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THESIS

AN EXPERT SYSTEM
FOR
SHIPBOARD MAINTENANCE

by

GORDAN EVANS VAN HOOK

September, 1990

Thesis Advisor:

Magdi Kamel

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91-07721



91 8 8 034

REPORT DOCUMENTATION PAGE				
1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED		1b. RESTRICTIVE MARKINGS		
2a. SECURITY CLASSIFICATION AUTHORITY		3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution is unlimited.		
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE				
4. PERFORMING ORGANIZATION REPORT NUMBER(S)		5. MONITORING ORGANIZATION REPORT NUMBER(S)		
6a. NAME OF PERFORMING ORGANIZATION Naval Postgraduate School	6b. OFFICE SYMBOL (If applicable) 37	7a. NAME OF MONITORING ORGANIZATION Naval Postgraduate School		
6c. ADDRESS (City, State, and ZIP Code) Monterey, CA 93943-5000		7b. ADDRESS (City, State, and ZIP Code) Monterey, CA 93943-5000		
8a. NAME OF FUNDING/SPONSORING ORGANIZATION	8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER		
8c. ADDRESS (City, State, and ZIP Code)		10. SOURCE OF FUNDING NUMBERS		
		Program Element No.	Project No.	Task No. Work Unit Accession Number
11. TITLE (Include Security Classification) AN EXPERT DATABASE SYSTEM FOR SHIPBOARD MAINTENANCE				
12. PERSONAL AUTHOR(S) Van Hook, Gordon Evans				
13a. TYPE OF REPORT Master's Thesis	13b. TIME COVERED From To	14. DATE OF REPORT (year, month, day) September 1990	15. PAGE COUNT 96	
16. SUPPLEMENTARY NOTATION The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.				
17. COSATI CODES			18. SUBJECT TERMS (continue on reverse if necessary and identify by block number)	
FIELD	GROUP	SUBGROUP	EXPERT SYSTEM, EXPERT DATABASE SYSTEM, DATABASE SYSTEM, U.S. NAVY, SHIPBOARD MAINTENANCE	
19. ABSTRACT (continue on reverse if necessary and identify by block number)				
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20. DISTRIBUTION/AVAILABILITY OF ABSTRACT		21. ABSTRACT SECURITY CLASSIFICATION		
<input checked="" type="checkbox"/> UNCLASSIFIED UNLIMITED <input checked="" type="checkbox"/> SAME AS REPORT <input type="checkbox"/> FOR OFFICIAL USE ONLY		Unclassified		
22a. NAME OF RESPONSIBLE INDIVIDUAL Kamel, Magdi		22b. TELEPHONE (Include Area code) 408-649-0771	22c. OFFICE SYMBOL AS/KA	

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An Expert Database System
for Shipboard Maintenance

by


Gordan Evans Van Hook
Lieutenant Commander, United States Navy
B.S., Texas A&M University, 1979

Submitted in partial fulfillment
of the requirements for the degree of
MASTER OF SCIENCE IN INFORMATION SYSTEMS

from the

NAVAL POSTGRADUATE SCHOOL
September 1990

Author:



Gordan Evans Van Hook

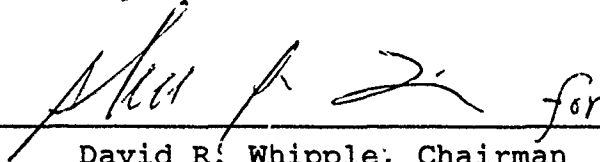
Approved by:



for Magdi Kamel, Thesis Advisor



Tung Xuan Bui, Second Reader

 for

David R. Whipple, Chairman
Department of Administrative Sciences

ABSTRACT

Current corrective maintenance practices in U.S. Navy ships follow troubleshooting guides found in the paper copies of technical manuals. These manuals are often difficult to find, maintain, and store, and guides are not easily followed. An expert system for troubleshooting could improve current practices by providing a centralized program that is easily maintained and followed. By coupling to a database of procedures, the precise steps to correct the problem could also be called. An expert database system allows an expanded knowledge base that is easily modified while maintaining the integrity of the expert system program.

A prototype system for troubleshooting the NAXI 100-2 Low Pressure Air Compressor was developed to illustrate the advantages of expert database technology in this application. VP-EXPERT and DBASE IV were used, and the prototype as demonstrated to SIMA, San Diego, was received favorably. Conclusions drawn supported the feasibility of such systems to assist in the performance of shipboard maintenance.



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DTIC TAB	<input type="checkbox"/>
Unannounced	<input type="checkbox"/>
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Distribution/	
Availability Codes	
Dist	Avail and/or Special
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Acknowledgement

The expertise and enthusiasm provided by SIMA, San Diego, was greatly appreciated, and proved invaluable throughout this study. The flexibility and progressive mindset displayed at all levels of the chain of command was an inspiration and a source of optimism for the Navy's current and future use of computer technology.

My greatest thanks go to my wife, Jacqueline Anne. Her constant support and patience throughout this research gave me the strength to persevere and keep a clear perspective. As always, she is my strongest ally, most honest critic, and closest friend.

I. INTRODUCTION

A. BACKGROUND

Within the warships of today's modern US Navy the effective corrective maintenance of main propulsion and auxiliary machinery requires a vast array of technical expertise and written reference material. Other than the supply functions on SNAP II (an installed minicomputer for administrative support) equipped ships, troubleshooting and repairs are completely manual, and often imprecise or misdirected. Some specific problems are as follows:

1. The expertise of technicians varies widely from ship to ship and from sailor to sailor. The more senior petty officers and chief petty officers show a wide range of experiences and knowledge. Even when specifically trained and coded for a certain class of ship or machinery, levels of expertise are far from standard.
2. Current troubleshooting practices rely heavily on a plethora of technical manuals, PMS (planned maintenance system) cards, owner's manuals, or pass down notes and checklists. All this paper does not hold up well on the deckplates, and important pages are often stained, torn, or removed in the repair process. Numerous paper copies also use an incredible amount of precious space, and this issue has prompted new research such as the paperless ship initiative to reduce the amount of paper on U.S. naval ships. Even with many duplicate copies present aboard ship, a needed technical manual often cannot be found in its assigned location.
3. Technical libraries are notoriously difficult to keep up to date, properly sorted, centrally located or distributed as required. Technical librarians are often junior sailors, or even worse, sailors who can not do anything else. They are usually not formally trained, and

often are held accountable for documentation to equipment that they have little interest in themselves.

4. There is often an inadequate record of maintenance actions performed on specific equipment. An automated system could conceivably keep an effective audit trail of the actions taken and how often. Manual notebooks and equipment material histories currently in use are often out of date, illegible, or misplaced.

5. Many sailors are intimidated by large unwieldy technical manuals that can be difficult to navigate through. The organization and logical flow of the troubleshooting sections of many technical manuals are not always intuitively obvious, and can further discourage the average sailor.

A computerized expert database system developed from a commercially available expert system shell and database management system could greatly mitigate many aspects of the aforementioned problems. By coupling an expert system to a database, the knowledge base could be greatly expanded while still maintaining the flexibility of a database system. This would allow the many changes due to frequent technical updates to be incorporated separately in the database while maintaining the integrity of the expert system program. This thesis will develop a prototype of such a system for a specific equipment to prove the viability of integrating expert system and database management technology in performing shipboard maintenance.

B. OBJECTIVES

The objectives of this thesis are to demonstrate the value of expert system technology in the performance of shipboard

maintenance, and to combine an expert system with a database management system to produce a working expert database system.

C. RESEARCH QUESTIONS

This study seeks to answer the following primary and secondary research questions:

Can an expert database system assist maintenance personnel in the performance of shipboard corrective maintenance?

It will also address the four following questions:

1. Can a commercially available expert system shell (VP-EXPERT) be used to develop a working prototype?
2. Can equipment technical documentation be stored in a commercially available database management system (DBASE IV) and effectively called upon by an expert system?
3. What are the benefits of using an expert system for troubleshooting shipboard machinery?
4. What type and degree of coupling will be required between the expert system and the database management system?

D. SCOPE

Shore Intermediate Maintenance Activity (SIMA), San Diego, provided the technical documentation for a NAXI 100-2 Low Pressure Air Compressor to form the prototype's knowledge base. The system has been designed to guide the user through the basic troubleshooting process by first identifying the symptoms, possible causes, and finally, what solutions are available. The system interfaces with a database management system to call up selected procedures to be used for problem

solutions. An initial prototype expert system was developed and taken to SIMA for testing by the appropriate resident experts. The expert system was then coupled to a database to form the final prototype to determine if this form of shipboard maintenance is a feasible application of an expert database system.

E. METHODOLOGY

A prototyping approach was followed in the design and development of this system. Knowledge was acquired for the system principally from the technical manual's troubleshooting guide and phone interviews with equipment experts from SIMA, San Diego. This knowledge was used to develop "if-then" rules for the expert system shell. The expert system interacts with the user with a set of questions, and the replies trigger the rules to provide expertise. Separate procedures to be used to complete the solution are kept in a separate database and called on demand.

F. ORGANIZATION

The following is a summary of the chapters:

I. Introduction - The background, objectives, research questions, scope, methodology, and organization of the research is presented.

II. Current Environment - The current maintenance practices in use in the fleet, and the current expert system and database technology available is reviewed in this chapter.

III. Analysis and Design of the Expert System Component - This chapter includes the decision domain, design and implementation of the expert system component.

IV. Analysis and Design of the Database System Component This chapter includes the definition, requirements, design and implementation of the database system component.

V. Conclusions and Lessons Learned - The first and second prototype reviews, the lessons learned using the VP-EXPERT shell and DBASE IV database system, and the research conclusions are presented.

Appendices - These sections include the expert system decision tree, sample consultation, the database object and domain definitions, relationships, update and control mechanisms, dataflow diagrams, and menus.

II. CURRENT ENVIRONMENT

A. CURRENT TROUBLESHOOTING METHODS

The current method for troubleshooting main propulsion and auxiliary machinery in U.S. Naval ships is an entirely manual process with the exception of the preparation of requisitions to the supply department for parts. A problem will usually be initially detected by a watchstander who is qualified to operate the equipment, but may not be qualified to perform any scheduled or corrective maintenance. His normal duties include the monitoring of equipment operating parameters and basic house cleaning within his assigned space. He is usually qualified to start, stop and monitor his assigned equipment only within the strict guidance provided by the Engineering Operating and Sequencing System (EOSS). EOSS is further divided into Engineering Operating Procedures (EOP) which are used for starting, stopping, and monitoring of normal operation, and Engineering Operating Casualty Control (EOCC) which is used to provide emergency response to equipment casualties.

The Naval Sea Systems Command (NAVSEA) provides all guidance for the normal operation, casualty control, preventive and corrective maintenance of shipboard engineering machinery. Technical manuals are provided to each ship for all assigned equipment. The paper and microfiche copies are kept

in a space designated as the ship's technical library, and a sailor is given the job as technical librarian. On large ships this may be a primary duty, but on most ships it is a collateral duty.

Technical manuals typically contain general descriptions of component systems, safety precautions, operating procedures, scheduled preventive maintenance, corrective maintenance (troubleshooting), system diagrams, parts list, and installation procedures. The technical manual forms the basis for EOSS and the Preventive Maintenance System (PMS), which are much more specific in their detail. Because they are more specific and detailed, EOSS and PMS take precedence over the technical manual, but corrective maintenance is usually performed using the technical manual alone. In some cases a PMS procedure may be used to correct a specific problem (i.e. replacing a clogged filter). Changes to procedures which require immediate attention may be sent via a radio message or class advisory, otherwise routine technical updates and changes are sent via normal naval correspondence.

