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DEPARTMENT OF DEFENCE

DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION

AERONAUTICAL RESEARCH LABORATORY

MELBOURNE, VICTORIA

Propulsion Branch Technical Memorandum 450

REPORT ON AN OVERSEAS VISIT IN OCTOBER/NOVEMBER 1986 TO REVIEW MAINTENANCE PROCEDURES FOR F404 ENGINE ELECTRICAL CONTROL UNIT AND RELATED MATTERS

by

G.F. Forsyth

Approved for public release.

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SUMMARY

The Electrical Control Unit in the F/A-18 Hornet aircraft is field-replacable but suitable test equipment for this unit is not available in Australia. Both the United States Navy and the Canadian Defence Forces, which also operate the Hornet aircraft, concede deficiencies in flight-line test facilities for this unit and various proposals have been put forward to rectify the situation. The main purpose of the visit to USA and Canada was to analyse these proposals and advise the Royal Australian Air Force of the potential of each proposal to meet Australian service requirements. During the visit the opportunity was taken to present three papers on ARL research at conferences in the USA, and to discuss future trends in gas turbine controls.

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CONTENTS

1.0 INTRODUCTION 1
1.1 RAAF Maintenance Levels and Procedures 1
1.2 Presentation of Papers 2
1.3 Engine Control Research Trends 2

2.0 ONE-DAY VISIT TO BOEING CONTROLS GROUP 2

3.0 VISIT TO MCDONNELL AIRCRAFT 4
3.1 Using AFTA to Read MSDRS Tapes 5
3.2 McAIR Buffer Box (EDAB) Proposal 5
3.3 Hardware and Software Standards 5
3.4 Project Direction 5

4.0 VISIT TO GE FORT WAYNE PLANT 5
4.1 ECU Manufacture 6
4.2 ATE units 6
4.3 Finding Faults 6
4.4 Careful with J61 6
4.5 ECU Reliability 6
4.6 ECU Tester for O and I Levels 7

5.0 ATTENDANCE AT AIAA AIRCRAFT SYSTEMS MEETING 7
5.1 NASA F404 Control Proposal 7
5.2 Overall Impression 8

6.0 VISIT TO WRIGHT-PATTERSON AFB 8
6.1 INTERFACE 9
6.2 Missile/Drone Controls 10
6.3 DMICS 10
6.4 PSC 10
6.5 ICLE 11

7.0 VISIT TO NRCC OTTAWA 11
7.1 NRCC Briefing 11
7.2 Tour of NRCC 12
7.3 Artificial Intelligence [AI] 13
7.4 Modelling 13

8.0 VISIT TO GE LYNN 13
8.1 ECU Swapping Harness 13
8.2 F404 Continuity Tester 14
8.3 Depot Tester ATE 14
8.4 ECU Reliabity Record 14
8.5 Other Talks at GE 14

9.0 ATTENDANCE AT 41ST MFPG CONFERENCE 14

10.0 VISIT TO MCDONNELL AIRCRAFT REPRESENTATIVES [NATC] 15

11.0 VISIT TO NAVAL AIR SYSTEMS COMMAND WASHINGTON 15
11.1 Possible Future Digital Controllers for F404 16
11.2 Other DEEC's on Related Engines 16
11.3 Other DEEC's 16
11.4 Burn-In on F404 ECU 16

CONTENTS cont.

12.0 VISIT TO AUSTRALIAN F18 PROJECT OFFICE (TFPO WASHINGTON) 17

13.0 VISIT TO NAVAL AIR PROPULSION CENTER 17
- 13.1 Background to Turbine Engine Control 17
- 13.2 Navy Control System Technology Programs 17
- 13.3 Helicopter Monitoring 19
- 13.4 F404 Work at NAPC 19
- 13.5 F404 ECU Maintenance 20
- 13.6 Exchange Possibilities 21

14.0 VISIT TO SYSTEMS CONTROL TECHNOLOGY 21
- 14.1 Controls Projects 21
- 14.2 Engine Maintenance 22

15.0 VISIT TO INTEGRATED SYSTEMS INC 22

16.0 GENERAL IMPRESSIONS 23
- 16.1 Relevance of ARL Work 23
- 16.2 Trend to Contracting Laboratories 23
- 16.3 Trend to Integrated Control 23
- 16.4 Recommendations on ECU Testers 24

17.0 ITINERARY 25

18.0 LIST OF CONTACTS [LISTED IN ORDER OF CONTACT] 26

19.0 REFERENCES 28

ANNEX A (See Separate Contents)
DOCUMENT CONTROL
DISTRIBUTION

ABBREVIATIONS AND DEFINITIONS.

ACSL	Computer simulation language
ADA	US Department of Defense standard software language
AFM	Advanced Fuel Management project [NAPC]
AFTA	Avionics Fault Tree Analyser [McAIR]
AFWAL	(US) Air Force Wright Aeronautical Laboratories
AHS	American Helicopter Society
AIAA	American Institute of Aeronautics and Astronautics
AIMES	Avionics Integrated Maintenance Expert System (McAIR Project)
ANU	Australian National University, Canberra
APOLLO	Workstation; single user graphics computer
ARL	Aeronautical Research Laboratory [Australian Department of Defence]
ARTERI	Analytic Redundancy Technology for Engine Reliability Improvement [NAPC]
ASEE	American Society of Engineering Education
ATE	Automatic Test Equipment
AUTOCODE	Extension to MATRIX$_x$ which produces program code [ISI]
BETA-TEST	Second phase or external testing (alpha=internal)
BMAC	Boeing Military Aircraft Company
CDF	Canadian Defence Forces
CEMSiv	Fourth generation of Comprehensive Engine Maintenance System [SCT]
CONTROL$_C$	A control system design and analysis software package [SYSCON]
DARPA	(US) Defense Advanced Research Projects Agency
DECK	Data set for a program or simulation (from a "deck of cards")
DECU	Digital Electrical Control Unit [GE proposal for F404 control]
DEEC	Digital Electronic Engine Controller - first generation of FADEC
DMICS	Design Methods for Integrated Control Systems [AFWAL]
DND	(Canadian) Department of National Defence
ECU	Electrical Control Unit [part of F404 control]
EDAB	Engine Diagnostics Adapter Box ("Buffer Box") [McAIR]
ELXSI	Multiprocessor computer system [Brandname]
EMS	ELXSI emulation of VMS, the VAX operating environment
EMS	Engine Monitoring System [Various]
ETHERNET	An interconnection standard for Local Area Networks
F404-400D	Dry (no afterburner) version of F404 engine
F404-GE-400	Engine in FA-18A and similar aircraft
FADEC	Full Authority Digital Engine Controller - second generation DEEC
FOCSI	Fiber Optic Control System Integration [NAPC]
FOSTI	Fibre Optic Sensor for Turbine Inlet [NAPC]
GE	General Electric
HP	Hewlett Packard; instrument/computer manufacturer.
IBM PC	International Business Machines (or compatible) Personal Computer
ICLE	Integrated Control Law Evaluation [AFWAL]
IECMS	Inflight Engine Condition Monitoring System [FA-18]
INTERFACE	INTegrated Reliable FAult-tolerant Control [AFWAL]
IRAD	Independent Research And Development funding (internal)
ISI	Integrated Systems Inc. [Produce MATRIX$_x$]
J61	Diagnostic connector on F404 ECU.
JTDE	Joint Technology Demonstrator Engine [NAPC]
MATRIX$_x$	A control system design and analysis software package from ISI
MECA	Multimission Engine Control for Aircraft [NAPC]
MFPG	Mechanical Failure Prevention Group
MIMO	Multi-Input Multi-Output control or simulation
MSDRS	Maintenance Signal Data Recording Set (on F404)
MU-LISP	Multi-User version of computer language LISP
McAIR	McDonnell Aircraft Co.

NAPC	(US) Naval Air Propulsion Center, Trenton, New Jersey
NARF	(US) Naval Air Rework Facility, Pensacola, Florida
NASA	(US) National Aeronautics and Space Administration
NASC	(US) Naval Air Systems Command
NATC	(US) Naval Air Test Center, Patuxent River, Maryland
NAVPRO	(US) Navy Production Office; Includes QA and Acceptance.
NEFF	Brandname for data acquisition front-end
NRCC	National Research Council of Canada
NWC	Naval Weapons Center at China Lake
N_1	Speed of rotation of compressor, etc.
N_2	Speed of rotation of power turbine cf N_1
PL/M	A microprocessor implementation of the computer language PL/1
POTC	[AFWAL/POTC] Division of AFWAL concerned with turbine engine control
PSC	Performance Seeking Control [AFWAL]
PhD	Doctor of Philosophy; particularly in science or engineering
QA	Quality Assurance; responsible for checking quality at production
RAAF	Royal Australian Air Force
RMIT	Royal Melbourne Institute of Technology
RSX	Resource Sharing EXecutive; a PDP11 operating system
RT11	Real Time operating system as used at ARL
SCT	Systems Control Technology
SEA-TAC	Seattle Tacoma International Airport
SRI	Stanford Research Institute, California
SYSCON	Systems Control [commercial arm; see SCT]
T56	Turboshaft engine
TFPO	(Australian) Tactical Fighter (FA-18A) Project Office
T_1/T_5	Temperatures at 1st and 5th engine stations
UETP	Uniform Engine Test Program [NRCC]
USAF	United States Air Force
USN	United States Navy
VAX	Computer system from Digital Equipment Corporation
VAXstation	Workstation; single user graphics computer cf VAX
VME	A standard for Printed Circuit Boards
XMAN	Expert Manager for CEMSiv [SCT project]

1.0 INTRODUCTION.

During October and November 1986, a visit to the United States of America (USA) and Canada was undertaken. The objectives of the visit included:

1. Investigation of means of improving reliability and testing of the Electrical Control Unit (ECU) for the F404-GE-404 engine[1,2,3] used in Australia's F/A-18A aircraft,
2. Presentation of three papers[4,5,6] on scientific work at ARL at two different conferences in the USA, and
3. Examination of current trends in turbine engine control system research.

Twelve establishments were visited; these comprised engine and aircraft manufacturers, military aircraft operators representatives and advanced control software specialists. The two conferences, at which the ARL papers were presented by the author, were attended. In the following sections highlights of the discussions held at the various locations are presented in chronological sequence.

Comments and recommendations relating to the major visit objective (1) above, have been collated in Annex A. Background information relating to this visit is provided in the following sub-sections.

1.1 RAAF Maintenance Levels and Procedures.

The need to provide a "means of improving reliability and testing of the Electrical Control Unit (ECU) of the F404-GE-404 engine used in Australia's F/A-18A aircraft" arises because a deficiency in current procedures. The Royal Australian Air Force (RAAF) divides engine maintenance procedures into three areas:

1. Operational procedures, called "O-Level" maintenance, involve flight line or in-aircraft testing; [in the US Air Force, this level of maintenance is also called O-level but the abbreviation stands for "Organizational" not "Operational"]
2. Intermediate procedures, called "I-Level" maintenance, involve tests on complete engines or engine systems or modules on a test stand;
3. Depot procedures, called "D-Level" maintenance, involve tests carried out at a maintenance or repair depot, including tests on components removed from the engine.

The testing at all levels is usually carried out by following a "Fault Tree". This is simply a checklist which follows a particular path to suit each documented problem. In order to proceed down each path, it is necessary to confirm that various items are not faulty before continuing. The problem which arises with the Electrical Control Unit (ECU) is the lack of a suitable tester for this unit at any of the maintenance levels in Australia. This means that the only way to confirm that the ECU is not the source of a problem is to change it. Since changing the ECU is a straight forward job, high on the fault tree, a large percentage of ECUs removed are expected to be serviceable. The removal of a serviceable ECU is referred to as a "false removal".

