Final Report on the Fuel Control System of the F100 Engine (1983)

Pages
53

Size
8.5 x 10

ISBN
0309326605

Panel on Fuel Control Systems; Committee on Mechanical Reliability; Air Force Studies Board; Commission on Engineering and Technical Systems; National Research Council

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Committee on Mechanical Reliability
Air Force Studies Board
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NATIONAL ACADEMY PRESS
Washington, D.C. 1983

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This report represents work under Contract No. F49620-79-C-0094 between the United States Air Force and the National Academy of Sciences.

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STATEMENT OF TASK

The Panel on Fuel Control Systems of the Committee on Mechanical Reliability shall assess factors which influence the reliability and life cycle costs of the F100 engine control system as used in the F-15 and F-16 aircraft weapon systems.

In pursuit of this task, studies will include the examination of the F-15 unscheduled components removal (AF 66-1) data and firsthand, on-site data at Air Force rework/repair facilities.

The panel will make its critical report, with particular emphasis on the failure and repair data, at the end of one year. Other complementary efforts may take longer to complete.

EXECUTIVE SUMMARY

Background

In December 1979, the Committee on Mechanical Reliability of the Air Force Studies Board established a Panel on Fuel Control Systems. It was this panel's task to review the maintenance and reliability of the unified fuel control (UFC) of the F100 engine. This engine powers the F-15 and F-16 aircraft. Approximately 2,000 engines are expected to be in the Air Force inventory by 1985.

The panel has met with representatives of the Air Force Logistics Command, the Air Force Systems Command, the manufacturer of the fuel control (Bendix), and the manufacturer of the F100 engine (Pratt and Whitney). A consultant to the panel has observed inspection and maintenance practices at air bases. The statement of task for the panel and the list of its members are located on pages ii and 1, and the visits of the panel and of its consultant are given in the section entitled Introduction.

Findings

The interim panel report bases its conclusions and recommendations, in large measure, on the following facts and on the panel's examination of the circumstances surrounding them.

- Today, four years since its introduction, the UFC averages about 400 hours of service between removals (MTBR = meantime between removals, 400 hours in this case).

- The design objective of the UFC is 1,000 hours MTBR.

- 350 hours is incurred for tests and calibration of each of the UFC's undergoing complete overhaul before leaving the depot. This is in addition to time for repair, replacement, etc.

- Existing data systems provide information about removal rates, without details as to causes. Even so, some of the leading causes of removal are known:

  1. First in importance has been failure of insulation in the stepper motors (the cause of 31.8 percent of removals). This problem resulted from an unauthorized change of material; on new and reworked units, the originally specified material is now used.

2. Next in importance are precautionary removals for which no cause was found (27.7 percent of removals).

- Different air bases show wide variations in removal rates. To some degree, such divergencies may result from genuine differences in operating conditions, but there may also be significant differences in maintenance practices.

Conclusions and Recommendations

General

The panel finds that there are many steps the Air Force can and should take to reduce the life-cycle costs of the UFC and reduce the impact of the UFC on life-cycle costs of the F-15 and F-16 weapons systems. More specific findings are detailed below. All of them are based on the panel's necessarily brief review.

- The panel recommends that the Air Force engage an independent industrial engineering contractor to examine the maintenance cycle of the UFC, with particular emphasis on the overhaul and rework process. The contractor should have access to realistic cost data, both on the direct costs of maintenance actions and on such indirect costs as those of down-time and inventory, so that the recommendations could be both specific and based on valid priorities.

Removals

- An obvious target for management and technical effort is the class of removals for which no defect is found (averaging 27.7 percent of removals, but as high as 35 percent at some bases). Better training, better manuals, and more complete and definitive procedures could be provided for base-level personnel to reduce this rate of apparently unnecessary removals at relatively small cost.

- The Air Force should examine the possibility, and cost versus effectiveness, of providing equipment at base level, or even on board the aircraft, for improving the diagnosis of malfunctions.

- The development of more effective diagnostic procedures and criteria for removal is hampered by a lack of data on causes. The Air Force data system 66-1 was designed for logistics management, not engineering analysis. The Air Force should consider undertaking a separate data-gathering effort, specific in this case to the UFC during the period of its introduction and early field use, to provide data for improving maintenance procedures, for design improvements, and for basic information on design practices.

Overhaul

- The panel concludes that a major and correctible source of cost in the logistic system of the UFC lies in the use of inappropriate and obsolete equipment in the overhaul ("rework") process.

- Overhaul of fuel controls at the depot, using current procedures, calls for 350 hours of tests and calibration for each unit before it leaves the depot. At this rate, a significant fraction of a unit's usage is consumed during rework. The panel understands that the Air Force plans to expand its overhaul facility based on the practices that call for this amount of test time and on the size of inventory that is thus implied. The panel observes that the manufacturer, Bendix, uses automated rework stands and test equipment that appear to require less test time during overhaul by a factor of 2.

- The panel strongly recommends that the Air Force equip its overhaul facility with automated stands and test equipment. Not only will this reduce the cost of rework, in time and in inventory, but fewer people, with less specialized skills, and fewer man-hours will be needed for the rework operation.

- The overhaul manuals covering rework practices are inadequate, to the point that such practices are simply not applied. Better guidance could be given to rework personnel, requiring of them less skill and improving their efficiency. The photographic guide sequence used at the manufacturer's plant is an example of the kind of system that could be more effective.

- The Air Force needs to take immediate steps to improve the technical orders and guidance covering rework operations.

Design

- The UFC is a complex component with about 4,300 mechanical parts, subject to continued wear and stressed by vibration, thermal changes, and corrosive substances. Of some 12 kinds of problems leading to design changes, however, the panel sees evidence that 5 either could have been foreseen for this environment or are of a type common to the design of many complex mechanical devices: (1) interference of parts, (2) inaccessibility of critical parts for maintenance, (3) inadequate protection against wear at critical points, (4) insufficient protection against corrosion, (5) material fatigue at points of stress. These judgments are observations of hindsight, of course. They point however to a continuing need for

- adequate design standards and practices;

- proper attention to <u>life cycle cost</u>, rather than to development cost or manufacturing cost, as the criterion for balancing design decisions, and

- accurate data on field performance to serve as a guide both for specific product improvements and improvements in general design practices.

- The panel finds that, at least specifically in the case of the UFC, the Systems Command and its responsible program office (in this case, the F100 engine SPO*) needs a more direct channel for information about operating experience than it may presently have. The present channels are by way of the Logistics Command and its standardized reports and by way of the contractors' representatives. Neither of these seems to the panel to be a fully satisfactory channel during the introductory phase of as complex a new product as the UFC.

*System Program Office.

I. INTRODUCTION

The Committee on Mechanical Reliability accepted the task of reviewing the F100 Fuel Control Systems in 1979. As of that time, this fuel control was experiencing about 400 hours MTBR (meantime between removals), as against a design objective of 1,000 hours. High removal rates and long repair times were costly, both per se and in their impact upon the inventory.

A decision was reached to form this panel and its chairman was formally appointed November 30, 1979. By early 1980, members were appointed, and a consultant was engaged later in the year. Between the panel members and the consultant, the following were visited, or representatives contacted, at one or more locations: Air Force Systems Command, Air Force Logistics Command, Air Force Tactical Air Command, McDonnell Douglas [builder of the F-15 weapons system], Pratt and Whitney [manufacturer of the F100 engine], Bendix [manufacturer of the unified fuel control (UFC) system as the F100 fuel control system is known], Kearfott [supplier of the stepper motor to be discussed], and DuPont [supplier of certain materials].

Data on the maintenance history of the UFC have been obtained from the AFM 66-1 data system, and from other sources. The panel's consultant reviewed all reports and presentations to the panel, reviewed failure analysis reports, reviewed the component improvement program tasks and technical orders, and examined the purchase specifications. Discussions were held with maintenance personnel of the First Tactical Air Command fighter wing, with maintenance personnel of the Air Force Logistics Command, and with engineering and logistics people of the F100 System Program Office.

II. HIGHLIGHTS OF HISTORY OF THE UNIFIED FUEL CONTROL SYSTEM

Background

The Unified Fuel Control (UFC) is currently in use with the F100 engine. This engine, designed by Pratt and Whitney Aircraft, powers the two-engine F-15 aircraft and the single engine F-16 aircraft. Figure 1 shows a drawing of the F100 with the UFC. A photograph of the UFC itself is shown in Figure 2. The device measures approximately 2' X 2' X 8". Its function is to meter the fuel and to schedule the nozzle area, as functions of: engine rpm, fan discharge temperature, burner pressure and engine electronic control. Inputs and outputs to the UFC are shown in Figure 3.

