e. the maximum operating condition of the combustor. Temperature and pressure data was acquired at up to 250 kHz sampling rate. The test setup is shown in Figure 34.

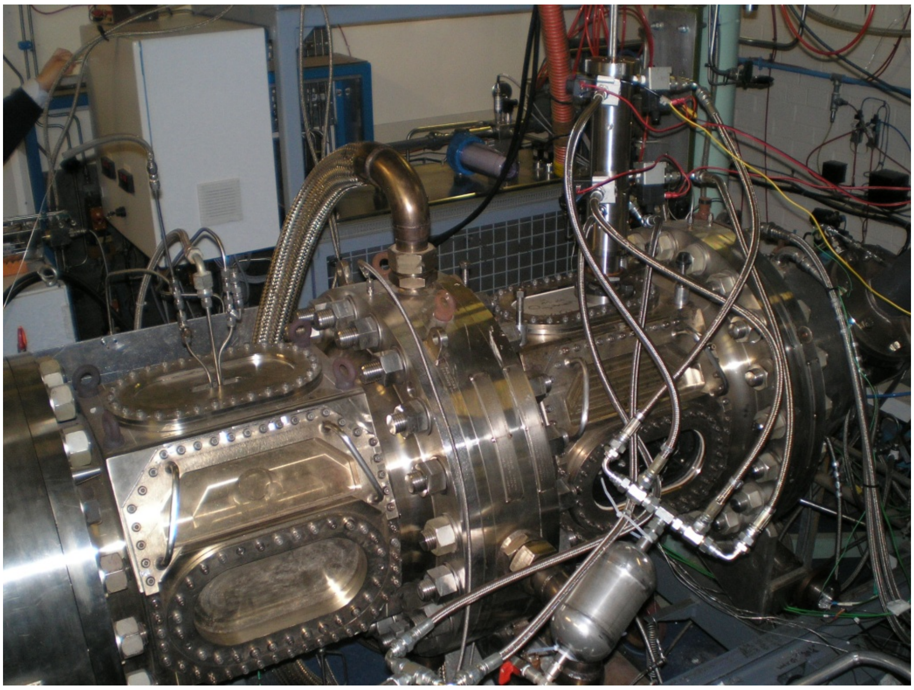


***Figure 34: RR IP rig installation***

In the VAC RM12 military turbofan tests the probes performed approximately 30 insertions each 170 mm downstream of the low pressure turbine at conditions of 4 bars and 1100 K. The test setup is shown in Figure 35.

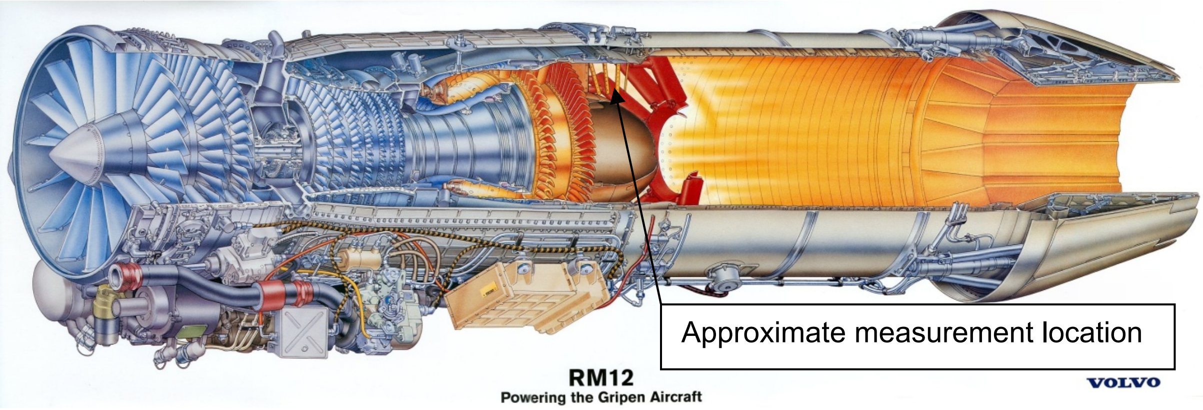


***Figure 35: The VAC RM12, showing approximate measurement location.***

Over the course of the three tests the pressure probes have proven their ability to measure steady and unsteady total pressure in real engine conditions up to 1900 K and 6 bar total pressure, at engine representative Mach numbers. A typical unsteady pressure signal from the Viper engine is shown in Figure 36. From these measurements useful information about the flow has been derived, including turbulence length scale and turbulence intensity, both of which are of use to the engine designer concerned with restricting heat transfer to engine components immersed in the hot flow.

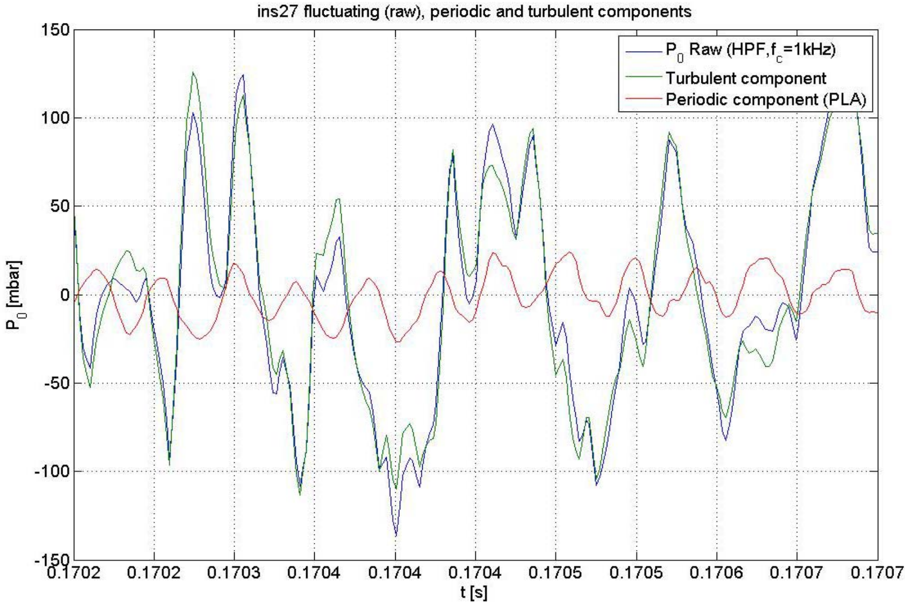


***Figure 36: Typical total pressure signal from the Viper engine***

In comparison to the pressure probes, which use a commercially available sensor to measure unsteady pressure, the temperature probes employ a prototype dual-thickness alumina substrate DTF arrangement. It has been found that at present the measured substrate surface temperatures are generally lower than predicted, resulting in low heat transfer rates and therefore a low total temperature result.

Various one-dimensional processing methods have been used to compute the heat fluxes from the surface temperatures, including those that account for curvature and variable thermal properties, however all have produced similar results. It is believed the error in the total temperature is due to lateral or axial conduction within the probe tip as a result of the high thermal diffusivity of the alumina substrate. Whilst the HEATTOP project has now come to an end, work will continue at Oxford over the coming months on thermal modelling in order to determine the causes of this error, and develop correction methods.

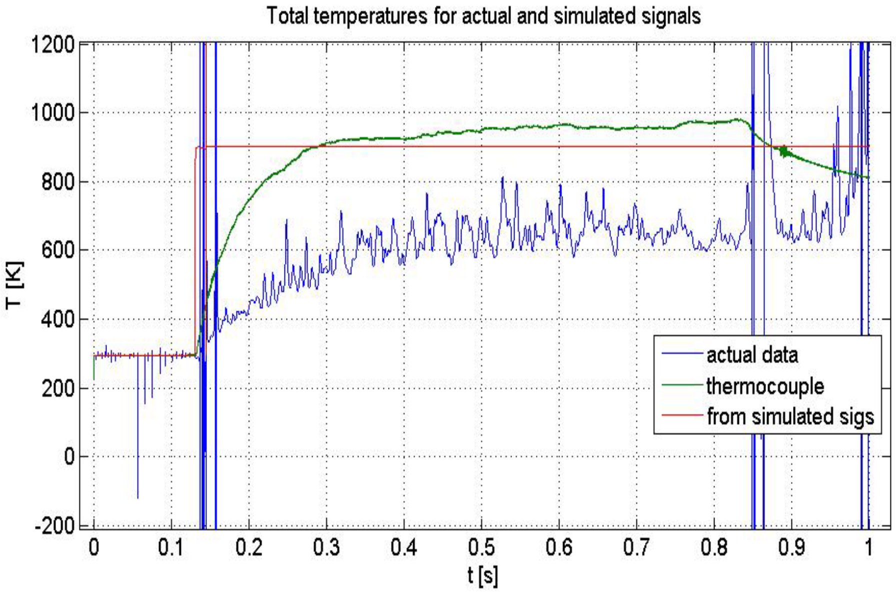
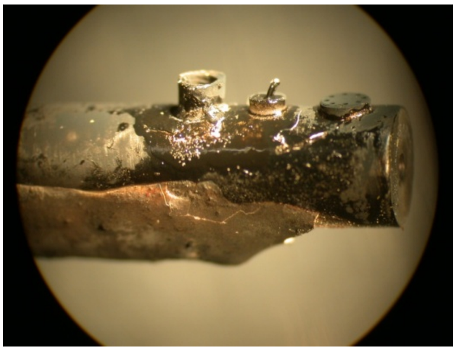
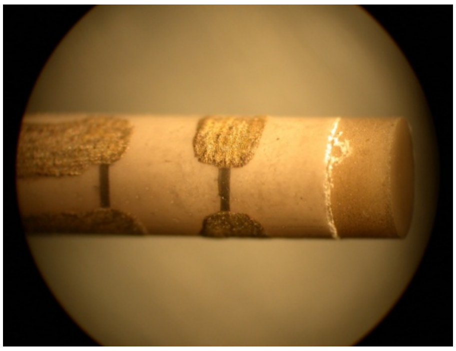


*Figure 37: DTFP total temperatures, 12800 RPM.*

Overall the probes have proven reliable and robust in all of the available flows under HEATTOP. The fast insertion pneumatic traverse mechanism has also proven robust and reliable in the hostile engine environment, and the system for quickly changing probes worked well. Neither the probes nor the fast-insertion traverse suffered any major technical or structural problems during engine testing. Photographs of the probes following the combustor tests are shown in Figure 38.





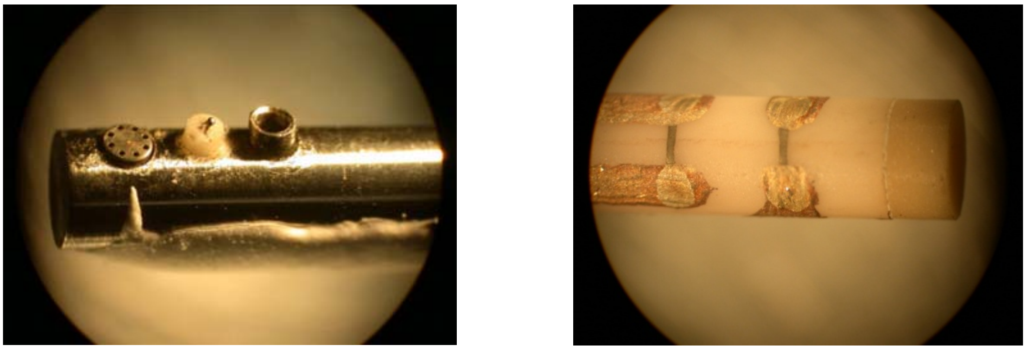


***Figure 38: Probes following combustor tests. Top pictures were taken directly after the tests, bottom pictures are the same probes after cleaning.***

With regard to the original objectives under HEATTOP robust probes and a robust and reliable fast-insertion system have been developed, and these have been demonstrated in real gas turbine environments and conditions representative of modern engines. Whilst the pressure probes have produced useful results the temperature probe data still requires further work on processing for it to be useful. With regards to technology readiness levels it could be considered that the overall technique has progressed from TRL 4 or 5 to TRL 6, however this is still very much an experimental technique for use on stationary gas turbines and development rigs as opposed to an in-flight sensor. In comparison with the state of the art this technique represents a step change in terms of both sensor survivability and measurement bandwidth. Current sensors are only able to measure low frequency fluctuations (< 1kHz), whereas during HEATTOP the pressure probes have demonstrated measurements up to 100 kHz, and the temperature data bandwidth is expected to be of the order of 10 kHz once processing is complete.

### 3.2.3.5 Non intrusive IR sensor for real time direct measurement of Turbine Inlet Temperature

**Objectives**

The Turbine Inlet Temperature (TIT) is a critical parameter of Gas Turbine combustors affecting material and coating lifetime of hot parts as well as combustion efficiency.

On line TIT monitoring systems would be important to maximize the gas temperature (and therefore the Gas Turbine plant overall efficiency), to increase the hot gas path components lifetime as well as to allow better maintenance scheduling. On development test combustor rigs, on the other hand, the real time measurement of TIT could provide a unique comparison for CFD modeling.

However no method appears to be neither available nor commercial instrumentation exists to accurately measure hot gas path temperatures under GT full scale conditions.

The objective of the activity performed within the Project has been the development and optimization of a non-intrusive measurement technique suitable for rig and engine tests at high temperatures and pressures. The main target for this application is to accurately measure gas path temperature at the combustor exit.

**Contractors involved**

Sensor development and testing activity have been carried out by ERSE (formerly CESI Ricerca). Siemens has provided the test rig (located at the DLR in Cologne) utilized for the testing activity and has manufactured the interfaces required for installation.

**Work performed**

We have developed and tested a non intrusive temperature probe for on line real time TIT measurements.

The measuring system is based on spectroscopic photometric measurements of the Infrared (IR) radiation emitted in a selected wavelength band by the CO2 molecules in the combustion gases. To minimize installation requirements, the probe has been designed in such a way it can operate through a single optical access.

A simplified theoretical model of the IR radiation absorption/emission process in hot gases has been preliminarily assessed by numerical simulations, in order to physically interpret the line-of-sight measurements of the gas temperature provided by the IR sensor. The possibility of implementing a two-wavelength method in the TIT measurements has also been investigated in laboratory tests, in order to avoid the need for an external calibration measurement technique. The sensor has been tested on the Siemens HPMC Rig installed on the HBK4 facility at DLR Cologne during a first testing campaign, where good results have been obtained in a limited temperature range up to around 1300 °C. Then, in order to complete the rig sensor validation and reach TRL6, it had been agreed with the consortium partners to postpone to future programmes the sensor tests on the Siemens Berlin test bed initially envisaged and to perform a further testing campaign on the same HPMC rig. The campaign was planned for the final phase of the project, but it was cancelled because of a sudden bad failure of the air-preheater of the HBK4 facility.

### End results

The simplified theoretical model has shown that, under typical full scale combustor conditions, i.e., for strongly absorbing gas paths with non-uniform temperature distribution, the value measured by the IR sensor is the average temperature over half the gas path closer to the detector.

The functional and performance tests of the developed sensor, which were carried out on the HPMC test rig under representative temperature and pressure conditions (T= 1500 °C, P= 9 bar), confirmed that the sensor could survive without damage nor environment disturb for the on-going rig testing activities. In comparing the signal achieved from the probe with the flame temperature provided by the rig control system, a good agreement between the two signals was observed during the initial phase of the test (i.e. during heating at temperatures between around 900 and 1300 °C). Subsequently the probe signal became noisy and the agreement between the two sets of data significantly worsened. At very high temperatures, the IR signal was no longer correlated with the flame temperature (probably due to an optical misalignment caused by thermal deformations of the measuring system).

At this point, in order to complete the rig sensor validation and reach TRL6, it was agreed with the consortium partners that it would have been worth performing a further testing campaign on the same HPMC rig by using an improved sensor. Therefore the sensor testing on the Siemens Berlin test bed initially envisaged has been postponed to future programmes. After further laboratory tests the probe was properly modified to overcome the problem encountered. A one-week testing campaign of the IR sensor on the HPMC rig at DLR-Cologne was planned. However, at the very last minute a bad failure occurred to the HBK4 facility (the air-preheater broke down), so that the whole campaign was cancelled and it was not possible to schedule a further campaign before the end of the project.

### Experimental activity on the test rig

Among the available rigs, the Siemens High-Pressure Multi-Combustor (HPMC) Rig installed on the HBK4 facility at DLR Cologne has been selected as the most suitable for the IR sensor testing.