When an ECU is changed, it is currently necessary to send it back to the USA for testing. This procedure takes considerable time which increases the number of spare ECUs needed to maintain the same number of serviceable engines. The questions which arise are:

Q1: Is it possible to reduce the number of ECUs removed from the engines by some testing procedure at the O or I-Level?

Q2: Is it possible to return serviceable ECUs already removed (through "false removals") to service by some testing procedure at, or prior to, D-Level (which is in USA for ECU)?

Q3: Are there any other testing procedures which could be beneficial in reducing the number of false removals?

The Canadian Defence Forces (CDF), which also operate F404-GE-400 engines in F/A-18 aircraft, commissioned an external contractor (Gastops Ltd.[1]) to do a design study for a F404 ECU tester to meet CDF requirements. General Electric (GE) has also designed several testers for the ECU ranging from simple O-Level cable continuity checkers to complex D-Level Automatic Test Equipment (ATE) which can identify problems in individual components within the ECU and is essentially the same as the equipment used to support the design and testing of the F404 ECU in the factory.

Accordingly, I was able to discuss the three questions above with representatives of the aircraft manufacturer (McDonnell Aircraft), the ECU manufacturer (General Electric Fort Wayne), the engine manufacturer (General Electric Lynn), and representatives of the other two major users of the aircraft (United States Navy (USN) and CDF).

1.2 Presentation of Papers.

Two papers, one written by my group leader and the other by myself, were accepted for the American Institute of Aeronautics and Astronautics (AIAA) Aircraft Design Meeting at Dayton Ohio. Other papers being presented there were also of interest. A third paper, co-authored by my group leader, was presented by me to the 41st meeting of the Mechanical Failures Prevention Group in Maryland.

1.3 Engine Control Research Trends.

I am a member of the "Engine Control and Data Systems" Group in the Propulsion Branch of the Aeronautical Research Laboratory (ARL) which forms part of the Australian Defence Science and Technology Organisation (DSTO). This group conducts background research into turbine engine control systems and propulsion data systems. Expertise gained in these areas is applied to support the operation of military aircraft in Australia. The evaluation of the F404 ECU test equipment proposals represents *one example* of the use of this knowledge. At present, I am also involved in the development of a digital controller for a small gas turbine engine used for research purposes. The trend to digital control of gas turbine engines is strong but there are still relatively few examples of their use in military engines.

2.0 ONE-DAY VISIT TO BOEING CONTROLS GROUP.

Boeing Military Aircraft Company [BMAC] undertake controls research from a site at SEA-TAC [Seattle-Tacoma] airport. I visited this establishment on my first working day in USA and met with Dr George Hennig, supervisor of the Control Sciences Group, in the absence of my original contact Dr Dagfinn Gangsaas who was overseas.

George discussed BMAC methods of applying classical-type frequency domain methods to "optimize" systems modelled using state-space representation. The technique involved:

- formulate "open loop" case;
- fit frequency response to roll-off Bode plots at 6 decibels (db) per octave [i.e. a pole of order one];
- add integrators (up to number of control outputs) to allow slopes to be smoothed (eliminate poles/zeros);
- fit to closed loop case and test.

As long as the slope of the Bode plot gives non-zero gain at zero frequency [DC] and falls to zero gain at frequencies well below those corresponding to any structural (aero-elastic) modes, the above technique works. The technique is largely based on theory developed by Professor John Moore of the Australian National University but BMAC interprets the theory according to aircraft design experience: BMAC found some difficulty initially in using the ANU theories but has since found that the technique allows "physical" interpretation to be given to modern design methods.

The above technique uses a Multi-Input Multi-Output [MIMO] approach and allows a single flight controller to replace separate lateral, longitudinal, dutch-roll etc. controllers. As well, if sideslip is one of the terms with an integrator and if sideslip input is held zero throughout a manoeuvre, the MIMO controller will automatically co-ordinate turns. The control surfaces involved may change with the aircraft configuration, but the method will not work with insufficient control power. Although some parameters may vary by as much as 100 to 1, adaptive control techniques are not used, although gains may be scheduled.

This approach was used on two recent BMAC studies, one of which was a US Tactical Fighter proposal and the other an in-house combat proposal. George noted that visualization appears easier using this approach and that there were less problems with parameter errors reflecting in the higher orders. [Higher order terms are usually more sensitive to errors in the assumed design parameters.]

BMAC still relies on engine companies to provide engine control systems but is now setting up its own research staff to support engine, propulsion and airframe integration. At this point in the discussion, we were joined by Dr Donald G. Iverson who is working on integration of propulsion control.

Don is a strong proponent of integrated propulsion control using airframe computers. Of the major US engine companies, only Garrett agrees with this approach at present; both General Electric [GE] and Pratt and Whitney prefer on-engine systems with triple and double-double redundancy respectively. Allison apparently has not declared its policy on this matter. Don noted that Russ Vizzini disagrees with him [see later report on talks with Russ] Don considers that the trend to use more and more computers, each over-specified [usually 50% more speed, 50% more memory] to allow for growth, and fitted in banks of 3 [triple redundancy] or 4 [double-double redundancy] leads to a weight and complexity penalty. If control software has to be written in ADA (this is current US proposal), then it could be run on a common bank of computers. [Engine companies (see sections on GE later) do not favour this approach since it makes it more difficult to differentiate between engine and airframe.]

Don proposed a system providing both flight control and propulsion control and comprising six identical computers, each performing multiple tasks. Engine control would simulataneously use any two or three but non-critical jobs would use just one of these computers. With such an arrangement, a good failure detection system is essential. discussion covered the merits of "similar" and "dissimilar" redundancy, fault detection methods, sensor connections and representation of the system being controlled.

With "similar" redundancy, the same program is run with the same (redundant) inputs on the same processor type. Any software "bug" would cause the same apparent fault on more than one processor. With "dissimilar" redundancy, three different versions of the program are run and each may use different hardware. Since the three answers may have different rounding errors and take different times to compute, the problem with dissimilar redundancy is to arrive at a method of comparing the results.

Don said that it is now accepted that faulty processor systems should detect their own faulty state. [It is not acceptable to allow a possibly faulty processor to vote to shut down a good one.] This approach needs hardware in each processor system, such as watchdog timers, to help detect processor and/or software malfunction. [Watchdog timers are counters which need to be reset by the processor at regular times; if the processor fails to reset the watchdog in a specified time, then the watchdog will attempt to restart the processor and if this fails will render it inoperative.]

Don said that engine behaviour models being used by BMAC were provided by the engine companies. BMAC has experienced particular problems with transient models which often include proprietary information, may be difficult to run and are sometimes impossible to interpret. The term "integrated propulsion control" was defined by Don to mean a single controller supervising the inlet, engine and nozzle. This was seen as most appropriate for combat aircraft where nozzle deflection may be used to improve manoeuvring ability.

Don considers that fibre optic sensors and cables are necessary for off-engine control. Problems may arise in transposing data from such sensors onto existing aircraft multiplexed buses. Don prefers the use of state-space models rather than transfer functions and does not use the Boeing EASY-5 software. He has also had some problems with an early Apollo version of MATRIX, but says the Vaxstation version seems satisfactory. He prefers BMAC's own in-house system which is currently proprietary.

Don and George referred to Uyloi Ly, a member of BMAC Control Sciences Group who was currently working at ANU. [On return to Australia, I was able to arrange for two members of our staff to visit ANU for a lecture by Dr Ly but a planned trip for Dr Ly to talk at ARL had to be cancelled when he needed to return to USA.]

George also mentioned that BMAC was involved in work on an "Advanced Propulsion Monitoring System" for which GE was the prime contractor. Apparently BMAC did the computer design but had yet to see a copy of the final report.

I discussed with George and Don the proposed ARL research agreement with ANU on robustness of control systems for use in turbine engine control. They had some constructive comments and offered some references[7,8,9], the first two of which I was able to sight at BMAC.

3.0 VISIT TO MCDONNELL AIRCRAFT.

One of the major reasons for this visit was to evaluate proposals being made by McDonnell Aircraft Company (McAIR) for development of test equipment for engine electrical units. A full discussion of the McAIR proposal and my recommendations arising from that are presented separately in Annex A.

My contact at McAIR was A. J. (Jerry) Volsen, Lead Engineer Electronics for the F/A-18 Advanced Design team. Five members of that team gave me a detailed presentation on advanced concepts for the possible use of an upgraded Avionics Fault Tree Analyser (AFTA) and other equipment on the Advanced Hornet (F18) program. I saw presentations and demonstrations of this work, done under Independent Research And Development (IRAD) funding, and including feasibility studies (and sufficient hardware/software design to support such studies) on:-

- Use of AFTA for engine diagnostics (Presented by Jerry Volsen and Carol Sanders)
- Use of AFTA for Maintenance Signal Data Recording Set (MSDRS) tape playback erase (Jerry)
- Possible future use of Avionics Integrated Maintenance Expert System (AIMS) to supplement AFTA in all three roles (Keith Blankenship and Mike Harris).

AFTA normally tests avionics by invoking the built-in test routines in the selected avionics unit. The ECU does not have this capability however and does not connect to the aircraft bus from which AFTA normally acquires all its data. For these reasons, extension to provide ECU testing capability represents a major upgrade to AFTA requiring a buffer box to connect to the engine, associated cabling and an engine simulator to verify the engine fault trees. Software to support the user interface, fault tree selection and the engine simulation also have to be provided. McAIR had not done any major work on the engine simulator but claimed to have done sufficient work on the other items to prove that such a role for AFTA was feasible.

One of the major stumbling blocks in using AFTA to diagnose faults in the existing ECU is the lack of any interconnection between the ECU and the rest of the aircraft systems. McAIR proposed to overcome this using an Engine Diagnostics Adapter Box (EDAB) plus improved access to data in the on-board MSDRS.

3.1 Using AFTA to Read MSDRS Tapes.

Since AFTA connects to the aircraft multiplexed bus, it can collect data from any other unit also connected to the bus. The MSDRS (defined above) records a wide range of events on magnetic tape cartridges. These data are currently under-utilized. McAIR is proposing an alternative data-collection scheme in which the tapes are not removed from the aircraft. Instead AFTA would be used to read the tapes in situ, to transfer these data to a database, and rewind and erase the tape. Some of these data relate to engine events such as the fault flags which lead to maintenance checks on the ECU. Accordingly, this proposed use of AFTA has potential application in the testing of the ECU.

3.2 McAIR Buffer Box (EDAB) Proposal.

Only some of the engine signals connect to the airframe for use by the MSDC/MSDR maintenance recording systems mentioned above. All proposals to check the ECU have assumed that additional connections to the ECU (usually via J61, the test connector on the ECU) will be necessary. The current McAIR proposal for the EDAB, includes buffer amplifiers, multiplexers, analog-to-digital converters and a microcontroller (Intel 8751 or similar) within the EDAB. This means that the ECU and EDAB combination will be treated as a testable unit by AFTA under the McAIR proposal. The EDAB will have a direct link (called the MC Link) to AFTA and will not communicate via the aircraft bus.

3.3 Hardware and Software Standards.

It is likely that VME standard boards will be used in the EDAB and that software would be written in PL/M with transfer to ADA some time in the future.

