

UNITED STATES AIR FORCE RESEARCH LABORATORY

ADVANCED DIAGNOSTICS

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This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER


ALBERT S. TORIGIAN, Lt Col, USAF
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The maintenance of avionics systems on current Air Force aircraft is plagued by problems in the areas of fault detection and fault isolation. Despite the built-in-test capabilities included in many subsystems and the availability of some diagnostic aids, there remains a costly problem of unnecessary removal of serviceable line-replaceable units (LRUs). This report describes the findings of a study conducted to assess current diagnostics processes and capabilities, define problem areas, and identify developing technologies with the potential to significantly improve the capability of Air Force units to accurately diagnose system failures. The study provided essential background for a new Air Force Research Laboratory program to address the diagnostics problem. This program, Predictive Failures and Advanced Diagnostics (PFAD), developing technology to more effectively isolate system faults and, where possible, accurately predict failure of a specific component before it occurs.

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PREFACE

This is the final technical report for Air Force Research Laboratory (AFRL) Contract No. F33615-99-D-6001, Technology for Readiness and Sustainment (TRS), Delivery Order 2 (DO 2) - Advanced Diagnostics. The program period was March 1999 through September 1999. The Air Force Project Manager was Mr. Paul Faas of AFRL/HESR. The prime contractor for TRS was Litton/TASC, and the TRS Program Manager was Mr. Patrick Vincent of Litton/TASC. The University of Dayton Research Institute (UDRI) was a subcontractor to Litton/TASC on the TRS contract. The DO 2 Project Manager was Mr. Michael Drake of UDRI. The technical lead was Dr. Frederick Stoll of UDRI. Major technical assistance was provided by Mr. Michael Craft of UDRI. The analysis of maintenance statistics was performed by Mr. Patrick Vincent and Mr. Bert Everhart of Litton/TASC. Also assisting in this task was Capt. Rudy Cardona of AFRL/HESR.

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SECTION 1. INTRODUCTION

The maintenance of avionics systems on current Air Force aircraft is plagued by problems in the areas of fault detection and fault isolation. Despite the built-in test (BIT) capabilities included in many line-replaceable units (LRUs) and the development of diagnostic aids now used by flightline technicians, there remains the costly problem of unnecessary removal, switchout, "swaptronics," and servicing of LRUs due to missed diagnoses. The Technology for Readiness and Sustainment program, DO 2 on Advanced Diagnostics, seeks to identify Advanced Diagnostic (AD) technologies that will provide improvements over current BIT and flightline diagnostic methods to provide more accurate fault isolation. An effective solution will both reduce maintenance expenses and improve the operational readiness of USAF aircraft.

Two main tasks were executed as a part of this program. The first task consisted of a review of current diagnostic practices, issues, technologies, and maintenance statistics. Interviews of flightline maintenance technicians and depot logistics personnel were conducted at five different USAF facilities. The Reliability Maintainability Information System (REMIS) was accessed to collect data to characterize the current scope of diagnostic discrepancies (NDFs, CNDs, RTOKs, BCSs, etc.). A large body of reports was reviewed to obtain a more detailed technical perspective on diagnostic issues.

The second task was to identify and assess candidate AD technologies. Over 20 technologies were identified. Literature on each technology was obtained, and a questionnaire was submitted to each technology source requesting a standardized body of information for each AD concept. The Kepner-Tregoe (K-T) analysis method was used to assess the candidate technologies with respect to customer requirements. The K-T analysis results were combined with qualitative analysis to establish recommendations for future Air Force research to mature and verify promising AD technologies.

Section 2 provides a review of the current diagnostics environment, in terms of lessons learned through interviews with maintenance personnel, and data from a maintenance information database that reflects the extent of problems with current diagnostics. Section 3 describes the method used to identify and screen AD technology concepts, and documents the

K-T analysis method used to assess the technologies against customer requirements. In Section 4, general results of the technology analysis are presented. Conclusions and recommendations are included in Section 5.

SECTION 2. REVIEW OF CURRENT DIAGNOSTICS

2.1. INTERVIEWS

2.1.1. Focus and Schedule

Interviews were conducted with personnel involved in activities related to diagnostics and maintenance of aircraft avionics systems at several USAF facilities. The purpose of the interviews was to hear the perspective of people involved in maintenance and diagnostics on a daily basis regarding current maintenance and diagnostic processes, and their perceptions of where problems are occurring in the current operating environment. This perspective was sought to enhance the ability of the research team to judge whether candidate AD technologies would be feasible and effective if implemented for current-generation aircraft.

A primary objective of this study was to identify AD technologies that are applicable to the widest possible range of USAF Mission/Design/Series (MDS) aircraft. However, because of the large number of MDSs and the large number of USAF facilities that operate and maintain these aircraft, it was necessary to restrict the interviews to a small number of representative groups of AF maintenance personnel, particularly those supporting fighter aircraft. Fighters present the greatest challenges to the packaging of on-board diagnostic systems (space limitations, weight limitations, access limitations, on-board resource limitations), and rapid maintenance and high reliability under combat conditions are vital to fighter operations. Personnel supporting flightline maintenance were interviewed, because first-level maintenance has the most time-critical diagnostic and repair responsibility. Depot personnel were consulted,

including both those involved in “production” (LRU/SRU servicing) and those involved in the development of avionics systems and the associated diagnostic and maintenance practices.

2.1.2. Summary of Lessons Learned

Key lessons learned during the interviews of maintenance and depot personnel are summarized below.

Positive Findings

- Many diagnostics tools and processes work satisfactorily (e.g. EDNA, DTM / CFRS, many BITs, some TOs).
- There is a high level of can-do attitude on the part of maintenance personnel.

Technician Training

The current level of training for O-level and I-level technicians is perceived as inadequate to support work requirements. In some organizations, technicians are expected to be qualified to service multiple aircraft types and multiple avionics systems on each type of aircraft; to use multiple diagnostic tools; and to become proficient on newly-introduced equipment with little or no training.

FI Documentation, TOs

- The TO update process is slow. Publication and distribution of TO updates can take up to six months to rectify after error corrections and FI improvements are identified. This reduces the technician’s confidence in the accuracy of the TOs.
- Some FI trees resort to “swaptronics” (trial-and-error switching of two or more LRUs) at certain stages to resolve ambiguity groups.

- Technicians desire more detail on electrical schematics.