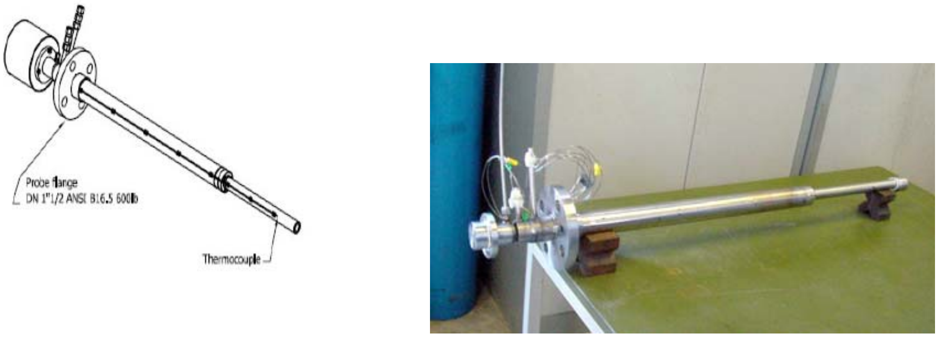


***Figure 39: The IR optical probe***

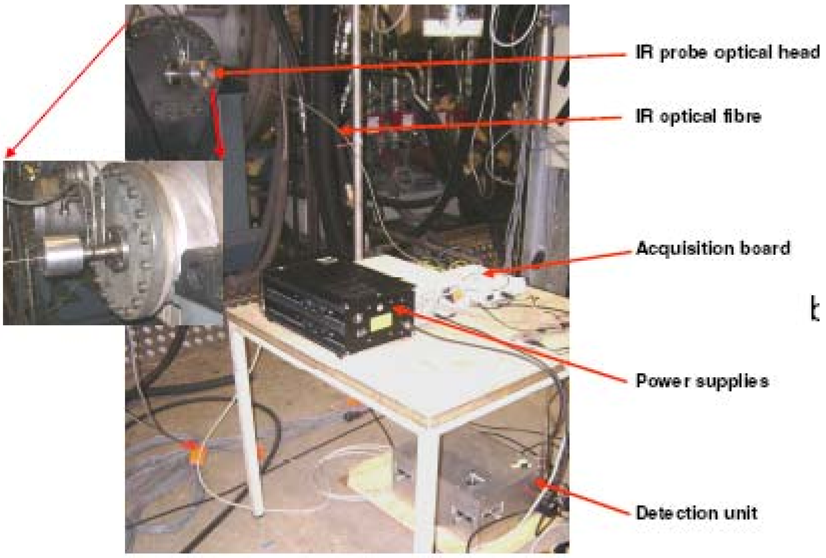


***Figure 40: The IR optical probe installed on the HPMC test rig***

The first testing campaign of the IR sensor on the HPMC rig was performed on July 2009. By means of spectral simulation by the HITRAN database an operating wavelength of the interference filter centered at 4473 nm had been selected. Measurements have been carried out during two separate tests, where the gas flow temperature was gradually increased up to the maximum value, then maintained almost constant for a given period and finally decreased down to ambient temperature. The signal achieved from the probe was then compared with the flame temperature provided by the rig control system. As shown in Figure 41, a good agreement between the two signals can be observed during the initial phase of the test (i.e. during heating at temperatures between around 900 and 1300 °C).

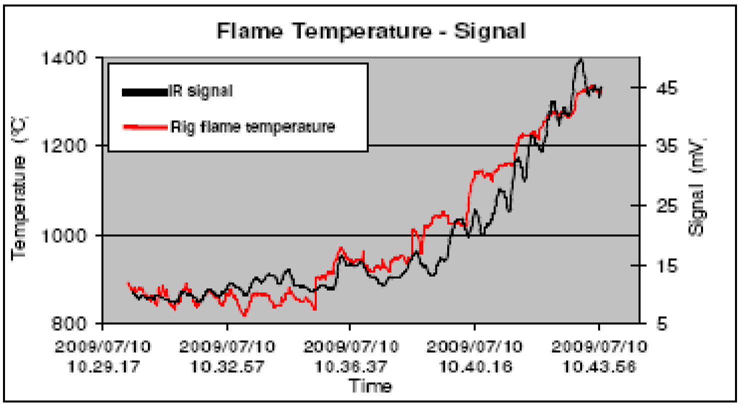


***Figure 41: Comparison between the measured IR signal and the flame temperature provided by the rig control system during the initial heating phase***

Subsequently the probe signal becomes noisy and the agreement between the two sets of data significantly worsens. At very high temperatures, the IR signal is no longer correlated with the flame temperature and it does not drop upon switching off the combustor. This behaviour is probably due to an optical misalignment caused by thermal deformations of the measuring system. As a consequence, operation of the IR sensor on the rig has been demonstrated up to less than 20 hrs.

Comparison between objectives and results

At the beginning of the HEATTOP project, a preliminary version of the IR sensor had been tested in laboratory and in non-systematic rig measurements up to around 1000 °C. The measurement accuracy had not been validated and the extent of the line-of-sight gas path actually sampled had not been clarified.

As a whole, we estimate that the technology, in spite of some positive rig test results, was still between TRL3 and TRL4.

Thanks to both the described modelling and laboratory activity during the HEATTOP project, the modified version of the sensor prototype has been demonstrated up to TRL4, i.e., in specified laboratory test environment. In addition, the technique has shown very good potential to become a useful plant measuring tool, as a consequence of the two-wavelength calibration option, which avoids the need for an external reference measurement.

The performed testing activity has allowed the IR sensor prototype to reach TRL5, whereas the measurement limits (temperature and lifetime demonstrated up to 1300 °C and about 15 hours, respectively) as well as the lack for collected data to validate the sensor accuracy have prevented complete TRL6 to be achieved.

In summary, as shown in the following table, at the moment the technology is suitable for development test rigs in GT stationary applications.

Further testing is needed to complete validation for full scale engine conditions and will be hopefully carried out in the near future in collaboration with interested OEM’s.

## 3.2.4 Tip Clearance measurement, WP5

### Background

The clearance between turbine blades and the inner housing of a turbo machines provides a path for hot gases to expand and bypass the turbine without doing work on the blades. The clearances generate undesired pressure drops that lead to losses in turbine efficiency.

In order to measure gaps present in an operating turbine and accomplish a controlled reduction of gaps, robust, reliable and accurate tip clearance sensors are necessary. Gaps are desired to be measured with an accuracy of better than 0.1mm.

Several tip clearance measurement systems are available that measure the gap between the blade tip and a sensor mounted through the machine housing. All these systems need to be calibrated to the specific turbine blade which limits the ease of us and introduces errors with blade aging, machine deformation and other time variant effects.

### Objectives and concept

On-line tip clearance measurement systems have additional challenging requirements of a desired life of more than 30,000 hours in an operating environment with temperatures up to 1000°C and continuous vibrations. The sensor must be rugged in the gas stream of a turbine. Goal in HEATTOP was to develop a millimeter wave system for accurate tip clearance measurements of 0.1mm, without the need for time consuming calibration processes and with an expected life time of 30.000 hours.

A feasibility study prepared by Siemens proposed two fundamental approaches for this task. The decision for a final system was made towards a bistatic RADAR system operating at the frequency range 60 to 90 GHz. The RADAR signals are radiated by the antenna probe through the ceramic sealing and scattered back by the moving blades inside the turbine. Simultaneously, a portion of the signal is transmitted directly from one waveguide to the other via the antenna to compensate heat effects. Figure 44 shows the system concept.

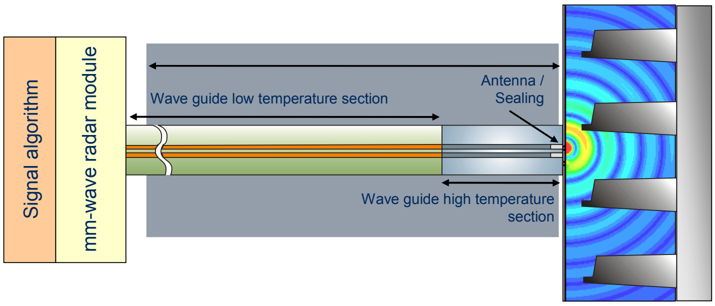


*Figure 42: Schematic of system concept*

After signal transmission to a PC, a newly developed algorithm roughly estimates the tip clearance by means of focusing on the blade tip, similar to the autofocus of a digital camera. After rough estimation, the signal can be reconstructed in the correct focal plane and fine tip clearance measurement can take place. This two-step algorithm ensures both high resolution and large measurement range. The current system is able to measure gaps between 0.1 and 10 mm with an accuracy of 100 to 200 µm over the entire range. Blade tip speed can be up to 500 m/s, so even largest turbines are supported. Measurement rate is lower than 1 Hz at this time, as the algorithm has not been implemented inside real-time hardware yet.

**Partners involved and their tasks:**

There have been three partners involved in Work Package 5.

Siemens AG , Germany

- Siemens developed the concept, did the specification of the sensor components, verified components in the lab, participated in the development of the antenna seal and performed most parts of the sensor testing. As new tasks Siemens manufactured an improved RF module, developed the data acquisition and signal analysis algorithms. In addition, Siemens task was the coordination of activities in Work Package 5.

Vibro-Meter (Switzerland)

- As manufacturer of a large variety of sensors for use by OEM in the aero and power generation industry, Vibro-Meter manufactured the wave guide, provided the seal for the sensor antenna and developed an appropriate probe design according to the engine specifications. Vibro-Meters task was further to provide and operate an RF tip clearance system for reference measurements.

Farran Ltd, (Ireland)

- The task of Farran was to develop and manufacture the RF module that generates the mm-waves.

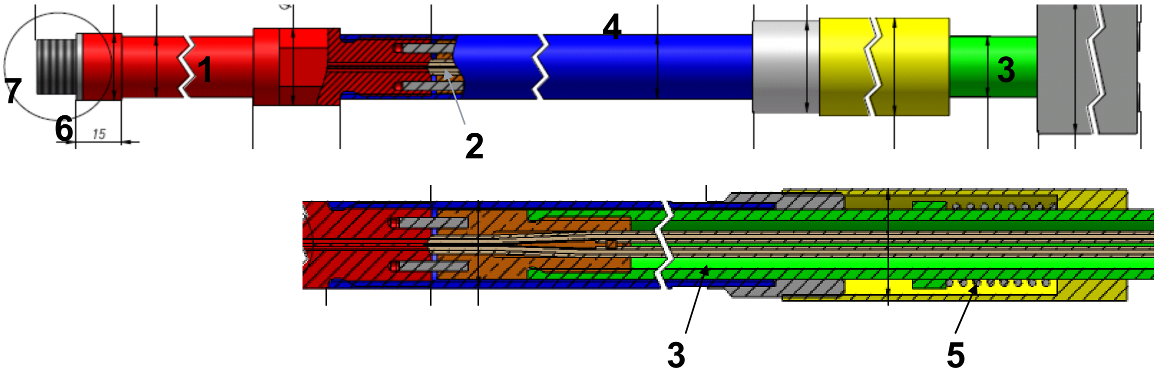
**Methodology**

The tasks was decomposed into subtasks of theoretical evaluation and concept development, component development and testing, signal processing and algorithms development, prototype design and validation testing.

Once the concept and measurement principle was defined that would meet the requirements derived in WP1 the partners started to design the system. This included evaluation of damping characteristics of wave guide material, their resistance to thermal loads, antenna properties, and options for sealing and its required thickness. The principle for simultaneous measurement of transmission and reflection was developed for this two-waveguide approach. Farran Technologies designed the RADAR module from conventional technology.

When materials and dimensions for wave guides and antenna were determined, a high temperature antenna probe with two adequate signal waveguides was specified by Siemens.

The wave guides consist of a high temperature section to withstand the high turbine temperature and a low temperature section for the cooler turbine sections. A novel developed ceramic sealing prevents hot gas to enter the waveguides. Several tests with brazing the ceramics were done to find the optimal solution. The entire probe was designed to withstand temperatures up to 1200°C inside the turbine and was manufactured by Vibrometer.



1. **High Temp waveguide: Inconnel HX**
2. **Low temperature waveguide: Copper**
3. **Inner tube: stainless steel AISI304**
4. **Outer tube: stainless steel AISI316**
5. **Spring: stainless steel C1**
6. **Thread: Inconnel HX**
7. **Waveguide front tip: Inconnel HX and Platinum**

***Figure 43: high temperature antenna probe***

***Figure 44: Sensor tip with sealed antenna***

After all components, such as waveguides, RF module and antenna were designed and manufactured; tests were performed to verify individual performance. Based on test results with Farran module the partners decided to realize a second module with a novel assembling technique for Millimeter-Wave circuits. This technique allows assembling modules on a circuit board. Hence, a small size and a suitable high frequency performance could be achieved, simultaneously.

Additionally electronic modules like signal synthesizer and filters, analogue-to-digital sampling board, appropriate housing and algorithms have been developed by Siemens to complete the measurement system hardware.

The final system consists of three main parts:

- the high temperature sensor with waveguide and antenna
- RF-box and
- digital signal processing box

The high temperature sensor probe feeds radars signals into the inner of the turbine. The radar-box can be installed directly on the outer side of the turbine housing. Both components meet the mechanical and thermal requirements for it.

Numerous tests were performed with the goal to verify component performance, system characteristics and to support development of algorithms. Tests with the complete system were done in order to determine accuracy-affecting parameters and finally to measure clearance directly. Benchmark tests with available measurement systems were done at the Berlin test bed gas turbine engine to have benchmark data available for accuracy assessment.

Tests in the engine were not done because accuracy and repeatability of measurements was not proven during rig testing.

## Results

To the author’s best knowledge for the first time ever mm-wave technology was applied to measure smallest lengths in a gas turbine environment. The developed sensor features this new concept and has newly developed components like the antenna with seal, miniaturized RF modules and a very complex algorithm for determination of blade position and clearance.

The first test results were obtained from laboratory evaluation of the algorithms in combination with different blade profiles and special measurement equipment. The tests showed the how different frequencies of the RF signal are capable to resolve inclination angles of blades and blade shapes.

Calibration to the specific turbine is not necessary when influential parameters like blade inclination and shape are known a priori and implemented into the algorithms.

The design has been successfully realized. Thermal gradient tests up to 1000°C have been performed showing that the hermeticity (leak test) was guaranteed.

An evaluation of the final complete high temperature system was done at a rotating test rig. It could be shown that the millimetre wave tip clearance measurement system meets most demands stated at project start. The measurement range goes from 0 to 10mm. The best achievable accuracy in some parts of the range was 0.1mm. In the critical range of 0-2 mm the achievable accuracy was about 0.2-0.4mm due to near field effects.

**Comparison versus State-of-the-Art**

State-of-the-art measurement systems for tip clearance apply capacitance sensors. The technique is well established. However, they require a complex calibration scheme, lack accuracy in the engine due to factors which can not be calibrated and have a reduced lifetime in respect to engine life cycles. Newer approaches utilize also electromagnetic waves, however at a significant lower frequency of 6 GHz.

Over the project duration a system was developed that is capable of overcoming the aforementioned drawbacks. The feasibility of the probe concept was proven both for the design and manufacturing phase.

In the validation phase with the complete probe during laboratory experiments at clean conditions the requirements could not fully demonstrated. Over the complete range the accuracy was not as good as 0.1mm and lacks behind capacitance and other RF sensors. Therefore not all objectives could be met.

While capacitance sensors do not require specialist support (except during calibration) and also 6 GHz systems are run without much specialist support, the mm-wave technology still requires a high level of specialist support when making measurements and for data analysis.

**Impact on industry and research sector**

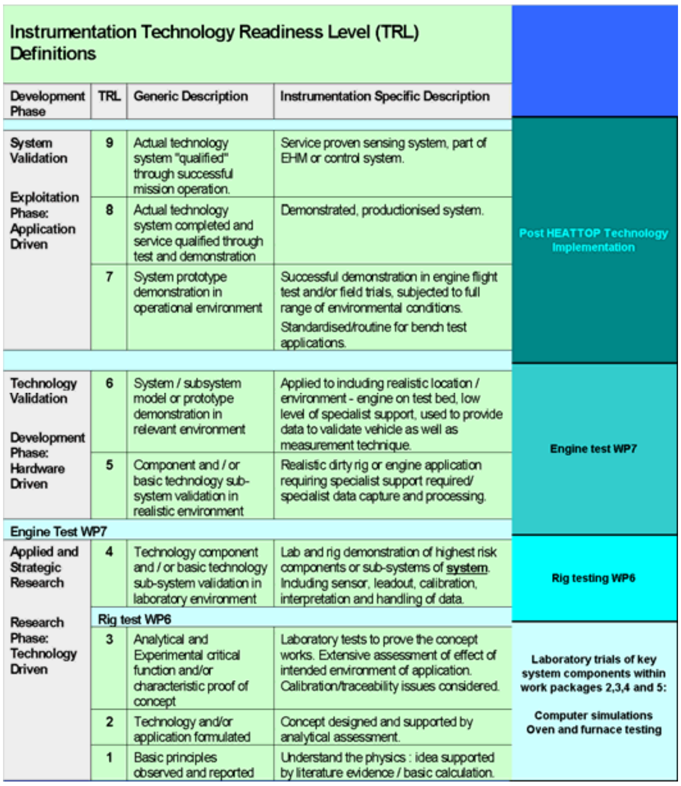
Currently there is a stronger impact seen in the research sector than for industry due to the unresolved accuracy issues. The developed algorithms may be used for imaging or distance measurement in other areas than gas turbines.

