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Advanced Turbine Systems Sensors and Controls Needs Assessment Study Final Report

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Instrumentation and Controls Division

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Larry Golan, Dan Fant, and Glenda Black of the South Carolina Energy Research and Development Center were instrumental in organizing and hosting the Advanced Turbine Systems Sensors and Controls Workshop.

Finally, we appreciate the valuable contributions and insights provided by all the participants at the workshop.

ABSTRACT

The Instrumentation and Controls Division of the Oak Ridge National Laboratory performed an assessment of the sensors and controls needs for land-based advanced gas turbines being designed as a part of the Department of Energy's (DOE's) Advanced Turbine Systems (ATS) Program for both utility and industrial applications. The assessment included visits to five turbine manufacturers. During these visits, in-depth discussions were held with design and manufacturing staff to obtain their views regarding the need for new sensors and controls for their advanced turbine designs.

The Unsteady Combustion Facilities at the Morgantown Energy Technology Center was visited to assess the need for new sensors for gas turbine combustion research. Finally, a workshop was conducted at the South Carolina Energy Research and Development Center which provided a forum for industry, laboratory, and university engineers to discuss and prioritize sensor and control needs.

The assessment identified more than 50 different measurement, control, and monitoring needs for advanced turbines that cannot currently be met from commercial sources. While all the identified needs are important, some are absolutely critical to the success of the ATS Program. After extensive discussions with turbine manufacturers and analysis of the workshop results, it was concluded that the highest priority needs are

1. Thermal barrier coating failure/health monitoring (on-line spallation detection during operation).
2. Accurate combustion gas temperature measurements and flame detection up to 1650°C (~3000°F) to enable the closed-loop control of pollutant emissions.
3. Fast pressure and differential pressure sensors to prevent the onset of stall and compressor instabilities (stall avoidance and control).
4. Fast and durable sensors and actuators along with advanced modeling (nonlinear dynamics) to control combustion instabilities caused by lean fuel mixtures.
5. Blade tip clearance measurement to enable active control to enhance gas turbine performance.

It is recommended that DOE implement a program to stimulate the development of the required new sensor and control technologies so that advanced turbines can achieve the goals established by the ATS Program.

Participants at the workshop expressed a desire for similar workshops in the future where they can exchange new ideas and discuss measurement and control issues associated with advanced gas turbines. Therefore, it is recommended that DOE seriously consider sponsoring an annual sensors, controls, and monitoring workshop. A suggestion was also made to form a Sensors and Instrumentation Working Group to encourage collaboration and to expedite sensor development and increase the relevance of R&D in sensors and controls.

1. INTRODUCTION

The Instrumentation and Controls Division of the Oak Ridge National Laboratory (ORNL) has performed an assessment of the sensors and controls needs for land-based advanced gas turbines being designed for both utility and industrial electric power generation. This assessment was cofunded by the U.S. Department of Energy (DOE) Advanced Turbine Systems (ATS) Program and ORNL. The goals of the ATS Programs are[1]

- Higher efficiency (utility systems 60%/industrial systems 15% improvement over today's best gas turbine systems).
- Environmental superiority in terms of reduced nitrogen oxides, carbon dioxide, carbon monoxide, and unburned hydrocarbons.
- Cost competitiveness (10% lower cost of electricity).

These goals are being met with significant design improvements over present-day systems. For example, cycle modifications to achieve the efficiency goals include intercooling, chemical recuperation, moisture injection in the turbine air flow, and reheat combustors. Fuel-to-air ratio in the combustors will be reduced to meet the emissions goals of the program. Also, firing temperatures will be increased by more than 121°C (250°F) to over 1427°C (2600°F), which will require approaches to reduce the temperature of turbine hot gas path hardware. One solution being developed is to coat the metal surfaces with a heat resistant material referred to as a thermal barrier coating (TBC); another is to provide improved air or steam cooling of the blades. Industrial turbines may also use advanced ceramics for hot gas parts.

One way to reduce the cost of turbine-produced electricity is by supplying highly reliable systems. Present-day turbines have over 95% availability, and new systems are expected to match or exceed this performance. The overall ATS Program goal is to demonstrate the technical performance of turbines such that the commercial market will select the new systems as the preferred technology.

[1] *Comprehensive Program Plan for Advanced Turbine Systems*, Report to Congress, February 1994.

2. OBJECTIVES OF STUDY

The primary objective of the assessment study was to determine the needs, if any, and requirements for improved sensors, actuators, and controls capabilities to meet the requirements of, and to ensure the success of, the ATS Program.

3. ASSESSMENT STUDY METHODOLOGY

The sensors and controls needs assessment was performed by visiting five turbine manufacturers: Pratt & Whitney; Westinghouse Corporation; Solar Turbines, Inc.; General Electric Company; and Allison Engine Company. During these visits, in-depth discussions were held with design and manufacturing staff to obtain their input regarding the need for new sensors, actuators, and controls for their advanced turbine designs.

In addition, we visited the Unsteady Combustion Facilities at the Morgantown Energy Technology Center (METC) to assess the need for new sensors for gas turbine combustion research. The METC facilities are used to study nonlinear flame physics and methods to control flame oscillations.

A one-day workshop was conducted at the South Carolina Energy Research and Development Center (SCERDC) in which industry, laboratory, and university engineers discussed and prioritized sensor and control needs. This workshop was exceedingly valuable in providing a forum for sensors, actuators, and controls users and specialists to share their needs, concerns, and proposed technical solutions.

4. ROLE OF SENSORS AND CONTROLS IN TURBINE SYSTEM PERFORMANCE

Reliable and accurate sensors and controls will be a key factor in assuring that the ATS Program meets the above goals with the new high-performance systems.

Accurate and reliable measurements and controls are key factors in assuring good performance of complex systems. One study[2] found that control and accessory systems are the major causes of unreliability in gas turbine systems (one-third of forced outage time and two-thirds of forced outages). New turbine designs will be much more complex in order to meet the efficiency, emissions, and lower cost electricity goals. This added design sophistication will require improved measurements and controls as well as new sensors to monitor and control new features of the systems. Therefore, it is likely that R&D will be needed to develop accurate, robust, and reliable sensors and controls required to both verify the new designs of critical components during testing and to assure that the new systems meet operational performance goals.

4.1 NEEDS IDENTIFIED BY VISITS TO MANUFACTURERS

As mentioned previously, we visited five turbine manufacturers to obtain their input regarding ATS sensor and control issues and the need for new sensors and controls not commercially available at present. We found that the needs could be classified into three areas: (1) sensors needed during the design and testing phase of new turbine development; (2) sensors and controls required for quality control during the manufacturing process; and (3) sensors and controls for monitoring, diagnostics, and control during operation. The results are summarized in Tables 1 to 3.

Table 1. Needs identified for turbine design and testing phases

Item No.	Parameter
1	Temperature measurements within the combustor or turbine
2	Torque measurement
3	Thermal effectiveness of TBC
4	Thermal efficiency measurements
5	Rapid response (20–30-ms) sensors
6	BTU value of incoming fuel
7	Fuel flow measurement
8	Improved accuracy of test information

Table 2. Needs identified to improve turbine component manufacturing efficiency and quality control

Item No.	Parameter
1	TBC application (in process, postprocess, and coating properties)
2	Internal temperature of blade casting molds

[2] *Comprehensive Program Plan for Advanced Turbine Systems*, Report to Congress, February 1994, p. 20.

Table 3. Needs identified for monitoring and control during turbine operation

Item No.	Parameter
1	TBC spallation detection
2	Temperature measurements within the engine
3	Signal transmission out of the engine (wireless sensors)
4	Compressor stall avoidance
5	Fast and accurate pressure and differential pressure sensors
6	Flame quality measurement
7	Blade temperature measurement
8	Vibration measurement
9	Combustion gas temperature measurement
10	Blade tip clearance measurement
11	On-line oil analysis and determination of the rate of change of particulates in oil
12	Low-cost NO_X reduction
13	Faster and more reliable actuators
14	Standardized signal levels
15	Longer thermocouple life
16	Efficient trend monitoring
17	Measurement of internal coolant temperature
18	Detection of hot gas path leakage
19	Detection of coolant leakage
20	Measurement of stress in turbine components
21	Detection of corrosion/oxidation
22	Drum level control

4.2 SENSOR NEEDS FOR COMBUSTION RESEARCH

The research staff at METC needs a high-temperature [2093°C (3800°F)] fast-response (3-ms) pressure sensor to study combustion instability caused by lean fuel mixtures. This area is also of interest because nozzle design and combustion chamber impedance interact to create oscillations in the combustion flame. The facility we toured was oscillating at ~300 Hz. The facilities at METC may also provide the means to evaluate new sensors and combustion controls developed by the R&D community.

