The European Virtual Institute for Gas Turbine Instrumentation (EVI-GTI)

www.cranfield.ac.uk/evi-gti

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ABSTRACT

It is arguable that the process of transferring advance sensor technology from the laboratory to application on a gas-turbine engine is not smooth or low-cost. What cannot be argued is that applied advanced sensor technology is required if future designs of gas-turbines are to meet the performance, durability and low cost of ownership targets set as part of the initial purchase negotiations. This paper seeks to address the difficulties and challenges of this knowledge transfer process, highlight the structural responses in both the US and the EU designed to assist this transfer, and to pose the question 'who should pay for sensor technology and when?' The paper is in three sections. It first introduces the European Virtual Institute for Gas Turbine Instrumentation then highlights some of the factors making sensor technology knowledge transfer difficult. Finally the response to this problem in the form of so-called 'teaming arrangements' in the US and the EU is discussed (the US propulsion instrumentation working group PIWG and the EU virtual institute for gas turbine instrumentation EVI-GTI) highlighting the current similarities between the technology drivers for gas-turbines for power generation and those for aero-engine propulsion.

1. INTRODUCTION

The concept of the 'Virtual Institute' arose through the European Union's Competitive and Sustainable Growth (GROWTH) programme as a response to a perceived complexity created by the various socio-economic systems in placed across the EU, member states, associated states and accession countries, together with the difficulty of bringing together companies and research organisations with similar interests across national, cultural and language barriers. The result is a series of projects spread around the European Union addressing different areas of activity and market sectors, one of which is the European Virtual Institute for Gas Turbine Instrumentation, EVI-GTI, which is supported through this programme for the 3-year developmental phase of its activities.

EVI-GTI is being launched as a pan-European membership organisation to provide a focal point and cohesion for the gas turbine instrumentation sector. It will operate within the challenging business environment of sensor development and exploitation and will assist gas turbine engine manufacturers and instrumentation companies to focus on their core competencies, reducing costs and time-to-market of sensors and engines.

A definition of a 'virtual institute' can be found on the Cordis GROWTH web pages, the funding body for the project EVI-GTI, and is:

"A network that links geographically dispersed complementary research and industrial capabilities with the potential to become a legal and self-supporting entity. The difference between Virtual Institutes and networks of other types is that a Virtual Institute needs to demonstrate the capability to become self-supporting"

VI's, therefore, are intended to form pan-European organisations to link geographically dispersed industrial sectors. One of several aims of primary importance to the networks formed by VI's is the rapid transfer and implementation of research results into industrial applications in any field of activity covered by their work programmes. The resultant networks and groups have the advantage of being able to make contacts within their industrial sectors and share knowledge and information of common interest.

2. EVI-GTI

EVI-GTI will launch as a private limited by guarantee not-for-profit organisation in the autumn of 2004. EVI-GTI will derive its working capital from the collection of membership subscriptions from member organisation. These subscriptions will be based on a tiered system dependent upon size of organisation and usage of the services provided by EVI-GTI. Any surplus funds will be used for the benefit of member organisations, through, for example, the provision of workshops and seminars. Its service offering is based on an internet-based interface through which member organisations can collaborate in the following areas:

- A strategy forum to facilitate the alignment of strategic aims
- Facilitation of collaborative R&D
- Networking to promote the exchange of sector-specific information and knowledge
- Access to extensive database facilities containing sector-specific information including:
    - Companies
    - Products
    - Competencies
    - Skills
    - Training opportunities
- Encouraging the mobility of skilled people within the sector.

In addition EVI-GTI will promote member organisations with a view to maximising funding allocations through national and EU programmes. EVI-GTI will also provide face-to-face networking and opportunities for promotion of member organisations through workshops and seminars. EVI-GTI's competitive advantages can be summarised as its focus, complete offering and professional management structure together with its "independent" status which will aid its approach to the varied stakeholders in its environment including those who hold potential funds for development of the next generation of products essential for the health of the industry as a whole.

EVI-GTI will be the European gas turbine instrumentation community's first choice for membership as Europe's leading sector-specific Virtual Institute, providing a 'one-stop-shop' for all sector needs and solutions, promoting alignment of strategic aims, collaboration, co-operation, information exchange, training and development across the spectrum of activities, and representing members' needs at every level within Europe.