# 3.3 Validation of Technologies, WP6/7

## 3.3.1 Validation approach

Work package 6 and 7 were dedicated to the planning, preparation of test vehicles for and execution of validation tests of all developed sensor technologies at conditions close to, or in some cases in excess of those in real engines. Rig testing was carried out under WP6 and Engine testing in WP7.

To enable a common understanding of the level of maturity of the developing technologies, Technology Readiness Levels (TRLs) were used to gauge the progress of the developing technologies into viable capabilities. TRLs were originally developed by NASA, and are now widely used in the aerospace and power generation industries to provide a common scale for comparing the readiness of the many disparate emerging technologies which have to converge to enable a new product to be realised.
The requirements for the demonstration of attainment of each of the Technology Readiness Levels 1-9 have generic definitions, which are widely accepted across industry. For the HEATTOP project a set of bespoke definitions, more focused on measurement technology, but still fully compatible with the accepted generic definitions were developed (see below).



**Instrumentation Technology Readiness Level (TRL) Definitions**

| Development Phase | TRL | Generic Description | Instrumentation Specific Description | |
|---|---|---|---|---|
| **System Validation**<br>**Exploitation Phase: Application Driven** | 9 | Actual technology system "qualified" through successful mission operation. | Service proven sensing system, part of EHM or control system. | **Post HEATTOP Technology Implementation** |
| | 8 | Actual technology system completed and service qualified through test and demonstration | Demonstrated, productionised system. | |
| | 7 | System prototype demonstration in operational environment | Successful demonstration in engine flight test and/or field trials, subjected to full range of environmental conditions.<br>Standardised/routine for bench test applications. | |
| **Technology Validation**<br>**Development Phase: Hardware Driven** | 6 | System / subsystem model or prototype demonstration in relevant environment | Applied to including realistic location / environment - engine on test bed, low level of specialist support, used to provide data to validate vehicle as well as measurement technique. | **Engine test WP7** |
| | 5 | Component and / or basic technology sub-system validation in realistic environment | Realistic dirty rig or engine application requiring specialist support required/ specialist data capture and processing. | |
| **Engine Test WP7** | | | | |
| **Applied and Strategic Research**<br>**Research Phase: Technology Driven** | 4 | Technology component and / or basic technology sub-system validation in laboratory environment | Lab and rig demonstration of highest risk components or sub-systems of system. Including sensor, leadout, calibration, interpretation and handling of data. | **Rig testing WP6** |
| | **Rig test WP6** | | | |
| | 3 | Analytical and Experimental critical function and/or characteristic proof of concept | Laboratory tests to prove the concept works. Extensive assessment of effect of intended environment of application. Calibration/traceability issues considered. | **Laboratory trials of key system components within work packages 2,3,4 and 5:**<br>**Computer simulations Oven and furnace testing** |
| | 2 | Technology and/or application formulated | Concept designed and supported by analytical assessment. | |
| | 1 | Basic principles observed and reported | Understand the physics : idea supported by literature evidence / basic calculation. | |

### 3.3.2 Validation planning

In the early stages of the project, an alignment of the resources of the consortium with the validation requirements of the project was carried out by the OEMs.

A comprehensive 'register of test vehicles' (D6.1/D7.1) was created, detailing the vehicles available to the consortium for technology validation testing of new instruments. The register gathered together key parameters of the available test environment (temperature, pressure, gas velocity, mechanical vibration) and any physical and administrative constraints to sensor installation.

The register was used to enable selection of suitable vehicles for validation and technology readiness level improvement of the measurement technologies being developed.

By aligning the validation requirements for the measurement technology being developed with the available test facilities, a 'test plan' (D6.2/7.2) was created relating individual technologies with the vehicles which would be used to validate them. This plan showed for each technology, how the technology readiness levels would be validated and improved through the use of the test vehicles. The test plan also showed for each test vehicle which technologies were to be validated on the vehicle, allowing experiments to be combined by the vehicle owners to optimise facility usage.

In the original work programme, it was envisaged that the rig testing WP6 and engine testing WP7 would be carried out sequentially, with WP6 concluding prior to the start of WP7. However, as the detailed validation plans were developed, it became obvious that the rig and engine test conditions were complimentary rather than a simple progression to application in tougher conditions. For example the highest temperatures could be obtained in combustion research rigs rather than in engine.

Consequently the test programme evolved into a series of tests on both rigs and engines throughout the latter half of the project, to allow each instrument/technology to be validated across the fullest range of conditions.

### 3.3.3 Test Vehicle Selection

Through the test planning process previously described, the test vehicles required for the technology validation of the programme were selected to minimise the number of vehicles used, whilst achieving all test requirements.

The rigs used for the execution of the WP6 test programme were:

- Rolls-Royce IP combustion Rig (Derby)

- Siemens HP Multi Purpose Combustion Rig (DLR, Cologne)
- Siemens Rotating Rig (Siemens CT)
- Volvo High Temperature Shaker Rig
- Lund University Combustion Rig with rotating target.

The engines used for the execution of the WP7 test programme were:

- Rolls-Royce Viper 201 turbojet (Ansty test bed)
- Siemens SGT6-5000F gas turbine (Berlin test bed)
- Volvo RM12 turbofan engine, with afterburner

## 3.3.4 Vehicle Modification and Measurement Validation Testing

Test vehicle modification and sensor installation design was undertaken by the OEMS, where possible using common interfaces for multiple instruments. Conventional reference instrumentation was provided by the OEMs where possible to provide independent validation data.

Testing was carried out with multiple technologies being validated on one or more facilities, as required to validate all key aspects of performance identified by the test plan. Data obtained from these rig and engine tests, and the subsequent analysis of both the data from the new instruments and reference instruments, are reported in Section 3.2 of this report, along with the detailed descriptions of the technology being validated.

### 3.3.4.1 Rolls-Royce IP combustion Rig

The IP combustion rig in Derby is able to generate gas temperatures in excess of 1600°C with flame tube wall temperatures exceeding 900°C, and also to generate unsteady effects such as rumble.

Within the rig, the flame is contained within an inner flame tube. To allow the installation of prototype instrumentation into the rig, a set of customised flame tubes were manufactured incorporating mounting features and access for the instruments to be tested in the facility. Additionally the rig outer casing was modified to enable the installation of both Conventional and rapid insertion traverse gears. The technologies tested on the IP rig were:

- Oxsensis dynamic pressure sensors
- VKI traversable dynamic pressure probe
- Cambridge University intermittent choked nozzle probe

- Oxford University dual thin film rapid insertion probe
- Onera thin film thermocouple under TBC
- Vibrometer improved high temperature thermocouple

Additional provision was made for reference instrumentation, including wall and gas temperature measurement thermocouples and conventional dynamic pressure sensors.

The first testing on the IP rig was of two Oxsensis dynamic pressure transducers in March 2008. Testing on the IP rig concluded in April 2009.

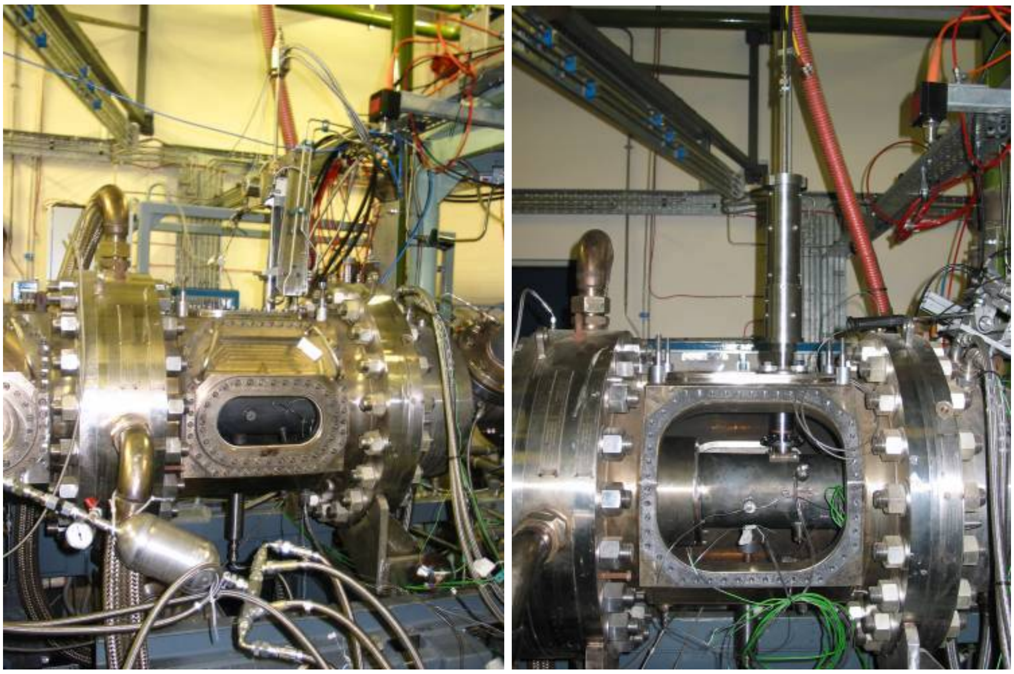


***Figure 45: Rolls-Royce IP Combustion Rig – Installation of VKI water cooled dynamic pressure probe in RTA190 traverse (left) & Oxford fast traverse probe (right)***

### 3.3.4.2 Siemens HP Multi Purpose Combustion Rig (HPMCR) at DLR

The High Pressure Multi Purpose Combustion Rig, (short HPMCR) is a test facility used for development of combustion system. The forecasting of the expected emissions and dynamic behavior of gas turbine combustion systems over the full operation range and under different boundary conditions requires burner tests under realistic conditions.

The HPMCR is capable of operating at conditions required for the development of the various combustion systems, which include among others the combustion systems for the SGT5-4000F(4) with 1/24 burners, the SGT5-8000H with 1/16 cans and the SGT5-7000F with 1/16 cans.

The operational capabilities are summarized in table below:

| | | |
|---|---|---|
| Compressor exit pressure PVII | bar | 30 |
| Compressor outlet temperature | °C | 550 |
| $\Delta$p combustor / pVII | - | 8% |
| Exhaust gas temperature | °C | 1750 |
| Flame temperature | °C | 1700 |

***Table 5: Maximum operational conditions of HP MCR***

For the testing of various combustion systems individual flow boxes which represent the design and boundary conditions of the respective gas turbine type are installed in the outer pressure vessel. Thus, the pressure vessel is the actual pressure boundary to the outer atmosphere, whereas the pressure difference over the flow box is minimal, just the portion as seen in real gas turbine. Hence, the rig is capable of producing nearly the same conditions and requirements on designs as instrumentation will face in the real full size gas turbine.

Figure 46 below shows the HP MCR.

Within the flow box there is the combustion system, comprising of air inlets, fuel nozzles, and combustion basket and transition piece. Downstream of the transition the rig is terminated by a vane simulation section, representing the first turbine row.

In HEATTOP tests were carried at the Platform Combustion System (PCS) which was instrumented with the different sensors.

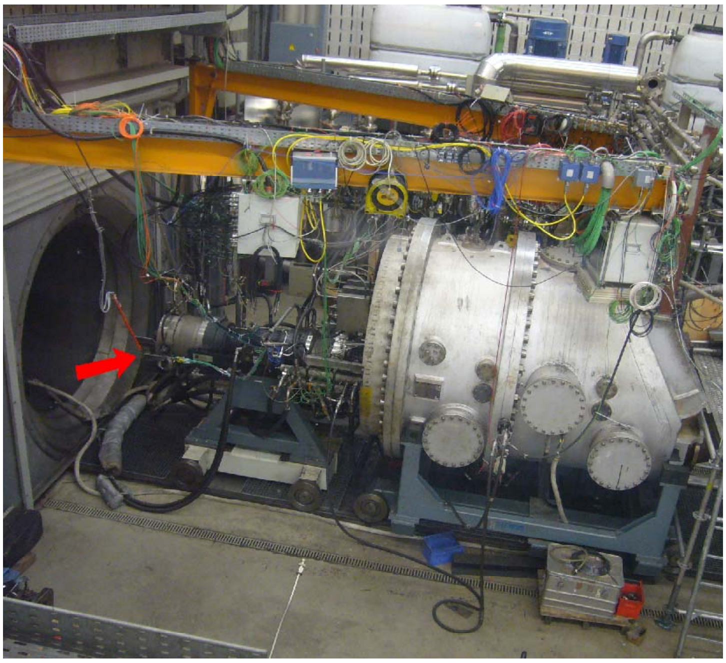


***Figure 46: HRMCR***

The HPMCR facility was used to validate sensors developed in WP3 and WP4 which are described in the following chapters.

- Fibre optic sensor: A heat shield and required support structure was designed that modified the exhaust of the rig.
- High temperature dynamic pressure sensor: placed in a first test into a Head end ports and secondly at the combustor basket close to the flame which required different access ports.
- IR probe: instrumented downstream of the transition piece

### 3.3.4.3 Siemens Rotating Rig at Siemens CT

The low temperature rotating rig, as shown in Figure 47, consists of a hub attached to a spindle that is driven by a motor. The hub of diameter 500 mm is equipped with sharp edged reference blade profiles as used in the lab tests. The blades are 130 mm in length and can be attached at 0°, 15° and 30° in order to simulate axial shift.

*Figure 47: Rotating rig with mm-wave probe*

The rig was especially designed for validation of the mm-wave tip clearance sensor developed by VM-CH, Farran and Siemens.

The target on accuracy with the mm-wave measurement system is 0.1mm which is hardly to demonstrate as an absolute value in an engine during operation. Therefore the accuracy tests were performed at a calibration rig at Siemens CT in Munich.

### 3.3.4.4 Volvo High Temperature Shaker Rig

The main objective of the work within this WP was to perform high temperature vibration test on test specimens coated with thin film thermocouples and TBCs (see chapter 3.2.1.5). In order to perform this test the rig furnace is designed and manufactured to be able to reach 1100ºC. A special fixture including en extender adapted to the test specimen has been designed and manufactured. The fixture and extender are made of a special high temperature alloy (Hastalloy X).

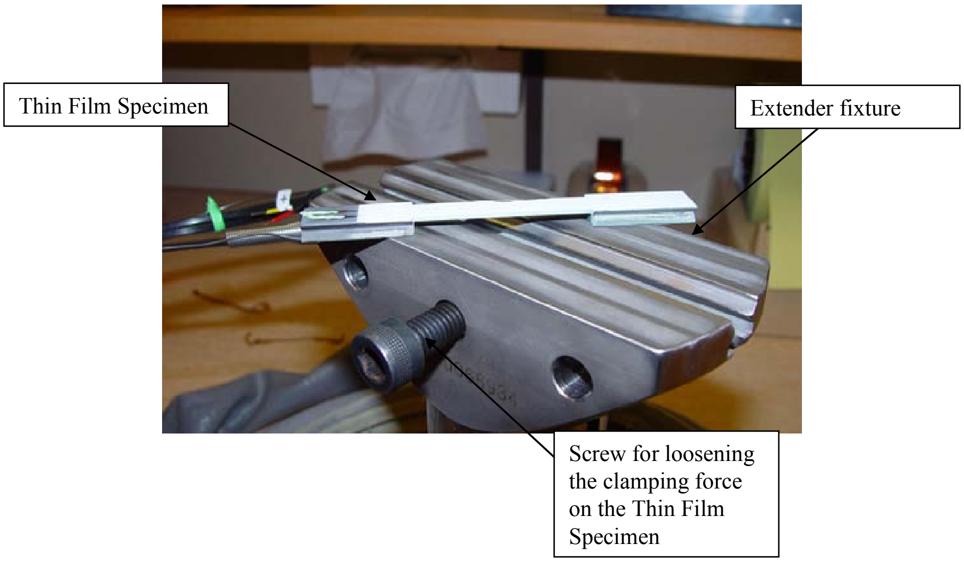


**Figure 4:** Fixture of hastalloy X and test specimen

A control accelerometer is positioned on the top of the vibrator table, but outside the hot area. An oil cooled mid-plate is mounted between the fixture extender and the vibrator table. The mid-plate and the extender including its feed are surrounded, inside the furnace, by a rubber made cover which serves as a secondary air supply cooling system. Vibration levels of the specimen were measured with LDV (Laser Doppler Velocimetry) equipment. The LDV equipment is positioned beside the furnace and the laser beam is angled into the furnace by a mirror. The beam is passing through a sapphire glass on the top of the furnace to measure response of the specimen during vibration and at high temperature.

