Sensors Towards Advanced Monitoring and Control of Gas Turbine Engines

Reporting

Project Information

STARGATE

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MEGGITT UK LIMITED

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Executive Summary:
The objective of this project is to develop a suite of advanced sensors, instrumentation and related systems that are necessary to facilitate the development of the next generation of green and efficient gas turbine engines. This will help to maintain and strengthen Europe’s position as one of the foremost producers of reliable, clean and environmentally friendly gas turbine systems. Sensors are a vital enabling technology to the development of the next generation of gas turbines (both aerospace and energy) that have reduced impact on the environment. They are critical to three distinct areas of business:

- Instrumentation for product development for validation of design tools and new products.
- Sensors fitted to engines in service as part of the engine control system.
- Sensors fitted to engines in service to monitor engine health.

Obtaining reliable and accurate measurements from all parts of gas turbine engines during development phases is critical to optimising the design to maximise performance. The role of sensors is also fundamental to the operational performance of gas turbines. The limitations of current sensors in terms of survival temperature, accuracy, stability, degradation with time, etc. limit how close to the maximum operating ceiling the gas turbine can be run. Consequently, engines are not run at their most optimal, which impacts thermal efficiency an specific fuel consumption.

Specifically the project looked to develop the following sensors:

- An ultra-high temperature dynamic pressure probe (~2000°C)
- High temperature entropy probes (~1000°C steady and (~500°C) unsteady)
- A novel design of sensor installation for accurate performance in unsteady flows
- A novel high temperature thermocouple (~1300°C)
- A high temperature thin film strain gauges (~400°C continuous)
- A high temperature optical accelerometer (750-1000°C)
- A high temperature tip timing sensor (~750°C)
- A high temperature optical tip timing sensor (600-1300°C depending on cooling)
- A novel long wavelength pyrometer (up to1500°C)
- A novel non-intrusive scanning pyrometer (600-800°C)
- Energy harvesting and wireless systems for large networks and rotating telemetry

These sensors have been validated in detail in the laboratory according to detailed uncertainty and lifing standards and specifications set out at the start of the project. Moreover, a range of detailed rig and engine validation trials have also be undertaken using well-characterised, controllable, and representative flows.

The engine OEMs involved in the project will provide a direct path to industrial exploitation and, indeed, some of the Partners are already in discussions with the OEMs about possible use of the sensor technology beyond the project. These include:

- University of Cambridge high temperature, low-drift thermocouples
• Dynamic pressure sensor with self-test
• Novel long-wavelength pyrometer
• Non-intrusive scanning pyrometer
• Modular wireless data-acquisition systems

These technologies are looking to be exploited in a number of ways, including:
• Integration into future validation trials for component and product design verification
• Integration into future and monitoring and control needs
• To augment, supplement, or replace existing sensor product lines

Project Context and Objectives:

> Concept and Objectives

The headline objective of STARGATE is to develop a suite of advanced sensors, instrumentation and related systems that are necessary to facilitate the development of the next generation of green and efficient gas turbine engines. This will help to maintain and strengthen Europe’s position as one of the foremost producers of reliable, clean and environmentally friendly gas turbine systems. The project is led by Meggitt in the UK and comprises 16 partners including academia and supply chain. The consortium includes many of the major gas turbine OEMs to act as primary exploitation routes, these being Rolls-Royce, Snecma, GKN, and Siemens.

1: Background and Drivers

1.1: Contribution to EU Objectives

Although sensors are a highly cross-cutting technology, the project is targeted primarily at the following areas:

Challenge 1: Eco-Innovation
Activity 7.1: The Greening of Air Transport
Area: 7.1.1.1: Green Aircraft
AAT.2012.1.1-3: Propulsion

Within AAT.2012.1.1-3 the project is targeting primarily “Advanced concepts and technologies for improving engine thermal and/or propulsive efficiency”.

Overall it is expected that this will directly contribute to the 2020 ACARE objectives of:

> 50% reduction in CO2
> 80% reduction in NOx during landing and take-off
> Reduce unburnt hydrocarbons and CO emissions by 50%
> To reduce external noise by 10dB (5dB in the shorter term)

There are several others such as Challenge 3 (Competitive Through Innovation), Activity 7.1.4 (Improving Cost Efficiency), Area: 7.1.4.2 (Aircraft Operational Cost), that can also be addressed through the influence of better engine health management.

The technology developed within this project is cross-sector as it is relevant to both aerospace and industrial gas turbines. Consequently, the work will also contribute to EU goals within the Energy sectors,
such as reduction of CO2, cost of ownership, etc.

1.2: Industry Drivers
Air transport is a vital sector within the EU economy. Studies show that the aerospace industry accounts for approximately 2.5% of Gross Domestic Product, creates (directly and indirectly) over 3 million jobs, and contributes in excess of €30Bn to a positive trade balance for Europe. The current annual growth rate of the aerospace industry is estimated to be about 5 percent, and this is likely to remain for at least the next 20 years. Around 3 million flights occur within Europe each year consuming some 30 million tonnes of kerosene. There are approximately 3.15 grams of CO2 per gram of kerosene (from the European CORINAIR manual), therefore the European aviation industry creates approximately 95 million tonnes of CO2 per year.

The contribution of aero-gas turbines to the overall man-made global CO2 emissions is estimated to be at around 2%. However, due to the growth of the industry, this is predicted to rise to around 3% by 2020. It is therefore necessary to continue to evolve aero-engine technology to ensure the continued contribution to the reduction of overall atmospheric emissions in line with ACARE 2020 goals described previously. Current industrial power gas turbine development is also pursuing similar goals as the aero-engine industry, i.e. to deliver better efficiencies with reduced environmental impact and reduced cost of ownership.

There are a number of ways in which gas turbine efficiency can be improved. Historically, most manufacturers have achieved this through piecewise evolution of individual component technology such as higher bypass ratios, more aerodynamically efficient blades or higher component operating temperatures. Sensors and instrumentation are not always perceived as technologies that can contribute significantly to improved gas turbine efficiency, yet they are fundamental enabling technologies.

They are a critical enabler to the gas turbine industry in three distinct areas of business:
➢ Sensors used during product development for validation of design tools and new products.
➢ Sensors fitted to engines in service as part of the engine control system.
➢ Sensors fitted to engines in service to monitor engine health.

Obtaining reliable and accurate measurements from all parts of gas turbine engines during development phases is critical to optimising the design to maximise performance. The role of sensors is also fundamental to the operational performance of gas turbines. The limitations of sensors in terms of survival temperature, accuracy, stability, degradation with time, etc. limit how close to the maximum operating ceiling the gas turbine can be run. Engines are run with a substantial safety margin in order to safeguard the critical components against mechanical failure simply because of the uncertainty in the measurement of key parameters. Consequently, engines are not run at their most optimal, which impacts thermal efficiency, specific fuel consumption and propulsive/generator efficiency. The issue is cross-sector, affecting both aero-engine and industrial power gas turbine products

1.2.1: Harsher Environments
The requirement to maximise the efficiency of the gas turbine, whether this is aerospace or industrial, has driven engines to operate with smaller and hotter cores with higher turbine inlet temperatures. The
historical rise in turbine entry temperature (TET) for aerospace gas turbines is in the region of 350°C over the last 30 years. The current and projected future turbine entry temperatures are well beyond the capability of the current state of the art instrumentation. Consequently, development of new products, design methods and tools are being validated using data extrapolated from more benign parts of the engine or data obtained from scaled or lower temperature test rigs. This increases the uncertainty of tools, and the need for test rigs increases the cost and timescale of product development. The impact of measurement uncertainty on the ability to predict performance and component life accurately is highly geared in the hottest parts of the engine. For example, an uncertainty in the temperature of some turbine components of only 10°C can change predicted life by up to 50%.