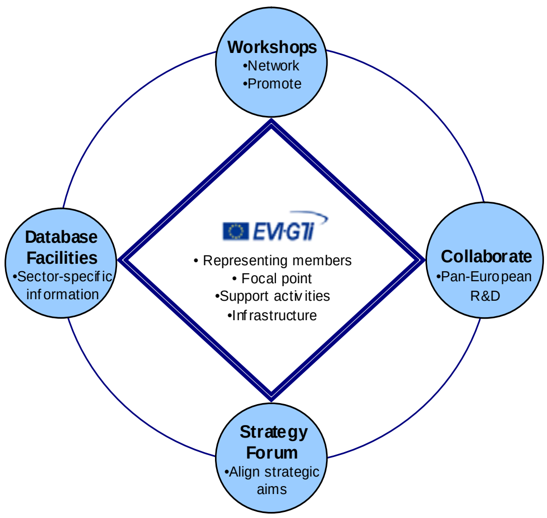

Figure 1: The EVI-GTI service offering

3. INDUSTRY ANALYSIS.

One of the most significant tools available to engineers wishing to design health management systems for engines, whatever the application, is data trending.

Simply put health management deals with data, and patterns of faults within this data give the most simple and immediate analysis of where corrective action is required. Several 'analysis suites' and commercial products have been generated for this work over many years. However the greatest worth is the basic simplicity of such a common sense approach to the health management of an engine or engine system.

This approach is equally valid to considering data trending to a fleet of engines. The point is that given the huge cost of asset management for a fleet of aircraft engines or power generation turbines, then if a common failure is present then it is simply bad business not to address common modes of failure in a systematic and rigorous manner. Extending this a little further it is clear that the bigger the size of an engine fleet under a single management structure the larger the potential for business advantage from this approach. Whilst many commercial airlines have substantial numbers of engines under their management, and whilst the major power generation utilities operate significant numbers of gas turbines, it is the US Air Force which operates the largest number of gas turbines anywhere in the world under a single ownership structure. If the 'business' application for the US Air Force can be described in terms of readiness for combat, then the model described above for data trending fits.

The US Air Force (USAF) owns some 25,000 engines with an asset value of some £32 billion (including spares and consumables). With new acquisitions such as the F22 this asset base is set to double in value to some $70 billion by 2015 (Friend [1]). Given this USAF engine asset base any analysis of fault data trending is most instructive. Sieg [2] demonstrated the implications of High Cycle Fatigue for the readiness of the war fighter (data trending for common failure mode and business advantage). Using 'Mission Capable Rates' (MCR) as a top level management tool, the reduction in operational fighter readiness over the past ten years from a historical high of some 88% to a year 2000 figure of 74% saw the significant gains made in MCR since the early 1980s significantly eroded. Further analysis showed that of some 128 class A fighter mishaps over this period, almost 54% were HCF related. For example four out of the top six safety issues on the F100-220/E and F110-100 engines are HCF caused.

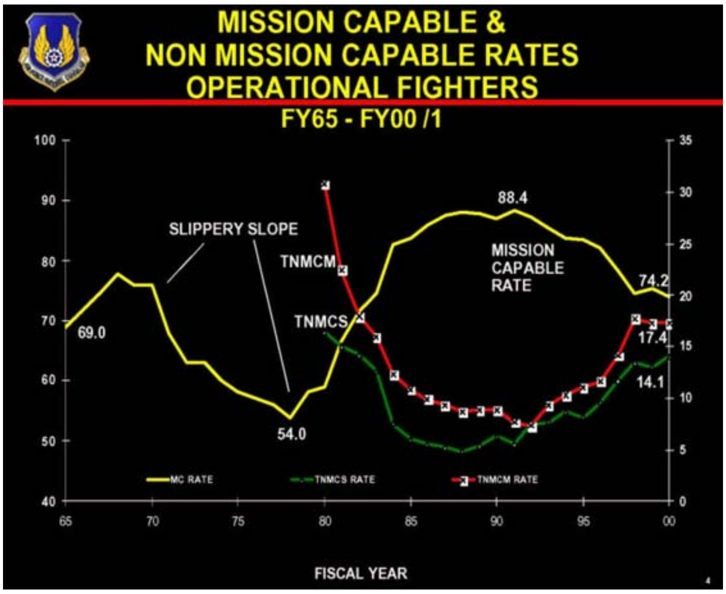

Figure 2. SIEG, S 2000 'HIGH CYCLE FATIGUE AND THE WAR FIGHTER.' 5TH NATIONAL HCF CONFERENCE, CHANDLER, ARIZONA.

