

AEROSPACE INFORMATION REPORT

SAE AIR4986

REV. A

Issued 1999-03
Cancelled 2009-10

Superseding AIR4986

Engine Electrostatic Gas Path Monitoring

RATIONALE

The E32 Committee voted to cancel this document since the committee no longer has resources to update this document. Sufficient information exists in the public domain for individuals to familiarize themselves with this technology.

NOTICE

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1. SCOPE:

Turbine engine malfunctions account for a substantial portion of the maintenance actions required to keep both fixed and rotary wing aircraft operational. Undetected incipient component failures can result in secondary engine damage and expensive unscheduled maintenance actions. Recent developments of electrostatic methods now provide the potential for the detection of foreign object ingestion and early detection of distress in gas path components. This SAE Aerospace Information Report (AIR) seeks to outline the history of the electrostatic technique and provides examples of state-of-the-art systems for both inlet and exhaust gas debris monitoring systems along with examples of most recent testing.

2. REFERENCES:

2.1 Applicable Documents:

A list of papers and reports which support the information provided in this document is included in Section 7.

2.2 Glossary of Terms and Acronyms:

A/D(C)	Analogue to Digital (Convertor)
AFB	Air Force Base
AVIDS	Air Vehicle Integrated Diagnostics System
BIT	Built In Test
DA	Design Authority
DRA	Defence Research Agency
DTEO	Development Test & Evaluation Organisation
EDMS	Engine Distress Monitoring System
EEMS	Electrostatic Engine Monitoring System
EGT	Exhaust Gas Temperature
EMS	Engine Monitoring System
FO	Foreign Object
FOD	Foreign Object Damage
HM(S)	Her Majesty's Service
HP	High Pressure
HUMS	Health & Usage Monitoring Systems
IDMS	Ingested Debris Monitoring System
IGV	Inlet Guide Vane
JAST	Joint Advanced Strike Technology
JSF	Joint Strike Fighter
LP	Low Pressure
Mk	Mark (refers to engine)
MOD	Ministry of Defence (UK)
NAWC	Naval Air Warfare Center
Ng	Gas generator speed
NOVA	NOVA Gas Transmissions Ltd
Np	Power Turbine speed

2.2 (Continued):

P & W	Pratt & Whitney
PSE&G	Public Service, Electric & Gas
RAF	Royal Air Force
RMS	Root mean squared
SHL	Stewart Hughes Limited
SI	Smiths Industries
Tachos	Tachometer
UK	United Kingdom
US	United States
USAF	United States Air Force
USMC	United States Marine Corps
USN	United States Navy
UTC	United Technologies Corporation

3. GAS PATH DEBRIS MONITORING TECHNOLOGY OVERVIEW:

3.1 Background:

One of the objectives of engine health monitoring techniques is to indicate and identify incipient faults occurring in the engine before they cause failure, which may be catastrophic. Several techniques are currently used which infer damage rather than detect it; for example, vibration monitoring may be used to detect blade rubs, however, this relies on the blade rub causing an out of balance or similar effect. Electrostatic monitoring has the capability to detect the debris produced by damaged components, thereby providing an indication of the actual fault condition, and of the integrity of the gas path components.

The principle of electrostatic monitoring of aero engine gas paths has been known since around 1970 when researchers at the United States Air Force Institute of Technology (AFIT) noted large voltage spikes in the exhaust stream of a J-57 jet engine. Research into the phenomenon continued and in 1977, Dr. R. Couch at AFIT, stated that the electrostatic method was a reliable means of predicting a large class of gas path failures previously thought to be unpredictable, as well as those which are predictable, by more standard gas path trending methods. After he retired, he continued his investigations with United Technologies Corporation (UTC).

Field tests were conducted on over 500 engines in conjunction with Tactical Air Command (TAC), Strategic Air Command (SAC) and Military Airlift Command (MAC). Observation and evaluation of damage during engine disassembly confirmed a relationship between the electrostatic signature and the failure mechanisms. An absence of false alarms was also demonstrated. This work led to the acquisition of 23 patents on various aspects of electrostatic monitoring.

3.1 (Continued):

In 1991, United Technologies granted Smiths Industries (SI) an exclusive world-wide licensing agreement for all rights to data, patents, technology and development, manufacturing and marketing.

In the United Kingdom, Stewart Hughes Ltd. became interested in electrostatic monitoring of engines in 1984. They undertook a two year program of research, which achieved the objectives of demonstrating the feasibility of the technique on an engine and also provided a good basic understanding of the physical mechanisms involved. This early work concentrated on monitoring within the core engine and in the tailpipe.

3.2 Outline Principle:

3.2.1 The principle of the electrostatic technique is to monitor electrostatically charged debris present in the engine.

3.2.2 Gas turbine engines produce electrostatic charges during normal operation and certain gas path component failures produce additional charges resulting in increased electrostatic activity in the exhaust path.

3.2.3 During normal healthy engine operation the electrostatic charge is produced mainly due to the combustion process. A "normal" (baseline) level of electrostatic activity can be established which varies with engine operating power, as the amount of air and combustion product varies.

3.2.4 When a component damage or debris ingestion occurs additional electrostatic charges are present in the exhaust gas which causes a variation to the baseline. The charged particulate produce an induced charge effect on a suitable sensor resulting in a time varying voltage signal.

3.2.5 Engine degradation or the ingestion of material result in an increase in the rate of production of the charged debris in the engine gas path. Improper/incomplete combustion, compressor or turbine blade rubs, erosion of the hot section components, combustor faults, seal wear and the passage of foreign objects through the engine are all examples of phenomena which generate electrostatic signals.

3.3 System Equipment:

3.3.1 Typical electrostatic monitoring systems comprise similar system components: sensor(s), signal conditioner(s), signal processor and groundstation computer. They can be configured as stand alone systems, with a dedicated signal processor and groundstation, or can be integrated into existing compatible engine health monitoring systems, with card level integration for the signal processing and the groundstation functionality embedded in the engine monitoring system computer. The system components have been designed to include built-in-test (BIT) capability.