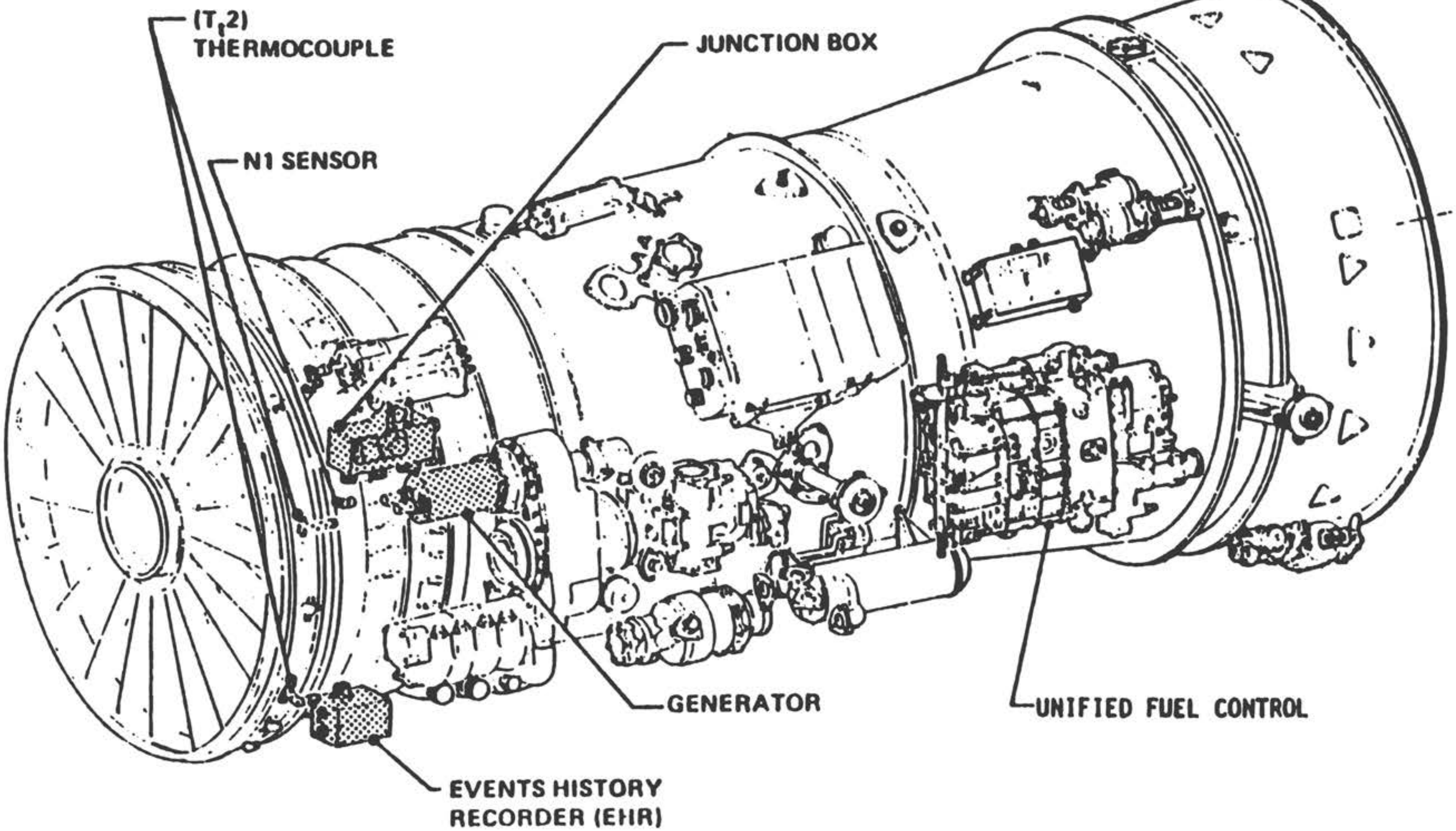
The UFC is a complex control device, containing about 4,300 mechanical parts. These include, beyond passive components such as tubing and filters, many valves, levers, cams, springs, and actuators. Each UFC costs $110,000. About 1,000 are now in service. Since about 6 percent of the units are removed each month for maintenance, the UFC serves as a good case for reliability studies concerned with early failures or "bugs".

First, however, the UFC must be placed in proper perspective. The UFC was developed specifically for the F100 engine. The F100 engine is not "just another engine" but a significant advance in aircraft propulsion. Its thrust to weight ratio is double that of predecessors (from 4 to 8). Such an advance was brought about largely by the use of new high-temperature materials and by more precise control of the engine parameters. In the operation of the F100, therefore, there is less margin for error, and greater demands rest on the UFC for precise control.

Important in the present context is the urgency of the development program that led to the F100. Some learning while flying the aircraft was anticipated. Although this may explain some of the early maintenance problems of the UFC, it does not detract from the use of the UFC as a case study for reliability investigations.

Several organizations are involved in the design and current maintenance of the UFC. The Air Force Systems Command is responsible for the design of the engine and has engineering cognizance through 1983. The F100 program office has the specific responsibility, supported by F100 engineering, logistics, and management groups. This office reports to the Deputy Director for Propulsion of the Aeronautical Systems Division. The Tactical Air Command flies the aircraft and provides first- and second-level maintenance functions. For the UFC, this essentially means that TAC personnel

F100



(T$_t$2) THERMOCOUPLE
JUNCTION BOX
N1 SENSOR
GENERATOR
UNIFIED FUEL CONTROL
EVENTS HISTORY RECORDER (EHR)

UNIFIED CONTROL

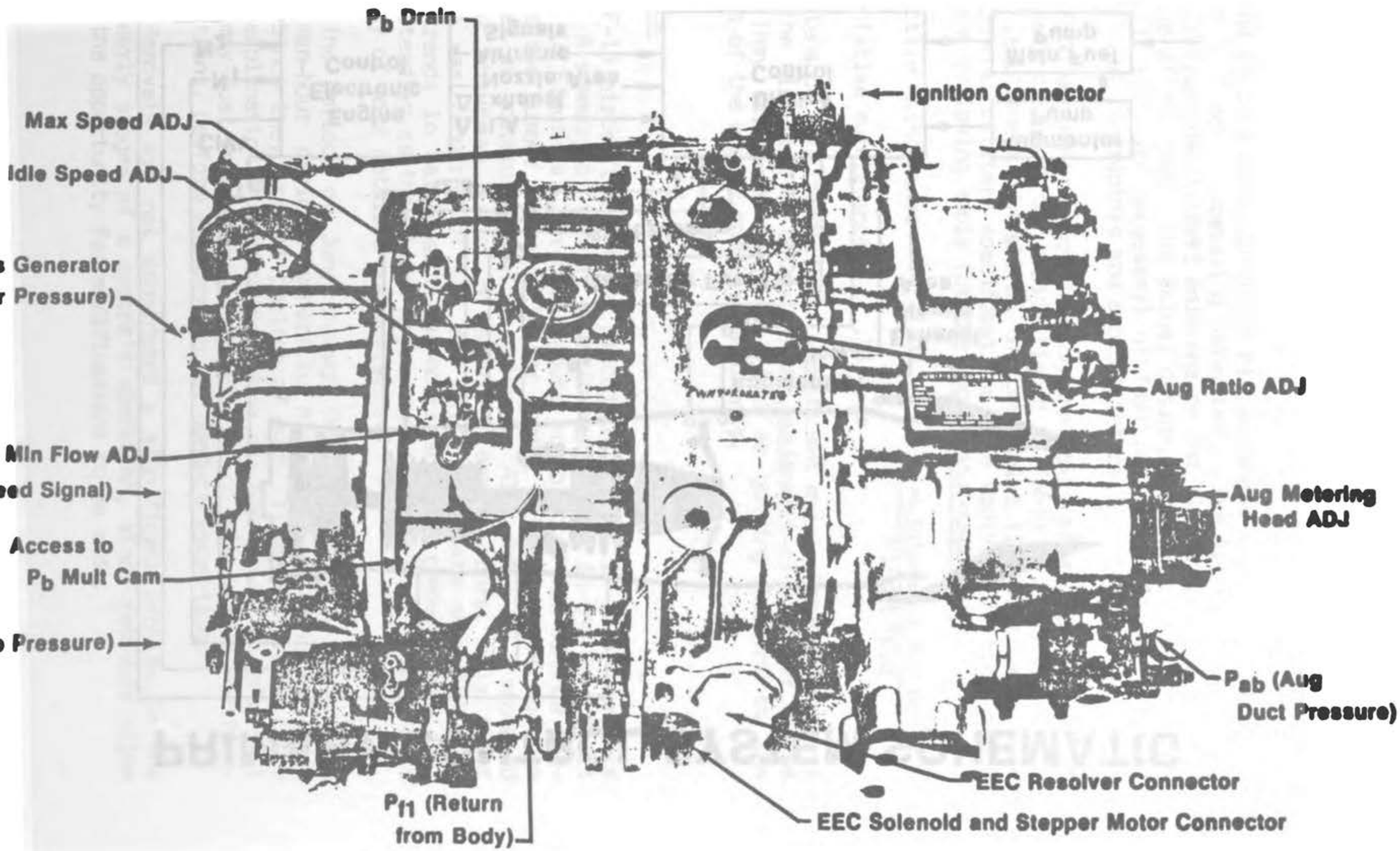


FIGURE 2

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PRIMARY CONTROL SYSTEM SCHEMATIC