Built In Tests (BIT)

- Much of the existing BIT works well.
- “Maximum allowable execution times” for executing BITs on certain LRUs may compromise effectiveness. For example, the BIT on the APG-70 radar system is restricted to 3 minutes, however, a comprehensive BIT on the radar system actually requires 5 to 30 minutes to complete.

Possible Sources of CNDs and RTOKs

- Some RTOKs can be attributed to vertical compatibility problems in 2- or 3- level testing. For example, the depot-level tests for an LRU may have less stringent performance tolerances than O-level or I-level tests.
- Some CNDs are believed to result from intermittent fault indications. These can have a number of sources, including:
 - ◆ Stresses to the system related to operating conditions and environmental factors (temperature, moisture, acceleration, air pressure, vibration) can stimulate intermittent circuit interruptions in flight. These stresses are generally not duplicated in ground-based testing.
 - ◆ LRU faults may sometimes be due to software code execution errors associated with the input values that accompany particular operating conditions. A failure to duplicate these input values and operating conditions during ground testing results in CND, NFFs, etc.

Fault Information Handling in Multi-Level Maintenance

- Often, little or no fault information (operational conditions, symptoms, fault indications) accompanies LRUs to the depot and/or backshop. This is judged by the depot and/or backshop technicians to hamper the diagnostic process.

Problems with the CAMS Maintenance Data Collection System

- The CAMS system is not integrated across bases and depots, preventing access to data that could be useful.
- The user interface is very cumbersome, complicated, slow, and user-unfriendly. This leads to incorrect data entry, sometimes inadvertently, sometimes intentionally. Technicians too often spend more time entering data than performing diagnostics, repairs, and maintenance.
- Technicians receive insufficient CAMS training. There is also inadequate linking between using organizations. An improved CAMS-like system (better user interface, linking between all organizations and depots) would improve diagnostics within the current climate by providing technicians with accurate maintenance data that encompassed the entire fleet.
- Inadequate tools for identification of bad-actor LRUs and SRUs.
- Inadequate tools for passing comprehensive fault report data between maintenance levels to aid diagnosis.

Bad Actors

- One source of “bad actors” (LRUs that repeatedly give fault indications in-flight but test out okay on the ground) is believed to be the failure to duplicate the adverse conditions present during flight (acceleration, vibration, temperature, moisture, air pressure, etc.) at the bench. There is evidence from depot work that so-called “shake and bake” testing (testing while

including some of these influences) helps identify some bad actors; however this type of testing is too costly to use for all depot-level testing.

2.2. USAF FLEET SIZE

The size of the USAF fleet of Legacy aircraft was established as part of an effort to determine the potential benefit of an AD system. Consideration was limited to active aircraft in the current USAF inventory which have been deployed in significant numbers, and which are beyond the initial developmental stage with respect to maintenance practices. The aircraft Mission/Design/Series (MDS) included in this top-level analysis are identified in Table 2.2, along with the total number of units in the active fleet. These data were obtained through a REMIS query.

Table 2.1. Current USAF Aircraft Quantities by MDS

Mission/Design	Units
A10	473
B1	93
B52	95
C130	713
C5	126
C141	175
F15	729
F16	1985
TOTAL	4389

2.3. CHARACTERISTIC MAINTENANCE STATISTICS FOR PROBLEMATIC DIAGNOSTICS

REMIS queries were run to obtain characteristic maintenance statistics that reflect the scope of diagnostic problems in the maintenance of USAF Legacy aircraft. Statistics were generated for a one-year period from June 1, 1998 to May 31, 1999. The following general avionics systems were used as the focus for the study:

- RADAR
- Bombing/Navigation
- Automatic Flight Controls/Instruments

Electronic Warfare avionics were excluded because many of these components are external and do not interface on any bus with other systems. Engine instrumentation was excluded because of the high level of attention already given to engine health monitoring and prognostics.

REMIS queries were run for the various MDS aircraft, including all appropriate Work Unit Codes (WUCs) necessary to embrace the avionics systems named above. The list of WUCs varied from MDS to MDS, depending on the avionics features of the respective MDS. The information was retrieved from REMIS for the following data parameters:

TOTAL_FAIL	Counter of all O-level maintenance events in response to fault report for specified WUC.
NO_DEFECT	O-level maintenance actions, in response to TOTAL_FAIL events, for which no defect was identified.
NO_DUPLICATE	O-level Could Not Duplicate (CND) on avionics equipment fault.
NUM_BENCHCHK	I-level Bench Check Serviceable (BCS).

DEPOT_EVENT LRU and SRU depot maintenance actions on nominally faulty LRUs and SRUs received from flight organizations.

RETEST_OKAY RTOK, no fault found during DEPOT_EVENT.

REMIS data summaries (summed across multiple WUCs) for one 12-month period are presented in Table 2.2. Several rates are computed and included in the table, including:

1. NDFs per AC per year
2. CNDs per AC per year
3. Depot Events per AC per year
4. RTOKs per AC per year
5. RTOK Rate (RTOKs per Depot Event)

As indicated in Table 2.2, the average number of NDFs per AC per year was 47, and the average number of CNDs per AC per year was 9. These numbers illustrate the need for improved diagnostics. The average number of Depot Events per AC per year was 4.3, with a much higher rate of 8.2 for F-16s. The overall average RTOK rate was only about 8%; however, this number may not reflect the true extent of the RTOK problem. Avionics production personnel at one ALC stated that many Depot Events that are, in effect, RTOKs are not recorded as such because some electronic adjustment or case repair is performed on LRUs.