Two test specimen coated with thin film thermocouples (Platinel II type) and TBCs have been provided by ONERA. Sheathed cables with Platinel conductors were connected to one side to the thin film thermocouples and to the other side to extension wires. Junction between extension wires and copper wires were placed in ice point reference equipment. Two K type thermocouples were used to measure test specimen temperatures.

Initial vibration test specifications were:

- Max. velocity: 50 mm/s.
- Frequency: 10-1000 Hz sweep mode (sweep rate of 3dB/Oct).
- Max. amplitude: 5 mm (10 Hz) - 0.05 mm (1 kHz).
- @700°C: 10 x 3 to 5 min vibration excitation.
- @1000°C: 10 x 3 to 5 min vibration excitation.

The first specimen (#9) was tested at room temperature and at 25 mm/s vibration velocity. Some Eigen frequencies were excited. At 910 Hz vibration velocity reached 132 mm/s. The thin film sensor was lost during the preliminary test due to excessive vibration velocity and/or insufficient adhesion of the alumina electrical insulating layer on the test pieces.

The second specimen (#10) was tested at 700°C and at 50 mm/s vibration velocity. After 12 min, during the third sweep, at 400 Hz, a loosening failure of the fixture extender occurred leading to excessive vibration velocities (up to 350 mm/s). The thin film sensor was lost due to these excessive vibration velocities and/or insufficient adhesion of the alumina electrical insulating layer on the test pieces.

Results show that vibration tests (Shaker Rig demonstration) could not be fully completed because of insufficient adhesion of alumina insulating layer on the substrates and/or failure of the test bench. Therefore the partners (Volvo Aero and ONERA) decided to perform this test after the project end.

Two improved test specimens have been manufactured by ONERA and will be tested by Volvo Aero.

#### 3.3.4.5 High Pressure Combustion Facility at Lund University

The high pressure combustion rig is a separate unit with its own dedicated supply systems for air, fuel and electricity. The rig is contained in four interconnected modules, separated from the Enoch Thulin laboratory but still having direct access to it, see Figure 48. The high pressure combustion rig is designed for so called single sector tests of burners for gas turbines and jet engines. The design specifications of the high pressure combustion rig were decided in close collaboration between scientific experts in the areas of modelling and diagnostics together with specialists from the industry. The size and performance of the test rig were chosen to guarantee that the experimental studies can be performed at industrially relevant conditions.

The specifications and specific features are:

- Maximum air flow rate: 1.2 kg/s.
- Maximum pressure: 16 bar.
- Preheated air temperature: up to 800 K.

- Steam generator to allow for studies of combustion in humid air.
- Systems for liquid and gaseous fuel, both systems have two independent fuel supply lines, normally used for main and pilot.
- Optical access to the combustion chamber.
- Afterburner to facilitate fuel evaporation studies.

The combustion air is provided by an air compressor (750 kW). Combustion air can be preheated by an electrical heater (1 MW). The test section has optical access from four sides with 100x100 mm rectangular windows in the combustion zone. The liquid fuel system can provide Jet-A and synthetic Jet-A up to 100 kg/h. A separate compressor and gas tank can provide natural gas up to 86 kg/h and 13 bar. The test rig is connected to the laser diagnostic laboratory with easy access to the laser equipment for CARS, Raman scattering, high repetition rate diagnostics, LIF, LDA, PIV, etc. High speed video systems are also available.

The high pressure combustion facility in Lund was considered a highly suitable installation for performing the validation of 2D-measurements of temperature fields, utilizing the thermographic phosphors investigated in WP3, on rapidly moving surfaces at elevated temperatures and pressures. The high pressure rig can provide well controlled validation conditions in terms of temperature and pressure. The test section is designed for optical / laser based diagnostics techniques. The laser and camera equipment can easily be provided from the optical/laser diagnostics laboratories nest door. The operating parameters for the tests carried out were temperature between 300 K and 800 K and pressure between 1 and 6 bar.

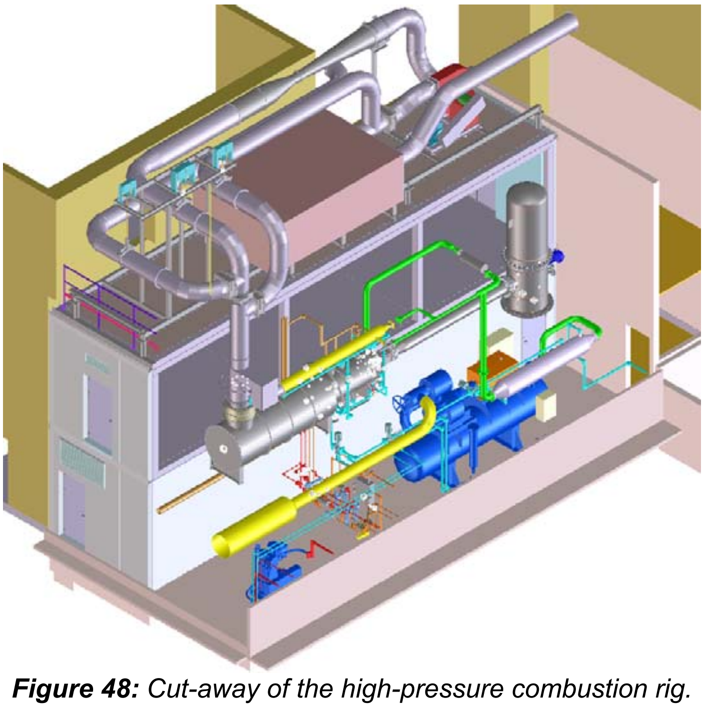


***Figure 48:*** *Cut-away of the high-pressure combustion rig.*

The rig was used to validate surface temperature measurements with the thermographic phosphors investigated in WP3, on rotating objects. Therefore, a number of modifications of the high pressure combustion test rig hardware were required in order to convert the rig from the normal operation when testing gas turbine or aero engine combustors.

### 3.3.4.6 Scitek Rolls-Royce Viper 201 turbojet.

The Rolls-Royce Viper mk 201 engine is a single shaft turbojet, with relatively easy access to the single stage HPT. TET is around 1100°K. The overall pressure ratio of 4-5. The engine provides a more challenging vibration environment than most modern vehicles, and the gas path contains much more particulate matter than produced by more modern combustion systems providing a challenge to gas path measurements.

*Figure 49: Viper 201 engine on 42 test bed at Rolls-Royce Ansty*
**(VKI probe cooling system installed to left of engine)**

The Viper engine was modified to provide two access ports for traversable instrumentation at the HPT exit. One of these ports has been designed to accommodate a steeper motor traverse routinely used for conventional aerodynamic instrumentation. A second port has been incorporated to accept a rapid insertion pneumatically operated traverse, supplied by Oxford University. Additionally, the turbine exit plane has been fitted with pressure tappings and thermocouples protruding from the near outer wall to provide extra reference measurements. Ports to mount Oxsensis dynamic pressure transducers both at turbine exit and over tip were also incorporated into the engine. A port to fit the Vibrometer dual wavelength pyrometer viewing the HPT blades was incorporated into the jet pipe.

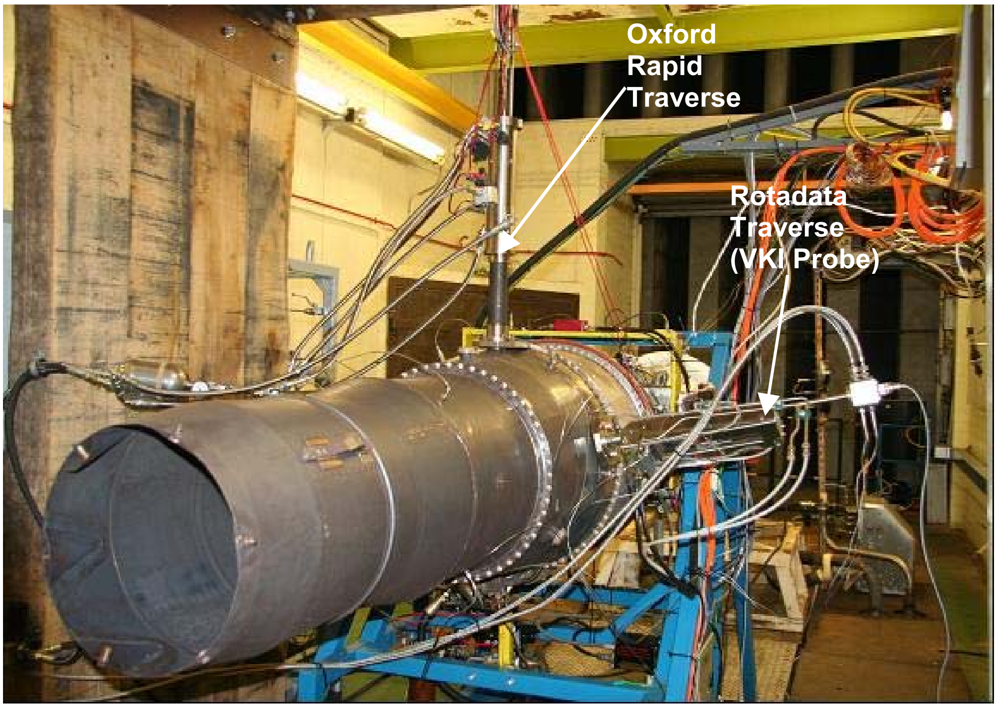


***Figure 50: Relative locations of two traverse systems.***

Testing commenced in October 2008 with initial trials of the traversable gas path instruments, and concluded with tests of the dual wavelength pyrometer in April 2010. During the campaign the following instruments were tested:

- Water cooled traversable wedge probe (reference)
- Oxsensis dynamic pressure sensors
- VKI traversable dynamic pressure probe
- Cambridge University intermittent choked nozzle probe
- Oxford University dual thin film rapid insertion probe
- Vibrometer dual wavelength pyrometer

### 3.3.4.7 Siemens SGT6-5000F gas turbine at Berlin Test Bed

The Berlin Test Bed provides a full scale gas turbine for testing.

The SGT6-5000F is a proven gas turbine for the 60 Hz market, based on the efficient 5000F technology platform. It provides some 208 MW of electrical output with an efficiency of 38.6%. It features 16 can-type combustors in a circular array and 13-stage axial-flow compressor with advanced 3D design technology and variable inlet guide vanes. The turbine has four stages and applies advanced cooling technology.

As the engine turns at 60Hz, there is no generator coupled to the Berlin Test Bed. Instead the energy of this testing engine is captured by a water brake.

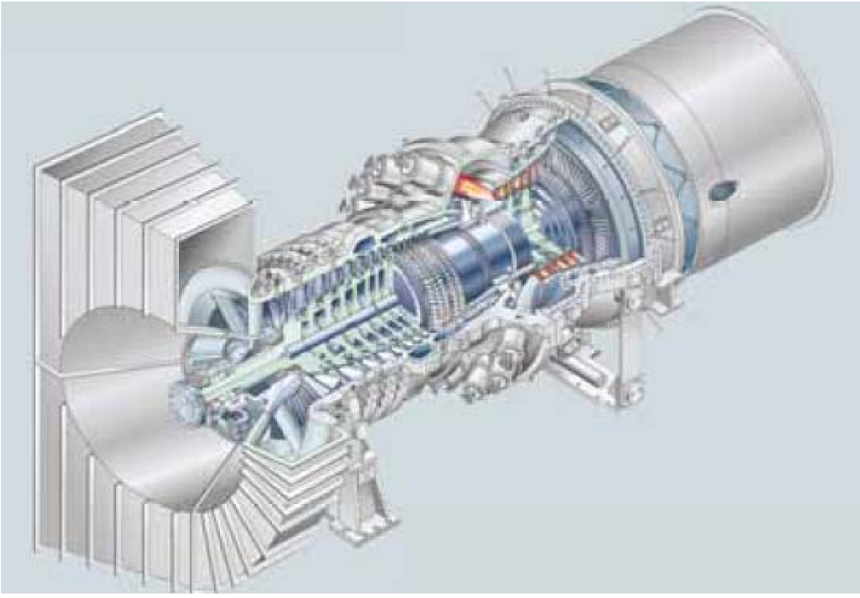


*Figure 51: SGT6-5000F*

The test bed provides options for new instrumentations, data acquisition, and data reduction for Siemens Energy. Focus is to develop new measurement techniques and technologies, run high risk trials and find and master technological limits. Tests at the engine help to validate design methodology and codes.

The engine provides the only opportunity for validation of new measurement systems at relevant environment of around 20 bars and flame temperatures inside the combustor of up to 1650°C.

The engine was used to validate the KEMA Pyrometer, Oxsensis dynamic pressure sensors and tip clearance measurement systems.

### 3.3.4.8 Volvo RM12 turbofan engine, with afterburner

The objectives of the work in this work package were to prepare RM12 engine for test of defined technology/equipment to be tested, to define test programs and to perform the engine test. The technologies/equipments to be tested are: thermo-graphic phosphors developed by Lund University, VKI unsteady pressure traversed probe, Oxford unsteady pressure and temperature fast traverse probe and Auxitrol flat tip thermocouples. Also VAC has undertaken to evaluate the results from Auxitrol flat tip thermocouples from the engine test.

The RM12 is the engine of the Gripen fighter. It is a dual shaft engine delivering a thrust of 53 kN, increased to 80 kN with the use of afterburner.

The measurement position in the outlet of the low pressure turbine on this engine offers the possibility to test under harsh conditions, with low risk to the engine. Temperatures typically reach 800-900°C, pressure 400-500 kPa and air speed around M0.5. Igniting the afterburner increases acoustical and radiation load.

The engine is fitted with four ports at a distance about five blade cords downstream the turbine. One of these was used for a reference rake providing 5 shrouded total temperature/pressure probes. The other three accommodated probes from test participants, enabling measurements to be taken under close to identical operating conditions.

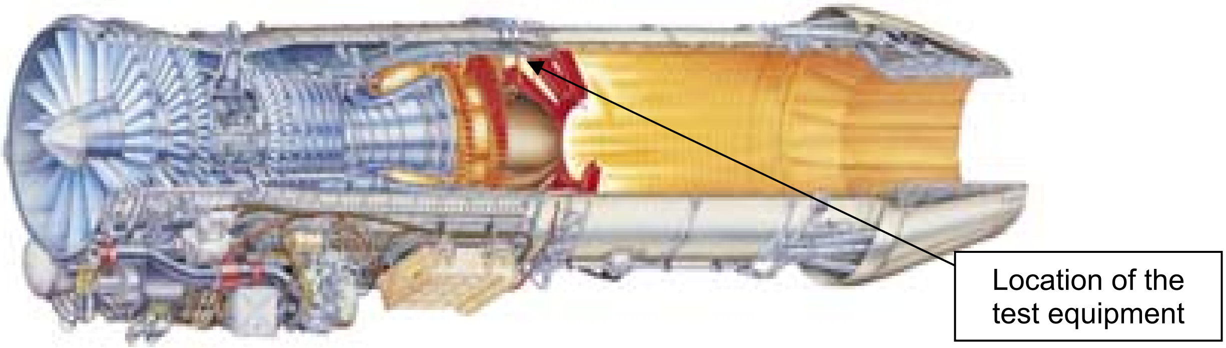


*Figure 52: Volvo RM12*

For tests with thermo-graphic phosphors, one exhaust seal instrumented with 6 thermocouples was available. These tests were done at a separate occasion because of the use of high power lasers and sensitive equipment. Pre-test, three positions were identified for measurement; the afterburner outlet, the liner and the flame holder support. All these require both the exciting laser beam and the responding light to pass through the exhaust channel. It turned out that it would not be possible to get visual access to the flame holder support, but both other positions were possible with careful positioning of the instruments. The outlet was also instrumented with thermocouples providing metal temperatures for comparison.

### 3.3.5 Validation status achieved

Results of the analysis of data obtained from lab, rig and engine test programmes was reviewed by the OEMs at the end of the project. This information on the measurement performance of the new technologies, in combination with OEM experience of the logistical challenges and reliability of the technologies observed during the rig and engine test campaigns, was used to assess the Technology Readiness Level (TRL) demonstrated by each technology during the validation programme.