The measurement of parameters such as gas temperature and blade metal or Thermal Barrier Coating (TBC) temperature in the hottest and most critical parts of the engine cannot currently be performed with sufficient reliability for health monitoring and control purposes for engines in service. Parameters are therefore derived from measurements in less hostile parts of the engine. This introduces additional uncertainty in the values, and requires additional margins to be incorporated into engine operating conditions. It should also be pointed out that as TETs increase, obviously so do exhaust gas temperatures (EGTs) by roughly an equivalent amount to the TET. Consequently, even the supposed “benign” regions of modern engines are presenting significant challenges for sensors.

1.2.2: Wireless and Less-Wired
In addition to the challenges above, development testing requires a large number of individual measurements to be collected simultaneously to characterize the performance of the machine fully. As many as 3000 parameters may now be recorded simultaneously on an engine development test with a significant proportion of these being from the rotating parts of the engine. The upward trend in numbers of measurements needed to characterise and optimise new gas turbine designs means very large volumes of wiring and pneumatic lines must be incorporated into test engines. This increases the cost and reduces the agility of the engine testing, limiting the amount of data which can be obtained from a single test vehicle. This can increase the number of test vehicles and amount of testing required to obtain the necessary data. In some cases the presence of the instrumentation lead-out and telemetry systems can also significantly alter the behaviour of the vehicle under test, reducing the relevance of the data obtained.

For engines in service, there is a growing need to monitor the health and performance of the engine, to enable the most efficient operation of the engine throughout its life. It is anticipated that this requirement will lead to a significant increase in numbers of sensors fitted for health monitoring, which in turn will lead to increased wiring and potentially weight increase (efficiency impact). Retro fitting of additional health monitoring sensors to engines already deployed could be extremely challenging to incorporate with existing wiring looms. Both the challenge of high parameter counts on development vehicles, and the need for more sensors on production engines can be met by wireless and less-wired technology to reduce the impact of the additional lead-out required.

1.2.3: Effects of Bypass Ratio on Fan/Compressor Stage Measurements
The drive for greater turbofan efficiency has resulted in a steady increase in bypass ratio, and consequently a reduction in the pressure and temperature rise in the air as it passes through the larger fan.
Proposed new engine architectures for even greater propulsive efficiency, such as open rotor and geared turbofan concepts, will result in even higher bypass ratios. This trend has two impacts on the requirements for performance instrumentation:

- As bypass ratio increases, the effect of fan efficiency on overall powerplant efficiency becomes stronger, meaning accurate determination of fan performance is critical to optimising powerplant efficiency.
- The change in temperature and pressure of the air passing through the fan becomes smaller, requiring much more accurate instrumentation to resolve the performance of the subsystem.

These two factors combine to drive a need for fan performance instrumentation with measurement uncertainty which is significantly better than the fundamental capability of much of the current state of the art.

1.2.3: Lab Gap Matrix, EVI-GTI, and HEATTOP

The cross sector impact of shortfalls in current instrumentation and sensor capability on the business of the gas turbine OEMs was the driver behind the formation of the European Virtual Institute for Gas Turbine Instrumentation (EVI-GTI), as a Thematic Network under a Framework 5 programme, with the support of the Engine Industrial Management Group. The EVI-GTI consortium involved all the major (aero and stationary) gas turbine manufacturers in Europe, along with representatives of the instrumentation and sensor industry, gas turbine users and researchers.

A study carried out by EVI-GTI in 2004 compared the current state of the art of gas turbine instrumentation with the current and projected needs of the gas turbine OEMs for measurement capability. This resulted in the first publication of the 'Lab Gap Matrix' (LGM). The LGM is a method of displaying the information in a form which highlights the gaps in the current state of the art, allowing the limited resources available to focus on the critical gaps and issues.

On the basis of the capability gaps in the 2004 LGM, the HEATTOP project (“Accurate, High Temperature, Engine Aero-Thermal Measurements, for Gas Turbine Life Optimisation, Performance and Condition Monitoring”) was formed. This was the first major sensors and instrumentation project to be funded by the EU under the auspices of the Framework 6 programme. The focus of HEATTOP was primarily on the hot-end sensors where most of the capability gaps existed.

On the basis of the HEATTOP project and also as a result of regular reviews as part of EVI-GTI meetings and other working groups, the LGM has been updated. The LGM is split into three individual matrices representing “aero-performance”, “rotating structures”, and “static structures”. There is also a matrix for enabling technologies, which includes signal transfer, telemetry and wireless. A traffic light colouring system is used to highlight the severity of the gaps. Many of the technology gaps still exist in the hottest section of the gas turbine. Moreover, there are also gaps emerging in cooler sections of the engine for the rotating parts, such as the fan.

Despite the successes of HEATTOP and other research programmes, it has become clear to that gaps are not closing quickly enough. This protracted evolution of the LGM is a very strong indication of not only the scale of the problem, but also of the complexity. Further research in to gas turbine sensors and instrumentation is, therefore, absolutely essential if the capability gaps are to be filled at an adequate rate.
These gaps cannot be filled by individual companies or partnerships alone. It requires the focussed attention of a substantial research project involving the breadth of skills and expertise of the EU community.

The STARGATE project has been set up to create the biggest impact on the LGM as possible within the constraints of the Call budget. It should be pointed out that STARGATE is NOT a direct follow-on from HEATTOP. The project contains largely new technologies and research initiatives. Clearly STARGATE cannot target all the gaps in a single project. However, the project has a Work Package structure that has been formed around the three primary areas of the LGM, namely:

- Gas path performance measurements (Work Package 3)
- Structural measurements (Work Package 4)
- Signal transfer and wireless (Work Package 5)

Under these themes, specific objectives have been extracted from the LGM that the STARGATE project will target. While there is a focus on high temperature sensor gaps, the remit of STARGATE is broader than HEATTOP by considering “cold” end sensors and wireless. Specifically:

- Measurement of gas temperature, pressure, and flow at very high temperature (>1000°C), particularly in the combustion and turbine sections of the engine.
- Accurate measurement of component temperatures (>1000°C) in the combustion and turbine sections of the engines.
- Measurement of blade gaps, component vibration, and displacements of turbine components at very high temperature (>750°C).
- More accurate performance instrumentation at lower temperatures (e.g. driven by lower pressure ratios across high bypass ratio fans).
- Wired and less wired sensing systems and telemetry

Project Results:
Summary of Project Progress

Overall the project has made generally excellent progress over its duration. Most of the technologies (WP3-WP5) have reached rig and/or engine trials to achieve a Technology Readiness Level close to or at 5. One of the sensor technologies hit some significant technical problems largely due to the very challenging nature of the materials and sensing techniques required to allow it operate in the given environment. This prevented it from being tested on a realistic rig or test bed, but it was still a significant achievement that the material issues could be largely resolved within the timeframe of the project.

For the uncertainty analysis activity (WP6), two workshops were held with world-renown expert Ron Dieck to assist and unify Partners in the calculation of their measurement uncertainty for the sensors they are developing. This resulted in 3 sets of uncertainty analysis: an initial one prior to laboratory tests, one update after laboratory data was available, and one further update when rig/engine data was available (where applicable). The result was a comprehensive estimate of the measurement uncertainty to go alongside the development of the sensor, which is critical if a measurement is to be meaningful.
For the rig and engine trails (WP7) a comprehensive register of available test facilities was created and Partners were assigned to rigs or engines within a specified time window. A test campaign was undertaken over the last year of the project and the resulting test data was documented in a detailed WP7 deliverable report.