Table 2.2. REMIS Maintenance Statistics for the Period 1 June 1998 to 31 May 1999

AC Mission/Design	Total AC Units	TOTAL_FAIL	NO_DEFECT (NDF)	NO_DUPLICATE (CND)	NUM_BENCHCHK (BCS)	DEPOT_EVENT	RETEST_OKAY (RTOK)	NDF per AC per Year	CNDs per AC per Year	Depot Events per AC per Year	RTOKs per AC per Year	RTOK Rate (RTOKs per Depot Event)
A10	473	26,946	15,020	2,422	992	800	96	32	5.1	1.7	0.20	12.1%
B1	93	19,609	13,049	1,678	654	145	16	140	18.0	1.6	0.17	11.0%
B52	95	11,705	6,178	671	27	263	34	65	7.1	2.8	0.36	13.0%
C130	713	50,764	23,857	3,818	1,193	185	36	33	5.4	0.3	0.05	21.6%
C5	126	25,251	12,919	416	1,770	154	5	103	3.3	1.2	0.04	3.3%
C141	175	18,895	6,017	314	1,316	590	14	34	1.8	3.4	0.08	2.4%
F15	729	112,610	70,734	19,711	6,602	489	67	97	27.0	0.7	0.09	13.9%
F-16	1,985	94,154	59,330	10,578	3,977	16,301	1,231	30	5.3	8.2	0.62	9.0%
TOTAL	4,389	359,934	207,104	39,608	16,531	18,927	1,499	47	9.0	4.3	0.34	7.9%

SECTION 3. ANALYSIS OF TECHNOLOGIES

A survey of existing and developing technologies was conducted to identify those with the potential to help solve the diagnostics issue. The Kepner-Tregoe method was used to evaluate candidate AD technology concepts. The K-T analysis method is described in this section. The method used to identify and down-select AD technology concepts for analysis is also documented and a questionnaire sent to AD technology sources is described. The analysis results are discussed in Section 4.

3.1. DESCRIPTION OF KEPNER-TREGOE METHOD

The K-T method was used to rank candidate AD technologies with respect to relative merit. The specific implementation of the K-T method was based on the implementation developed in a previous study.

3.1.1. Customer Requirements

Based on discussions with the USAF Technical Monitor, a list of customer requirements was generated, and the relative priority of each requirement was assigned on a scale of 1 to 5. The Customer requirements and priority rankings are listed in Table 3.1.

Table 3.1. Customer Requirements and Relative Priority

No.	Customer Requirement	Priority (1-5)
1	Applicable to multiple Legacy systems	5
2	Improve fault isolation performance	5
3	Reduce CND/BCS/UR/RTOK	5
4	Minimal impact on existing system design	5
5	Reduce logistics footprint	4
6	AEF deployable	4
7	Minimal training requirement	3
8	Deployable by 2005	3
9	Commonality of parts and equipment	3
10	Affordable	2
11	Low risk	1

3.1.2. Evaluation Criteria

Evaluation criteria were identified for use to grade candidate AD technologies. The Evaluation criteria differed from the customer requirements because they were selected to provide criteria that could be more easily assessed using information gathered during the study. Evaluation criteria were identified in the four categories of Cost, Schedule, Technology Impact, and Risk, as shown in Table 3.2. The Evaluation criteria were mapped to the customer

requirements by the application of a Quality Function Deployment (QFD) Correlation Matrix, which will be discussed shortly.

Table 3.2. Evaluation Criteria and Relative Importance

No.	Evaluation Criteria	Relative Importance
	<i>Cost</i>	
1	R&D Required to Mature	7
2	Initial Acquisition	6
3	Sustaining Cost	2
4	Benefit	8
5	<i>Schedule - Time Required to Mature</i>	6
	<i>Technology Impact</i>	
6	Aircraft Availability	10
7	Aircraft Weight, Balance, Space	5
8	Ease of Retrofit	5
9	Support Equipment Footprint	10
10	Training Requirements	7
11	Multiple Aircraft MDSs	8
12	Impact on System Performance	3
13	Impact on Pilot Workload	4
14	<i>Risk – Risk Factor</i>	7

The “Relative Importance” scores in Table 3.2 were obtained as follows. A QFD correlation matrix was set up, as shown in Table 3.3. Rows correspond to customer requirements, and columns correspond to evaluation criteria. Rankings of L (Low), M

(Medium), H (High), or blank were assigned to each cell, based on the relative importance of an evaluation criterion to a customer requirement. Numerical scores for the rankings were L = 2, M = 5, H = 8. A "Total Score" was computed for each evaluation criterion by multiplying the ranking score for each cell with the corresponding customer priority number, then summing these products for each column. The "Relative Importance" of each evaluation criterion was obtained by normalizing the total score values to a maximum of 10.

Table 3.3. Quality Function Deployment (QFD) Correlation Matrix to Correlate Evaluation Criteria with Customer Requirements

Customer Requirements	Customer Priority	Evaluation Criteria													
		COST				SCHED	TECHNOLOGY IMPACT							RISK	
		R&D Required to Mature	Initial Acquisition	Sustaining Cost	Benefit	Time Required to Mature Technology	Aircraft Availability	Aircraft Weight, Balance, Space	Ease of Retrofit	Support Equipment Footprint	Training Requirements	Multiple Aircraft MDSs	Impact on System Performance	Impact on Pilot Workload	Risk Factor
Applicable to multiple Legacy systems	5	M	L		H	L		L		M		H			L
Improve fault isolation performance	5				L		H				L				L
Reduce CND/BCS/UR/RTOK	5				H		H			M	M				L
Minimal impact on existing system design	5	L	M			L		H	H			L	H	H	L
Reduce logistics footprint	4						L			H		M			L
AEF deployable	4		L			L	M			M	M				L
Minimal training requirement	3	M	L	L		L					H	L		L	L
Deployable by 2005	3	M			L	H	L		M						L
Commonality of Parts and Equipment	3		L	L		L	L			M	L	H			L
Affordable	2	H	H	H		M		M							L
Low Risk	1														H
Totals		25	21	12	20	23	27	15	13	28	22	25	8	10	28
Relative Importance		7	6	2	8	6	10	5	5	10	7	8	3	4	7

3.1.3. K-T Scoring Method

The K-T scoring procedure involved an application of the evaluation criteria and relative importance numbers, discussed in the preceding section, along with input data from several different sources. The determination of numerical scores for the K-T analysis is discussed first.

An example K-T scoring matrix is shown in Table 3.4. The five columns include the evaluation criteria (Section 3.3.2), weight (equal to Relative Importance from Table 3.3.), rationale for the score, the score on a scale of 0 to 10, and the product weight \times score. Some

evaluation criteria list positive characteristics, whereas some list negative characteristics; the score is assigned using the convention that 10 implies the best possible outcome and 0 implies the worst possible outcome. The total weighted score is the sum of the weight \times score products. The normalized total weighted score is the percentage of the maximum possible score obtained. The maximum possible score of 900 assumes a perfect score of 10 for each evaluation criterion. In the example shown in Table 3.4, a normalized score of 49.6% was obtained.