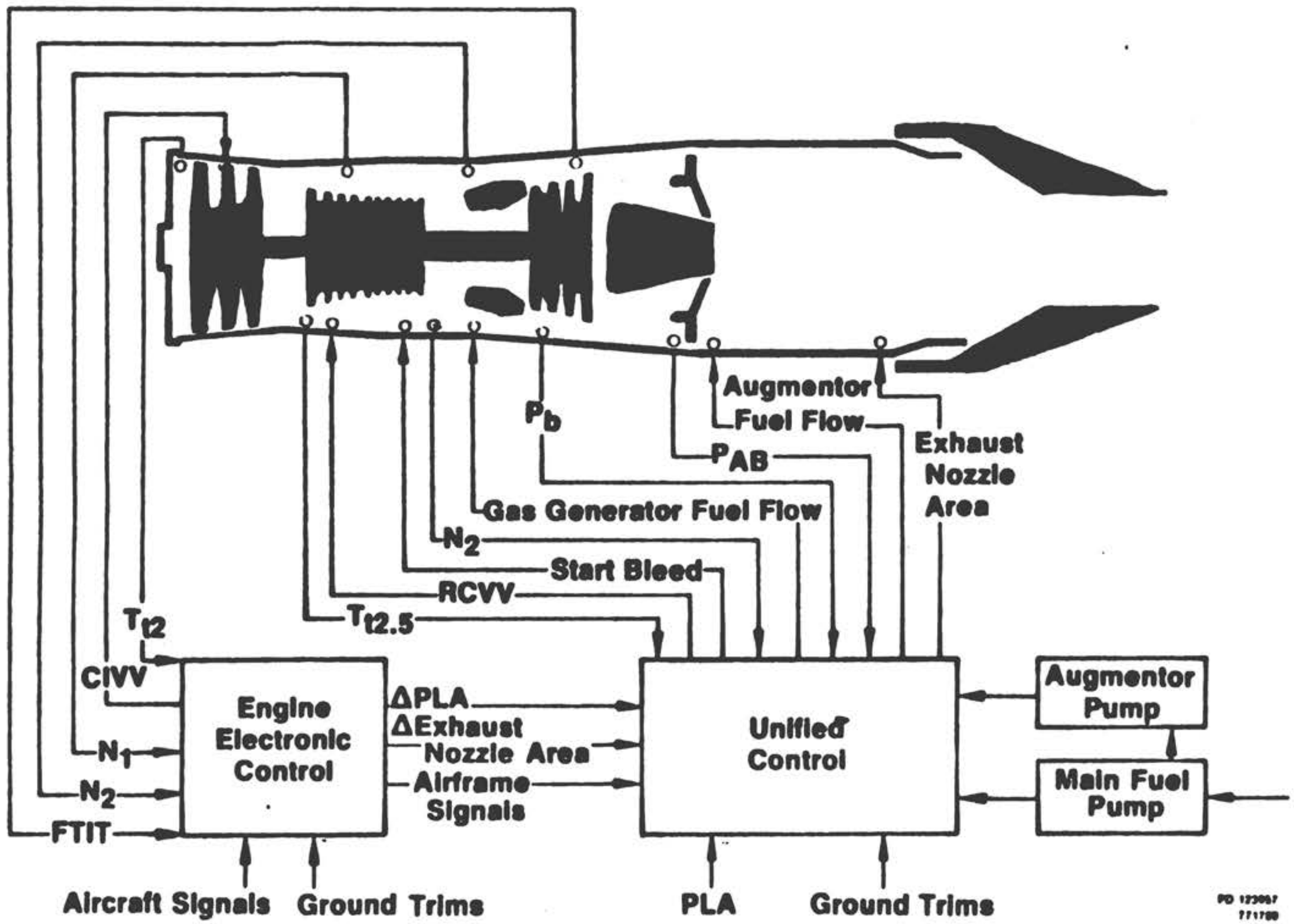


FIGURE 3

remove and replace the unit under circumstances that are defined by measurement of engine operating parameters. The Air Force Logistics Command provides depot-level maintenance and will assume engineering cognizance after 1983. The actual design, manufacture, and modifications (if such are necessary) of fuel control units are provided by a series of contractors and subcontractors.

The F100 engine was purchased on the basis of a detailed set of requirements covering the topics listed in Table 1. In addition to specific requirements in all of the categories listed, a large number of general military specifications also apply. For field maintenance the following apply for the engine and components:

Corrective maintenance	1.27	Maintenance Man Hours / Flight Hour
Preventative maintenance	.73	

The maintenance requirements are significant mainly because they are used by the Air Force to determine the assignment of manpower to the field. They serve as objectives and as guiding factors to the designers of the engine and its components.

Experience

The F-15 aircraft was first placed in service in 1975, the F-16 in 1979. A summary of the UFC maintenance history in the F-15 fleet is shown in Figure 4. In this figure are plotted maintenance manhours and the number of removals per month, for maintenance of the F-15 fleet as accomplished at base-level. Also shown is a smoothed curve for the mean number of aircraft engine hours; only minor smoothing was required of the raw data. The data show that the overall trends in maintenance man-hours and UFC removals have increased steadily as the flight-hours have increased. Certain points are worthy of more detailed consideration.

(1) The periods of June through October are high maintenance man-hour periods (generally high removal periods also). Since they are not periods of high flight-hours some other explanation is necessary. None has been found to date. It may just be a more convenient time to make system modifications, perform maintenance, or conduct inspections.

(2) Removals are not considered a significant problem in the early stages of a system's operation, since removals allow the opportunity for modifications to be made.

TABLE 1

REQUIREMENT CATEGORIES

CHARACTERISTICS

- Performance
- Physical Characteristics
- Reliability
- Maintainability
- Environmental Conditions
- Transportability
- Durability, Useful Life, & Low Cycle Fatigue

DESIGN AND CONSTRUCTION

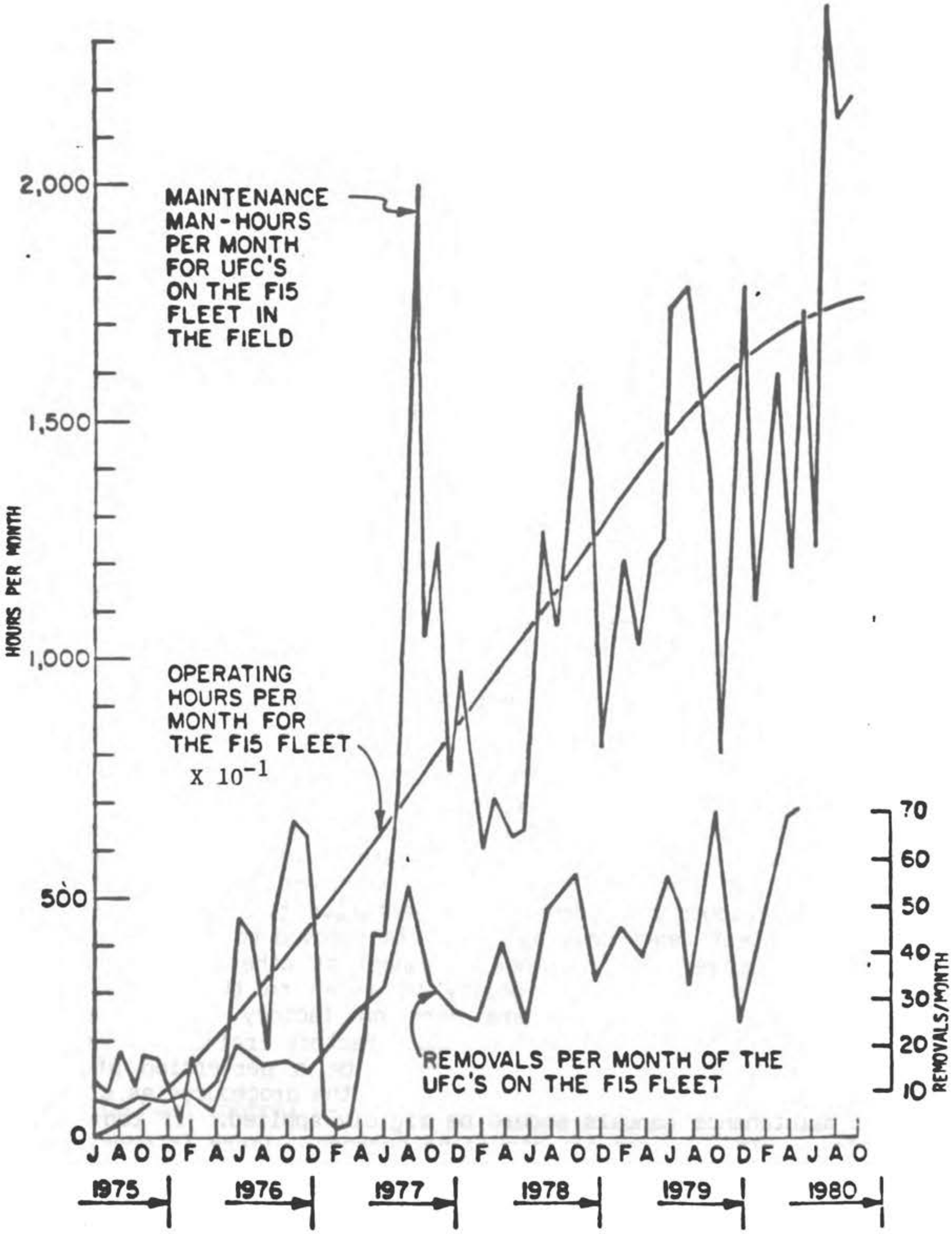
- Materials, Parts, and Processes
- Electromagnetic Interference
- Identification and Marking
- Workmanship
- Interchangeability
- Safety
- Human Performance/Human Engineering
- Storage

DOCUMENTATION

LOGISTICS

- Maintenance
- Supply
- Facilities and Facility Equipment

PERSONNEL AND TRAINING



HOURS PER MONTH
2,000
1,500
1,000
500
0
MAINTENANCE MAN-HOURS PER MONTH FOR UFC'S ON THE F15 FLEET IN THE FIELD
OPERATING HOURS PER MONTH FOR THE F15 FLEET X 10⁻¹
REMOVALS PER MONTH OF THE UFC'S ON THE F15 FLEET
70
60
50
40
30
20
10
REMOVALS/MONTH
J A O D F A J A O D F A J A O D F A J A O D F A J A O D F A J A O
1975
1976
1977
1978
1979
1980

FIGURE- 4

Figures 5 and 6 show the same basic data as Figure 4, plotted on a per-removal or a per-flight-hour basis, and smoothed. Data are available, approximately monthly, giving removals, maintenance-hours, and flight-hours for the reporting period. The central curve in Figure 6 shows, at each quarter, the median flight-hours per removal. A moving period of four quarters was used to calculate each median. The upper and lower curves show respectively the maximum and the minimum flight-hours per removal for all data reported in that quarter. Figure 6 provides curves of maintenance man-hours per flight-hour, similarly constructed. The remarkable flatness of the median curve does not indicate improvements in relative maintenance-hours.