Clearly this in itself has a dramatic implication for operating this large fleet of engines into the future. However, the consequences of having to manage this common failure mode at the time of failure are not trivial. These failures have immediate impact on the missions that can be flown. Restrictions on operations and combat capability (analogous to a commercial business advantage), life reductions leading to forced removals of hardware and possible parts shortages and the additional monitoring and maintenance workload all serve to drive up the cost of ownership. In response to this analysis the approach was to mitigate the risk and to transition new technology between engine programmes. Risk mitigation was to be accomplished through an acceleration of six safety fixes for the engines in question, and a transition R&D programme was put in place to source solutions to the operational HCF problems to then drive component improvement programmes. The key message from the technology transition R&D initiative was "don't pursue Science for Science's sake."

4. KNOWLEDGE TRANSFER

Evidence suggest that the message to be taken from any transition R&D programme put in place to source solutions to operational problems in gas turbines is to consider instrumentation alongside other more usual component improvement programmes, to start instrumentation and sensor technology acquisition ahead of need if possible, and to team with others sharing IPR if necessary. There is a considerable amount of sensor development conducted within Universities and Research Institutes both in the US and across the EU. The vast majority of this valuable work is not known to engine manufacturers, and even less influences engine development programmes. Yet clearly there is a strong case that given the operational demands made as a requirement of future engine sales, condition monitoring, prognostic health management and the business penalties of not producing power either for electricity generation of supporting flight, advanced targeted and robust (long life) instrumentation is a fundamental requirement. It is worth exploring why so little instrumentation development 'jumps the divide' between the laboratory and gas-turbine application. For the engine manufacturer the issue is one of 'no-one makes instruments for the hostile environment in which we operate.' For the dedicated instrumentation company the issue is 'no-one will fund the development costs and guarantee sufficient production to satisfy commercial requirements, and for the University researcher the issue is 'no-one understands how difficult it is to make this measurement.' Between these three perhaps stereotypes it is possible to see the true nature of the problem. It is not one so much of technology, but it is one of teaming – the art of working in collaboration across different sectors of the same supply chain.

It is convenient to start the comparison of the respective technology drivers by an examination of the US based analysis, which is more developed than that for the EU. A considered review of these two US sectors is provided by Germon [3] as part of the EVI-GTI workpackage 1 contribution to the Limerick workshop titled EVI-GTI Strategic Direction / Development Plan / IPR issues. In this the US Vision 21 is identified as a significant technology driver for the power generation sector, particularly relevant for this paper is the Instrumentation, Sensors and Control Systems program (ICSC).The Vision 21 technology roadmap identifies improvement to component performance as key, expressed as both efficiency and environmental benefits, as well as time sectors for identified developmental approaches. As yet the EU does not have such strategic clarity. The US program derives significant benefit from the role of NETL, via sponsored workshops and interaction with a large number of US Universities. Similarly for aero-engine propulsion the structural significance of the well established US Propulsion Instrumentation Working Group (PIWG) is important and reacts well to the challenge of the AFRL VAATE Program, the HCF Science and Technology Program and through linkages with the Arnold Engineering Development Centre (AEDC). As for the power generation sector, in comparison with the US, the EU lacks this strategic 'coupling' with any coherence.

In part the European Virtual Institute for Gas Turbine Instrumentation (see www.cranfield.ac.uk/evi-gti was established to begin to secure coherence in these two sectors for advanced instrumentation and sensor technology. The Institute draws direction from both the aero-engine propulsion and power generation sectors, as well as the important supply chain commercial instrumentation manufacturing companies. However, until focussed targeted instrumentation development projects are established with participation appropriate to the aspiration of an EU response to the US, the structural inadequacies of the EU will remain.