3.4 Project Direction.

McAIR has concluded that a joint McAIR/GE/Customer program could develop Operational [O] or Intermediate [I] level engine test capability but that independent efforts by any one of these groups is unlikely to succeed. McAIR sees some of these proposed new AFTA functions becoming on-board functions for the AIMES expert system when avionics improvements provide space and added on-board computing power for such extensions. McAIR claims that the first flight of the AIMES demonstrator in January 1986 was the first flight of an expert system in a fighter aircraft.

For more information on this proposal refer to detailed report and recommendation of Annex A.

4.0 VISIT TO GE FORT WAYNE PLANT.

I was privileged to be one of the first foreign visitors to this new facility in Indiana. ECU manufacture, previously carried out at the GE Evendale plant near Cincinatti, is now performed here in this robot assisted factory.

My contacts for this visit were Jim Bingel, the Shop Manager, and Dennis Berry, Program Manager F404/400 Electronic Controls, who drove from Evendale (Ohio) to talk with me. Dennis took me on a guided tour of the F404 test area where I saw the F404 ECU test stands and Jim showed me the control system manufacturing area. I also saw new facilities for making state of art surface mounted electronic hybrid modules and saw some of the test modules made using these facilities. I discussed future trends in control units, control diagnosis and low-end test equipment [i.e. that with considerably less complexity than the full ATE] with Dennis and local engineering design staff including Ron Haack and Jim Dolle. Jim Bingel then gave me a guided tour of the impressive robotic part handling facilities of the new plant

4.1 ECU Manufacture.

The F404 ECUs are assembled using resistors of typical values mounted on external pins on the modules. The Automatic Test Equipment (ATE) is used to confirm values which are then soldered down, covered with water-proofing and retested. This testing and retrimming is done with the ECU in an oven and the modules are tested for thermal effects by dunking the test frames holding the modules into cold and hot baths alternately.

4.2 ATE units.

I saw several types (variants) of ATE in use or being built. Typically, they make use of a HP mini-computer with various brands of test instrumentation. The same units are used to test ECU modules, trim ECUs and find faults in ECUs returned for repair. Several ATE units were being put together for the US Navy Air Station at Jacksonville, Florida.

4.3 Finding Faults.

Typically a faulty module or ECU will show a saturated output on one or more analog amplifier. Units with transient or intermittent faults are usually found using the thermal "dunking" method mentioned above. Non-faulty units, which comprise about half of all units returned, are harder to test than faulty units and, in most cases, take more time to test.

4.4 Careful with J61.

Several people noted that the "test connector" J61 can be a problem if care is not taken, since the signals to J61 are direct and not buffered. The US Navy has apparently lost an engine because a test instrument connected via a long cable to a J61 connector, shunted the fan speed N_1 signal sufficiently to allow the controller to overspeed the engine. All of the proposals currently being examined use a "buffer box" connected to J61 to provide isolation between the controller and the test equipment. Some of the GE personnel I spoke to at Fort Wayne were of the opinion that the "buffer box" would need to be considered part of the engine and be GE's responsibility. The buffer box responsibility could be even more difficult to define if Pratt and Whitney engines using GE controls eventuate as currently proposed.

4.5 ECU Reliability.

GE representatives emphasised that although the F404 ECU was "old" technology, based on "mature" and therefore reliable technology, it was even more reliable than expected. The main problem is the significant numbers of "good" units removed as "faulty".

4.6 ECU Tester for O and I Levels.

GE has proposed several test instruments for use with the ECU. One recent proposal was similar to the McAIP AFTA proposal except that it had no connection to the aircraft bus. It used an Intel 80186 microprocessor but the processing speed was not fast enough to perform transient tests; typical response time was one second or slower. AFTA would not be able to use the aircraft bus to acquire ECU data at a sufficient rate to perform transient data tests.

A problem noted by GE, but not addressed by the McAIR proposal, was that relating to alternator failure. In particular, Jim Dolle seemed keen to have a power supply to simulate and test the alternator.

The McAIR proposal would redefine the future of AFTA, particularly as the US Navy does not currently use it at O-Level. Extra test sequences would need to be developed jointly by GE and McAIR.

In general, the concensus appeared to be that the McAIR proposal using AFTA was feasible as long as GE contributed to the development.

5.0 ATTENDANCE AT AIAA AIRCRAFT SYSTEMS MEETING.

This was a three day conference organized jointly by the American Institute of Aeronautics and Astronautics (of which I am a member), the American Helicopter Society and the American Society of Engineering Education. It was held at the Marriott Hotel in Dayton Ohio, from 20 to 22-Oct-86.

On the first day, I attended the presentation of five papers on Fighter Aircraft Systems and three papers on Propulsion-Airframe Integration as well as the opening address and Wright Brothers lecture on HiMAT. [The HIghly Manoeurable Aircraft Technology project involved the use of part scale aircraft (X-29) to test the theories involved in simulated combat.]

On the second day, I presented two papers[4,5], one of which I wrote. Both were well received. I also attended the presentation of four other papers on Aircraft System Effectiveness, two papers on other topics and a panel session on Flight Testing. As well as the conference sessions, I also attended an evening paper by Dr Paul McCready given at the University of Dayton. This paper, titled "Stretching the Limits of Nature and Engineering", clearly showed Dr McCready's approach to innovation and was most entertaining. Later in Washington, I was able to see the model Pterodactyl described by MacReady in his talk.

On the third day, I attended the presentation of five papers on future projects which were largely funded by the Defense Advanced Research Projects Agency (DARPA).

After the conference, I spent some time at the nearby USAF Aircraft Museum.

5.1 NASA F404 Control Proposal.

In a private conversation after the session on the second day, during which we had both given papers, W.F (Frank) Burcham of NASA Dryden indicated that he would like to run a collaborative program on a Full Authority Digital Engine Controller [FADEC] for the F404-400 engine. He suggested GE plus at least one operator of this engine would be necessary for a viable project. He said: (i) The program to develop a FADEC for the F100 engine used in the F-15 (which involved NASA, USAF and Pratt & Whitney) was very successful:

- some figures (such as acceleration) improved up to 15%;
- diagnostics and reliability were much improved;
- production of the resulting Digital Electonic Engine Control (DEEC) is now under way;
- there was a possibility of adding control interaction with the flignt control.

(ii) F404-GE-400 engine will not show an equivalent improvement because:

- F404 engine is trimmed closer to surge line;
- F404 engine control is currently more reliable;
- F404 engine is less prone to flame-out and other problems encountered with the F100 engine.

(iii) GE has not agreed with the NASA proposal yet but has shown signs of increased interest. NASA already has an F-18 available at the Dryden base.

(iv) US Navy is currently not very interested. [On later visit to US Naval Air Systems Command I confirmed this point; in fact representatives seemed positively disinterested; see later.]

5.2 Overall Impression.

I noted an overall trend in the papers presented to regard the engine plus its intake and nozzle as a single unit and some favoured controlling this unit from the airframe computers. Core engines may either:

- have on-board control system with external "trim" signals, or
- have engine software moved to the remote airframe computer [this is termed Propulsion Control].

Other control arrangements proposed included the use of a subset of integrated control where the flight control passes requests to the propulsion control, and the use of deflecting nozzles as a flight control element. Work was described on several configurations with canards and nozzles contributing to pitch control. A DARPA study showed use of a deflecting nozzle should provide improvements in yaw control especially in sub-sonic "dogfights".

6.0 VISIT TO WRIGHT-PATTERSON AFB.

My contact at Wright Field was Lester Small. Lester explained the USAF nomenclature system in which the 1300-strong Air Force Wright Aeronautical Laboratories (AFWAL) has Avionics, Materials, Flight Dynamics and a 350-strong Aero Propulsion (PO) divisions. PO is further divided into Turbine Engine (POT), Ramjet, Power and Fuels and Lubricants sections. The 130-person POT is divided into Performance (POTA), Advanced Development (POTP), Research (POTX) and Components (POTC) branches. Lester's Control group, along with Turbines and Augmented Combustion groups, forms the Components Branch, which is designated AFWAL/POTC.

It soon became apparent that a high percentage of the work being handled by Lester's group is done by external contractors. The group appeared to have five engineers but did almost all of its work by letting contracts to various US firms and consortia. A wide range of projects were mentioned, with a major current area of emphasis being the definition of the form of second generation digital engine controls, and the development of Flight/Propulsion integration control laws and architecture. As well, the group sees a role in identifying and initiating investigations of emerging control technologies for long-term applications; the time-scale here extending to the next century!

Lester defines a first generation digital control as one comparable with that developed for the F404-100 engine proposed for the F-20 aircraft. Another first generation unit, the F100-220 DEEC is actually a single channel FADEC with hydro-mechanical backup and Lester worked on the definition of the form of this controller in 1973. A link between this DEEC and the Flight Control System was proposed in 1973/74. NASA sees this link as being able to move the fan operating line up and down. A future trend (second generation control) is to power engine controls from battery backed sources with no separate alternator for the controls.

A second generation controller would thus be all electric, have no mechanical backup (e.g. PW2037), be redundant, use fly-by-wire technology and have "digital-geared peripherals" such as simpler fuel pumps and shared hydraulics.

The flight-engine control integration subject encompasses combat roles and control logic for canards, nozzles and wing surfaces and includes architecture, fault tolerance and maintainability issues.

The final form of the digital engine controller and the means to implement control integration are both expected to become clear over the next ten years. One reason for the relatively slow progress towards implementation is the required amount of interchange across existing boundaries; the dividing line between engine and airframe, which is still quite strong, will need to be relaxed. The longer term aim is to double the thrust/weight capability of turbine engines by the turn of the century. This would require both hotter and lighter engines.

6.1 INTERFACE.

The INTEgrated Reliable FAult-tolerant Control for Engines program aims to develop and bench test a second generation FADEC that provides a substantial improvement in reliability, maintainability and integration capability. [Note that an improvement in performance was assumed but not expressed.] This will require between US$3 and 4 million per year (1985-88) of 6.3* funding from the US$50 to 70 million spent each year on engine control research and development in the USA. [US$10 to 20 million of this total is spent in advanced R and D; the rest is largely applied to near-term problem solving.]

The approach to be used in INTERFACE involves:

- Studies of the configuration tradeoffs;
- Detailed design and fabrication;
- Extensive bench testing for:
  - a) fault tolerance,
  - b) hardware reliability and maintainability,
  - c) flight control integration,
  - d) system maintainability,
- Software simulation;
- Environmental test.

Two teams are involved under this contract:

A. GE (Both AEGB Div, Evendale; and ACSD Bingington), and Draper Labs (Guidance and Control manufacturers of the Apollo guidance)

B. Pratt and Whitney (United Technologies), Hamilton Standard (United Technologies), and Northrup.

* 6.3 funding relates to Advanced Development; USA research funding is also provided within categories 6.1 Basic Research; 6.2 Applied Research and 6.4 Engineering Development

Team B is using a low-bypass version of the F100 engine called the PW1120. The system maintainability specification requires the contractors to identify faults to single Line Replacable Units (LRU) and to replace that LRU without recalibration of the system. The layout of the system (all done in simulation) comprises the FADEC interacting with a real-time simulation of the engine, the flight model, comprising a real-time aircraft model, and pilot input, all connected via a token-passing ring network.

6.2 Missile/Drone Controls.

For drones and missiles using low-cost expendable engines, the cost of the engine control can be a significant portion of the "throw-away" cost; e.g. the Williams F107 (700 pounds thrust) in the cruise missile costs US$100k/engine of which US$25k is for the control. Smaller engines such as the 200-pound Teledyne engine in the Harpoon show that the control system absorbs an even greater proportion of the total unit cost. Two US$700k contracts have been let to Williams and Teledyne to produce low cost generic control systems which should cost about US$2000/engine. The controls will not use redundancy, will use simplified sensors and will not be man-rated (i.e. not suitable for bigger engines). The running tests are scheduled for late 1988.