Eighteen technical orders have been issued for design modifications on the UFC. Although these changes can be incorporated immediately into engines still in production, retrofitting into operating engines usually takes several years. Unless safety of flight is involved, modifications are incorporated only during a removal for other causes.

Figures 4, 5, and 6 cover only maintenance operations at base and intermediate levels. Depot-level repair is more time consuming. Table 2 compares experience to date at depot level, [350 maintenance man-hours (mmh) per unit], with that at TAC bases for base level maintenance operations -- 30 mmh/unit. This latter figure is consistent with roughly 35 mmh/unit derived from the broader data of Figure 4.

There is a considerable difference in the removal rates at different bases. This is illustrated in Table 3. Holloman AFB, with 128 aircraft, had 90 removals in a 6 month period while Langley, with 133 aircraft, had only 30. These bases experience about equal flight-hours per aircraft. A lower removal rate at Langley may be due to the presence of a Bendix representative there. He normally inspects and tests each unit before it is removed to make sure that removal is required. Maintenance personnel at other bases express the belief that with such a policy to refer to they could also reduce their removals; if there were no factory representative present, they could have their own people factory trained. However, such practices are considered by some to be a perversion of the maintenance system. Indeed, some hold that the procedures as stated in the maintenance manuals should be rigidly applied. If too many removals result, the manuals should be changed. There is considerable merit to both points of view.

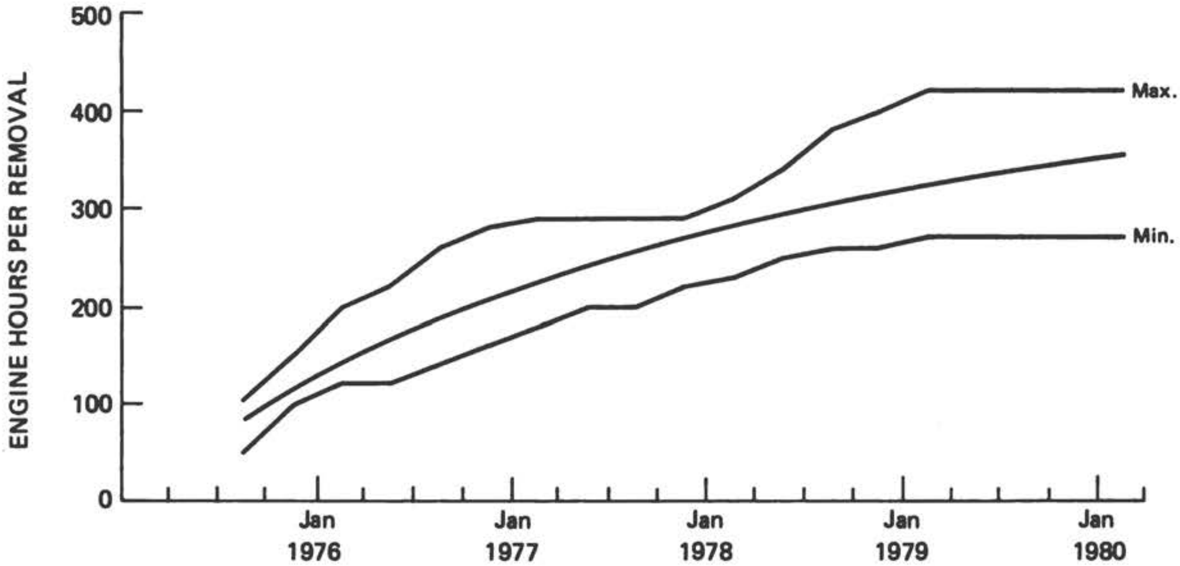


FIGURE 5

F100 Fuel Control -- TAC and Overhaul Base Maintenance History

Smoothed median, maximum, and minimum lifetime curves. Maximum and minimum lifetime of controls removed in each quarter. Moving medians of four quarters.

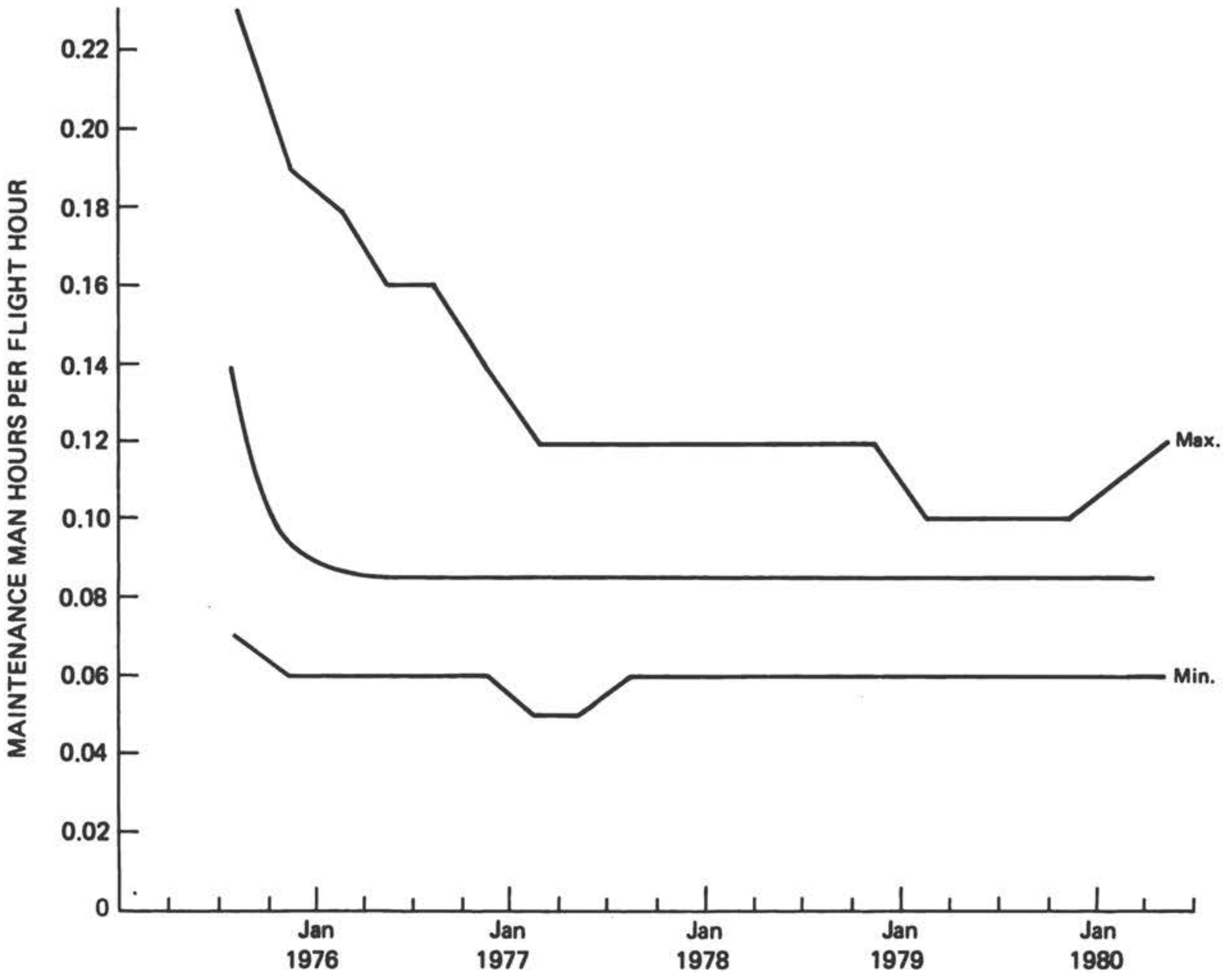


FIGURE 6

F100 Fuel Control -- TAC and Overhaul Base Maintenance History

Smoothed, maximum, and minimum curves, maintenance hours per flight-hour. Maximum and minimum in each quarter. Moving medians of four quarters.

TABLE 2

MAINTENANCE TIMES

DEPOT REPAIR	350 mmh/unit
O&I REMOVAL	
Remove & Replace	12 mmh/unit
Suppressor Test	8 mmh/unit
Engine Test	6 mmh/unit
Transport	4 mmh/unit
TOTAL	30 mmh/unit

NOTE: mmh = maintenance man-hours

TABLE 3

TAC

Base Removal Rates UFC

MONTH	BITBURG AB* 141 Aircraft	EGLIN AFB 57 Aircraft	HOLLOMAN AFB 128 Aircraft	LANGLEY AFB 133 Aircraft	LUKE AFB 152 Aircraft
Nov 79	7	1	13	4	13
Dec 79	4	-	9	5	2
Jan 80	8	6	15	4	13
Feb 80	3	1	15	4	6
Mar 80	7	4	20	5	11
Apr 80	1	9	18	8	12
TOTAL	30	21	90	30	57

*Operating data in Germany, included for reference.

However, it is the panel's judgment that not only is the experience and skill of such a person desirable at each base, but that a definite policy is needed to control or limit removals. In Table 3, it should be noted that the Bitburg data are included for reference. The reasons for the favorable removal rates are not known. Colder weather, more mature pilots, readily available spare parts, the longtime it takes to have a unit reworked, and better mechanics are the factors that are considered significant for the difference.