When a watchstander detects a problem and takes immediate action in accordance with EOCC, the equipment is secured and a sailor qualified to perform the required troubleshooting is called to the space. If the problem's cause is not immediately obvious, the technical manual is consulted. Most technical manuals contain a troubleshooting guide which can be followed to narrow the problem down to its specific cause. This cause

is matched with a specific solution to the problem, usually a reference to the page and paragraph of a corrective maintenance procedure. The corrective maintenance procedure outlines the specific steps to be followed, the tools and parts required, and any safety precautions and considerations.

Problems arise as soon as the cause of equipment casualty is not readily apparent and the technical manual must be consulted. First a copy of the technical manual must be found. If a copy is kept in the engineering space, the chances are that it is in poor condition. Space copies are typically stained with various greases and oils and plagued by many torn and missing pages, and retrieved loose pages are frequently shoved back in the manual at random locations. These copies are also usually out of date and missing the latest revisions and changes. If a copy of the technical manual must be checked out of the technical library, it may be in better condition, but first it must be found. The manuals are kept in shelves in order of their assigned NAVSEA TECHNICAL MANUAL number, so first the index must be found, the number looked up, and the manual found (provided the last user replaced it properly). Since it is usually a collateral duty, the technical librarian must fit the proper care of the library in with his own primary duties and watchstanding. His duties as the technical librarian include making sure manuals are properly checked out and returned, ensuring they are kept in the proper order on the shelf, and entering the appropriate revisions and changes

as they arrive. Successful ships know the importance of this job, but on many ships there may be a tendency to relegate this task to a more junior sailor or one that is less skillful in his primary maintenance duties. Consequently, the quality of the technical library often suffers due to inattention or neglect. Even if the technical librarian is exceptionally competent and diligent, he cannot be present 24 hours a day, and must rely on proper procedures being followed in his absence. In the rush of a critical repair, proper procedures in the technical library are usually given an expectedly low priority.

Once found, the technical manual must be searched for the troubleshooting guide. Troubleshooting guides do not follow a standard format and may vary greatly in logic and clarity between different technical manuals. Some are in paragraph form, while others are tabular or follow a flowchart format. Many sailors are immediately intimidated by the heft and complexity of many technical manuals, especially those for the larger auxiliary and main propulsion pieces of equipment. Reading competency may also vary greatly between sailors, which can increase anxiety when faced with multiple volumes of technical jargon. The result is that many sailors will perform troubleshooting in a haphazard "hit or miss" fashion with only a cursory glance at the technical manual. They often rely heavily on their own experience and expertise which can vary

greatly between individuals, and this often results in an inconsistent or ineffective troubleshooting effort.

An expert system for engineering maintenance could alleviate many of the problems that exist in the current environment. The central location of a computer would solve many of the problems caused by duplicate copies in poor condition. There would be no lost time searching the spaces or the technical library shelves for the proper technical manual. The troubleshooting guide could be logically and clearly presented by a series of questions which would guide the user to the specific problem and solution. This would avoid the intimidation and endless page turning morass of the large manuals by focusing the user's attention strictly to the question at hand. Since the expert system is providing the bulk of the expertise, the system could accommodate a wide range of experience and technical competence. An accompanying database called by the expert system could logically organize the corrective procedures called for display and printing.

Corrective maintenance, or troubleshooting, as a problem domain lends itself exceptionally well to expert system development. According to Leibowitz [Ref. 1], a task candidate for an expert system must have the following characteristics:

- 1. The Task Should Be Well-bounded.**

The task should encompass a relatively specific amount of knowledge, consisting of facts within a narrow scope.

Machinery troubleshooting is a perfect example of a well-bounded and specific task.

2. The Task Involves Symbolic Versus Numerical Processing.

This refers to the execution of symbols or strings of characters. Significant numerical calculations could be better performed with conventional programming languages. Troubleshooting requires little or no numerical calculations.

3. The Task Can Be Solved Relatively Quickly.

If a task requires more than a few weeks to solve than an expert system would not be appropriate. Most equipment can be quickly analyzed, and the troubleshooting process itself is not time consuming when considered separately from the physical process of component disassembly.

4. The Task Is Performed Frequently.

The usefulness of an expert system is maximized when the expert system is used to solve a task repeatedly. Shipboard equipment is run constantly under harsh environmental conditions, and breakdowns are frequent. An expert system to perform these tasks would get plenty of use to justify its development.

5. There Is A Significant Difference Between the Best and Worst Performers.

A task is more suitable for an expert system when there is a large discrepancy between the best and worst performers of the task. As previously discussed, this is

certainly the case for most sailors performing troubleshooting in the fleet.

6. Test Data Is Available.

This is not a firm requirement, but can be helpful. There are plenty of successful troubleshooting cases to serve as comparisons for determination of expert system performance.

7. There Should Be Consensus on How the Task Can Be Solved.

The experts must agree on how to solve the task. Again, troubleshooting procedures are clear and well-bounded, and there is little room for variation from prescribed solutions.

8. Experts Exist and Can Participate.

There are plenty of sailors available to tap for expertise, and to evaluate a system. SIMA San Diego is a particularly good source of qualified technicians with current and recent shipboard experience in troubleshooting.

B. EXPERT SYSTEMS

An *expert system* is a knowledge-based computer system that attempts to replicate what human experts normally do. Human experts may make decisions, recommendations, or actually perform tasks. They may also train others to do these same tasks or make the same decisions. Expert systems are designed to perform these functions also. [Ref. 2]

For this study the term expert refers to a troubleshooting repair person who is particularly adept at his job. The expert system enables a user with a problem (i.e., how to find the cause of machinery failure and a way to repair it) to use a computer system as they would an expert advisor to guide them through diagnosing what might be causing the problem and how to solve it. This is called a *consultation*.

Like a human expert, the system can extract additional information or data from the user with questions related to the problem. During a consultation the system can also answer questions about why certain information is needed and the reasoning steps gone through to reach a conclusion, and it can make recommendations for solving the problem at the end of the consultation. [Ref. 3]

The distinguishing characteristics of expert systems are that they:

1. Contain symbolic programming and reasoning capabilities.
2. Contain a knowledge base about a specific decision domain distinct from the inferencing mechanism.
3. Contain an inference engine distinct from the knowledge base.
4. Can handle unknown, uncertain, or conflicting data.
5. Allow a programmer or user to modify segments of the program easily.
6. Have a facility to explain their advice or reasoning process.

7. Use if-then rules (heuristics) extensively, but not necessarily exclusively. [Ref. 3]

Expert systems can be created for a computer using programming languages, expert system shells, or system development tools which fall between programming languages and shells. Programming languages provide the most flexibility, but they are more difficult to use because the system developer is required to design from scratch both the knowledge base and the inference engine to access it. Using a programming language is therefore more expensive and time-consuming. An expert system shell can be easier and quicker to use than programming languages or development tools. Since the inference engine is preprogrammed in an expert system shell, a systems developer's main work is to create the knowledge base. Microcomputer versions of expert system shells, such as VP Expert, are especially useful for developing prototype systems such as will be developed in this study. Expert system shells are easily affordable and readily available on the open market. Expert systems developed using a shell are also easier to expand, update and maintain [Ref. 3]. In the case of VP Expert, the expert system shell selected for this study, technical assistance is available from the manufacturer over the phone [Ref. 4]. A system for shipboard maintenance could easily be developed and maintained by personnel with limited computer background or expertise.

C. DATABASE MANAGEMENT SYSTEMS

A database is a self-describing collection of integrated records. It is self-describing in that it contains, in addition to application data, a description of its own structure called a *data dictionary*. In a database system, all application data is stored in the database. [Ref. 5]

A database is more than a collection of files. It includes the files, a data dictionary, and a description of the relationships among the records in the files. These relationships are stored and recalled during database processing and are represented by additional system data known as *overhead data*. Overhead data includes linked lists, indexes, and similar data. It is in this manner that a database can be a collection of integrated records. [Ref. 5]

The advantages of using a computerized database system in the shipboard environment are obvious when considering the current filing systems and technical libraries in use throughout the fleet. Databases can store large amounts of operational data and can be queried on an ad hoc basis, which makes them the ideal foundation for decision support systems. The data stored in a database can be readily accessed and processed, which allows users to get answers much faster. With the addition of a database management system (DBMS) the utility of the database is even greater.

The DBMS is a program (or group of programs) that allows stored data to be integrated, reduces data duplication,

ensures data integrity, eliminates program dependency on file formats, and allows even complicated objects to be easily understood, represented, and retrieved. In short, a DBMS is the program which processes the database. [Ref. 5]

A database system consists of five major components: hardware, DBMS software and application programs, the database itself, procedures, and people. Database systems are often classified by the number of users and the number of applications they support. [Ref. 5]

In a single-user database system, only one user at a time processes the database. In a multi-user database system, the database is processed by many users concurrently. Multi-user systems require more hardware and special precautions to prevent two users using the system concurrently from interfering with each other [Ref. 5]. Database systems can also support one or many applications. An application is simply a system that processes a portion of the database in order to meet the information need of a distinct functional area of an organization [Ref. 6].

For this study, a single user, multi-application database system will support the requirements of an engineering maintenance database system. There are many low cost, readily available commercial products to fill this requirement, and a microcomputer, as commonly found on most ships, will provide the adequate hardware.

D. EXPERT DATABASE SYSTEMS

While a simple computer-based database system would greatly assist in providing the information needs of a ship, in particular in the area of engineering maintenance, such a system joined or coupled to an expert system presents an even greater range of possibilities. What makes the bridge between database management and an expert system possible is the fact that databases and expert systems' knowledge bases are both first and foremost *information-bearing systems*. Although often considered technically distinct and separate, their deeper, more fundamental similarities suggest a natural union.

[Ref. 7]

When moving up from a simple database to an expert database one should view the database as an extension of the knowledge base. The advantage of coupling an expert system to a database is that a large amount of information can be organized and accessed separately while the knowledge base remains intact. Additions, modifications, and deletions can be easily performed through a menu-driven format of the database management system without affecting the integrity or logic of the expert system. While most database systems are easily understood and learned, changes to the expert system's knowledge base require much more training, and the user must have an intimate knowledge of the logic involved. It is far more efficient to store large amounts of varying information in a database, and design the knowledge base to contain a

single set of invariant rules. Therefore, when a database is used in this fashion, it becomes an *information base*, and can be considered as a part of the overall knowledge base. To distinguish the rules of the original knowledge base from the information base, they are referred to as the *rule base*

[Ref. 4]. Figure 1 provides an illustration of the concept of the expert database system.