The scores assigned in the K-T scoring matrix were obtained from three different sources. Criteria in the "Cost" category were scored based on the results of the cost/benefit analysis, discussed in Section 3.1.4. Criteria in the "Schedule" and "Technology Impact" categories were scored based on vendor questionnaire responses, with screening and modification by the project team based on the study of technology information and lessons learned during the interviews with maintenance personnel. The score for the "Risk Factor" category was obtained as a result of the risk analysis discussed in Section 3.1.5.

3.1.4. Cost/Benefit Analysis

3.1.4.1. Definitions

The cost/benefit analysis was performed to obtain estimates of monetary costs and benefits associated with maturing and deploying an AD technology. Cost was divided into three subcategories:

1. R&D costs
2. Acquisition costs
3. Sustaining costs

Both the sustaining costs and benefits were computed assuming an average remaining service life of 20 years for the current fleet of USAF Legacy aircraft. The following general formulas were used to compute the various cost and benefit numbers:

R&D Costs – One-time development costs to mature an AD technology and demonstrate its implementation on one aircraft MDS.

Acquisition Costs – One-time cost to acquire an AD system. This includes implementation on multiple MDSs, all MDS-specific design and development work, purchase of all equipment and software, installation of on-board systems, etc. Because some AD technologies include on-board systems or hardware, the calculation of acquisition costs was based on the projected cost per aircraft. The total acquisition cost was then given by the following equation:

$$(Acquisition\ Cost) = (Acquisition\ cost\ per\ AC) \times (Number\ of\ AC).$$

Sustaining Costs – This cost category accounts for the cost of maintaining the on-board and/or ground-based equipment associated with an AD technology, including the cost of spares. Because some AD technologies include on-board systems or hardware, the calculation of sustaining costs was based on the projected cost per aircraft per year. The total 20 year life-cycle sustaining cost was then given by the following equation:

$$(Total\ Sustaining\ Cost) = (Sustaining\ cost\ per\ AC\ per\ year) \times (Number\ of\ AC) \times (20\ years).$$

Benefit – The anticipated monetary benefits of a deployed AD system were provided by technology vendors as a part of the survey questionnaires (see Section 3.3). However, it was apparent from the responses that in some cases, different responses were based on different assumptions, and in many cases, projected benefits were completely speculative, with no quantitative basis. Therefore, a method was developed to estimate potential benefits using a common basis for all technologies.

Table 3.4. Example K-T Scoring Matrix

Evaluation Criterion	Wt.	Rationale	Score (0-10)	Wt. x Score
COST				
R&D Required to Mature	7	Comments of the grader relating to the Score assignment are listed here.	5	35
Initial Acquisition	6		4	24
Sustaining Cost	2		6	12
Benefit	8		7	56
SCHEDULE				
Time Required to Mature	6		9	54
TECHNOLOGY IMPACT				
Aircraft Availability	10		0	0
Aircraft Weight, Balance, Space	5		2	10
Ease of Retrofit	5		3	15
Support Equipment Footprint	10		4	40
Training Requirements	7		5	35
Multiple Aircraft MDSs	8		6	48
Impact on System Performance	3		7	21
Impact on Pilot Workload	4		8	32
RISK				
Risk Factor	7		9	63
Total Weighted Score			445	
Normalized Total Weighted Score			49.4%	

The first step was to estimate a baseline benefit value representing the maximum possible savings attainable with a 100% effective AD system. The next step was to estimate the fraction of this benefit that each AD system concept could be expected to provide based on the features of the system, and the judgement of the project team of the value of each system feature. This judgement was by necessity somewhat subjective, but all AD system concepts were judged on an equal basis.

3.1.4.2. Calculations

As a part of the survey questionnaire (Section 3.3), AD technology vendors were asked to provide their cost estimates in the three categories (R&D Required to Mature Technology,

Acquisition Cost per Aircraft, and Sustaining Cost per Aircraft per Year). The vendor-supplied values were used to establish characteristic values for the three categories. To determine specific cost values (and scores for the K-T analysis) the vendor-supplied values were compared on the basis of similar technological approaches, and where obvious discrepancies were found, the values were modified for use in the calculations.

Example Cost Calculations: Assume that an example technology features the following unit cost values:

- R&D required to mature = \$1.75M
- Initial acquisition per AC = \$5K per AC
- Maintenance per year per AC = \$1.75K per AC per Year

Consistent with the baseline benefit calculation performed in Section 2.4, the fleet size basis corresponded to F-16C Block 40/50 and F-16D Block 40/50 for a total of 638 aircraft. A mean remaining AC life of 20 years was used. The following cost numbers were obtained:

- Initial acquisition = $(\$5000/AC) \times (638 AC) = \$3.19M$
- Maintenance (sustainment) per year = $(\$1,750/AC/yr) \times (638 AC) = \$1.12M/yr$
- **20Year Life-Cycle Cost** = $\$1.75M + \$3.19M + \$1.12M/yr \times (20 yr) = \$27.3M$

3.1.5. Risk Analysis

A risk analysis was performed to establish the score (1-10) for the risk evaluation criterion in the K-T scoring matrix. The purpose of the risk analysis was to account for uncertainties associated with proposed technologies that threaten the goals of technology

application, or threaten to compromise critical characteristics and performance of the current system. A risk analysis matrix was created for each AD technology to determine a risk score. The risk analysis matrix was based on a list of risk elements that was formed by the project team and approved by the government technical monitor. A total of 12 risk elements were identified in the following four categories:

1. Technical risk
2. Financial risk
3. Schedule risk
4. Operational risk

These risk elements are listed in the example Risk Assessment matrix shown in Table 3.5.

The scoring for each risk element involved two grades that are reflected in the two grading columns in Table 3.5. Grades of L(ow), M(edium) and H(igh) were assigned, with the following numerical equivalencies: L=2, M=5, and H=8. The first grade, "Impact of Occurrence," was a technology-independent grading of the severity of the impact should a risk element occur. The impact of occurrence grades, shown in Table 3.5, were determined by the project team and approved by the government technical monitor. A "High" impact of occurrence corresponds to an undesirable outcome. The second grade, "Likelihood of Occurrence," was technology-specific. Example dummy input values for likelihood of occurrence are shown in Table 3.5. The number in the "Score" column for each risk element is the product of the numerical scores for impact of occurrence and likelihood of occurrence. The "Total Score" at the bottom of the table is the sum of the all risk element scores. The range of possible total score values was 126 to 504 for minimum to maximum risk. The K-T input value was obtained by a linear mapping of the total score range 126 to 504 to the range 10 to 0 (Least risk: 126 maps to 10; Most risk: 504 maps to 0).