Table 4 tabulates from recent data the most common reasons for UFC removal. Almost 60 percent of the removals are associated with two causes: a faulty stepper motor and "unconfirmed" reasons. A removal is called "unconfirmed" if no defect is found after a bench check. It seems likely that these are due either to transitory contamination or to faulty diagnostic procedures. The active 40 percent of the removals was caused by a large number of other problems.

Development work is currently under way to provide improved stepper motors. Improved filters have been added; these should reduce the "unconfirmed" removals caused by contamination. However, TAC maintenance personnel state that an improved "fault tree" is required. The present diagnostic routine requires that certain checks to be made if a problem is reported. If these checks do not indicate a problem, the UFC is to be removed and sent to the depot for further testing. The possibility that nothing is wrong is not considered before removal.

Engine Management

Engine development and improvements are the responsibility of the F100 program manager. He is supported by engineering, logistics, and other specialists within the F100 program office. Logistics engineering and engine management support are also available from the Materials Management-Propulsion Division of the Air Logistics Center at Kelly Air Force Base, where depot rework is accomplished. Changes in design are approved by a configuration control board made up of representatives of the F100 program office, TAC, and AFLC.

Since the F100 engine is now in service, its further improvement is supported by a Component Improvement Program (CIP), a program specific to the F100 engine. Pratt and Whitney is the prime contractor for the F100 engine design and development, as well as for the CIP. When a problem is isolated in the field, a sequence of events is begun to correct the problem. Important milestones are listed in Table 5. Those parts undertaken by the contractor are identified. The final contractor product is an Engineering Change

TABLE 4

CURRENT REMOVALS

(1979 Data)

Percentage	Malfunction	Nature of Problem
31.8	Stepper Motor	Hot Fuel/Insulation Interaction
27.7	Unconfirmed	Contamination
		Faulty Diagnostic Procedures
6.6	Inability to Adjust	
5.1	Start Problems	
5.0	Leaks	Seals
4.1	Damage	Maintenance Errors
2.5	Augmentor	
1.9	Contaminated	Water & Dirt in Fuel
15.3	Miscellaneous	

TABLE 5

SEQUENCE FOR DESIGN CHANGES

	Identify Problem
	Propose CIP Task
	CIP Task
Contractor Efforts	Start Design Effort
Contractor Efforts	Hardware Print Available
Contractor Efforts	Start Testing
Contractor Efforts	Complete Testing
Contractor Efforts	ECP Acceptance
Contractor Efforts	Submit ECP to Government
	Government Action on ECP
	First Production Incorporation
	MMT Tests
	Flight Tests

Proposal (ECP), submitted to the government, defining the change exactly and its method of incorporation. Typically production changes, retrofit kits for the field, and changes in technical publications are involved. If the change is accepted the government responds with a Technical Order (TO) which authorizes it. To date approximately 18 TO's have been issued on the F100 engine. Generally speaking, the most expensive portion of a change is in the providing of retrofit kits. Typical figures might be:

Engineering	$ 50 K
Changes to Production Engines	66 K
Kits	250 K
Manuals	30 K

TO's are generally written to support more than one engineering design effort. During 1980, for the UFC, seven CIP tasks were authorized at a total cost of approximately $675,000. Almost half of this money went to developing a hermetically sealed stepper motor. Although complete data have not been available to the panel, a review of the CIP task costs prior to 1980 is given in Table 6. To 1980, a total of $1,007,000 had been spent. About half of this was devoted to the stepper motor. Thus, to date, a total of $1.7 million has been devoted to component improvement of the UFC, half on the stepper motor. These costs, of course, only represent the contractor costs and do not reflect internal government costs associated with the project. Table 6 also shows the scheduled contract or completion time from the start of design to the submission of an ECP.

Of particular interest is the decision process that selects projects to be funded by the CIP. Problems can be identified from four sources:

(1) From Pratt and Whitney through their field representatives

(2) From data in the AFM 66-1 information system

(3) From field failure reports

(4) Directly from TAC maintenance personnel

In practice, most data come from Pratt and Whitney. The contractor stations experienced representatives at operating bases, where they provide both first-hand experience and a two-way exchange of data between Pratt and Whitney and TAC. With information from

TABLE 6

CURRENT ENGINEERING TASKS

Prior to 1980

Task No.		Actual Cost to Date	Start Design to ECP
337		$ 127K	30 Months
343		20K	28
364		50K	22
563		0	--
566		119K	26
575		521K	17
618			25
626		12K	19
663		69K	7
736		6K	7
744		58K	6
761		25K	36
	TOTAL	$1,007K	

this source, Pratt and Whitney proposes changes or tasks for component improvement. These are evaluated by the F100 program office using whatever data are available. Projects are undertaken based on the availability of funds and on priority. The highest priority is given to performance and safety. It should be pointed out that there is considerable competition for the funds with other engine projects and with other engines.

III. FINDINGS

Cost

The cost of an unreliable UFC, or the value of improving the reliabiity of the UFC, can be great. Based upon the 1,923 removals that are covered in the data available to the panel, the total cost to the Air Force can be estimated:

Base and Intermediate Level:	1,923 Removals @30 hours/removal @$15/hour =	$ 865K
Depot Level:	1,923 Removals @350 hours/removal @$22/hour =	$14,800K
Loss of Aircraft Usage*:	1,923 Removals X 6 hours @$2000/hour =	$23,076K
	Total Cost =	$38,741,000

The current cost rate, similarly calculated, is about $1.5 million per month or $18 million per year. If this much money is currently being lost to UFC unreliability, one may question whether the $675,000 spent last year for improvements to the UFC is enough. It is possible that many of the current removals are for engineering problems already solved. Assuming that the stepper motor problem has been solved, Table 4 shows that the unconfirmed removals are at least 30 percent of the remaining total.

The rough estimates just given do not reflect the true costs of change. An accurate cost/benefit analysis would compare life cycle costs, including the cost of change and the cost to the government to make that change. A factor of risk is also involved and is hard to quantify: a known problem with known solution is often preferred to the uncertainty of change. A change can make a situation worse, and at the least will introduce a period of confusion.

These data show, however, that the UFC has been a costly problem. An analysis of the problem may give insights into further reliability considerations.

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*On the average, 6 hours of down-time are required for removal and replacement of a UFC.

Purchase Requirements and Specifications

The purchase requirements specify the number of maintenance man-hours at the base and intermediate level, for different missions. The specifications serve more as a goal than as a basis for negotiations with the contractor. The 1.27 maintenance man-hours/flight hour in the specifications can be compared with the current value of 4 mmh/flight-hour for the engine and .09 mmh/flight-hour for the UFC. It is not new to suggest that maintenance reouirements should actually be enforced, if not in the form now stated, then in some other manner. The problem of enforcement is not unique to the Air Force but is common in all military services. It is not a problem common in commercial transactions, because in most cases commercial purchases are for equipment with which the manufacturer has considerable experience. The Air Force should find ways, for new or untried equipment, to set up strong incentives, as well as penalties, to encourage contractors to pay more than lip service to the costs of maintenance and reliability.

Design

It is difficult to criticize the design of the UFC. It involved a new approach, consistent however with past practice. Considering the requirements, the design philosophy, and the complexity, it is gratifying that the UFC works as well as it does. It should be pointed out that some individual units are approaching 1,500 flight hours without maintenance. Such experience, even with only a few units, is evidence of good basic design. In retrospect, certain things might have been designed differently; however, most decisions appear to have resulted from reasonable trade-offs. In preparing a design there are so many constraints that must be met (on performance, weight, strength, cost, etc.) that secondary effects often receive inadequate attention. These secondary effects (differential thermal expansion, misalignment, vibration, etc.) cause many problems, some of which will certainly be in the nature of "surprises." The more firmly the designer and the Air Force are committed to the objective of minimizing life-cycle cost (rather than development cost, say, or manufacturing cost) the greater will be the incentive to address the so-called "secondary" issues effectively. Such matters are discussed further in the section on "Early Bugs".

Problem Solving

If the history of the UFC maintenance is reviewed, one could overlook the frequency of early removals as the cost of introducing a new and unique system and reducing it to practice. However, what is striking is that after five years two main problems are as yet unresolved. One also should note that the contractor is proposing, and the Air Force is accepting, lead times of up to two years to do the engineering of required changes. It appears to the panel that changes could be proposed and effected more rapidly than this. This seems worthy of further study.

A second point to note is that much of the technical information available to the Air Force about field performance of the UFC comes through the contractor rather than through independent military channels. Although this is not necessarily bad, it can put a different perspective on problems and on priorities. Almost every one interviewed by the panel agreed that the connection between the field and the F100 office could be strengthened. The Naval Air Systems Command, for example, stations representatives at all bases to provide this kind of liaison. Such a representative provides first-hand experience, on a continuous basis, to balance what is provided by the contractor.

Trouble Shooting

Many of the TAC maintenance personnel claim that they are removing "no defect" UFC's from the aircraft because this is required by the maintenance fault tree analyses. Often, they would not remove a unit except that, lacking confidence in their own understanding of the UFC, they choose not to gamble. Two things can be done:

(1) Change the maintenance manuals so that they accurately reflect current thinking.

(2) Provide simple test equipment for improved field evaluation.

At Langley AFB, the Bendix representative is providing the equivalent of (1) and to some degree (2); at this base, the removal rate is 1/2 to 1/3 that of other bases without adverse impact on flight operations. Properly trained and guided Air Force personnel could provide a similar function with significant savings in cost.

"Early Bugs"

Design engineers have a reasonable understanding of the factors that affect the ultimate life of a component, even though they may not be able accurately to predict lifetimes. Life-limiting factors are fatigue, wear, and corrosion, depending upon the nature of the environment. Engineers also understand what must be done to prevent such problems. Alternative designs of the UFC were probably sketched in the conceptual stage, and from these a final design selected that took the life-limiting factors into account.