4.3 ADDITIONAL NEEDS IDENTIFIED AT WORKSHOP

The needs discussed above were presented to industry and research organizations at the one-day workshop at the SCERDC. Additional needs were identified by workshop participants. These are listed in Table 4.

Table 4. Additional needs identified during Sensors and Controls Workshop

Item No.	Parameter
1	Optical sensors and communications for reduced electromagnetic interference (EMI) sensitivity
2	Enhanced fault detection/accommodation
3	Direct measurement of combustor flame temperature for closed loop control
4	Fast-response fuel flow sensor to compensate for combustion instabilities
5	Rugged sensors for in situ measurement of combustion precursors and products
6	Improved techniques for measuring burner pattern factor and temperature profile
7	Measurement of rotor and stator metal temperature
8	Transient and steady-state cooling flow and temperature
9	Coolant leakage detection and measurement
10	Component stress measurement
11	Combustor liner temperature measurement
12	Combustor pressure and delta pressure
13	Combustor vibration
14	Corrosion/oxidation detection in steam turbine
15	Heat recovery steam generator swell prediction/control
16	High H_2 fuel gas monitoring

4.4 OTHER ACTIVITIES IN GAS TURBINE SENSORS AND CONTROLS

There was a presentation at the Clemson workshop on the activities of the Propulsion Instrumentation Working Group (PIWG). The PIWG was formed in 1995 to promote the development and use of research or test sensors and instrumentation for aircraft turbine engines. Current members are Arnold Engineering Development Center, Allied Signal, Allison, General Electric, NASA Lewis Research Center, Pratt & Whitney, and Wright Labs. The PIWG goals are to encourage collaboration on instrumentation development, focus limited resources on critical problems, utilize experience to expedite sensor development, and increase the relevance of federal R&D programs. The PIWG is using a methodology similar to our approach for land-based turbines. All PIWG members are providing their sensor and control requirements. PIWG will then assess the availability of existing methods to meet the needs before suggesting new sensor R&D. The members have agreed to share existing technology as appropriate and to promote the development of new measurement methods that the group needs. Table 5 lists the needs for aircraft engine instrumentation improvement identified by PIWG.

Table 5. Instrumentation improvement needs identified by the PIWG

Item No.	Parameter
1	Strain measurement
2	Surface temperature measurement
3	Blade displacement
4	Pressure measurement
5	Clearance measurement
6	Gas temperature measurement
7	Slip-rings
8	Emissions measurements
9	Telemetry

To improve strain measurement, development is required on wires, overcoats, sheaths, adhesives/attachment methods, thin-film sensors, and nonintrusive measurement techniques. To improve blade displacement measurement, the PIWG recommends development of new algorithms/software, data acquisition hardware, optical and nonoptical sensors, and stress correlations. Surface temperature measurements might be improved with development of multiband pyrometry, use of temperature sensitive phosphors, film thermocouples, and improved thermocouple wiring.

The PIWG also is recommending development of pressure sensors using high-temperature wiring and possibly even the use of pressure sensitive paints. In the area of telemetry, there is a need for development of high-temperature electronics that can operate up to 204°C (400°F).

The PIWG plans to publish a roadmap of aircraft instrumentation needs in the fall of 1996.

4.5 RECOMMENDATIONS OF THE ATS SENSORS AND CONTROLS WORKSHOP

The ATS Sensors and Controls Workshop was held at the Clemson University Madren Conference Center on April 17, 1996. This workshop, jointly organized by ORNL and SCERDC, brought together 32 participants (see Appendix A for the workshop agenda and a list of participants) to jointly discuss and prioritize sensor and control needs for advance gas turbines. Each participant had the opportunity to make a few informal remarks regarding his or her company's view of the needs for turbine sensors, controls, monitoring, and diagnostics. Following the discussion, three breakout groups were selected: (1) combustion/emissions group; (2) TBC/nondestructive evaluation (NDE) group; and (3) operational performance monitoring group. After approximately 1 h of discussion and debate, each group reported its conclusions regarding sensor and control needs to the workshop to establish consensus on the most important needs. The results of the breakout session are presented in the following sections.

4.5.1 Combustion/Emissions Group

This group concluded that combustion instability is a major problem as a result of the very lean fuel-to-air mixtures that will be required to meet ATS emissions goals. There is a need to avoid flashback and improve measurement of fuel/air mixing. There are also needs for sensors to measure flame intensity, gas temperature, high-temperature dynamic pressure, acoustic energy, and emissions species (CO/NO_X). Table 6 lists the specific sensors and key characteristics identified by this group. These measurements will provide data to interpret combustion dynamics and feedback for control of lean fuel combustion to increase combustion stability, to optimize performance, and to meet ATS goals.

Table 6. Specific sensor needs identified by Combustion/Emissions Group

Sensor	Response time	Accuracy (%)
Flame intensity	5 ms	1–2
Pressure (dynamic)	5 ms	5
Species	20–50 ms	0.25 / 2 ppm
Acoustics	20–50 μs (20–50 kHz)	< 5

4.5.2 Thermal Barrier Coating/Nondestructive Evaluation Group

This group concluded that a fundamental understanding of TBC properties is critical to the ultimate success of ATS. TBC integrity has a primary impact on the first-stage turbine blades and vanes. In situations where the TBC is the prime reliant, it is mandatory that means be provided to prevent severe engine damage that could result from unexpected loss of the TBC. Without such positive verification, the full capability of the TBC cannot be fully exploited. Measurements of electrical/optical properties, mechanical/elastic/thermal properties, and TBC material characteristics as a function of temperature and age are needed immediately. Sensor concepts include (but are not limited to) thermographic phosphors embedded in the TBC; fast, accurate, high-temperature fiber-optic thermocouples embedded in the blades or vanes; line of sight optical or microwave examination or fluorescent effect measurements looking for the spectrum of key oxides. However, an optical path to view the phosphors must be provided for some of these methods to be applied. Other concepts include monitoring chromium and aluminum migration since this provides an overall assessment of TBC/bond-coat degradation. Verification of proper TBC application during manufacturing is also of critical importance for quality assurance consideration.

NDE technology was also discussed by this group. They concluded that there are several NDE techniques that are either off-the-shelf or near commercial availability, including eddy current, thermal wave, dielectric, capacitive, ultrasonic, and X-ray fluorescence.

4.5.3 Operational Performance Monitoring Group

This group prioritized the needs for turbine monitoring and control during operation (see Table 7). They concluded that including stall sensing as a part of the turbine control system is the highest priority operational monitoring need for success of the ATS Program. Compressor stall detection will require new, accurate, and fast-response pressure and differential pressure sensors. Another high-priority need is for new temperature sensors to measure combustion gas temperatures up to 3000°F. Other high-priority needs are blade tip clearance measurement and detection of TBC spallation during operation (one manufacturer stated that TBC spallation detection is critical to ATS success and that a rapid shutdown system will be required to prevent turbine damage if spallation occurs).