Table 3.5. Example Risk Assessment Matrix

ID No.	Risk Element	Occurrence (L/M/H)	Likelihood (L/M/H)	Score
TECHNICAL RISK				
1	Redesign of existing system required	H	L	16
2	Technology concept not a comprehensive AD system	H	L	16
3	Required manufacturing processes not available	M	L	10
4	High-uncertainty developments required	L	L	4
5	Technology not tested	L	M	10
FINANCIAL RISK				
6	R&D plan not well defined	M	M	25
7	Cost uncertainty for technology insertion	M	H	40
SCHEDULE RISK				
8	R&D plan not well defined	M	M	25
9	Key technologies not demonstrated	L	L	4
OPERATIONAL RISK				
10	High level of user training	H	L	16
11	Increased fault isolation time	H	M	40
12	Maintainability problems	M	M	25
Total Score				231
K-T Input (0 to 10)				7
Scale: 126<->504 maps to 10<->0 for K-T input (reverse scale)				

3.2. IDENTIFICATION AND SELECTION OF TECHNOLOGIES

A search was performed to identify companies and organizations actively pursuing research and development in the field of advanced diagnostics for aircraft. Searches were performed using the following resources:

- Documentation (papers, conference reports, etc.) supplied by AFRL/HESS.
- Internet searches.
- Literature and referrals obtained during interviews with USAF maintenance personnel.

- Referrals from technology vendors.

After compiling information on the various technologies, each was subjected to a screening process. The features and attributes of each technology were evaluated against the goals of the project. Technologies were selected that could be expected to contribute to a reduction in CNDs, RTOKs, etc. and/or improve aircraft readiness by decreasing diagnostics and maintenance time; or could be retrofitted onto existing aircraft platforms.

Upon completion of the screening process, twenty candidate technologies were identified for the formal analysis process. For each technology, the formal analysis included:

- A more in-depth analysis of the technology attributes.
- Detailed study of technical and product literature.
- Evaluation of questionnaire response (if received).
- Field reports and testimonials, if available.
- K-T analysis (including risk analysis and cost / benefit analysis).

During the execution of the detailed analysis, six of the twenty AD system concepts were rejected for K-T analysis for one of the following reasons:

- The system concept was only a technology component, rather than an AD solution.
- The system was not defined in sufficient detail to allow assessment.

Fourteen AD system concepts were therefore subjected to the full K-T analysis.

3.3. TECHNOLOGY SURVEY QUESTIONNAIRE

A survey questionnaire was sent to commercial and government organizations associated with approximately twenty AD technology concepts (see Section 3.2). The purpose of the questionnaire was to solicit a consistent body of knowledge about each technology that would facilitate the comparison of features, costs, and benefits for the various concepts using the K-T analysis method described in Section 3.1. The questionnaire requested the following information:

1. A narrative vision for a complete AD system.
2. A narrative description of the current status of required technologies.
3. A narrative description of a technology maturation program.
4. Estimates for K-T analysis inputs in the areas of cost/benefit and scheduling (see subsections 3.1.3, and 3.1.4).

Self-assessment on all K-T analysis evaluation criteria related to technology impact and risk (see subsections 3.1.3, 3.1.5).

SECTION 4. DISCUSSION OF RESULTS

This section contains a general discussion of the results of the AD technology survey and the K-T analysis. The technology survey incorporated information from two sources: the general literature on various and proposed technologies related to AD, and the AD system vision statements and self-assessments provided by technology vendors in response to the technology questionnaire discussed in Section 3.3.

The AD system concepts generally drew from a finite set of technology components, explained in Section 4.1. A major theme developed during the study was the need to differentiate between diagnosis and maintenance of the avionics “infrastructure” (communication

busses and permanent wiring), and diagnosis of LRU faults. This is further discussed in Section 4.2. Results of the K-T analysis are discussed in Section 4.3.

4.1. AD TECHNOLOGY COMPONENTS

Each technology reviewed featured one or more of the technology components described in the following paragraphs.

Communication Bus and Wiring Maintenance: The communication busses and permanent wiring found on an aircraft represent test voids; i.e. the systems are not subjected to routine maintenance. Wiring and busses degrade over time, causing intermittent failures during flight or, in the case of degraded busses, sluggish response of aircraft systems. Field implementations have shown that performing routine maintenance on the bus systems can significantly reduce diagnostic problems and improve aircraft availability.

In-Flight Data Capture: CNDs reflect an inability to duplicate on ground a fault indication detected during flight. This can result from environmental conditions (temperature, moisture, vibration, etc.) or aircraft system states associated with flight that are not duplicated during ground tests. Therefore, many maintenance personnel believe that diagnostic improvements can be achieved by obtaining better documentation of system information at the time a fault indication occurs. Most aircraft already have some form of on-board data capture, but this is usually limited to highly filtered fault indications and/or basic flight condition data. More comprehensive on-board in-flight data capturing systems are proposed. The additional data could be used for real-time in-flight diagnostics, or for post-flight, ground-based diagnostics.

On-Board Diagnostics: An on-board diagnostic system would continuously monitor for fault indications, and would process fault-related information in real time to identify a faulty component. While newer platform designs such as the F-22 and JSF have plans for advanced on-board diagnostic systems, such a system has not been implemented on a Legacy aircraft outside of BITs.

Distributed Diagnostics: A distributed diagnostic system generally includes multiple distributed components (reflecting subsystem monitoring) throughout an aircraft, plus a central diagnostic component to integrate the results and provide higher level diagnostics. This general concept may be impractical for Legacy aircraft due to the high retrofit costs.

Advanced Diagnostic Algorithms: There is a large family of proposed methods for performing the analytical diagnostic process. Many of these methods incorporate some form of artificial intelligence (e.g., neural networks, fuzzy logic) and machine learning. Some work focuses on efficient methods for building system models. It is proposed that information in maintenance history databases be processed to contribute to improved diagnostic rules.

Interactive Diagnostics: An AD system that includes interactive software has the capability of leading a technician step-by-step through the entire diagnostic and repair process. This feature can decrease training requirements while maintaining a system's performance level.