6.3 DMICS.

This program, being a 1983 to 1986 project on design methods for Integrated Control Systems, was nearly finished at the time of my visit. It was run with two teams:

A. Northrup/GE/SCT

B. General Dynamics/Pratt and Whitney/Honeywell

In each case the first contractor was responsible for the airframe model, the second for the engine model and the third for the controls.

The project was purely analytical, involving mathematical models and simulations, including:

- a full non-linear thermodynamic engine model; [These, one from each team, are probably the most extensive engine models ever produced.]
- linear point models developed using linear design tools, and
- simple real-time models derived from the other two.

The pilot input was important in this program. [SCT later told me that the Northrup/GE/SCT program involved use of the Northrup F/A-18 pilot flight simulator to close the pilot/machine loop.] It appears that some of the work from this project will flow on into INTERFACE and it is hoped that DMICS will lead to a flight test vehicle in the 1990s.

6.4 PSC.

The Performance Seeking Control program is a cruise (not manoeuvre) option. It is a joint GE/Northrup program and uses an Adaptive Trim Control concept. Real-time models of the engine and airframe are used to define the optimum cruise point; i.e. minimize fuel flow for a set airspeed. This may lead to a possible 2 to 5% improvement in range for no increase in hardware.

6.5 ICLE.

This is a 2.5 year program on Integrated Control Law Evaluation proposed for commencement in the (US) Spring of 1987. It is in four parts:

1. system analysis
2. bench test hardware
3. test hardware/software issues
4. analysis.

7.0 VISIT TO NRCC OTTAWA.

My contact for this one day visit to the National Research Council of Canada's Division of Mechanical Engineering was arranged through Don Ruditski, Head of the Engine Laboratory, who serves on a TTCP panel [HAG8 now HTP7] with Denis Frith of ARL. During the morning of my visit, Don arranged a briefing on work done by the group. After lunch, he conducted me and a visitor from the Greek Airforce (on a two week AGARD assignment: he arrived the same day) on a tour of the facilities. This was followed by a meeting with Roland Gagné of the Systems Laboratory who is hoping to create a real-time model of a T56 engine and later extend this to the F404 engine.

7.1 NRCC Briefing.

The morning briefing was conducted by Don, two members of his staff and Capt. J. Henry of the Department of National Defence (DND), for the benefit of both visitors. I commenced by asking Don for the names of contacts at Leigh Instruments and DND regarding Crash Position Indicator, which may feature in Ken Fraser's proposed visit in April 1987. I left several cards with Don for forwarding to Leigh and DND. Don indicated that NRCC was unlikely to be interested and Bill McMillan of DND, who would have been interested, has been posted and is moving very soon.

I then gave a run-down on information I had so far gathered on my trip. This included:

- proposal to use AFTA for data collection and engine diagnostics [see section 3];
- GE Fort Wayne feeling that a box similar to AFTA would be usable but would be improved with the addition of alternator test functions and an internal analog-digital converter for connection to a fixed buffer box on the engine [section 4]; and
- USAF's DMICS program with F404 models [see sections 6 and 14].

Don indicated that DND had not proceeded any further with GASTOPS proposal[1] for the development of a F404 ECU diagnostic unit and were unlikely to do so without specific requirements being raised. He also said that DND felt that its current inventory of F404 ECUs [about 35] was likely to be sufficient, with lower than expected ECU faults and the relatively short time required for repair and testing of removed units through GE Fort Wayne.

Capt Jim Henry of DND, who is doing a Masters thesis on work at NRCC, described his work on analysing IECMS engine data. He said he tried to:

- establish precision and repeatibility of IECMS data;
- investigate methods for trending using dynamic (transient) data.

This was done by:

1. Comparison of IECMS data with NRCC test cell data. [Note that NRCC test cell has extra probes including those to allow separate measurement of afterburner fuel flow, not measured during flight.] There was a bias difference between some NRCC and IECMS data (e.g. T_1, T_5) but after a bias correction technique was applied, precision of sensors, etc. appear comparable.
2. Airborne assessment. [Note part of Uniform Engine Test Program UETP]

He used laboratory results to help to define the airborne engine data precision and compared this experimental estimate with the measured errors. In order to analyse only data relating to rapid accelerations, [where engine response is not dependent on pilot rate of power lever movement] the method ignores all data where the nozzle did not close and then re-open when recording started as the engine reached the Military Power level [Mil-Power]. Using this technique, he has obtained a matrix of data plots for 5 to 30 degrees Celsius inlet temperature. He had reached no conclusions relating to P_0 or T_1. For the same engine, fuel flows were consistent to within ±2% and N_1/N_2 to within ±0.5%. He indicated that he was unable at present to reject any of these matrix pairs.

During the data collection a High Pressure Compressor [HPC] fault was found and repaired. Two sets of data had been collected before the repair and four after but, comparison of the two "before" data sets revealed that an engine change had occurred. This leaves only one data set before the event and four after. Jim advised that he knew, via Denis Frith, of work being done on IECMS data by Peter Frith, Tony Runacres and Graeme Merrington of ARL. He also noted that NRCC has developed its own steady state F404 engine model (based on NRCC test cell data) as well as using the GE-supplied engine acceptance data.

Major Bruce Cossar of DND spoke to me by telephone and explained that he was unable to attend NRCC to meet me due to being involved in the acceptance testing of some new equipment. He indicated that DND would be interested in looking at a proposal for an F404 ECU tester but was unlikely, at the moment, to initiate a request for such a proposal. I promised to send him a copy of my visit report.

7.2 Tour of NRCC.

I was shown test facilities and data acquisition systems in the Engines laboratory. These included the T56 engine rig, the F404 engine test stand, PDP11/34 based data acquistion systems and a new MicroVAX data processing system.

T56.

A water cooled brake dynamometer was connected to the T56 engine which was fully instrumented. Pressures and temperatures were piped down to the control room to the scanivalves and data acquisition system. A current problem concerns control of the T56 (nominally a fixed speed engine) at speeds different from the design speed. A modified fuel controller with more range of adjustment is to be tried.

F404.

This test stand is being modified to add hydraulic repositioning of the thrust cradle and to use thrust flexures suitable for both compression and tension. NRCC has added to the GE procedures for the F404 engine: these extras include improved measurement of fuel flow. Fuel flow to the total engine is redundantly measured and the fuel to core engine is diverted to an off-engine measuring circuit comprising a temperature sensor, two flow meters and another temperature sensor before coming back on engine. A couple of the signals on J61 are also used but neither of these is N_1 [see section 4].

Data Acquisition.

The test cell systems run RT11 (Version 5.3 at the time of my visit) and are being standardized to include NEFF signal conditioning equipment.

Data comparison was being carried out by a new MicroVAX with VT241 and Visual 230 terminals and HP7550 plotter. Ethernet (to run under DECnet) was being installed between the MicroVAX and the test cells and possibly also to the PDP11/55 in the site computer centre for networking to the site IBM mainframe. A PDP11/55 running RSX was in use on a rotor balance rig.

Stewart Hughes instrumentation is being acquired for vibration work [person working on this was already on way to MFPG conference, see later section]. This is likely to be used on ship turbines for the Canadian Navy.

7.3 Artificial Intelligence. [AI]

Don noted that Rolls Royce was already using AI on Adour and RB199 engines for vibration analysis. NRCC will try using an expert system for the rotor balance rig which requires operator expertise to set up and select correct transducers.

7.4 Modelling.

Roland Gagné of Systems Lab showed me the new AD100 array processor which was on a VAX at that stage but was to be moved to a MicroVAX. He noted that the other contender for this work was an EAI Simstar which was rejected on cost. The AD100 has 5 processors and provides high level systems calls to solve differential equations and similar problems. Roland showed me the proposed modelling arrangement which uses NRCC data (as look-up tables plus linear interpolation) for compressor maps, etc. The person working on this project took up another position soon after starting and this may delay this project. [ARL is not alone in having problems attracting people in the control/modelling field.] Roland was currently writing routines to allow existing ACSL programs to be used on the AD100. [Note: ACSL is a registered trademark for a "Simulation Language" written for mainframe computers.]

8.0 VISIT TO GE LYNN.

A major presentation was made by GE on the following topics:

- ECU Cable Swapping Harness;
- F404 Continuity Tester;
- Depot Tester (ATE);
- ECU Reliability Record.

Craig Litster, Australian NAVPRO QA Officer, was present and GE was represented by Eric Stilphen Ray Grady, Ed Jeffrey, John Welch and William Anderson. Bob Grant and Phil Grear provided the F404 field maintenance reports. John Smith, the local Australian TFPO officer, was unavailable apart from a brief meeting on my arrival.

8.1 ECU Swapping Harness.

This is a set of long cables which allow the ECU on one engine to function as the ECU for the other Cooling is still provided by the engine on which the ECU is mounted. Some early Electrical Field Interference (EFI) with this arrangement has been overcome by changes to the cable screening. [There is a conflict between cable capacitance and cable screening that makes it difficult to establish the correct level of screening.] I understand that Australia has not decided to order this unit. Annex A discusses all tester options further.

8.2 F404 Continuity Tester.

GE originally proposed a two-part tester for the electrical components on the F404 engine. The mock-up of the ECU tester was rejected because of perceived problems with size and ergonomics. [The US Navy has a 30 pound (14 kilogram) limit on individual pieces for O-Level equipment.] As well as being a "big yellow box", this tester had a very large number of knobs and dials. However, the second part of this proposal did proceed and the "Continuity Tester" was produced. The Continuity Tester tests harnesses and other electrical components on the engine and can detect open or shorted sensors, etc. It can perform only very rudimentary testing in the ECU itself. The current US Navy version of this tester is rated for full O-Level environment and has no connection for the ECU. A more complicated model [which may be available in a cheaper non-military environment version] still under test at GE would add connection to the J61 connector and enable some detection of ECU errors. The extra fault trees for that testing have yet to be developed but the hardware prototype is being tested. Ed Jeffrey noted that a problem with the AFTA approach (McAIR) is that the engine is normally serviced in USA by mechanics and not avionics personnel.

8.3 Depot Tester ATE.

The US Navy has decided to purchase two ECU ATE units. The first is currently being made for Jacksonville Naval Air Station for 1988-89 delivery, and the second has been delivered to North Island Naval Air Station (San Diego) in California. The GE proposal to the Spanish Air Force for F404 engine ground support includes an ATE for the test stand. Since this Spanish proposal is under the Foreign Military Sales (FMS) agreement, it would be possible for Australia to also order an ATE under FMS. This would reduce the price significantly relative to the last GE quotation to the RAAF for an ATE. Further reductions may be possible if the environmental chamber was manufactured in Australia to GE drawings and GE used some of their offset obligations on this project. Annex A discusses the ECU tester proposals in detail.

8.4 ECU Reliabity Record.

GE presented me with some tables[23,24] on ECU removal rates. Again representatives noted that the high removal rates are due to the ease of removal of the ECU, the dependence of other engine components on the ECU for correct operation and the lack of an on-engine ECU tester.

8.5 Other Talks at GE.

I briefly discussed the controller for T700 engine with Paul Misoda, and arranged contacts for Ken Fraser's proposed visit to discuss matters relating to the Black Hawk helicopter. Craig Litster noted a lack of communication to him from ARL. He offered to help with any future visits to Lynn.