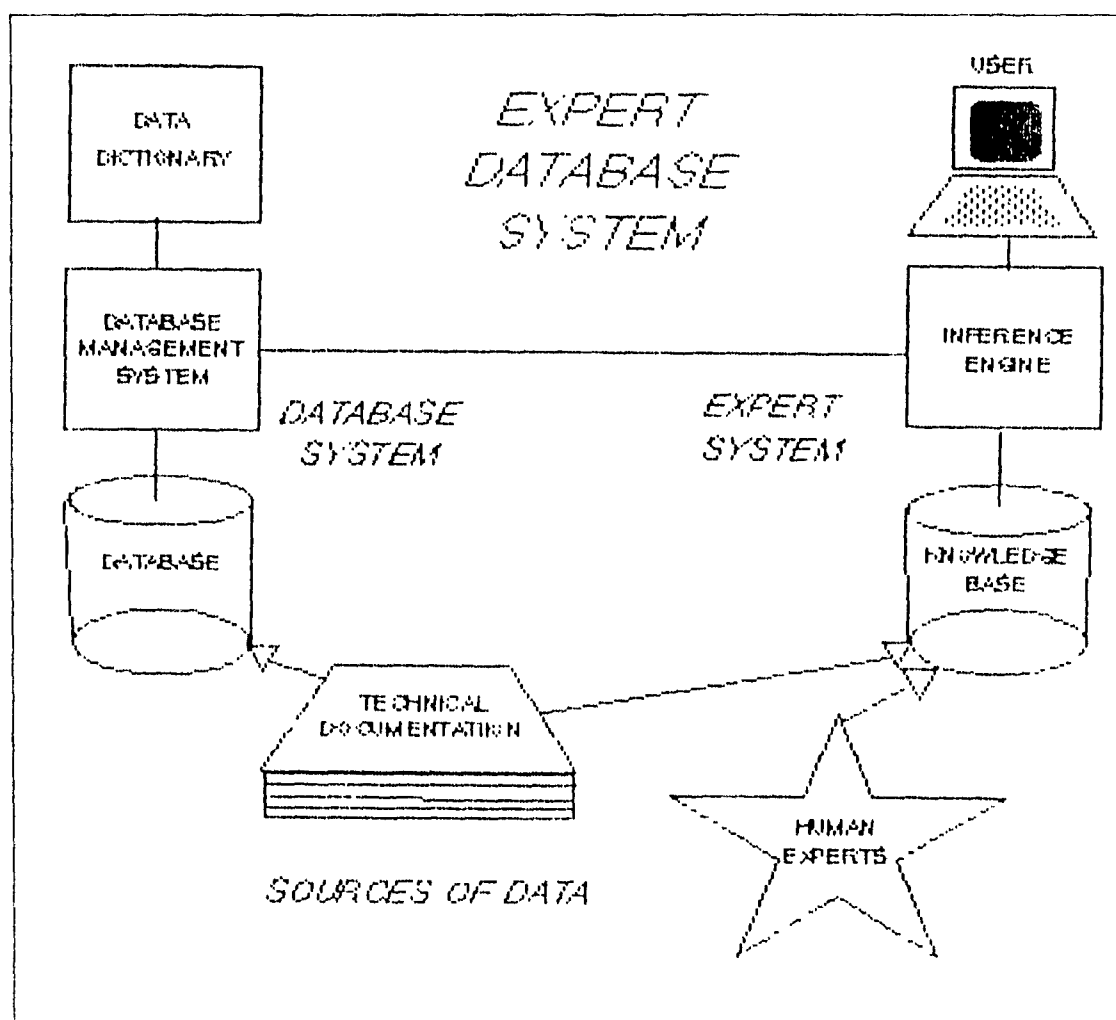


Figure 1. The Expert Database System.

A simple expert database system consisting of a commercially available expert system shell and a compatible database management system can provide an ideal system for assisting in the troubleshooting of shipboard engineering equipment. The troubleshooting guide can be extracted from the technical manual to form the basis for the knowledge of the rule base. The logic of most troubleshooting guides lends itself well to the rapid translation into a series of if-then rules. Questions to the user will be answered, compared to the rule base, and a cause and solution to the problem given. A separate database can then be accessed by the expert system to provide the detailed procedures required to correct the problem. Since these procedures are the portions of the technical manual that are most likely to be changed by periodic technical updates from NAVSEA, their retention in a database facilitates ease of access and modification if required, without influencing the basic logic of the rule base.

VP-EXPERT has been selected as the expert system shell for this study. It has a relatively low cost, is widely available and used, is easily installed on microcomputers, has good technical support, and has facilities for coupling with database files.

DBASE IV will be used for the database management system. It is also readily available at a low cost, easily installed, has good technical support, and is compatible with VP-EXPERT.

Together these two systems will be joined to form a prototype
Engineering Maintenance Expert Database System.

III. ANALYSIS AND DESIGN OF THE EXPERT SYSTEM COMPONENT

A. THE OVERALL SITUATION STUDIED: THE EXPERT'S DOMAIN

1. Decision Selection

The general area under study is the corrective maintenance or "troubleshooting" of a piece of machinery that is not operating according to prescribed specifications. For this study the particular machinery involved pertains to main propulsion or auxiliary shipboard equipment. These systems are largely electro-mechanical in nature with associated electrical and electronic control and monitoring systems.

Troubleshooting was selected as the subject for this expert system development for several reasons:

1. Troubleshooting is a vital and mission essential process in U.S. Naval ships, and it is performed by only a few selected experts in a particular ship. This expertise can be variable and scarce.
2. Troubleshooting decisions involve informed judgement applied in a deductive logic well-suited to expert system development.
3. Troubleshooting decisions are made in a reasonable amount of time and are clear, structured and well-defined.

2. The Decision Making Process

Troubleshooting is the process of analyzing the symptoms of a given problem, determining the cause, and applying a solution to correct the problem. In this process a qualified technician, the expert for the purpose of this

study, initially surveys the problem, checks a few obvious possible causes, and then refers to a checklist or troubleshooting guide if the problem was not immediately corrected. Troubleshooting guides as provided by most equipment technical manuals are usually arranged with a flowchart or checklist of possible causes under each of a number of common problems. The expert then checks each possible cause on the list to determine what is causing the problem. [Ref. 8]

The process of checking a possible cause requires its own expertise as the information given in the guide is usually only a question as to whether or not a given condition exists. The technician must possess a certain expertise to make many of these determinations. For example, a troubleshooting guide may ask if a certain electrical switch is defective, and it is up to the technician to make that determination. The prototype developed for this study will be restricted to the expertise provided by the technical manual, but further iterations could be expanded to include the full expertise required of the troubleshooting technician.

B. DOCUMENTING THE PROTOTYPE

1. System Proposal

The expert system portion of the Engineering Maintenance Expert Database System is constructed from a technical manual troubleshooting guide using the VP-EXPERT

expert system shell. For the purpose of this study, a prototype system was developed to troubleshoot the NAXI 100-2 Low Pressure Air Compressor. With minimal training of a designated technician, similar systems could be developed and maintained using the technical manuals of each piece of engineering equipment found on a particular class of ship. Most technical manuals possess a troubleshooting guide which is logically laid out in such a fashion as to allow the rapid translation into a set of if-then rules of the expert system shell. At the low initial purchase cost of the system shell, virtually an unlimited number of equipments could be supported. Such a system would free shipboard technicians from reliance on numerous unwieldy paper copies of technical manuals while presenting a clear and concise approach to troubleshooting each piece of equipment.

While users of the system could be any technician qualified to work on the particular piece of equipment for which he is troubleshooting, system development and maintenance should be restricted to one or two trained individuals to maintain the knowledge base integrity.

2. Prototype System Description

a. System Overview and Objective

The prototype system will ask the user a number of questions about the operating conditions of the equipment to determine the symptoms and possible causes of a given problem. When a problem has been isolated, the user will be presented

with a solution to the problem. The solution is based upon the backward chaining inferencing through the rule base to arrive at a value.

b. Recommendations to be Made by the System

For prototyping purposes, the system is limited to the problems, causes and solutions given in the troubleshooting guide of the technical manual [Ref. 8]. A given problem will have several possible causes. Questions to the user will be used to isolate a cause and present a simple solution. When required, more detailed solution procedures will be referenced by the paragraph in the technical manual, and the actual procedure steps will be called and displayed from an accompanying database.

3. Prototype Knowledge Base Design

The nature of the troubleshooting problem dictates that there can be many possible causes to many problems, and in turn many possible solutions. Therefore, the knowledge does not lend itself well to segmentation or a standard dependency diagram.

Appendix A, Figures A1 and A2 depict a graphic representation of the decision tree used to form the rule base. The first question to the user determines if the equipment will start when turned on. A negative response forms the first premise for rules 0 to 11, which all lead to causes why the compressor may not start and provide a solution to the problem. An affirmative response to the start question leads

the user to the remaining rules dealing with a compressor that starts and then shuts down. This group is further broken down into three groups for how long the compressor runs before shutting down.

Rules 12 to 15 deal with a compressor that shuts down after three to five seconds, and rules 16 to 18 are for a compressor that shuts down within two minutes. The remaining rules are for a compressor that runs longer than two minutes before shutting down, with the exception of rules 23 to 27 which deal specifically with high water in the separator holding tank, rules 49 to 54 deal with high temperature, rules 61 to 68 which deal with low water, and rules 69 to 72 which deal with high liquid level in the condensate sump. Each of these groups are invoked separately whenever these particular causes have been identified because they can be causes of more than one type of shutdown. For example, a high water condition could cause the compressor to shut down in three to five seconds as per rule 13, or it could be the cause of an automatic shutdown after the compressor has run for longer than two minutes. In each of these cases, a separate WHILETRUE clause in the ACTIONS block of the program will be called to find the cause of the high water, high temperature, low water, or high condensate level.

Referring back to Appendix A, once it has been determined that the compressor runs for longer than two minutes, then the rules are further grouped as follows: rules

19 to 22 and 28 and 29 deal with automatic shutdowns, rules 30 to 33 are for a compressor that will not automatically stop or unload, rules 34 to 37 are for a compressor that will not automatically restart in the automatic mode, rule 38 is specifically for a safety valve lifting prematurely, rules 39 to 47 are for low receiver air pressure, rules 55 to 60 deal with high seawater outlet temperature, and rules 73 to 81 are for an abnormal noise in the compressor.

C. PROTOTYPE IMPLEMENTATION

Appendix B is provided as a sample consultation using the prototype system, which has been given the name The LPAC Troubleshooter. The user of the system is expected to be familiar with the VP-EXPERT's basic operations and options available through the introduction and control screens. Chapter 1 of the VP-EXPERT manual [Ref. 4] provides an adequate explanation of the basic commands needed, and the prototype's introductory screens also review how the user can make selections.

Refer to Appendix B for the screen displays and the types of questions asked during an actual consultation with The LPAC Troubleshooter.

IV. ANALYSIS AND DESIGN OF THE DATABASE COMPONENT

A. SYSTEM DEFINITION

The database system developed for this study is titled The Shipboard Maintenance Database. It is intended to serve as a prototype for use with the expert system developed for this thesis, the LPAC Troubleshooter. As a prototype, this system has been developed to demonstrate the value of coupling a database to an expert system to form an expert database system to assist in the performance of corrective maintenance in U.S. Navy ships. While this particular database provides the necessary basic information to conduct certain corrective maintenance tasks, an actual shipboard system could be greatly expanded to include preventive maintenance, safety precautions, mission impact, and full supply interface for parts support. However, for the purpose of this study, the system scope has been limited to only those objects required to perform corrective maintenance.

Users of this system would include sailors performing corrective maintenance on U.S. Navy shipboard auxiliary and main propulsion equipment, the division Leading Petty Officer responsible for maintaining and updating the system, the division Chief Petty Officer, and the Division Officer. The prototype for this study will use the NAXI 100-2 Low Pressure Air Compressor as the equipment example, but the system has

been designed to include all of the engineering equipment in a destroyer-sized ship.

As a stand-alone system without the expert system, users could access the database to obtain basic equipment and system characteristics, information on equipment problems, symptoms, and the corrective procedures and parts required to correct a problem. All information used by the system will be restricted to, and taken directly from the equipment's technical manual.

The purpose of such a system would be to effectively automate a ship's technical manual, thereby freeing the maintenance technician from cumbersome paper copies and providing a centralized access to technical information. As a separate system from the expert system, a database could be more easily updated and modified than the expert system's rule base. A separate database also allows greater access to the technical information for purposes other than troubleshooting.

This study will use the DBASE IV database management system for implementation. This software is readily available, relatively easy to learn, and compatible with the hardware currently in the fleet. The prototype is considered entirely feasible in its current form as a shipboard database application.

B. USER'S REQUIREMENTS

The user's requirements are designed to meet two goals: data requirements and functional requirements.