The TRL assessment for each technology deliverable, and evidence to support each level achieved are tabulated in the following table:

**Technology delivery: Table 2 of Original proposal**

| | **Development targets as defined by Annex T2**<br>**(New sensor hardware and improved error compensation)** | **Task** | **Lead partner** | **Technology Deliverable & Changes to deliverable as a result of research carried out** | **TRL 3 Validation** | **TRL 4 Validation** | **TRL 5 Validation** | **TRL 6 Validation** | **TRL 7 Validation** | **Report References** |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Laboratory tests to prove the concept works. Extensive assessment of effect of intended environment of application. Calibration/traceability issues considered. | Lab demonstration of highest risk components or sub-systems of system. Including sensor, leadout, calibration, interpretation and handling of data. | Realistic dirty rig or engine application requiring specialist support & specialist data capture / processing. | Applied to realistic location / environment - engine on test bed, low level of specialist support, used to provide data to validate vehicle as well as measurement technique. | Successful demonstration in engine flight test, or field trials subjected to full range of environmental conditions. Standardised/routine for bench test applications. | |
| 1 | An improved code for correction of radiation and conduction losses, aging, corrosion, contamination and cycle drift of a sensor in a hot turbine area (>1000 C) | 3.2 | Aux | Matlab software code | Individual error effects identified and contributions calculated. Some lab validation carried out. | no level for code, only for projects used on an engine | | | | D2.5 |
| 2 | Improved fast response thermocouples and improved attachment techniques for high frequency measurements | 2.1.3<br>2.1.4 | Aux<br>VAC | | Suceesful time response lab trials | Shaker tests proved robustness, calibration in high accuracy furnace | Successful RM12 test with some specialist support | Successful RM12 test with support needed to install | More testing planned | D2.1, D2.2 |
| 3 | A new thermocouple type as a result of a Design of Experiment by changing all parameters one by one (<1100 C) | 2.2 | VMUK | New design and manufacturing method for optimised type 'n' thermocouple patented | Cyclic testing in labs. | Cyclic testing in labs, | IP combustion rig tgas path temperatyres sucessfully measured , using spoecialist support | Engine trials, including long timescales still needed | | D2.3, D2.4 |
| 5 | Thermocouples for very high temperatures (<1500 C) | 2.4 | Aux | | Lab trials to select suitable materials for future very high temperature t/cs. Machining trials of candidate materials. | Assemble and test combinations of thermocouples, results upto 1500C, tests need to be continued. | Plan was only for lab trials within HEATTOP | | | D2.6 |
| 6 | An embedded fiber optical high temperature sensor (<1200 C) | 3.1 | Sie | Two systems trialed : Fibre Bragg Grating (FBG) and black body radiators. | Lab trials of fibre and packaging materials completed sucessfully. | Trials of fibres including calibrations. Longterm stability testing in lab. | Rig test on heat shield component. Data good, but both systems still require specialist support. | Engine testing embedded in vane, when lonrterm stability is established. | | D3.1, D3.2 |
| 7 | A pyrometer corrected / calibrated for transmission and fouling | 3.2 | Kema | | Oven testing at component level | Lab demonstration of fouling correction | Short engine test ~200hors, need longer run to demonstrate performance at higher levels of fouling | Longer runs needed to get results with more fouling | | D3.3, D3.4 |
| 8 | Improved optical designs for Pyrometers (decreased degradation) | 3.2 | VMUK | Degradation mechanisms study, and dual wavelength pyrometer to minimise these effects | Oven trials with simulated contamination on optics, analysis of real in-service contaminants | Oven trials with simulated contamination on optics, analysis of real in-service contaminants | Viper engine HPT engine running with modified emisivity blades, specialist support needed to interpret data. Only 10s of hours run. | | | D3.5, D3.6 |
| 9 | A pyrometer optical system for longer wave lengths | 3.2 | VMUK | | | | | | | |
| 10 | Thermographic phoshors for quasi 2D temperature measurement on airfoils, under high temperature and presssure | 3.3 | Lund | | Lab tests of phosphor materials | Rotating target trials in combustion rig (BAM phosphor). | Static component application in RM12 engine. High level of specialist support needed. Temperature data obtained from YAG:Dy | | | D3.7 |
| 11 | A fast response cooled pressure probe for high pressure (HP) turbine exit, (<1100 C) | 4.1.1 | VKI | | Successful plasma torch tests in lab, cooling system proven. | Viper engine turbine exit test successful, with some running repairs to electronics. Some unexplained differences in steady pressure cf other techniques | IP combustion rig test, good data with minimal intervention, but specialist support needed. | Worked well on RM12 test (specialist support, minimal intervention) but differences between steady pressure data obtained and other measurements.. | | D4.1, D4.2,D4.3 |

***Table 6: TRL assessment by OEMs***

**Technology delivery: Table 2 of Original proposal**

|  | **Development targets as defined by Annex T2**<br>**(New sensor hardware and improved error compensation)** | **Task** | **Lead partner** | **Technology Deliverable & Changes to deliverable as a result of research carried out** | **TRL 3 Validation** | **TRL 4 Validation** | **TRL 5 Validation** | **TRL 6 Validation** | **TRL 7 Validation** | **Report References** |
|---|---|---|---|---|---|---|---|---|---|---|
|  |  |  |  |  | Laboratory tests to prove the concept works. Extensive assessment of effect of intended environment of application. Calibration/traceability issues considered. | Lab demonstration of highest risk components or sub-systems of system. Including sensor, leadout, calibration, interpretation and handling of data. | Realistic dirty rig or engine application requiring specialist support & specialist data capture / processing. | Applied to realistic location / environment - engine on test bed, low level of specialist support, used to provide data to validate vehicle as well as measurement technique. | Successful demonstration in engine flight test, or field trials subjected to full range of environmental conditions. Standardised/routine for bench test applications. |  |
| 12 | An optical fibre multiplexable pressure sensor (<1000 C) | 4.1.2 | Oxs | High TRL sensor for dynamic pressure, but static pressure, temperure measurements lower TRL, but feasibility lab demonstrated only. | Succesful lab bench trials and calibrations including at high temperature | Early viper engine turbine exit test successful, with some running repairs | Siemens, Viper and IP rig tests successful with minimal intervention | Rolls-Royce EFE HP rig application obtained valid data without specialist support.<br>Berlin engine test, test without specialist support. Lonterm trial on Didcot Power plant. | Installed in XWB dev engine ready to test. Connected to existing site dynamic data systems. | D4.1, D4.2 |
| 13 | An intermittent choked nozzle probe for total pressure and temperature (<1600 C) | 4.1.3 | Ucam |  | Succesful lab bench trials and calibrations in ovens | Early viper engine turbine exit test successful, but sample rate lower than expected (10s vs 1s). Specialist support needed. Data not fully validated against other techniques yet. | IP combustion rig test, good data with minimal intervention specialist support. Data not fully validated against other techniques yet. |  |  | D4.1, D4.2 |
| 14 | A non-intrusive IR sensor for turbine inlet gas temperature measurements (<1600 C) | 4.2 | Cesi |  | Lab trials of concept and components | Lab demo of system on test cell with different gas pressure/temperature prfiles | Rig testing on Siemens combustor. Specialist support needed, accuracy difficult to prove without reference instrument, but functionality demonstrated. |  |  | D4.1, D4.2 |
| 15 | A mm-wave blade tip clearance sensor for use in long-time monitoring (10,000 hrs) under high temperatures (<1100 C) | 5 | VMCH |  | Components assessed on linear stage rig. | RF Module, waveguide and antenna demonstrated in lab. Brazing techniques demonstrated in oven test. Full system demo in lab on rotating rig. | Accuracy issues need to be adressed prior to engine test. Will need specialist support. |  |  | D5.1, D5.2, D5.3 |
| 16 | Thin Film Thermocouples | 2.5 | Onera |  | Tests of insulation, sensitivity,installation on Ni substrates in lab | Vibration testing of installed sensors. Vibration rig test failed, some flaking of sensor off surface. Burner rig installation, survived testing, credible data during run but t/c failed on shutdow |  |  |  | D2.7, D2.8 |
| 17 | Fast response total pressure and thin film temperature probes for measurements in the turbine section | 4.1.4 | Uox | Rapid traverse system demonstrated to high TRL, but dual thin film temperature sensor for gas path TT is not yet proven. | Succesful lab bench trials and calibrations | Survived and traverse worked well in Spey/Viper/IP rig / RM12 but no valid temperature data, physics of DTF is not as predicted. |  |  |  | D4.1, D4.2, D4.4, D4.5, D4.6 |

*Table 7: TRL assessment by OEMs, continued*

# 4 HEATTOP Publishable Results

## 4.1 Overview of exploitable knowledge of HEATTOP

The following set of tables provides an overview of developed sensors, their specific feature and their intended application. More details follow in section 4.2 below.

| Sensor# | Technology | WP | Partner | Area of application | | Main purpose of application | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | stationary GT | Aero engine | R&D | New engine design | Prototype testing | Monitoring | Key characteristic | Max conditons | TRL before HEATTOP | TRL after HEATTOP | Competitive differentiators/ unique feature | Estimated benefit/technical improvement for end user (first time costs, efficiency, emissions, life cycle costs, availability, reliability, fuel flexibility, operational flexibility) |
| 1 | An improved code for correction of radiation and conduction losses, aging, corrosion, contamination and cycle drift of a sensor in a hot turbine area | 2 | AUX | Potential | Potential | Potential | Potential | Potential | Potential | Compilation and formulation of errors, aging and drift issues of thermocouples | n.a. | 1 | 3 | Individual error effects identified and contributions calculated. Some lab validation carried out. | May be used for error correction of thermocouples in look-up table. May be used in correcting drift of existing thermcouples in the fleet when replacements are not foreseen. |
| 2 | Improved fast response thermocouples and improved attachment techniques for high frequency measurements | 2 | AUX, VAC | yes | yes | yes | no | yes | no | A fast response thermocouple with characteristic flat shape for wall temperture measurement<br>Accuracy: Within ±0.4% in lab | 1050°C | 3 | 7 | fastest TC available on the market with special customized shape<br>Generally, cylindrical shape TC for air temperature measurement; Specific shape for wall temperature measurement<br>Life time: much better than traditional thermocouples (>150hrs) | - Ability to measure real wall temperatres and to measure temperature transients<br>- As function of air flow characteristic 0.2 sec can be reached,<br>- Compliant with norm ASTM E230, class 1<br>Reduced cost/time<br>-improved transient accuracy for temperature surveys |
| 3 | A new thermocouple type as a result of a Design of Experiment by changing all parameters one by one (<1100 C) | 2.2 | VMUK | yes | yes | yes | yes | yes | Potential | Thermocouple capable of maintaining Class 1 accuracy (0.04%) over operational life (25000 hrs) | 1050°C | 3 | 6 | Drift and accuracy is better than conventional Type K | Greater confidence in Exhaust Gas Temperature measurement and EGT margin erosion leading to improved effiency and better maintenance scheduling<br>Improved accuracy /life for very high temperature dev test and gas path measurements<br>better future product performance,<br>Longer life/better accuracy production engine TGT probes: better engine control |
| 4 | Novel thermocouple | 2.2. | UCAM | yes | yes | Potential | Potential | Potential | Potential | operation up to 1200°C with lower drift | 1200°C | 1 | 2 | temperature capability, life, drift and accuracy are better than current conventional thermocouple | better engine control, improved fuel efficiency and component life estimation |

*Table 8: Exploitable knowledge*

| Sensor# | Technology | WP | Partner | Area of application | | Main purpose of application | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | stationary GT | Aero engine | R&D | New engine design | Prototype testing | Monitoring | Key characteristic | Max conditons | TRL before HEATTOP | TRL after HEATTOP | Competitive differentiators/ unique feature | Estimated benefit/technical improvement for end user (first time costs, efficiency, emissions, life cycle costs, availability, reliability, fuel flexibility, operational flexibility) |
| 5 | Thermocouples for very high temperatures (<1500 C) | 2.4 | AUX | yes | yes | yes | no | potential | no | Thermocouple with ceramic sheath for extremly high temperature1500°C Accuracy: +/-0,5-0,6% reading (B type TC) | 1500°C | 2 | 4 | Extended temperature range for measurent applications<br>Currently no sensors are available at 1500C for direct measurement<br>Current state of the art : TC for temperature up to 1150°C | Provide accurate measurements at high temperatures.<br>Easy, fast installation and inexpensive measurement to get reliable engine data.<br>Improving flexibility and reliability of engines.<br>TRL still low, but when available should give similar benefits to above, but in hotter parts of engine. |
| 6 | Embedded fiber optical high temperature sensor (<1200 C) | 3.1 | Sie<br>IPHT<br>AOS | yes | no | yes | no | Potential | future | Thin Palladium foil acting as Black body radiator fixed to a silica fiber for temperature measurement | 900°C | 3 | 4 | Very fine spatial resolution due to small size of sensing element of 10 micron. The foil acts as radiating element measuring directly the temperature where it is attached | Accurate point measurements such as bond coat temperature allow verifcation of coating designs and CFD simulations. Control of material temperatures is needed to reduce life cycle costs and enhance operational flexibility. Engine reliabilty can be improved by controlling temperature limits of coating and optimizing |
| | | | | yes | no | | no | Potential | future | Sapphire fiber sensor with FBG multiple gratings for temperature measurement | 1200°C | 1 | 3 | Highest temperature potoential of 1700°C Sapphire with FBG is new technology to measure gas temperature; temperature distributions in solid structures | May be used in hotter parts of the engine. Has potentil for hottest parts. Can be used for componet and gas temperature measurements.<br>Sensors may increase reliabilty and availability of measurements. |
| | | | | yes | no | yes | Potential | no | Potential | Silica femto-second lasered FBG for temperature measurement | 800°C | 1 | 4 | Robust packaging with muliple FBG in silica fiber<br>- allow temperature distribution measurements up to 3 locations | - Can be used in components with lower temperatures<br>- increased availability of sensor and monitoring<br>- life time of sensors ptentially incresed. |
| 7 | A pyrometer corrected / calibrated for transmission and fouling | 3.2 | VMUK | Potential | no | Potential | no | Potential | no | Pyrometer, capable of lower temperature measurements than current systems | 1200°C | 2 | 3 | Can measure over wider range of temperatures without excessive noise | Could additional functionality to pyrometers such as relight detection<br>Potentila for blade health monitoring in energy products |
| 8 | Improved optical designs for Pyrometers (decreased degradation) | 3.2 | VMUK | Potential | yes | yes | no | Potential | Potential | Pyrometer insensitive to lens contamination | 1200°C | 3 | 5 | Can be used for long service intervals without cleaning. | Could lead to higher TETs hence better efficiency and emissions<br>Potential to increase on-wing life of pyrometers used in control systems on current products: reduced maintenence cost, better performance (less margin needed for pyro error) |
| 9 | A pyrometer optical system for longer wave lengths | 3.2 | VMUK | Potential | yes | yes | no | Potential | Potential | Pyrometer capable of lower temperature measurement than current system | 1200°C | 2 | 3 | Can measure over wider range of temperatures without excessive noise | Could additional functionality to pyrometers such as relight detection, others see above |
| 10 | Thermographic phoshors for quasi 2D temperature measurement on airfoils, under high temperature and presssure | 3.3 | Lund | Potential | Potential | yes | no | Potential | future | Thermographic Phosphor paint for online non-intrusive 2D temperature measurement | 1400°C | 1 | 3 | Non intrusive, high time resolution, high precision and accuracy | Fast temperature measurement enable estimation of life cycle, performance and condition monitoring.<br>Potential use to establish surface temperature of TBCs on development and R&D testing. Very longterm could be an EHM application to checking health of coatings. |