9.0 ATTENDANCE AT 41ST MFPG CONFERENCE.

I drove from Washington to attend the last morning of the three day meeting organized by the Mechanical Failure Prevention Group. This was the group's 41st meeting and was held at the Naval Air Station at Patuxent River Maryland. The MFPG meeting is sponsored by the US National Bureau of Standards, Office of Naval Research and Army Materials Technology Laboratory in cooperation with the American Helicopter Society.

I arrived slightly late due to traffic problems but was able to listen to the last half of a talk by Derek Astridge, then of Westland Helicopters. I noted that he had made considerable use of helicopter gear vibration data collected in Australia. The following two papers by Paul Howard of Tedeco and Ron Stewart of Stewart Hughes [UK] related to helicopter monitoring equipment and again work done at ARL was mentioned. I then presented a paper written by Cec King and Ken Fraser. This paper covered a wide range of work in helicopter monitoring done at ARL by the authors, Neil Swansson, Shane Favaloro, Max Atkin, Peter McFadden, Ray Krieser and others. This paper was extremely well received, particularly the part describing the work done by Peter McFadden on Wessex gear vibration analysis. Many people asked for copies of the reference list and the conference organizer Larry Mertaugh had a number of copies made and distributed. During question time, one engineer complimented Peter for the papers he has published in this field and described his own application of the ARL methods in factories. A list of people who asked for further details is included in the list of contacts [Sect. 18]. It includes two senior engineers from United Technologies Sikorsky Aircraft. The presentation at this meeting has been followed up by visits of more senior staff from ARL to Sikorsky.

Neil Swansson from ARL and Lincoln Wood of RMIT, who were both on USA attachments at the time, were present at this conference along with staff representatives of the Australian Embassy, Washington, including the RAN representative. The support during question time was much appreciated. Lincoln Wood, who was on attachment to Sikorsky Engineering, sent Ken Fraser of ARL a facsimile on 3-Nov-86 in which he said, referring to this conference: "The ARL paper was very well received and generated a lot of interest with regards to signal processing. You may be interested to know that, in my assessment, ARL appears to be further advanced in condition monitoring than any US group represented at Maryland. Of course, the Westland/Stewart-Hughes group was way out in front."

After lunch the conference organizers had arranged a tour of NATC. Unfortunately, I had to move on to my next appointment, which was with the McDonnell Aircraft representatives at NATC.

10.0 VISIT TO MCDONNELL AIRCRAFT REPRESENTATIVES [NATC].

The main contact for this meeting was supposed to be Steve Kapinos. He, and most of his colleagues, were unavailable due to attendance at the funeral of a pilot killed in the crash of a F-18 several days earlier. I was able to talk in general terms with Larry Thomas and gained an impression that they would have been unlikely to have been able to contribute much additional information about the F404 Engine Control Units.

It was the only time on the whole trip that prior arrangements made were not carried out and the reason was beyond criticism. I much appreciate the effort Larry made to talk with me in the circumstances.

11.0 VISIT TO NAVAL AIR SYSTEMS COMMAND WASHINGTON.

Both this visit and the following one were to buildings in the same group as my Motel in Washington. At Naval Air Systems Command [NAVAIR or NASC] my contact was John Carver. I briefed John on the purpose of my visit and on discussions held so far. We then discussed several aspects of engine control.

11.1 Possible Future Digital Controllers for F404.

John said GE had made several proposals for digital controllers for the F404. Only the proposal referred to as the Digital Engine Control Unit [DECU] had been funded so far and the decision not to proceed further with this had probably made other proposals more difficult to fund. The latest GE proposal, referred to as DEEC/F404, was raised 6 to 9 months prior to my visit. This proposal aims to:

- use the latest surface mount technology;
- reduce the price of the ECU by 50%;
- provide a digital controller with the same form and function as the existing ECU;
- save approx 3 pounds [1.4 kg] in weight; and
- use the T700 proposal [see below] as its technology base.

The DEEC/F404 proposal has not been funded and could take over two years to convert into hardware after acceptance. John seemed to think that upgrade of the F404-400 ECU was unlikely except as part of a general engine upgrade some time in the future. He noted that the Advanced F-18 project was in "moth-balls".

[Note that the DECU used in the F404-100 and RM12 is not a direct replacement for the ECU in the F404-400. It was designed for single engine installations such as in the F-20 and Gripen (Griffon) aircraft. Several actuators and some engine components would need to be changed on the F404-400 to use this controller.]

11.2 Other DEECs on Related Engines.

A DEEC is being designed for F110 evaluation and a DEEC is being built for the T700 engine and is likely to be available within two years [to improve the competitiveness of the T700 with the RTM322 engine from Rolls Royce and TurboMeca which was designed with digital control].

11.3 Other DEECs.

The first Pegasus F402-RR-404 engine proposed for the AV8B Harrier upgrade had just been delivered. This engine uses a two-channel DEEC with mechanical backup. Each DEEC has a built-in fault diagnosis system to keep track of all faults which occur in flight. It uses Ultra Violet erasable Programmable Read Only Memory (PROM or UVPROM) based software to allow software revision without hardware changes. [Take lid off box and change PROMs; top board visible has actuator PROMs etc. while the next board (rest of PROMs) is accessible by lifting the top board on its flexible connections; i.e. do NOT need to disconnect any boards to change software.]

11.4 Burn-In on F404 ECU.

US Navy is asking GE to burn-in ("shake and bake" test) ECU before shipping. GE is currently seeking to amend this proposal in some repects, most notably by requesting that time spent in setup procedures be counted as burn-in time.

This raises the question as to whether Australian ECUs are to receive the burn-in treatment.

12.0 VISIT TO AUSTRALIAN F18 PROJECT OFFICE (TFPO WASHINGTON).

In the afternoon, I had a short visit to the Australian FA-18 Project Office [originally called the Tactical Fighter Project Office and still using the abbreviation TFPO], where my contact was WGCDR R.P. (Dick) Hedges. I advised Dick on the purpose of my visit and the progress so far and left copies of the new McAIR AFTA proposal [Section 3 and Annex A] and some details of GE reliability data [Section 8]. He was unable to advise whether the GE Continuity Tester [Section 8] had actually been ordered. Suggested I ring John Smith (TFPO at GE Lynn) regarding this and advising him that GE appears to have a better proposal for a test stand in mind.

13.0 VISIT TO NAVAL AIR PROPULSION CENTER.

The Naval Air Propulsion Center is at Trenton, one of the three cities which make the TRI-CITY of Trenton-Philadephia-Wilmington. Of all the establishments I visited, this was the closest style of establishment to Propulsion Branch at ARL.

My main contact here was Russell W. (Russ) Vizzini, Program Manager Advanced Engine Control Systems. Russ presented me with a folder of information on the subject of engine control research being done in-house or externally with NAPC funding. Engine control research was discussed in the light of the other information I had collected on this subject.

The presentation from Russ covered the background to the engine control field and various projects which NAPC were involved in.

13.1 Background to Turbine Engine Control.

In the 1950s and 1960s, turbine engines such as the TF30, used hydromechanical control with temperature limiting. During the 1970s engines such as the F100 and F404 retained the hydromechanical control but added electronic trim. Newer designs now use electronic control with hydromechanical backup. In the 1990s, advanced engine controls will use dual path or "fail operational" electronic controls. This will be followed by multi-path integrated propulsion/airframe control with such technologies as "fly-by-wire", "fly-by-light" and optical sensors.

The dual channel control systems will reduce mission abort rates even without added reliability. Current flight systems show much lower abort rates than engine systems do. With fully redundant engine controls, it should be possible to increase the Mean Time Between Failure from about 100 engine hours to 500 hours and at the same time reduce the mission abort rate from over 1000 to 1 per million flight hours. [This occurs because the probability of two failures occurring is the product of the probability of each failure; if this probability is small, then its square is infinitesimal.]

NAPC sees the trend as towards an "integrated system architecture" where aircraft systems such as the Electronic Flight Control, Diagnostic Data System, Electrical Power Supply and Hydraulic Power Supply all interact with the engine sub-systems such as the Electronic Engine Control, Fuel System and Direct Drive Actuators.

13.2 Navy Control System Technology Programs.

Russ described six NAPC advanced propulsion control system programs and an engine monitoring program. These were:

1 F100 FADEC Certification completed in 1985;

2 Advanced Fuel Management (AFM), a four year program completed 1986;
3 A program on Analytic Redundancy Technology for Engine Reliability Improvement (ARTERI) which should complete the three-year development phase in 1987; a follow-on program will test and demonstrate the improvements achieved;
4 A major long term program on Fiber Optic Control System Integration (FOCSI) which is a joint project with DOD and NASA to demonstrate "fly-by-light" and for which only a single year (1987) contract had then been funded;
5 A Fibre Optic Sensor for Turbine Inlet (FOSTI) temperatures was to be the subject of a two year from 1986 contract;
6 Multimission Engine Control for Aircraft (MECA) which is another joint project, this time with NWC, and was about to start; and
7 EMS which is a proposal to extend existing F-15 Engine Monitoring System technology to suit the F-18.

F100 FADEC Certification.

Pratt and Whitney had been contracted to arrange the certification of the Full Authority Digital Engine Control (FADEC) for the F100 engine. This project had been successfully completed before my visit.

AFM Program.

The Advanced Fuel Management program had already been completed by Pratt and Whitney. This program involved the examination of the hardware needed by second generation digital engine controls and the contract involved installation of redundant electronics and sensors, advanced actuators and pumps on the Joint Technology Demonstrator Engine (JTDE). Arrangements considered included the use of twin centrifugal fuel pumps, redundant actuators comprising direct drive valves and tandem rams, dual hydraulic systems, redundant sensor sets and dual/dual electronic computers. Improvements in the fuel and hydraulic pumps saved more mass than that taken up by the redundant electronics and sensors allowing an overall mass saving while improving reliability, durability, maintainability, and cost. Operability was also improved since the FADEC offered improved response for better transient operation and more precise steady state operation. A future extension of this project may look at further increases in hydraulic pressures (to say 8000 psi) to further reduce hydraulic system mass.

ARTERI.

Like AFM, the program on Analytic Redundancy Technology for Engine Reliability Improvement (ARTERI) was to use the JTDE for the follow-on evaluation phase. The development, for which General Electric is the prime contractor, uses the GE23 Variable Cycle Engine and completion was expected in 1987. The aim was to design an analytically redundant control engine system which should be fault tolerant and capable of accommodating a single sensor, electronics or actuator fault throughout the engine operating envelope. In the ARTERI concept, the controller includes a real-time model of the engine/controller system and uses component tracking and failure detection filters to keep track of all sensors, actuators, etc.

FOCSI.

The Fiber Optic Control System Integration (FOCSI) project involves GE, P&W, BMAC and McAIR as contractors. It aims to design, fabricate and test a totally integrated fibre-optic propulsion/flight control system for application to advanced military aircraft. FOCSI is a joint project involving NASA, USN, US Army and USAF in four phases: Design Study; Design Fabrication; Engine Test and Flight Test. It is hoped that the flight test will take place in 1995.

One of the considerations is the location of the engine control: three options include an on-engine FADEC, an off-engine FADEC using optical interconnection and for comparison, an off-engine FADEC using wire cable. The required mass of wire cables clearly shows that the last option is not realisable and shows a cabling mass advantage for the first option which has been selected for the initial flight test. A major portion of this program involves the development of fibre-optic compatible sensors and actuators.

FOSTI.

The Fiber Optic Turbine Inlet Temperature Measurement System program (FOSTI) is separate from FOCSI since it involves the commercialization of technology developed in-house at NAPC. The probes use a metal film on the end of a ceramic walled sapphire fibre to detect temperature: this has then to be joined to standard silica fibres and pass through a multiplexer to the conditioning unit. Initial testing will use six probes arranged around a natural gas burner. Allison Gas Turbines (AGT) is expected to be the contractor.