In 2015 an extension of 4-months was requested to allow STARGATE to address a few technical delays that were occurring. This was subsequently granted, increasing the end date of the project from October 31st 2015 to February 29th 2016.

All deliverables have been achieved with the deliverables reports felt to be of a high quality. While many of the deliverables were delivered close to the original plan, it is accepted that a number were significantly later than planned. This was primarily to ensure the appropriate level of scientific quality was achieved rather than submitting a substandard report in order to meet a timescale. All milestones have also been achieved with one exception, which relates to the sensor project discussed above, which hit technical difficulties and was unable to obtain data from a rig trial.

The project has submitted one patent application (SIL pressure sensor) and several further applications are being consider by other partners. The project has been very active on dissemination, with a significant presence of partners at 3 EVI-GTI conferences, amongst others. Moreover 3 summary publications were made in specific European Parliament magazines, specifically The Parliament Magazine and Pan-European Networks. STARGATE also had a stand and made a presentation at the EC AeroDays conference in October 2015 for which it was awarded best session paper. Many of the partners have also submitted in to scientific journals.

The project has resulted in a number of exploitation opportunities with several of the partners discussing follow-on activity with engine OEMs and supply chain beyond the completion of STARGATE.

WP3: Gas Path Performance Measurements
WP3: 3.1 High-Temperature Dynamic Pressure & Entropy Probes

1. Background and Overall Objectives of the Work

The initial overall objective for Task 3.1 is to develop a range of cooled and uncooled pressure and entropy probes. VKI, Onera, Siemens and Snecma are involved in this task. VKI leads the design study, Onera develops the requisite thin film temperature sensor for entropy probes and Snecma/Siemens provide design specifications and application envelopes as well as technology evaluation and validation in conjunction with VKI.

2. Summary of Progress Towards Objectives

• Design, manufacturing and evaluation of uncooled steady-state entropy probe
• Development of almost all the processes required for thin film temperature sensors manufacturing (photolithographic masking, sputtering), allowing Laboratory evaluation of prototypes deposited on planar
substrates,
• Design of the head of the steady-state probe and development of probe manufacturing processes.
• Manufacturing of the parts of the head of the steady-state probe (sensor holder, metallic parts) including connection elements (tracks and connection pads, measurement cable).
• Laboratory evaluation of thin film temperature sensors showing a good stability of the characteristics with cycling between 200 °C and 1000 °C and an effect of the resistance drift limiting the maximum operating temperature at 800-900 °C.
• Design, manufacturing and evaluation of uncooled unsteady-state entropy probe
• Design of the head of the unsteady-state probe.
• Design of the pressure probe.
• Manufacturing of the parts of the head of the steady-state probes (sensor holder, metallic parts).
• Manufacturing of two pressure probes.

3. Exploitation Plans, Dissemination Activity and Next Steps

VKI and Onera has not conducted dissemination activity within WP3 due to the work not reaching a suitable level of maturation.
A small amount of additional work and time would allow producing and testing the first functional prototypes of steady and unsteady-state probes. For that, Onera and VKI will have to continue their cooperation and look for the corresponding funding.

WP3: 3.2 Accurate Performance Instrumentation for Unsteady Flows
ULO/RRUK Contribution to 3.2

1. Background and Overall Objectives of the Work

Steady-state’ stagnation temperature probes are used during gas turbine engine testing as a means of characterising the engine running condition and also to establish individual engine component performance. These probes are typically mounted behind rotating stages of turbo-machinery, where the wakes shed from passing blades create an unsteady flow field. The purpose of this task is to gain an understanding of how this flow field unsteadiness affects the measurement of stagnation temperature. This understanding is necessary to quantify and improve the measurement accuracy needed to demonstrate small component efficiency gains. Additionally the improved understanding of probe performance will facilitate the development of advanced probe designs that offer improved measurement accuracy compared to the current state-of-the-art. The overall objectives of the task are:

• To gain a fundamental understanding of the mechanisms involved in unsteady flows that affect the measurements acquired from ‘steady-state’ stagnation temperature probes,
• To use this understanding to develop correction methodologies for measurements from ‘steady-state’ probes in unsteady flows, and
• To develop advanced probe designs that deliver better measurement accuracy in unsteady flows compared to the current state-of-the-art.

2. Summary of Progress Towards Objectives
The technical achievements of the work can be summarized as follows:

- Five stagnation temperature probe designs were tested in an oscillating jet stream to simulate the effects of unsteadiness and its influence on total temperature measurement error.
- Using the results from these tests it was possible to determine aero-thermal phenomena contributing to temperature measurement error and propose revised designs.
- The modified designs were built and tested and these showed significant improvement in temperature measurement error as a result of reducing the influence unsteady effects.
- The design recommendations were adopted by Rolls-Royce for new stagnation probe designs and built for new test campaigns via additive manufacturing techniques.

3. Exploitation Plans, Dissemination Activity and Next Steps

This work package forms part of the Rolls-Royce strategy to reduce stagnation temperature measurement uncertainty. This is important to allow incremental performance enhancements to be adequately demonstrated.

In this context, contributions to measurement uncertainty arise from; fundamental sensor performance, temperature recovery performance and the measurement environment (e.g. unsteady effects). Within the work performed here the impact of unsteadiness is seen to be significant in terms of measurement uncertainty at the target level. By careful probe design using low conductivity configurations the uncertainty can be reduced to within the target level.

Work has been presented at the 2015 EVI-GTI Conference. “Investigating the impact of flow field unsteadiness on gas-path stagnation temperature measurements”. Clare Bonham, Adrian Spencer, Dylan Wise and Katsu Tanimizu.

WP3: 3.3 High Temperature Thermocouples

UCAMB Contribution to 3.3.

1. Background and Overall Objectives of the Work

Nickel based thermocouples are widely used to measure temperature in gas turbines. The turbine entry temperatures of the engine exceed the current temperature capability of conventional Nickel based thermocouples, which drift significantly above 1000 °C. The conventional thermocouples need to be located further downstream in the engine to be able to operate reliably for a time matching the maintenance intervals of the engine. Thermocouples with higher temperature capability would allow moving the temperature measurement upstream: this will produce an advantage in terms of control and efficiency of the engine. The major challenge is associated with the increase in temperature, as this is severely detrimental for both drift and mechanical integrity of the conventional thermocouples.

The research undertaken at the University of Cambridge as part of STARGATE aimed at studying the behaviour of a new thermocouple devised in the Department of Materials Science and Metallurgy. This thermocouple, called double wall thermocouple, is based on a composite sheath, made of two walls. The new thermocouple aims at minimising the contamination from the sheath to the thermoelements, so resulting into a low drift temperature sensor. In particular, during the STARGATE project the behaviour of the double wall thermocouples at temperatures as high as 1300 °C was studied. In addition to that, the use of high temperature coatings was explored as a mean to achieve at high temperatures a longer life.
compared to conventional uncoated sensor.

2. Summary of Progress Towards Objectives

- Development of double-wall thermocouples tested up to 1300°C
  - Significantly reduced drift (at least 85%) was observed by measurement compared to standard thermocouples

- Assessment of the performance of coated thermocouples for oxidation and life compared to standard alloy thermocouples, which resulted in significantly improved life (6 times or more)

- Rig tests of advanced thermocouples on a wide range of rigs, including thermal cyclic tests, vibration tests, isothermal tests, engine tests, and combustion rig tests.

3. Exploitation Plans, Dissemination Activity and Next Steps

Discussions with OEMs and thermocouple manufacturers are undergoing in order to exploit commercially the technology. Different markets are currently under consideration including Aerospace, Heat Treatment, Nuclear and Automotive.

