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KNOWLEDGE BASED JET ENGINE DIAGNOSTICS

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ABSTRACT

A fielded expert system automates equipment fault isolation and recommends corrective maintenance action for Air Force jet engines. The knowledge based diagnostics tool was developed as an expert system interface to the Comprehensive Engine Management System, Increment IV (CEMS IV), the standard Air Force base level maintenance decision support system. XMAN™, the Expert Maintenance Tool, automates procedures for troubleshooting equipment faults, provides a facility for interactive user training, and fits within a diagnostics information feedback loop to improve the troubleshooting and equipment maintenance processes. The application of expert diagnostics to the Air Force A-10A aircraft TF-34 engine equipped with the Turbine Engine Monitor System (TEMS) is presented.

INTRODUCTION

XMAN is a knowledge-based software tool designed for advanced diagnostics support of complex aeromechanical equipment. Developed as an expert user interface to a large, historical maintenance database, XMAN automates procedures for troubleshooting equipment faults. The expert maintenance tool has been field tested and is operationally supporting flightline maintenance diagnostics for the Air Force A-10A weapon system.

XMAN represents a significant step forward in the evolution of maintenance information and integrated diagnostics systems. A means of improving the diagnostics process is provided through visibility into troubleshooting performed at the equipment level and feedback of information to the equipment manager. Interactive user training is provided in addition to the automation of the maintenance diagnostics function. The user remains a key factor in the equipment diagnostics process. Training and user acceptance of the expert system are facilitated by keeping the technician in the troubleshooting loop, while providing explicit diagnostics guidance and allowing ready access to data pertinent to the specific equipment fault.

Presented is a summary of troubleshooting performed by XMAN during its evaluation period and initial operations at eight Air Force A-10A bases. The specific application addressed is that of the TF-34 jet engine equipped with the Turbine Engine Monitor System (TEMS). Under Air Force contract, XMAN is the expert system interface to the Comprehensive Engine Management System Increment IV (CEMS IV), Engine Diagnostics and Trending (ED & T). This interface is discussed and a typical troubleshooting session presented. Design concepts underlying the expert system architecture are highlighted. The potential for expansion of XMAN to other aeromechanical equipment is addressed.

EVOLUTION OF XMAN AS AN AUTOMATED DIAGNOSTICS TOOL

The origins of XMAN date back to the early stages of the CEMS IV program (see Figure 1). CEMS IV is the standard Air Force jet engine management system for maintenance decision support. Systems Control Technology, Inc. (SCT) developed CEMS IV under Air Force contract to support the information intensive processes associated with On-Condition Maintenance (OCM). CEMS IV fuses data from a number of disparate DoD maintenance information systems including CAMS (Core Automated Maintenance System) and engine specific automated monitoring systems.

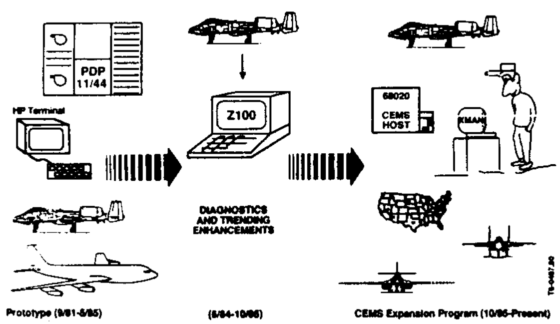

Figure 1 XMAN Development can be Traced Back to the Early Days of MIMS and CEMS IV.