Table 7. Ten highest priority operational performance monitoring needs

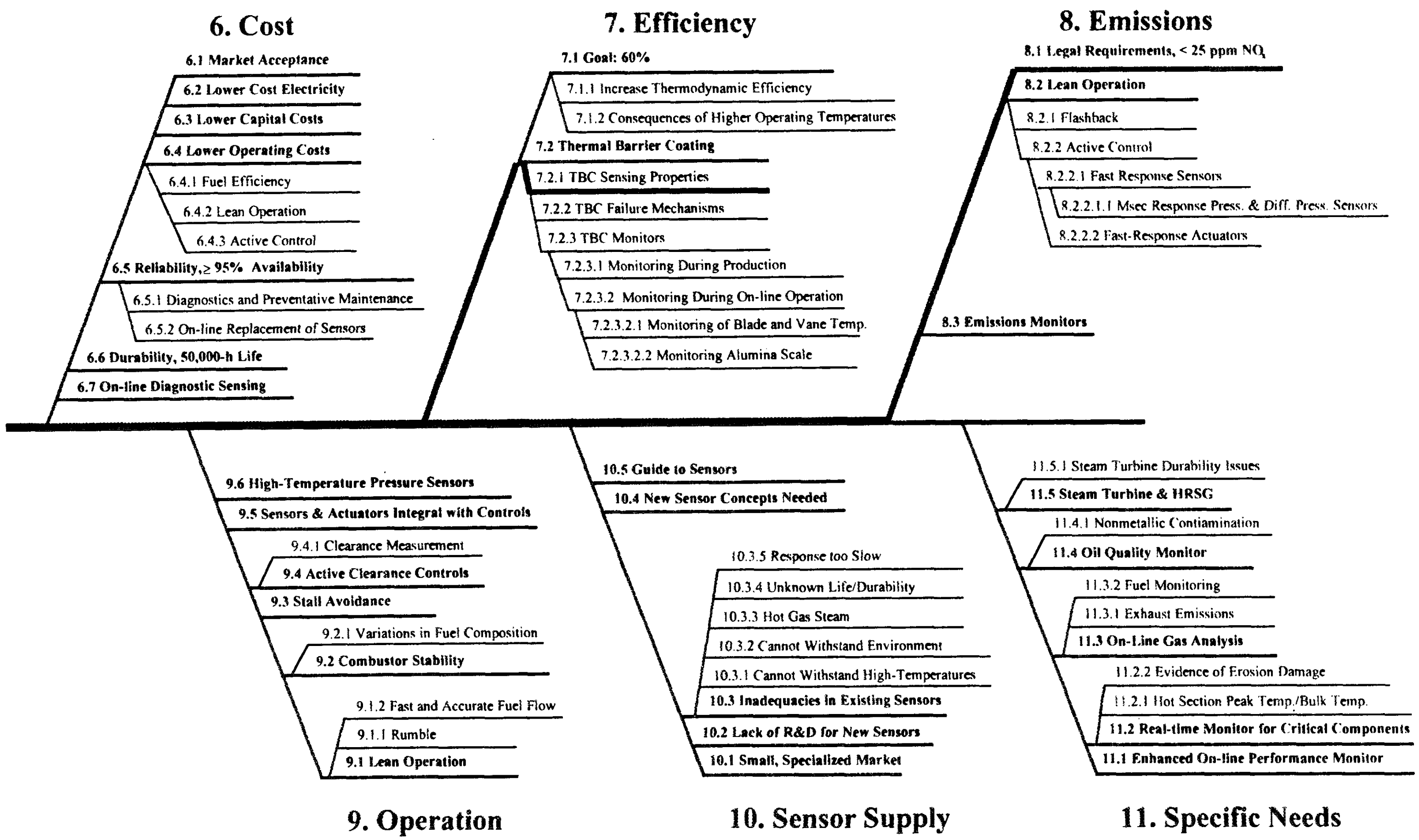
Item No.	Parameter
1	Stall anticipatory sensing and control (need fast and accurate pressure and differential pressure sensors)
2	Gas temperature measurement up to 3000°F
3	Blade tip clearance
4	TBC spallation detection
5	Blade temperature measurement up to 2000°F
6	Efficient trend monitoring
7	Flame quality and stability measurement and control
8	Hot gas path leakage measurement
9	Vibration measurement
10	Data transmission to remote sites

5. BASIS OF THE NEEDS IDENTIFIED BY THE MANUFACTURERS

During both the site visits and the ORNL/Clemson Workshop, the gas turbine manufacturers were very forthcoming about existing and anticipated needs for improved sensors, actuators, and controls. The use of sensors and controls on advanced gas turbine systems is driven by at least five considerations:

- Business considerations include cost—both capital and operating—and efficiency, which is related to the product cost—electricity.
- Operational considerations include the advanced systems needed to operate advanced turbines reliably and safely.
- There are legal considerations as well; the emissions from new turbines must meet federal standards.
- Durability—The ATS Program goals of 50,000 h for component lifetimes extend substantially beyond the experience base of many turbine components and materials as well as sensor and controls equipment.
- Sensor Supply—The combination of relatively small quantities and exceptional needs of the gas turbine market means inadequate market pull for vendors to invest in the development of highly specialized devices for gas turbines.

There are specific needs for new sensors and actuators in several areas. For example, on-line monitors for TBCs or stall detection and prevention are absolutely critical to the success of the ATS Program. A loss of as little as a one-quarter to one-half square-inch area of the TBC from the first stage blades or vanes in a turbine operating at temperatures of ~1427°C (2600°F) may not be immediately catastrophic. However, continued, undetected operation could result in blade degradation if combustion is not shut down within a reasonable time. Figure 1 illustrates some of the interconnections and relationships that depend strongly upon the availability of appropriate sensors, actuators, and control technologies. This diagram forms the basis for the organization of this section. For example, Fig. 1 shows that the major objective of the ATS Program is to develop new land-based gas turbine engines that produce electricity in a more economical way than current gas turbine technology. The major drivers are cost, efficiency, and emissions. Critical paths to program success are TBCs, lower NO_X emissions, and market acceptance of the new gas turbine technology.



The number to the left of each item refers to the corresponding section within this report

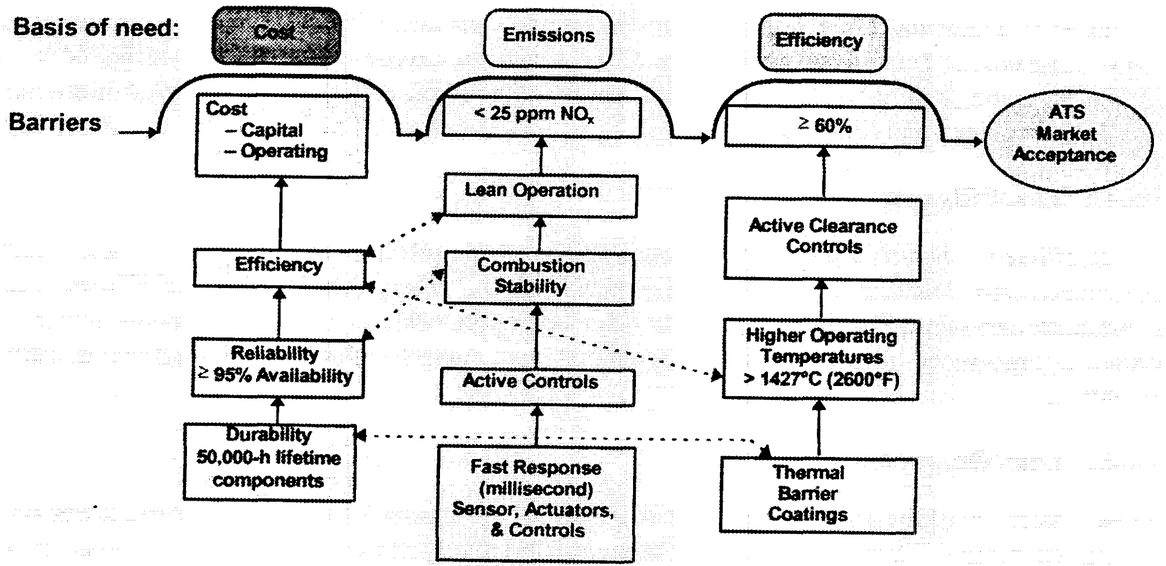
Fig. 1. Overview diagram of the sensors, actuators, and controls needs of the ATS program.

6. COSTS—BUSINESS AND MARKET CONSIDERATIONS

6.1 MARKET ACCEPTANCE

The overall metric of success for the ATS Program is market acceptance. The potential barriers to market acceptance are illustrated in Fig. 2 and fall into four categories:

- Costs—capital and operating.
- Efficiency of operation.
- Reliability and durability.
- Legal requirements in emissions standards.



Dashed lines indicate interrelationship between areas.

Fig. 2. Three potential barriers on the critical path to ATSs.

6.2 LOWER COST ELECTRICITY

Lower capital costs combined with lower operating costs as outlined in Sect. 6.4 are projected to reduce the delivered cost of electricity (over that of a typical fossil-fired steam plant). A goal of the ATS Program is to reduce the cost of electricity by 10%.[3]

Large land-based gas turbine engines have already been installed for base-load power generation. Oil-fired turbine-based generators have been used for peaking power generation for many years. Part of their attractiveness is the relatively low capital cost and shorter construction time for the installation as compared with a fossil-fuel-fired steam plant. A utility can quickly add power

[3] *Comprehensive Program Plan for Advanced Turbine Systems*, Report to Congress, February 1994, p. 1.

generation capacity in 100–300-MW increments to follow the growth of electric power usage in a region.