1. Data Requirements

Data requirements are the data elements stored in the database to support the applications. This study will follow an object-oriented methodology to fulfill these requirements.

a. Data Objects

An *object* is a named collection of properties that sufficiently describes an entity in the user's work environment. [Ref. 5]

For this study, the objects defined included EQUIPMENT, SYSTEM, CORRECTIVE PROCEDURE, and PROBLEM. Appendix C provides the specifications and diagrams for each of these objects.

b. Object Descriptions

(1) Equipment Object. The EQUIPMENT object is used to describe any piece of main propulsion or auxiliary equipment found in a ship's engineering plant. Its properties include a name (EName) which it is commonly referred to, a specific model number (modelno), the systems it is composed of, its manufacturer (manufact), its technical manual (Techman), and the number of units (number) found on this particular ship. Appendix C provides the full domain descriptions for each property.

(2) System Object. The SYSTEM object describes each of the systems which make up a piece of equipment and as such is an object property of the EQUIPMENT object. Its properties include a common name (SName), a brief description of its purpose (SDescript), the equipment it is found in, and any problems that could be associated with the system. As an example, a piece of equipment such as the low pressure air compressor, consists of the following systems: electrical, air, dehydrator, fresh water injection, etc. The electrical system could have a problem such as open undervoltage relays. Problem is a multi-valued (MV) property, in that a given system can have many possible problems.

(3) Corrective Procedure Object. The CORRECTIVE PROCEDURE object describes a procedure used to correct an equipment problem. It consists of a task name, a brief description (TDescript) of what it is supposed to do, the problems it corrects, the specific steps (TProcedure) of the procedure, and any parts required to perform the procedure. For example, the task "Replace high level drain switch" is performed to correct the problem of "high water in the separator holding tank".

(4) Problem Object. The PROBLEM object describes a problem that a system of a piece of equipment may experience. Its properties include a common name (PName), the symptoms, the cause of the problem, the corrective procedure

(procedure) to correct the problem, and the system that usually has the problem.

2. Functional Requirements

Functional requirements consist of the applications' update, display, and control mechanisms used on the data objects to satisfy the user's information needs. They are best illustrated with data flow diagrams as per Figures C2 to C6 in Appendix C.

An application is a collection of menus, reports, forms, and programs that addresses the needs of a user group.
[Ref. 5]

For this study the database system has been designed to support two applications: The Leading Petty Officer application and the Troubleshooting application. Appendix C provides a summary of the update, display, and control mechanisms for each application.

a. The Leading Petty Officer Application

According to the dataflow diagrams in Appendix C, Figures C2 through C6, the leading petty officer is responsible for all aspects of maintaining The Engineering Maintenance Database. This means that this user's application must be able to create, edit, and delete instances of the EQUIPMENT, SYSTEM, CORRECTIVE PROCEDURE, and PROBLEM objects. Although creations and deletions would be rare, technical updates from NAVSEA could require frequent editing of the CORRECTIVE PROCEDURE object.

(1) Leading Petty Officer Update Mechanisms. The leading petty officer (LPO) creates all objects using data from the technical manuals. If a piece of equipment is new to the ship or it has not yet been entered into the database, the leading petty officer enters all new instances of the EQUIPMENT, SYSTEM, CORRECTIVE PROCEDURE, and PROBLEM objects. Changes to the database in the form of technical updates are taken from data provided by NAVSEA technical updates and directives. These are usually changes to corrective procedures or parts. Figure C8, in Appendix C, is an example of a form that the leading petty officer would use to enter new EQUIPMENT, SYSTEM, CORRECTIVE PROCEDURE, and PROBLEM objects or to update existing instances.

Figure C9 is a form to delete an EQUIPMENT object. This would be a rare occurrence and would result in removing the associated SYSTEM, CORRECTIVE PROCEDURE, and PROBLEM objects.

(2) Leading Petty Officer Display Mechanisms. This application requires only one printed report, a list of all equipment and their technical manuals to validate the assigned equipment with the technical library.

(3) Leading Petty Officer Control Mechanisms. The main control required for this application is to ensure that only the leading petty officer or his designated chief petty officer (CPO) or division officer (DIVO) has access to add, delete or edit data. This can probably best be achieved

with a required password to protect the integrity of the database.

b. The Troubleshooting Application

The Troubleshooting application will be used by sailors acting as technicians performing corrective maintenance on main propulsion or auxiliary machinery. It can either be accessed directly through the installed DBASE IV DBMS, or via the VP-EXPERT expert system if a troubleshooting rule base has been established for the particular equipment.

(1) The Troubleshooting Application Update and Display Mechanisms. This application has no create, edit or delete mechanisms. Maintenance technicians will access the database for the display or printing of information, but will not be able to alter the data in any way. Screen displays will be called to view the records of each object, or to provide a report of problems by system or symptoms. These displays will also contain the corrective procedure task to correct each problem. A report of the task and its procedures from the CORRECTIVE PROCEDURE object record can then be called for display, or printed and carried to the work space. Figure C10 shows sample reports of problems, and Figure C11 shows a display of the corrective procedure.

(2) The Troubleshooting Application Control Mechanisms. Access to the troubleshooting application will be restricted by password to those petty officers qualified to

work on the equipment. Reports can be printed and distributed separately to other sailors for training purposes only.

C. DESIGN

The design blueprint for the Engineering Maintenance Database includes the logical database design and the application design. The logical database design consists of the database schema, application subschemas, and relation diagrams and definitions, while the application design consists of the control mechanisms and the formats for forms, reports, and menus.

1. Logical Database Design

a. Database Schema

The *schema* or *conceptual view* is the structure of the entire database. It includes the structure of all data types to be used by each application [Ref. 5]. Table C2 provides the schema of the Engineering Maintenance Database.

b. Application Subschema

The subschema is that portion of the database processed by a particular application. It is also known as the *logical view* or *application view* [Ref. 5]. Table C2 gives the subschema as each column for leading petty officer and troubleshooting.

c. Relations

The Engineering Maintenance Database is a *relational database*. In other words, it is built upon the

relational model. The relational model is a concept that data is organized and stored in two dimensional tables called *relations*. Relations can be considered files, and each row in the relation as a record. The concept of a record as a collection of data items is similar to a relation being considered a collection of attributes. In a relation, rows are called *tuples* and columns are called *attributes*. [Ref. 5]

In designing the database, the previously discussed objects will be used to form relations. By a process known as normalization, the relations will be formed by transforming the object properties into attributes. A relation diagram will identify the *relationships*. A relationship is an association between attributes or rows. Most relationships can be better understood when broken down to *binary relationships*. A binary relationship is a relationship involving only two record types. A binary relationship can be *one to one*, *many to one*, or *many to many*. Each of these relationships can be either mandatory or optional. [Ref. 5]

(1) Object Types. To transform the objects into relations, the structure of each object must be analyzed. In this system three objects are *compound objects* and one is an *association object*. A compound object contains at least one object property, that is at least one of its properties is actually another object. Consequently, a compound object is represented by at least two relations, one for each object. An

association object is similar to a compound object, but it is used to document a relationship between two or more objects.

Refer to the object diagrams and relation diagrams in Appendix C. The EQUIPMENT object contains the SYSTEM object (MV means there are many systems), the SYSTEM object contains EQUIPMENT and PROBLEM objects, and CORRECTIVE PROCEDURE contains the PROBLEM object. Therefore, EQUIPMENT, SYSTEM, and CORRECTIVE PROCEDURE are compound objects. The PROBLEM object contains both CORRECTIVE PROCEDURE and SYSTEM objects. Since it documents a relationship between the SYSTEM and CORRECTIVE PROCEDURE objects, it is considered an association object. Part V of Appendix C illustrates each of the objects transformed into relations and their binary relationship to each other.

(2) The Relationships. Each piece of equipment must have many systems and each system must belong to only one piece of equipment; therefore, the relationship is a mandatory one to many between the EQUIPMENT and SYSTEM relations. Each system can have many problems and each corrective procedure could correct one or many problems. Each problem must affect a system, and must have a corrective procedure. Therefore, the relational representation of PROBLEM clearly shows it to be an association object with mandatory many to one relationship to both SYSTEM and CORRECTIVE PROCEDURE.

(3) The Keys. The relations and relationships of this system form a *simple network*. A simple network is a collection of records and one-to-many relationships among the records where one record may have more than one parent [Ref. 5]. In this system, PROBLEM has parents SYSTEM and CORRECTIVE PROCEDURE. The keys of each relation are used to form the relationships of a network. A key is a group of one or more attributes that uniquely identifies a row. Every relation has at least one key [Ref. 5]. For the EQUIPMENT relation, the equipment's name, the attribute EName, is the key of the relation (as indicated by underlining in the diagram). The one-to-many relationship is effectively formed by placing the key of the parent in the child (the many side), and is then known as a *foreign key* within the child. Therefore, the key of EQUIPMENT, EName is placed within SYSTEM to form a mandatory one to many relationship. The key of SYSTEM, SName, and CORRECTIVE PROCEDURE, Task, are placed in the child PROBLEM as foreign key attributes. Table C1 shows each of the attributes for each relation and their definitions, including foreign keys.

2 Application Design

As previously discussed in the requirements portion, the Engineering Maintenance Database System has two applications: the Leading Petty Officer and Troubleshooting. Each application subschema was summarized in Table C2, and the scope of each application was thoroughly discussed under the

database requirements. This section will cover the application control mechanisms, and the design of the menus required.

a. Control Mechanisms

Control mechanisms can be either menu-driven, command-driven, or a combination of the two. The applications in this system will be menu-driven for the following reasons:

1. Although slightly slower, menus are largely self-explanatory and easier to use than commands.
2. Time for training is at a premium aboard ship, and menus require less training.
3. There is no need for exceptionally fast data input or retrieval.

b. Menu Options

The first menu is the Main Menu, and it will direct the user to the application desired. Figure C12 is an example of the main menu options. The next level will present the user with a list of options for the application chosen. For the Leading Petty Officer application, the next menu is shown in Figure C13. The second level menu will provide a list of actions that can be performed on the object data selected from the first level menu. Figure C14 is an example of the second level menu for the Leading Petty Officer application when equipment is selected. A similar menu would appear for each of the other objects if selected. A selection from this menu would lead to the required form or report to perform the action selected. The term "browse" refers to viewing the

records without modifying them, and the "print equipment list" refers to the equipment technical manual list previously discussed in the requirements section.

The menus for the Troubleshooting application are similar except the options for the user are restricted to browse and print.

The second level menu offers the user access to the CORRECTIVE PROCEDURE and PROBLEM objects only. Figure C15 is an example of the Troubleshooting first level menu. The second level menu offers the actions available in this application. For corrective procedure data, the second level menu would appear as Figure C16.

For problem data, the user would be presented with more options since there are additional reports available for this data. Figure C17 is an example of the second level menu for problem data. Selection of display or print problems report would lead to a third level menu for the user to select the problems by system or problems by symptom report as previously discussed in requirements. Figure C18 is the third level menu for these options. Selection from this menu, as with previous menus presented, will require additional forms so that the user can indicate the desired record data, such as the problems for what system or symptom.

D. IMPLEMENTATION

The Engineering Maintenance Database was implemented using the commercially available DBASE IV software package. DBASE IV was selected because of the author's own familiarity with the system and its widespread use and availability.

1. Creating the Database Files

A separate directory was first established within DBASE IV for inclusion of the Engineering Maintenance Database. From the DBASE IV control center screen, a separate catalog was created titled ENGMMAINT.CAT to hold all files, forms, reports and the two applications.

Database files were created for each of the objects defined in the requirements phase, with their names shortened within the required eight characters of a DOS filename. The files included: EQUIP (for equipment), SYSTEM, CORRECT (for corrective procedure), and PROBLEM. The file structures followed the domain and relation definitions of the requirements phase, with the exception of the CORRECTIVE PROCEDURE property TProcedure. This property was defined to hold a series of procedures within a memo field that should be followed to complete a corrective procedure task. The original database file CORRECT was structured in accordance with the object CORRECTIVE PROCEDURE domain definition for TProcedure. Sample records were placed in the file and worked well within the confines of the DBASE IV environment. Problems arose when attempting to use the CORRECT.DBF file with VP-EXPERT and the

LPAC TROUBLESHOOTER program. Although VP-EXPERT can call most .dbf files, it would not call files with a memo field. Therefore, the TProcedure field of the CORRECT file had to be limited to the maximum 254 characters of a normal field. This created a severe limitation in space available for the corrective procedure steps.