CEMS IV is an outgrowth of SCT's Maintenance Information Management System (MIMS™). CEMS IV integrates data acquisition and processing functions to trend engine performance, display graphical diagnostics data products, and flag engine malfunctions (see Figure 2). Data are displayed to the flightline and intermediate maintenance technicians in a format which is easily usable and readily accessible. Only those data that pertain to that individual's work requirements are displayed. The prototype CEMS IV was evaluated in an operational environment at Barksdale Air Force Base, Louisiana (917th TFG, AFRES) for three and one-half years before Air Force direction was given to expand the system implementation. [1]

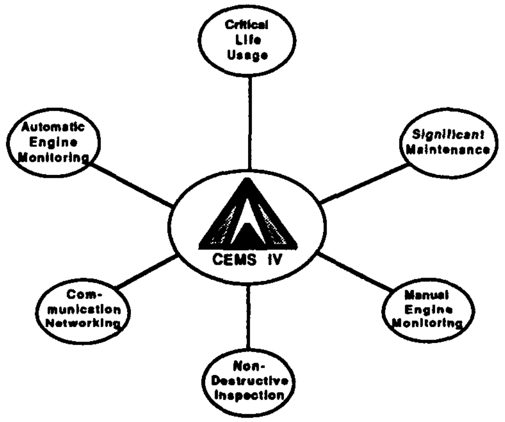

Figure 2 CEMS IV Integrates a Number of Disparate Maintenance Information Functions.

CEMS IV is currently undergoing expansion to twenty-one Air Force A-10A bases worldwide. Engine maintenance decision support for other aircraft types (e.g., F-16, B-1B, KC-135R, C-17) may be provided for up to sixty bases at Air Force option. Demonstrations of CEMS IV support have already been performed for the F100-220 engine (F-15 and F-16 aircraft) and the F108 engine (KC-135R aircraft). The CEMS IV software is approximately eighty percent generic, allowing flexibility in specific type-model-series (TMS) engine applications.

From the early stages of operational evaluation, it was evident that an expert system would enhance the CEMS IV man-machine diagnostics interface. SCT began the development of an expert system in early 1984. Under internal research and development funding, SCT produced an expert system kernel which serves as the XMAN software control system.

The software engineering principles guiding the development of MIMS (i.e., generic, table driven software, independent of specific hardware or equipment applications) also led to the development of a generalized expert system kernel. Tailoring is carried out through a process of knowledge engineering for the specific TMS engine or equipment application. XMAN is written in LISP and is resident on a microcomputer (PC compatible) operating under MS-DOS.

As a software refinement under SCT's CEMS IV contract with San Antonio Air Logistics Center (SA-ALC), XMAN's knowledge base has been tailored to troubleshoot and diagnose engine malfunctions on the TF-34 engine. The troubleshooting knowledge base is based upon the technical order (T.O.) logic trees developed by the engine manufacturer for analyzing engine malfunctions using CEMS IV. Thus, for the A-10A/TF-34 application, XMAN serves as a T.O. prompting system as well as an expert troubleshooting tool.

TYPICAL APPLICATION

The diagnostics procedures associated with interpreting CEMS IV data products, troubleshooting engine alarms, and recommending corrective maintenance action are automated by XMAN. The expert diagnostics function is a menu option on the CEMS IV workstation (see Figure 3).

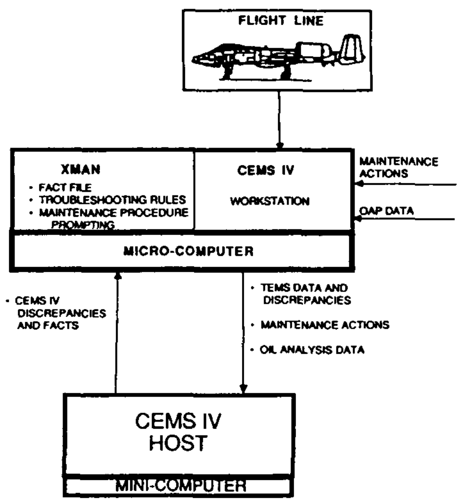

Figure 3 XMAN Resides on the Same Microcomputer as the CEMS IV Workstation.

XMAN troubleshoots engine discrepancies which are generated by both the on-aircraft engine monitoring system (TEMS) and CEMS IV. The discrepancies generated by TEMS are engine events (e.g., core overspeed, turbine temperature exceedance). TEMS-generated discrepancies are passed down to CEMS IV and stored in the host database. CEMS IV generates engine discrepancies based upon abnormal performance, wearmetal trends and parameter limit exceedances not flagged by the TEMS.