Meggitt UK Contribution to 3.3

1. Background and Overall Objectives of the Work

This activity does not relate to the development of thermocouples, but is to do with improving methods for life testing of thermocouples for aerospace. There is currently no standard methodology for aerospace for the lifing assessment of thermocouples to understand the drift in accuracy due to prolonged exposure to high temperatures and temperature cycling. While good practices exist, they do not take in to account to the duty cycle a typical thermocouple will encounter in the engine and hence it is not clear whether these best practises are valid. Meggitt wished to develop a new method based on detailed testing of thermocouples under cyclic conditions. Specifically the overall objectives are:

- Develop a highly accurate test facility based on uncertainty analysis
- Manufacture appropriate thermocouples test units
- Perform long term isothermal and thermal cycling tests
- Calculate the drift for each thermocouple
- Propose improvements to existing best practice

2. Summary of Progress Towards Objectives

The project has made the following of achievements towards the above objectives:

- Completion of baseline isothermal drift test
- Definition of thermal cycle profile
• Performed 3 thermal cycle drift tests
• Developed a data processing methodology to extract drift values from test data
• Updated the uncertainty analysis on the basis of experimental results.
• Proposed options to modify existing drift methodology and next steps for future research.

Overall the work proved somewhat inconclusive in terms of generating a new methodology and/or standard for drift testing of aerospace-grade thermocouples. While it would appear that the thermal cycle does affect the drift, the test methodology is both more complex to implement, more difficult to process, and generally much more unreliable in terms of issues with equipment and uncertainties in data.

3. Exploitation Plans, Dissemination Activity and Next Steps
Currently there are no plans to adopt a thermal cycling methodology for thermocouple drift testing as the results are still inconclusive. Moreover, the results show that testing in such a manner is more convoluted, time-consuming and prone to unreliability, which makes it undesirable at present for new production introduction projects. However, as there are still questions to be resolved in terms of the true influence of the thermal cycle, some additional discussions will be had with Cambridge University to establish what other testing would be useful outside of STARGATE. If a method could be determined that could incorporate the influence of the thermal cycle but without the associated complexity and time constraint, that would be very valuable.

WP3: 3.4 Dynamic Pressure Transducer with Self-Test

1. Background and Overall Objectives of the Work

Dynamic pressure sensors are required for safe engine operation and in development of new engines. Existing pressure sensors, even if very reliable, do not have the capability to perform self-checks on the integrity of the measuring line, i.e. to control if the pressure sensor is operating properly.

The overall objective of STARGATE WP3.4 was to achieve TRL4 with a dynamic pressure sensor that enables self-check and fault detection over the entire measuring chain (piezoelectric sensing element, cable and signal conditioning unit) as well as redundancy.

2. Summary of Progress Towards Objectives

• The sensor was developed over the course of the project and was mounted on a combustion chamber test rig in order to validate its performance. A standard Meggitt sensor (CP235) acting as reference sensor was also installed at the same time. Failures were simulated during the test by successively opening and closing signal transmission lines and test injection line thanks to the specific test equipment developed.

• The measuring chain prototype operated as expected, validating its capability to (i) detect failures (indicated through the DC output voltage that drops to predefined values) and (ii) still provide a correct measurement output when a failure is detected in a transmission line (demonstration of redundancy feature) or in the test signal injection line. It also demonstrated that a potential loss of self-checking capability does not impact the measurement.
3. Exploitation Plans, Dissemination Activity and Next Steps

The technology maturity achieved with STARGATE is sufficient to move to the product development phase. Meggitt SA is working with major European energy OEMs to take this technology forward to application. A combined measurement can indeed only be achieved with a safe and robust measuring chain such as the one developed in this project. Some technology building blocks matured in STARGATE will also be applied to Meggitt’s future products for lower SIL applications. It shall also be noted that the fail safe and redundant concept developed within STARGATE for a piezoelectric dynamic pressure sensor can be similarly applied to piezoelectric accelerometers for aero-engines applications (e.g. safety critical and remote or difficult to access applications). It is also Meggitt’s plan to promote and deploy this technology in the aerospace market.

Work Package 4: Structural and Mechanical Measurements
WP4: 4.1 High Temperature Strain Gauges

1. Background and Overall Objectives of the Work

In the work to design and develop advanced gas turbine engines, resistance strain gauges are used to provide static and dynamic strain measurements on various hot structures, in order to validate design codes, strain and stress calculations. As the object on which the gauge is attached is deformed in a direction, the electrical conductors forming the gauge, aligned in this direction, become narrower and longer. This change in the geometry of the conductors causes an increase in the electric resistance of the gauge.

The main objective for Onera in collaboration with GKN Aerospace, is to develop, manufacture and evaluate electrical and metrological characteristics of Thin Film Strain Gauges (TFSG) in order to assess the feasibility of static gauges usable up to 500 °C. The starting point of the study was the knowledge of Onera on manufacturing dynamic TFSG made of palladium-chrome (Pd-Cr) directly deposited on metallic pieces, using sputtering and photolithographic masking technique.

2. Summary of Progress Towards Objectives

In summary most of objectives were met. The results obtained show:

• A good stability of the gauge resistance at ambient temperature during thermal cycling.
• Low resistance drift levels for T≤800 °C.
• High apparent strain levels, mainly due to high temperature coefficient of resistance of gauge material.
• Reproducible axial and transverse gauge factors respectively equal at room temperature.
• The possibility to evaluate transverse sensitivity of axial gauges.
• A good stability of the response of the gauges during the tensile-compression and bending fatigue tests.
• The development of a temperature compensation system was initiated.
3. Exploitation Plans, Dissemination Activity and Next Steps

Exploitation of thin film strain gauge technology to be discussed with OEMS (know-how licensing, technology transfer).

Onera has not conducted dissemination activity within WP4/task 4.1. The preparation of a publication in a scientific journal is expected in 2016 on thin film strain gauges. More fatigue testing and gauge factor evaluation data at 500 °C should be obtained. Development of coating cement should be necessary to reduce breakings of wire to thin film connections. Development of a suitable temperature compensation system.

WP4: 4.2 High-Temperature Fibre-Optic Accelerometer

1. Background and Overall Objectives of the Work

Accelerometers can provide information about the performance and condition of gas turbines. They are typically used to monitor casing vibrations to ensure that machines are shut down in situations where vibration levels exceed normal bounds. In some cases additional accelerometers are used for condition monitoring of gas turbines. There are a variety of accelerometer technologies with piezoelectric accelerometers being the common choice for vibration monitoring of gas turbines. Continuous use temperature is about 650 °C. However, with significant increases in gas turbine operating temperatures in recent years, there is a requirement for accelerometers to operate to higher temperatures.

This work aims to provide optical accelerometers with an extended temperature range for use in performance and condition monitoring in the hot sections of gas turbines. The target for maximum continuous operating temperature is initially 750 °C. The design will be based on a Fabry-Perot optical sensor measuring the distance between a flexible membrane and a backplate; the change in distance being a function of the magnitude of the applied acceleration. The sensor will be validated by detailed laboratory tests and complementary rig trials, such as using the GKN high temperature shaker rig.