2. Creating the Forms and Reports

Custom forms and reports were created quickly using DBASE IV's form and report design screens and form generators. Final products closely resembled those presented in the design phase with a few alterations for practical purposes.

A form was not created for deletion of files as this function is performed easily using the installed DBASE IV menus. A form format was chosen for the problem reports by system and symptom since the lengths of the fields made a columnar format impractical and difficult to read.

The forms for entering and updating file records use fields with 50 character window widths. If the field contains data of greater than 50 characters, then the data can be entered or read by using the cursor arrows to scroll the data through the window. Directions to this effect are in the field labels and as memos at the bottom of the screen when the field is in use.

3. Creating the Applications

The Leading Petty Officer and Troubleshooting applications were created using the DBASE IV application

generator. The menus created differed only slightly from those presented in the design phase, and in the sample screens given in Appendix C, part VI. Since both applications are within the ENGMAINT catalog, there was no need for a main menu holding both applications. Either application can be selected from the DBASE IV control center within the ENGMAINT catalog. Passwords were not used within the scope of this implementation, but each of the applications could easily be protected using DBASE IV's file protection system.

a. The Leading Petty Officer Application

This application was created under the name LPO. It's main menu is in a horizontal bar format with each selection leading to a pop-up menu. A separate exit option was included to allow exiting back to the DBASE IV control center or to DOS. The pop-up menus closely follow the second level menus presented in the design phase, and their actions use the custom forms and reports already created. The delete action uses the same form as the add and modify actions, but the user is unable to add or modify from this selection. Deletion is performed using the DBASE IV Menu (F10), selecting Records and Mark Record for Deletion or Blank Record. The browse action will display all records in DBASE IV's columnar browse format.

Under the Equipment Data selection, the fifth selection on the second level menu will produce the equipment technical manual report presented in the design phase. The

system, corrective procedures and problem data selection are all the same as the equipment data, except there are no reports.

b. The Troubleshooting Application

This application also uses a horizontal bar menu for the main menu, and menu selections are the same as presented in the design phase. The same exit menu is also used in this application. Under problem data, the second level menu offers a browse selection which allows viewing with no add, modify or delete capability. The Print a Specific Problem selection calls a command file which asks the user for the specific problem to print in the report format PROBREP. The Problems Reports selection activates a third level menu which offers a problem report by system or symptom. Each of these selections calls a separate command file which asks the user for the system or the symptom desired. When the system or symptom is provided, the reports are printed in the SYSPROBS or SYMPROBS formats.

The corrective procedures selection from the main menu activates a second level menu which allows the user to either browse the corrective procedure records, or print a desired corrective procedure. The latter selection calls a separate command file which asks the user which corrective procedure should be printed.

4. Data Input

The actual records created within the database files were the minimum required to illustrate the database system's capabilities and potential for shipboard use. Data on the low pressure air compressor was input as the only piece of equipment, but the system could contain data on all shipboard equipment. All corrective procedures that could be called by the expert system were included, but not all possible corrective procedures were included. The EQUIPMENT, SYSTEM, and PROBLEM files contain only one record each for sample purposes.

A complete working system would require records for each piece of equipment, each system within that equipment, all possible problems, and each corrective procedure.

V. CONCLUSIONS AND LESSONS LEARNED

A. FIRST PROTOTYPE DEMONSTRATION

The first prototype consisted of the first version of the expert system without an associated database. Additionally, the rules for several of the branches of the decision tree had not been fully implemented; specifically the high water, low water, and high condensate branches. It was intended to simply demonstrate the concept of using an expert system for shipboard maintenance, and to allow users to provide first impressions toward its potential for useful application.

The initial prototype was demonstrated for review by SIMA, San Diego. The demonstration was conducted on an actual shop computer in the Compressor Maintenance Shop, and the prototype was run by sailors who perform compressor maintenance aboard ships stationed in San Diego. In addition, each of the technicians who used the system had recently served on a U.S. Naval ship, and were intimately familiar with the environment and current troubleshooting practices in the fleet. User experience levels ranged from the Repair Officer (05) and Assistant Repair Officer (04), both of whom are degreed engineers and classified as engineering duty officers, to the shop chief petty officer (E7) and two shop technicians, a second class and third class petty officers (E5 and E4).

All users quickly picked up how the system worked in a matter of minutes and agreed that a system of this type would be very useful aboard ship. All agreed that such a system would avoid many of the problems previously cited, and fleet sailors could be trained to utilize and maintain the system. A copy of the system was left for an extended review of 30 days, after which observations were recorded. Suggested additions to the system revolved mostly around user interface issues. Some of the suggestions given were as follows:

1. Improve the user interface with touch screens, light pens, or mouse support.
2. Include graphics to facilitate user interface, i.e. provide a picture or graphic representation of the machinery so the user can mouse on to a part or component suspected and shortcut the majority of the rule base (reduces consultation time).
3. Link the system with the Supply Department's parts database, i.e. if a solution requires a part replacement then the user can check its inventory status and fill out a requisition through the system.
4. Increase the references to the technical manual, and provide all corrective procedures as called for in the recommended solutions.

Each of these suggestions could lead to a greatly enhanced system, especially in terms of ease of user interface. However, they were each determined to be beyond the scope of this study, with the exception of portions of suggestion 4.

Suggestion 1 would entail the use of hardware not yet available in the fleet. Although VP-EXPERT provides mouse support, it is only available in the graphics mode of

operation. VP-EXPERT does provide for the incorporation of graphics within a consultation as suggested by 2, and follow-on studies could possibly explore the incorporation of this feature.

Suggestion 3 would best be addressed through the manipulation and interface issues of current shipboard databases for parts support. While this study explores the possibility of linking an expert system with a database, as broad a system as suggested is beyond the scope of this prototype.

Suggestion 4 was partly incorporated in successive iterations of the prototype. References to the technical manual, when applicable, were placed within appropriate solutions in the program. The initial prototype did not couple with a database, but a skeletal sample database has been developed and linked to the system to show the added capabilities and increased effectiveness possible with an expert database system. The development and implementation of the complete database required for a working system was also beyond the scope of this study.

B. THE SECOND PROTOTYPE

The second prototype of the expert system included all possible branches of the decision tree. All references to the technical manual were included, and additional clauses were

added to link the system to the Engineering Maintenance Database.

Within the ACTIONS block, a MENU clause was added to assign the CORRECT.dbf file's TASK field as the choices for the Procedure variable. A separate ASK statement for Procedure asks the user which procedure is desired, and presents a list of the records within the CORRECT file, by task name, for the user to choose from. The FIND Procedure clause is used to trigger the ASK Procedure statement after all solutions that require a corrective procedure. When the user selects the desired task from the list, a WHILETRUE clause in the ACTIONS block calls the record selected from the CORRECT file and triggers a FIND Message clause. This clause causes the first rule (RULE 00) to fire and display the TProcedure field of the record for the task selected.

The end result was a prototype for a simple expert database system. The second prototype was demonstrated to the same group of users from SIMA, San Diego. All users found the system easy to master, and quickly picked up the additional capability to call and view corrective procedures. The added potential offered by such a system was quickly recognized, and all agreed that such a system would be of value for performing shipboard maintenance. Their review and evaluation of the system resulted in the following additional suggestions:

1. The window for the display of the corrective procedure needs to be larger to allow a more detailed and clear

listing of the procedure's steps as contained within the technical manual. Use less abbreviations within the text of the steps.

2. Parts should be included with the corrective procedure. Their description should include their stock number, and the technical drawing number they are found within.

3. The ability to call and view drawings would be useful in the troubleshooting process.

4. Some of the task names presented in the list of procedures were unclear as to their purpose or function.

5. It would be useful to be able to manipulate the database management system from VP-EXPERT to conduct queries.

6. Incorporate the database within the new CD-ROM technology.

As with the first prototype, each of the suggestions made by the users could lead to a greatly enhanced and more powerful system. Suggestion 1 deals with the field constraint of DBASE IV of 254 characters because of the inability of VP-EXPERT to call files with memo fields. Possibly another expert system shell could perform this function, but the current version of VP-EXPERT is limited in this respect. A possible solution would be to continue the procedure's steps in additional 254 character fields which could also be called by the expert system. This would allow the procedures to be displayed in their entirety as per the technical manual.

Suggestion 2 could be implemented by including parts' stock numbers and drawing numbers in the Parts field of the

CORRECT file. The expert system could then call and display this field in addition to TProcedure.

Suggestion 3 is not practical using VP-EXPERT. While the system can incorporate graphic images and diagrams created in GMODE, its drawing function is primitive and only the simplest system drawing could be made. The detail required for serious troubleshooting is found in the technical manual or ship's drawings. VP-EXPERT is unable to call and display a graphic file such as .pcx. A simple line diagram displayed when a rule fires might provide some illustrative value for the user.

Suggestion 4 is a limitation of VP-EXPERT. Field names displayed as menu choices are truncated to 20 characters. Therefore, care must be taken to ensure a field that will be provided as a menu choice is as descriptive as possible within this constraint.

Suggestion 5 would lead to a truly powerful expert database system. VP-EXPERT is unable to invoke the database management system, and can only call a file as specified in the program. Data can be read in and out of the file, but all of the queries, menus, and separate applications available in a system such as DBASE IV cannot be accessed.

Suggestion 6 would be entirely feasible once the new CD-ROM technology and hardware is introduced to fleet units. CD-ROM offers a huge memory capacity in very little space, and opens many possibilities for the storage of technical libraries. Consideration would have to be given to the file

formats used, and their compatibility with an appropriate expert system shell such as VP-EXPERT. An expert database system using CD-ROM technology could bring the "paperless ship" concept to fruition.

The final opinion of the users who reviewed the second prototype was that there are definitely many useful possibilities for an expert database system in performing shipboard corrective maintenance. While the prototype is far from complete as a working system, it served its purpose by illustrating the potential value of automating the knowledge found in the technical manual and human experts.

C. LESSONS LEARNED

The study proved to be a success in demonstrating the feasibility and potential of using expert database technology to perform shipboard troubleshooting. Using VP-EXPERT and DBASE IV in a prototyping approach provided some valuable lessons.

1. Using VP-EXPERT

VP-EXPERT proved to be extremely simple to use, yet very powerful in its expert system capabilities. It was easily learned using its tutorial, and the manual was relatively clear and straight-forward. However, some important points were left out of the main text, and only included in the keyword reference. The examples provided were excellent and provided some useful additions to the program.

VP-EXPERT's inability to call database files with memo fields proved to be a major source of frustration when attempting to couple the expert system and database. This was not covered at all in the manual, and only resolved with a call for technical assistance from the vendor. It also proved to be a major limitation to the expert system and the database system design. It could have been resolved by including the desired text in the knowledge base, or by calling a separate text file containing the procedure. However, this would have defeated a large part of the purpose of the study to show the value of coupling to a database. Inclusion in the knowledge base or text files would make the input and update of these procedures a slow and tedious process, and simply not practical for shipboard use. The expert system program should stand alone and require few changes in the future. Technical procedures are subject to frequent updates, and if included in the knowledge base would require frequent tinkering with the program. A database management system is a more appropriate tool for data that requires frequent updating.

2. Using DBASE IV

DBASE IV proved to be a useful and easily learned system for implementing the Engineering Database Management System. The form, report, and menu generators allowed rapid custom design, and the applications generator saved a great deal of programming time. The design screens and manual were straight-forward and clear. Reference 6 proved extremely

useful also, and provided excellent examples for application development.

