OTIC FILE COPY

(4)

APRL-PROP-TM-455

AR-005-575

AD-A210 374

DEPARTMENT OF DEFENCE

DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION

AERONAUTICAL RESEARCH LABORATORY

MELBOURNE, VICTORIA

Propulsion Technical Memorandum 455

REPORT ON AN OVERSEAS VISIT
JUNE 1988

DTIC
ELECTE
JUL 19 1989
S D
D

by

D.E. GLENNY

Approved for Public Release

DISTRIBUTION STATEMENT A
Approved for public release;
Distribution Unlimited

FEBRUARY 1989

89 7 18 048

AR-005-575

DEPARTMENT OF DEFENCE
DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION
AERONAUTICAL RESEARCH LABORATORY

Propulsion Technical Memorandum 455

REPORT ON AN OVERSEAS VISIT
JUNE 1988

by

D.E. GLENNY

SUMMARY

A visit was undertaken in June 1988 to attend the 71st Symposium of the AGARD Propulsion and Energetics Panel (PEP) on Engine Condition Monitoring - Technology and Experience held in Quebec Canada and to visit selected industry, military and research facilities in Canada and USA. The latter visits were to discuss methods for assessing gas turbine performance when operating with and without faulty components. A total of 8 establishments were visited in Canada and the USA. In the course of the visit an opportunity was taken to hold preliminary discussions on the establishment of Key Technical Areas (KTA) in the newly formed TTCP HTP-7. At the conclusion of the tour a visit was made to the Singapore Ministry of Defence (and Singapore Aircraft Industries) to discuss aspects of Performance Monitoring and the installation of the GE F404 in the Skyhawks of the Royal Singapore Air Force.

DSTO ARL MELBOURNE

POSTAL ADDRESS: Director, Aeronautical Research Laboratory,
P.O. Box 4331, Melbourne, Victoria, 3001, Australia

CONTENTS

1. INTRODUCTION

The Aerodynamics and Aeropropulsion Division at ARL has through its Engine Performance Group carried out a research and development programme into engine performance assessment techniques and fault identification procedures on military gas turbines. The Laboratory through contacts established with colleagues overseas and more recently through TTCP HAG 8 has been able to make significant contributions in the field of Engine Performance Monitoring.

This visit was undertaken partly in response to a request to present papers to the 71st Symposium of the AGARD Propulsion and Energetics Panel (PEP) on Engine Condition Monitoring - Technology and Experience and partly to visit selected industry, military and research establishments carrying out work complementary to that being performed at ARL on Engine Performance Assessment. Particular emphasis was given during the visit to performance aspects of the GE F404 and T700, the P & W TF30 and Lycoming T53 engines which are operated by the Australian Services. A detailed itinerary of the visit is given below:

.	30 May - 3 June	71st AGARD PEP on Engine Condition Monitoring - Technology and Experience Quebec, Canada.
.	6 June	National Research Council Ottawa, Canada.
.	7 June - 8 June	General Electric Company Lynn, Massachusetts.
.	9 June	Textron Lycoming Stratford, Connecticut.
.	10 June	Naval Air Propulsion Center Trenton, New Jersey.
.	13 June - 14 June	US Army Aviation Applied Technology Directorate, Fort Eustis, Virginia.
.	15 June	Kelly Air Force Base (USAF) San Antonio, Texas.
.	16 June	South West Research Institute San Antonio, Texas.
.	20 June	Arvin Calspan Corporation Buffalo, New York State.
.	23 June	Singapore Ministry of Defence and Singapore Aircraft Industries Singapore.

2. VISIT HIGHLIGHTS

Highlights of the conference and scientific discussions which took place during the visit are given in the following sections.

2.1 AGARD Symposium

A main part of the visit was to attend the 71st AGARD PEP on Engine Condition Monitoring - Technology and Experience. ARL had been invited by the AGARD Executive to attend and present papers to this particular Symposium: AGARD meetings are normally restricted to attendees from NATO countries. Two Australian papers were presented, these were:

- Gas Path Analysis and Engine Performance Monitoring in a Chinook Helicopter, and

- Identification of Dynamic Characteristics for Fault Isolation Purposes in a Gas Turbine Using Closed-Loop Measurements.

The papers were given by Glenny and Merrington respectively of the Engine Performance Group, ARL.

The symposium which covered nearly a full week of presentations, attracted 42 separate papers (one of which, paper 17, was withdrawn) ranging from theoretical discourses to the inevitable sales pitches. The attendance by AGARD standards was excellent with over 200 observers representing most NATO countries. A list of papers presented is given in Appendix A: a set of conference preprints is held by the author and will be forwarded to the ARL library once the conference proceedings have been published in full. The Programme was divided into seven sessions entitled:

(i) Military Operations
(ii) Civil Experience
(iii) Manufacturer's Perspective
(iv) Turboprops and Turboshafts
(v) Systems
(vi) Diagnostic Methods
(vii) Advanced Technologies

In addition one afternoon was set aside for technical tours which included:

a. Defence Research Establishment
Valcartier, Quebec,

b. CFB Bagotville (F-18 Base), or

c. Local Paper Mill.

Because of obvious interest in F404 operations the author elected to visit the Canadian Forces F-18 Base at Bagotville.

Military Operations

Eleven papers were given in this session, topics ranged from overviews on generic and particular monitoring and maintenance management systems to a minority of

papers which gave details of service experiences and analytical methods used in assessing engine condition. The former batch of papers provided, to varying degrees, basic introductory information on setting up Engine Monitoring Systems (EMS).
As noted by Hess of Navair, comprehensive EMS requirements are now included in the USA Military Specification for Turbojet and Turbofan engines, and Turboshaft and Turboprop engines MIL-E-500E (AD) and MIL-E008593E (AS) respectively. The Air Forces of Canada, United Kingdom and Europe in general, now either suscribe to the US Specifications or have developed their own specifications for monitoring engine condition.

The paper by Schofield et al of Canada gave a comprehensive resume of Canadian Forces policy with Engine Condition Monitoring techniques ranging from Magnetic Particle Detectors, Vibration Analysis, Performance Trending to an indigenously developed "On Line Debris Monitor - Ferroscan" developed by the Atomic Energy of Canada Ltd.

British interest in EHM is best summarised in their (Air Staff Target) AST 603 trial which involved the installation of data recording systems in 12 operational RAF Hawk trainers. Data analysis encompassed monitoring for:

- Life usage,
- Mechanical Condition,
- Performance, and
- Limit Exceedance.

As a result of this Air Staff Target, monitoring programmes are to be introduced in one form or another on at least six RAF fixed wing aircraft and 3 rotary wing aircraft. EHM is now a widely accepted maintenance tool in UK, and will be introduced on all new aircraft including the new European Fighter Aircraft (EFA) and the Anglo-Italian helicopter EH101.

In contrast to the broad approach adopted by the British, the German philosophy was much more limited. The OLMOS (On Board Life Monitoring System) developed in the Federal Republic of Germany for use in their Tornado aircraft is restricted to assessing engine and aircraft usage and to monitoring limit exceedances; it is not to be used as a vibration or a performance indicator.

The most comprehensive monitoring system described at the symposium was the CITS or Central Integrated Test System as installed on the USAF B1-B bomber. This system continually monitors the performance of 34 aircraft (principal) systems including the four engines: approximately 19,000 parameters are available for recording and display purposes. Systems architecture is designed to isolate faults, automatically, to a single LRU (Line Replaceable Unit) with a minimum of human intervention. Development problems have been considerable, with numerous false failure indications occuring especially in the engine diagnostic area. A month-long evaluation of CITS has been conducted on an operational B-1B base to determine system reliability and usefulness. (To an independant observer it appears to be a bit late in the application process having instrumented 13 aircraft/engines to be checking on system usefulness).

Only two papers, one by the Canadians on CF-18 (F404) EPM and another by Turkey on F110 Engine Monitoring for the F16C/D gave specific analyses of monitored data. The former paper was very explicit and detailed analyses for three separate 'windows':

- IECMS Take-Off Record,
- Engine Test Cell Data, and
- Ground Test Runs.

Effects of changes in fuel specific gravity, high pressure turbine efficiency and compressor vane geometry are described in terms of engine/component performance shifts, i.e. intake mass flows, engine acceleration times and fuel flow schedules. Fault libraries or matrices derived from engine simulations (computer modeling) are given for changes in component or module properties (efficiencies or flow areas). The Turkish paper described an Engine Monitoring System developed by GE Evendale and a Minimum Essential Engine Tracking System developed by the USAF. Typical data outputs were given in terms of status of tracked components and those items closest to specific life limits on each engine. No data on engine performance levels or gas path condition of engine components were available.

Civil Experiences

Five papers were presented on civil experiences, four of which were given by representatives of Lufthansa, British Airways, Alitalia and Air France. The final paper was given by the Vice-Director of the Municipal Energy Board, The Hague Holland, and was more concerned with the concepts of combined cycles for electricity and heat production, than monitoring of the plant for maintenance purposes. An additional paper (42) by Rolls Royce on their COMPASS system was also presented in this session.