6.3 LOWER CAPITAL COSTS

As outlined in this document, the advanced gas turbines have several unique requirements for sensors and controls. Because of the relatively small market, custom sensors and controls designed specifically to meet these requirements can only be obtained at a premium price. This can substantially increase the capital cost. Seeking lower cost alternatives, for instance by adapting and using low-cost sensors and controls that operate under similar conditions for a mass market such as the automotive market, could reduce the capital costs of sensors and controls.

6.4 LOWER OPERATING COSTS

Greater initial capital costs for additional sensors and controls must be offset by lower, long-term operating costs. Total costs over the life of the advanced turbine will be strongly affected by its efficiency and reliability. The measures needed to maintain emissions within legal limits also affects efficiency and reliability.

6.4.1 Fuel Efficiency

Fuel efficiency is also a part of the overall efficiency picture from two aspects, (1) minimizing fuel costs and (2) minimizing emissions, especially NO_X. The effort to maximize efficiency and minimize emissions drives the need for lean operation, which, in turn, drives the needs for special high-speed pressure sensors, actuators, and controls to implement active, real-time controls.

6.4.2 Lean Operation

Lean operation of the gas turbine means to use a fuel–air mixture that approaches the lower limit of combustibility. That is, the fuel–air mixture is relatively dilute. Lean operation is discussed in more detail in Sect. 9, Operation.

6.4.3 Active Control

Active control refers to an integrated system such as the lean burn control where the time response of the system allows feedback control to be used to dampen out pressure fluctuations, burner instabilities, etc. Other forms of active control, mentioned elsewhere, refer to sensing the blade tip clearance in the compressor or the turbine and adjusting the clearance by changing the diameter of the housing to follow the growth of the blade length relative to the expansion of the engine shell as the engine goes from a cold start to operating temperatures. Affordable and reliable sensors for blade tip clearance are needed as well as reliable actuators to adjust the clearance.

6.5 RELIABILITY, MAINTAINABILITY, ≥ 95% AVAILABILITY

In general, the current generation of gas turbine engines is highly reliable, with over 95% availability. Any new systems must match or exceed this availability in commercial use. If these advanced turbines are to be accepted by the utilities industry, they must provide the high availability required to avoid the cost of purchase of replacement power if the unit goes down unexpectedly.

6.5.1 Diagnostics and Preventative Maintenance

A variety of sensors is needed for diagnostic purposes. In some cases, signal processing can be used to extract diagnostic information from existing sensor signals. The ability to monitor and anticipate equipment malfunction and take preventative action is key to minimizing downtime. Diagnostics are directly related to durability issues, which include stress and life management or machine health.

6.5.2 On-line Replacement of Sensors

As a cost containment measure, and in lieu of sensors with proven 50,000-h lifetimes, on-line replacement of certain sensors during system operation is an option that needs to be explored. Sensor installations must be designed for easy access and replacement. Some redundancy among sensors would allow sensor replacement during operation; otherwise, they can be replaced during scheduled maintenance.

6.6 DURABILITY (50,000-H COMPONENT LIFE)

Achieving 50,000-h component lifetimes[4] will require comparable sensor lifetimes (or on-line replacement). Sensor durability in the more extreme temperatures is essentially unknown. Lifetimes under these conditions have not been documented. It is not even certain that an appropriate sensor technology has yet been identified for these uses.

6.7 ON-LINE DIAGNOSTIC SENSING

The economics of the gas turbine industry are changing. The turbine manufacturers are increasingly taking over after-sale maintenance as a part of their business. General Electric (GE) has incorporated gas turbine system maintenance into its business.

On-line diagnostic sensing is being used in steam turbine generating plants today. Westinghouse provides on-line remote monitoring and diagnosis from its Orlando facility for installations all over the United States. This may be even more important for ATS generating systems, as some may be remotely located and operated. Diagnostic sensors must meet the same reliability and durability requirements as those for sensors used for control.

[4] I. G. Wright, R. W. Harrison, and M. A. Karnitz, personal communication, Mar. 20, 1996.

7. NEEDS RELATED TO EFFICIENCY

7.1 GOAL: ≥ 60%

One of the benefits expected from the ATS Program is greater efficiency of utility gas turbine generating systems. When combined with a heat exchanger, the hot exhaust gases from the turbine are used to generate steam for a topping cycle that increases the efficiency of the plant to levels greater than 50% compared with 40% or less for an efficient steam plant.

The ATS Program plan calls for improvement of overall gas turbine generating system efficiency to ≥60%. Combined cycle gas turbine systems with a heat recovery steam generator in series can now achieve efficiencies close to 60%.

7.1.1 Increase Thermodynamic Efficiency

To achieve ≥60% overall system efficiency for utility gas turbines, firing temperatures will have to increase to 1427°C (~2600°F) compared with the current 1288°C (2350°F) firing temperatures.[5] This increase in firing temperature will require improvements in turbine airfoil materials, coatings, and cooling effectiveness. In addition, the longer component life goal of ATS (50,000 h) will place additional constraints on airfoil materials and coatings.

7.1.2 Consequences of Higher Operating Temperatures

Both materials and sensors are being pushed beyond the point where engineering data exist for the combination of temperatures and duration of use involved. For instance, as shown in Fig. 3, data taken at ORNL on metal sheathed thermocouples for periods up to 1000 h shows substantial changes due to diffusion of contaminants from the sheath to the thermoelements at temperatures above 1100°C.

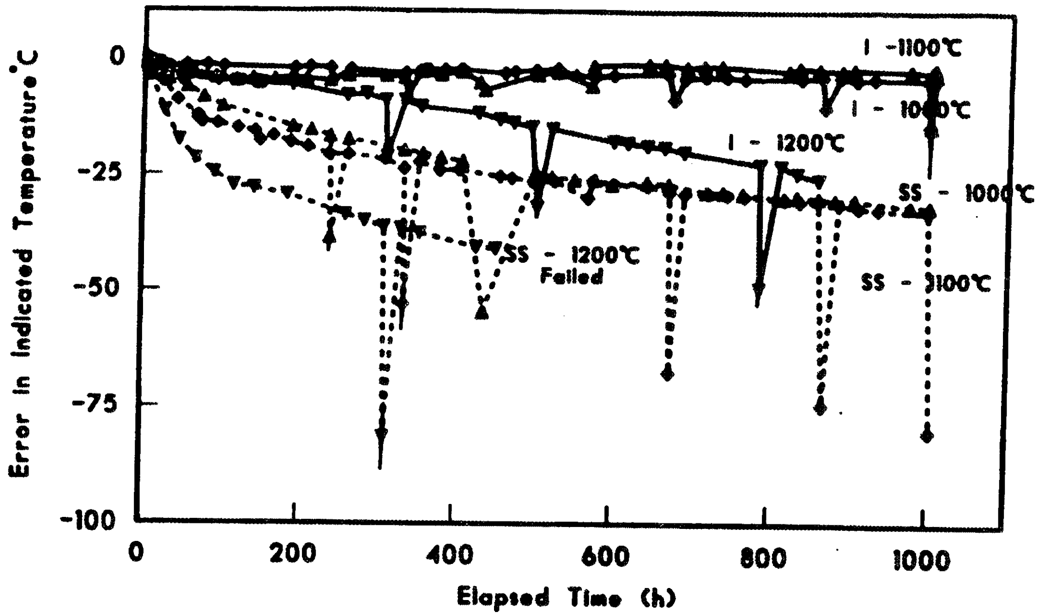
7.2 THERMAL BARRIER COATINGS

In an effort to shield the blades and vanes from the higher operating temperatures, TBCs are applied to the blade and vane surfaces. As shown in Fig. 4, the actual structure of the TBC is a multilayer arrangement. A major effort is in progress to develop self-reliant TBCs to reduce the operating temperatures of ATS turbine airfoils while providing oxidation and corrosion protection to satisfy the longer life requirements. It is anticipated that TBCs can provide a temperature differential that will reduce the airfoil substrate temperatures to acceptable levels. This is expected to result in adequate strength over the life of the turbine. Such TBCs must be reliable since spallation could result in a temperature rise of the airfoil materials that exceeds acceptable limits, thereby leading to premature failure.

7.2.1 TBC Sensing Properties

Because of the importance of the TBCs to the life of the turbine and because of the long runs between maintenance or inspections, on-line monitors for the integrity of the TBCs will be necessary. To more directly monitor the condition of the TBCs, some physical parameter of the coating could be selected, and a measurement technique that can serve as an indicator of coating

[5] *Comprehensive Program Plan for Advanced Turbine Systems,* Report to Congress, February 1994, p. 17.