- 3.3.2 The sensors have been developed to meet the different environmental and detection requirements of the two ends of the gas turbine or jet engine. They are mounted integral to the engine being monitored. Two basic sensor designs have been developed: ring or hoop sensors which form a complete ring around the intake or exhaust air; discrete "button" type sensors which have adequate visibility across the jet pipe to enable monitoring of debris across the duct. Different sensor implementations have been developed and tested. Further details are included in 4.1.2, 4.1.3, and 4.2.3.
- 3.3.3 The function of the signal conditioner is to receive the low level charge signals induced onto the sensors and convert them to higher level voltage signals for input to the processor.
- 3.3.4 The acquisition, analysis, and data storage are carried out and controlled by the processor using dedicated cards and processing software. In general terms the analysis algorithms are generic although implementation requires some tailoring for a given application.
- 3.3.5 The processing uses the sensor signals, engine signals, such as tachos and torque and also aircraft signals to identify when during the flight the ingestion or incipient fault started to occur. Real time data acquisition and processing is carried out with results stored for post mission analysis and long term data storage on the ground station.
- 3.3.6 Real time data analysis is carried out on the processor and the results stored in a suitable memory storage device. The data is downloaded by removing a memory cartridge which is then read by the ground station computer for deeper analysis and long term trending. An indication could be provided on the aircraft for the ground maintenance crews so that the status of the engine is known on aircraft turnaround.
- 3.4 Summary Status of Electrostatic Monitoring:
- 3.4.1 Two companies are currently involved in the development and application of this technology. The capabilities of the electrostatic gas path debris monitoring technology have been tested and demonstrated. The technology is implemented on a wide range of gas turbines and jet engines. These applications are generally in the form of demonstrations on specific installations (e.g., test bed or for a particular engine test) or for particular customers. The electrostatic monitoring technology and systems require tailoring to meet application specific requirements. This generally has to be carried out for each engine implementation in the same way as other monitoring systems require adaption for particular applications.
- 3.4.2 It has been shown that the technology can detect a range of gas path faults, including: blade rubs, seal erosion, nozzle guide vane erosion and combustor faults. The capability of the technology to detect and discriminate ingested foreign objects is discussed in this document under the Shoeburyness tests.

- 3.4.3 If the potential of this technology and the available systems are to be realized they need to be taken up by engine manufacturers and/or operators in order to achieve wider experience over greater accumulated engine running hours. In this respect the electrostatic gas path debris monitoring systems are no different to other engine health monitoring techniques for detecting the rare occurrences of faults within reliable engine systems.
- 3.4.4 Structured and controlled trials have recently been carried out using Spey Mk101 engines at Shoeburyness. These trials include seeding debris, both damaging and non-damaging, into the intake of the engine. Both company's systems were installed on the engine. Some of the engine testing was carried out blind (i.e., the number and types of debris ingested were not known at the time of the analysis). The outcome and results from this test are summarized in this document.
- 3.4.5 This document describes the current individual system implementations and the engine testing carried out to demonstrate the capability of this technology.

4. SYSTEM IMPLEMENTATIONS:

4.1 Stewart Hughes Limited:

Stewart Hughes Limited have developed two implementations of the electrostatic gas path debris monitoring technology. These are: Ingested Debris Monitoring System (IDMS), with sensors installed in the intake for detecting and discriminating ingested material; Engine Distress Monitoring System (EDMS), with a sensor installed in the exhaust duct or tail pipe of the engine, for detecting engine gas path faults.

- 4.1.1 Sensors have been developed for the exhaust duct/tail pipe and for the engine intake.
- 4.1.2 The IDMS sensors are mounted on the inside of the intake forming a complete ring around the intake air. They are of a laminated tape construction with each of the tapes in the laminate being individually flight approved, full flight approval for the composite sensor has not yet been granted. Design Authority (DA) approval for trial flights was gained on the basis of previous evidence. In the event that a retrofit application was identified, all available evidence would need to be submitted to the equipment DA during modification approval. For new applications the systems would need to be approved as part of the main development program. The initial work was based on using three IDMS sensors to provide information to enable the monitoring and discrimination of ingested foreign objects (into categories of potentially damaging and non-damaging) to be carried out. Recent work has focused on reducing the IDMS sensor fit requirements to two instead of three. This has been demonstrated to be feasible without comprising the information required from IDMS.

- 4.1.3 EDMS sensors have been developed for the airborne application. These are discrete button type sensors which are mounted to be flush with the tail pipe or exhaust duct. These can be tailored for mounting in existing instrumentation ports or via borescope ports if these are in a suitable location. The size and weight of these sensors have been minimized while ensuring that adequate "visibility" of the exhaust gas is maintained. The use of the button sensor was evolved following extensive development and testing of a wide range of sensor types and configurations on several engine types. EDMS sensors for installed ground based gas turbines are tailored to be suitable for the application and to require minimum modifications to the engine.
- 4.1.4 The acquisition, analysis, and data storage for IDMS and/or EDMS are carried out and controlled by the processor using dedicated cards and processing software. In general terms the analysis algorithms are generic although implementation requires some tailoring for a given application.
- 4.1.5 For IDMS the processing uses the IDMS sensor signals, EDMS sensor signals, engine signals, such as tachos and torque and also aircraft signals to identify when during the flight the ingestion occurred. Real time data acquisition and processing of IDMS and EDMS is carried out with compressed results stored for tertiary or post mission analysis (where relevant) and long term data storage on the ground station. The majority of the IDMS analysis is carried out in the airborne processor.
- 4.1.6 For EDMS the processing uses the EDMS sensor signal and other engine signals, such as tachos and torque. Real time data acquisition and processing is carried out with compressed results stored for tertiary and post mission analysis and long term data storage on the ground station. The tertiary analysis may be carried out in the airborne unit if necessary.
- 4.1.7 Data analysis is carried out on the processor and the results stored in a suitable memory storage device. The data is downloaded by removing the memory cartridge.
- 4.1.8 Ground based functions, which may include reports of IDMS events, tertiary or post mission analysis and diagnostics from EDMS data, display of data and results and long term trending are carried out in the ground station. These functions can be provided in a separate ground station which includes additional facilities for input of engine and maintenance information and configuration of the airborne processor. The other option is for the dedicated IDMS and/or EDMS functions to be provided in a software module for inclusion in an existing ground station which has the additional facilities required.