MECA Program.

Multimission Engine Control for Aircraft (MECA) is another joint Navy project and aims to conceptually design an engine control system for Navy multimission fighter/attack aircraft. It was expected that Allison and GE would run parallel programs.

EMS Options.

Each of the programs mentioned above concentrate on facets of the design of the next generation digital engine controls and the integration of these controls with other aspects of the aircraft control. The FOCSI program includes a look at Engine Monitoring Systems (EMS) as a concept. EMS is also being studied as part of a plan to upgrade the F/A-18 Inflight Engine Condition Monitoring System (IECMS). With FADEC systems using two or more separate "controllers" for redundancy, EMS can be built into the system, as a separate processor in each redundant controller, a separate job in each controller or as a separate processor connected to both controllers.

13.3 Helicopter Monitoring.

Jim O'Donnell discussed a possible monitoring task on USN SH-3 Sea King helicopters. I gave details of ARL work on transmission monitoring of the Mk50 Sea King helicopter operated by the RAN and promised to send a copy of the ARL paper which I presented at the MFPG meeting. Jim noted that very little work had been done on the role of temperature sensors in detecting problems in gearboxes. [This was also mentioned by Bill Sullivan of the Naval Air ReWork Facility (NARF), Pensacola, in discussions after the MFPG meeting at NATC.]

13.4 F404 Work at NAPC.

Al Kush (later joined briefly by Theodore E. (Ted) Elsasser, Manager Large Engines and Performance Division) discussed work done at NAPC on F404. During the F404 development, NAPC received test engines from GE Lynn and NAPC performed all tests [except those relating to endurance] on these engines. [Cooling problem arising from the high exhaust temperature (F404 has concentrated high energy flow) precluded long term testing in existing NAPC test cells without added cooling to stack.] The F404 was subject to more testing than any other engine, including:

- *Altitude test for performance using inlet screens not intake;*
- Functional test at corner points on envelope: e.g. AB light at minimum temperature and pressure;
- Distortion tests on inlet; and
- Ingestion tests, e.g. ice and water.

NAPC simulates altitude by pumping the exhaust to atmosphere to simulate lower ambient pressure, throttling the inlet (or ram as appropriate) and by conditioning the inlet temperature using a number of heat exchangers. The distortion test used an Inlet Random Frequency Generator developed by GE for original B1 bomber engine[17]. The F404 easily accommodated large distortions.

I was joined at this point by Barry Yuhas, who has polymer, combustion and aero-dynamic experience. [He noted that polymer, i.e. plastics, experience relevant to soot formation problem.] Barry discussed F404 derivative testing:

1984 DECU Comparison Tests.

These tests ran a direct comparison (by swapping) proposed DECU and current ECU on CIP (Component Improvement Program) version of engine. The DECU proved to be not very reliable and had some other problems.

RM12 Derivative for VOLVO Flygmotor.

This is a derivative of the F404-100. The -100 and RM12 are optimized for single engine installations. The RM12 uses a DEEC with a single channel plus backup and has some substitution modes. It is significantly more expensive than the F404-400 version. It has a combat mode (high T_5 setting) added during the "wet" part of the power range (afterburner on).

F404-400D.

This is a dry (no afterburner) version of the F404 being developed to re-engine the A6F. It also uses a special ECU but this does NOT use digital technology. It needs modified schedules since the nozzle is not adjustible. The A6F uses a curved exhaust pipe but the test cell uses a straight pipe to keep the engine thrust line in the direction of thrust measurement along the test cell.

Growth Version.

Barry expects a growth version of the engine to be developed in the 1989/91 timeframe and that this engine will use a FADEC.

Beth Grem took me on a tour of the test cells where I saw the F404-400D being installed in the altitude cell. I noted that the instrumentation being used included NEFF 620 signal conditioner, as used at NRCC. NAPC also still uses Tektronix 4006 high resolution monochrome displays in the test cells.

13.5 F404 ECU Maintenance.

Thomas R. Metz, Program Manager, Reliability/Maintainability Engineering Programs, discussed F404 ECU maintenance. Thomas arranged for computer printouts on Navy actions on ECU over the previous 18 months to be available for discussion. The Navy has approximately 1000 F404 engines.

This list highlighted several points:

- Electrical Control Unit, Part 2747L00 was variously referred to (largely by different bases) as the ECU, the ECA (Electrical Control Assembly) and CAE (Control Assembly Electrical);
- Approximately 150 actions on this component were taken over this period;
- Some units have up to five actions, but they include replacement after repair, etc.; and
- A large number of "cannibalisation" actions, where ECU from a "good" engine is swapped to a problem engine, occurred.

This last point, which indicates units being swapped between engines for diagnosis, may indicate that the US Navy needs an O Level ECU tester!

13.6 Exchange Possibilities.

The possibility of staff exchanges between NAPC and Propulsion Branch ARL was mentioned by several people while I was at NAPC. Since my visit, action to pursue staff exchanges has been taken.

14.0 VISIT TO SYSTEMS CONTROL TECHNOLOGY.

Systems Control Technology (SCT) is one of a pair of related companies which "spun-off" from the nearby Stanford Research Institute (SRI). The other company Systems Control (SYSCON) is a commercial company now owned by British Petroleum (BP). SCT, as a US military contractor, is now run separately to SYSCON because of SYSCON's foreign ownership. [SYSCON markets the control design program $CONTROL_C$ which is a competitor for $MATRIX_X$ in the design and analysis of control systems (see next section).]

SCT is a company of about 200 people of whom 18% have PhDs. SCT has been an independent company since 1981. There are four main operating divisions, each with about five departments of 5 to 10 people. [These departments include a group working in AI applications.] Two of these departments were engaged in work relevant to my visit. These were Maintenance and Logistic Systems department in the Systems and Products Division (R.L. De Hoff is leader, my contact was Timothy Jellison) and the Control and Instrumentation department of the Advanced Technology Division (Stephen M. Rock, group leader and contact).

14.1 Controls Projects.

My first contact was with Stephen Rock who spoke about SCT work on engine controls He spoke of a number of Technology Demonstrators, some of which have been already mentioned under AFWAL or NAPC.

F100 DEEC Program.

This very successful program involved Ron De Hoff from the beginning and Steve towards the end. It led to the production of the F100-220 engine, one of the first military engines to use digital control.

Variable Cycle Engine.

SCT was involved in the mathematical modelling of the GE23, a variable cycle engine design this was a demonstration of the limit of technology. An interim report on this project is about to be published.

Allison GMA200.

SCT supplied the logic for Bendix to put in the controller box this was tested by running a model on a hybrid computer.

DMICS.

SCT was in one of the two teams engaged in this USAF integrated control design methodology program SCT was strongly involved with Northrop in flight simulation

Sensor Fault Detection.

SCT is involved in a computer modelling project with Walter Merrill of NASA Lewis to detect F100 sensor faults. Steve noted that modelling errors swamp the measurand noise in this project which is now on-test at Lewis.

Engine Modelling and Parameter Identification.

The aim is to produce an improved F404 cycle deck with more accurate compressor and combuster, etc. parameters. This is needed if integrated control is to be demonstrated. This F404 model also involves Tim Horling of NAPC and Roger Burton of NATC. It involves largely a refinement of parameter identification techniques; SCT is working with the USN to try to extract transient data from USN test data.

Failure Accommodation.

Steve noted that the usual method of failure accommodation used the "Bank of Kalman Filters" approach which has proved to be a good technique except for the accommodation of a faulty rotor speed. Typically 11 inputs are used for 6 outputs.

14.2 Engine Maintenance.

At this point, Tim Jellison took over the presentation. Tim said that CEMSiv, developed four years previously by SCT, was now the standard USAF maintenance support tool for engines. A new extension of this[43] is XMAN which is a menu option on the CEMSiv workstation. XMAN is being implemented for the TF34 engine and will be ported to the F100-220 next, with the first F100 demonstration scheduled for early 1987 at Nellis AFB.

XMAN currently has 57 different alarms or rule files and was written in-house by SCT ... MU-LISP. It is presently deterministic and not a learning or AI program. The next version will add inferences" with "certainty factors" and learning. The current version has over 400 decision nodes and the prototype had been installed for field trials the week before I arrived. Tim gave me copies of the presentations[39,40,41,42,43] on both CEMSiv and XMAN and I was able to see a demonstration of the latest version from Jill Josselyn, one of the authors. SCT requested a copy of the ARL paper on IFDIS[52].

15.0 VISIT TO INTEGRATED SYSTEMS INC.

Yet another derivative of SRI, Integrated Systems Inc (ISI) markets the software package MATRIX$_X$ which appears to be widely regarded as the best control design and analysis package on the market. My contact at ISI was Andy Mills who is the Director of Marketing.

Andy showed me new versions[46,47,48,49,50,51] of MATRIX$_X$ running on VAXstations and IBM PCs. He told me that ISI was about to deliver a field test version of an ELXSI implementation to NASA Dryden for beta testing. He estimated that an ELXSI version would cost about US$85k when available, and explained that it ran under the VAX-VMS emulator on the ELXSI which is called EMS. This comes as a three part set: Compile Time, Operating Set and VAX Utilities: only the Operating Set part is needed to use MATRIX$_X$ since an object file is supplied

Currently, most sales of MATRIX$_X$ are for use in the VAX environment and ISI has released its new Version 6 only for the VAX and VAXstation [and of course for the ELXSI]. PCs and non-VAX mainframes use Version 5 and older workstation products such as that for Apollo still use Version 4. [This may explain the comments at Boeing about the VAX version being much better than the Apollo one!]

I was most impressed with the workstation and PC versions; I do not see that the mainframe versions can be justified for purchase by a customer unless very large and complex systems need to be modelled. The AUTOCODE option which writes Fortran 77 or ADA code for the controller designed by $MATRIX_x$ seems like a quick way to eliminate the routine steps from a control design process. [I have since arranged an ARL order for an IBM PC and the appropriate version of $MATRIX_x$; funds for the purchase of AUTOCODE by ARL are being requested during the 1988-9 financial year.]

16.0 GENERAL IMPRESSIONS.

One of the most impressive aspects of this visit to USA and Canada was the enthusiastic reception I received wherever I visited.

16.1 Relevance of ARL Work.

I was pleased to discover, both by the reception to the papers I presented and by talks with staff at other establishments I visited, that work being done at ARL is regarded as relevant and of high standard. It is sometimes difficult to maintain an even perspective of local work standards when Australian effort is (in relation to USA) so small in this area.

16.2 Trend to Contracting Laboratories.

I noted when discussing AFWAL/POTC in section 6 that there was an almost complete trend to the use of contractors to do all the research. This trend was not as marked in the US Navy establishments (and may of course not be as notable in other sections of AFWAL) and certainly not as defined at NRCC. While I can see an increased role for contractors is possibly justified in Australia, I was somewhat alarmed at this trend. In ten or twenty years time when the contracts are no longer being supervised by people with the background of Lester Small, will the whole system collapse? Since no one in the laboratory will have relevant experience, will the officers who currently arrange the placement of external contracts be replaced by ex-contractor personnel? In that case, who will monitor for conflict of interest? Personally, I would hope that basic research, and a proportion of applied research and development, should always be done in-house.

16.3 Trend to Integrated Control.

The marked trend noted in overseas control research is towards integrating the engine into a propulsion control system including the intake and nozzle and then further integrating that into a combined system with the flight control. This trend was confirmed in almost all discussions but there was no uniformity of opinion on how it could be done.