Two of the airline papers described engine monitoring systems in use on the A310 and A320 Airbuses. These aircraft/engines employ a flexible engine monitoring procedure developed by General Electric called GEM (Ground based Engine Monitoring) and is described in more detail in paper 22. The implementation of these monitoring systems in reducing maintenance costs, their contribution to early failure detection and monitoring the performance of high by-pass ratio engines was well documented. The basic systems were very similar and used data derived in flight at steady state cruise conditions recorded either manually or automatically. Data were invariably analysed at a base station having been transferred to the ground at the completion of each flight, or telemetered back to base by satellite. The systems analysis procedures were applicable to the military role, but the data source was invariably obtained from a well controlled steady state environment, not normally the case in a military operations.

The final paper in this session was given by Rolls Royce on their COMPASS system. This method has been developed as a generalized Ground-Based Monitoring System for application to both civil and military engines from any manufacturer. The method uses gas path analysis techniques and Kalman Filtering Methods, with the addition of a proprietary "highlighting algorithm", to assess engine or module performance whilst simultaneously accounting for sensor errors and noise. Specific examples of results using this technique were presented, but due to the proprietary nature of the procedures it was not possible to assess its validity or effectiveness. Rolls Royce are proposing to market the method through a "Neutral Host" (or independent software company) to protect their algorithms and participants' data files, hence its application to all engines.

Manufacturer's Perspective

Six papers were presented by representatives from P & W, GE, RR, SNECMA and MTU. With the exception of one paper given by GE, they were all concerned with military engine monitoring.

The commercial GE paper detailed the development of their GEM, Ground based Engine Monitoring Systems, and its introduction and application to the CF6 and CFM56 families of engines. A detailed description was given of system hardware, instrumentation and their connections, via the Propulsion Multiplexer (PMUX), to engine sensors. Operational experience on the CF6-803 had encountered problems with:

- water contamination of tranducers,
- impedance matching of temperature signals, and
- incorrect match of engine baselines with data capture windows.

Not withstanding the implementation problems, Lufthansa, through diligent use (continual monitoring and appraisal of data) are reporting quantifiable savings as a result of:

- early failure detection,
- improved module management,
- "cold" fan trim balancing, and
- reductions in fuel and overhaul repair costs.

GE believe that application of the GEM system to their series of engines promises to give better engine maintenance: the GEM concepts and its applications will increase with the development of miniaturized electronics and full authority digital engine controls (FADEC). (It must be noted that the GEM system, as with RR COMPASS and the equivalent P & W procedures, are currently only configured around company engines). The requirement to transfer design technology or company confidential data to be incorporated in these systems preclude them being applied to alternate manufacturers unless through a "Neutral Host" as proposed by Rolls Royce.

The GE military engine monitoring presentation described engine monitoring systems for the F101-GE-102 (B-1B aircraft) and F110-GE-100 (F-16 C/D aircraft) engines, designed and built in Cincinnati. The GE F404 as operated by the RAAF comes from Lynn and little, if any, cross reference of monitoring systems concepts or design data occurs within the company. (The Inflight Engine Condition Monitoring System (IECMS) as used on the RAAF GE F404 engines was conceived and developed by the US Navy in conjunction with McDonnell Douglas, GE were only responsible for the sensor package and software algorithm development). The GE (Cincinnati) presentation on their EMS detailed, as with the unrelated GEM system, the development and introduction of the equipment and system in the B-1B bomber and the F-16 C/D aircraft. The EMS ability to detect faults or failures in Line Replacable Units (LRU), and its capabilities in parts life tracking and engine exceedance recording was presented, however no analytical procedures were detailed. As with the majority of papers in the first part of the symposium, considerable detail on system definition, specification and installation was given but little background of analytical techniques were presented.

The SNECMA and Rolls Royce papers, the former being given in French, described a series of inservice trials, and detailed the philosphy behind the need for usage monitoring and cycle counting. Again details of the system, and in particular blackboxes, tended to dominate the presentations, however monitoring objectives were well described.

The final paper in this session, by MTU, on Engine Thrust Rating for the Rolls Royce RB199 was quite different, it described a recently installed procedure on German Tornado aircraft which employs a thrust rating concept for setting up the RB 199 engine in place of the conventional HP turbine temperature limiter. With the introduction of Digital Engine Control Units (DECU) on the RB 199, a facility became available which allowed the engines to be set to a given thrust level defined as a function of low compressor speed (with due allowances made for the effects of ambient conditions), component deterioration and turbine limiting temperatures. This procedure, in contrast to setting the engine to a given maximum temperature with consequently higher and more variable thrust levels, enables consistent thrust levels to be obtained, and shows considerable potential for increasing turbine blade life. The procedure is similar in concept to that being introduced on RAAF Atars which are set to a fuel flow and thrust limit rather than a specific maximum exhaust gas temperature.

Turboprops and Turboshafts

Three papers were given in this session; two papers gave results of inservice monitoring trials while the last one was devoted to test cell performance.

The first paper analysed inflight, manually derived performance data for three engines - P & W PT6 and P120 and GE CT7. Performance trends for fuel flow, turbine temperature and engine speed were presented for set operating conditions. Fault diagrams for various combinations of these trends have been generated and are to be used to indicate faults in the engine. The method follows basically the engine manufacturers' trend analysis procedures.

The second paper, on an in service monitoring trial, used data acquired automatically using specialised instrumentation in a Lycoming T55 engine in a RAAF Chinook helicopter. Specific cases were analysed in relation to the performances of the system as a whole and its ability to predict component performance using simplified gas path analysis procedures.

The final paper described the repeatability of a series of back to back tests carried out on a Canadian Forces Allison T56-14 turboprop engine following rebuild of the compressor. This work was carried out to establish baseline repeatability of test results prior to carrying out performance tests on "super smooth" compressor blade coatings which are purported to offer significant aerodynamic improvements and hence savings in fuel consumption. Little specific data on engines with coated compressor blades is currently available and it is anticipated that these, well-controlled tests will provide definitive answers to the claims of the coating manufacturers.

Systems

Six papers were presented in this session, again, they were predominately component or blackbox in orientation. The paper by GE Avionics dealt basically with the integration of monitoring equipment into the aircraft/engine sub-systems. It was noted that, with the introduction of MIL STD 1553 buses and FADEC engine controllers, more comprehensive monitor systems can be developed, installed and if required retrofitted. However it was emphasised that the benefits of a monitoring fit must be balanced against the cost of the investment.

A second paper presented by SFIM, a French instrumentation company, described application of various monitoring systems to three types of commercial aircraft. Details on a range of recording modes and their advantages as effective maintenance tools were presented but again little detail on analytical techniques or cost benefits of the variety of systems was given.

Two papers on vibration analysis and diagnostics were presented by Stewart Hughes (UK) and jointly by Rolls Royce and MOD PE of the United Kingdom. The former paper detailed methods of selecting the most appropriate vibration parameters to monitor so as to maximise fault detection capabilities. A number of examples on FM discriminators and their application to gear monitoring were given. The use of "transputer" technology to assist in airborne data processing was touched upon in the development of avionic hardware: Stewart Hughes are actively participating in developments and application of Fourier Analysis chip technology for inflight vibration diagnostics. The second vibration paper was more concerned with the development of computerised vibration diagnostics to enable relatively inexperienced service personnel to carry out investigatory engine tests. The study encompassed identification of equipment and analytical procedures ranging from basic hand plotting of vibration levels to the use of a Mechanical System Diagnostic Analyser (MSDA) marketed by Stewart Hughes. Knowledge Based or Expert System procedures are being included in the vibration diagnostic package which will be used initially as a ground based system but will later on be extended to give an onboard capability.

The final two papers were on Fault management in Power Plant Controls and an Installed Thrust Predictor for Monitoring Jet Engine Performance. The Controls paper reviewed the development of digital engine controls and discussed the emergence of fault isolation capabilities that could be built into them. Built in fault detection capabilities and fault accomodation procedures were discussed along with their associated hardware and software. Few specific details or examples were given. The Thrust Predictor is an extension of a device developed and marketed by Computing Devices of Canada: CDC have had extensive involvement with systems for determining installed thrust. Their latest paper (at Quebec) foresaw the thrust meter being used in a given installation to monitor engine thrust degradation with time and to assess engine trim during initial engine installation and maintenance actions. Observation or trending of decrements in thrust level as against determining absolute thrust levels relieves, somewhat, the need to calibrate the meter to its actual environment. The integration of the device with other monitoring systems was alluded to but was not developed.

Diagnostic Methods

This session produced the most theoretical papers of the symposium in that detailed expositions were given on both steady state and transient diagnostic procedures. The topics included complex extensions to gas path analysis, ranging from procedures to:

- decrease uncertaintity of estimates of parameters,

- identify faults where the number of measurands is smaller than the numbers of variables to be diagnosed,

- develop influence coefficients to account for sensor faults as well as gas path faults, and

- minimise noise;

to methods for:

- identifying faults in engine components from correlations of engine transient data,

- modelling of engine transient responses using estimation theory to match both experimental and simulated data (with noise added), and hence

- developing fault libraries based on calculated changes in engine spool dynamics, i.e. engine time constant and gains.