4.1.9 IDMS Analysis and Signal Processing:

- 4.1.9.1 An aeroengine intake is open to ingestion of a wide variety of materials, many of which may be non-damaging. Signal processing techniques have been developed which provide continuous monitoring of the intake air for the detection of any "unusual" occurrences. These are then processed further to enable verification of the occurrence as potentially damaging debris. The signal processing enables discrimination between harmless objects and potentially catastrophic ingestion. In addition, the presence of undesirable levels of sand, salt, or dust in the intake air can be monitored. This information may be used to identify the need for compressor washes or to compile data relating to the atmosphere in which the aircraft is operating with respect to blade erosion or corrosion.
- 4.1.9.2 The analysis and discrimination algorithms have been reviewed and enhanced as a result of the data and experience gained during the Shoeburyness trial. The main objectives of the enhancements were: to improve the classification and discrimination capability with a reduced false alarm rate; to achieve this using a reduced IDMS sensor fit; to reduce the complexity of the analysis; to improve the correlation and corroboration between IDMS, EDMS, and other engine data.
- 4.1.9.3 The initial analysis is focused on identifying whether single objects or fine particulate, such as sand, salt, or dust are being ingested. If the material is fine particulate further processing is carried out to monitor whether increased amounts of debris are being ingested. Correlation with EDMS data is also carried out.
- 4.1.9.4 If a single object is monitored as being ingested further analysis, including correlation with EDMS, is carried out to identify whether: the object is potentially damaging or non-damaging; whether the ingested object actually caused damage during its passage through the engine; and, where appropriate, whether the object travelled through the engine core or by-pass duct.
- 4.1.9.5 During the development and implementation phase an additional category has been introduced for single objects, "possibly damaging". This category has been used where the current database and classification does not provide unequivocal evidence that the object can be classified as potentially damaging or non-damaging. The number of ingestions classified in this category will reduce with increased database and experience.

4.1.10 EDMS Analysis and Fault Detection:

- 4.1.10.1 EDMS has been developed with the objectives of providing an early warning of incipient fault conditions, and identifying the type of fault (for example, whether a blade rub, combustor fault, etc.).
- 4.1.10.2 Various signal processing techniques have been developed to identify different components of the EDMS signal in both the time and frequency domains. The baseline footprint of each of these parameters is established when the engine is in a known healthy condition. This is used as a datum to identify incipient fault conditions.

- 4.1.10.3 The research and development work included investigation into fault modes and wear mechanisms experienced by an engine. These relate to how and when debris is produced. The EDMS analysis and interpretation is based on this knowledge and has resulted in the identification of fault specific EDMS signal component characteristics. Engine testing has demonstrated that the signal characteristics for the faults monitored to date are generic.
- 4.1.10.4 The use of several components in the analysis and indication of faults aids the discrimination of fault type and also increases confidence in the fault indication.

4.2 Smiths Industries:

- 4.2.1 The electrostatic engine monitoring system (EEMS™) is a non-intrusive, real-time, direct measurement, engine condition monitoring technique utilizing the accumulation of charged clouds in the engine exhaust path to provide a prognostic and diagnostic indication of the engine health.

The rate of occurrence and characteristics of these charged clouds have been shown to have the potential to be an accurate and reliable diagnostic indicator of engine deterioration. The ability to trend these rates and set thresholds provides an early warning prognostic indication of engine component failures.

The EEMS sensor monitors the electrostatic charge present in the engine exhaust path. The amplitude and shape of the detected electrostatic pulse is a function of variables such as: charge magnitude, charge distribution, charge velocity and sensor characteristics. Each failure mechanism produces very specific and unique charge characteristics which, when analyzed, provide direct correlation to a specific engine anomaly.

- 4.2.2 The EEMS architecture is generic and software driven which enables the EEMS to be configured for specific engine applications. The EEMS system software allows for tailoring of pulse classifications, caution and warning thresholds and trending of EEMS data for each specific engine type. While the electronics are common to all engine applications via the flexibility and adaptability inherent in the software, the form and fit of Smiths patented annular "hoop" sensor is engine application specific.
- 4.2.3 The EEMS utilizes a single, annular capacitive "hoop" sensor which is located at the rear of the engine or tailpipe. The EEMS sensor can be integral to the engine for airborne operation or external for ground operation. The airborne version is normally plasma sprayed flush with the engine or tail pipe wall using insulator and conductor materials that have matching characteristics to the base material of the engine. Testing has demonstrated that the plasma sprayed hoop sensor has the same longevity and durability as the engine material it is attached to and is transparent to engine operation.
- 4.2.3.1 In cases where an engine has a variable geometry (i.e., reheater/afterburner) the EEMS sensor is implemented as a gasket which is inserted between the last two modules on the engine upstream of reheat/afterburn. This gasket resembles a "sandwich" with the conductor centered between two insulators and requires no modification to the engine parts. (The EEMS sensor is not used with the afterburner.)