***Table 9: Exploitable knowledge, continued***

| Sensor# | Technology | WP | Partner | Area of application | | Main purpose of application | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | stationary GT | Aero engine | R&D | New engine design | Prototype testing | Monitoring | Key characteristic | Max conditons | TRL before HEATTOP | TRL after HEATTOP | Competitive differentiators/ unique feature | Estimated benefit/technical improvement for end user (first time costs, efficiency, emissions, life cycle costs, availability, reliability, fuel flexibility, operational flexibility) |
| 11 | A high temperature water-cooled fast response total pressure probe for hot gas path measurements (in combustion chambers and turbine hot sections) | 4 | von Karman Institute (VKI) | yes | yes | yes | no | yes | no | 8mm diameter cooled probe. Based on a piezoresistive pressure sensor, delivers the steady and unsteady pressure signal. High bandwidth (~60 kHz). Continuously immersed. | Tested up to 4 bar, over 1600 degC continuous, peak 2000degC. | 1 | 5 | To the author's best knowledge, this is the only probe continuously immersed into the gas stream able to measure high frequency total pressure fluctuations.<br>Besides, using the virtual 3-hole mode, this probe can also deliver the periodic fluctuations of yaw angle, static pressure and Mach number. This is a very unique feature and this is the only probe existing at this moment to deliver these quantities. | The possibility to measure steady and unsteady total pressure, yaw angle, static pressure and Mach number inside the gas path allows obtaining detailed radial distributions at combustor exit or at any interstage location in HP, IP or LP turbines.<br>The interest is to validate CFD simulations, related to unsteady loads on the turbine and improve component design (both for turbines and combustors).<br>Most likely short term exploitation in combustion R&D rigs to analyse noise sources and combustor instabilities. Should neable noise reduction and more efficient combstor designs. |
| 12 | An optical fibre multiplexable pressure sensor (<1000 C) | 4.1.2 | Oxs | yes | yes | yes | Potential | yes | Potential | Dynamic pressure sensor to temperatures up to 1000°C | 1000°C | 3 | 7 | Is the only sensor available that can measure at 1000°C.<br>Further unique feature is the simultenous measurement of static and dynaminc values | Sensor is applied for special meaurement tasks in R&D. Has potential for second source sensor for combsution dynamics monitoring. Impact on engine availability, reliability, first time costs.<br>Already in se for combustor stability, turbine flutter and exhaust duct noise measurements in R+D end engine development tests. Potential long term in service applicationfor engine health or combustion control. |
| 13 | An intermittent choked nozzle probe for total pressure and temperature (<1600 C) | 4.1.3 | UCAM | yes | yes | yes | no | yes | no | Aspirated probe for measuring stagnation quantities and gas composition based on choked nozzle theory | 4 bar, 1600°C | 2 | 5 | Measurements of stagnation temperature,stagnation pressure and gas compositionin in combustor rigs and turbines up to 1600°C with continuosly immersed probe. | Measurements of steady total pressure, total temperature and gas composition inside the gas path. The installation cost is reduced by the use of one probe only to measure more variables. Maximum achievable temperature measurements are higher and erros lower compared to standard thermocouples.<br>RR: Application to combustor R+D rigs planned. Better accuracy and reduced cost relative to existing capability. Being considered as alternative/additional tool for gas path temperature measurements in hottest engine sections on R+D and engine development. |
| 14 | A non-intrusive IR sensor for turbine inlet gas temperature measurements (<1600 C) | 4.2 | ERSE (formerly CESI-R) | yes | Potential | Potential | Potential | Potential | in future | A non-intrusive IR sensor for on line real time TIT measurements | 9 bar 1300 C proven, higher possible | 3 | 5/6 | Currently, to the authors' knowledge, no other method or commercially available instrument exists for on line real time TIT measurements | On line real time measurement of TIT is:<br>- a unique source of data for CFD modeling comparison in R&D and new design applications<br>- a useful tool for increasing overall GT plant efficiency and hot gas components lifetime<br>limitations on current design (gas path size) mean not yet applicable to smaller aero engines, but keeping 'watching brief' as non-intrusive nature of technolog is attractive. |
| 15 | A mm-wave blade tip clearance sensor for use in long-time monitoring (10,000 hrs) under high temperatures (<1100 C) | 5 | SIE, VMCH, Farran | yes | Potential | Potential | Potential | Potential | in future | Gap measurement system, using mm-waves with 77 GHz and waveguides | 1100°C | 1 | 4 | - calibration free system<br>- sensor tip consits only of sealing<br>- avoiding of failure prone MI cables | Cccurate measurement needed for turbine design verification and GT operation<br>Needed to reduce gaps and improve efficiency<br>Current tech is sized for larger energy product, but lloking on VMCH progress on smaller applications. |
| 16 | Thin Film Thermocouples | 2.5 | Onera | Potential | yes | yes | no | Potential | no | Temperature measurement at the interface of TBC and metallic structural component by using thin film thermo couples. | 1000°C | 2 | 4 | Thin film technology is a unique technique to obtain reliable temperature evaluation at the interface between Thermal Barrier Coating and metallic component | Improvement of reliability and response time of surface and interface temperature measurement<br>Potential use on TBC coated rig parts in combsution R+D testing and possibly engine development testing, to validate TBC effectiveness and fine tuning cooling |
| 17 | Fast response total pressure and thin film temperature probes for measurements in the turbine section | 4.1.4 | UOXF | yes | yes | yes | no | Potential | no | A probe inserted into the flowpath for fractions of a second to measure high bandwidth temperature and pressure | 6 bar 1627C proven, higher possible | ~4 | ~6 | Uncooled, high measurement bandwidth. | Measurements using these probes are expected to allow benefits in terms of efficiency, emissions, and life cycle costs. |

***Table 10: Exploitable knowledge, continued***

## 4.2 Details of Publishable Results

### I. & II. Improved fast response thermocouples

High frequency response time thermocouple for wall temperature measurement in engine environment:

- Accuracy compliant with norm ASTM E230, class 1
- Response time estimated to 0.2 sec. with a Mach 2 air flow
- Possible market: aeronautic and industrial gas turbines
- Demonstrator tested on engine
- TRL7 reached

High stability K type thermocouples, after several thousands of hours on engine:

- Long term accuracy compliant with norm ASTM E230, class 1
- Market: gas turbines
- Industrial products
- TRL9

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### III. Advanced Stable Thermocouple System as results of Design of Experiment

- Result: Optimised thermocouple system for exhaust gas temperature measurement. Better than Class 1 accuracy (~0.25%) over the life of the thermocouple for temperatures up to 1050C.
- Application: Aerospace and industrial gas turbines within 1-2 years.
- Stage of development: TRL 6 prototype.
- No further collaboration required.
- IP retained within VMUK as trade secrets.

- Contact: Mark.langley@meggitt.com

### IV. Advanced High Temperature Thermocouple

A new Nickel based thermocouple in MIMS configuration has been designed at the Department of Materials Science and Metallurgy of the University of Cambridge. The new thermocouple allows temperature measurements up to 1200ºC with a total drift of about 2ºC: this is a significant improvement compared to the conventional Ni based thermocouples which can have drift as high as 15-20ºC. The thermocouple can be used in gas turbine

environment, but other potential markets are industrial process control, heat treatment and furnaces where temperatures up to 1200ºC need to be measured.
The new sensor is at the stage of laboratory development and currently a prototype is being built. The prototype will be later extensively tested to evaluate performance over long time exposure (above 1000h) and in real gas turbine environment before it can become commercially available. The development phase is expected to take 3 years.
A patent application has been filed for the new sensor on the 31st of March 2010.

- Result: Enhanced knowledge of degradation mechanisms in thermocouples resulting in a concept system that could deliver increased stability at very high temperatures (up to 1200C).
- Application: Aerospace and industrial gas turbines within 2-3 years.
- Stage of development: TRL2 concept.
- UCAMB seeking additional research funding to complete the studies.
- UCAM IP protected by patent submission.

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## V. Ceramic based thermocouple for temperature measurement up to 1500°C, in engine environment:

- Laboratory sub-systems done
- Laboratory tests underway for TRL3-TRL4 reaching at the end of the year
- Potential market: gas turbines
- Collaboration sought with an expert on high temperature ceramic to metal soldering

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## VI. Embedded Fiber Optic Sensors

### Description:

Within the HEATTOP project Siemens has developed and demonstrated fiber Bragg gratings sensors embedded in high temperature components of gas turbines for solid temperature measurement.

Fiber Bragg gratings (FBG) are sections of short length (~5mm) in an optical fiber that filter out light at a particular wavelength. The FBGs are inscribed into a fiber by means of high power laser pulses and phase masks. This alters the refractive indexes in the fiber core in a way that light is selectively reflected at a very narrow range of wavelength while it is transmitted at other wavelengths. Temperature changes alter the center of the wavelength of the light reflected from an FBG by compressing or stretching the grating. That causes a change in the grating period and so the peak reflectivity is shifted accordingly to $\lambda i+\Delta\lambda$. With a curve fitting algorithm the shifted peak wavelength is determined. The shift in wavelength $\lambda$ can be converted to a temperature change. The fiber with fiber Bragg gratings is placed lose in a protecting steel capillary or in a long eroded hole of 500μm diameter. Several gratings with different wavelength form a sensor array in one fiber.

Together with the partners IPHT and AOS the first Sapphire Bragg grating (FBG) sensor multiplexing was achieved. A Sapphire based FBG sensor was inscribed in IPHT Jena by high-energy fs laser and has been demonstrated at temperatures up to 1200°C with temperature drifts below ±5K. As a further unique feature, the highest temperature stability has been achieved with $T > 1750°C$, as the most severe conditions a fiber-optic temperature sensor can be used. Other FBG types built and tested were silica Bragg grating sensors. Fs-FBG achieved an accuracy of ±3K up to 800°C.

### Possible Applications:

FBG sensors with multiplexable capabilities are addressed for applications in R&D for stationary gas. Envisaged components are turbine vanes and combustor parts where the degree of intrusion has to be kept small. The advantage of increased life time and the integration of multiple sensing elements into on fiber will be beneficial.

A side effect of the sensors which is to measure also strain could be utilized in the future if this feature is developed more by further research. The principle is known but more research is needed to distinguish between stress and temperature.

FBG sensors with silica fibers may be used in stationary gas turbine measurements of temperature distributions.

### Stage of development:

Sapphire FBG: The current stage of development is still rather low. The sensor was tested in the lab and a prototype with package was manufactured and integrated into a heat shield for rig tests. More laboratory sensor samples are available and are ready for encapsulation and application testing in gas turbines.

Still, a very strong expert support is needed for data acquisition and analysis. TRL is 4.

Silica FBG are at a higher development stage, TRL5, but are applicable only to temperatures below 800°C.

### Black Body Radiator sensors

### Description:

The sensor element of the blackbody fiber radiation thermometer is a 25micron thick Palladium foil that acts as a Blackbody radiator. The foil is laser welded onto the end of an Inconel tube of 1mm outer diameter and 0.5mm inner diameter. Inside is a 100/125um low-aperture multimode fiber in a distance of about 0.5mm to the Pd-foil end cap. The small fiber aperture leads to a small angle of view and guarantees that only radiation from the foil is collected. The heat radiation is transmitted over the fiber to a detection unit. Interrogation base on measurement of total intensity emitted from the foil in a defined spectral band and is performed with InGaAs-detectors.

The intensity is an exponential function of the temperature. This curve needs to be calibrated for the specific sensor set-up.

The thin foil allows accurate measurement with a high spatial resolution. The sensor is usable for temperatures up to 900°C with accuracy of ±8K.

### Possible Applications:

The sensor could be used for temperature measurements in stationary gas turbine components where a strong temperature gradient exists. It could measure accurately temperatures at the surfaces of coatings and sub-layers at vanes and combustor parts.

### Stage of development:

The sensor has been demonstrated in rig tests and has undergone long term tests over 5000hours. The demonstrated TRL is 5. High level of expert support is needed for calibration and instrumentation.

Collaboration is offered to energy production and aircraft engine designer for further-reaching R&D.

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## VII. A pyrometer corrected / calibrated for transmission and fouling

A boroscope hole pyrometer has been designed and constructed. It includes a facility for on-line calibration for fouling and transmission losses, thus enhancing the instrument with self-inspection capability. Other objectives were a modular design in order to be able to interface easily with a wide range of turbines and ease of installation and maintenance of the system. Temperature range is from 500-1200 degrees C.

The instrument is designed for use in heavy-duty, land-based gas turbines. The utilisation is envisaged to be by service providers in the gas turbine maintenance and trouble shooting industry.

The instrument can be used for commercial services

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## VIII. & IX. Advanced Pyrometer Design Know-How

- Result: An advanced pyrometer system that is insensitive to most types of lens contaminant for HP turbine blade measurement.
- Aerospace and industrial gas turbines within 3-5 years.
- Stage of development: TRL 5 prototype.
- Collaboration sought in order to undertake additional engine testing and further performance measurements.
- Collaborator with available engine test equipment (either OEM or university).
- Patent protection will be sought at a later stage upon completion of studies.
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## X. Thermographic phoshors for quasi 2D temperature measurement on airfoils, under high temperature and presssure

Blue emitting phosphors have been investigated and reported for possible use in thermometry. Currently available thermographic phosphors in general have the drawback of long emission lifetimes obstructing the possibility to time gate for background discrimination and to measure on fast moving otargets. An additional problem is that many thermographic phosphors have emission in the red spectral region, making them vulnerable to black body radiation at high temperatures. The work carried out within Heattop reports the temperature sensitivity for nine phosphors considered suitable for accurate temperature measurements in harsh conditions, such as in gas turbines, both in single points and in two dimensions (2D). However, the technique is still to be considered novel and commercialization is not on the agenda at the present state.

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## XI. A high temperature water-cooled fast response total pressure probe for hot gas path measurements (in combustion chambers and turbine hot sections)

Unsteady pressure measurements in the hot sections of gas turbines are currently restricted to wall static pressure measurements up to temperatures of 1000°C. No experimental techniques exist to perform measurements inside the gas path at combustion chamber exit or in HP or LP turbine stages. This includes radial traverses to obtain time-resolved total pressure, yaw angle, static pressure, flow Mach number and turbulence level.

A high temperature cooled unsteady total pressure probe has therefore been developed, to be continuously immersed into the hot gas stream to obtain time series of pressure with a high bandwidth and therefore statistically representative average fluctuations at the blade passing frequency of turbine rotors. This concept is based on the use of a conventional miniature piezo-resistive pressure sensor, located in the probe tip to achieve a bandwidth of at least 40 kHz. Due to the extremely harsh conditions, the probe and sensor are heavily cooled by highly pressurized water.

Several prototypes of different pressure ranges have been built and the probe technology has been validated in different engine tests and in a combustion rig up to temperatures exceeding 1600°C.

The availability of this new probe technology opens a totally new area of measurements formerly unavailable. For the industrial gas turbine industry as well as for the aero-engine industry, this will enable detailed flow field surveys both in combustion research as well as in turbine aerodynamics. This will enable further validation of combustion simulation codes and provide more realistic boundary conditions as an experimental input for turbine aero-thermal simulations.

This cooled probe technology may be used in other industrial sectors as well, anywhere high temperature processes are used, for example in steel or chemical industry.

Collaboration may be envisaged as a service provider to engine manufacturers or any industrial partner to perform measurements on site with existing probes. Collaboration may be offered as well for high temperature cooled probe designs for similar applications.

Industrialization by an instrumentation vendor may be another possibility to market the product as a “turn-key” system.

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## XII. An optical fibre multiplexable pressure sensor (<1000 C)

| **Exploitable Knowledge** (description) | **Exploitable product(s) or measure(s)** | **Sector(s)** of application | Timetable for commercial use | Patents or other IPR protection | **Owner** & Other Partner(s) involved |
|---|---|---|---|---|---|
| Sensor design for high temperature operation | Dynamic pressure sensors for long term use at 600°C, prototypes for use at 1000°C | Power generation turbines – combustion monitoring and control<br>Aero-engines ground based development | Estimate 2 years to design-in to new engines, significant deployment 2014<br>In use for future engine programmes in 2 years | Patents covering critical design elements applied for. Principle is public domain so not patentable | Oxsensis are IP owner.<br>Ongoing collaborative projects running with Rolls-Royce and Siemens |
| Optical interrogation method for measurement of dynamic pressure | Bench-top four channel dynamic pressure interrogator | Power generation turbines – combustion monitoring and control<br>Aero-engines ground based development | Estimate 2 years to design-in to new engines, significant deployment 2014<br>In use for future engine programmes in 2 years | | Oxsensis owned |
| Optical interrogation methods capable of extracting dynamic and static pressure | Multi-Parameter Interrogator for use with Oxsensis sensor to measure static and dynamic pressure and sensor temperature | Power generation turbines – combustion monitoring and control<br>Aero-engines in flight use for combustion control | Improvement to first product for land based use so similar time frame (2014 for significant deployment)<br>In flight use in next generation of engines beyond 2015 | | Oxsensis are owner<br>Ongoing collaborative projects running with Rolls-Royce and Siemens |

## Sensor design for high temperature operation

### Sensor Description

Through HEATTOP Oxsensis has demonstrated the design of high operating temperature sensors. The sensor has an inherent capability (dependent on interrogation method) to measure pressure (static and dynamic) and sensor temperature. The sensor operates as an Extrinsic Fabry Perot Interferometer (EFPI).

The main advantage of the Oxsensis sensor partly developed within HEATTOP is the maximum operating temperature. The absolute temperature is set by the optical material used which is sapphire with a melting point of 2053°C and a maximum use temperature in excess of 1200°C.

Whilst the basic principle of the sensor is well established there has been significant innovation in packaging the optical train to enable stable operation in extreme environments, notably at high temperature but additionally high vibration applications.