Considerable interest was shown in these latter methods, which attempted to deduce engine component changes or faults from transient data. While many observers had reservation about use of transient data (analysis under steady state conditions is difficult enough), it was agreed that procedures based on the assessment of engine spool dynamics with and without faults looked promising and could identify faults which would not necessarily be discernable by other techniques.

Advanced Technologies

Four papers were presented in this the final session. Topics discussed included:

- advanced control and monitoring of rocket engine - Space Shuttle,

- an intelligent, on condition monitoring system for determining ferro-magnetic debris in lubricating oil,

- a method for assessing debris in a gas path flow, and

- the development of a plume spectrometer to monitor exhaust gases of rocket engines.

The penultimate paper presented by Stewart Hughes was of interest for its application in gas turbine monitoring. The paper described the development of an electrostatic device to evaluate the presence of engine gas path flow particulates or debris. The device based on some original NASA work has been used to monitor effects of blade tip rubs and to assess dust ingestion in a gas turbine. The non-intrusive hardware has been patented and is commercially available.

2.2 VISIT TO NATIONAL RESEARCH CENTRE CANADA (NRCC) OTTAWA CANADA

Dicussions were held with:

Mr. Don Rudnitski	Head of Engine Laboratory
Mr. Jim McLeod	Research Officer
Ms. Sue Abu-Hakima	Research Officer

Main areas of interest were in F404 engine performance which included:

- exchange of data through the F/A-18-MOU-Canadian Forces and RAAF,
- fault testing in F404,
- instrumentation and test methods, and
- development of engine models.

It was agreed that an exchange of data should occur as soon as possible, preferably before the end of August 88. It would include ARL supplying data on:

- Results from ARL transient F404 engine model detailing effects of OAT for a number of PLA excursions at sea level conditions. Data would be presented in a normalised form.
- A comparison between ARL's experimental tests on the F404 and the results from the transient engine model for a limited set of conditions.
- Details on input arrays and switches used by ARL on their GE F404 SCAT model for comparison with the Canadian equivalent.
- ARL vibration philosophy used in analysing F404 test data.
- Specification by ARL of out-of-balances, to be input in to NRC test running of their Allison T56 engine, this would include location of vibration pick up probes for data to be supplied to ARL.

NRC would respond by supplying:

- data on stage stacking methods used in their F404 and T56 steady state models, and
- results on out-of-balance tests on their T56 engine to ARL specifications.

Canadian transient fault analysis techniques have concentrated on correlations of data acquired during IECMS ground take-off phase when the aircraft exhaust nozzle is in a closed position At present NRC do not propose to continue the work of Henry (paper 37 AGARD Symposium), rather they are to develop alternative procedures which will culminate in the development of a transient F404 engine model. NRC have a Research Engineer working full time on engine model development. The first application will be in the area of steady state and transient simulation for the Allison T56. This work will then be extended to the F404.

NRC instrumentation and test procedures were discussed and inspected. Special instrumentation on their F404 comprises:

- 4-off GE bellmouth pressure rakes,
- 2-off boundary layer pressure rakes in bellmouth for mass flow correlations,

- 2-off GE temperature and pressure rakes at station 2.1 - Fan outlet duct,
- 1-off GE temperature and pressure rake at H.P. compressor outlet,
- 1-off static pressure at H.P. compressor outlet,
- 1-off Temperature at H.P. compressor inlet and the Nozzle exit area via J61 plug on the ECU (On return to Australia it was found that this plug should not be used without GE permission - ARL will follow this up with NRCC and GE),
- 7-off accelerometers monitored through a Stewart Hughes Mechanical System Diagnostic Analyser (MSDA), and
- 4-off water wash nozzles for compressor cleaning.

Canadian/NRC transient data from the F404 test cell are recorded through an IECMS and a NEF system but these are limited in their overall acquistion rate. They are not as comprehensive as the system used at ARL.

The visit concluded with a short briefing by Ms Sue Abu-Hakima on NRCC involvement in Artificial Intelligence. Ms Abu-Hakima a research officer has been seconded to the Engine Laboratory to work on expert systems as applied to engine diagnosis and fault identification. A number of questions were raised during a short briefing on ARL TF30 IFDIS program and a written request for information has been forwarded to Mr. Denis Frith at ARL.

2.3 VISIT TO GENERAL ELECTRIC, LYNN, BOSTON.

Discussions were held over 2 days on performance and operating behaviour of the GE F404 and T700 engines.

GE F404

Contacts were made with:

Eric Stilphen	Foreign Military Sales
John Kiley	Manager F/18 Australia & Canada Programs
Bob Knutsen	F404 Test Engineer
Mark Taylor	F404 Service Engineer, Controls and Accessories
Craig Litster	RAAF Resident Quality Assurance Engineer

The meeting commenced with a discussion of ARL's current engine testing program to assess F404 performance and diagnosis of faults using transient data. A copy of G.L. Merrington's (ARL) paper to ASME was handed over for reference. GE suggested a number of methods for implanting engine faults during ARL's next test series these included:

- Setting Fan or Compressor Guide Vanes to top or bottom of limits; a range of combinations may be used.
- Engine could be run with variable geometry failure or in the default mode, without any deleterious effects. (In this regard GE stated that

the recent F404 failures in the 1st and 3rd High Pressure compressor stage were due to a failure or malfunction of only one variable guide vane and not due to a misscheduling of the complete system, even then it was only prevalent during high 'g' decelerations).

- Resetting density corrector.
- $T_{2.5}$ sensor - pin and yoke has range of positions and could be set to its upper and lower limits.
- A_8 Variable Exhaust Nozzle feed back system, decrease or increase length of actuators.
- Bleed off from PS3 to main fuel control unit. GE have done some work in this area but were unable, or unwilling, to discuss results of tests.

General Electric would not comment specifically on the effects of any of the suggested fault inputs, but would be prepared to comment on proposed tests if ARL forwarded a schedule to them. ARL requested information on availability of separate (i.e. to MFCU) $T_{2.5}$ probes, GE stated that they had used a dedicated probe during engine testing but installation had involved modifications to compressor casing in the region of the flow splitter at inlet to the HP compressor. It was pointed out that there was a borescope hole at this location, and that ARL with some ingenuity could perhaps develop their own sensing system. A probe at this location would not necessarily replicate the $T_{2.5}$ values obtained by the MFCU probe, but would be indicative of temperature levels and the profile. GE suggested that a comprehensive list of faults could be obtained from the trouble shooting manual or from major causes of inflight shutdowns. A typical current shutdown list is given in Table 1. Comment was also made on the possibility of implanting a number of faults into the GE F404 transient engine model rather than carrying out series of engine tests: ARL pointed out that this was difficult with an object code model. GE in response suggested that if a list of data inputs, for changes to the model, could be forwarded to GE via NAVPRO in Washington, then GE would investigate the possibility of incorporating these modifications into the basic computer program.

GE T700

Contacts were made with:

Paul Misoda	Manager T700 International Programs
Thomas Gale Jr.	International Support Programs
Judy Sukaloski	Manager Turboshaft Performance Analysis
Richard Vandermolen	Manager Turboshaft/Turboprop Systems Analysis
Nick Fiermonte	T700 Controls
Craig Litster	RAAF Resident Quality Assurance Engineer
Flt.Lt. Gerry Mann	RAAF Project Engineer - Sikorsky Aircraft

These discussions concentrated on performance and operating behaviour of the GE T700 engine as supplied to the RAN and RAAF. In particular ARL was concerned with methods for assessing engine module performance with either GE steady state engine computer model (as supplied to ARL through the RAAF) or on a mobile engine test stand (METS). ARL inquired as to the status of their (ARL's) request for an update to the T700 object coded engine model which GE had supplied in part fulfillment of a Type II Contract Data Requirement List (CDRL). (The specification against which the engine was purchased includes the supply of a source coded thermodynamic engine model). GE stated that they have a standing rule not to supply source decks to "foreign customers" not withstanding the requirements in Military Specification MIL-E-008593E; GE also stated that they had not received ARL's request (via RAAF) for an updated object code model to run with a range of incremental inputs. The RAAF Project Engineer, from Sikorsky, agreed to forward a copy of the request to GE. In the meantime some discussion on the capabilities of engine model currently held by ARL ensued. Vandermolen stated that ARL's basic requirements were in-built into the computer model (87210) but the program required recompiling to allow ARL more direct access. Input terminology would have to be supplied to ARL, and GE would have to discuss with senior management if extended output arrays, to give component efficiencies, could be released. Vandermolen stressed that all the data which was requested was in the object code and only relatively minor adjustments would be necessary to the program to the give the required outputs, little extra work would be incurred by GE. In general terms on T700 engine program and performance Sukaloski and Vandermolen made the following comments:

. Cycle deck gives "average" engine performance, approximately 5% above "min-spec".

. Model has no stall margins built into the output routine - surge is not a problem on T700.

. GE uses two deterioration models average and sandy, see Table 2 and 3.

. Full deterioration criterion is - 9% SHP using as a base a quoted $T_{4.5}$ at intermediate rated power for a min-spec engine.

. Engine influence coefficients have been supplied to US Army. Australia can request, but no guarantee of delivery. It should be noted that data reduction and model derivatives are not the same and should not be interchanged.

. Reynolds Number indices are used in model at the following conditions,

- Turbine	0 - Altitude
- Compressor	10K - Altitude

. Correction parameters are as given below.