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The CEMS IV host is a Motorola 68020, System V Unix™-based super minicomputer. The expert system, resident on the standard Air Force microcomputer, accesses the CEMS IV database via a direct RS-232 link or a leased line modem. XMAN extracts facts from the CEMS database. These facts are transferred from the host system to the microcomputer and stored in a troubleshooting fact file. Troubleshooting facts and technician inputs are used by XMAN to diagnose engine discrepancies. Throughout the troubleshooting session, the technician may access the CEMS IV database directly and recall pertinent diagnostics data. The XMAN control system links the engine discrepancies present to the appropriate troubleshooting rule file (i.e., knowledge base). When troubleshooting is completed, XMAN prompts the user with corrective maintenance procedures. [2]

Troubleshooting a Rising Wearmetal

A typical equipment discrepancy summary produced by XMAN upon analysis of the CEMS IV database is shown in Figure 4. Shown in this summary are the following:

a. a reference number for each discrepancy;
b. the equipment serial number (ESN);
c. the aircraft location;
d. the equipment discrepancy; and
e. the date of the discrepancy.

In this example, an engine alarm generated by a rising oil wearmetal trend is analyzed. CEMS IV has forecast that the iron concentration in engine GE205293 is due to exceed the allowable limit.

```
E Q U I P M E N T   D I S C R E P A N C Y   S U M M A R Y

REF ESN      LOCATION           DISCREPANCY               DATE
----------- --------- -------------------------------- -------
1 GE205012 A770211-1 NFTR FORCASTD BELOW LIMIT (CEMS) 87JUN01
2 GE205137 A750262-1 LEVEL 1 TEMS:NF VIBS - LEV 1     87MAY29
3 GE205293 A750300-2 FE   FORCASTD ABOVE LIMIT (CEMS) 87MAY29
4 GE205317 A760550-1 LEVEL 1 TEMS:SLOW START          87MAY22
5 GE206512 A750264-2 FFGT (FFG .TND) ABOVE LIM (CEMS) 87JUN01




Please select a REF number >
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Figure 4 The Equipment Discrepancy Summary Indicates Alarms Which Require Troubleshooting.

The technician initiates the XMAN troubleshooting session by entering the equipment discrepancy reference number (in this case, 3). Once selected, XMAN activates the appropriate fact file and decision tree (i.e., rule file) corresponding to this engine problem.

An XMAN troubleshooting display is shown in Figure 5. In the middle window of this display, XMAN asserts facts derived from the CEMS IV database. Troubleshooting questions are posed along with answers automatically derived from the CEMS IV historical database and the user's affirmation or rejection.

```
 GE205293 |        EXPERT TROUBLESHOOTER         |  A750300-2
ALARM:
      ED/CEMS DETECTED MALFUNCTION - C001                MODE: STEP
   IRON (FE) CONCENTRATION FORECASTED OVER LIMIT

ASSERTIONS:
1. Is it possible that FE DATA SCATTER caused the alarm ?  XMAN: NO
                                                           USER: NO

2. Was maintenance (for example, an oil change) done prior XMAN: NO
to this alarm and is the FE concentration RETURNING to     USER: NO
the level found BEFORE the MAINTENANCE ?

3. Are CORE VIBRATION levels INCREASING in any of the      XMAN: YES
channels?                                                  USER: YES