"I" indicates Inconel-600 sheath. "SS" indicates stainless steel sheath.

Fig. 3. Drift of 0.040-in.-diam sheathed Type K thermocouples at 1000°, 1100°, and 1200°C in vacuum. *Source:* R. L. Anderson, J. D. Lyons, T. G. Kollie, W. H. Christie, and R. Eby, "Decalibration of Sheathed Thermocouples," p. 977 in *Temperature, Its Measurement and Control in Science and Industry*, Vol. 5, American Institute of Physics, 1982.

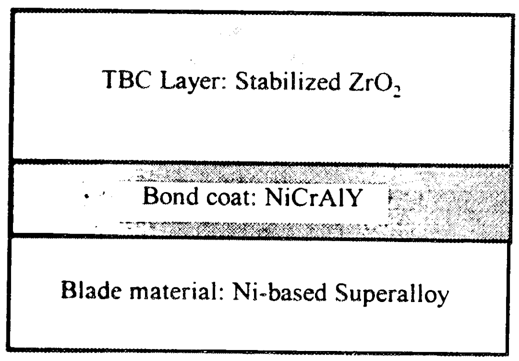


Fig. 4. TBC and bond coat layers as applied to substrate.

integrity or, even better, the degree of degradation could be developed. To develop these measurement techniques, the physical properties of the coatings and how they change as a function of temperature, pressure, and environment and, further, how these properties are changed by contamination, must be determined. It must be possible to relate measured changes in the TBC and their effect on the integrity of the coating. The ability to distinguish the difference between normal and abnormal change is also key to such measurements.

The material characteristics needed for measurement include:

- electric and optical properties,
- acoustic (ultrasonic) properties,
- mechanical–elastic properties, and
- thermal properties.

While some of these properties are known for the bulk materials, these may not be accurate for the TBCs in thin-film form. Most of these properties will be affected by the deposition process so that on-line monitors for the manufacturing process will be needed as well as for inspections.

7.2.2 TBC Failure Mechanisms

Another part of the background information needed to make reliable TBC measurements is a definition and understanding of the failure mechanisms. This information is needed to predict both failure on-line in an operating gas turbine and off-line during the fabrication of new and refurbished blades.

7.2.3 TBC Monitors

Because the integrity of the TBCs on the gas turbine components is essential for the success of the ATS Program, careful consideration is needed of the sensor requirements for this relatively new technology. While it is true that TBCs have been used in high-performance military aircraft engines, they are inspected at more frequent intervals than is planned for advanced gas turbines. Long-term durability of TBCs required by ATS is outside the design experience of this technology. Perhaps the only way to compensate for this lack of design data (since accumulation of 50,000-h durability data would have to have been started several years ago to meet ATS Program schedules) is to use sensors to monitor the TBCs, both in manufacture and in use.

The TBCs must provide large temperature gradients (several 100°C) to reduce blade and vane temperature. Measurement of the thermal conductivity of the coatings during the manufacturing process is needed for quality control, since simply measuring coating thickness may not be sufficient to detect anomalies in the thermal conductivity of the applied coatings.

7.2.3.1 Monitoring during production

Improved in-process measurement is needed during the manufacture of TBC coated components. Monitoring of the quality and uniformity of the coating as it is being applied and possibly using the output of such a monitor for feedback control of the coating process is needed. Again, the measurement related properties of the TBCs need to be understood to realize this monitor.

Several types of coating monitors are available from the NDE community. These are mostly for off-line or end-of-line use. The techniques include

- eddy current,
- thermal wave,
- dielectric (capacitance),
- ultrasonic, and
- X-ray fluorescence.

Some other possibilities that might be explored include

- optical—both spectroscopic and scattering methods—and
- microwave.

The semiconductor industry has similar interests in monitoring the temperature of wafers with thin dielectric coatings during rapid thermal processing. They have also investigated a combination of ellipsometry[6] and radiation thermometry as a method for measuring the temperatures of these complex systems.

On-line thickness sensors are needed for the application of TBC layer. Improvements in high-volume, off-line coating thickness measurement technology could reduce the cost of manufacture as well. Single-point detection is not sufficient. Measurement of the coating thickness distribution over the complex shape of the blades and vanes is also needed. There is also concern regarding verification that cooling ports (air holes) are not plugged as a result of the bond coat/TBC application process.

The surface finish of the turbine components is important. In configurations that use combined TBC/air cooling, a boundary layer of cooling air must be maintained at the surface of the air foil, particularly at the leading edge. The TBC surface must not result in turbulent flow of the cooling air layer. Sensors for in-production measurement of surface finish are needed. Many existing surface finish measurement techniques are "end-of-line" or off-line techniques for relatively flat surfaces. Efficient measurement of the surface finish of complex shapes such as turbine blades is a more challenging problem.

7.2.3.2 Monitoring during on-line operation

The critical importance of the integrity of the TBCs leads directly to the requirement for an on-line monitor of the TBC layers. The requirements for such a sensor are that it be able to detect a spallation of a one-quarter to one-half square-inch area[7] and that it have a response time sufficiently fast to allow fuel flow to be cut back soon enough to avoid irreversible damage to the blade. This also means that the TBCs' on-line monitor will have to be capable of "seeing" the 100% of the blades or vanes facing the hot gas stream exiting the combustor. Monitoring the exhaust gas stream for particles released by the TBC has also been suggested. In any case, these monitors must also be highly reliable. False alarms cannot/will not be tolerated. Detection of the degradation of the TBC layer to allow an orderly shutdown and repair would be preferable if

[6] Ellipsometers are instruments designed to measure the rotation of polarized light as reflected by a surface.
[7] ORNL/Clemson Workshop.

the predictive capability was 100%. It might be the same as existing sensor hardware in the turbine but with different data processing to monitor coating degradation.

At least two sensor concepts were suggested at the ORNL/Clemson workshop: (1) embedding thermographic phosphors in the TBC and (2) using the degree of formation of the Al_2O_3 scale layer at the interface of the bond coat and TBC as a measure of coating degradation.

7.2.3.2.1 Monitoring of blade and vane temperatures

With uncoated blades, optical radiation thermometers have been used, at least during turbine test and qualification. It is not possible to use simple radiation thermometry on the TBC covered blades or vanes since the coating is transparent/translucent to the radiation, and the uncertainty in emissivity and hence in temperature is unacceptable.

The thermographic phosphor approach is well understood,[8] but the implementation in an operating turbine would not be straightforward. Optical path(s) penetrating into the combustor would be required. This then requires some means to avoid fogging or coating the lens or fiber-optic exposed to the combustor interior.

7.2.3.2.2 Monitoring alumina scale formation/appearance of chromium

As illustrated in Fig. 4, a coating of NiCrAlY is used as a bond coating between the blade material and the TBC. During turbine operation, the aluminum gradually diffuses to create a layer of alumina (see Fig. 5), which weakens the bond coat-to-TBC interface. The increase of alumina concentration at the interface to the TBC can be taken as an indication that the bond coating is losing effectiveness and may lead to loss of the TBC layer.

An on-line sensor based on detecting the appearance of alumina or disappearance of aluminum within the bond coat may provide a mechanism for assessing TBC integrity. In addition, when the spallation occurs, the bond coat may be exposed to such a degree as to allow the detection of bond coat constituents such as chromium.

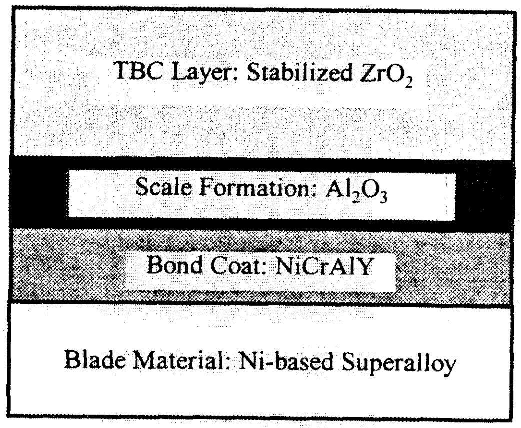


Fig. 5. Region of Al_2O_3 scale formation, which leads to cracking and spallation.

[8] K. A. Wickersheim, S. O. Heineman, H. N. Tran, and M. H. Sun, *Proceedings of Digitech '85*, May 1985, ISA Paper No. 85-0072, Instrumentation Society of America, Washington, D.C., 1985, pp. 87-94.