- 4.2.3.2 For ground test stand operation, the EEMS sensor consists of a simple, free standing hoop made of any conductive material that can withstand the environment at the rear of the engine. The conductive hoop sensor is isolated electronically from the holding fixture by ceramic or phenolic bushings.
- 4.2.3.3 The characteristics of each sensor are determined and the generic EEMS electronics are adjusted by the software to obtain the proper sensitivity.
- 4.2.4 The EEMS electronics monitors the sensor output for the detection of the electrostatic charge and provides the signal filtering for noise rejection as well as programmable gain adjustments. The sensor electronics provide a comprehensive BIT function for accurate fault detection and fault isolation between the sensor and sensor electronics.
- 4.2.5 The EEMS data acquisition component samples the sensor outputs, provides pulse detection and filtering, and contains the interface to the software processor. The sensors are continuously digitized via a 12 bit A/D converter, sampling at 10 KHz rate per channel to maintain pulse fidelity. The digitized output is scanned for the presence of a pulse generated by a charged cloud in the engine exhaust path. The amplitude threshold levels are programmable and are set by software during initialization. Additionally, the pulses are digitally filtered to increase noise immunity. The filter values are also programmable and set simultaneously with the amplitude threshold. When an electrostatic pulse is detected, the hardware stores the pulse data and alerts the software.
- 4.2.6 The EEMS software data processing provides the electrostatic pulse characterization using pulse signature features such as pulse width, number of zero crossings, polarity of the first peak, RMS, etc. Using a neural network based pulse recognition process the pulse record is classified as a particular type or an unknown. Following the classification of EEMS pulses, the pulse rate for each class of pulse is calculated. This pulse rate information indicates the relative health and condition of the engine. As damage occurs the pulse rate will exhibit a large increase that will continue to grow as the damage condition worsens.
- 4.2.6.1 Thresholds are set with different warning levels for specific pulse signatures. These "caution" and "warning" thresholds indicate whether immediate corrective action or scheduled maintenance action is required. The software data processing classifies (bin categories) and the detection trigger levels are programmed during system initialization. The ability to program these features enable the EEMS to be more adaptive to different engine types and failure mechanisms.
- 4.2.7 The EEMS interfaces via RS-232, RS-422, ARINC 429 or other port to the host processor and acts as the communicative link providing warning indication trending data as well as subsystem mode and BIT status. Engine regime data such as torque, Ng and Np speeds, EGT, etc. are provided to the EEMS via this interface which are used to alert maintenance crews of high pulse rate detection, provide cockpit indications and subsystem health indication.

4.2.8 The EEMS contains a comprehensive self-test capability to identify and isolate faults within the system. There are three BIT modes: start up, initiated, and periodic. Start up BIT is executed at system activation and consists of sensor and sensor electronic health tests, sensor calibration, data acquisition functionality checks and processor and memory tests. Initiated BIT is a user commanded mode which, when activated, will suspend pulse monitoring and execute the tests performed during start up BIT. Periodic BIT is a non-intrusive system monitoring function that is executed as part of normal system operation.

5. TESTING AND DEMONSTRATION OF TECHNOLOGY:

This section provides a summary of the development and testing of the electrostatic technique carried out by SHL and SI. The reports and documents which support the information presented in this section are listed in Section 2.

5.1 Stewart Hughes Limited:

- 5.1.1 Research work, carried out between 1984 and 1986, was complemented and progressed with hardware and software development and testing of EDMS on a wide range of engine types and applications. Testing of IDMS was more limited, the development work included experimental testing on a small gas turbine. Flight trials were carried out, with the primary aim of demonstrating the sensor reliability and robustness and some of the analysis algorithms.
- 5.1.2 The initial engine test of EDMS was carried out in 1985 on a Rolls Royce Viper engine. This was a seeded fault test, with a faulty compressor blade fitted into the engine to produce a blade rub. The engine was first run in a (datum) healthy condition. EDMS detected the blade rub in real time, demonstrating the capability of the technique.
- 5.1.3 Further engine testing of EDMS was carried out on a range of engines, as described in 5.1.10. The research program was also continued, albeit on a smaller scale, so that engine test results could be further investigated if required.
- 5.1.4 It was at this stage that interest was aroused in the application of the technique as a FOD detection system. The next phase of research concerned investigation of aspects specific to this application and was carried out on a Palouste engine.
- 5.1.5 IDMS Initial Testing:
- 5.1.5.1 A series of tests were undertaken using a Palouste engine at Royal Navy Air Force Yard Fleetlands. The early tests were to establish whether or not real foreign objects would be charged when they entered an engine and the later tests to substantiate the verification algorithms developed during the research phase.

- 5.1.5.2 Initial testing employed Polymer/Epoxy sensors. The sensing performance of these sensors was satisfactory for the duration of the tests but damage due to debris impacts did occur. Tape sensors constructed using flight approved self-adhesive tape were, therefore, employed during later testing. The tape sensors have been used during all subsequent test phases including the BAC 1-11 and Tornado trials.
- 5.1.5.3 A range of debris types known to have caused foreign object damage were identified, ranging from locking wire to concrete particles, and these were ingested into the instrumented Palouste intake from three surfaces: tarmac, concrete, and aircraft specification alloy sheet. A minimum of 60% of particles of each type were found to carry a detectable charge with the majority being in the high 80 and 90% range. Impacts with the duct wall generally increased the charge and the majority of most types of debris then became detectable.
- 5.1.5.4 Further ingestion tests were carried out using a range of typically ingested objects - some potentially damaging and some not. This phase was used to demonstrate that the verification algorithms and signal conditioning methods developed during the research phase were applicable and did not give rise to a high level of false alarms. Various combinations of these techniques were tried with varying trigger levels on data collected from 22 known events. Thirty-two alarms were generated by the best combination; 29 of which were associated with the real events and only three were "false alarms".
- 5.1.5.5 As a result of these findings the program was progressed into a flight trials phase on the BAC 1-11.
- 5.1.5.6 The Palouste testing also covered aspects related to the development and understanding of EDMS. Several sensor configurations and designs were tested to determine the optimum performance, with minimum modification required to the engine. In addition several fault types were seeded or simulated on the engine to further the development and understanding of the fault mechanisms, debris production and resultant signal characteristics.
- 5.1.6 IDMS Trial on BAC 1-11:
- 5.1.6.1 The main objectives of the first IDMS trial involved identifying a flight-worthy sensor and proving the analysis algorithms developed during the experimental work.
- 5.1.6.2 The first flight trials of IDMS were conducted on a Defence Research Agency (DRA) Farnborough BAC 1-11 in 1989. The intake sensors were of a laminated tape configuration mounted in three complete "ring" strips around the inside of the intake nacelle forward of the front face of the compressor. A lead-out cable was used to connect the laminated tape sensor to the IDMS conditioner mounted on the inside of the nacelle structure. As the lead-out cable was so small, just 1 mm in diameter, it was possible to pass the cable through the center of an intake skin rivet thereby eliminating the need for complicated and costly intake modifications.