In contrast, engineers are still not fully aware the nature of "early bugs." Neither the technical literature nor collective experience address this kind of problem. If the collective experience of a large number of new systems were codified and reported to engineers, designers might then be able to avoid the more common "early bug" failures, by knowing what to watch for.

The panel has reviewed and classified all design changes made to date in the UFC. The results are summarized in Table 7. The frequency of each kind of problem is shown in the first column. In each entry, the first number is the count of confirmed problems. Where there is a "+" and a second number, the second number is "not confirmed, but probable." Unknowns are not included. As can be seen, the most frequent problems in the UFC were (1) contamination and (2) distortion due to thermal and pressure expansion. Also shown in Table 7 is a judgment as to whether each particular problem was predictable in the design. If sound engineering experience such as this were available on a large number of components, the compilation could offer valuable aid when design trade-offs are contemplated. Such a compilation, initiated now, would not help the UFC but could be of assistance to designers of future systems.

TABLE 7

NATURE OF EARLY BUGS

Kind	Number of Problems	Predictable
Contamination	5	No
Thermal and Pressure Expansion	4 + 4	No
Hydraulic Vibration	2	No
Economy	1	No
Interference of Parts	1	Yes
Improper Maintenance	4	No
Manufacturing Deficiency	1	No
Reduce Maintenance Man Hours	1	Yes
Improve Wear Resistance	2	Yes
Corrosion/Reaction	2	Yes
Jamming	1 + 1	No
Fatigue	1	Yes

IV. DISCUSSION OF PROBLEMS

Decision on Removal

It is clear from Table 3 that air bases differ substantially in their removal rates for UFC's. The difference is especially pronounced between Holloman and Langley Air Force Bases. There are some operational reasons for this, the details on relative flight hours, relative readiness, and number of in-flight failures must be recognized in a full comparison between bases. The Bitburg experience should also be studied. Nevertheless, a major cause is rather clearly a difference in the standards of judgment used at different bases.

It is conceivable, of course, that the highest removal rate might be the most cost effective. However, as Table 4 shows, the "unconfirmed" removals average 27.7 percent, and are as high as 35 percent at some bases. Certainly, a program for improved diagnostic procedures and handling at the base level could reduce unnecessary removals at relatively small cost. Further, the predictable problems, even though they may be addressed by design changes, should be explained to the operating and base maintenance staff in a comprehensive communications program.

The panel makes the general observation that as operational systems become increasingly sophisticated one cannot expect operational and base maintenance personnel to be capable of detailed analysis of functional problems. A wide variety of effective diagnostic sensors for mechanical systems is now commercially available for monitoring of operating condition. Such sensors could be integrated with computer analysis to improve maintenance decisions and to isolate components that cause problems. It is the panel's judgment that it would be economical to provide facilities and training at the base level so as to substantially reduce unnecessary removals.

UFC Rework Procedures

The panel recommends that present procedures at San Antonio can and should be made more cost effective. The use of poorly conceived and obsolete test equipment is a major problem. This problem will not be corrected by the expansion of existing facilities. A further problem is that the most effective rework personnel have unique experience and are therefore difficult to replace and many are nearing retirement.

It was indicated to the panel that 350 hours are required for tests and calibration of each of the UFC's undergoing complete overhaul before leaving the depot. Since the current meantime between failures (MTBF) is roughly 400 hours, and even the mature MTBF projected by the engine manufacturer is but 1,000 hours, a unit expends a good part of its life in the rework process.

Bendix has demonstrated that a properly automated test stand can be used to reduce significantly the work time and to supplement the skills of personnel. One nine-hour test plan, for example, was reduced to 30 minutes with automation. Equipment with this capability should be used at San Antonio. It has been projected that automated systems can reduce personnel costs by 40 percent; skill requirements can also be reduced, and the readiness of the UFC inventory would be increased. From the descriptions given the panel of the new equipment planned for the enlarged San Antonio rework facility, it appears that commitments may already have been made for equipment far less effective than is now possible or desirable.

It is also clear to the panel that the technical orders covering rework at San Antonio are inadequate. The visual guide photographic sequence system used by Bendix is an example of the kind of instruction and guidance that can be much more effective. New technical orders incorporating an approach of this kind should be published.

Current methods of handling UFC's in the field does not protect against internal corrosion and water contamination, such problems are found in numerous units sent to San Antonio for rework. Operational, diagnostic, and handling methods should be examined.

Failure Analysis on UFC

Trouble analysis at a base is governed by a "fault tree". The present fault tree logic leads almost inevitably to the removal of a UFC from service. Better diagnostic equipment on the aircraft or at the base could reduce unnecessary removals. Further training of personnel, and effective practices to guide their use of judgment, could also reduce unnecessary removals without increasing the risk of undiagnosed faults.

A lack of technical data on causes of failure, in the present information systems, makes it difficult to develop better fault tree logic. Better data would also improve judgments about the need for and priority of engineering changes.

V. DESIGN CHANGES

It is clear that a major cause of failure in the UFC has been the electrical insulation of the stepper motors made by Kearfott. Bendix has indicated that the original duPont polyimide insulation gave no problems. This material was replaced by a modified material from the same supplier for reasons not explained. Most problems encountered with the stepper motor have been in units with the modified material. The corrective action taken by Bendix and Kearfott has been to return to the original resin. In the meantime, many units with stepper motors having the inferior insulation remain in service. The questionable motors cannot conveniently be replaced because the UFC must be fully disassembled for replacement.

It seems to the panel that the responsibility for the change in the electrical insulating material should be documented, and that procedures should be developed to assure that decisions for changes of this kind are made only with explicit authority and after explicit review. If the problem is as described to the panel, it is one that should not have occurred.

The standard Air Force information systems G 337 and AFM 66-1 do not give detailed technical data on causes of removal. It has not been possible, therefore, for the panel to evaluate the balance or adequacy of the current UFC engineering effort directed at remaining problems of function or durability. In general, wear, corrosion, and leakage are problems that can be mitigated when they are identified and accurately defined. One example of a class of problem that may merit further attention is that of leakage. In 1979, 7.4 percent of removals were associated with leakage. The panel understands that no further reduction in removals for this cause is to be expected. In the judgment of the panel, however, sealing technology has advanced significantly in recent times, so that leakage may merit further attention. Similar comments apply to problems of corrosion and contamination.

VI. SUMMARY: CONCLUSIONS AND RECOMMENDATIONS

1. There is a need to review the maintenance fault tree in order, to reduce the number of UFC's that are returned for overhaul without discernible fault.

2. The reasons for variations in UFC removal rates at different air bases should be examined.

3. Steps should be taken to improve the accuracy of diagnoses in the field. Among the steps are improved personnel training based on current experience, diagnostic equipment on base, onboard monitoring instruments. The panel concludes that relatively simple instrumentation at the flight line could pay its way in averting unnecessary maintenance actions. Indicators such as those used by Bendix in automated test stands should be evaluated for field use.

4. The rework manual available to maintenance staff is considered to be inadequate and should be modified.

5. The experience at Bendix with automation in rework and testing is proof that such an approach is effective. The proposed procurement of automated test equipment not specifically designed for the UFC should seriously be questioned. The Bendix equipment, which is now operated by Bendix, has demonstrated its value. Equipment such as this should be considered for adoption.

6. There is need for improvement in the procedures for addressing reliability problems. First, complete and unbiased failure analysis is essential. Second, failure analysis should be documented in an information retrieval system, making it available for review and statistical analysis. Third, funding must be channeled to solve real problems on a timely basis. The Component Improvement Program (CIP) program seems to the panel to operate slowly, with data that are incomplete, and slow in coming and may not reflect valid priorities.

7. For the longer term:

A data system is desirable that records the real nature of the "early bugs" encountered as new systems are introduced.

Test facilities should be automated.

Field test units should be deployed for monitoring operating status.

8. The panel has been impressed by the progress made in the development of electronic fuel controls. In the judgment of the panel, for the longer term, the Air Force will find it highly

desirable to turn to full-authority electronic fuel controls. These will offer totally new possibilities in flexibility of performance, diagnostic capabilities, greater reliability and a longer lifetime than purely mechanical systems.

9. The panel considers that it is desirable and possible for the Air Force, in its procurement actions, to increase its emphasis on overall life cycle costs, which would place greater importance on reliability and maintainability.

APPENDIX 2

Figure 1	Composite plot showing MTBUR data based on Pratt and Whitney data covering the period June 1980 - May 1981, and Air Force data on F-15s and F-16s covering the period June 1981 - May 1982.
Table 1	San Antonio-ALC Labor Standards for Repair and Test of UFC.
Figure 2	Composite plot of interim report data for the period June 1975 - October 1980 on UFC based on F-15 fleet only, and for the period October 1980 - June 1982 on UFC based on F-15 and F-16 fleets. The data consists of: (a) Maintenance Man-Hours per month; (b) Operating Hours per month; (c) Removals per month.
Table 2	San Antonio-ALC Standard Test Hours per UFC.