The only problems arose on several occasions when the system did some inexplicable actions such as switching from the catalog in use and failing to save several newly input records. Each of these occurred on several different sessions and can probably be attributed to "bugs" noted in the earlier versions of DBASE IV. Otherwise, the system was found to be ideal for implementing the simple applications used in this study.

3. Prototyping

Sponsorship of this study by SIMA, San Diego proved invaluable in the prototyping process. Because of frequent underway periods, it was not possible to use an actual ship for demonstrating the prototypes. However, since SIMA's primary mission is to assist ships with maintenance and repairs, their personnel were intimately familiar with all aspects of the equipment maintenance and operation, as well as the common practices found in the fleet. All of the sailors in the compressor shop had recently completed shipboard tours, and now work exclusively on ships homeported in San Diego. They proved to be an invaluable source of knowledge and insight into what would be useful in the shipboard environment. The entire command was exceptionally computer-literate at all levels, even the compressor shop had its own micro-computer tied into a local area network . The lowest

level technicians were conversant with micro-computer usage, and had definite ideas on what they liked and disliked.

Since a large measure of the feasibility and usefulness of this application depended on the reaction of the fleet sailor as its primary user, the prototyping approach was the only appropriate method of development. The approach lends itself well to expert systems development as a whole, regardless of the application. The result was a system that illustrated to the users the unique possibilities of using expert systems in the shipboard environment.

D. SUMMARY

The study proved to be a success in answering the primary question of whether an expert database system is a feasible tool for the performance of shipboard maintenance in U.S. Navy ships. The prototype illustrated the potential utility of such a system and was favorably received by fleet sailors. Limitations were found in the size of the field that VP-EXPERT could call, which may limit the potential of the current version of this particular shell for this application. However, the inclusion of technical documentation within a working database, and the coupling of this database to an expert system, showed great potential utility, regardless of the particular tools used.

APPENDIX A

THE EXPERT SYSTEM DECISION TREE

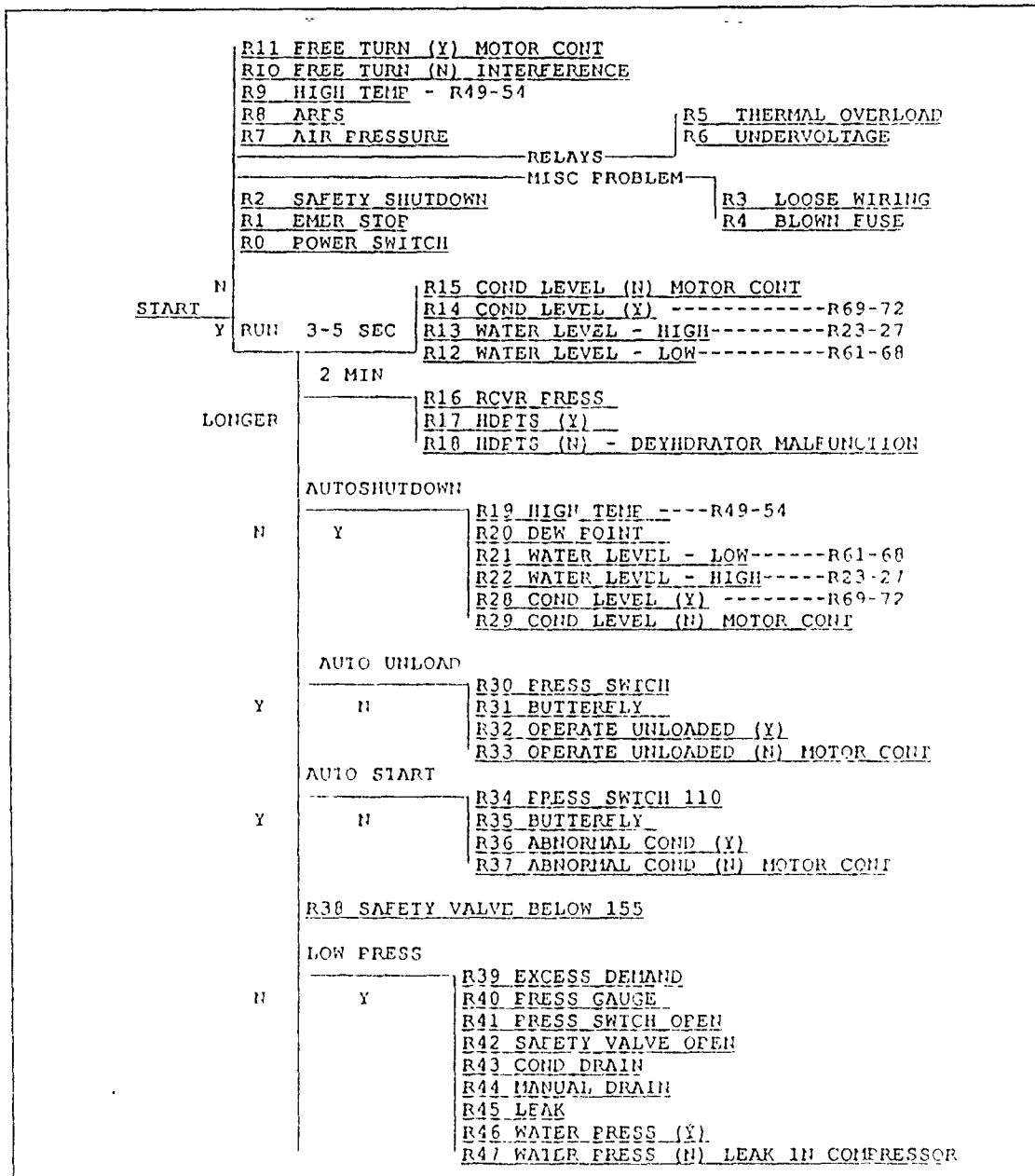


Figure A1 The Lpac Troubleshooter Decision Tree (part 1).

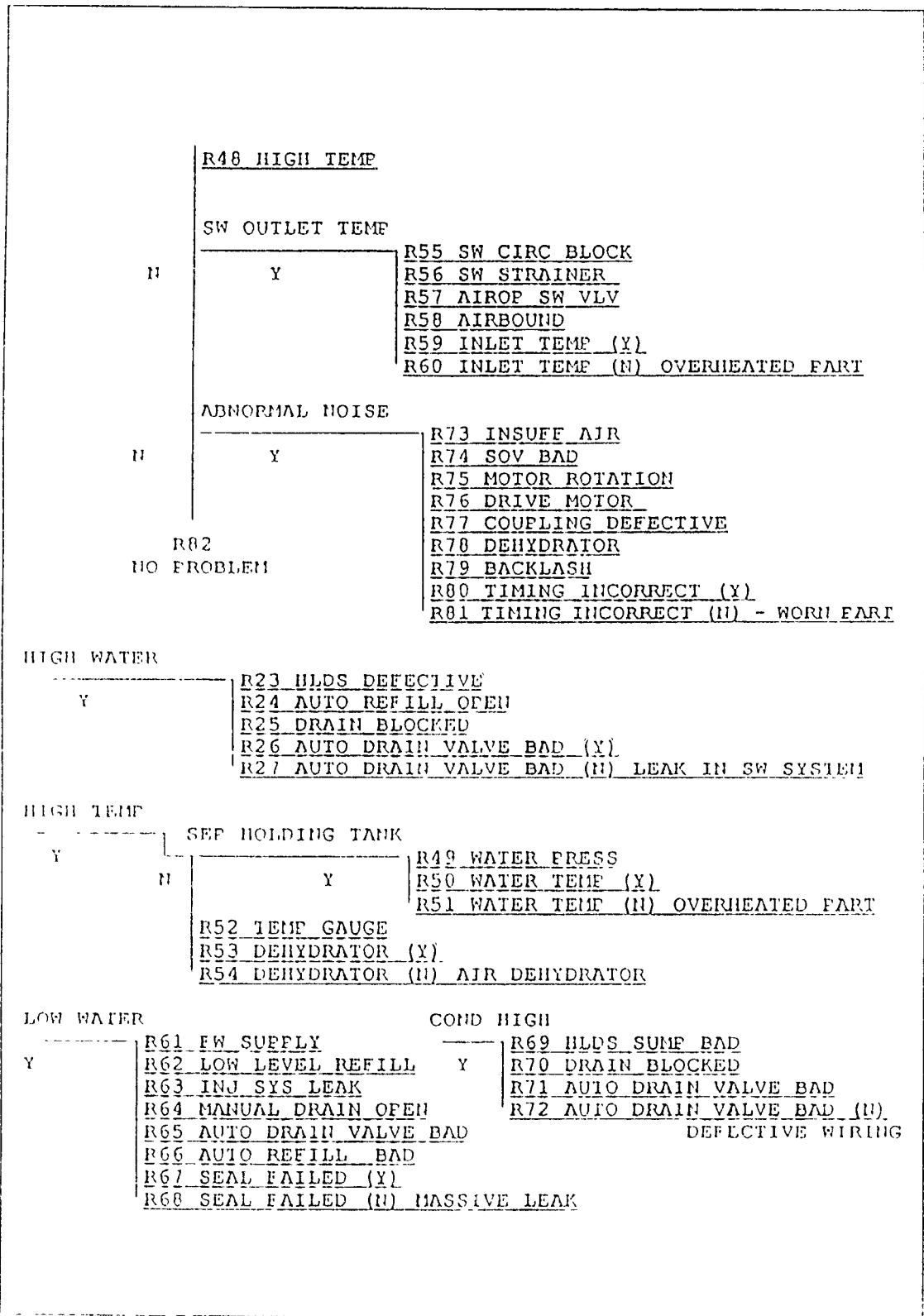


Figure A2 The Lpac Troubleshooter Decision Tree (part 2).

APPENDIX B

I. AN LPAC TROUBLESHOOTER CONSULTATION

A. OVERVIEW

This appendix is an example of a consultation using The LPAC Troubleshooter. The figures that follow are similar to the actual screen displays of a consultation as run on an IBM AT compatible personal computer. In this appendix, the choices which would normally be highlighted on the monitor screen have been shown in **bold and underlined** type.

The user must first access the VP-EXPERT program from DOS, and then consult the LPAC.kbs file. In an expanded shipboard system, there could be a separate file for each piece of equipment, each with its own KBS extension. For the purposes of this study, there is only one file available. Once the selected file is loaded, the user is guided through the introductory screens and then begins the consultation. The example provided in this appendix is a consultation for a compressor that starts, but shuts down automatically due to a high water level caused by a faulty high level drain switch. The reader may also find it helpful to refer back to the decision tree provided in Appendix A to trace the logic involved in each question of the consultation.

B. THE CONSULTATION

Figure B1 is VP-EXPERT's opening screen when executed from DOS with the executable command VPX. To begin the consultation the user can select 4Consult which is highlighted, by pressing either 4 or Enter. A list of filenames held will be displayed (this list can also be called by pressing 6Filename from the opening screen) as in Figure B2. Each application written in VP-EXPERT is categorized as a "knowledge base" and given the extension KBS. If applications were written for other equipment, they would be seen here if they reside in the main program. If applications are stored elsewhere, they can be called by selecting 7Path, and specifying the drive and directory. For The LPAC Troubleshooter application, the user should select LPAC.KBS.

Figure B3 shows the intermediate screen as the file is being loaded, and Figure B4 shows the blank control screen. At this point the user selects 2Go, which is highlighted, by pressing 2 or Enter. Figure B5 is the welcoming screen, and Figure B6 introduces the user to the system and gives basic instructions on how to select answers.

Figure B7 is the screen for the first question which the user answers Yes to show that the compressor starts. Figure B8 shows the next question to which the user responds Longer to show the compressor runs longer than two minutes. In Figure B9, the user responds Yes to show that an automatic shut down has occurred. By referring to Appendix A, it can be seen that

this response leads into the Autoshtutdown branch of the decision tree.