ACTION:
      Borescope the engine compressor and high pressure turbine
     (HPT) according to the procedures contained in T.O.
     1A-10A-2-71MS-1.  Return to XMAN upon completion.
>Press RETURN to continue.                          87JUN03(1746)
```

Figure 5 The Technician Interacts with XMAN Through the Expert Troubleshooter Display.

In this example, the XMAN fact generator has asserted that erratic data did not cause the alarm. Following the XMAN assertion, the technician is asked to accept or reject this automated analysis of CEMS IV data. Since the technician in this example is relatively new to automated engine diagnostics, he asks for help in interpreting data scatter. The user presses <HELP> on his keyboard. XMAN responds with the graphical display shown in Figure 6. Typically, several levels of HELP complexity are available to the maintenance technician. The complexity ranges from high-level descriptions to graphical displays highlighted by inverse video and pointing arrows. By pressing the <RETURN> key, the user cycles through the high-level to low-level HELP displays.

In Figure 6, a typical wearmetal pattern is displayed, and the text explains what to look for in distinguishing real data trends from erratic data. The technician presses a special function key to exit from the HELP utility and resume XMAN troubleshooting.

Fresh with new insight into data scatter, the user presses the <HOME> key to access the actual CEMS IV data. The <HOME> key is dedicated to spawning CEMS IV from the LISP environment. In this instance, the rising trend is clearly distinguished from data scatter (see Figure 7).

After returning to the troubleshooting session, the user concurs that iron data scatter did not trigger the alarm. XMAN proceeds with the next assertion, i.e., that corrective maintenance has not had a positive effect on the iron trend. Again, the technician may ask for help in interpreting the data before responding to this question (HELP), and he may analyze the CEMS IV data directly (HOME). In this case, no significant maintenance action (e.g., an oil change) was performed on this engine recently.

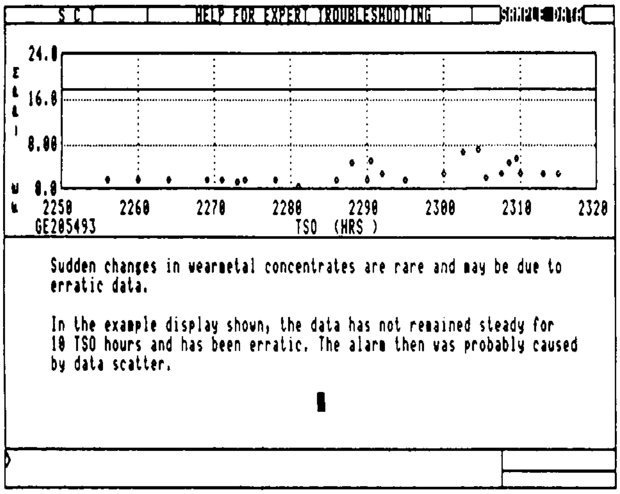

Figure 6 **The XMAN Help Facility Guides the Technician Through the Diagnostics Process.**

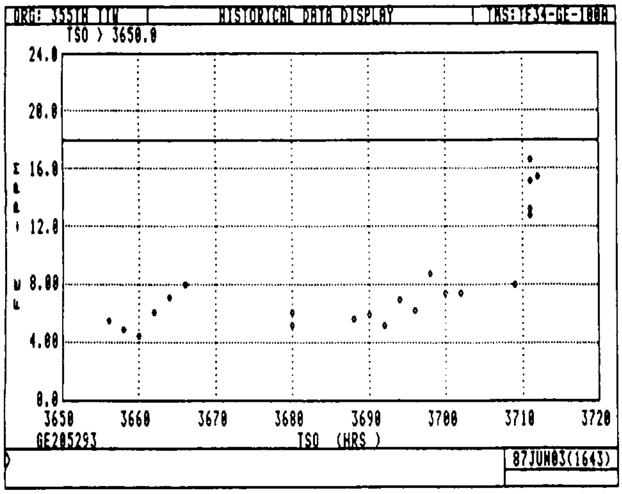

Figure 7 **The User May View Pertinent Diagnostics Data by Pressing the <HOME> Key.**

Next, XMAN asserts that core vibration levels are rising on the engine. Examination of the data indicates that front frame and exhaust frame vibration readings at core frequency are increasing slightly (see Figure 8). Based upon the analysis to this point, XMAN recommends that the technician schedule the engine for a borescope inspection. The user is instructed to return to XMAN upon completion of this task.

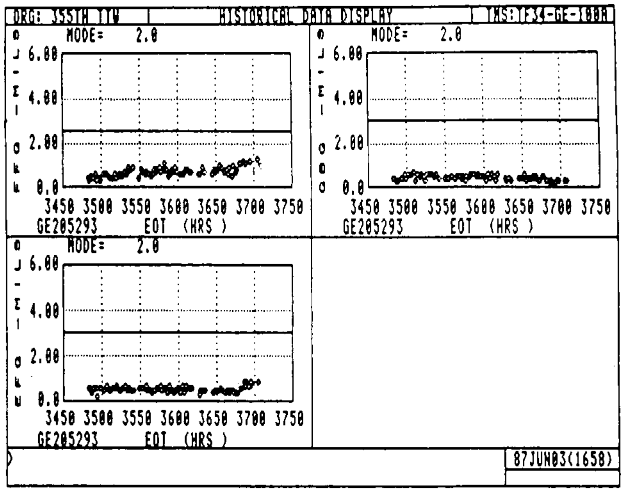

Figure 8 **Core Frequency Vibration Levels Show Slightly Rising Trends in the Example.**