- $T_{4.1}$ θ index is .91
- $T_{4.5}$ θ index is .85
- Fuel Flow θ index is .55

. Power turbine speed (Np) is set nominally at Np = 104.5 and is normally invariant. Np variations have little effect on engine running line but bleed flows will change its position.

. Engine model uses separate component characteristics for axial and centrifugal compressor stages and for the blower of the particle separator.

. Operating point solution requires static pressure at exit of blower to be ambient, with a choked mass flow. First estimates are made with set values of main compressor and blower mass flow (W_1 + W_{13}) to give indicative values of blower exit pressure, an interactive solution is then obtained using a range of ($W_1 + W_{13}$).

- Neither gas generator or power turbine are run with choked characteristics.

From the above discussions, it was obvious that contacts with GE technical engineering staff as opposed to technical sales personnel generated more interesting and fruitful dialogue. Similarly in the area of module assessment on the METS, whilst GE were reticent about using this procedure, "it was not warranted in the T700", specific data was forthcoming, in particular:

- Curves for splitting hot end from cold end have been supplied to US Navy and were available on request: US Navy were having difficulties in measuring T_3, a main indicating parameter.

- Station 3 and 2.5 probes were available.

- Venturis were required for determination of particle separator mass flow, and for T_4 calculation using a mass flow temperature balance.

- Module influence coefficients have been generated.

- Detailed engine test instrumentation drawing was supplied, Figure 1.

- There is absolutely no (trim) adjustment on the engine. In light of information obtained later at NAPC on the F404 ECU this latter statement may not be strictly true.

Following the comprehensive performances briefing a much less detailed description of the T700 Control System was given. The relative roles of the Hydro-Mechanical and Electrical Control Units were described. The HMU provides gas generator control (N_1) in areas of acceleration, stall, N_1 overspeed and variable geometry. The ECU trims the HMU to satisfy load requirements so as to maintain a constant rotor speed (N_R) and load sharing, it also limits the power turbine inlet temperature, $T_{4.5}$. The ECU also controls access to contingency power by resetting $T_{4.5}$ limits in the case of one engine being inoperative (OEI). In lockout condition - the ECU is disconnected from HMU - however the engine can still attain maximum power but there is no - N_1 governing, no - $T_{4.5}$ limiting or - load sharing. Stall and over-speed protection are still available and power is controlled by changes to the collective. GE are also developing a DECU for the T700. An interesting aspect of this controller is the ability to aquire engine data via a RS 232 port; data available are, Torque, N_1,N_R and $T_{4.5}$. Whilst this is not comprehensive enough for engine monitoring purposes, it should allow calculation of maximum power available. The only negative aspect of the port is that it cannot be used in flight due to a possibility of cross talk or electro-magnetic interference (EMI). This was a revealing statement, as it is understood that a number of US Army Black Hawk incidents have been related to EMI.

The visit to GE Lynn concluded with requests by ARL for the availability of Engineering Design Reports for GE T700, similar to F404 reports (R80AEG001 Vols 1-5) currently held by ARL. After some abortive discussions, GE eventually stated that they would not even provide GE reference numbers or titles of the requested reports without legal and corporate advice.

2.4 VISIT TO TEXTRON LYCOMING, STRATFORD, CONN.

Discussions on aerothermodynamic performance of turboshaft engines, and AVCO Lycoming T53 engine in particular were held with:

Ted Smith	Service Centre Engineer
Jim Love	Supervisor Technical Publications Engineer
Dave Collings	Chief T55/T53/ATE Engine Performance
David Tate	Compressor Development Manager
Kenneth Collinge	Diagnostic Technology Manager
Philip Fogel	Engine Performance Analysis Manager
Sol Silverstein	Engine Performance Analysis Manager

An overview was given of ARL's research and investigatory program on fault diagnosis, stage stacking and engine modelling. It was explained that a T53-L11 would be used to validate a number of aspects of this program and that ARL would like access to detailed component and engine design data. It was gratifying that Lycoming had assembled such a cross section of technical experts whilst the factory production staff were on strike. All participants at the meeting, including the visitor from Australia, had to cross the picket line. Major discussions were held with Collinge and Fogel and a detailed description was given of T53 design philosophy and performance. Methods of data presentation for turbine performance were defined, in particular, use of Lycoming N_2opt. This factor, used extensively in AVCO's engine specification documents, defines N_2opt as the power turbine speed which gives maximum shaft horsepower for a given gas generator speed. Turbine characteristics as used are in the form of equivalent specific work (change in turbine enthalpy as a ratio of corrected turbine inlet temperature) as a function of the product of corrected mass flow and turbine non dimensional speed, i.e $\Delta H/\theta_4$ versus

$$\frac{W\sqrt{\Theta_4}}{\delta_4} \times \frac{N}{\sqrt{\Theta_4}}$$

Data analysis correction parameters for the T53 engine are as given below:

Wf_c	θ	index is	.712
SHP_c	θ	index is	.587
$T4_c$	θ	index is	.986
EGT or $T5_c$	θ	index is	.85

The indices, in comparison to the text book values of $\theta = 1$ & .5 which were derived from a non dimensional analysis, are empirically generated so as to collapse actual data onto single lines.

During discussions on performance, and it is believed that once ARL's bona fides had been established, three reports on T53 design were handed over, these covered:

- testing of T53 compressor,
- compressor characteristics, including maps with development blading, and
- basic T53 compressor design data ranging from flow path geometries through the compressor to individual blade aerofoil sections and their design criteria.

These data will prove most useful in ARL work on engine performance. Some comments were made in the wind-up session on engine diagnostics for turboshaft engines, in particular, Lycoming emphasised that provided proper data were available, it was not difficult to isolate problems in either the hot or cold sections of the engine. It would be more difficult to split a postulated compressor fault into either the axial or centrifugal components. On referring to the Engine Performance work being carried out under the auspices of TTCP HAG8, it was stated that Lycoming had provided the UK member with a T55 engine model in SAE AS 681C format. This model was to be used in influence coefficient calculations and a cooperative degradation study to be undertaken by TTCP countries. Australian TTCP members were unaware of this fact and this aspect is to be taken up with newly formed TTCP HTP7 for possible inclusion as part of one of its KTA's (Key Technical Areas).

2.5 VISIT TO NAVAL AIR PROPULSION CENTER (NAPC) TRENTON - NEW JERSEY

Discussions on operation of F404 with imbedded faults, engine models and possible attachment of personnel to NAPC were held with,

Theodore Elsasser	Manager Large Engines and Performance Division
Al Kush	Project Engineer
Barry Yukas	Senior, F404 Project Engineer
Chris Georgiou	Performance Analysis
Howard Scott	P & W F404 Project Engineer
Bill Jorgenson	T700 Project Engineer

NAPC have recently completed testing of a P & W built F404 engine; from comments made by project engineers it was apparent that control over engine hardware, operational behaviour and design data was more flexible with P & W than GE. NAPC suggestions on input of faults into an F404 were similar to GE comments but, from the experience with P & W testing, allowable margins were less constrained. NAPC have run with FGV and CVGV up to 10^{o} off schedule with no apparent distress being experienced by the engine. In addition to the mechanical/physical modifications which can be made to induce faults, the ECU was identified as having three trimming potentiometers controlling:

- N_1 - fan speed schedule,
- T_5 - Exhaust Gas Temperature Limits, and
- WFA/B Afterburner fuel flow rates.

Whilst these trimmers are not normally accessible in the production engine test cell they have been used by GE, P & W and NAPC to retrim/modify the engine performance. The potentiometers are accessible by removing the front plate from the ECU. It was suggested that the settings should initially be adjusted at a click or ¼ turn at a time. No specific guidance was available on implementation other than the adjustments should be kept within the following limits:

- $N_1 \pm 300$ rpm,
- $T_5 \pm 150°F$, and
- AB Ratio units ± 65 units.

It was thought that on T_5 one click approximated to $2.5^{o}F$ and on N_1 one click was equivalent to 10 rpm. As there was some degree of hysteresis in the potentiometers, it was recommended that adjustments and tests should be carried out on a spare ECU, and the original unit should be retained for reference running of the engine. On completion of engine testing the ECU should be returned to the overhauler for re-setting up.

The only detailed experience on fault tolerant operation at NAPC was in two test series. The first was with false p_3 signals (essentially bleed-off from the MFCU), this work was in two areas:

- afterburner studies, and
- slowing engine accelerations from 4 - 5 seconds, to improve turbine blade life.

The false p_3 work is reported in:

NAPC-PE-89 F404 Engine CIP - Flight Support Altitude Exploring Tests H.C. Scott and M. Growlove.

The second series of fault tests were in association with the development of a FADEC for the F404 and were concerned with the injection of multiple sequential faults and the subsequent controllability of the engine. No details were available on these tests. In discussions on engine operating problems, reference was made to the recent series of 1st and 3rd stage compressor blades failures. Whilst NAPC was involved with GE in seeking a solution they were unable to conduct tests at Trenton in their altitude test cell. The cell is not able to replicate the required transient intake airflows during the specified flight manoeuvres, a dive from 60K-10K feet. The inflight tests are designed to generate a T_1 lag - due to thermocouple response - which will put the CVG off schedule, and hence allow a malfunctioning variable geometry blade to cross a flutter boundary.