8. NEEDS RELATED TO EMISSIONS

8.1 LEGAL REQUIREMENTS: < 25 PPM NO_X

To meet the legal emissions standards for NO_X, the engines must run lean. The higher operating temperatures required to achieve the thermodynamic efficiencies tend to operate in the opposite direction—increasing the NO_X content with increasing temperature. The only recourse at this time is to operate with a "lean" fuel-air mixture at the lower limit of combustion. The legal requirements for emissions allowed represent a potential cost if fines are levied against substandard operations. Additional costs for emissions monitoring may also be incurred. Again, proven sensing technology that is field hardened and capable of long-term operation without excessive maintenance may not currently be available. This may not be an absolute barrier, however. Current practice in aircraft engines is to test the engines for emissions during initial testing and after overhauls. On-line monitors are not used and may not be needed if the turbine is operated under conditions known to produce low emissions of monitored species.

8.2 LEAN OPERATION

Lean operation of the gas turbine may lead to a fuel-air mixture that is near the limit of combustibility. The closer to the combustion limit that the gas turbine can be operated, the better it is in terms of fuel economy and minimum NO_X emission. On the other hand, the closer to the combustion limit the turbine is operated, the closer the approach to unstable conditions. Minor fluctuations can drive the operating point into the region below the limit of combustion, resulting in flameout in the extreme case. Operation close to the margin will require active control including fast sensors and actuators with an *overall* millisecond response time. Capability to modulate the fuel flow at frequencies up to ~1000 Hz is needed to implement active control. Standard process pressure transducers typically are filtered to have a time constant of 1 to 2 s to reduce noise. For lean operation of the gas turbine, pressure transducers need to be located very close to the combustor. This minimizes the length of the pressure sensing lines in order to achieve the required frequency response. This, in turn, leads to the requirement for high-temperature transducers because they must be located close to the engine shell.

8.2.1 Flashback

Flashback can occur under conditions approaching stall where the air flow from the compressor is not sufficient to keep the flame from propagating back into the compressor section.

8.2.2 Active Control

As described above, active control of the combustor requires high-speed sensing and control of the fuel flow to the burners. Currently, pressure sensors are used, but METC has developed an on-line infrared sensor that is tuned to an OH band.[9] They have been able to stabilize the oscillations in a single burner by modulating the fuel flow. Because of the complex interactions among multiple burner nozzles, an integrated combination of sensors (sensor fusion) may be required to achieve a wide enough range of turbine operation for various grades of fuel.

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[9] Personal communication, Dr. George A. Richards, METC.

8.2.2.1 Fast response sensors

Fast response sensors are needed for operational control of the fuel–air mixture as well as safety systems. Optically based sensing is inherently fast, but the volume of data required to get 100% coverage, for instance, of the first stage turbine blades and vanes means that the data transmission and processing are also factors in achieving millisecond system response times for control of the fuel–air mixture.

8.2.2.1.1 Millisecond response pressure and differential pressure sensors

Pressure and differential pressure sensors are commercially available; however, they may not be designed to withstand the high-temperature environment near the shell of the turbine. These transducers must be mounted close to the sensing point to maintain the pressure transmission lines short to achieve good frequency response. Mehl[10] and Gillis[11] at NIST have employed tuned transmission lines* from a high-temperature (400°C) pressure cell to a pressure transducer near room temperatures for pressure signal transmission up to several kilohertz.

8.2.2.2 Fast response actuators

To complete the fast response control loop, reliable actuators with commensurate response times are needed. For control of fuel flow, for instance, inexpensive, high-speed actuators might be adapted from automotive fuel injectors. These would need to be tested for gas turbine operating conditions.

Actuator reliability was described as a problem by at least one manufacturer. Therefore, more *reliable* actuators as well as fast response actuators are needed.

8.3 EMISSIONS MONITORS

To monitor compliance with emissions regulations, a continuous species monitor is needed with 20–50-ms response with an uncertainty of 2 ppm or less for NO_X and other regulated species such as CO and hydrocarbons versus ~1/4 % for common atmospheric gases.[12]

The emission of certain gases must be controlled by virtue of the Clean Air Act. These are NO_X, CO, SO_2, volatile organic compounds, and unburned hydrocarbons. In addition, these "regulated emissions" must also be monitored to assure that they remain at acceptable levels. To minimize the formation of these gases, the combustion must be controlled with a proper mix of air and fuel. The condition that minimizes this formation is a very lean burning fuel–air mixture operating close to the lower limit of combustibility.

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*Normally these would merely be referred to as pressure sensing lines; however, in order to achieve maximum response, these lines are specially tuned to match the pressure source and are therefore more properly termed *pressure transmission lines*.

[10] J. B. Mehl and M. R. Moldover, "Specific Heat and Virial Coefficient Measurements with a Spherical Resonator," in *Proceeding of the Eighth Symposium on Thermophysical Properties, Vol. 1, Thermophysical Properties of Fluids*, ASME, New York, N.Y., 1982, pp. 134–141.

[11] K. A. Gillis, M. R. Moldover, and A. R. H. Goodwin, "Accurate Acoustic Measurements in Gases Under Difficult Conditions" *Review of Scientific Instrumentation*, pp. 2213–2217 (September 1991).

[12] Outcome of ORNL/Clemson Workshop working sessions.

9. OPERATION

9.1 LEAN OPERATION

Lean operation was discussed in Sect. 8.2.

9.1.1 Rumble

Rumble is an observed phenomenon in gas turbine engines that describes low-frequency oscillations in the combustor. The frequencies are generally less than 100 Hz and can cause *low cycle fatigue* (LCF) damage in engine components. These fluctuations can be as great as 20 psi or as low as 0.1 psi. Rumble is a generic, industrywide problem resulting from dry–low NO_X operation. In the past, the problem could be finessed by running with a higher fuel-to-air ratio, but this is no longer possible because of the requirement to minimize NO_X production.

9.1.2 Fast and Accurate Fuel Flow

One way to minimize rumble is thought to be to modulate the fuel flow with ~180° phase shift to dampen the oscillations. To realize this kind of active control system will require fast, accurate pressure or differential pressure sensors that can withstand the temperatures near the combustor section of the turbine. In addition, fast, accurate actuators to regulate the fuel flow are needed to close the loop. One of the conclusions from the ORNL/Clemson workshop was that the dynamic pressure sensors for combustor control should have a time response of about 5 ms with an accuracy of 5% (see Table 6. Sect. 4.5.1).

9.2 COMBUSTION STABILITY

The air stream from the compressor section flows past multiple burner nozzles where fuel is sprayed into the flowing stream and ignited. These flows are highly turbulent, and there are often complex interactions among the multiple burners.

The problem of combustion stability can be subdivided into the degree of fuel-to-air mixing and flashback.

A "flame intensity" monitor transducer with at least a 5-ms response time may be useful for monitoring flame stability. Intensity fluctuation could be used to generate feedback to the control system.

Combustion stability is closely related to performance, emissions, and safety. As stated previously, for reasons of fuel efficiency and low NO_X production, the fuel–air ratio is maintained at the edge of combustibility. Very small pressure fluctuations can drive the ratio into a region such that the fuel–air ratio will not support combustion. The flame in the combustor will be extinguished, resulting in a flameout.

Other effects of pressure fluctuations are more complex and not completely understood. The opinion expressed by several people during the course of the study was that the ATS Program could benefit from advanced modeling of nonlinear combustion dynamics. With multiple burners in the combustors, there are complex flow and interactions that can be set up. Even in single burners, as experiments at METC have shown, pressure fluctuations can be amplified by resonance in the combustor cavity.

9.2.1 Effects of Variations in Fuel Composition

Advanced gas turbines must have a wide range of operation and it must accommodate changes in the fuel composition. A valuable on-line sensor that would promote operating stability would be an economical, on-line, fuel heating value meter. This would allow the control system to respond to gas fuel composition changes in real time.

Also needed is a rapid response fuel flow sensor that can be integrated into the control system with a fast response actuator.

9.3 STALL AVOIDANCE

Stall refers to the disturbance of the air stream entering and flowing through the compressor stage of the turbine. In aero applications, stall can occur when the air stream entering the intake is predominantly parallel to the intake. This prevents the engine's compressor blades from properly inducting the air into the engine. The ability to adjust the angle of the compressor vanes helps to avoid this condition. There are, however, other contributing factors. The result of a stall condition is that while fuel is still being injected into the combustor, there is insufficient air flow through the combustor to continue the desired combustion level. Fuel tends to accumulate and then when air does begin to flow, the accumulated fuel burns more rapidly than desired.