- 5.1.6.3 Prior to commencement of these trials details of the sensor specification and installation details were passed to the engine design authority Rolls-Royce for assessment. An operational limitations document was issued by Rolls-Royce authorizing, for the purposes of flight testing, the installation of the SHL IDMS on the test aircraft. The only restriction placed on the trial was that the installation should be inspected after each flight for the first 10 flights and thereafter at regular intervals.
- 5.1.6.4 The BAC 1-11 flight trials were successfully concluded in 1991 with the objectives achieved. Some 800 flight hours and 20,000 installed airframe hours were achieved with no reported malfunction or degradation of performance.
- 5.1.6.5 The sensors are still installed on the BAC 1-11 and are inspected regularly. The last formal report was provided in September 1996, the sensors had accrued approximately 50,000 installed hours and 1500 flight hours.
- 5.1.7 Tornado IDMS Trial:
- 5.1.7.1 Following on from the success of the BAC 1-11 trial it was decided to extend the application of this technology by installing IDMS into the intake of the No. 1 (Port) engine of a DRA Bedford Tornado aircraft. The main aims of this trial were to:
- Assess the performance of IDMS in a buried intake environment.
 - Assess the effects of weather on the IDMS hardware and signal analysis techniques.
 - Assess the optimum spacing of the three ring sensors for a Tornado intake.
 - Define a pre-production specification based on the outcome of the trials.
- 5.1.7.2 Before commencement of the trials Rolls-Royce were provided specification and installation details for fitting of IDMS sensors and other equipment to the trials aircraft. Approval for the flight trials was granted.
- 5.1.7.3 As far as the installation was concerned, this trial was effectively trouble free. One minor problem occurred with the lifting of a small section of sensor tape. However, this was easily and simply repaired by the ground tradesman at DRA Bedford with no further problems reported. The IDMS while installed in Tornado ZA 326, accrued some 70 flying hours and over 5300 airframe installed hours without any serious problems. The aircraft was operated in the supersonic regime during the trial. The sensors are still installed on the aircraft and are inspected regularly. The last formal report on the sensors was received in August 1996, the sensors having accrued approximately 35,000 installed hours and 400 flight hours.
- 5.1.7.4 Analysis of in-flight data showed that in clear air conditions the IDMS monitored events with a good degree of success and only a few false alarms. However, in cloudy, rain or condensing conditions the success rate was reduced. The signal processing algorithms have since been improved to enhance the performance in these type of conditions.

5.1.8 Flight Trials of EDMS on Sea King Helicopter:

- 5.1.8.1 The Sea King trial had two objectives: to develop a flight-worthy EDMS and to validate electrostatic engine data from the Gnome engine.
- 5.1.8.2 Two discrete button EDMS sensors were mounted on the engine exhaust duct. These were conveniently engineered to fit into existing unused instrumentation ports thus reducing jet pipe modification costs to a minimum.
- 5.1.8.3 Data analysis was carried out on an on-board EDMS signal processor, which stored the processed data in non-volatile memory. At the end of the flight, or after several flights, the data was downloaded, using a small data retrieval unit, onto a ground based computer for further analysis. The trial also involved validating the on-board processing system. This was achieved by tape recording raw data for analysis at SHL and comparing these results with the downloaded data.
- 5.1.8.4 The Sea King trial ran for approximately ten months and collected over 70 flying hours of in-flight data from the Gnome engine. The EDMS functioned satisfactorily and there was no reported interference with any other aircraft system.

5.1.9 Hercules Engine Test Stand EDMS:

- 5.1.9.1 In 1991, in response to a request from the Allison T56 engine Support Authority, SHL was contracted to develop an EDMS system for the Hercules engine test stand at RAF Lyneham to meet a particular monitoring requirement. However, it became obvious that by monitoring every engine pass-off test, no matter how short, it was possible to generate an EDMS baseline footprint of a typical standard Allison T56 engine in terms of time domain power average and frequency domain characteristics. The baseline, set up from several engines, all in a healthy condition, has been shown to be applicable to all engines of the same type at RAF Lyneham.
- 5.1.9.2 To date, EDMS has monitored over 300 engines during pass-off tests and has accrued over 800 operating hours. EDMS has been shown to be able to positively detect:
 - a. Oil dumping in the exhaust due to seal failure
 - b. Seal break in runs after engine rebuild
 - c. Combustor burning
 - d. Grit wash runs to restore compressor efficiency

5.1.10 Additional Engine Tests - to 1992: EDMS was tested on other engines and rigs over this time period.

5.1.10.1 Marine Gas Turbines: Extensive trials on marine gas turbines were carried out during endurance testing of the engines. Engine testing was carried out on three different types of gas turbines. Typical faults and conditions detected included the following:

- a. Combustor faults
- b. Seal break in
- c. Turbine seal damage
- d. Effectiveness of compressor washing

In some cases EDMS indicated the developing fault hundreds of hours before the conventional monitoring techniques also used during the trial. During the endurance testing the engine was subject to routine inspection, including borescope inspection. Information from the inspections correlated with the EDMS indication of the engine condition.

A stand-alone EDMS was installed on the test bed and used by the test bed staff with limited support from SHL. The developing fault conditions were monitored and detected by the test bed staff.

In addition shipboard trials of EDMS were carried out to demonstrate that the EDMS installation and performance did not affect and was not affected by the shipboard environment. The demonstration achieved the objectives.

5.1.10.2 Other Engine Testing: EDMS has also been tested and demonstrated on the following engines:

- a. T56 at National Research Council, Canada
- b. Rolls-Royce helicopter engines, production and development on the test bed
- c. Combustor development test rig

In all cases the capability of EDMS has been demonstrated successfully, with any indication of faults or additional debris in the exhaust gas corroborated with information about the engine condition or operating mode (e.g., debris seeding tests).