Following some previous correspondence between ARL and NAPC the possibility of an attachment from ARL to NAPC was discussed. Elsasser was most supportive of such a suggestion and would welcome an ARL engineer to work on F404 engine testing and investigation work. He stressed that as NAPC was working on advanced F404s, some problems could arise over classified data, however he did not see this as an insuperable problem. It was agreed that NAPC would write to ARL confirming their discussions and propose a short term attachment of an ARL officer to NAPC.

2.6 VISIT TO US ARMY AVIATION APPLIED TECHNOLOGY LABORATORY FORT EUSTIS, VIRGINIA

This visit was arranged to discuss US Army's philosophy and approach to engine testing and module condition assessment and their experiences with the GE T700 in the Black Hawk. The opportunity was also taken during the visit to discuss some outstanding editorial aspects of the TTCP HAG 8 Final Report on "Gas Turbine Engine Performance Monitoring".

Discussions were held with:

Robert L Campbell SR	Team Leader-Mission Support Equipment.
Roger Hunthausen	US Army TTCP HAG 8 Member.
Paul Redden	Aerospace Project Engineer.

Bruce Thompson	Aerospace Project Engineer.
David Stall	Aerospace Project Engineer.

The major part of the discussions on GE T700 engine testing were held with Bob Campbell. Campbell was a member of a 6 man US Army team tasked to carry out a study on "Turboshaft Engine Testing at Intermediate Level". A comprehensive report on this particular visit has been forwarded to RAN via SAMR. The main conclusions of which are summarised below:

- On wing testing was not cost effective. In the case of a Black Hawk it would tie up a twin engine helicopter, just to trouble shoot a single engine.

- Off wing testing at level 2 and 3, intermediate level maintenance, should be carried out on a Mobile Engine Test Stand (METS) preferably using a modified US Navy METS to isolate faults to a modular level. The main modification to the METS requires the addition of an automatic data acquisition system.

- The METS instrumentation suite should be enlarged to allow module assessment, minimum number of parameters is given in Table 4.

- On wing fault isolation was extremely difficult even with dedicated portable analyser like the Howell PEATS (Portable engine analyser and test system). The PEATS should be used to check engine performance and condition - that is, confirm existence of fault - but trouble shooting should be carried out away from the aircraft under more controlled conditions.

- A suitcase tester should be used to check out the ECU; faulty ECU's should be returned to depot level.

With the acquisition of the Seahawk and Black Hawk by the Australian Services particular interest was shown in all T700 engine operations: the US Army also uses this engine in the Super Cobra and Apache helicopters. For at least 3 years the US Army has carried out a trial of an Enhanced Diagnostic System in a single Apache helicopter using a Lier Siegler recorder to acquire data. The recorder is interfaced via the aircraft's 1553 BUS and serves as a means of monitoring engine, airframe and fire control systems. The monitored data is used to assess and diagnose faults in the total weapons system. A prototype Expert System is being developed for the Apache and a brief demonstration of the system was given. The Apache monitoring system is only a proof of concept and includes the following capabilities on engine performance:

- provision is made for automated HIT and power check, however both can be pilot initiated,

- test results are generated and displayed in flight to give an indication of go-no-go power levels, and

- results are stored for ground analysis, trending and presentation.

The data/performance algorithms are being developed by General Electric taking into account pre-specified degradation indices. The performance estimation routines are only a small component of the EDS system, its major role is to monitor and maintain the effectiveness of the fire control or weapons system using an Expert System as a means to this end. A final report will be available in January 1989. Brief mention was made of US Army's policy of fitting (Crash) Flight Data Recorders to all helicopters. However of more interest was a proposal to fit SMITHS recorders in 3 (T53 powered) Cobra helicopters. The monitoring system would be used for:

- engine lifing,
- mast balancing, and
- engine performance.

This program is as yet unfunded. At the end of the discussion some comments were made on T700 operations in general, these were:

- 13% of US Army engine removals were for corrosion, FOD and dust ingestion
- The ECU was a major source of problems, ECUs are removed in the field and repaired at depot. The US Army have not acquired an ECU test set and are unable to diagnose faults to specific levels.
- Turbine modules have been the major module changed, but it is rare for them to be repaired in the field. Faults could have been simple - failed bolts - but until a METS is acquired they are difficult to rectify.

2.7 VISIT TO KELLY AIR FORCE BASE, SAN ANTONIO TEXAS

The visit to Kelly AFB engine overhaul and test centre was arranged to discuss the use of "URBAN type" differential gas path analyses, DGPA. Engineers contacted were:

Ron Wingenter	Chief of Engine Test Branch
George Carrol	Performance Engineer

Kelly AFB has a very large depot level engine maintenance section, it is run as a commercial enterprise with Kelly tendering for contracts. Maintenance and overhauls are carried out on a cost plus basis and are paid for by the respective USAF operating units. The facility is currently undergoing major renovations with two new Allison T56 automated test cells being constructed. These 4000 SHP engines, as used in the Hercules and Orion, will be run against dynamometers rather than a propellor to absorb power. Through contacts with Louis Urban at Hamilton Standard and the TTCP HAG8 (Action Group) it was understood that Kelly AFB was using DGPA techniques on the GE TF39 and P & W F100 to assess module degradation and condition. In discussions on use of DGPA, it was soon very obvious that the URBAN programs were being used in an automated manner. Not withstanding this, the operators had built up a large knowledge and data base for the GE TF39 with engine results from intermediate level engine tests at Travers and Dover AF Bases being built into the system. Kelly personnel were then able to advise on module exchanges to be made at these off-site test facilities. Kelly performance engineers appear to have established a credible reputation for TF39 module condition assessment. The DGPA procedures for the P & W F100 have not been implemented as yet and there are some problems with the program. Urban the "author-inventor" of these methods has retired and it is unlikely that he will be able to advise the test personnel at Kelly. From questioning of the performance engineers using the DGPA procedures, it was clear that they had little if any knowledge of the theory or assumptions used in the methods. Whilst this knowledge is not necessary at a working level, it will be required if DGPA procedures are to be implemented on the P & W F100. Module assessment methods, and more specifically GPA techniques, are highly dependent on assumptions made in their formulation and the range of measurands used. TTCP HAG8 has been highly critical of some of these commercially available packages and has suggested a critical review of one of the methods. An uninformed application of DGPA techniques to the F100 at Kelly AFB could produce quite negative results in comparison to those achieved on the TF39.

2.8 VISIT TO SOUTHWEST RESEARCH INSTITUTE SAN ANTONIO TEXAS

The purpose of this visit was to follow up contacts made by D.A. Frith on possible extensions of IFDIS to the EMS being developed by SwRI for the P & W TF30 engine. This engine is used in the F111 aircraft operated by the USAF and by the RAAF. Contact was made with:

Richard Somers	Manager Avionics & Support Systems
Hugh Spence	Project Engineer
Ron Knuppel	Project Engineer

The EMS being implemented at SwRI on the F111 is part of the USAF CEMS IV maintenance (monitoring) and management program. Phase 1 - prototype trial is being carried out on a test aircraft at Sacramento AFB, Phase 2 will involve 6 - 8 aircraft from a training squadron. Acquisition rates in Phase 1 are at 4 samples/sec/channel with the exception for p_{s4} which is at 8 Hz. The p_{s4} acquisition rates in the prototype trial are too low to be used in its role as a stall detector; in the phase 2 trial, p_{s4} acquisition rates will be increased to 100 Hz, however the remaining parameters will be reduced to 2 Hz. A pre and post event recording algorithm, similar to PPER record in the F/A-18 aircraft, is to be incorporated in the data acquisition software similar to PPER record in the F/A-18 aircraft but the algorithm has not been defined. It was suggested, on the basis of work at ARL by Merrington, that acquisition rates of at least 5-10 Hz would be more appropriate. SwRI indicated that they were using solid state memories for data acquisition storage, and they were unsure if a PPER, at an acquisition rate of 5-10 Hz, could be stored in their limited buffer space. ARL's program and analysis techniques for both PPER and performance trending were then described. Discussions then concentrated on some initial data received from the test aircraft and SwRI gave their initial analyses for some cruise records. Data correlations were poor and obviously inconsistent. From a brief scan of the records it was apparent that the data had not been corrected for ambient conditions or engine operating point: data had been correlated for a reference engine speed alone. The ARL work on the Chinook - Engine Performance Monitoring was described as an example of techniques to be used in data correlations. SwRI conceded that their engine performance background was limited, and that they had difficulty in obtaining information from engine manufacturers. Somers expressed interest in ARL's capabilities and suggested that SwRI could contract ARL to carry out analysis work, or participate in an exchange of personnel.

In further discussions on alternate aircraft systems Somers and Spence indicated that they had previously had an involvement with GE on the ECU for the F404. In fact they were well conversant with the 3 trimming potentiometers mentioned earlier at NAPC and their functions. Whilst reluctant to talk in detail about the ECU they gave references to reports and manuals. These are listed below with a contact address.