2. Summary of Progress Towards Objectives

The main achievements can be summarized as follows:

- Design and selection of packaging and optical materials to achieve the environmental and performance requirements set out at the start of the project.
- Development of suitable joining process for fixing sensing element to substrate.
- Improve reliability of the joint between the proof mass and the diaphragm of the sensing element.
- Redesign of the outer package to cope with 750 °C.
- Testing at the high-temperature GKN vibration facility.
We have successful designed and fabricated high-temperature accelerometer prototypes that meet most of the key specification set out at the beginning of the project. The achieved level of maturity can be characterized as TRL4. We will be working closely with OEM’s to determine routes for exploration and adoption of the optical acceleration sensor. In particular, applications on gas turbines for aircraft and power applications will be sought. We already have had some initial discussions with Siemens with regards to a possible engine test. The ultimate aim is that the OEM will buy sensors for test and measurement.

The idea of compensating the temperature cross-sensitivity of the accelerometer by simultaneously measuring the temperature of the transducer element has been filed in a recent patent application (GB2500255A).

WP4: 4.3 High-Temperature Microwave Tip Timing Sensor

1. Background and Overall Objectives of the Work

Blade tip timing is used to measure blade vibrations of turbine or compressor blades, allowing for long term blade health monitoring and better planning of maintenance. No sensor currently available is capable of performing long-term monitoring in hot sections of gas turbines due to limited survivability in high temperature environment, usually because of contamination of the sensor surface by combustion by-products over time. Microwave tip timing sensors are unaffected by contamination but currently limited to 250°C. The overall objective of STARGATE task 4.3 is to develop a sensor for tip timing measurements based on the microwave technology with a high temperature capability (up to 750°C) for long-term operation.

2. Summary of Progress Towards Objectives

Technical progress can be summarised as follows:

- Five high temperature probes have been manufactured and assembled. All critical high temperature assembly processes related to the new sensor design have been validated.
- After completion of the 500 thermal cycles, the probe was tested in isothermal conditions at 750°C for 500 hours. During the test, the probe’s performance was continuously monitored through the recording of its resonant frequency and notch depth to identify any variation in time.
- The thermal cycling campaign has proved successful. The probe physically survived throughout the 500 cycles and was still fully operational at the end of test.
- The performance of the new microwave tip timing sensor was assessed mainly on Meggitt’s low temperature spin rig. Good performance was achieved compared to conventional and reference sensors installed on the rig.

3. Exploitation Plans, Dissemination Activity and Next Steps

15 of 29
The market trend is to standardize tip-timing sensors and systems. Indeed, OEMs want to buy off-the-shelf system instead of keeping their internal system to reduce cost. With this new microwave technology, Meggitt can be an important player and supplier in Europe for vibration monitoring in hot engine sections for long term operation. The high temperature measurement capability gained within STARGATE is a must to have to enter this market and ultimately target blade health monitoring in operation.

The next steps towards a potential introduction of this new technology are to get a better understanding of in operation blade health monitoring needs and roadmaps to engine OEMs (both for energy and aerospace market segments) and to then mature the technology up to TRL 6.

WP4: 4.4 Optical Tip Clearance/Tip Timing Sensor

1. Background and Overall Objectives of the Work

It is well known that optical tip timing sensors with their small spot size can resolve very small blade vibrations that cannot be detected with other sensors. In the world of tip timing we call this ability superior spatial noise. These sensors are especially useful for measurements in the first few turbine rows where blades are short and stiff and even small vibrations on the order of a few hundred micrometres, but at relatively high frequencies, can lead to very high and dangerous strain values. While optical sensors in general suffer from reliability issues, mostly related to contamination and humidity, probe lifetime and reliability in the hot environment of a gas turbine, however, become even more of an issue as standard un-lensed fibre bundle probes have to be placed a few mm away from the hot blade tip.

Similar to tip timing sensors, tip clearance sensors are severely affected by the spot size of these sensors on the blade as well. Common capacitive clearance sensors have a spot size of 5-10 mm and the measured gap distance depends on the blade geometry with its pockets and squealer tips. It is common practice, before a measurement campaign, to build exact geometrical replica of the engine blade profiles and calibrate each sensor in a laboratory spin rig: A costly and time consuming process and the calibration becomes easily corrupted with any axial shift of the blade in the engine with respect to the sensor.

The goal of this task was to develop a new optical probe that can operate without cooling in all compressor and turbine rows, and can measure tip timing and tip clearance at the same time. Given the small spot size, this probe would work for all blade geometries (without specific calibration) and because of its long working distance (~50 mm) the probe would have a considerably longer lifetime (situated in the area of secondary cooling and prone to less contamination). The proposed sensor is based on the measurement of arrival times and therefore compatible with current blade vibration monitoring systems. Clearance measurements are based on triangulation.

2. Summary of Progress Towards Objectives

- During this period we have developed and built a complete measurement system based on the optical tip timing and clearance probe. The system combines the optical sensor, mounting hardware, lead fibers,
fiber couplers, fast optical detection; FPGA based electronics, as well as a software interface.

- Output of the system are online blade to blade clearance, full signal blade forms on demand, as well as blade arrival times for each blade, compatible with standard tip timing analysis software.
- The system was tested under engine relevant conditions in the lab and evaluated in a laboratory spin rig using real turbine and compressor blade geometries.
- A test opportunity in the compressor section of a large gas turbine was identified and a full engine implementation prepared.

3. Exploitation Plans, Dissemination Activity and Next Steps

In the next steps we will perform the planned compressor and turbine engine testing. We plan to integrate the system into an existing in-house tip timing analysis system and make it available for standard engine testing.

WP4: 4.5 Long Wave Pyrometer for TBC Measurements

1. Background and Overall Objectives of the Work

Turbine inlet temperatures of next generation gas turbines have to be increased in order to be thermodynamically more efficient. To protect the metallic blades from these high temperatures and to guarantee long life, turbine blades are often protected by a thermal barrier coating (TBC). Detailed knowledge of the temperatures of the turbine blade and the TBC is critical to evaluate the effectiveness of cooling designs as well as identify problematic blades during service. Conventional short wavelength pyrometry (~ 1 µm) is not suitable due to substantial errors as the TBCs are usually semi-transparent in this wavelength region. Therefore much longer wavelengths (~ 10 µm) are required. At these wavelengths the TBC is effectively opaque and its temperature can be measured directly.

While the use of pyrometry to measure TBC temperature has been investigated for many years, no existing method is satisfactory. This task aimed to develop a state-of-the-art system that overcomes these current shortfalls using a rigorous experimental approach by Siemens, Meggitt UK and ZAE Bayern. This included extensive spectral TBC and combustion gas lab analysis under consideration of real in-engine conditions, design work and conceptual pyrometer lab tests and resulted in manufacturing a pyrometer and performing engine tests at the Siemens Berlin Gas Turbine Test Centre. Finally the system has been verified using detailed experimental investigations in the laboratory and on the Siemens combustion test facility.

2. Summary of Progress Towards Objectives

Technical achievements can be summarized as follows:

- Detailed investigation of infrared-optical properties of the TBC and combustion gas.
- Design of the LWIR pyrometer setup including definition of spectral window of measurement based on the above measurements
- Validation of the optical and mechanical design via build and test of a “benchtop” laboratory pyrometer
• Build of engine pyrometer and calibration lab tests
• Engine test in Siemens test bed that showed very encouraging measurements
• A detailed uncertainty analysis of the temperature measurement in the engine environment
• Revised prototype design to improve signal-to-noise ratio

3. Exploitation Plans, Dissemination Activity and Next Steps

Exploitation plans

The developed and validated LWIR pyrometer will be further optimized and tested at the Siemens Berlin test facility in line with the strategy for improving the gas turbine design and validation to lead to more cost-effective and environmentally friendly engines. A broader use of the LWIR pyrometer is intended to be undertaken by the partners in order to contribute to the progress in energy efficiency in Europe for reducing the energy consumption and thereby decreasing the emission of carbon dioxide.