After completion of the borescope inspection, the XMAN troubleshooting session is resumed, this time in the automatic processing mode. XMAN automatically scans down to the last assertion previously processed. The user is asked if the borescope revealed significant turbine or compressor damage, and the response in this case is negative. Figure 9 shows the recommended XMAN action for this engine discrepancy. The engine is to be placed on the CEMS IV WATCH list in order to keep the engine under surveillance. The WATCH list maintains a record of engines which require special attention or follow-up service. CEMS IV advises the user when a review or action is due. In order to facilitate access to the WATCH list, XMAN issues the CEMS IV WATCH command line when the user presses the <HOME> key. Further analysis is necessary if the wearmetal reading continues on its trend or is correlated with serious vibration increases.

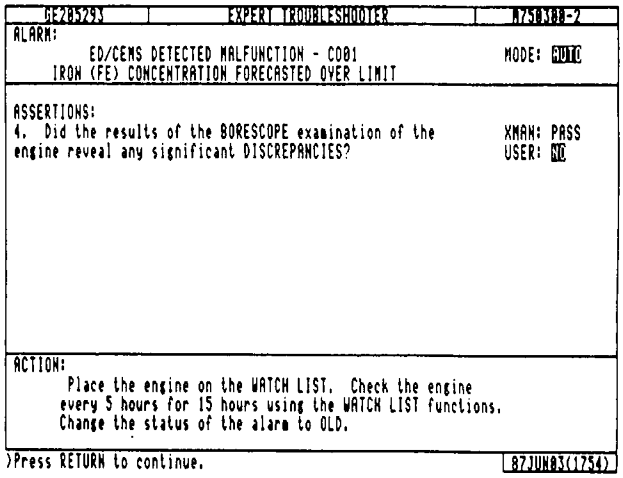

Figure 9 **XMAN Recommends a Maintenance or Follow-Up Action Upon Completion.**

At several points in the scenario described, the user may have responded "PASS" rather than entering a yes or no response. This response is programmatically equivalent to acceptance of the XMAN assertion. However, the audit trail or journal of the troubleshooting activity shows that the user entered an "I Don't Know" response.

OPERATIONAL EVALUATION

An audit trail of all engine troubleshooting performed allows visibility into actual discrepancies processed in the field. At each base, XMAN tracks all engine alarms analyzed locally including user responses and recommended maintenance actions. The entire XMAN session may be recreated using the troubleshooting results which are captured in an archived fact file. This archived file includes the engine discrepancy, time, date, and user stamps, facts generated, and user responses.

Archived engine fact files are received from the bases periodically. Results are assimilated from all bases in a central analysis location, and troubleshooting effectiveness summaries are produced. Although not yet formally implemented, this detailed usage information may be analyzed by the equipment manager (e.g., repair depot engine managers) to evaluate diagnostics procedure effectiveness on their fielded weapon systems. In addition to high-level summaries of recommended actions versus equipment alarms, lower level detail of user interaction with the expert system and CEMS IV are clearly traceable.

For the first time, the equipment manager has actual field level troubleshooting information available to allow improvement in maintenance diagnostics technical orders. Further closure of the maintenance diagnostics loop is possible through correlation of XMAN recommended actions with actual maintenance performed (i.e., AFTO 349 information available through the CEMS IV/CAMS (Core Automated Maintenance System) interface. This correlation is currently under investigation.

Troubleshooting Summary

XMAN was installed at Barksdale Air Force Base, Louisiana, for user evaluation and operational testing in October 1986. A six-month evaluation period preceded the release of XMAN to seven other Air Force bases. These bases included Davis Monthan AFB, Myrtle Beach AFB, England AFB, Glenn L. Martin Airport (Maryland Air National Guard), Nellis AFB, Sacramento Air Logistics Center, and San Antonio Air Logistics Center. XMAN was released for operational use in late April 1987. The evaluation results presented focus on the user evaluation operations at Barksdale AFB.