F404 Electrical Control Unit - Tech Manual: Depot Maintenance

Pt No 7072 M22 GO1
7072 M22 GO2
7055 M98 GO3
4921 T86 GO1
7072 M22 GO4

C/o Naval Air Tech Service Facility

700 Robbin Ave
Philadelphia PA 19111 USA.
(Data on trimmers are available in Chapter 6).

2.9 VISIT TO ARVIN CALSPAN, BUFFALO, NEW YORK STATE

Discussions were held with Dr Michael Dunn of Calspan on effects of dust and gas ingestion on the operating behaviour and stability margins of gas turbines. The meeting was brief, as Dunn had just returned from attending an ASME gas turbine conference in Amsterdam. Calspan was formed in 1978; it had its origins in the former Cornell Aeronautical Laboratory. In recent years it has been acquired by Arvin and is now run as two separate entities, Arvin Calspan (A-C) and Calspan-UB. The latter organisation is a non profit making research laboratory which uses Arvin Calspan (A-C) facilities at cost.

Dunn's time is mainly spent with A-C, working in the Physical Sciences Department. In recent years he has carried out a number of studies on the effects of dust ingestion and over pressures on engine operating behaviour. Of particular interest was the effect of:

- erosion on compressor blades,
- build up of glassified dust on turbine temperature probes, and
- glassification of dust in turbine nozzle guide vanes.

Not withstanding the almost universal fitment of particle separators in the intakes of newer helicopters, fine dust is still a major problem. The untrapped particles, ranging from fine abrasive dust to almost soft chalkie powder, can erode or deposit on aerofoil sections, and hence alter compressor characteristics. This will eventually reduce engine operating margins. The deposition and glassification problem is of more concern as it can significantly reduce turbine nozzle guide vanes areas and move the engine running line closer to surge. Dunn quoted the example of the British Airways 747 over Indonesia in which 4 surges occurred almost simultaneously due to glassified volcanic dust sticking to and blocking the nozzle guide vanes. The engines were only able to be restarted and run at low power with bleed valves and anti-icing valves open. Any attempt to accelerate the engine only repeated the surge as the bleed valves closed. Perhaps more deceiving is the blockage or glassification effect on temperature probes or air cooling passageways in turbine blades : the blocked ducts caused an increase in both gas and blade temperatures. In the case of an Allison T56 engine which is directly controlled by measured turbine inlet temperature, turbine sections had been completely burnt out in a matter of minutes, due to erroneous thermocouple signals. Dunn has discussed these problems with civilian airworthiness authorities; however, unlike the US Military, they did not show any particular concern. Dunn also mentioned that the US Army have experienced glassification problems in the GE T700 on the Black Hawk and suggested that it could be a problem in the Australian environment. Calspan work on gas ingestion was limited to explosive (nuclear) overpressures or blast effects, and they were not concerned with asymmetric effects of rocket/missile exhaust on engine stability. Dunn stated that whilst Calspan had not been involved in the latter area, he understood that NASA Lewis had some interest. The visit concluded with an inspection of the Calspan engine test facility. Calspan are carrying out trials on a P & W F100 PW220. Dust is metered into the engine intake at varying rates during normal engine operations and transient and steady state performance changes assessed. More spectacular was the large shock tube situated upstream of the engine through which short term overpressures could be applied. It is understood that Δps of the order of 1.5 psig (mean) could be generated for periods of up to 20 milliseconds at the fan face of the engine. The visit concluded with an exchange of technical papers and technical data.

2.10 VISIT TO SINGAPORE MINISTRY OF DEFENCE, DEFENCE MATERIALS ORGANISATION AND SINGAPORE AIRCRAFT INDUSTRIES

This visit was arranged as a follow up to a visit made by an ARL staff member during the Commonwealth Defence Science Organisation Conference held in Malaya and Singapore in February 1988. During the former visit DMO expressed interest in ARL work on Engine Performance Monitoring in transport, helicopter and fighter aircraft, and suggested a visit by appropriately qualified scientists.

Discussions were held with:

Mr Tay Kok Phuan	Assistant Director Aeronautical System Program Office.
Mr Tam Kok Yan	Propulsion Department
Mr Lee A.	Propulsion Department
Mr Ramanathan G.	Propulsion Department

The Defence Materials Organisation within the Singapore Ministry of Defence is responsible for development work carried out in the Royal Singapore Air Force (RSAF), it also works closely with Singapore Aircraft Industries (SAI). The major project at SAI is the re-engineering of RSAF Skyhawks with a non afterburning version of the General Electric F404 engine. A briefing was held in the DMO Air Logistics Department on ARL's work in performance and assessment methods for the following RAAF aircraft/engines:

- . Iroquois - T53
- . Chinook - T55
- . Hercules - T56
- . Mirage - Atar
- . F/A-18 - F404

Particular interest was shown on monitoring procedures for T53, T56 and F404 engines, as these are used by the RSAF. It was explained that ARL's monitoring methods for the RAAF F404 were built around the F/A-18 IECMS engine monitoring system which is not being installed in the Skyhawks F404 refurbishment. After the ARL presentation, DMO gave details on their semi-automatic monitoring system which is being installed in the Iroquois helicopter. The system is based on a Teledyne Avionics PAR-Power Analyser and Recorder. A report covering experiences to date was handed over to ARL. In support of the Skyhawk/F404 operations, DMO is to install an Engine Temperature Cycle Counter (ETCC) in their aircraft. This equipment has been purchased from Jet Electronics, it was originally developed for

for the Northrop F20 aircraft. The ETCC will allow F404 life in terms of equivalent full cycles, time at maximum power and engine hours to be assessed: maintenance procedures will also encompass a comprehensive parts life tracking system. Ground based test equipment will include an F404 Mobile Engine Test Stand; the standard of instrumentation and data acquisition to be installed on the METS is at present unknown. It was clear from these brief contacts that DMO are still developing their maintenance philosophy for the introduction of the F404 into service and were keen to obtain contacts within Australia, it is understood they were trying to arrange a visit to ARL and HDH sometime in September 1988. The remainder of the Singapore visit was spent discussing and inspecting the installation of the F404 in the Skyhawk fighter. The Singaporean F404 has the following features:

- it is non afterburning,
- it has a hydromechanical fuel control unit with a digital engine control unit as a back up,
- it has a titanium centre casing, and
- it is installed in the aircraft with a cranked exhaust duct.

SAI have had a number of problems with the F404 installation. These are detailed below together with current solutions:

- The cranked exhaust duct was incorporated because the engine centre line and the engine accessory positioning was not in the same relative position as on the original engine installation. The bend introduced hot spots in the exhaust duct. A solution, provided by GR, was to incorporate a row of vortex generators directly downstream of the turbine rotor exit. While successful in reducing the hot spots the modification has involved a thrust loss of approximately 5% at full power.

- A number of engine stalls were experienced at high angles of attack and low airspeed, top left of flight envelope. The stalls were repeatable and have been recorded on a telemetered data acquisition system. The incorporation of small strakes (approximately 250 mm long by 50 mm wide) on either side of the fuselage upstream of the intake has resolved this problem. The stall was triggered by distorted flow at the compressor face: the distortion was a result of a flow separation from the intake lip, in that a vortex from the wing leading edge was being diverted upstream and ingested at high angles of attack. The vortex was identified by work carried out in a water tunnel in the USA by EIDETICS INT. It was interesting to note that the problem has not occurred in the two seat trainer which has a longer nose section. SAI staff also indicated that engine stalls were less likely to occur in aircraft fitted with a nose mounted (offset) refuelling boom. ARL has officially requested copies of F404 inflight stall data for comparison with a previous stall incident recorded on an Australian F/A-18 aircraft.

- A second installation problem occurred during low speed approaches in that the Skyhawk aircraft tended to yaw on landing. A solution was suggested by a Northrop engineer who had experienced similar problems in early jet aircraft developments. The engineer hypothesised that air was being expelled by one side of the bifurcated intake; "the engine was receiving more air than it needed". The Northrop and SAI solution was to extend the intake splitter up to the engine compressor face. This modification has been implemented satisfactorily on a number of aircraft.

Currently SAI have re-engined six single seater and one trainer aircraft. The program is being pursued with vigor: an outside observer can only be impressed with the enterprise with which the Singaporeans are carrying out this program.

3.0 CONCLUDING REMARKS

The visit which included an invited attendance at an AGARD symposium was very enlightening. Discussions held during the AGARD conference demonstrated that studies in Australia are well regarded. In particular, the paper on transient fault diagnosis by Merrington elicited considerable interest for its novelty; this diagnostic problem is acknowledged as being extremely difficult. Many new contacts were made at the conference both in the civil and military areas of engine performance assessment. Not withstanding the considerable interest and work being devoted to the development of hardware and software for engine monitoring programs, one is left with a feeling that the cost effectiveness of some of the systems still has to be justified. As in the case of the F/A-18, many monitoring systems have been proposed, developed and installed but little work has been undertaken on implementing analysis procedures for diagnosing faults. Pre-and Post Event Records from the US Navy (and Australia) F/A-18 are still being analysed on the basis of in-house experience: ARL's analytical work to define fault libraries for transient engine records is unique. Module/component analysis, which is a major requirement for many operators using on condition maintenance programs, still has not been satisfactorily addressed. Engine companies have proposed systems but as noted in TTCP HAG-8 it is not possible to validate the procedures due to company confidentiality and a lack of basic knowledge on the assumptions used. ARL still has an important, independent, role in assessing these methods as well as providing advanced techniques for the Australian Services.