### Potential Applications for Oxsensis Sensors

The primary market for Oxsensis sensors is in Gas Turbine gas path measurements within the hot zone of the engine. The use of the sensor here is for monitoring and control. The sensors have application in a range of engine sizes including aero-engines, aero-derivative power generation and large frame engines.

Further applications are being considered in other power generation sectors with extreme environment requirements including coal gasification and nuclear environments. Additional markets also exist in related markets including oil and gas exploration and extraction.

### Development Stage

Oxsensis sensors have been demonstrated to TRL6 in a range of Gas Turbines and a number of prototypes are now in operation in engines in operational power stations. Further development is still required to complete product development in certain areas, notably the robustness of the fibre lead out to enable installation without breakage.

### Collaborator Details

Oxsensis continues to seek testing partners to provide opportunities to test sensors and provide input on current and future sensor requirements.

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## Optical Interrogator for Dynamic Pressure

### Interrogator Description

Oxsensis Dual Wavelength Interrogator (DWI) is a bench top instrument capable of interfacing with up to four Oxsensis sensors providing simultaneous, independent readings of dynamic pressure. The interrogator is suitable for use in control room environments. The final output is an analogue voltage (range is programmable) via BNC outputs. The interrogator uses off the shelf telecoms optics components and digital signal processing. The interrogator will measure pressure across a frequency range up to 20kHz with the pressure range dependent on the attached sensor specifications.

### Potential Applications for Oxsensis Sensors

The primary market with Oxsensis sensors is in Gas Turbine gas path measurements within the hot zone of the engine. The use of the system here is for monitoring and control. The sensors have application in a range of engine sizes including aero-engines, aero-derivative power generation and large frame engines.
Further applications are being considered in other power generation sectors with extreme environment requirements including coal gasification and nuclear environments. Additional markets also exist in related markets including oil and gas exploration and extraction.

### Development Stage

The interrogator is product ready and suitable for deployment in operational environments. The interrogator is CE marked and has a Class 1 laser safety designation. At this stage only limited further development is taking place for the DWI in order to improve the user interface and improve functions such as self diagnosis and calibration.

### Collaborator Details

Oxsensis continues to seek testing partners to provide opportunities to test sensor systems and provide input on current and future sensing requirements.

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## Multi-Parameter Optical Interrogator

### Interrogator Description

Oxsensis Multi-Parameter Interrogator (MPI) is an advanced interrogator capable of extracting multiple measurements simultaneously from a single Oxsensis sensor. The MPI is still in development but is expected to be made available as a product in a variety of formats including as a bench top instrument for the power industry and in a miniaturised format for in-flight use in aviation where some interrogator functionality may be integrated into the FADEC (Full Authority Digital Engine Controls).

### Potential Applications for Oxsensis Sensors

The primary market with Oxsensis sensors is in Gas Turbine gas path measurements within the hot zone of the engine. The use of the system here is for monitoring and control. The sensors have application in a range of engine sizes including aero-engines, aero-derivative power generation and large frame engines.
Further applications are being considered in other power generation sectors with extreme environment requirements including coal gasification and nuclear environments. Additional markets also exist in related markets including oil and gas exploration and extraction.

### Development Stage

The MPI is still in development and is currently not available as a product. Laboratory demonstrators have been built with the first tests in realistic (combustion rig/engine) environments expected before the end of 2010.

### Collaborator Details

Oxsensis continues to seek testing partners to provide opportunities to test sensor systems and provide input on current and future sensing requirements.

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## XIII. An intermittent choked nozzle probe for total pressure and temperature

The intermittent aspirated probe for measurements of stagnation pressure and temperature in high temperature flows is a new concept probe to measure time averaged stagnation quantities. It measures gas composition if a gas analyser is connected to the system. One single probe measures three quantities replacing three separated standard sensors: thermocouples, pneumatic pressure probes and aspirated probe for gas analysis. The probe measures temperature up to 1800K with an achievable accuracy of ±0.6%, thus noticeably increasing the maximum temperature operating limit and the accuracy typical of standard thermocouples.
The probe is addressed to be used in gas turbines, in rigs and engines, in combustors and high pressure turbines. Several probe prototypes have been tested in laboratory, in combustor rigs and in a small engine.

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## XIV. A non-intrusive IR sensor for turbine inlet gas temperature measurements

We have developed and tested a non intrusive temperature probe for on line real time measurements of the Turbine Inlet Temperature (TIT) based on the detection of the Infrared (IR) radiation emitted in a selected wavelength band by the CO2 molecules in the combustion gases. The sensor is suitable for stationary GT applications,

The sensor can be operated without damage nor environment disturb up to temperatures as high as T = 1500 °C and pressure of the order of P = 9 bar. However, reliable temperature measurements have been demonstrated only in a limited temperature range (up to around 1300 °C). Modifications of the experimental apparatus have been implemented to extend the reliable measuring range up to 1500 °C. On the other hand, the demonstrated limit in gas pressure is related to the test rig conditions, but, according to both components laboratory testing and theoretical modelling, it is estimated that pressures up around 20 bar could be achieved. New performance tests are foreseen before the end of the year.

Since at our knowledge still no method or commercially available instrumentation exists which accurately measures gas path temperatures at the combustor exit, the developed sensor (which is in the form of a demonstrator) for its unique features appears to be very promising both in R&D and new design activities (as a testing tool) and in industrial plants (for monitoring purposes). On development test combustor rigs, for example, the real time measurement of the TIT would provide a unique source of data for CFD modeling comparison, while in industrial plants on line TIT monitoring systems would be important to maximize the gas temperature (and therefore the overall GT plant efficiency) as well as to increase the hot gas path components lifetime.

In order to complete the sensor validation, measurement accuracy and long-life operation must be assessed both in rig and engine tests. The two-wavelength detection scheme for absolute temperature measurements should also be demonstrated in a representative environment.

As for rig testing, it is expected to make progress already within 2010.

Then, further collaborations by OEM's and/or owners of full scale rigs/engine test beds would be needed.

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## XV. Tip clearance sensor

### Description:

A mm-wave sensor for measurement of tip clearances in the hot section of a turbine was developed by Siemens in collaboration with partners Vibro-Meter and Farran. The sensor uses electromagnetic waves with 77 GHz that propagate through wave guide channels and radiate through an antenna towards the turbine blades where they are reflected. With a combination of focusing the reflected signal and applying phase based measurements the technique can be used for gaps in the range from 1 to 10 mm and for temperatures up to 1100°C. The targeted accuracy of ±0.1 mm was only partly achieved in a small range whereas the accuracy level is ± 0.4 mm elsewhere.

### Possible Applications:

Targeted application is the use at stationary gas turbines. The probe can be used at the compressor and at the hot turbine section. Other turbo machinery presents also market options however require more R&D work to make size and weight suitable for smaller engines.

### Stage of development:

A prototype probe was manufactured and tested in the lab. Achieved TRL: 4

The accuracy may be improved by adapting and refining the near field radiation model that simulation radiation of the antenna when clearances become very small. In addition it is indicated that increased power levels and frequency switching of the RF signal may help to obtain a more steady measurement. These are fields that would need to be addressed in further R&D efforts

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## XVI. Thin Film thermocouple for temperature measurements at the surface of metallic components or at the interface between Thermal Barrier Coating and metallic component

The first exploitable result is the know how to produce Thin Film thermocouples to measure temperatures and calculate heat fluxes at surface of combustor or engine components. The product consists of a sputtered multilayer (bond coat, insulating layer, thin film thermocouple, connection pads and protecting layer) deposited on metallic substrates by ONERA. The second exploitable result is the know how to produce Thin Film thermocouples overcoated with Thermal Barrier Coating (TBC) to measure temperatures and calculate heat fluxes at TBC/metal interface of combustor or engine components. The product consists of a sputtered multilayer (bond coat, insulating layer, thin film thermocouple, connection pads and protecting layer) deposited by ONERA on metallic substrates and of a TBC deposited over the sputtered multilayer by a supplier.

Partners involved in the exploitation would be among others engine manufacturers licensed by ONERA.

Further additional research and development work would be necessary to transfer the technology within the framework of a contract between ONERA and engine/sensors manufacturers.

The estimated benefit/technical improvement for end users concerns mainly the reliability and the response time of surface and interface temperature measurements.

Market applications are among others related to temperature measurements and heat flux evaluations in sector of aero-engine & stationary gas turbine industry for R&D, new design and prototype testing of gas turbines.

Collaboration sought

On the basis of HEATTOP satisfactory results, further development of Thin Film thermal sensors by ONERA in cooperation with industrial partners would increase the performances of Thin Film thermocouples and promote the application of thin film technology to thermal sensors.

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## XVII. Uncooled fast-insertion temperature and pressure probes for gas turbine engine measurements

Uncooled fast-insertion temperature and pressure probes have been developed that are capable of surviving in the hottest parts of gas turbine engines. The pressure probe is capable of measuring total pressure with a bandwidth from DC to 100 kHz, from which turbulence information can be derived. At the time of writing work is still ongoing to interpret the temperature probe data in order to resolve the flow total temperature over a similar bandwidth. The current prototype fast insertion measurement system has proven extremely rugged and has performed reliably in a range of engine environments.

Both probes have been extensively validated in real engine environments up to 1900 K at low Mach numbers but it is envisaged they could operate under virtually any conditions available in modern gas turbines. Using uncooled probes greatly simplifies the measurement system as well as reducing production costs; the system is compact and easy to adapt and install to various engines and rigs. The entire measurement system can be loaded into a small estate car for transportation to the test site, where it can be operated at a distance of 25m.

Further development work is planned in order to minimize the probes further still whilst maintaining the same levels of robustness, as well as developing the system to allow remote yaw angle and insertion depth variation in order to measure flow angle, static pressure and Mach number across the gas path.

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# 5 Dissemination of knowledge

## 5.1 External dissemination

Below is a list with dissemination by partners of the consortium. It is sorted by research area and partner.

### 5.1.1 Thermocouples design

VMUK

- Langley, M. A., "Design of High Temperature Thermocouples", VKI Lecture Series on Advanced High Temperature Instrumentation for Gas Turbine Applications, May 2009.

Onera

- P. Kayser, 2009, Feasibility of thermal barrier-coated Platinel® II thin film thermocouples deposited on nickel superalloy components, application to temperature measurement, 4th EVI GTI Conf. Norrköping, Sweden September 23-25, 2009, Conference presentation (no written paper)

UCAM

- SCERVINI, M. & RAE, C.M.F. "Thermocouple degradation mechanisms", in Advanced high-temperature instrumentation for gas turbine applications - VKI Lecture Series 2009-06, Edited by J.F. Brouckaert
- Four journal papers under preparation
- http://www.msm.cam.ac.uk/utc/thermocouple/pages/MicheleScerviniMainPage.html

### 5.1.2 Surface temperatures

*SIEMENS*

- Willsch M., Bosselmann T., Ecke W., Latka I., Thiel T. , 2007, Measurement of vane integrity with embedded sensors, concepts and first results, Joint EVI-GTI and PIWG Conference, University of Rhode Island, 29.10.-01.11.2007
- Bosselmann T., Willsch M., Ecke W. , 2008, "The rising demand for energy: a potential for optical fiber sensors in the monitoring sector", Proceedings

of SPIE, Vol. 6933 "Smart Sensor Phenomena, Technology, Networks, and Systems", Ed. Wolfgang Ecke, pp. OG_01-OG_10, DOI: 10.1117/12.780718

- Willsch M., Bosselmann T., Flohr P., Kull R., Ecke W., Latka I., Fischer D., Thiel T., 2009, "Design of fiber optical high-temperature sensors for gas turbine monitoring", Proceedings of SPIE Vol. 7503 "20th International Conf. of Optical Fibre Sensors", Eds. J. Jones, B. Culshaw, W. Ecke, J.M. Lopez-Higuera, R. Willsch, pp. 7R1-7R4, http://dx.doi.org/10.1117/12.835875

- Willsch M., Bosselmann T., Ecke W., Latka I., Thiel T. , 2007, Measurement of vane integrity with embedded sensors, concepts and first results, Joint EVI-GTI and PIWG Conference, University of Rhode Island, 29.10.-01.11.2007

*IPHT,*

- Ecke W. 2007, "Fiber Bragg Grating Sensor Systems for Measurement of Strain, Vibrations, and Temperature Distributions", 2nd Airport-Seminar "Structural Health Monitoring", Fraunhofer Institute for Non-Destructive, Testing, Dresden, 06./07.11.2007
- Ecke W., Willsch R., Bartelt H., 2009, "Fibre-optic Structural Health Monitoring in the Energy Industry", Invited Paper to: 14th Opto-Electronics and Communications Conference, OECC 2009, Hong Kong,13.-17. July 2009
- Ecke W., 2010, "Fibre Optic Sensing at Extreme Temperatures", Invited Tutorial Lecture to the Workshop of Norwegian Metallurgical Industry "Måleteknologi og separasjonsteknologi", Sørlandsparken Kristiansand, Norway, 17.-18.02.2010

### Conference Papers

- Ecke W., 2008, "Applications of FBG sensors", Invited Tutorial, 19th International Conference on Optical Fibre Sensors, Perth/Australia, 14.-18.04.2008; Official Tutorial Download at: http://obel.ee.uwa.edu.au/OFS-19/technical_programme/workshop.php
- Fischer D., Latka I., Ecke W., Bosselmann T., Willsch M., 2008, "Sapphire Fiber Fabry-Perot Interferometer for Measurement of High Temperatures", Proceedings of SENSOR+TEST 2008 "OPTO & IRS$^2$ Conferences", ISBN 978-3-9810993-3-1, Nürnberg 06.-07.05.2008

### Scientific Journal Paper

- Busch M., Ecke W., Latka I., Fischer D., Willsch R., Bartelt H., 2009, "Inscription and characterization of Bragg gratings in single-crystal sapphire optical fibres for high-temperature sensor applications", Meas. Sci. Technol. Vol. 20, 115301, http://dx.doi.org/10.1088/0957-0233/20/11/115301

*VM-UK*

- Hallam, A., "The Use of Optical Pyrometry for Gas Turbine Condition Monitoring", IMechE seminar, April 2010.

*KEMA*

- R.A. Rooth, KEMA Boroscope Pyrometer development/validation test results, 2nd JOINT EVI-GTI / PIWG INTERNATIONAL GAS TURBINE INSTRUMENTATION CONFERENCE, Sevilla, 2008
- M.F.G. Cremers, R.A.Rooth, KEMA, A SOFTWARE MODULE FOR CORRECTING PYROMETER MEASURED TEMPERATURES, XIX Biannual Symposium on Measuring Techniques in Turbomachinery Transonic and Supersonic Flow in Cascades and Turbomachines, Belgium, April 7-8, 2008

*ULUND*

- Särner, G., M. Richter, and M. Alden, Investigations of blue emitting phosphors for thermometry. Measurement Science and Technology, 2008(12): p. 125304.

2008_Meas_Sci_Technol_19_125304.pdf

## 5.1.3 Gas path aerodynamic measurements

*VKI*

**Published and/or presented: (2 Archival Papers, 7 Conference Papers, 1 Best Paper Award)**

- Brouckaert, J.F., Mersinligil, M., Pau, M., "*A Conceptual Design Study for a New High Temperature Fast Response Cooled Total Pressure Probe*", 14 pages, ASME Turbo Expo Conference, Berlin, Germany, June 9-13, 2008. ASME Controls, Diagnostics & Instrumentation Committee 2008 Best Paper Award.
- Brouckaert, J.F., Mersinligil, M., Pau, M., "*A Conceptual Design Study for a New High Temperature Fast Response Cooled Total Pressure Probe*", Journal of Engineering for Gas Turbines and Power, Vol.131, No. 2, March 2009.
- Brouckaert, J.F., Mersinligil, M., Pau, M., "*Development of a high temperature fast response cooled total pressure probe*", 2nd Joint EVI-GTI / PIWG International Gas Turbine Instrumentation Conference, Seville, Spain, September 24-26, 2008.