16.4 Recommendations on ECU Testers.

Detailed discussion of the possible test arrangements for the electrical components on the F404-GE-400 are discussed in a separate Annex. As a result of that discussion, I am recommending that, subject to sufficient funds being available and the costs being reasonable:

1 The General Electric proposal for a "cable continuity" tester be accepted; and

2 The McDonnell Aircraft proposal to extend AFTA to read MSDRS tapes and test the ECU via a EDAB be seriously considered.

The General Electric proposal for RAAF to acquire an Automatic Test Equipment (ATE), including an environmental chamber to suit the ECU, is considered unwarranted for the expected number of ECU removals and faults in Australia, unless significant cost savings could be made and faults could be rectified in Australia.

A short seminar discussing information and impressions gained during this overseas visit was given by the author at ARL on 3-Dec-86.

17.0 ITINERARY.

11-Oct-86 > > 12-Oct-86
Travelling (Week End)

13-Oct-86 Rest day

14-Oct-86 BOEING Flight Controls, Seattle, Washington

15-Oct-86 Travelling

16-Oct-86 McDonnell Aircraft Company, St Louis, Missouri

17-Oct-86 General Electric Company, Fort Wayne, Indiana

18/19-Oct-86 Week End

20-Oct-86 > > 23-Oct-86
AIAA/AHS/ASEE Aircraft Systems Meeting, Dayton, Ohio
[Presented two papers in sessions on 21-Oct-86.]

24-Oct-86 Air Force Wright Aeronautical Laboratories [AFWAL]
POTC division, Dayton, Ohio

25/26-Oct-86 Travelling and Weekend

27-Oct-86 National Research Council of Canada, Ottawa

28-Oct-86 Travelling

29-Oct-86 General Electric River Works, Lynn, Mass.

30-Oct-86 AM:
41st Mechanical Failure Prevention Group Symposium
PM:
McAIR [Naval Aviation Test Center]
BOTH at Patuxent River, Maryland

31-Oct-86 AM:
Naval Air Systems Command, Crystal City, Virginia
PM:
RAAF F18 Project Office, Crystal City, Virginia

1/2-Nov-86 Travelling and Week-end

3-Nov-86 Naval Air Propulsion Centre, Trenton, New Jersey

5-Nov-86 AM:
Systems Control Technology, Palo Alto, California
PM:
Integrated Systems Inc., Palo Alto, California

6/7/8-Nov-86 Travelling (Includes one rest day)

18.0 LIST OF CONTACTS [LISTED IN ORDER OF CONTACT].

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2 George Hennig, Supervisor, Control Sciences Group, *BMAC*, 11th Floor, Boeing North Tower Sea-Tac Airport

3 Donald G. Iverson, *BMAC* as above.

4 A.J. (Jerry) Volsen, Lead Engineer - Electronics, F/A-18 Advanced Design, *McDonnell Aircraft Company*, PO Box 516, St. Louis, Missouri 63166. [(314)234-2070]

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37 Timothy G. Jellison, Engineer, *Systems Control Technology*, as above.

38 Andy Mills, Director Marketing, *Integrated Systems Inc.*, 101 University Avenue, Palo Alto California 94301-1695 USA [Since moved to: 2500 Mission College Bvd , Santa Clara CA]

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CONTENTS
ANNEX A

A.1 BACKGROUND. A-1
A.1.1 Engine Control Unit. A-1
A.1.2 DECU. A-2
A.1.3 Maintenance Requirements. A-2
A.1.4 Operations (O) Level. A-2
A.1.5 Intermediate (I) Level. A-2
A.1.6 Depot (D) Level. A-2
A.1.7 Fault Diagnosis Procedures. A-3

A.2 PREVIOUS PROPOSALS FOR EQUIPMENT. A-3
A.2.1 Original GE Proposals. A-3
A.2.2 GASTOPS Proposal. A-3
A.2.3 GENRAD Avionics ATE System. A-4

A.3 CURRENT PROPOSALS A-4
A.3.1 GE Continuity Tester. A-4
A.3.2 Cable Swap Loom. A-4
A.3.3 McAIR AFTA Proposal. A-4
A.3.4 GE Full ATE Proposal. A-6

A.4 LEVEL OF SUPPORT JUSTIFIED. A-6
A.4.1 Local Repair of the ECUs. A-6
A.4.2 Local D-Level Testing. A-7
A.4.3 Local O-Level Testing Using AFTA. A-7
A.4.4 Local O-Level Testing Using Cable Swap. A-7

A.5 FUTURE TREND OF ENGINE CONTROL UNITS AND TESTING EQUIPMENT. A-7
A.5.1 Role of Expert Advisors (AI). A-7
A.5.2 Replacement of ECU with a Digital Unit. A-8

A.6 RECOMMENDATIONS. A-8

A.7 REFERENCES. A-8

ANNEX A
PROPOSALS TO IMPROVE F404 ECU MAINTENANCE

A.1 BACKGROUND.

The Electrical Control Unit (ECU) is a Line Removable Unit (LRU) for the F404-GE-400 engine. Since the RAAF has no test apparatus to determine whether a removed ECU is faulty, any ECU removed needs to be returned to the USA for testing. This is costly in itself but also implies that a higher level of spare ECUs needs to be maintained. Since the ECUs are complicated and expensive items, ARL has been asked[3] to consider possible methods of improving fault detection and isolation for this unit and some of the related engine components. This situation is further complicated by various proposals to replace the current ECUs with updated units at some time in the future. This means that measures taken now must take the life-span of the existing ECUs and ECU technology into account. In October and November 1986, I travelled to USA and Canada to look at the possible means of testing these items.

A.1.1 Engine Control Unit.

The F404-400 engine has a mixed hydro-mechanical and electrical control system. The major component of the electrical system (referred to as the ECU) is a fuel-cooled transistor unit mounted directly on the engine and powered by the engine alternator. As well as basic electrical tasks such as:

1 Ignition,
2 Electrical power (Alternator),
3 Flame detection, and
4 Electrical interconnection;

the electrical control system which includes the ECU performs the following tasks:

5 Isochronous governing above intermediate power (N_1 speed limit);
6 Turbine temperature control;
7 Scheduling afterburning fuel flow;
8 Scheduling variable geometry such as:
   8.1 Fan geometry, and
   8.2 Nozzle area control during afterburning;
9 Power lever override for either:
   9.1 Aircraft signals such as weapons release, and
   9.2 Approach power control system;
10 Monitor functions such as:
   10.1 Detection of fan overspeed,
   10.2 Detection of various electrical failures,
   10.3 Detection of stuck nozzle control, and
   10.4 Provision of signals to airframe monitoring system.

[Note that the Hydromechanical (Main) fuel control (MFC) controls the compressor geometry.]

The ECU is equipped with a test connector (J61) which directly connects to ECU inputs and outputs as well as some internal ECU signals. This direct connection can be a benefit but also produces a problem in that any connection to J61 must be well buffered in order not to impair the ECU reliability.

A.1.2 DECU.

General Electric proposed an updated version of the ECU which incorporated digital logic. This unit was a functional replacement for the ECU with added performance and a claimed increase in reliability. The major enhancements improved transient response and compensated for droop (Engine power dropping as heat and blade creep reduce performance from set level). The diagnostic ability of the unit was also increased by the provision of built-in test routines and indicators for these and an increase in the pins on J61 to 128.

The DECU was not purchased by any of the major F404-400 customers and did not proceed. It is not the same as the redundant digital controller on the F404-100 (which is optimized for single engine fitment) and nor is it a Full Authority Digital Engine Controller (FADEC). There was also some doubt concerning the level of isolation provided for the new J61 connector on this unit; it appears that the lack of buffering was still present to some extent.

A.1.3 Maintenance Requirements.

The maintenance requirements normally arise when a pilot has reported an engine problem, avionic equipment has reported possible engine misbehaviour or analysis of recorded airframe/engine data has indicated a possible engine problem. Diagnosis would proceed first on the installed engine and migrate through Intermediate Level to Depot Level if a problem, which could not be repaired in the field, was found.

A.1.4 Operations (O) Level.

At operations level the engine is usually diagnosed as a complete system with the ECU fitted. The use of ECU test hardware would be practical only if:

1 The test procedure took less time than unit replacement,
2 The test was definitive and not based just on elimination,
3 The test discovered a reasonable percentage of faulty units, and
4 The test did not indicate a significant percentage of serviceable units to be faulty

A.1.5 Intermediate (I) Level.

Depending on the result of the O-Level testing, the I-Level testing may be either on a removed module or a removed engine. With a removed engine, similar testing procedures to those for O-Level may be used except that more time can obviously be involved since removal has already occurred. With a removed module, it would be necessary to simulate engine signals to test the ECU. This would require more complex and more intelligent hardware.

A.1.6 Depot (D) Level.

Depot level testing would involve either simple repairs, full verification of repaired ECU's or simpler selection procedures to authorize deployment to a remote repair centre. The Automatic Test Equipment (ATE) used on avionics boards could be programmed to carry out such functions if there were sufficient faulty boards to warrant such action

A.1.7 Fault Diagnosis Procedures.

Current fault procedures for the engine involve the use of "fault trees" where simple tests progressively and systematically eliminate various assemblies likely to cause the indicated fault. Depending on the fault, as many as 13 units may be suspect before testing begins. The tests do not involve ECU diagnostics and hence ECU faults are defined by elimination of the other possibilities. Such a test is not definitive and fails in the presence of two or more faults.

A.2 PREVIOUS PROPOSALS FOR EQUIPMENT.

Various proposals for test equipment, with applications in this area, have been made. General Electric (GE) has specified or designed several testers for the ECU ranging from simple O-Level cable continuity checkers to complex D-Level Automatic Test Equipment (ATE) which can identify problems in individual components within the ECU. The ATE is essentially the same as the equipment used to support the design and testing of the F404 ECU in the factory.

A.2.1 Original GE Proposals.

GE originally proposed a two-part tester for the electrical components on the F404 engine. The separate parts handled the ECU and the cabling respectively. The mock-up of the ECU tester, which would have been capable of testing both installed and removed units, was rejected because of perceived problems with size and ergonomics. [The US Navy has a 30 pound (14 kilogram) limit on individual pieces for O-Level equipment.] As well as being a "big yellow box", this tester had a very large number of knobs and dials.

However, the second part of this proposal did proceed and the "Continuity Tester" was produced. The Continuity Tester tests harnesses and other electrical components on the engine and can detect open or shorted sensors, etc. It can perform only very rudimentary testing in the ECU itself. The current US Navy version of this tester is rated for full O-Level environment but has no connection for the ECU.

A.2.2 GASTOPS Proposal.

The Canadian Defence Forces (CDF), which also operate F404-GE-400 engines in F/A-18 aircraft, commissioned an external contractor (Gastops Ltd.[1]) to undertake a design study for a F404 ECU tester to meet CDF requirements. The GASTOPS proposal consists of a rugged portable computer which connects via an adapter to J61 of the ECU. Considerable software would need to be written to cover both open-loop and closed-loop testing. The advantage of this approach is the use of a PC which may have multiple uses, the disadvantage is the large amount of information and software needed. It would not appear practical without the direct involvement of GE.

It would appear that the Canadians have not proceeded any further with this proposal and were unlikely to do so without specific requirements being raised. They feel that the current CDF inventory of F404 ECU's [about 35] was likely to be sufficient, with lower than expected ECU faults and the relatively short time required for repair and testing of removed units through GE Fort Wayne.

A.2.3 GENRAD Avionics ATE System.