Integrated Maintenance Systems: This title represents a comprehensive maintenance and diagnostic system under which all aspects of maintenance and diagnostics are coordinated, including maintenance data, inventory, scheduling, repair time, etc.

Air-to-Ground Data Transfer: Status and/or fault data that is automatically transmitted to a ground-based station offers the ability to perform ground-based diagnostics while an aircraft is in flight. This could enable maintenance personnel to prepare for repair actions before the aircraft arrives, thereby reducing turnaround time and increasing sortie rate.

4.2. DIAGNOSIS AND MAINTENANCE OF COMMUNICATION BUSES AND PERMANENT WIRING

A strong theme that emerged during the study was that communication busses and permanent wiring fell into a test void; i.e. they were not subjected to regular diagnosis and maintenance. The busses and wiring represent the "infrastructure" on which avionics systems are based. Inherent in LRU BITs and general fault isolation procedures is the assumption that busses and wiring are performing properly. The health of permanent wiring in aging commercial

aircraft has become a well-publicized maintenance concern in recent years, and aging Air Force aircraft face the same concern.

There are current USAF programs underway to review maintenance practices and identify diagnostic tools for permanent wiring, so this issue will not be considered further in this report. However, there is evidence that neglected bus maintenance may constitute an even larger problem to avionics diagnostics than faulty wiring. The "Proud Falcon" program was started at Nellis Air Force Base in the early 1990s based on the premise that that a significant number of CNDs, RTOKs, and in-flight intermittences were the result of degraded or out-of-spec bus systems, rather than failed LRUs. The Multiplex Bus Fault Isolator (MBFI) was developed in response. Most LRUs on the F-16 communicate via MIL-STD 1553 communication busses. Using the MBFI, the Proud Falcon crew performed maintenance on the busses and routinely found problems such as:

- Faulty connectors (damaged, worn, loose, dirty)
- Unshielded cabling
- Faulty splices
- Out-of-spec stub lengths
- Use of incorrect transformers
- Out-of-tolerance couplers
- Shorts to ground
- Out-of-spec transformers

Proud Falcon first used the MBFI to inspect the Enhanced Central Interface Unit (ECIU) busses. After 12 months, the average ECIU failure rate fell from 16.25 to 4.3 units per quarter. The estimated saving was \$1,186,157. A 1995 study compared the CND rates of these aircraft with the rest of the Air Force F-16 Block 40s. TICARS was used to collect data for five LRUs. The average CND rate for all five LRUs was 32% for the Air Force overall, while the Proud

Falcon CND rate was 4.4%. It was estimated that if the Air Force used the MBFI to clean up the busses on Block 40 aircraft alone, it would realize a unit cost savings of \$38,498,606 and exchange cost savings of \$4,027,336 each year.

The MBFI is currently supported by TISMD at Hill AFB, and is deployed as standard equipment at all F-16 bases. User feedback attests to the value of the MBFI at reducing CNDs and improved aircraft availability. However, the MBFI requires a high level of user training and experience, and this has prevented it from being adopted as a routine maintenance tool at most F-16 bases. Commercial bus diagnostic tools and software that expand on the capabilities of the MBFI have been produced.

Why has bus maintenance not been more widely recognized as a key factor in diagnostics? The explanation seems to be that the MIL-STD 1553 bus is extremely robust, and continues to perform its basic communications functions even in a highly degraded state, albeit with greatly reduced efficiency.

Based on the indications of the large influence of bus maintenance on diagnostic effectiveness, it is concluded that busses must be maintained as the starting point for the deployment of an AD system. This could be implemented either through routine bus maintenance performed using tools such as the MBFI, or by incorporating bus health monitoring and diagnostics as part of an AD system.

Since the MBFI bus diagnostic tool is already standard equipment at F-16 bases, **the additional costs for complete implementation of the MBFI would be small**, consisting of the cost of additional technician training, and the labor costs during the bus maintenance operations. Based on limited studies with the MBFI and related commercial products, the benefits of routine bus maintenance in terms of reduced CNDs and other improvements to diagnostic efficiency may be very large.

4.3. ADVANCED DIAGNOSTIC CONCEPTS

4.3.1. General Comments

The survey of AD technologies incorporated information from two sources. The first source was general technical and product literature on various and proposed AD technologies. The second source was the survey questionnaire responses provided by technology vendors. The survey questionnaire responses were designed to solicit both a complete AD system vision from the vendor and a self-assessment of the system concept with respect to the evaluation criteria (including risk, cost, and benefit) used in the K-T Analysis. It is recognized that the vendors were only able to put minimal effort into the voluntary questionnaire, and that their responses are therefore preliminary and cursory. Therefore, the K-T analysis inputs were made with consideration of the vendor's self-assessment, but also using the judgement of the project team reflecting the literature information, the lessons learned from the interviews (Section 2.1), and comparisons of the different AD system concepts.

The K-T analysis method was applied to fourteen specific AD concept proposals submitted by commercial and government organizations. However, the concepts considered do not encompass all possible approaches, nor do they reflect the vision of all organizations involved in applicable technologies. Furthermore, some organizations that submitted questionnaires have other AD system concepts that were not divulged due to business sensitive issues. Recognizing these limitations of scope, the K-T analysis results are discussed here in terms of general approaches rather than specific technology sources.

A general assessment of the AD system concepts is offered. There was generally a large disparity between the AD system visions offered by vendors and the current state of technologies. The AD concepts were generally not well defined, either with respect to technical details, or with respect to the development program required to mature and verify a system. Most concepts would require simultaneous developments in multiple disciplines, and involve complex details in terms of hardware design and fabrication, software development, system integration, and incorporation of aircraft configuration information. Because of the diverse

nature of Legacy aircraft, the complexity of any individual aircraft, the limited research funds available, and the prohibitive cost of major modifications to existing aircraft systems, the authors believe that a viable AD solution must be relatively simple in architecture while targeting a high-benefit diagnostic niche. Recent experience has shown that an AD concept that proposes major revisions to the current maintenance environment will be expensive, and may not be readily accepted by end users. Finally, although AD concept rankings are provided in the following section, no single AD path proved to be inherently superior to all others. Any future proposals for AD systems should be judged on their individual merits, with strong consideration given to the degree to which all system features are defined, sources for all technologies are identified, technology maturation steps are specified, and a realistic scope is targeted.