During eight months of use at the 917th TFG, XMAN aided processing of over 700 engine discrepancies. A summary of the most frequently occurring CEMS IV and TEMS alarms is shown in Figure 10. The three most frequently processed CEMS IV alarms include:

a. Fan speed trim margin forecasted below limit;
b. A below limit trend in corrected fan speed versus corrected temperature; and
c. Chromium forecasted over limit (an oil wearmetal abnormality).

Note that a large percentage of the alarms diagnosed did not require immediate maintenance attention. XMAN recommended alarm deletion in these instances. This insight into alarms inappropriately generated allows for the possibility of fine tuning of the CEMS and TEMS software to reduce this undesired characteristic. Other recommended actions based upon XMAN analysis of CEMS IV generated alarms focused on the scheduling of engine water washes (a problem typical of the A-10/TF-34 due to gun gas ingestion) and engine placement on the CEMS IV surveillance list (WATCH).

The most frequently analyzed TEMS engine discrepancies included shifts in the interstage turbine temperature and core flameout. Recommended actions concentrated on checkout of the monitoring system rather than actual engine repair. The results analyzed are indicative of the overall excellent health of the TF-34 engines at Barksdale which have been supported by TEMS and CEMS IV for over five years.

ALARM \ ACTION	DELETE	WATCH	TROUBLESHOOT OTHER ALARM	SCHEDULE WASH	REPLACE T5 AMP	REPAIR TEMS
NFTR FORECASTED BELOW LIMIT	234	19	5	17		
NFTS TREND BELOW LIMIT	37	5	17			
CR FORECASTED OVER LIMIT	9	50				
LEVEL 1 TEMS:T5 SHIFT	16	10			2	
LEVEL 2 TEMS:NG FLAMEOUT	4					1

Figure 10 The XMAN Audit Trail Allows Insight into Actual Troubleshooting Performed in the Field.

CONCLUSIONS

Integrated diagnostics, performance reliability, and equipment maintainability are taking on increasingly crucial roles in Department of Defense weapon system support strategies. New methods for providing critical maintenance and logistics information in a timely manner and with limited user interaction are essential. Computer programs which embody forms of human expert problem solving abilities offer significant supportability benefits in an era of increasing equipment sophistication and decreasing service personnel availability.

XMAN offers enhanced diagnostics and interactive training in a commercially available software package. As the services gear equipment diagnostics programs toward portable maintenance aids (e.g., IMIS (Integrated Maintenance Information System)), XMAN offers a proven operational maintenance diagnostics troubleshooting capability. As an integrated diagnostics tool, this expert system allows insight into actual troubleshooting performed, evaluation of results, and the feedback loop to improve diagnostics procedures.

REFERENCES

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2. De Hoff, R.L., Dolny, L.J., Jellison, T.G. and N.S. Pratt, "XMAN™ - An Expert Maintenance Tool", AUTOTESTCON '86 Proceedings, Sept. 1986, San Antonio, TX.