9.4 ACTIVE CLEARANCE CONTROL

The clearance between the blade tip and the compressor housing represents a possible leakage path for air in the compressor. The clearances change as the engine warms up. Sensors and on-line active control of blade clearance in the compressor section are needed to maximize efficiency.

A similar problem exists in a more extreme environment in the turbine section. Implementing active clearance control is a much more challenging problem in the higher temperature turbine section.

9.4.1 Clearance Measurement

Improved blade tip clearance measurements are needed to implement active clearance control. Blade tip clearance determines the gas leakage around the turbine or compressor blades and hence directly influences the efficiency. Currently, blade tip clearances are determined indirectly, but direct blade tip clearance measurement is needed for control. Measurement systems for blade tip clearance are currently used in engine testing but may not be reliable enough to meet the availability goals established for advanced turbines.

9.5 SENSORS AND ACTUATORS INTEGRATED WITH CONTROLS

As a result of a very tightly coupled and fast responding physical system, the sensors, actuator, and controls system must also be integrated as a system. Traditional application of analog controls may not be sufficient. Real-time digital signal processing may be required and incorporated as part of the sensing and control loop. This offers the opportunity to integrate higher levels of flexibility and functionality into the control system.

9.6 HIGH-TEMPERATURE PRESSURE SENSORS

As discussed in Sect. 8.2.2.1.1, fast pressure sensors are needed that can be located in close proximity to the gas turbine shell and hence to temperatures of around 205°C (400°F).

10. SENSOR SUPPLY

10.1 SMALL, SPECIALIZED MARKET

Instrument manufacturing constitutes a sizable segment of the U.S. economy. This is indicative of the important role measurement, control, and instrument systems play in American manufacturing. The value of instruments and related products shipped in 1992 was $135 billion.[13] In 1992 there were ~10,000 instrument or instrument related companies with 901,000 employees. If we calculate the ratio of employees to companies, we find that a "typical" instrument company is relatively small with fewer than 100 employees. There are a few large Fortune 500 sized firms, such as Honeywell or Rosemount,[14] but a large majority of the instrument manufacturers are relatively small and make only a few products. As a consequence, relatively few instrument manufacturers have sufficient capital to invest in long-term R&D and are primarily interested in getting products out the door. Sensors and actuators for specialized needs such as many of the needs of the ATS Program do not represent a sufficiently large market or potential return for the sensor manufacturers to invest their own funds in developing sensors or actuators for this limited market—especially for such severe applications.

Special configurations of sensors are often needed for installation in gas turbines. The number of access ports is limited, and any installed sensors must minimally impact the gas flow through the turbine. Thus, consideration must be given to the sensor profile presented to the gas flow.

10.2 LACK OF R&D FOR NEW SENSORS

Currently there are three approaches used by the gas turbine manufacturers to obtain sensors and actuators for their products.

- Find a near fit in some sensor manufacturer's catalog and contract with that manufacturer to build a special product, at extra cost, that meets the requirements of the gas turbine. Two disadvantages of this approach are (1) the extra costs are often disproportionately large and (2) the manufacturer may not be interested if the manufacture of the special product might interfere with normal production.
- Develop the special product as a joint venture, with the turbine manufacturer funding a part of the development costs. At the workshop, it was agreed among the turbine manufacturers that this was generally a thing of the past. They still participate in joint ventures but without funding for the sensor manufacturer. The turbine manufacturer's contribution is to make facilities available to test the new sensors.
- Develop an instrument as an Internal Research and Development (IRAD) project.[15] The engine manufacturers with defense contracts have used this method in the past.

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[13] *Statistical Abstract of the United States 1992—The National Data Book*, 112th Edition, U.S. Department of Commerce, Washington, D.C., 1992, p. 737.

[14] Division of Emerson Electric.

[15] A program widely used by defense contractors. A percentage of a procurement contract can be used for defense-related internal R&D.

10.3 INADEQUACIES IN EXISTING SENSORS

During the course of the assessment study, it was determined that, although there are existing sensors being used in turbine measurement applications, many of theses sensors are in need of improvement or replacement in order to meet the increased demands of the ATS Program. The following sections discuss some of the areas identified.

10.3.1 Cannot Withstand High Temperatures

Alternatives to current thermocouple technology are needed to measure exhaust tèmperatures. Currently, the firing temperatures are a maximum of about 1288°C (2350°F). ATS firing temperatures are expected to reach 1427°C (2600°F). This approaches the melting temperatures of base metal thermocouples (such as Type K, Chromel/Alumel), and the decreased electrical resistance of ceramic insulation can result in significant errors. Various methods for measuring gas temperature using noncontact probes generally require line-of-sight access, which creates a design problem in itself. In addition, optical access requires windows, which tend to be fogged by combustion products after a time. These techniques have been used in gas turbine tests with run times of 50 to 60 h maximum where the degree of fogging experienced is acceptable.

10.3.2 Cannot Withstand High-Temperature Gas Turbine Environment

Sensors and transducers that must be mounted in or near the engine must withstand temperatures of around 205°C (400°F). This is outside the range of most electronics devices without extra cooling. Special high-temperature electronics that will withstand temperatures to 300°C (572°F) are available in GaAs but as custom production at a very high premium.

10.3.3 Hot Gas Stream

Sensors in the hot gas path in the turbine are needed for both performance and durability. They are needed for both turbine development testing and for real-time service operation.

The key parameters that need to be measured in the hot gas path include the following:

- Measurements needed in combustor section
  - Flame temperature
  - Temperature distribution
  - Liner temperature
  - Dynamics—pressure differential pressure and vibration
- Rotor and stator metal temperatures
- Internal coolant temperatures
- Transient and steady-state cooling flow and temperature
- Pressure and rate of change in pressure
- Hot gas path leakage
- Coolant leakage
- Component stress
- TBC spallation

10.3.4 Unknown Life/Durability

Sensor durability needs focus on measurements within the turbine environment as well as effects due to the external operating environment. The purpose of the sensors is to permit the control of the turbine within safe (to the turbine) parameters. Extreme temperatures or pressure can damage or destroy turbine components and possibly the sensors themselves. Most vulnerable are the first-stage turbine vanes and blades that are directly exposed to the hot gas from the combustor. Air and fuel flow must be controlled to maintain the temperatures of turbine components within design operating margins.

The challenges to sensor durability include the following:

- For an uncooled sensor in the turbine hot gas path, the temperature may range from 1370°C (2500°F) to as much as 1650°C (3000°F). Blade coolant temperatures may range up to 593°C (1100°F). Heating transients of around 100°C (212°F)/min are expected.
- Gas velocities in the gas path can range from Mach 0.1–1.2. Sensors in this environment are subject to vibration from the turbulent gas flow and from pressure pulses generated in the combustor due to complex interactions among the burner nozzles. Sensors attached to the blade may also be subjected to higher frequency vibrations of the blade.
- The pressures in the turbine can range from 3 MN (450 psi) up. In addition, the differential pressures across various parts of the engine can be as much as 0.7 MN (100 psi).
- Not only must the sensor suffer no physical damage itself, but it must also not be a source of damage to the turbine. Furthermore, little or no change in the turbine operation is allowed because of the presence or intrusion of the sensors into the hot gas stream.

10.3.5 Inadequate Speed of Response

Many of the standard process transducers and sensors are too slow for proposed advanced turbine applications. In some cases, as mentioned above, the signal conditioning is intentionally filtered to reduce the introduction of "noise" into the electronic system. In some cases, the frequency response of the transducer is limited by the design of the sensing element. Redesign of the sensor, the electronics, or both may be necessary to achieve the needed response times. In some cases, existing sensor concepts may be inadequate.

10.4 NEED FOR NEW SENSOR CONCEPTS

New sensors are needed to actively control flame stability so that the turbine can be operated closer to the combustion limit of the fuel–air mixture. It is thought that the combustion stability could be controlled if fast sensors and actuators were available for real-time modulation of the fuel–air ratio. Detection of pressure fluctuations in the combustor for active control requires fast response sensors.

Other sensors needed to improve combustion stability include a wide area combustion profile detector(s) as well as detectors for measurement of mass distribution in the combustor.

Another factor is that measurement science is changing rapidly and will be affected dramatically over the coming decade by new and emerging technologies such as fiber-optic sensors, smart sensors, instruments-on-a-chip, and virtual instruments. Measurement systems are starting to incorporate intelligence which, if included in control systems, promises to substantially increase the efficiency and safety of operations. In addition, the automotive market is driving some of these developments. The result should be the availability of mass produced sensors and actuators that are relatively inexpensive. In addition, the automotive sensors will be fairly tolerant of environmental extremes. There is a need to evaluate some of the available sensor technologies to determine if they can be adapted economically to meet the needs of the advanced gas turbines.