4.3.2. K-T Analysis Results

Twenty AD system concepts proposed by 14 different commercial and government organizations were considered for K-T analysis. Six concepts were rejected for final K-T analysis for reasons discussed in Section 3.2. Four of the concepts were related to diagnosis and repair of communication busses and permanent wiring discussed in Section 4.2. The remaining 10 concepts were grouped into four general categories for discussion in subsequent sections. These four categories correspond to four of the seven technology components described in Section 4.1 that reflect the dominant feature of each concept. The categories are:

1. Interactive Diagnostic Systems
2. On-Board Diagnostic Systems
3. In-Flight Data Capture Systems
4. Integrated Maintenance Systems

K-T scoring trends are based on these four categories, and selected technology features are noted and discussed.

4.3.2.1. Interactive Diagnostic Systems

The three highest-scoring technologies involved interactive ground-based diagnostics. This attribute offered the general benefit of more efficient diagnostic procedures, and addressed the priority of a user-friendly system that avoids the need for highly trained or specialized technicians.

Two of the concepts featured interfaces to communications busses. This is attractive from the standpoint of requiring very minor modifications to the aircraft, while tapping into a source of extensive information on avionics systems performance. One concept emphasized an advanced diagnostic process that combines model-based and case-based reasoning and incorporates an integrated knowledge base. This diagnostic process provides the basis for natural evolution into predictive maintenance. The concept also emphasizes the use of COTS hardware and software that can be applied to any aircraft, which is attractive for the goal of serving multiple Legacy aircraft designs. Another feature emphasized in this category is advanced PMAs.

The biggest criticism of interactive (ground-based) diagnostic systems is that, when used as the sole AD system component, they do not address the concern that a significant number of intermittent fault indications surround the physical flight environment or occur because of system configurations or inputs that only occur in flight.

Using the vendor-supplied unit cost estimates applied to 638 aircraft (F-16C/D Block 40/50) with an 20-year average remaining service life, the **predicted life cycle cost** in this category was in the range **\$5M-\$20M**. AD solutions in this category were predicted to correct 40% to 60% of diagnostic problems remaining after full implementation of communications bus maintenance (which was estimated to provide a 50% improvement).

4.3.2.2. On-Board Diagnostic Systems

The second highest scoring group of technologies was in the category of on-board, real-time diagnostic systems. Three AD system concepts fell into this category. Real-time, on-board diagnostics can potentially eliminate the problem of trying to duplicate a fault on the ground that so often results in a NFF or CND. All three concepts use a distributed architecture (see Section 4.1). One concept emphasized multi-level diagnostics, featuring both distributed subsystem diagnostics and a global integrator performing higher-level diagnostics. This concept also emphasized artificial intelligence and mining of maintenance database information to optimize the diagnostic analysis. The second concept would involve monitoring of the processor performance and software execution in each LRU. The third concept emphasized advanced techniques of model input for model-based diagnostics.

The biggest drawback of the three concepts considered was the extensive level of modifications or retrofitting that would be required. All three concepts seemed to offer comprehensive diagnostic solutions that would be practical if designed in from the start, but which would require expensive retrofits for Legacy aircraft.

Using the vendor-supplied unit cost estimates applied to 638 aircraft (F-16C/D Block 40/50) with a 20-year average remaining service life, the **predicted life cycle cost** in this category was in the range **\$18M-\$48M**. AD solutions in this category were predicted to correct 70% to 80% of diagnostic problems remaining after full implementation of communications bus maintenance (which was estimated to provide a 50% improvement).

4.3.2.3. Flight Data Capture

This solution category may seem ill chosen in that it refers only to a single technology component within an AD system. However, it was singled out because one vendor possesses a demonstrated system for high-speed, in-flight data capture that could serve as the basis for diagnostics that incorporate the actual system data associated with a fault indication. The recording system is physically compact and light, and in its simplest form requires only easy-to-

implement interfaces with communications busses. It features removable, high-volume solid-state data storage. It is easily adaptable to different aircraft designs by importing the system ICD. On ground, the system interface incorporates a user-friendly GUI. The proposed diagnostics would be ground-based, though the data collection system opens up the possibility for in-flight diagnostics. Proposed diagnostic capabilities also include the playback of full system data for duplicating in-flight inputs to LRUs.

The AD concept in this category was found deficient in that the complete AD system concept was not well defined. The current data-gathering tool requires an expert-level operator. Little indication was given for a vision of the system operating in the current O-level maintenance environment. Therefore, this technology was perceived as an AD component, rather than a complete system solution.

4.3.2.4. Integrated Maintenance Systems

Three of the AD system concepts analyzed fell into the category of integrated maintenance systems. These concepts go far beyond improved diagnostics, incorporating highly integrated and automated inventory planning and control, maintenance planning, and documentation. Some diagnostic-related functions proposed for these systems are listed below:

- Incorporate data mining and machine learning
- Address the CND problem by improving the initial problem analysis.
- Address the RTOK problem by continued application of “expert system” and “model based” technologies to provide directed troubleshooting assistance throughout the fault isolation process.
- Integrate PMAs, maintenance information systems, data collection systems, pilot debrief, etc. using radios, modems, and LANs.
- Use air-to-ground data transfer to enable early ground-based diagnostics and preparations for maintenance actions while an aircraft is still returning from a mission.

The proposed solutions in this category are attractive from the standpoint of designing an optimal maintenance system that automates and integrates many parts of the logistics system. However, for the focus of the current study, these concepts suffered in several ways. First, they are extremely costly solutions, both to develop and deploy, and are not likely to be achievable in the five-year time frame specified. Second, they would require major changes to existing maintenance information systems (such as CAMS) and major changes to current O-level operations. These factors indicate extreme risks for the proposed solutions, and are therefore judged unacceptable for application to Legacy aircraft.

5. CONCLUSIONS AND RECOMMENDATIONS

A study was conducted to explore Advanced Diagnostic technologies that could be applied to USAF Legacy aircraft to improve the diagnosis of faults in avionics systems. The first task was to review current diagnostic practices, issues, technologies, and maintenance statistics. The second task was to identify and assess candidate AD technologies. Over twenty technologies were identified and assessed.