Australia has purchased a General Radio (GENRAD) Automatic Test Equipment (ATE) system for diagnosis of board faults on removed avionics boards. This ATE could be extended to test removed ECU boards if there were sufficient demand for such tests. Such an extension would be very expensive and unlikely to be justified by the small number of repairs likely to be required by Australia. Use of the avionics ATE has not been considered further.

A.3 CURRENT PROPOSALS

Proposals currently available for consideration include:

A.3.1 GE Continuity Tester.

Equipment to test cable integrity is a prerequisite for any ECU testing. As noted in section A.2.1 above, GE already offers such equipment. A more complex model [which may be available in a cheaper non-military environment version] still under test at GE would add connection to the J61 connector and enable some detection of ECU errors. The extra fault trees for that testing have yet to be developed but the hardware prototype is being tested.

If the cost of this unit is reasonable, I believe it would be worth purchasing but the most appropriate version would need to be selected.

A.3.2 Cable Swap Loom.

With a twin-engine aircraft, it is theoretically possible to eliminate faults in certain engine subassemblies by using inter-engine cables to swap assemblies from one engine to the other without physical removal. [This process should not be performed unless full cable testing has already been carried out and requires use of both engines.] GE has certified a set of long cables which allow the ECU on one engine to function as the ECU for the other. Cooling is still provided by the engine on which the ECU is mounted. Some early Electrical Field Interference (EFI) with this arrangement has been overcome by changes to the cable screening. [There is a conflict between cable capacitance and cable screening that makes it difficult to establish the correct level of screening.] I understand that Australia has not decided to order this unit.

A.3.3 McAIR AFTA Proposal.

The Avionics Fault Tree Analyser (AFTA) unit is being developed by British Aerospace Australia (BAeA) under contract to McAir to test avionics equipment. McAir has proposed[2,10] a number of extensions to the role of this equipment.

A.3.3.1 Use of AFTA For ECU Fault Detection.

McAir is proposing a set of "Fault Trees" in the AFTA unit which would extend the existing tests by incorporation of those ECU tests which can be performed without disconnecting the ECU. AFTA normally tests avionics by invoking the built-in test routines in the selected avionics unit. The ECU does not have this capability however and does not connect to the aircraft bus from which AFTA normally acquires all its data. For these reasons, this represents a major upgrade to AFTA requiring a buffer box to connect to the engine, cabling and an engine simulator to verify the engine fault trees as well as software to support the user interface, fault tree selection and the engine simulation. McAIR had not done any major work on the engine simulator but claimed to have done sufficient work on the other items to prove that such a role for AFTA was feasible.

One of the major stumbling blocks in using AFTA to diagnose faults in the existing ECU is the lack of any interconnection between the ECU and the rest of the aircraft systems. McAIR proposed to overcome this by using an Engine Diagnostics Adapter Box (EDAB), and by providing improved access to data from the on-board Maintenance Signal Data Recording Set (MSDRS).

A.3.3.2 Using AFTA to Read MSDRS Tapes.

Since AFTA connects to the aircraft multiplexed bus, it can collect data from any other unit also connected to the bus. The MSDRS (defined above) records a wide range of events on magnetic tape cartridges. These data are currently under-utilized. McAIR is proposing an alternative data-collection scheme in which the tapes are not removed from the aircraft. Instead AFTA would be used to read the tapes in situ, to transfer these data to a database, and rewind and erase the tape. Some of these data relate to engine events such as the fault flags which lead to maintenance checks on the ECU. Accordingly, this proposed use of AFTA has potential application in the testing of the ECU.

A.3.3.3 McAIR Buffer Box (EDAB) Proposal.

Only some of the available engine signals are *transferred* to the airframe and are recorded by the MSDRS. All proposals to check the ECU have assumed that additional connections to the ECU (usually via J61, the test connector on the ECU) will be necessary. The current McAIR proposal for the EDAB, includes buffer amplifiers, multiplexers, analog-to-digital converters and a microcontroller (probably Intel 8051 family) within the EDAB. This means that the ECU and EDAB combination will be treated as a testable unit by AFTA under the McAIR proposal. The EDAB will have a direct link (called the MC Link) to AFTA and will not communicate via the aircraft bus.

A.3.3.4 Hardware and Software Standards.

It is likely that VME standard boards will be used in the EDAB and that software will be written in PL/M with transfer to ADA some time in the future

A.3.3.5 AFTA Project Direction.

McAIR has concluded that a joint McAIR/GE/Customer program could develop Operational [O] or Intermediate [I] level engine test capability but that independent efforts by any one of these groups is unlikely to succeed. McAIR sees some of these proposed new AFTA functions becoming on-board functions for the Avionics Integrated Maintenance Expert System (AIMES) when avionics improvements provide space and added on-board computing power for such extensions. McAIR claims that the first flight of the AIMES demonstrator in January 1986 was the first flight of an expert system in a fighter aircraft.

A.3.3.6 AFTA Project Deficiencies.

The AFTA approach will not produce a full test system capable of all the functions of the GE proposal. Among the deficiencies noted for this approach are:

1. There is a lack of any test routine to determine alternator failure;
2. There is a lack of any method of stimulating transient failures, such as thermal cycling can achieve;
3. The McAIR proposal would require a redefinition of the role of AFTA, particularly as the US Navy does not currently use it at O-Level;
4. Extra test sequences (fault trees) would need to be developed jointly by GE and McAIR; and
5. While the engine is normally serviced by mechanics, AFTA is usually used by avionics personnel.

A.3.4 GE Full ATE Proposal.

General Electric uses a full ATE system in testing and setting the ECU parameters on the production line. This consists of a Hewlett Packard (HP) computer, a range of test instruments and an environmental chamber which allows the ECU to be subjected to sharp temperature gradients. This is a depot style facility for removed units. The US Navy has decided to purchase two ECU ATE units. The first is currently being made for Jacksonville Naval Air Station for 1988-89 delivery, and the second has been delivered to North Island Naval Air Station (San Diego) in California. The GE proposal to the Spanish Air Force for F404 engine ground support includes an ATE for the test stand. Since this Spanish proposal is under the Foreign Military Sales (FMS) agreement, it would be possible for Australia to also order an ATE under FMS. This would reduce the price significantly relative to the last GE quotation to the RAAF for an ATE. Further reductions may be possible if the environmental chamber was manufactured in Australia to GE drawings and GE used some of its offset obligations on this project. This would still be a very expensive item of hardware and is not suitable for transportation between bases.

A.4 LEVEL OF SUPPORT JUSTIFIED.

The level of support justified for the ECU depends on several factors. These factors include the likely failure rate of the ECUs, the likely removal rate of the ECUs if there is no O or I-Level tester and the likely removal rate with such a tester. A higher level of support would be required to provide local, in lieu of overseas, repair of ECUs.

Based on US Navy and GE records[23,24,38] and the relative number of engines in service, I believe that planning should be based on the assumption that eight ECUs will become faulty in any given 12-month period and that eight other events will lead to removal of the ECU if no ECU tester is available. The "pipeline", through USN to GE Evendale and back via USN, for the return of removed ECUs is estimated at 18 months. The "false removals" thus lead to a requirement for 12 extra spare ECUs and the faults to a similar figure. A number of spares would be carried anyway; these will be ignored as they will remain the same in all cases. Variations in the level of local support would affect the requirement for spare ECUs.

A.4.1 Local Repair of the ECUs.

Local repair of the ECUs implies the availability of a D-Level tester and a repair facility. The turn-around time for all units, faulty or not, would become only three months. This would save 20 spare units but is the most expensive option. This option has not been considered further, since the level of repairs anticipated would hardly justify such expenditure.

A.4.2 Local D-Level Testing.

Local D-Level testing requires a GE ATE in Australia. The turn-around time for the non-faulty units would become three months but the faulty unit turn-around time would remain 18 months. This option requires only 14 spares and so saves 10 spare units. I do not believe it will ever be possible to purchase a complete ATE and environmental chamber for the cost of 10 spare ECUs.

A.4.3 Local O-Level Testing Using AFTA.

The only additional hardware required for local O-Level testing using AFTA is the EDAB "Buffer Box" and most non-faulty units should no longer be removed. At best, this would halve the spares requirement to 12; more realistically it will save 10 spares which is a similar saving to that provided by the D-Level Tester option, but at a much smaller cost.

A.4.4 Local O-Level Testing Using Cable Swap.

Local O-Level testing using the Cable Swap Loom allows the ECU of one engine to be electrically swapped with the ECU on the other engine. I have estimated that this procedure would halve the number of non-faulty ECUs removed and produce a spare requirement of 18. The saving of 6 spares is the lowest for the systems being considered but this system may represent the least expensive option.

A.5 FUTURE TREND OF ENGINE CONTROL UNITS AND TESTING EQUIPMENT.

The method to be adopted for testing of RAAF ECUs must provide a long term solution to the ECU diagnosis problem; the method should be readily able to accommodate likely future ECU changes. The two points identified here concern future trends in testing methods and future upgrade of the ECU itself.

A.5.1 Role of Expert Advisors (AI).

The "Fault Tree" approach lends itself to computer assistance. This is even more true if information on fault histories is kept, allowing more likely subassemblies to be tested before less likely ones. I would envisage that an Expert Advisor similar to the ARL-funded IFDIS[52] could assist greatly in identifying which tests should be performed next for any given fault signature. The AFTA proposal from McAIR envisages that an expert system will be a future development. Both the AFTA and ATE systems would be similarly enhanced with the incorporation of expert systems, but the AFTA system may benefit more from a knowledge-base approach because it would be more widely distributed.

A.5.2 Replacement of ECU with a Digital Unit.

At some time in the future, a digital replacement for the ECU will probably be offered. I believe this offer may become available as early as the 1990s, and that the replacement unit will include built-in test facilities. This means in effect that the EDAB of the McAIR proposal would become redundant but only a change of software would be needed for AFTA to continue the O and I-Level ECU test role. The GE ATE would still include the Environmental Chamber but quite a few of the test instruments would need to be changed in my opinion. I see the ease of updating the AFTA to match the envisaged ECU upgrades as a factor in favour of the McAIR proposal.

A.6 RECOMMENDATIONS.

I have considered all of the above options. It seems sensible to have a specific method of testing the cable looms and seems also that an ECU tester could be justified if the cost did not outweigh the savings and added convenience. The McAIR proposal seems the best option as long as the costs are shared amongst users of this engine. Accordingly, I wish to make the following recommendations:

A. The "Continuity Checker" made by GE be considered for purchase.

B. Australia support the development of AFTA to test the F404-400 ECU, presumably via CIP funding or some other joint development with other users.

C. Australia support the involvement of General Electric as the ECU manufacturer in this project.

D. In the event that the AFTA proposal does not proceed, the General Electric "Cable Swapping Loom" be considered for purchase.

The General Electric Automatic Test Equipment (ATE) proposal is not seen as cost effective unless, for other reasons, it is considered necessary that repair of the ECUs be carried out in Australia.

A.7 REFERENCES.

[Numbers are those assigned in main document.]

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The Electrical Control Unit in the F/A-18 Hornet aircraft is field-replacable but suitable test equipment for this unit is not available in Australia. Both the United States Navy and the Canadian Defence Forces, which also operate the Hornet aircraft, concede deficiencies in flight-line test facilities for this unit and various proposals have been put forward to rectify the situation. The main purpose of the visit to USA and Canada was to analyse these proposals and advise the Royal Australian Air Force of the potential of each proposal to meet Australian service requirements. During the visit the opportunity was taken to present three papers on ARL research at conferences in the USA, and to discuss future trends in gas turbine controls.

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