- Brouckaert, J.F., Mersinligil, M., Desset, J., Pau, M., "*High temperature cooled fast response pressure probe*", in VKI LS 2009-06, „Advanced High Temperature Instrumentation for Gas Turbine Applications", May 11-14, 2009, von Karman Institute, Rhode Saint Genese, Belgium.
- Mersinligil, M., Desset, J., Brouckaert, J.F., "*Combustion Rig and Gas Turbine Engine Measurements with a High Temperature Cooled Fast Response Pressure Probe*", 4th EVI-GTI International Gas Turbine Instrumentation Conference, Norrköping, Sweden, 2009.
- Brouckaert, J.F., "*A New Fast Response Cooled Total Pressure Probe for Measurements in Very High Temperature Gas Turbine Environments*", Ercoftac Yearly Seminar, December 3, 2009, Brussels, Belgium.
- Brouckaert, J.F., "*Design Study and First Unsteady Measurements with a Fast Response Cooled Total Pressure Probe in Very High Temperature Gas Turbine Environments*", ETE' 2009 Second EUREKA International Symposium on Environmental Testing Engineering Towards an information exchange between Academy and Industry, 26-27 November 2009, Royal Military Academy, Brussels, Belgium.
- Mersinligil, M., Desset, J., Brouckaert, J.F., "*First Unsteady Pressure Measurements with a Fast Response Cooled Total Pressure Probe in High Temperature Gas Turbine Environments*", ASME Turbo Expo 2010, Glasgow, UK (accepted for Journal Publication in the Journal of Engineering for Gas Turbines and Power)

To be presented: (3 Conference Papers)

- Mersinligil, M., Desset, J., Brouckaert, J.F., "Turbine and Combustion Chamber Measurements with a Cooled Unsteady Total Pressure Probe", European Turbine Network, 5th International Gas Turbine Conference "The Future of Gas Turbine Technology", 27-28 October 2010, Brussels Belgium
- Mersinligil, M., Desset, J., Brouckaert, J.F., "High Temperature High Frequency Turbine Exit Flow Field Measurements in a Military Engine with a Cooled Unsteady Total Pressure Probe", 9th European Turbomachinery Conference, Istanbul, Turkey, March 21-25, 2011.
- Brouckaert, J.F., Mersinligil, M., Desset, "Development and Use of a Cooled Unsteady Total Pressure Probe for Turbine and Combustion Chamber Measurements", 3rd Joint PIWG / EVI-GTI International Gas Turbine Instrumentation Conference, Newport News, VA, USA, October 26-29, 2010.

UOXF

- Lubbock, R. J., & Oldfield, M. L. G. 2008. Unsteady gas turbine flow measurements using fast-insertion high bandwidth total temperature pressure probes (EVI2008-029), 2nd joint EVI-GTI / PIWG international gas turbine instrumentation conference, Seville, Spain.
- Oldfield, M. L. G., & Lubbock, R. J. 2009. Fast insertion pressure and temperature probes. In Advanced High Temperature Instrumentation for Gas Turbine Applications, VKI LS 2009-06.
- Lubbock, R. J., & Oldfield, M. L. G. 2010. Fast response instrumentation for gas turbine flow measurements, Experimental methods for health

monitoring of fluid systems, Institution of Mechanical Engineers London SW1H 9JJ

- Lubbock, R. J. Oxford University DPhil thesis (planned for end of 2010).
- Further conference /journal papers planned for 2010/11.

*OXSENSIS*

- EVI-GTI/PIWG 2007 – US – Ultra-High Temperature Sensor System for Measuring Static and Dynamic Pressure and Temperature
- Aerolink Wales 2008 – UK – New Harsh Environment Sensors and Integrated Systems for Aero Applications –the Optical Approach
- ISA 54th Instrumentation Symposium – US – Ultra High Temperature Sensor Systems for Static and Dynamic Pressure, and Temperatureltra High Temperature Sensor Systems for Static and Dynamic Pressure, and Tempera
- EVI-GTI 2008 – Seville, Spain – Rig Testing of High Temperature Sapphire Fibre Optic Sensor
- AVFOP 2009 – San Antonio, US - High Temperature Fibre Optic Pressure Sensors fro Engine Dynamics and Health Monitoring
- ESA Workshop 2009 – Noordwijk, Netherlands – Fibre-Optic sensors, Engines to Airframes
- EVI-GTI 2009 – Norrkoping, Sweden – Quasi-static pressure measurements using high temperature dynamic pressure sensors
- Sensor and Test 2009 – Nuremberg, Germany – Optical Sensors for Harsh Environments
- VKI Lecture Series 2009 – Belgium – High Temperature Sapphire Fibre Optic Sensor
- IMechE Workshop 2010 – London, UK – Optical Sensors for Gas Turbine Combustion Monitoring
- ASME Turbo Expo 2010 – Glasgow, UK – Static and dynamic pressure measurements with temperature correction using high temperature optical pressure sensors

*ERSE*

- I. Gianinoni, “Non-intrusive IR sensor for real time direct measurement of Turbine Inlet Temperature “, Advanced high temperature instrumentation for gas turbine applications, VKI LS 2009-06, ISBN-13 978-2-930389-94-X, 2009 by the von Karman Institute for Fluid Dynamics, Belgium, 2009, pp. 1-22
- U. Perini, C. Cherbaucich, L. De Maria, I. Gianinoni, E. Golinelli, S. Musazzi, G. Rizzi, “Sviluppo di sensoristica innovativa basata su sistemi elettro-ottici per la diagnostica di componenti e macchine”, Convegno

Nazionale AEIT - Sostenibilità energetica: Tecnologie e Infrastrutture. La ricerca incontra l'industria, Catania (Italy), 27-29 Settembre 2009

- I. Gianinoni, E. Golinelli, S. Musazzi, U. Perini, "Rig testing of an optical IR sensor for Turbine Inlet Temperature Measurements", 4th EVI-GTI International Gas Turbine Instrumentation Conference, Norrköping (Sweden), 23-25 September, 2009

*UCAM*

- Massini M., Miller R.J., Hodson, H.P., A Novel Technique for Measuring Stagnation Quantities and Gas Composition in High Temperature Flows, ASME TURBO EXPO 2010, Glasgow, UK, GT2010-22920 (to be presented 14-18 June)
- Massini M., Miller R.J., Hodson, H.P., Intermittent Aspirated Pressure and Temperature Probe, "Advanced high temperature instrumentation for gas turbine applications", VKI Lecture Series, May 11-15, 2009 , von Karman Institute, Bruxelles, Belgium
- Massini M., Miller, R. J., Hodson, H. P., Novel Technique for measuring stagnation quantities and gas composition in high temperature flows, 4th EVI-GTI International Gas Turbine Instrumentation Conference, Sept 23-29, 2009 , Norrkoping, Sweden
- Massini M., Miller R.J., Hodson, H.P., Intermittent Aspirated Probe for Measurement in High temperature Flow of Stagnation Quantities, ASME TURBO EXPO 2008, Berlin, Germany, GT2008-50581 and accepted for Journal Publication on Journal of Turbomachinery

### 5.1.4 Tip clearance measurements

- Flohr, 2007; EVI-GTI 2007 conference: HEATTOP - a European project for evaluation, development and demonstration of high temperature gas path instrumentation
- Ziroff et all: EVI-GTI 2008 conference: Millimeter wave blade tip clearance sensor
- Ziroff at all, VKI lectures 2009: High temperature non contact clearance measurements
- Schicht, A. Huber, K. Ziroff, A. Willsch, M. Schmidt, Absolute Phase-Based Distance Measurement for Industrial Monitoring Systems

### 5.1.5 Further dissemination

General information about HEATTOP can be found under:

**EU Transport Research Knowledge Centre**

http://www.transport-research.info/web/projects/project_details.cfm?id=35086&backlink=%2Fweb%2Fcommon%2Fsearch.cfm&referer=modes*7%7Cispostback*true

**EU commission research topics and Cordis**

http://ec.europa.eu/research/transport/projects/article_6499_en.html

http://cordis.europa.eu/fetch?CALLER=FP6_PROJ&DOC=61&QUERY=0128a33a7a79:196f:35801f01

**Service d'information scientifique et technique**

http://eurofed.stis.fgov.be/Interviews%5C2005-2006%5Cinterview_18.htm

## 5.2 Internal dissemination

Internal dissemination took place over regular consortium meetings every 6 months to share work progress and achievements.

Kick off meeting was the first option to share ideas and intentions about techniques to be developed.

The 6 month meeting took place in Düsseldorf in March 2007, the 12 month consortium meeting was held in September 2007, hosted by ERSE.

The 18 month consortium meeting was hosted by Rolls-Royce in Derby in March 2008. The meeting was the Mid-term review where the EU commission and an external expert discussed the achievements and the plan ahead. During this meeting, the consortium members visited the IP Combustion Rig Facility and also viewed the Viper engine.

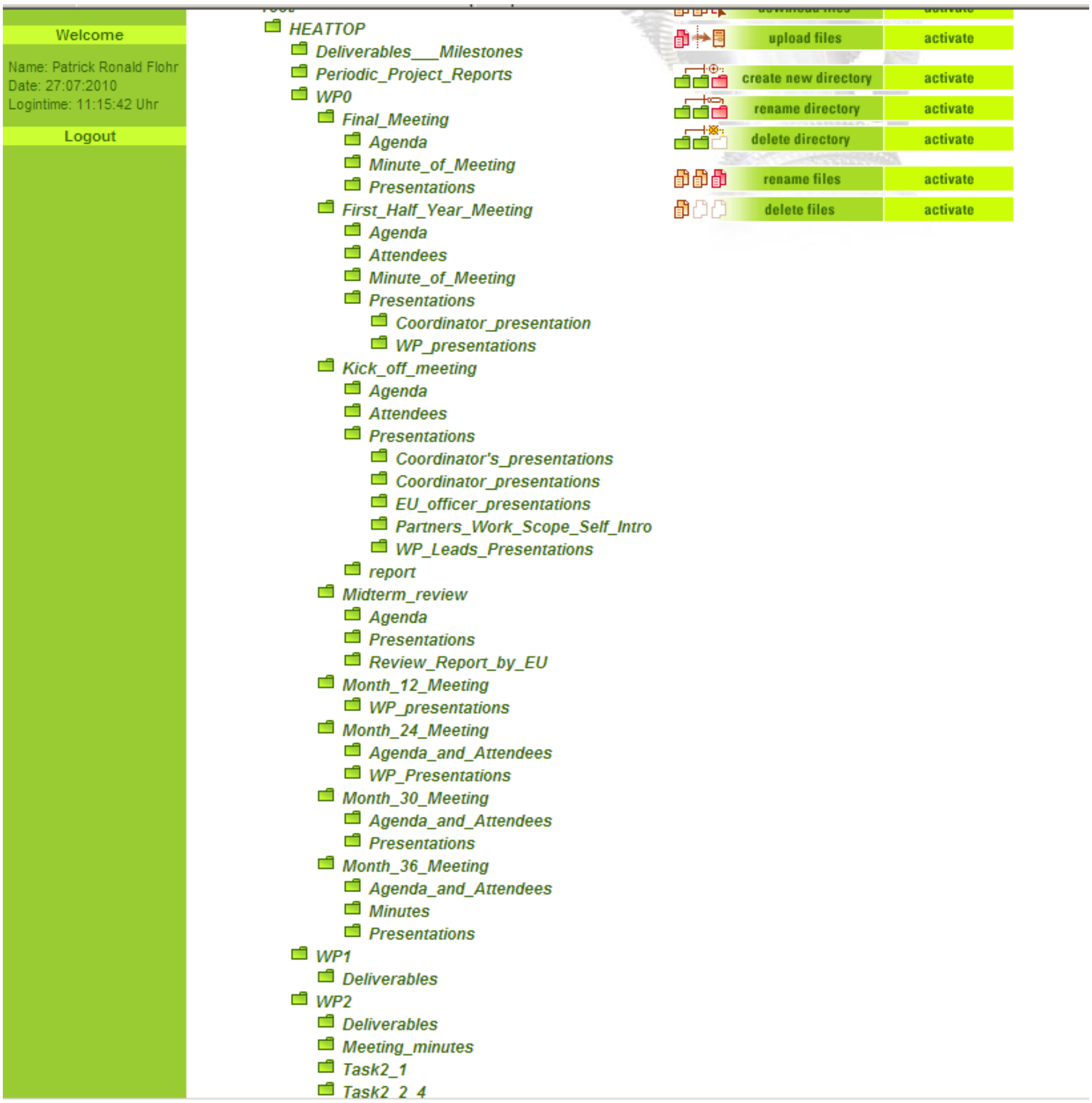
Consortium 24 month meeting held in September 2008 in Seville.

Consortium 30 month meeting held in April 2009 in Cambridge, UK

Consortium 36 month meeting held in Sep 2009 in Norköpping, Sweden combined with a tour to Siemens Industrial Turbines in Finspong

The Final consortium meeting was held in April 2010 and was hosted by Oxsensis at Rutherford Appleton Laboratory, UK

A further channel of dissemination was the the HEATTOP web space provided by SIEMENS:
https://extranet.pg.siemens.com/pg/e/ft_login/index.php



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- HEATTOP
  - Deliverables___Milestones
  - Periodic_Project_Reports
  - WP0
    - Final_Meeting
      - Agenda
      - Minute_of_Meeting
      - Presentations
    - First_Half_Year_Meeting
      - Agenda
      - Attendees
      - Minute_of_Meeting
      - Presentations
        - Coordinator_presentation
        - WP_presentations
    - Kick_off_meeting
      - Agenda
      - Attendees
      - Presentations
        - Coordinator's_presentations
        - Coordinator_presentations
        - EU_officer_presentations
        - Partners_Work_Scope_Self_Intro
        - WP_Leads_Presentations
      - report
    - Midterm_review
      - Agenda
      - Presentations
      - Review_Report_by_EU
    - Month_12_Meeting
      - WP_presentations
    - Month_24_Meeting
      - Agenda_and_Attendees
      - WP_Presentations
    - Month_30_Meeting
      - Agenda_and_Attendees
      - Presentations
    - Month_36_Meeting
      - Agenda_and_Attendees
      - Minutes
      - Presentations
  - WP1
    - Deliverables
  - WP2
    - Deliverables
    - Meeting_minutes
    - Task2_1
    - Task2_2_4

and by the European Virtual Institute for Gas Turbine Instrumentation, EVI-GTI,
http://www.evi-gti.com

European Virtual Institute for Gas Turbine Instrumentation

EVI-GTI is a membership organisation for the Gas Turbine Instrumentation Community. Created in response to a need for a focal point and greater coherence in the sector, the organisation results from a 3-year EU funded GROWTH project.

2010 Joint PIWG and EVI-GTI Fall Conference
Newport News, VA
October 26 through October 29, 2010

## 5.3 Patent applications

WP2

- GB No. 1005509.3, Authors: Michele Scervini, Dr Cathie Rae, UCAM

WP3

- WO 2009 / 135814 A1, TEMPERATURE MEASUREMENT AT PARTS OF A FLUID KINETIC MACHINE, Bosselmann, Willsch, Thiel, SIE, AOS

WP5

- EP 2 042 830 A1, Device and method for measuring radial air gap with millimeter waves, Bosselmann, Willsch, SIE
- WO2008/009917 A1 Gap Measurement on turbines, Ziroff, Evers, SIE

# 6 Conclusions

The HEATTOP project developed sensors and probes which are critical for efficient, economic, reliable and environmentally friendly operation of gas turbines in aero engines and in stationary power generation facilities. The current limits of instrumentation had to be stretched, while at the same time accuracy and reliability needed to be improved.

The developed sensors and probes operate under the harshest conditions and reflect the strong requirements of gas turbine OEMs in aero and industrial areas. Based on that, it is obvious that the developments were very challenging. For some sensors the developers did break new grounds and some ‘Firsts’ were developed. This led to an increase of Technology Readiness Level of 2 or more stages.

Requirements for stationary gas turbine are naturally different that those for aero engines. At both engines the same measurements are needed. However size, weight and access of probes are very different. Here, need for further R&D work is required to provide probes that are applicable to both types of engines.

Reviewing the intentions at the beginning of the project we see that the key demands in European engine industry - improving efficiency and reliability and greener engines are still valid.

The new sensors address those demands. They have improved applicability to very hot regions and survive longer operation times. Hence, reliability was increased. To be used for monitoring purposes most of the sensors are not mature enough and accuracy is not always confirmed. More work is ahead and needs to be addressed. Examples are:

- Improved calibration procedures
- Error correction methods
- Less demanding cooling schemes
- Validation and cross comparison of related measurements. Need for more, especially systematic validation testing
- Pyrometry: Development of probes as two wavelength, increased operation time (lens cleaning) and operating ranges, online rotating equipment; improving service intervals; thermal mappings of blades
- 2D measurements with Phosphors
- TC, TFTC: Applying knowledge about TC degrading mechanisms and drift issues; develop partnerships with material vendors for research and manufacturing; improve structural issues and solving mechanicals issues; increase TRL of ceramic TC
- Tip clearance validation, increasing accuracy, general assessment of various sensor types, tip timing
- Heat flux sensors, flow angle; entropy measurement
- Bring fiber optic sensors to a higher TRL value, increase temperature range and multiplexability

The partner in HEATTOP would like to continue R&D work in this area and encourages others to join in the effort to provide better instrumentation for more efficient, reliable and greener engines.