There was generally a large disparity between the AD system visions offered by vendors and the current state of AD technologies. For the most part, the AD concepts lacked definition, both with respect to technical details and the development program required to mature and verify a system. Concepts generally require coordinated development and activities in multiple areas, including hardware design, software development, system integration, and incorporation of aircraft configuration information. Given the diversity of Legacy aircraft, the complexity of avionics on each aircraft, the limited research funds available, and the prohibitive cost of major modifications to existing aircraft systems, the authors believe that a viable AD solution must be relatively simple in architecture while targeting a high-benefit diagnostic niche. AD concepts that propose major revisions to the current maintenance environment were judged to be unacceptable due to high cost, difficulty in implementation, and probable resistance by the end users.

No single AD concept studied was judged to be inherently superior to all others. Therefore, any proposed AD system considered for development by the USAF should be assessed on its individual merits, with strong consideration given to the degree to which all system features are defined, sources for all technologies are identified, technology maturation steps are specified, and a realistic scope is targeted. The following recommendations are made as guidelines for future Air Force research activities for maturing and verifying candidate AD technologies for aircraft avionics:

1. A range of proposed AD solutions appear to be viable for development and application to Legacy aircraft in the near future. The following features are given the highest overall recommendation, given the tradeoff between diagnostic benefits and acceptable development risk:
 - Additional on-board, real-time data capture
 - Off-board diagnostic processing
 - Advanced diagnostic software:
 - ◆ Configurable, platform-independent interface software
 - ◆ Advanced diagnostic algorithms (e.g., artificial intelligence, advanced reasoning, fuzzy logic)
 - ◆ User-friendly GUI (interactive diagnostics, easy operation, low requirements for user expertise)
2. Consider supporting the maturation of an AD system that includes on-board diagnostics. On-board diagnostics could offer many optimal benefits, such as speed, small footprint for support equipment, and better in-flight feedback on aircraft health to the pilot. However, a viable on-board AD system must emphasize low development and acquisition cost; ease of retrofit; and low impact on aircraft weight, balance, and space.
3. Properly maintained communications busses are required for effective avionics diagnostics. The MBFI is now a standard bus diagnostic tool at all F-16 bases, yet while it has been demonstrated to be a powerful tool, it is not being fully utilized because of the high level of

user expertise required and inadequate training of technicians. There is evidence that proper maintenance of communications busses provides large decreases in diagnostic problems. Routine maintenance of communication busses (and permanent wiring) should be considered. The assessment of new AD technologies must be performed on the basis of properly functioning communication busses.

APPENDIX A. List of Abbreviations

AC	-	Aircraft
AD	-	Advanced Diagnostics
AEF	-	Air Expeditionary Force
AFRL	-	Air Force Research Laboratory
AIS	-	Avionics Intermediate Shop
BCS	-	Bench-Checked Serviceable (I-Level)
BIT	-	Built In Test
CAMS	-	Core Automated Maintenance System
CBR	-	Case-Based Reasoning
CFRS	-	Computerized Fault Recorder System
CND	-	Could Not Duplicate
COTS	-	Commercial Off-The-Shelf
DLA	-	Defense Logistics Agency
DO	-	Delivery Order
DTM	-	Data Transfer Module (F-15)
ECIU	-	Enhanced Central Interface Unit
FI	-	Fault Isolation
GUI	-	Graphical User Interface
LRU	-	Line Replacement Unit
MBFI	-	Multiplex-Bus Fault Isolator
MBR	-	Model-Based Reasoning
MDS	-	Mission Design Series
MFL	-	Maintenance Fault List
MOCC	-	Maintenance Operations Control Center
MTTR	-	Mean Time To Repair
NDF	-	No Defect Found
NFF	-	No Fault Found (O-Level)
NRTS	-	Not Repairable This Station
O-Level	-	Organizational Level (at the flight organization)
PMA	-	Portable Maintenance Aid
QFD	-	Quality Function Deployment
QPA	-	Quantity Per Aircraft
REMIS	-	Reliability & Maintainability Information System
ROI	-	Return On Investment
R&M	-	Reliability & Maintainability
RTOK	-	Re-Test O.K. (Depot Level)
SRU	-	Shop Replacement Unit; usually a circuit board that plugs into
TO	-	Technical Order
TPS	-	Test Program Set
TRS	-	Technology for Readiness and Sustainment
UDRI	-	University of Dayton Research Institute
WUC	-	Work Unit Code

APPENDIX B. REMIS ALGORITHMS

- **Cannot Duplicate (CND) Action**

If the record's first position of the Work Unit Code (WUC) is not equal to zero (i.e. not a support general record), and Units is greater than zero (i.e., this is a completed maintenance action) and the Action Taken Code equals "H" and How Malfunction Code equals "799" or "812" or "948", then augment the Number of Cannot Duplicate Actions.

- **Bench Check Serviceable (BCS) Action**

Add one each time the first two positions of the on-equipment WUC is not equal to "01" through "09" and the How Malfunction Code Classification equals 1 or 2 and the Action Taken Code equals "P" or "R" and there is a related off-equipment record whose WUC equals this on-equipment record's WUC and its Action Taken Code equals "B" and its Type Maintenance Code is not equal to "R" (depot) or its When Discovered Code is not equal to "S" (during depot maintenance).

- **Unscheduled Removal**

If the first two positions of the on-equipment or off-equipment WUC is not equal to "01" or "02" or "03" or "04" or "05" or "06" or "07" or "08" or "09" and the Type Equipment equals "A" and the Type Maintenance Code equals "B" or "S" or "Y" and the Action Taken Code equals "P" or "R" and the How Malfunction Code Classification equals 1 or 2 and there is not a related off-equipment record whose WUC equals this on-equipment record's WUC and its Action Taken Code equals "B", then augment Units to Removals (Unscheduled).

- **Retest OK (RTOK)**

Add one unit each time the first two positions of the WUC is not equal to "01" through "09" and the Action Taken Code of the off equipment record equals "B" and its Type Maintenance Code equals "R" (depot) or its When Discovered Code equals "S" (during depot maintenance).

- **MTTR (On-Equipment)**

$$\text{MTTR} = \frac{\text{REPAIR HOURS (ON)}}{\text{REPAIR ACTIONS (ON)}}$$

- **MTTR (Off-Equipment)**

$$\text{MTTR} = \frac{\text{REPAIR HOURS (OFF)}}{\text{REPAIR ACTIONS (OFF)}}$$

Source: AFCSM 25-524, Volume III, 1 August 1996