- 5.1.11 Engine Testing Since 1993: EDMS has been tested or used on the following engines during this period:
- a. T56 at RAF Lyneham, as described in 5.1.9
 - b. Reheated/Afterburn Engine - In this application the EDMS sensor was installed in the reheated/afterburner section of the engine. EDMS was used to monitor the exhaust gas during both normal and reheated/afterburn operation of the engine. These tests demonstrated the capability of EDMS to monitor and detect abnormal engine deterioration in both engine operating regimes.
 - c. Current New Engine Development Program - In this application the sensor was mounted in an existing instrumentation port and data was acquired during normal engine running. The engine was also instrumented with tip clearance probes, the EDMS results correlated well with the measured tip rub data.
- 5.1.12 Shoeburyness Trial: The Shoeburyness trial was set up with the primary objective of demonstrating that there are accurate and clearly defined methods for determining, from electrostatic sensor outputs and other engine parameters, when potentially damaging foreign objects (FO) have been ingested into the engine. The secondary objective was a demonstration of the system's ability to indicate whether FO, categorized as potentially damaging, actually did damage.

The trial was carried out in two phases with phase two used as the basis for assessment of the system's ability. The results had to demonstrate that there was strong evidence that the system had the capability to achieve a probability of detection of 90% with a false alarm rate of 10% with an increased database.

The trial involved blind testing of IDMS and EDMS on Spey Mark 101 engines. A range of objects, damaging and non-damaging, were seeded into these engines. The seeded objects included split pins and washers, blanking plugs, pebbles, chalk, tool tags and plastic cups.

The IDMS analysis and classification techniques were tested and refined during the trial on the basis of the increased database covering "fault and no-fault" cases. In addition the feasibility of using a reduced IDMS sensor set to detect foreign objects, without compromising information concerning the ingested object was proved. The benefits of the combined IDMS/EDMS approach was also demonstrated.

The outcome of this trial demonstrates the feasibility of using this approach for monitoring and discriminating ingested debris. The trial also showed that enhancements and improvements in probability of detection, missed alarm rate (correct classification) and false alarm rate can be achieved as the fault population and database increases.

5.1.12 (Continued):

During the trial EDMS was used to monitor deterioration in engine health. From EDMS consequential damage to the LP and HP compressors was detected and diagnosed as well as other engine deterioration. The results were confirmed with engine disassembly reports. EDMS was also used to corroborate IDMS detection and classification of foreign objects passing through the engine, including discrimination of when the ingested object passed through the by-pass duct. Engine surges were also detected.

5.2 Smiths Industries:

5.2.1 The electrostatic engine monitoring system (EEMS) has been successfully tested and proven during thousands of hours of operational engine testing, over the past fifteen years, on over 500 different engines of the following types: F-100, F-110, F-119, TF-41, TF-30, TF-33, J-57, J-79, JT-8, T-700, T-800, CT-58, Aerospey Mark 202, Marine Spey SM1C, RB-211, FT-4, FT-8 and Siemens V-84.2. Smiths EEMS testing is currently planned, or in progress, on the LM-1600, LM-2500, GE Frame 5, 7 and 9, Avon, Allison, F-404 and F-414 engine types.

5.2.1.1 This operational demonstration testing, both ground and airborne, has conclusively proved that the EEMS can provide enhanced safety through early warning by predicting potential engine component damage and failures well before they will occur (normally 80 to 100 h) and can identify the specific incipient failure mechanism. Cumulative EEMS diagnostic testing has provided an empirically based EEMS diagnostic database which has shown that, once the relationship of a specific EEMS electrostatic pulse shape has been established to a specific failure or damage mechanism, this pulse shape vis-à-vis damage failure mechanism relationship is universally repeatable across all different engines and engine types.

5.2.1.2 For example, in a recent in situ test of an aero-derivative marine gas turbine engine, the Smiths EEMS detected and identified two potentially catastrophic failure mechanisms that were occurring simultaneously based on comparison of similar pulse signal shapes contained in Smiths proprietary EEMS diagnostic database. These pulse shapes were matched with similar ones obtained in previous EEMS testing and indicated combustor can delamination and turbine seal erosion with an early warning margin of 60 and 150 operating hours, respectively.

5.2.1.3 The Smiths Industries EEMS is undergoing testing on the AV-8B Pegasus -406 and -408 engines at the U.S. Naval Depot at Cherry Point, North Carolina to establish application specific EEMS pulse rates, binning (classes of pulses) requirements, caution/warning thresholds/trigger levels, and a Pegasus engine EEMS diagnostic "map".

- 5.2.2 The myriad of tests of the Smiths EEMS, both ground and airborne, have consistently proven the EEMS engine condition monitoring capability provided by the prognostic (detection of incipient failures via increases in pulse rates) and diagnostic (identification of specific failure mechanisms via repeatable pulse shape signatures) features inherent in the EEMS design. Smiths is currently finalizing the development of a real-time EEMS diagnostic system based on a proprietary neural network/expert system implementation.
- 5.2.2.1 Operational flight testing has successfully demonstrated the flightworthiness and viability of the integral plasma sprayed and gasket "sandwich" annular EEMS sensors to withstand the rigors of the full engine flight regime operation and environment for both fixed and variable geometry engines.
- 5.2.3 As indicated in the Introduction, the electrostatic technology, upon which the Smiths EEMS technology is directly evolved from and based, has been evolving over the last 20 years. First developed by United Technologies Corporation (UTC), Smiths Industries obtained full world-wide rights to the technology, patents, trade secrets and know-how, via an October 1991 Licensing Agreement, and has enhanced and developed the EEMS to where it is ready for application specific customization and production.
- 5.2.3.1 Since October 1991, Smiths has been involved with a continuum of EEMS demonstration test programs which have formed the basis for evolving a third generation EEMS system for real-time engine condition monitoring which will provide continuous status of the core engine including any damage resulting from ingested debris.
- 5.2.4 Selected Operational Demonstration Test Summary:
- 5.2.4.1 Fixed Wing Aircraft Applications:
- 5.2.4.1.1 In the 1980's, a series of joint EEMS ground and flight tests were conducted, in conjunction with the U.S. Air Force, at K.I. Sawyer AFB, Michigan; Charleston AFB, South Carolina; and MacDill AFB, Florida on the J-57 (B-52); TF-33 (C-141); and F-100 (F-16) engines, respectively. These tests demonstrated that the EEMS can detect incipient failures and damage that are not manifested by either other engine instrumentation or degraded engine performance.
- 5.2.4.1.2 During the MacDill AFB tests, the EEMS identified a turbine blade crack in an F-100 engine which was not indicated by any other engine performance indications and instruments and was not detectable during a borescope visual inspection. Based on the EEMS indications, an engine teardown and inspection was subsequently accomplished and the turbine blade crack was observed and verified.