Figure B10 shows the first question of the Autoshtutdown branch, and the user has indicated No for the high temperature question. In Figure B11, the user again responds No to the high dew point question, and in Figure B12 high water in the separator holding tank has been identified as a symptom of the problem. Referring back to Appendix A at this point, it can be seen that this response leads to a separate tree for high water. In the program, this is achieved by the use of a separate WHILETRUE clause in the ACTIONS block. When Water Level=High, then this clause will fire a separate FIND High Water Solution.

Figure B13 instructs the user to continue the troubleshooting process to find the cause of the high water. Figure B14 is the first question of the high water tree, and the user responds Yes to indicate that the high level drain switch is defective. Figure B15 is the solution to the problem instructing the user to replace the switch.

In this particular example the solution may appear overly obvious, but the value of these systems are often in the preceding questions which triggered the user to check the switch. Once the cause of the problem has been identified, the solution is often obvious. This particular example took less than one minute to run, and the longest possible example has never taken more than two minutes. In actual troubleshooting

cases aboard ship, it is expected that consultations could take considerably longer since the machinery itself must be checked to make the determinations required to answer the questions. The time required for a consultation is considered to be well within the 20 minute envelope considered appropriate for expert system applications.

<p style="text-align: center;"> VP-EXPERT Version 2.1 Copyright (c) 1988 By Brian Sawyer All Rights Reserved Editor Portion Copyright (c) 1984,1985,1987, Idea Ware Inc Published by Paperback Software International </p>	
RULES	FACTS
<p> 1Help 2Induce 3Edit 4Consult 5Tree 6Filename 7Path 8Quit 1Help 2Go 3Whatif 4Variable 5Rule 7Set 8Edit 9Quit </p>	

Figure B1 VP-EXPERT's opening screen.

<p style="text-align: center;"> VP-EXPERT Version 2.1 Copyright (c) 1988 By Brian Sawyer All Rights Reserved Editor Portion Copyright (c) 1984, 1985, 1987, Idea Ware </p>	
FILES	
Choose a file:	
<u>LPAC.KBS</u>	
<p> 1Help 2Induce 3Edit 4Consult 5Tree6Filename7Path 8Quit 1Help 2Go 3Whatif 4Variable 5Rule 7Set 8Edit 9Quit </p>	

Figure B2 VP-EXPERT's screen listing available knowledge bases.

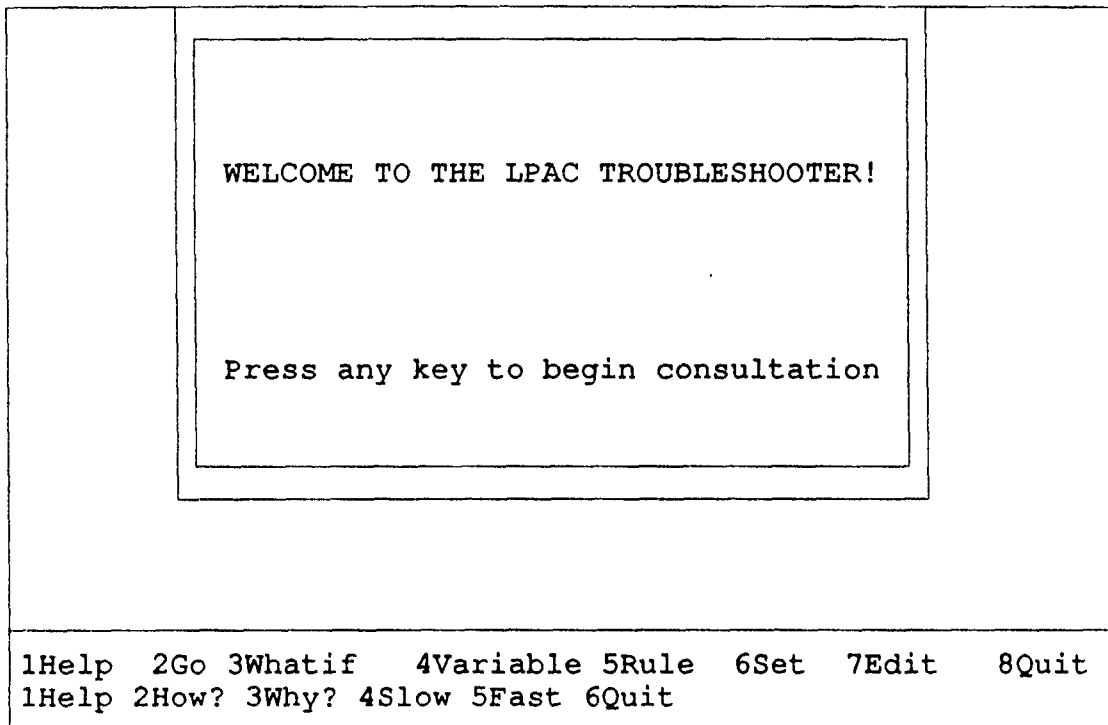


Figure B5 The LPAC Troubleshooter welcoming screen.

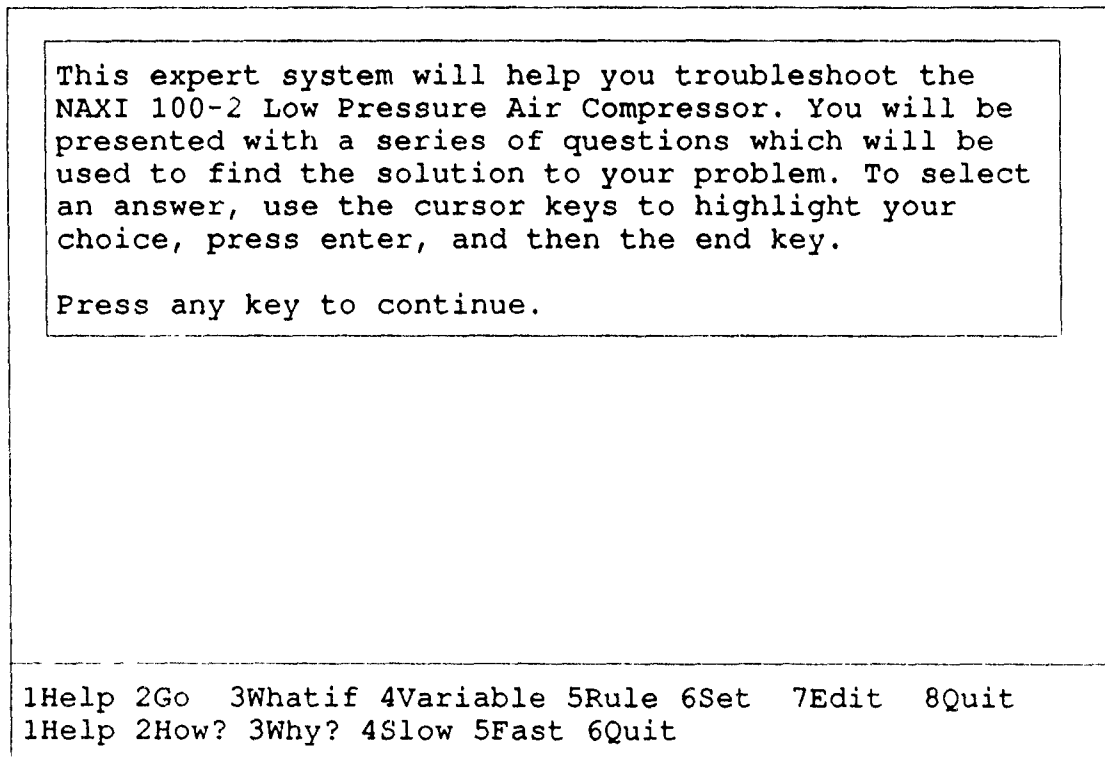


Figure B6 The introduction and instruction screen.

Does the compressor start when manually turned on?
Yes No

Enter to select END to complete /Q to Quit ? for Unknown

Figure B7 The first question with yes selected.

Does the compressor start when manually turned on?
Yes No

How long does the compressor run before stopping?
3-5 Secs 2 Min Longer

Enter to select END to complete /Q to Quit ? for Unknown

Figure B8 The second question with Longer than 2 Min selected.

Does the compressor start when manually turned on?		
<u>Yes</u>		No
How long does the compressor run before stopping?		
3-5 Secs	2 Min	<u>Longer</u>
Has compressor automatically shut down with remote alarm?		
<u>Yes</u>		No
Enter to select END to complete /Q to Quit ? for Unknown		

Figure B9 The third question with Yes selected for autoshtutdown.

How long does the compressor run before stopping?		
3-5 Secs	2 Min	<u>Longer</u>
Has compressor automatically shut down with remote alarm?		
<u>Yes</u>		No
Is the compressor air discharge temperature above 160.deg?		
Yes		<u>No</u>
Enter to select END to complete /Q to Quit ? for Unknown		

Figure B10 The fourth question with No selected for high temp.

Has compressor automatically shut down with remote alarm?	
<u>Yes</u>	No
Is the compressor air discharge temperature above 160.deg?	
Yes	<u>No</u>
Is the dehydrator dew point temperature above 65 deg?	
Yes	<u>No</u>
Enter to select END to complete /Q to Quit ? for Unknown	

Figure B11 The fifth question with No selected for dew point.

Is the compressor air discharge temperature above 160.deg?		
Yes	<u>No</u>	
Is the dehydrator dew point temperature above 65 deg?		
Yes	<u>No</u>	
Check the water level in the separator holding tank. Is it high or low?		
<u>High</u>	Low	Normal
Enter to select END to complete /Q to Quit ? for Unknown		

Figure B12 The sixth question with high water selected.

Troubleshoot to correct cause of high water.

Press any key to conclude consultation

Figure B13 Instruction to continue troubleshooting high water.

Is the high level drain switch in the holding tank
defective?

Yes

No

Enter to select END to complete /Q to Quit ? for Unknown

Figure B14 Selecting Yes for high level drain switch defective.

Service or replace high level switch.

Press any key to conclude consultation

Figure B15 The final screen identifying the solution.

APPENDIX C

THE SHIPBOARD MAINTENANCE DATABASE

I. OBJECT DIAGRAMS

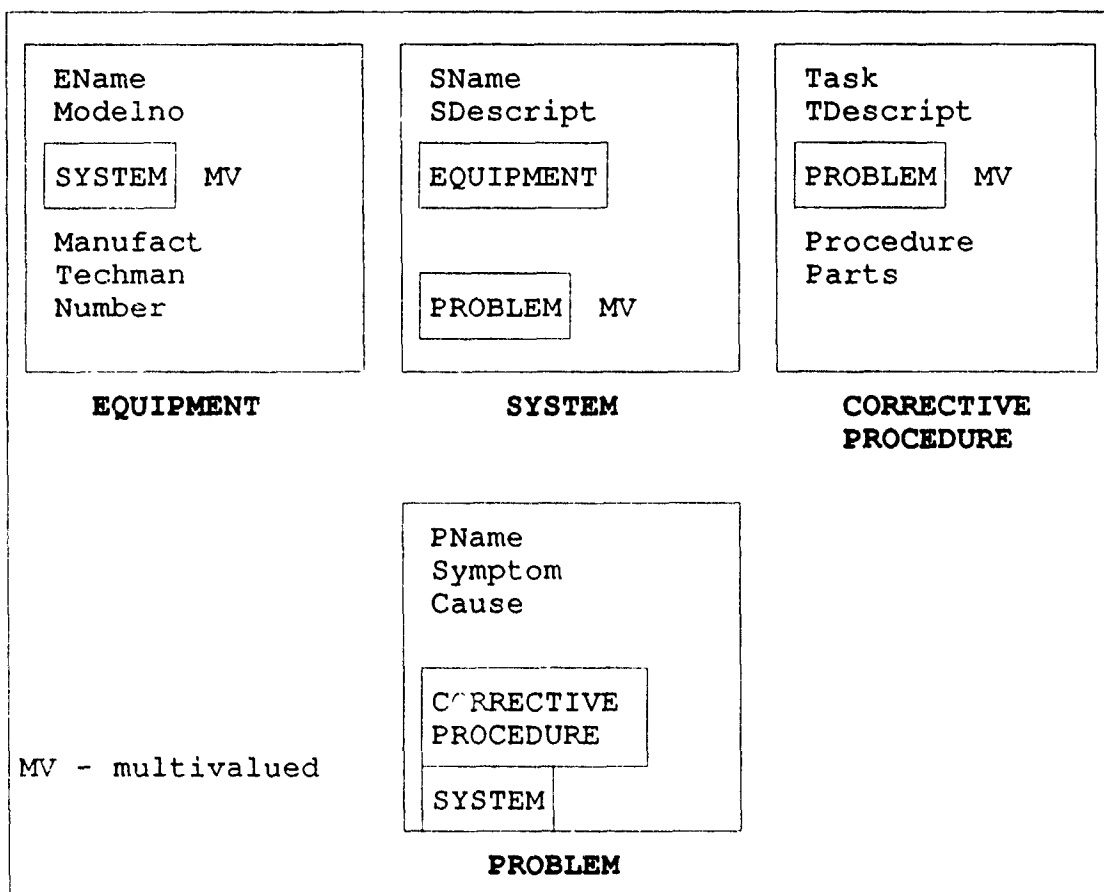


Figure C1. Engineering Maintenance Database System object diagrams.