UFC RELIABILITY IMPROVING

Mean time between unscheduled removal (MTBUR) is increasing

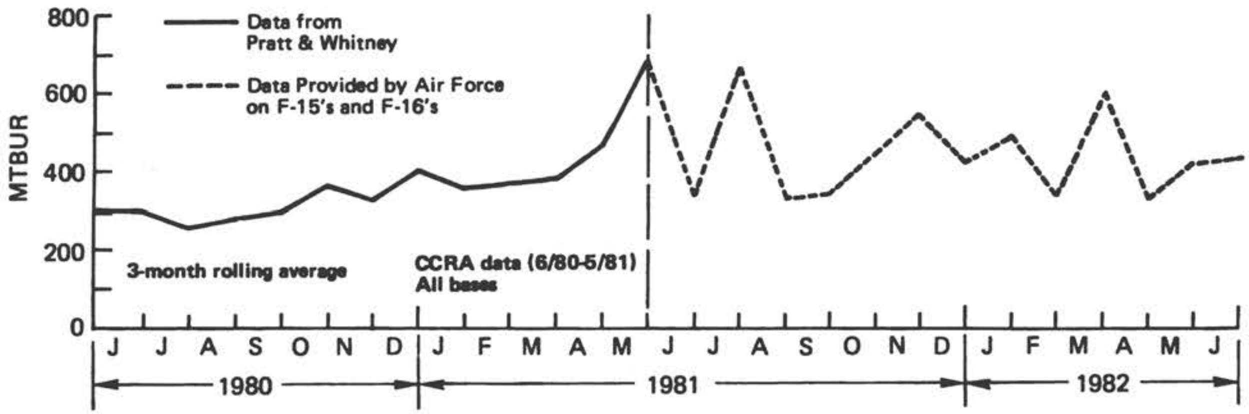
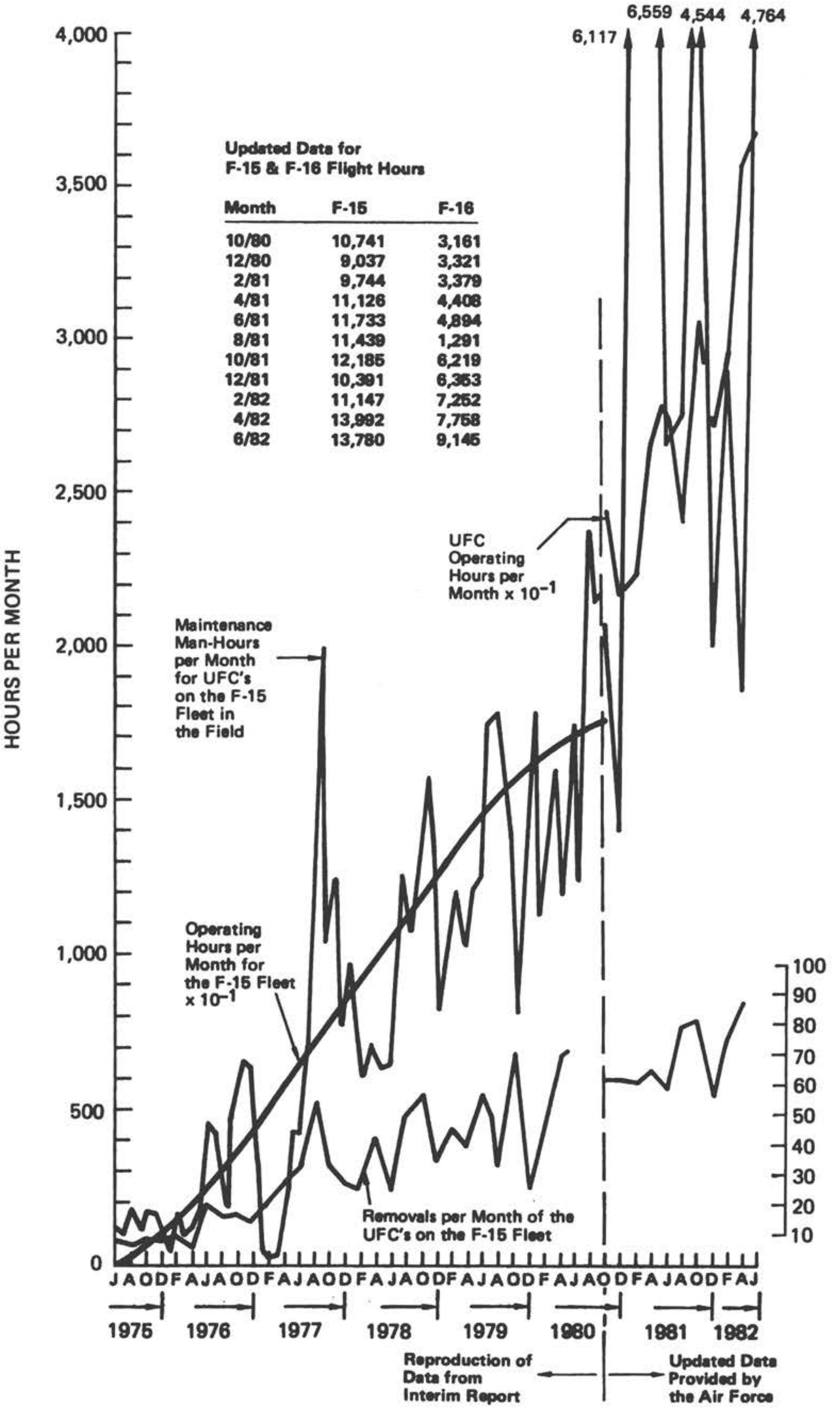


FIGURE 1

Table 1 SAN ANTONIO-ALC LABOR STANDARDS*
FOR REPAIR AND TEST OF UFC

Actions	Hours
Receiving, unpacking, depreservation and "as received" inspection and electrical check	6.6
Overhaul, demate, part replacements and minor repair	65.9
Run as received, testing, including augmentor set-in, gas generator set-in, sub-assembly testing and final testing	233.9
Safety wire, preservation, tagging and final inspection	16.0
Present modifications and updates	18.8
	341.2

* Does not include delays due to equipment, material or available personnel. The hours do not include time for assembly. The Air Force supplied this data.



Updated Data for F-15 & F-16 Flight Hours

Month	F-15	F-16
10/80	10,741	3,161
12/80	9,037	3,321
2/81	9,744	3,379
4/81	11,126	4,408
6/81	11,733	4,894
8/81	11,439	1,291
10/81	12,185	6,219
12/81	10,391	6,353
2/82	11,147	7,252
4/82	13,992	7,758
6/82	13,780	9,145

FIGURE 2

Table 2 SAN ANTONIO-ALC STANDARD TEST HOURS PER UFC*

(a)

	PWA50002 & 5[4]	PWA50004[5]	PWA50173[6]	PWA50175[6]	TOTAL
Minor[1]	40				40
Major[2]	136	32	43	20	231
Maximum[3]	162	61	77	21	321

(b)

WORKLOAD MIX (%)

	FY80	FY81	FY82	FY83	FY84	FY85	FY86
Minor	26	7	31	25	20	20	20
Major	67	88	65	65	60	55	50
Maximum	7	5	4	10	20	25	30

(c)

UNITS FOR REPAIR PER YEAR

FY81	FY82	FY83	FY84	FY85
738	773	1,159	1,314	1,405

(d)

YEARLY TEST STAND TIME REQUIREMENTS IN HOURS

	FY81	FY82	FY83	FY84	FY85
Minor	2,080	9,600	11,600	10,520	11,240
Major	149,919	115,962	173,943	182,028	178,563
Maximum	11,877	9,951	37,236	84,423	112,671
Total	163,876	135,513	222,779	276,971	302,474

*Air Force supplied data.

1 No demating of UFC.
2 Requires demating and sub-assembly testing and modifications.
3 Complete overhaul which involve disassembly to detail items.
4 PWA50002 & 5-test stands for augmentor testing and completely assembled UFC testing.
5 PWA50004-test stands for gas generator section sub-assembly testing.
6 PWA50173 & 5-test stands for small sub-assembly preset and calibration testing.

APPENDIX 3 - BRIEF ON SAN ANTONIO-ALC's UFC TEST STAND WORKLOAD ANALYSIS*

UFC Testing - Types of Repair

Minimum	Check and Test, External Adjust
Major	Disassembly to Major Component, Repair, Assembly, Test
Maximum	Complete Disassembly, Repair, Assembly, Test

Workload Projections by Type of Repair

Type	FY81	FY82	FY83	FY84	FY85
Minimum	7%	31%	25%	20%	20%
Major	88%	65%	65%	60%	55%
Maximum	5%	4%	10%	20%	25%

Workload Quantity Projections for Organic Repair

Actual FY81	Actual FY82	FY83	FY84	FY85
738	773	1,159	1,314	1,405

Workload Quantity by Type of Repair

Type	FY81	FY82	FY83	FY84	FY85
Minimum	52	240	290	263	281
Major	649	502	753	788	773
Maximum	37	31	116	263	351

Current Test Stand Times in Hours (October 1, 1982)

Type	PWA50002 & 5	PWA50004	PWA50173	PWA50175	Total
Minimum	40	0	0	0	40
Major	136	32	43	20	231
Maximum	162	65	77	21	325

Workload Test Stand Time Requirements in Hours

Type	FY81	FY82	FY83	FY84	FY85
Minimum	2,080	9,600	11,600	10,520	11,240
Major	149,919	115,962	173,943	182,028	178,563
Maximum	11,877	9,951	37,236	84,423	112,671
Total	163,876	135,513	222,779	276,971	302,474

Average Hours per UFC Text/Repair

	FY81	FY82	FY83	FY84	FY85
(Manual)	222.0	175.3	192.2	210.8	215.3

* Air Force Data and Analysis

Test Stand Computation: $TS = \frac{\text{Number of UFC's} \times \text{Average hours per UFC}}{\text{Test Stand Availability}}$

Assume: 2 shift/5 day week/52 weeks/77% availability
Test Stand Availability = 3203 hr.