The company and laboratory visits provided considerable information of interest to Australian Defence Forces. However, it was clear that prior to any meeting, discussion topics should be well defined, and that the host company should be requested to provide technical engineers or scientists not just technical salesmen. The majority of contacts during this visit were in the former category. However in most cases meaningfull discussions only occurred after the visitors credentials had been established. The major problem is still with company confidentiality: this was most evident at GE Lynn where even Report Numbers were denied. Not withstanding the above, considerable insights into current engine performance assessment and operating behaviours were attained.

F404 IN-FLIGHT SHUTDOWNS
ENGINE-CAUSED DRIVERS - 1986-4/88

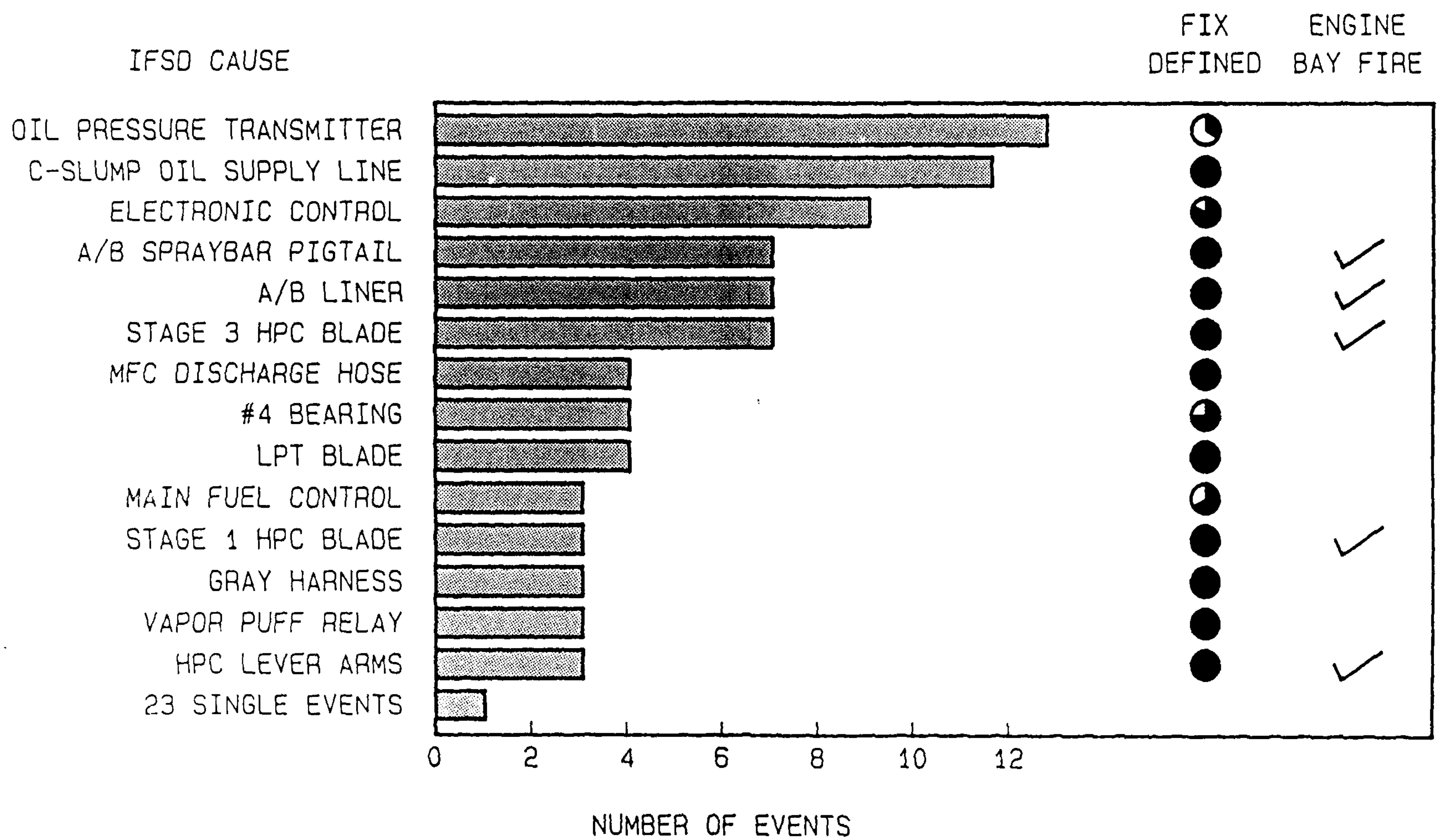

TABLE 1

AVERAGE ENVIRONMENT DETERIORATION MODEL

DETERIORTION MODEL BUILDING BLOCKS:

1) BASE DECK MODELS AVERAGE ENGINE COMPONENT PERFORMANCE

2) DETERIORATE COMPONENTS USING PRESCRIBED ALOGRITHM BASED ON OBSERVED T700 FIELD HISTORY

AVERAGE ENVIRONMENT MODEL:

-2.0% AIRFLOW CAPACITY AT CORE SPEED

-1.0 PTS. COMPRESSOR EFFICIENCY (OVERALL)

-1.5 PTS. GAS GENERATOR TURBINE EFFICIENCY

-1.0 PTS. POWER TURBINE EFFICIENCY

+0.75% GG CHARGEABLE COOLING FLOW

FIXED RELATIVE AMOUNTS OF DEGRADATION — 12% SHP DOWN FROM AVERAGE

TABLE 2

SANDY ENVIRONMENT DETERIORATION MODEL

DETERIORTION MODEL BUILDING BLOCKS:

1) BASE DECK MODELS AVERAGE ENGINE COMPONENT PERFORMANCE

2) DETERIORATE COMPONENTS USING PRESCRIBED ALOGRITHM BASED ON OBSERVED T700 FIELD HISTORY

SANDY ENVIRONMENT MODEL:

-4.0% AIRFLOW CAPACITY AT CORE SPEED

-2.0 PTS. COMPRESSOR EFFICIENCY (OVERALL)

-1.5 PTS. GAS GENERATOR TURBINE EFFICIENCY

-1.0 PTS. POWER TURBINE EFFICIENCY

FIXED RELATIVE AMOUNTS OF DEGRADATION — 16% SHP DOWN FROM AVERAGE

+0.75% GG CHARGEABLE COOLING FLOW

TABLE 3

PARAMETERS MONITORED

*	1.	GAS GENERATOR ROTOR SPEED
*	2.	POWER TURBINE SPEED
**	3.	LOAD DEMAND SPINDLE POS
**	4.	POWER AVAIL SPINDLE POS
*	5.	TORQUE (ENGINE INDICATED)
**	6.	TORQUE (DYNAMOMETER)
**	7.	BLEED VALVE POSITION
*	8.	POWER TURBINE INLET/EXHAUST GAS TEMP
**	9.	FUEL INLET PRESSURE
**	10.	FUEL FLOW
**	11.	BAROMETRIC PRESSURE
**	12.	ENGINE INLET AIR TEMP
**	13.	COMPRESSOR DISCHARGE PRESSURE
**	14.	COMPRESSOR DISCHARGE TEMP
*	15.	ENGINE OIL PRESSURE
**	16.	ENGINE OIL TEMP
**	17.	BELL MOUTH STATIC
**	18.	AND TOTAL PRESSURE
**	19.	PT CASE FLNG VIB
**	20.	INLET CASE FLNG VIB
**	21.	AGB CASE FLNG VIB
**	22.	INLET VARIBLE GEOMETRY POSITION
**	23.	ANTI-ICE PRESSURE
**	24.	ANTI-ICE TEMP