Power Generation	Engine Propulsion
HEET	VAATE)
Performance	Performance
Combustion Emissions Controls	Nozzle technology, higher efficiencies and pressure ratio. Active control
Hot Section Lifing, Materials Maintenance	advanced materials Reduce develop. Prod.& Maint. cost
Data Validation.	Reduce time into production
Diagnostics and Instrumentation	Health / life monitoring

Table 1. US Technology Drivers for Power Generation & Engine Propulsion.

5. US RESPONSE

Again it is convenient to discuss the respective teaming arrangements using the context of the transition R&D programme put in place to source solutions to the operational HCF problems. It has already been concluded that for instrumentation the essential problem is not one so much of technology, but rather it is one of lack of effective teaming – the art of working in collaboration across different sectors of the same supply chain. The US High Cycle Fatigue Science and Technology programme was established in support of the IHPTET programme with the objective of a 50% reduction in HCF related maintenance costs. The approach is to run 8 targeted action teams which deliver using a very large R&D budget of some $134 million. The component parts of the HCF S&T programme can be summarised in the following way.

- *Passive Damping.*
- *Materials Damage Tolerance.*
- *Component Surface Treatments.*
- *Component Analysis.*
- *Demonstrator Engines.*
- *Aeromechanical Characterisation.*
- *Forced Response.*
- *And most significantly for the purposes of this paper - **Instrumentation.***

Each group has an action team, which includes Government Agencies, Industry, and Universities as their members. Each action team is responsible for both the management of individual work done within their technical area, and co-coordinating the HCF S&T program with all working groups.

Gas Turbine Sensor Development Interest and Ranking

(list and ranking developed during May 9 & 10, 2002 PIWG Meeting in San Diego, Ca.)

	Thermal Barrier Coating "Health"	Wireless Rotational & Stationary	Combustor Dynamic Pressure mapping	Dynamic Rotating Strain	Surface Temperature Map (2100 F)	Surface Temperature Map (2500 F)	Blade Tip Deflection	Hi-Temperature (1400 F) Dynamic Pressure	Tip Clearance	Planar Gas Path Temperature (1800 F)	Planar Gas Path Temperature (3200 F)	Emissions including Combustor
VAATE	5	3	1	3	5	5	5	3	3	3	5	3
AFRL	Y	Y	~	Y	Y	Y	Y	Y	Y	Y	Y	Y
DOE	5	1	3	3	5	5	3	3	3	5	5	5
NETL	Y	~	Y	~	Y	Y	Y(?)	Y	Y	Y	Y	Y
NASA	3	5	3	3	5	5	3	5	5	3	5	5
GRC	Y	Y	Y	~	Y	Y	Y	Y	Y	Y	Y	Y
PIWG	2	5	1	3	5	5	3	5	3	3	5	3
(aero)	Y	Y	~	~	Y	Y	Y	Y	Y	Y	Y	Y
PIWG	5	1	5	1	5	5	3	3	3	5	3	5
(ground power)	Y	Y	Y	N	Y (1)	Y(2)	Y	Y	Y	Y(3)	Y(4)	Y
Total Score	20	15	13	13	25	25	17	19	17	19	23	21
Ranking	4	7	8	8	1	1	6	5	6	5	2	3
Top 5	^				^	^					^	^

Ranking Description: Y or ~ or N — interest in sensor development captured as Yes, Minimal or No; 1 or 3 or 5 — ranking of importance assigned 1 for low, 3 for medium, 5 for high

Notes: (1) on metal surfaces
(2) on non metal surfaces
(3) planar measurement
(4) open measurement

Figure 3 US Instrumentation Priorities
www.oai.org/PIWG

The Propulsion Instrumentation Working Group (PIWG) was formed some seven years ago to co-operatively address critical propulsion engine development test instrumentation and sensor issues, see www.oai.org/PIWG. Members are the US Air Force Arnold Engineering and Development Centre, the Air Force Wright Laboratory, Allied Signals Engines, Allison Engine Company, General Electric Aircraft Engines, NASA Lewis Research Centre and Pratt and Whitney, with the Ohio Aerospace Institute as an administrator. There is scope for significant advances in instrumentation and sensor technology to address the need of IHPTET, VAATE and the HCF S&T.

6. EU RESPONSE

In response to these US developments, the EU have funded the development of EVI-GTI, see www.evi-gti.com EU contract G4RT-CT-2002-05087. Membership is inclusive, see (**e-mail:** membership@evi-gti.com).