Test Stand Capability Assuming Automation Schedules

FY	Semi-Automated	Total Months Available	Automation	Total Months Available
81	23 + (8)	348	0	0
82	31 + (6)	387	0	0
83	(24) + (15)	69	(24) + (20)	427
84	0	0	44 + (5)	586
85	0	0	49	588

Factors Involved for Distribution of Workload Type

a. As UFC configuration changes stabilize, retrofit incorporates are authorized which increase the major type repair workload. (Currently the PLAP Retard Modification is required to be installed in all repaired UFC's).

b. The repairables generated in Europe are presently being shipped to Dowty, Inc. in England for servicing. Their present capability is in the minimum type repair with all others returned to the depot for repair. The rate of their repair will cause fluctuations in the different repair type in which they are engaged.

c. As the UFC's mature, servicing will increase with prolonged use. The balance of repair types will be predicted on the balance of the UFC life cycle.

Factors Involved in Test Stand Requirements

a. Test stand availability and utilization is dependent on the planned work force for production testing of the UFC. Typically a two shift per day, five days per week, 52 weeks per year is assumed. Counting for system down-time either during holidays, preventative maintenance or actual test stand repair; past history results in a 77% availability.

b. The throughput of repaired UFC's is dependent on the required test times to return a unit to a serviceable condition. Workload standards are typically tied to Technical Order requirements. As changes are approved, these test times are subject to fluctuation.

c. The factors defined for the distribution of workload type must be considered in determining test stand requirements as follows:

   1) Additional workloads generated to install configuration changes.
   2) Deferred workloads through alternate repair sources.
   3) Increased repair of UFC's as units mature.

d. The ability to maintain a qualified work force with the expertise to anticipate probable failure modes and assess the best course for corrective action. The success of this factor hinges on the ability to keep experienced test stand operators and maintaining a training program for new personnel. Upon successful completion of the automation modifications to the test stands, this factor should become less recognizable in terms of fluctuations in test times for repair of the UFC's.

Problems Anticipated

a. The test stand projections for manual testing/repair of the UFC versus the anticipated workloads are the driving requirement for either adding more test stands or reducing the test times.

b. The installation of test stand modifications for inclusion of the automation changes begins 8/81 and continues through 10/83. The projections and workload analysis determined during this process did not reflect the installation period when equipment will be down. The automation contract allows a 42 month installation period. In addition, correlation testing must be scheduled and accommodated. Total out of service time cannot be projected with current figures. Installation through correlation testing on a new test stand has been averaging five months. The period of out-of-service time is very critical in the area of the PWA50004 test stand during 8/82 through 2/83. The workload on the gas generator sections require the most extensive part of the PLAP Retard modification to the UFC (conversion of Lot IV UFC's to Lot VII and testing is performed on the PWA50004).

c. The activation of production testing of the UFC's via automation processes will be initiated after the software Physical Configuration Audit (PCA) to occur around 11/82. The installation of the retrofit modification and production incorporated modifications of test stands being delivered will result in approximately 24 test stands which could immediately become capable of use via the automation processes. Advance planning will need to anticipate training and production scheduling changes to take maximum advantage of all the modified test stands. It is highly unlikely that all test stands modified can be immediately turned over to the automation procedures; however, the staggering schedule of turnover to the new process should be kept to a minimum time period. The figures reflect that the test stand operations can result in a one shift operation by sometime in FY83 from present two shift plus overtime operating requirements.

APPENDIX 4

Letter from Mr. Sanchez to the Air Force Studies Board dated 25 March 1983 with attached graph of a 3 month rolling average curve

DEPARTMENT OF THE AIR FORCE
HEADQUARTERS SAN ANTONIO AIR LOGISTICS CENTER (AFLC)
KELLY AIR FORCE BASE, TEXAS 78241

REPLY TO ATTN OF: MMPR (MMPRJ, P. M. Matis, 56481) 25 MAR 1983

SUBJECT: Panel Report on F-100 Fuel Control Systems, Comments Concerning (Your Ltr, 4 Mar 83)

TO: Air Force Studies Board
National Research Council
ATTN: Kenneth S. McAlpine
2101 Constitution Avenue
Wash DC 20418

The subject report was reviewed and the following comments are offered:

a. On page 3, item 1: The statement appears to be fairly accurate based on the Mean Time Between Demand (MTBD) which includes units pulled from the field for Time Compliance Technical Order (TCTO) change, for preventative corrective action, component change and includes total demands on the depot for any reason. We would like to submit the attached 3 month rolling average curve of the F-15 and F-16 UFCs which shows only the Mean Time Between Unscheduled Removals (MTBUR). This curve more realistically shows the reliability improvement of the UFCs. This data shows that as the units receive the latest improvements, the MTBUR has been increasing and is above the 1/2 of the design goal level.

b. Page 4: "The fact that the MTBUR remains less than 1/2 of the design goal indicates that serious problems remain." The same comments as item 1 pertain.

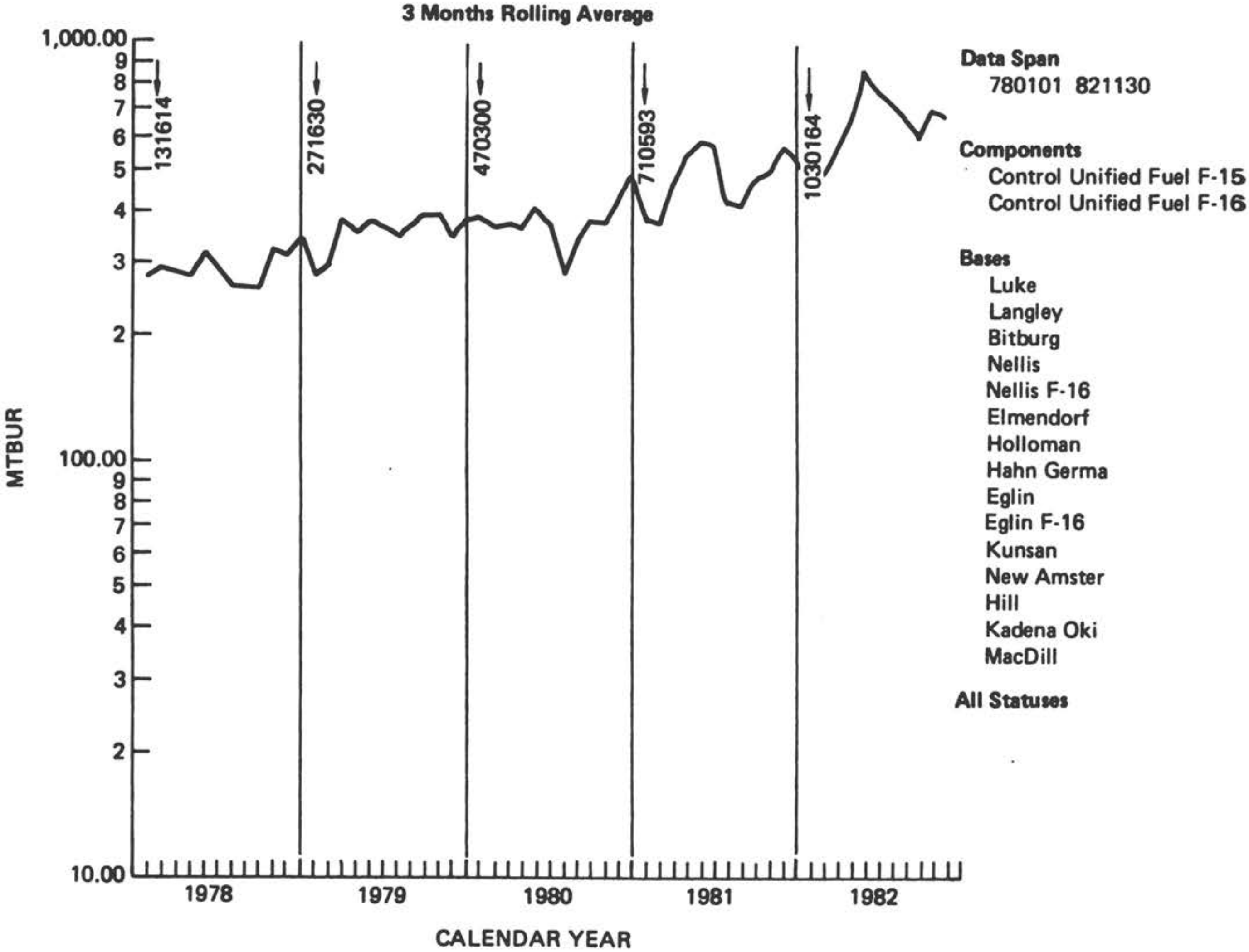
c. Page 4: "The opening of the new building and the introduction of 37 semi-automatic test stands has not improved appreciably the maintenance hours as of November 1982." These new semi-automatic stands are the same as the old stands previously installed. They were not installed to reduce the maintenance time per unit, but to help perform the additional workload of units received for repair.

d. Page 5: The number 27 should be 37.

e. Page 5: "This in turn must be tied to reliability level of the UFC." The reliability of the UFC has been understated in this report. See comments on item 1.

ALEX SANCHEZ
Chief, Engineering and Reliability Branch
Propulsion Management Division
Directorate of Materiel Management

1 Atch
MTBUR Curve



3 Months Rolling Average
1,000.00
9
8
7
6
5
4
3
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100.00
9
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MTBUR
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271630
470300
710593
1030164
1978
1979
1980
1981
1982
CALENDAR YEAR
Data Span
780101 821130
Components
Control Unified Fuel F-15
Control Unified Fuel F-16
Bases
Luke
Langley
Bitburg
Nellis
Nellis F-16
Elmendorf
Holloman
Hahn Germa
Eglin
Eglin F-16
Kunsan
New Amster
Hill
Kadena Oki
MacDill
All Statuses