Future activities

Future work will be done in order to exploit the knowledge derived in this project for other applications relating to non-contact temperature measurement using infrared radiation. Furthermore the LWIR pyrometer will be revised and optimized in order to improve the capability and to reduce the measurement uncertainty.

WP4: 4.6 Novel, Non-Intrusive Scanning Pyrometry

1. Background and Overall Objectives of the Work

A standard intrusive pyrometry a has negative impact on the integrity of blades during the measurement as the pyro probe causes turbulences in the turbine chamber. A non-intrusive concept will avoid turbulences and has no negative impact on blade lifetime. The tasks in this project were as follows:

➢ Subtask 4.6.1: Concepts of non-intrusive pyrometry, ray tracing, constant spot size, multi path
➢ Subtask 4.6.2: Conceptual investigations and lab tests
➢ Subtask 4.6.3: Development of a demonstrator suitable for small & medium gas turbines
➢ Subtask 4.6.4: Investigation of multi-wavelength properties for temperature evaluation
➢ Subtask 4.6.5: Bench or rig tests of demonstrator (link to WP7)

2. Summary of Progress Towards Objectives

Achievements can be summarised as follows:

• The concept of a non-intrusive pyrometer was developed
• Various light guiding concepts were investigated and verified by means of ray tracing
• A thermal simulation of the design to investigate the possible temperatures at various points on the
An optimised design was selected which looked most promising for the envisaged application. The system was tested on a Siemens Industrial Turbomachinery test bed. Here it was found the installation to be extremely easy compared to conventional traversing techniques. The probe could be permanently installed to an existing borescope hole within very short time.

The tests proved very successful. The temperature readings were in the expected range which is known from simulations and also from synchronous measurements using the conventional traversing Pyrometer. The spatial resolution of the signals was very high due to the small spot sizes.

3. Exploitation Plans, Dissemination Activity and Next Steps

At the Lincoln factory all turbines ready for shipment are undergoing a production test for quality assessment. This includes a pyrometry test, which is done with a conventional traversing system. The traversing method has a negative impact of the product life time of the blades, inducing turbulences while measuring. The non-intrusive pyrometer would be a perfect replacement with the benefit, that causing no turbulences while measuring, it has no impact on the blade life time at all.

A second example of exploitation would be in servicing applications for industrial turbines. For condition maintenance it is important to monitor certain parameters over time and record it. Blade temperatures could be perfectly monitored with a non-intrusive pyrometer.

Work Package 5: Wireless and Less-Wired Sensors

Sub task 5.1.1 Power harvesting in Harsh Environments

1. Background and Overall Objectives of the Work

Independence from battery power is highly desirable for wireless sensors for use in gas turbine product development testing, and almost essential if wireless sensors are to be deployed as permanent features of in-service products. This is not only to avoid the maintenance burden of battery changes, but also because battery technology limits the environment of application of wireless sensors more severely than the electronics limitations do. Power harvesting is therefore a key enabler to wireless sensor deployment on gas turbines.

The objective of this sub task was investigating technologies for harvesting power from the environment around the sensor, and also storage for that power. Two different energy sources were investigated: Harvesting from mechanical vibration (Kinetic Harvesters) and harvesting from temperature differences (Thermal Harvesters). Additionally high temperature supercapacitor technology was investigated, in order to provide temporary storage for harvested energy, without introducing the environmental limitations of rechargeable battery technology or current low temperature capacitor technology.

2. Summary of Progress Towards Objectives
Development of a Kinetic Harvester: A range of single and multi-beam designs were investigated and tested on a Rolls-Royce Gnome engine. To harvest vibration energy on a gas turbine was a big challenge due to the very small vibrations. A broad bandwidth is needed that contains high q-value to be able to deliver enough power to the sensor and ZigBee communication circuit. In spite of all these challenges we succeeded to design a harvester that could power the sensor system, including during the power hungry start up sequence.

Thermal Harvester: The high temperature (600-800 °C) thermoelectric energy harvester went from simulations to synthesis of materials and fabrication of test prototypes. We also made measurements on a 1-couple module which did show that the technology is feasible, however very demanding and difficult to build at current state. We also showed with commercial thermoelectric modules (which had to be tested at lower temperatures) the feasibility that the high temperature energy harvester could power a Wi-Fi sensor node.

Supercapacitor: Working cells at 178 °C with capacitance of 80 mF for the cell was obtained during the tests and proves that energy storage in high temperatures is viable. N-doped carbon composite is a good electrode material since it is easy to produce and in our case origins from a renewable source, cellulose. Other carbon allotropes are to be explored in future to reach higher capacitance. High temperatures need an electrolyte that behaves like a liquid at elevated temperature without boiling hence the choice of ionic liquid is crucial for the behaviour and performance of the cell.

3. Exploitation Plans, Dissemination Activity and Next Steps

Dissemination Activities: 3 abstracts describing respectively the thermal harvester, Kinetic Harvester and Supercapacitor developments have been submitted for inclusion in the EVI-GTI conference in September 2016. A range of other scientific publications have been made.

Sub task 5.1.2 Power management and efficient data transfer (UCOV)

1. Background and Overall Objectives of the Work
Independence from battery power, or where there is no option, maximising battery life, minimising maintenance intervention, is key to enabling wireless sensor deployment on Gas Turbine Engines (GTEs). The objective of this sub task is developing technologies for optimising the use of available power, whether this is battery power, energy harvested from the environment, or a combination of the two. This is to be achieved through through minimising data transmission by means of data pre-processing and/or data compression.

2. Summary of Progress Towards Objectives

UCOV undertook research on power-efficient data transfer methods for wireless transfer on battery/self-powered sensing devices in GTE monitoring applications. Because these devices are power limited and radio transmission is expensive, reducing the amount of data transmitted is vital.

The work investigated:
- Sensed phenomena: examining data characteristics, informational content, compressibility, reduction methods. All work related to this was completed by M18. This work evaluated the feasibility of applying data reduction techniques to the parameters of interest in GTE monitoring (temperature, acceleration). Key to this was the development of five case studies with RRUUK to allow data reduction analysis to be...
related not only to raw temperature and acceleration readings but also informational outputs, i.e. peak acceleration and dominant frequency.

• Node and network: examining constraints that affect operation on real hardware; energy and environment. For this a pre-existing wireless temperature-sensing platform and software stack were used to implement UCOV’s data reduction techniques, which had the potential to reduce transmissions by up to 90%. Through energy consumption profiling several improvements to the software were identified and implemented, reducing the average energy usage by 75%. The start-up energy requirements of the device were reduced by ~95%.

• WSN interoperability: integration of sensor nodes with harvesters and sensor networks with less wired systems. From M12-M18, the work focused integration challenges of time stamping and feasibility of implementing WSN integration and acceleration-based case studies in LabView, the software used by Scitek’s less wired concentrator. During M18-M36, the following work was completed:
  o Proof-of-concept LabView implementations from M12-M18 were transferred to the cRIO platform (Section 3.3.1)
  o The integration of the UCOV wireless sensor network with both STK (less wired sensing) and CHAL (power harvesting) was completed (Sections 3.3.2 & 3.3.3)
  o Several rig tests were carried out to validate interoperability, measurement validity and time synchronisation drift (Section 3.3.4).

3. Exploitation Plans, Dissemination Activity and Next Steps

Use of these data compression methodologies into other fields, including cloud data storage and large volume data transfer between test facilities is now being considered partly as a result of its inclusion in the EVI-GTI workshop. The incorporation of energy saving and data compression methods into Engine Health Sensor networks is being considered.