*	ENGINE SENSOR
**	TEST STAND SENSOR ADDED

TABLE 4

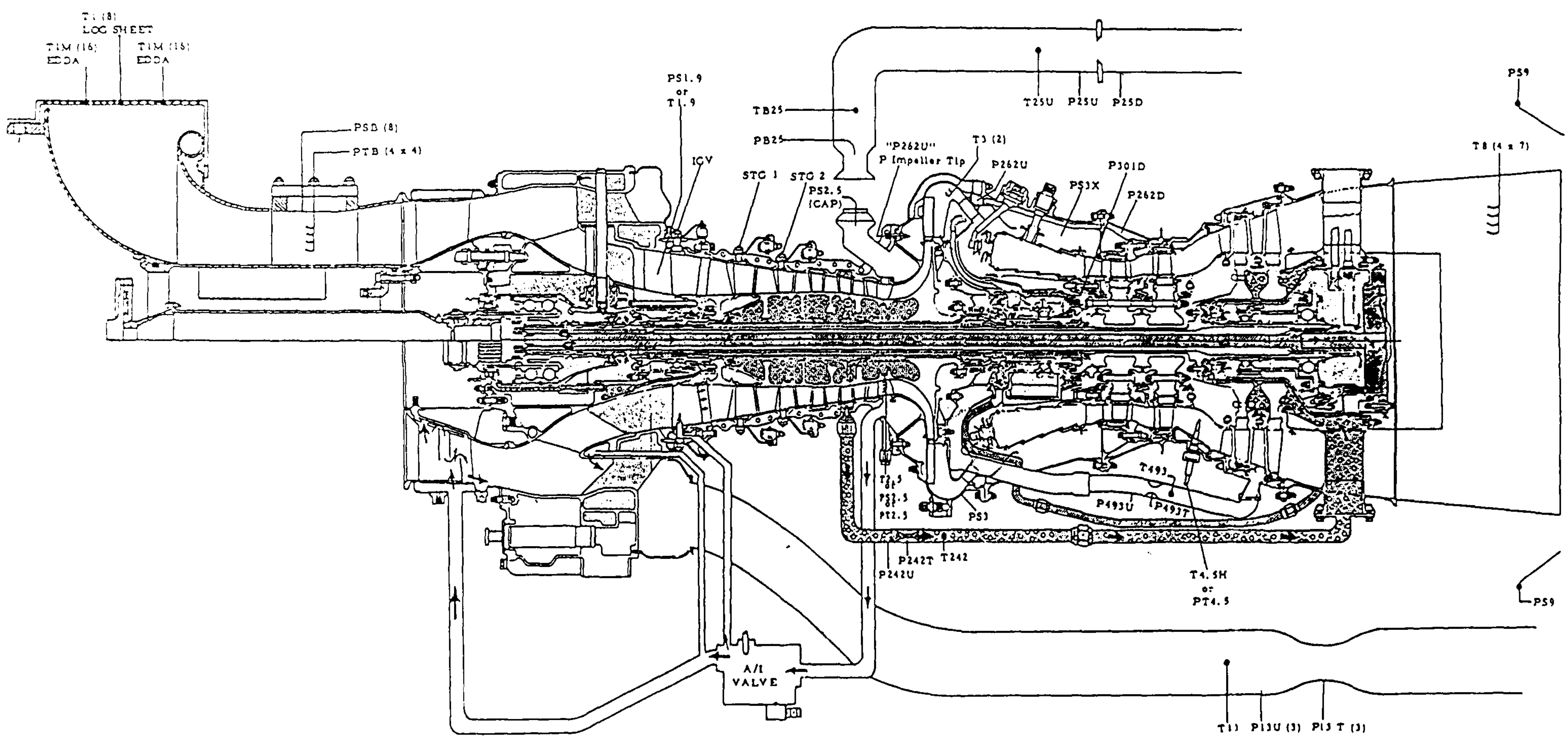

FIGURE 1. GE T700 TEST MEASURANDS

PROGRAMME FOR 71ST SYMPOSIUM OF THE AGARD PROPULSION AND ENERGETICS PANEL ON ENGINE CONDITIONING MONITORING - TECHNOLOGY AND EXPERIENCE

SESSION I – MILITARY OPERATIONS

SESSION II – CIVIL EXPERIENCE

DISTRIBUTION

AUSTRALIA

Department of Defence

Defence Central
- Chief Defence Scientist
- FAS Science Corporate Management (shared copy)
- FAS Science Policy (shared copy)
- Director, Departmental Publications
- Counsellor, Defence Science, London (Doc Data Sheet Only)
- Counsellor, Defence Science, Washington (Doc Data Sheet Only)
- S.A. to Thailand MRD (Doc Data Sheet Only)
- S.A. to the DRC (Kuala Lumpur) (Doc Data Sheet Only)
- OIC TRS, Defence Central Library
- Document Exchange Centre, DISB (18 copies)
- Joint Intelligence Organisation
- Librarian H Block, Victoria Barracks, Melbourne
- Director General - Army Development (NSO) (4 copies)
- Defence Indsutry and Materiel Policy, FAS
- Director, International Programs

Aeronautical Research Laboratory
- Director
- Library
- Chief - Flight Mechanics and Propulsion Division, W.H. Schofield
- Head - Propulsion Branch, D.A. Frith
- Branch File - Propulsion
- Authors: D.E. Glenny

Materials Research Laboratory
- Director/Library

Defence Science & Technology Organisation - Salisbury
- Library

WSRL
- Maritime Systems Division (Sydney)

Navy Office
- Navy Scientific Adviser (3 copies Doc Data sheet only)
- Aircraft Maintenance and Flight Trials Unit
- RAN Tactical School, Library
- Director of Naval Aircraft Engineering
- Director of Naval Air Warfare
- Superintendent, Aircraft Maintenance and Repair
- Director of Naval Ship Design

Army Office
- Scientific Adviser - Army (Doc Data sheet only)
- Engineering Development Establishment, Library
- US Army Research, Development and Standardisation Group

Air Force Office
- Air Force Scientific Adviser
- Aircraft Research and Development Unit
  - Scientific Flight Group
  - Library
- Engineering Division Library
- Director General Aircraft Engineering - Air Force
- TFPENG2-AF
- AIRENG2-AF
- UHPENG
- Director General Operational Requirements - Air Force
- HQ Air Command (SMAINTSO)
- HQ Support Command
  - SLENGO
  - AIRENG2

Statutory and State Authorities and Industry
- Hawker de Havilland Aust Pty Ltd, Victoria, Library
  - D. Lock
- Hawker de Havilland Aust Pty Ltd, Bankstown, Library
  - J. Eldridge

SPARES (10 copies)
TOTAL (70 copies)

AL 149 DEPARTMENT OF DEFENCE

DOCUMENT CONTROL DATA

PAGE CLASSIFICATION
UNCLASSIFIED

PRIVACY MARKING

1a. AR NUMBER	1b. ESTABLISHMENT NUMBER	2. DOCUMENT DATE	3. TASK NUMBER
AR-005-575	ARL-PROP-TM-455	FEBRUARY 1989	AIR 86/038

4. TITLE

REPORT ON AN OVERSEAS VISIT
JUNE 1988

5. SECURITY CLASSIFICATION (PLACE APPROPRIATE CLASSIFICATION IN BOX(S) IE. SECRET (S), CONF.(C) RESTRICTED (R), UNCLASSIFIED (U)).

U	U	U
DOCUMENT	TITLE	ABSTRACT

6. NO. PAGES
33

7. NO. REFS.

8. AUTHOR(S)
D.E. GLENNY

9. DOWNGRADING/DELIMITING INSTRUCTIONS
Not applicable.

10. CORPORATE AUTHOR AND ADDRESS

AERONAUTICAL RESEARCH LABORATORY
P.O. BOX 4331, MELBOURNE VIC 3001

11. OFFICE/POSITION RESPONSIBLE FOR:

SPONSOR RAAF
SECURITY -
DOWNGRADING -
APPROVAL CFPD

12. SECONDARY DISTRIBUTION (OF THIS DOCUMENT) Approved for public release.

OVERSEAS ENQUIRIES OUTSIDE STATED LIMITATIONS SHOULD BE REFERRED THROUGH ASDIS, DEFENCE INFORMATION SERVICES BRANCH, DEPARTMENT OF DEFENCE, CAMPBELL PARK, CANBERRA, ACT 2601

13a. THIS DOCUMENT MAY BE ANNOUNCED IN CATALOGUES AND AWARENESS SERVICES AVAILABLE TO....
No limitations.

13b. CITATION FOR OTHER PURPOSES (IE. CASUAL ANNOUNCEMENT) MAY BE [X] UNRESTRICTED OR [ ] AS FOR 13a.

14. DESCRIPTORS

Visit reports
Gas turbine engines
Performance tests
Skyhawk aircraft

15. DRDA SUBJECT CATEGORIES
0081D

16. ABSTRACT A visit was undertaken in June 1988 to attend the 71st Symposium of the AGARD Propulsion and Energetics Panel (PEP) on Engine Condition Monitoring - Technology and Experience held in Quebec Canada and to visit selected industry, military and research facilities in Canada and USA. The latter visits were to discuss methods for assessing gas turbine performance when operating with and without faulty components. A total of 8 establishments were visited in Canada and the USA. In the course of the visit an opportunity was taken to hold preliminary discussions on the

PAGE CLASSIFICATION
UNCLASSIFIED
PRIVACY MARKING

THIS PAGE IS TO BE USED TO RECORD INFORMATION WHICH IS REQUIRED BY THE ESTABLISHMENT FOR ITS OWN USE BUT WHICH WILL NOT BE ADDED TO THE DISTIS DATA UNLESS SPECIFICALLY REQUESTED.

16. ABSTRACT (CONT.)

establishment of Key Technical Areas (KTA) in the newly formed TTCP HTP-7. At the conclusion of the tour a visit was made to the Singapore Ministry of Defence (and Singapore Aircraft Industries) to discuss aspects of Performance Monitoring and the installation of the GE F404 in the Skyhawks of the Royal Singapore Air Force.

17. IMPRINT

AERONAUTICAL RESEARCH LABORATORY, MELBOURNE

18. DOCUMENT SERIES AND NUMBER	19. COST CODE	20. TYPE OF REPORT AND PERIOD COVERED
Propulsion Technical Memorandum 455	47-3141	

21. COMPUTER PROGRAMS USED

22. ESTABLISHMENT FILE REF.(S)

G5/179/344

23. ADDITIONAL INFORMATION (AS REQUIRED)