- 5.2.4.1.3 At the conclusion of the C-141 (TF-33 engine) EEMS ground and flight tests at Charleston AFB, the DCS Plans of the Military Airlift Command wrote "the experience gained with the EEMS at Charleston AFB proved the theory of electrostatic monitoring and the EEMS can accurately monitor performance and identify the area(s) of deterioration within the engine while operating in an operational environment."
- 5.2.4.1.4 An EEMS test was conducted at the U.S. Navy Air Warfare Center (NAWC) at Lakehurst, New Jersey on a J-79 engine removed from an F-4 Phantom. The primary purpose was the exploratory development of a generic U.S. Navy neural network for mechanical equipment diagnostics. Smiths provided EEMS hardware and software including diagnostic data from Smiths self-training EEMS neural network. The final U.S. Navy test report stated "the Smiths EMS worked as advertised." Based on the results of this test, the U.S. Navy requested that the EEMS be set up at the NAWC Trenton facility to monitor F-110 and F-404/-414 engine tests.
- 5.2.4.1.5 Smiths recently completed an F-119 EEMS ground test at Pratt & Whitney (P&W) sponsored by the Joint Advanced Strike Technology (JAST) Program Office. Based on the promising test results, a F-119 EEMS flight test demonstration is expected in the near future.
- 5.2.4.1.6 Under the auspices of the USN AV-8B Program Office and the USAF/USN/USMC Joint Strike Fighter (JSF) Program Office, Smiths is currently under contract to conduct an EEMS ground test of the AV-8B Pegasus -406 and -408 engines to demonstrate the full spectrum prognostic and diagnostic engine conditioning monitoring capability of the EEMS using a neural network/ expert system implementation.
- 5.2.4.2 Rotary Wing Aircraft:
- 5.2.4.2.1 Initial EEMS helicopter testing was accomplished on a HH-53E helicopter at the Sikorsky, Stratford, Connecticut facility. The flight test was conducted using an EEMS sensor made of tubular steel mounted externally aft of the engine. These tests confirmed that the EEMS could detect and capture electrostatic pulse signatures in flight and store them in an on-board computer.
- 5.2.4.2.2 In late 1991, the EEMS was integrated into a test cell for the initial test run of a new, small turbo-shaft helicopter engine. The EEMS demonstrated two significant accomplishments. The EEMS was able to monitor and accurately track the initial break-in period for this new engine and, approximately 460 hours into the initial test run, flagged the presence of an incipient failure beginning to occur in the compressor. The engine and test cell instrumentation did not indicate the presence of the problem until 67 hours after the EEMS early warning indication. The engine was shut down and teardown and inspection verified the presence of the compressor problem.
- 5.2.4.2.3 Smiths EEMS has also been operated as part of the U.S. Navy AVIDS program at the NAWC Trenton, New Jersey facility to monitor the T-700 engine which is used on the Navy's SH-60 aircraft.

5.2.4.2.4 The most recent EEMS airborne test was jointly sponsored by the UK Ministry of Defence, Bristow Helicopter and Smith Industries, with participation by the UK Civil Aviation Authority, on a Sikorsky S-61 helicopter owned and operated by Bristow for HM Coast Guard at HMS Dadaelus at Lee-On-the-Solent, England. The EEMS was flown and operated for over 800 operational flight hours. During this period, a scheduled engine changeout was accomplished and resulted in unequivocal evidence that the EEMS electrostatic pulse signatures are repeatable for different engines of the same type. Consistent signals reflecting compressor rub, turbine seal wear and salt water were detected, captured and identified for both CT-58 engines to verify repeatability of the specific pulse shape versus failure/damage mechanism relationship. These tests also verified the viability and reliability of the plasma sprayed annular EEMS sensor for airborne use.

5.2.4.3 Industrial and Marine:

5.2.4.3.1 Smiths was requested by the UK Royal Navy to put the EEMS on a Marine Spey engine at the Admiralty Test Facility at Pyestock, England. The EEMS was fitted to the engine for the final 600 hours of a 3000 hour endurance test. The condition of the engine was unknown at the initiation of the trials. The test site is constructed to simulate conditions at sea including the injection of salt water spray during engine operation. The EEMS continuously monitored the engine operation and was able to distinguish fresh water (used for periodic compressor washes) from salt water. During this test the EEMS accomplished the detection and identification of two potential catastrophic failures simultaneously.

5.2.4.3.1.1 During the early stages of the EEMS test (2400 to 2750 hours) a certain pulse type was generated at a rate of approximately 50 pulses per minute. At around 2750 hours this same pulse signature rate increased to 140 pulses per minute. A comparison with known pulse shapes from other previous EEMS tests indicated that the failure was in the combustor section. A borescope inspection was done at 2810 hours and it was verified that two combustor cans had delaminated. Following replacement of the two failed combustor cans, this particular pulse rate decreased to about 10 pulses per minute. The EEMS provided in excess of 60 hours of early warning from the time the pulse rate increased until the time the combustor cans were replaced.