WP5: Task 5.2 Rotating signal transfer (RRD, RRUUK)

1. Background and Overall Objectives of the Work

Key objectives for the rotating signal transfer task were:

• High Speed Data Transmission for wireless measurement: Overcome the radio frequency data transmission as limiting factor for simultaneous multi-channel high-frequency measurements.
• Miniaturization of Telemetry: Reduce the physical volume of the rotating telemetry modules for simplified and cheap integration solutions in high-speed spools of small gas turbine engines.
• High Temperature electronics feasibility study: Overcome / Reduce need for complex cooling systems, causing high design and operating costs and often affecting the test subject
• Alternative Power Source for Battery Powered Units: Higher temperature range higher capacity battery technology needed to extend operational window for battery powered systems. Target -40°C to +150°C.
Against these four objectives, achievements can be summarized as follows:

- Numerous antenna designs were conceived and trialled. The optimal design was successfully checked and shown to be working for 15 transmitters. The new antenna system completed successfully several test missions.
- The transmitter layout was redesigned to increase the channel count per transmitter and to add additional features. New PCB components were selected to achieve a smaller packaging of the circuit board. After successful testing of the 4 ch S/G transmitter, an 8 ch transmitter of the same size was subject to vibration and temperature testing to confirm the reliability of the components. The prototype testing in 2015 demonstrated the performance and reliability of the new 8 channel transmitter.
- Most functions of a rotating telemetry system were realized in HT components, although there were some unresolved issues, mainly in regard to physical size, power consumption, and robustness. In general, the board demonstrated the capabilities according to the manufacturer spec. The function of the HT demo board at 170°C was confirmed.
- The objective of this task was to identify and validate alternative battery technology to provide capability up to the temperature limits of -40°C to +125°C. A type of lithium-chloride battery from the oil and gas industry was selected as the best candidate for the high temperature telemetry application. After lab testing, the batteries were tested in an engine representative environment. No leakage or loss of performance was observed with the batteries throughout the trials. Batteries are now ready for deployment on current telemetry systems.

3. Exploitation Plans, Dissemination Activity and Next Steps

The high capacity core telemetry technology is being deployed to component rig testing. The high temperature batteries developed in STARGATE are to be deployed on the specific Rolls-Royce engine development programme to power the LP shaft telemetry system. Further work is planned to investigate specific unresolved issues within the four tasks listed above.

WP5: Task 5.3 Mixed wireless and less-wired large on-engine sensor networks (STK)

1. Background and Overall Objectives of the Work

Reducing lead-out is key to more efficient testing in the short term, and in the longer term will enable reduced wiring weight and complexity on production engines. A major issue with any multiplexed sensor system is the accurate synchronization of data from multiple sensors. The challenge is even greater where an engine is instrumented with a mixed suite of wired multiplexed, wireless data concentrators and fully wireless nodes.

The objective by all partners in this task will be to collaborate to develop hardware and protocols to enable fully mixed suites of wireless and less-wired sensors to operate without data synchronization issues. A mixed network will be assembled, including sensor nodes incorporating technology from tasks 5.1 and telemetry system from 5.3 as well as wireless multichannel data concentrators and conventional wired...
sensor, to assess and optimise data timing synchronisation.

2. Summary of Progress Towards Objectives

- Two accelerometer versions of wireless data concentrator units were designed and manufactured as part of the original objectives. Both units were tested over long periods in OEM engine test bays to ensure that the electronics as fitted in the enclosure were robust and reliable and that over long periods did not exceed temperatures that were above the manufacturers’ specifications. These tests were also intended to debug the software and add features that will enhance ease of operation. These units were also used to carry out a test where two nodes were used to record and transmit data.

- A Battery Unit was developed as part of this project to allow the system to be self-contained and totally independent of the engine and test bed systems. This is a very important feature as it allows the system to be deployed quickly with no need to be interfaced or powered by the test bed or engine systems which makes it particularly attractive. Engine instrumentation is normally planned well in advance and any additional instrumentation is nearly impossible to add unless it is totally self-contained.

- The results of the extensive testing showed the design and implementation of the data acquisition system to be highly successful, with it providing accurate data over the duration of testing as well as being reliable within the difficult environment in which it had to operate.

3. Exploitation Plans, Dissemination Activity and Next Steps

The data concentrator is now a SCITEK product that would not have been possible before Stargate. The units were exhibited on the STARGATE stand at Aerodays 2015 in London. The main intended customer industry is Aerospace and we are hoping that a UK OEM will purchase a number of these units. SCITEK also had an enquiry to use this device as an engine control unit (ECU) of a micro gas turbine that will be used in automotive applications as an electrical generator.

This system is versatile and is to be offered in a number of configurations for use with any type of sensor. SCITEK also intends to carry out further development and testing of this unit beyond STARGATE. Other potential industrial applications are in the energy business to carry out condition monitoring in gas pipes and in for use in Autonomous marine applications. SCITEK is in discussion with potential customers in both of these sectors.

Work Package 6: Uncertainty and Lifing Assessment

1. Background and Overall Objectives of the Work

WP6 was created to ensure that all partners follow a consistent and unified methodology of assessing the uncertainty of each measurement technique developed in WP3-WP5. This methodology was based on the European Standard in Uncertainty Estimation, mainly the ISO-GUM and its revisions, as well as other appropriate ISO norms related to accuracy of measurements. Each partner created a table of error sources for sensor technique and was carried out before and after the development work planned in WP3-
WP5.

The overall objectives of WP6 are:

- Collect the appropriate ISO standards on measurement uncertainty and make them available to all partners to adopt a consistent and unified methodology
- Establish a detailed uncertainty analysis (exhaustive list of critical error parameters) for each sensor to be developed within WP3-WP5, including critical ageing effects
- Create a reporting template containing a matrix of error and ageing parameters for each partner to complete and update after sensor development/improvement within WP3-WP5
- Update of uncertainty analysis based on sensor performance in laboratory environment
- Manage partners in order to ensure that no partner moves into WP7 (rig trials) without properly quantifying laboratory-level sensor performance
- Update of uncertainty analysis based on rig trial data and compare achievements with targets set out in WP2

2. Summary of Progress Towards Objectives

- The project developed a methodology and spreadsheet tool to unify the assessment of uncertainty. This was taught to the Partners as part of training workshops at VKI by Ron Dieck, as shown below.

- Further workshops with Ron Dieck were subsequently held at VKI to assess the Partner’s initial estimates of uncertainty for their sensors.

- As additional data emerged from laboratory trials, modelling, and rig trials, the uncertainty estimates were updated.

- The final estimates of uncertainty were included alongside the overall measurement performance data for each sensor and compared against the initial specifications set out in WP2.

Work Package 7: Rig and Engine Trials
General WP7 Progress (GKN Contribution)

1. Background and Overall Objectives of the Work

The overall objectives of WP7, lead by GKN, were to develop test rig register, to issue test plan definition for each task in the project and to coordinate rig trial activities in the entire project.

Moreover, in terms of being rig owner the objectives were to undertake needed rig modifications, preparations and perform tests to be done at chosen GKN rigs.
2. Summary of Progress Towards Objectives

Some example testing campaigns is given below:

• Testing of kinetic harvesters has been performed in several stages as design was improved. The tests did not require any major rig modifications and was proceeding well. The test was to characterize the output of the harvester at different frequencies and g-loads.

• Testing of new, double wall and coated thermocouples was about to test the robustness of the new thermocouples at different g-loads at both ambient temperature and high temperatures. Different excitation cycles were applied. Firstly the thermocouples were exposed to a standard vibration cycle typical for a military jet engine. After that a harder test containing high g, sinus excitation was performed. The test was performed well according the plan.