One desirable quality that is emerging from the intelligent sensors field is that of on-line or self-calibration. This will increase the operating reliability and reduce the operating costs. An alternative is to design the sensor or actuator and its installation so that the sensor can be replaced with the system running. This would reduce the need for nonexistent durability data.

10.5 SENSOR SELECTION GUIDE

The gas turbine manufacturers' representatives at the ORNL/Clemson workshop agreed that they would like to have help in just keeping up with the sensor technology that is available. There are numerous annual buying guides for sensors, but the need is for a guide to *qualified* sensors. There is also a need for monitoring and evaluating new sensor technology as it appears. Typically, today the time to market of technologies emerging from university laboratories is on the order of 7 to 10 years.

11. SPECIFIC APPLICATION NEEDS

11.1 ENHANCED ON-LINE PERFORMANCE MONITOR

A monitor is needed which integrates the signal from a multiplicity of outputs to calculate and display a high-level view of the performance of the system in real time. Since this is a computed value or values—more than one parameter might be displayed—it could easily be customized to the needs and requirements of the customer. The key to this is the presentation of readily comprehensible information rather than a collection of data that must be interpreted. For instance, it might display overall instantaneous system efficiency along with a statistical process control (SPC) chart of efficiency for the previous hour, day, month, or all of the above on command. It might display the instantaneous cost of the product that includes the fuel costs and efficiency. This could become more important with deregulation and the advent of power markets.

11.2 REAL-TIME MONITOR FOR CRITICAL COMPONENTS

A real-time system "health" monitor is needed to assure that the system is operating safely and that maintenance or corrective actions can be taken in an orderly manner before damage or suboptimal performance occurs. The "health" monitor might also display an integrated system "health" score with detail available for exceptions and out-of-tolerance signals. Such a system would need to have both predictive and data logging capabilities.

11.2.1 Hot Section Peak Temperatures/Bulk Temperatures

One example of a parameter that might measure one aspect of the "health" of the system is logging of the peak temperatures experienced by the system components. The operator would need to know if component temperatures had ever exceeded safe tolerances.

11.2.2 Evidence of Erosion/Damage

Another type of parameter that can be an indicator of system health is a monitor that could detect evidence of erosion—especially of the TBC layer. In this case, a monitor to detect particles in the exhaust gas stream is needed.

11.3 ON-LINE GAS ANALYSIS

Inexpensive, robust analysis capability is needed to optimize system performance in relation to the fuel characteristics and quality.

11.3.1 Exhaust Emissions

Analysis of the exhaust emissions is needed to show that the gas turbine meets legal requirements for emissions. It may also be needed to provide feedback to the combustion control system to maintain lean burning conditions. Analysis systems are currently too expensive, complex, and unreliable to be used as a part of the turbine control system. There is a need for a cost-effective, reliable analysis system capable of meeting the durability requirements of the gas turbine system.

11.3.2 Fuel Monitoring

The quality and energy content of natural gas fuel vary considerably. On-line analysis of the incoming fuel is needed to control the engine at its optimum operating point. This might be analysis of composition, but as suggested earlier, might be a fuel heating value monitor.

11.4 ON-LINE OIL QUALITY MONITOR

An oil quality monitor for the lubricating system of the gas turbine engines is needed. Such a monitor should provide on-line indication of oil cleanliness. It should be able to detect and discriminate between normal foreign matter and system degradation material. It would be desirable to have some analytical capabilities in the monitor to help trace the source of the contamination.

11.4.1 Nonmetallic Contamination

The oil quality monitor needs to detect and evaluate nonmetallic contamination. Buildup of carbon, for instance, might indicate the overheating of a lubricated component.

11.5 STEAM TURBINE AND HEAT RECOVERY STEAM GENERATOR

Although steam turbines are a mature technology, the long run times between major overhauls may extend beyond the current experience base. Sensors are needed for on-line corrosion and oxidation detection as well as sensors for thermal stress measurements in the turbine rotor, the shell casings, and the heat recovery steam generator.

Better sensors and controls, possibly using fuzzy logic, are needed for the steam drum level to predict and control system swell (the expansion of the water reservoir inventory).

11.5.1 Steam Turbine Durability Issues

A monitor is needed to detect condensed water droplets entrained in the steam supply to the steam turbine. If these are allowed to enter the turbine section, they can result in severe erosion of the turbine blades.

12. CONCLUSIONS

The sensors and controls needs assessment identified more than 50 different measurements and control and monitoring needs for advanced turbines that are not currently being met by commercial sources. While we agree that all the identified needs are important, several are absolutely critical to the success of the ATS Program. After extensive discussions with turbine manufacturers and analysis of the workshop results, we conclude that the highest priority needs are

1. TBC failure/health monitoring (on-line spallation detection during operation).
2. Accurate combustion gas temperature measurements and flame detection up to 1650°C (3000°F) to enable the closed-loop control of pollutant emissions.
3. Fast pressure and differential pressure sensors to detect the onset of stall and compressor instabilities (stall avoidance and control).
4. Durable sensors and advanced modeling (nonlinear dynamics) to control combustion instabilities caused by lean fuel mixtures.
5. Blade tip clearance measurements to enable active clearance control. This would enhance overall engine performance.

13. RECOMMENDATIONS

It is recommended that the DOE ATS Program develop a research program to stimulate the development of the required new sensor and control technologies so that advanced turbines can achieve the goals established by the ATS Program. For example, TBCs are an absolute requirement to protect turbine blades at the higher gas temperatures required by ATS efficiency goals. Exposure to the severe environment can result in spallation of the TBC. Therefore, methods are needed to detect TBC spallation during operation. Combustion temperature measurement and stability control are necessary when using lean fuel-to-air mixtures to meet increased efficiency and lower emissions goals. To ensure maximum power output for minimum fuel consumption, it is desired to operate as close to stall as safely possible. Therefore, improved sensors to predict the approach to stall conditions and fast and reliable controls are essential to obtaining the maximum cost benefit from the new turbine designs and meet the ATS goal of 10% lower cost electricity.

Several participants at the one-day sensors and controls workshop expressed a desire for similar workshops in the future where they can exchange new ideas and discuss measurement and control issues associated with combustion/emissions, TBCs, and operational performance monitoring. Therefore, it is recommended that DOE consider sponsoring additional sensors, controls, and monitoring workshops in 1997. A suggestion was also made to form a Sensors and Instrumentation Working Group to encourage collaboration and to expedite sensor development and increase the relevance of R&D in sensors and controls.

A reliable source of information on qualified sensors appropriate for application to ATS is needed. A formalized effort for test and evaluation of existing and recently developed sensors is needed to provide turbine manufacturers with reliable performance information so they can select the best device for their needs.

APPENDIX A

ATS SENSORS AND CONTROLS WORKSHOP

A.1 AGENDA

Clemson University's Madren Center
April 17, 1996
7:30 am to 4:30 pm

Wednesday, April 17, 1996 (Seminar Room I)

7:30 am	*Continental Breakfast*
8:00 am	*Welcome to Clemson/SCERDC* L. Golan / D. Fant, S. C. Energy R&D Center
8:05 am	*Workshop Goals & Expectations* T. Johnson, DOE - Headquarters D. Fry, DOE - Oak Ridge National Laboratory
8:15 am	*Industrial Perspective* Allied Signal Engine Company Allison Engine Company GE - CRD & Power Generation Pratt & Whitney / UTRC Solar Turbines Incorporated Westinghouse Power Generation
9:15 am	*Input from Participants* DOE Labs, Vendors, EPRI, Universities
10:00 am	*Break*
10:30 am	*Participant Input Continued*
12:00 noon	*Working Lunch (Meeting Room I) & (Formation of Focus Groups)*
1:00 pm	*Breakout into Focus Groups* I. Operational Performance Monitoring - Moderator: D. Fry II. Thermal Barrier Coatings / NDE - Moderator: J. McEvers III. Combustion / Emissions - Moderator: R. Allen
2:30 pm	*Break (as needed)*
3:00 pm	*Presentation of Group Findings and Prioritized Needs*
4:15 pm	*Summary and Closing Statements* - D. Fry and D. Fant
4:30 pm	Depart
5:30 pm	*Informal Evening Wrap-up Session*

A.2 ATTENDEES

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