Temp. rakes high temp (>750C) steady	1
Temp. LE instr high temp (>750C) steady	1
Dynamic gas pressure (wall tapping)	2
Pressure rakes high temp (>750C) dynamic	2
Pressure rakes high temp (>750C) steady	3
PSP	3
Pressure LE high temp (>750C) steady	3
Traversable inst. high temp (<750C)	10
Acoustic emission fault prediction	4
Accelerometers	5
Tip Timing (flutter)	6
Tip Timing (synchronous modes)	6
Steady strain gauges high temp. (>700C)	8
Wire and ceramic gauges (dynamic)	8
Wire and cement gauges (dynamic)	8
Thin Film straingauges (dynamic)	8
Steady strain gauges med. temp. (300C-700C)	8
Tip clearance	11
Surface heat flux	7
Thermocouples:- Thin film	9
Thermocouples:- Thin film under TBC	9
Thermocouples surface temperature	9
Pyrometry	12
Conductivity measurements of coatings	13

Table 2 EU Instrumentation Priorities

The need for gas turbine engine manufacturers to focus on core competencies and reduced costs together with increased operational flexibility and speed, and the consequential use of already limited resources in these areas, means that the development of advanced sensors and sensor technologies is likely to shift increasingly towards specialists, like universities and research organisations, and instrumentation supply chain companies who already possess valuable experience in innovative research and commercial exploitation respectively.

Three ‘themed’ areas for advance study have presented themselves from the priority ranking of EU instrumentation; these are called HAPLO, MEFINE and TELHMON details of which are given in figures 4 a-c.