• Testing of optical accelerometer in GKN shaker rig required design and manufacturing of a special fixture for the accelerometer and optic fiber cable. The test was about: responsivity over signal bandwidth, maximum temperature test (750°C), resolution investigation, uncertainty across dynamic range and temperature dependence on responsivity.

• Test of new thermocouples for in thermo-shock rig was thermal cycling to show improved endurance and drift properties compared to conventional thermocouples. It was a long term test run for seven days continuously, heating and cooling the thermocouples for three minutes each. The test was originally planned to be done at GKN afterburner rig but this was changed to the thermo-sock rig due to higher test value as well as cost reasons.

• The fatigue test of thin film strain gauges was run in GKN fatigue rig in order to validate fatigue requirements of the thin film installation technique. The test showed no major fatigue issues.

Potential Impact:

> IMPACT

In the short-term, the technical impact of this project will be relatively modest due to the conservative nature of the highly regulated industries in which these technologies are applied. While many of the technologies have made significant advancement up the Technology Readiness ladder during the project, several years of further development will be required in many cases to bring the technologies to the point that they can either be applied directly or considered for new production introduction. However, with major engine OEMs being involved in the project there is a strong route to exploitation and, indeed, some of the Partners are already in discussions with the OEMs about the next steps for the development and application of their technology (see later).

One positive short-term technical impact that the project will have is that the high-level results are to be discussed at the upcoming EVI-GTI conference on September 2016 in Berlin. This discussion will be used to review and update the Lab-Gap Matrix, which is a key tool in understanding where the industry is currently in terms of sensor and associated technologies. This could yield proposals for future projects or
feed in to strategy for the various industrial management/advisory groups that are associated with EU research such as the EIMG (Engines) and EqIMG (Equipment).

From a societal point of view in the short term, the project will have a positive impact in terms of sustainment and, potentially, increase of jobs to support the future projects that have been (and will be) spawned off the back of STARGATE. It has been already stated that a number of discussions are on-going with OEMs in terms of future partnerships to develop the technologies further. For the academic institutions, the project has yielded a substantial number of conference and journal publication opportunities and there are already plans by a number of the academic partners to present at conferences this year and next year. In this context, the project has helped to sustain or increase the visibility of academic bodies within the scientific community, which could lead to project or funding opportunities in the future.

Most of the impacts of STARGATE will occur in either the medium or long-term, but to achieve this will require proactive action from the Partners to bring their technologies to the appropriate level of maturation via future projects and collaborations (either funded or self-funded), and to ensure continued dialogue with OEMs and Supply Chain. If this is achieved the anticipated impacts will be:

- Gas turbine engines with lower specific fuel consumption and therefore reduced CO2 emissions due to reduced design uncertainties. Improved measurements in the gas path will enable better optimisation of design and analysis tools to optimise future turbomachinery efficiency.

- Engines that are run closer to their optimal conditions due to reduced uncertainties of key measured parameters, particularly temperature. Better knowledge of blade surface health and IP/HP gas temperature will enable higher operating temperatures and hence improved thermal efficiency. This will lead to reductions in fuel consumption and emissions over the life of the gas turbine.

- Improved engine design through more extensive engine development measurements. This will be made possible through advances in wireless sensor technology to allow far greater coverage and flexibility of instrumentation on development engines without the enormous installation and management burden (wire, data, etc.).

- Better component temperature measurements will enable the reduction in secondary air usage from the compressor to cool critical components. Cooling air can be up to 7% of an engine’s total airflow. Any reduction in this can significantly improve efficiency and therefore reduce CO2 emissions and environmental impact.

- Gas turbine engines with lower specific aerodynamic losses due to optimised or actively controlled and monitored radial tip clearances of turbine blades. The will reduce wasted air over the rotor tip and improve overall engine efficiency and environmental impact.

- Gas turbine engines with lower emissions due to optimised design for combustors. Better validated models for combustion processes will enable reduction of NOx, unburnt hydrocarbons, PM10s etc.
• Gas turbine engines with decreased spares and material use. If critical components can be monitored more accurately and linked in to engine health management regimes, this might allow for components to be replaced when they are near end-of-life and not at fixed intervals as defined by the maintenance scheduling of the aircraft or power station.

• Gas turbine engines with decreased weight due to better design validation data. More accurate models will prevent over-sizing/over-engineering of parts due to uncertainties in the aero and thermodynamics.

> DISSEMINATION

In the proposal a number of primary dissemination activities were identified as part of the dissemination planning. Specifically:

➢ EVI-GTI
➢ Conferences organised by the EU Commission (e.g. AeroDays)
➢ ASME (e.g. Turbo Expo)
➢ PowerGen
➢ Training and short courses at the von-Karman Institute

The project has been successful in disseminating through these channels (as well as others) to ensure good visibility of the STARGATE project. Some specific examples are:

• There was attendance at a number of EVI-GTI/PIWG events through the duration of the project. These were the 2013 conference in Baden, Switzerland, the 2014 conference in New Jersey (with PIWG), and the 2015 EVI-GTI conference in London. A number of presentations were made by the STARGATE partners at each of these events.

• A presentation was made at the AeroDays conference in October 2015 that summarised the objectives and achievements of STARGATE. It was awarded Best Paper for its session and a further publication is being made for a Commission-scientific journal. There was also a project stand available all week during the conference and was hosted by the Coordinator, Rolls-Royce UK, Loughborough University, and Scitek.

• There has been attendance and presentation at a range of other scientific conferences as well as those listed above, including Tempmeko and ASME Turbo Expo.

• Two publications were made in the Research Review within Parliament Magazine in 2013 and 2015. These were 1-page overviews of STARGATE and technical progress. A third 3-page publication was made in Pan European Networks in late 2015 outlining a summary of achievements of the project against objectives.

• A number of scientific papers have been submitted to and accepted for learned journals.

• Two training courses were held at VKI to train Partners and other attendees on the application of uncertainty analysis. These courses were run by world-renown expert Ron Dieck.

Many of the Partners have plans to disseminate at future events, including the next EVI-GTI conference in
Berlin on September 2016.
Unfortunately it was not possible to create a project website within the timescale of the project due to IT constraints within Meggitt. However, it is hoped that, with the assistance of the EC, a website can be created after the completion of STARGATE that can highlight the objectives of the project, key achievements, and give links to publically available documents.

> INTELLECTUAL PROPERTY
Meggitt SA has submitted a patent application as part of the development of their pressure sensor with failure detection circuit. Additional patent opportunities have been identified by a number of the Partners (e.g. VKI and Chalmers), but no further applications were made within the duration of the project.

> EXPLOITATION
As stated, the engine OEMs involved in the project will provide a direct path to industrial exploitation and some of the Partners are already in discussions with the OEMs about possible use of the sensor technology beyond the project. These include:

- University of Cambridge high temperature, low-drift thermocouples
- Dynamic pressure sensor with self-test
- Novel long-wavelength pyrometer
- Non-intrusive scanning pyrometer
- Modular wireless data-acquisition systems

These technologies are looking to be exploited in a number of ways, including:

- Integration in to future validation trials for component and product design verification
- Integration in to future and monitoring and control needs
- To augment, supplement, or replace existing sensor product lines

The Partners will continue to look for opportunities with the OEMs within STARGATE about potential future projects and collaborations to mature their technologies to TRL6.

As mentioned, high-level results are to be discussed at the upcoming EVI-GTI conference on September 2016 in Berlin. This discussion will be used to review and update the Lab-Gap Matrix, which is a key tool in understanding where the industry is currently in terms of sensor and associated technologies. This could yield proposals and partnerships for future projects to develop the technologies further.

List of Websites:
Not currently available

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