5.2.4.3.1.2 At approximately 2700 hours, the rate for a different pulse signature started to increase dramatically from zero (about 85 hours before the combustors were replaced) and it was determined that another incipient failure was occurring in parallel with the combustor can failure. The pulse rates continued to increase asymptotically until approximately 2950 hours when the pulse rate saturated the memory of the EEMS ground computer. Again, a comparison with prior known pulse shapes indicated a problem in the turbine section. Physical teardown and inspection verified advanced seal erosion in the first stage turbine.

5.2.4.3.2 The Smiths EEMS has been successfully tested on industrial engines, including aero-derivative engines, used for power generation/co-generation, natural gas transmission, and oil pipelines and pumping stations. EEMS pilot pre-production prototype programs are currently ongoing with PSE&G of New Jersey (power generation/co-generation), NOVA of Alberta, Canada (natural gas) and Saudi Aramco of Saudi Arabia (oil).

5.2.4.4 Health and Usage Monitoring Systems (HUMS):

5.2.4.4.1 Although EEMS is an autonomous, self-contained engine condition monitoring system, it can be integrated into other mechanical diagnostic systems such as HUMS. The EEMS data acquisition and processing functions can be repackaged to fit into other multi-functional health monitoring systems such as Smiths HUMS which is being developed under contract with the UK MOD for the Chinook helicopter.

5.3 UK MOD Shoeburyness Trials:

5.3.1 Background: Following the work undertaken by UK MOD on both the Stewart Hughes and Smiths Industries systems outlined in 5.1 and 5.2 a decision was taken to carry out further back to back trials of the available electrostatic systems installed in a Rolls-Royce Spey Mk 101 engine at DTEO Shoeburyness. The primary objective of the trial was the demonstration of foreign object detection and classification capability. A secondary objective was a demonstration of capability to detect actual damage. Initial testing of the systems during early 1995 involved the deliberate insertion of potentially damaging and non-damaging items into the running engine. This blind testing confirmed the ability of all of the sensors to detect electrostatically charged particles and that the Stewart Hughes combined system had the potential for foreign object detection and classification but that the SI system was poor on detection and classification was unachievable. Generally the sensor technologies were proven but the processing and analysis was not sufficiently developed. The companies used the data collected and details of the item ingested to improve the processing and prepare for a further series of tests.

5.3.2 Phase II Trials: The second phase of trials consisted of three test sets:

- a. Test Set 1: One run with eight ingestions, four non-damaging and four potentially damaging. These were open runs aimed at system checking.
- b. Test Set 2: Four runs with a total of 17 ingestions; these were blind and were intended to be the prime test set.
- c. Test Set 3: Three runs with a further 17 ingestions, again blind, to provide a further test set to be used as required.

5.3.3 Results:

5.3.3.1 Test Set 2: Following analysis of both contractor results and scrutiny of the video tapes it was concluded that 3 of the objects from test set 2 were not ingested and that 2 ingested objects did not pass through the engine. The results were, therefore, analyzed out of a total of 14 for SHL and 12 for SI.

5.3.3.1.1 Stewart Hughes: The Stewart Hughes results for the 14 events from test set two were as follows:

- a. Of the 14 ingestions all the foreign objects were identified.
- b. Of these six were correctly categorized (mainly non or possibly damaging). The remainder were miscategorized.
- c. All surges were identified.
- d. There were four false alarms.

5.3.3.1.2 Smiths Industries:

- a. Of the 12 ingestions, six were correctly identified as foreign objects. A further two (frangible objects) were identified as surges.
- b. There were a further four false alarms.
- c. Of the four false alarms, two were surges classified as foreign objects.
- d. No attempt was made to categorize the foreign objects as either non-damaging or potentially damaging.

5.3.3.2 Test Set 3: Test set three had 17 ingestions planned; one was assessed as having missed the intake, one was an unfair test for SI since it was left in the intake on start up and then wrapped around an IGV but one was a double ingestion, the results were assessed out of 17 for SHL and 16 for SI.

5.3.3.2.1 SHL Results:

- a. Of the 17 ingestions, 14 foreign objects were identified.
- b. Of these 14, ten were correctly categorized and four were miscategorized.
- c. There were two false alarms.
- d. There were two surges that were correctly identified.

Between the two sets of runs SHL undertook a review of their analysis technique and altered some of the limits applied to the various factors which are used to characterize the FO. The effects of this can be clearly seen in the results of test set three. Of the three missed ingestions, one was a double ingestion (chalk stick and DZUS fastener) and although the process did not flag up two objects, SHL personnel identified this as an odd event; probably the result of a multiple ingestion. The remaining two were reanalyzed after the evaluation and were identified. These had previously been ruled out of consideration due to a detection threshold in the processing. Minor alteration of the threshold and application of the standard classification algorithm would result in correct classification of both of these objects.

It can be seen from the above set of results that SHL have produced a detection and analysis system that is highly capable of detecting objects entering the engine. Of perhaps greater importance is their ability to discriminate between damaging and non-damaging FO. The latest trial contained a number of ingestions during accelerations and although these were detected they formed the majority of the miscategorizations. SHL have identified this as a weakness in the determination of velocity factor during transients and have suggested a possible solution to this problem. There were two false alarms one of which was very close to the charge factor threshold which is being continually refined as experience increases. It is clear that the false alarm rate is commendably low and further experience should reduce it further.

5.3.3.2.2 SI Results:

- a. Of the 16 ingestions 7 FO events were recognized with three FO events categorized as surge.
- b. There were no false alarms.
- c. There was one surge that was correctly identified.

From the results of test set 2 and test set 3 the FO detection rate was much improved over the initial testing (13 out of 28 compared with 4 out of 13); even more impressive was the reduction in the false alarm rate (FAR) with only four false alarms. Two of the ingestions were designed to be particularly difficult to detect: the first was during an acceleration where it could have been masked by the naturally occurring increase in activity level and the second the simultaneous drop of the DZUS fastener and the chalk. SI did well in both of these cases only falling down by calling the chalk stick a surge.