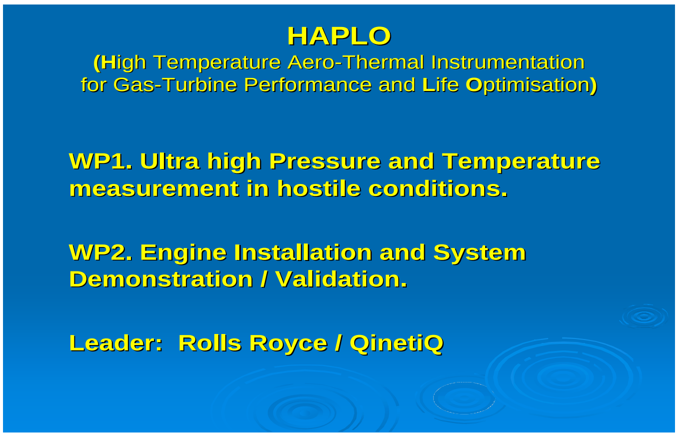

Figure 4a HAPLO

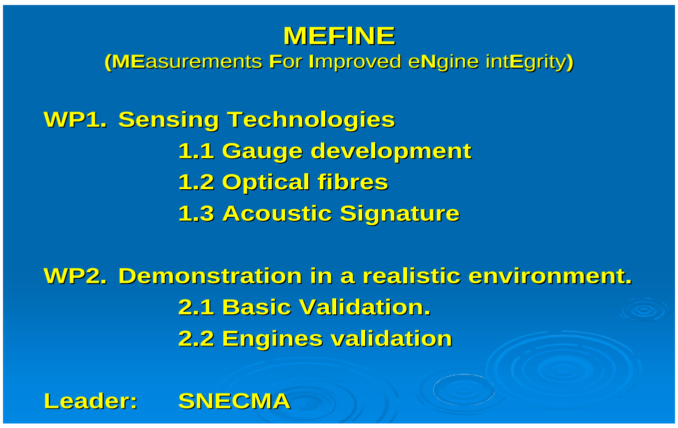

Figure 4b MEFINE

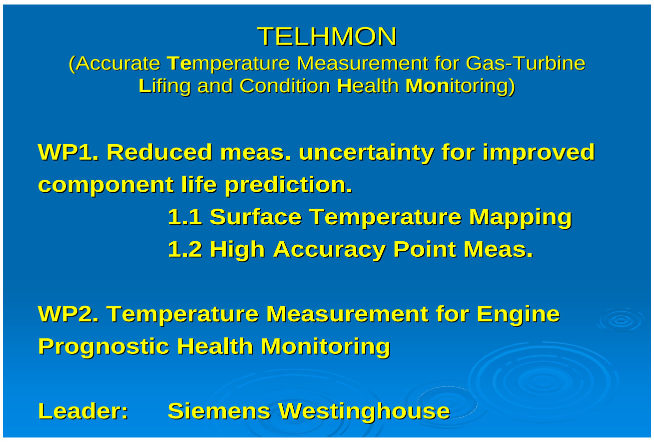

Figure 4c TELHMON

Theme	Important Areas
HAPLO	High Gas Temp. rakes
	High Gas Temp. rakes for pressure.
	High temperature dynamic pressure.
	Pressure sensitive paints
	Temperature sensitive paints
MEFINE	High temp. strain gauges, dynamic & steady
	High temperature accelerometers
	Tip timing
	Tip clearance
	Thin film sensors
TELHMON	Thermal coating conductivity and integrity
	High temp. surface thermocouples + thin film
	Pyrometry and other non contact methods

Table 3 Instrumentation Themed Research Areas.

7. CONFERENCES and TRAINING

Important to raising the profile of Gas Turbine Instrumentation are Conferences and CPD and other training. To this end EVI-GTI has already supported the 1st International Gas Turbine Instrumentation Conference at the Hotel Tryp Apolo, Barcelona, 28th / 29th September 2004. Some 60 delegates attended 4 Sessions with 24 Speakers in a joint EU / US forum to initiate debate about the future ambition for instrumentation in engine demonstrators. Attendees were Instrumentation developers and users from Universities, Research Organisations, Manufacturers, End Users and Supply Chain Companies.

This conference is to run again during 2005, see figure 5 below.

The 2nd EVI-GTI International Conference on Gas Turbine Instrumentation
September 2005
Dubrovnik, Croatia
Visit www.evi-gti.com for more information.

Figure 5 Future EVI-GTI Conference.

Specialist training is already on offer, principally through VKI via EVI-GTI stimulated 'Advance Measurement Techniques for Aero Engines and Stationary Gas Turbines' March 1 – 5, 2004 and a more recent VKI Introduction to Measurement Techniques October 4 – 8, 2004,see http://www.vki.ac.be/educat/lect-ser/index.html .

8. FRAMEWORK PROGRAMME 7

The Technology Readiness Levels for the proposals described in this paper, specifically HAPLO, MEFINE and TELHMON are described as high technology readiness level projects (>5). This terminology defines near term introduction into engine technology. For future programmes such as those proposed for the EU framework 7 lower levels (0-5) are suggested allowing for more exploratory research. This approach will permit greater ‘risk sharing’ from the EU Instrumentation supply chain (the US provides a very useful working example of this approach) and allows potential access to EU demonstrator engine programmes supported by key Industrial partners in EVI-GTI. The more exploratory studies will permit examination of MEMS / Nano-technology / Sensors initiating engine architecture / DARPA equivalents for example.

9. SUMMARY

The achievements to date have been to set the EU research, commercial and industrial requirements for gas turbine instrumentation and to compare these with the results of the earlier US analysis. There is a strong correlation between the market requirements which should come as no surprise. Significant work has been conducted to priority score these requirements and this in turn is driving three STREPS, these are the so-called HAPLO, MEFINE and TELHMON proposals.

The 1st OEM / Supply Chain / Researchers International Conference on Gas Turbine Instrumentation has been established with a strong representation from the US PIWG. This forum will run again for 2005 and then bi-ennial after that. Significant training schemes have been established and post June 2005 EVI-GTI when the current EU contract terminates it is intended that this work should continue as for example “The European Gas Turbine Instrumentation Society”.

There are distinct similarities between the technology drivers for power generation gas turbines and those for aero-engine propulsion. This is matched by the responses of the respective US and EU instrumentation communities in their declared priority lists for instrumentation and sensor development to meet the demands of the technology drivers. One other argument from this paper is that given the similarity in demand, and the similarity in response, then not only is it prudent to collaborate pan US and pan EU, but instrumentation and sensor technology presents the best (and lowest risk) option for US / EU collaboration. The message is that the EU and the US share similar industrial and commercial challenges; collaboration benefits all, with little risks.

ACKNOWLEDGMENTS

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