II. OBJECT SPECIFICATIONS

A. OBJECT DEFINITIONS

1. Equipment Object

EName; Equipment names
Modelno; Equipment model numbers
SYSTEM; SYSTEM object; SUBSET [SNAME] MV
Manufact; Manufacturer's name
Techman; technical manual number
Number; number of units

2. System Object

SName; System names
SDescript; System purpose
EQUIPMENT; EQUIPMENT object; SUBSET [EName]
PROBLEM; PROBLEM object; SUBSET [PNAME] MV

3. Corrective Procedure Object

Task; Task name
TDescript; Action performed
Procedure; Corrective procedures
PROBLEM; PROBLEM object; SUBSET [PName] MV
Parts; Equipment parts MV

4. Problem Object

PName; Problem name
Symptom; Problem symptoms
Cause; Cause of problem
SYSTEM; SYSTEM object; SUBSET [SName]
CORRECTIVE PROCEDURE; CORRECTIVE PROCEDURE object,
SUBSET [Task]

B. DOMAIN DEFINITIONS

1. **Cause**
Text 100
What is causing the problem
2. **EName**
Text 30
Name of a specific piece of equipment
3. **Manufact**
Text 30
Name of the manufacturer
4. **Modelno**
Text 15
Unique alpha-numeric combination identifying the equipment
5. **Number**
Numeric 2
The number of units of an equipment found aboard ship
6. **Parts**
Text 100
A list of parts required to perform the task. Each part given by technical manual figure/index number.
7. **PName**
Text 50
The name of the problem in a piece of equipment
8. **SDescript**
Text 250
A brief description of the purpose and function of a system
9. **SName**
Text 30
Name of a system found in a piece of equipment
10. **Symptom**
Text 100
A description of the symptoms of the problem
11. **Task**
Text 30
The corrective maintenance job to be performed

12. TDescript

Text 100

A brief description of the task

13. Techman

Text 16

An alphanumeric combination of the NAVSEA technical manual number

14. Procedure

Memo

This field references a separate text file containing the detailed steps to perform a corrective maintenance task.

III. DATAFLOW DIAGRAMS

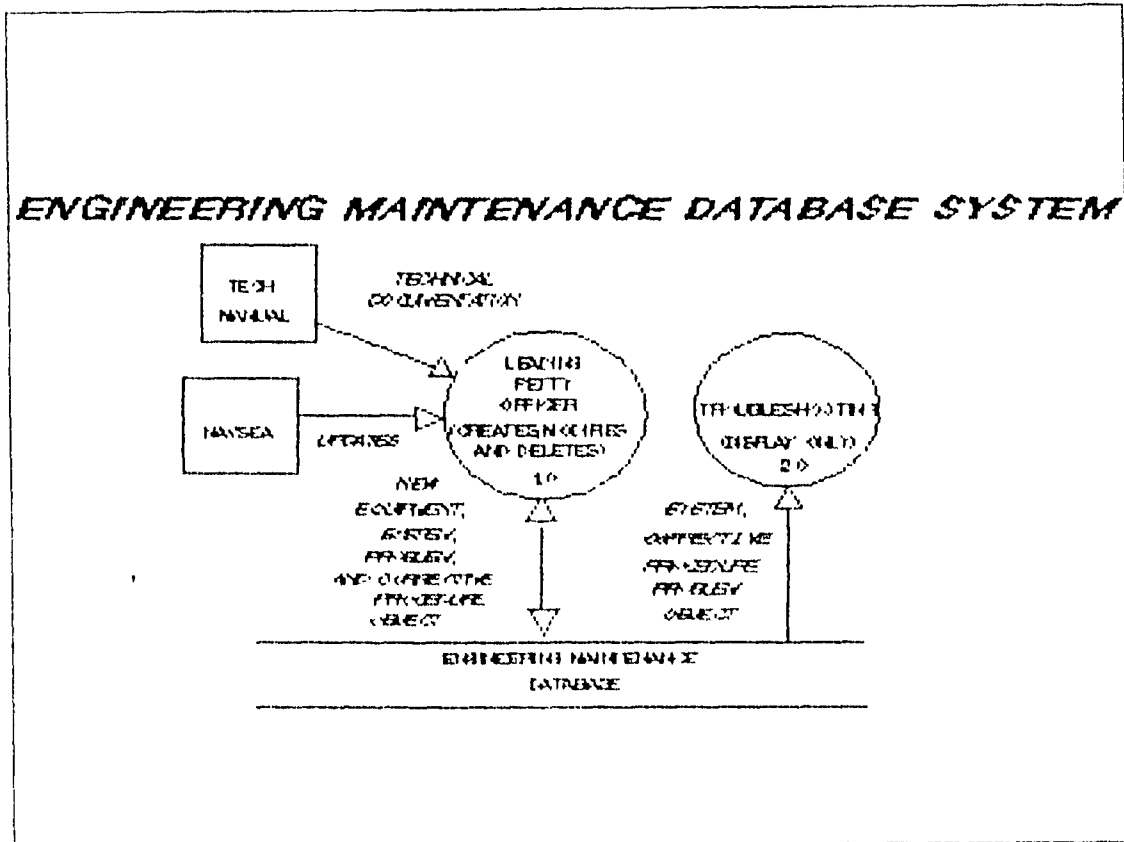


Figure C2 The Engineering Maintenance Database System Dataflow Diagram

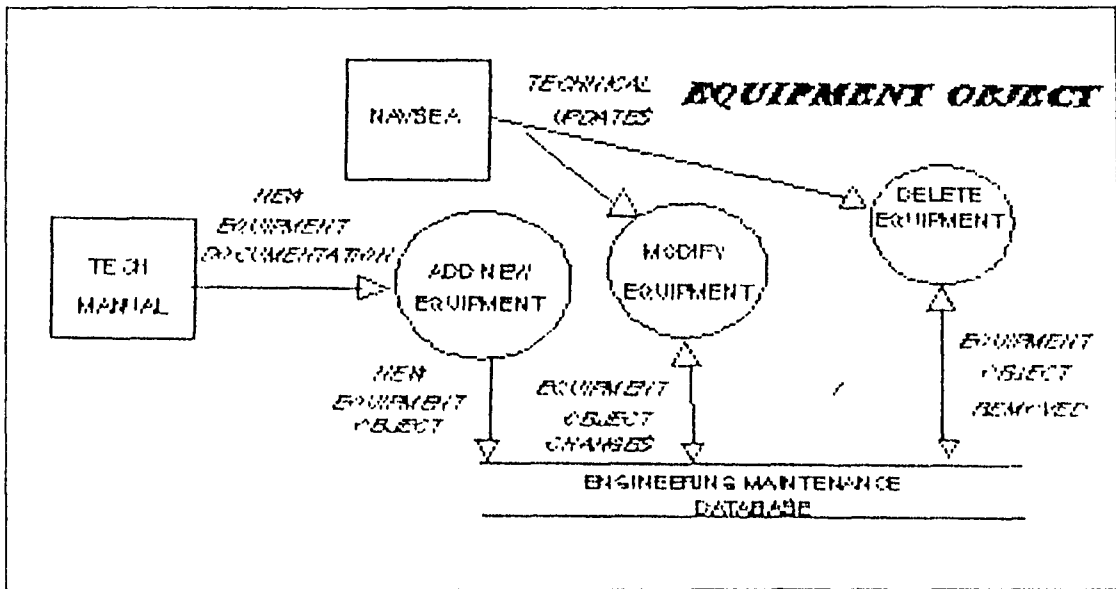


Figure C3 The EQUIPMENT Object Dataflow Diagram.

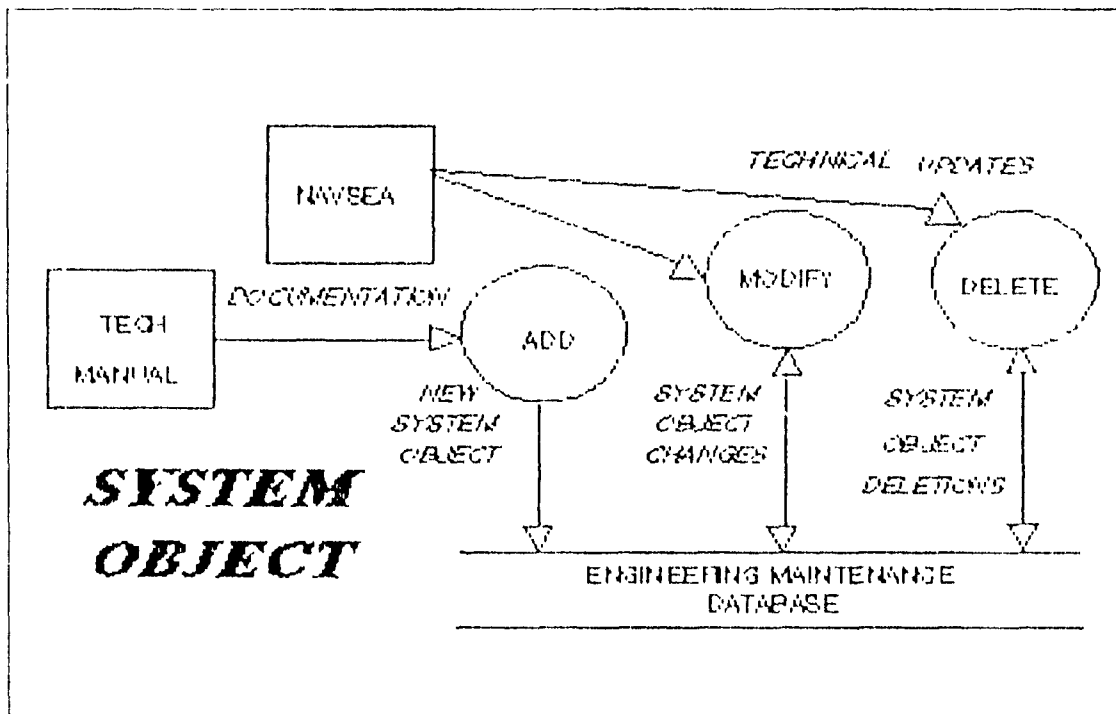


Figure C4 The SYSTEM Object Dataflow Diagram.

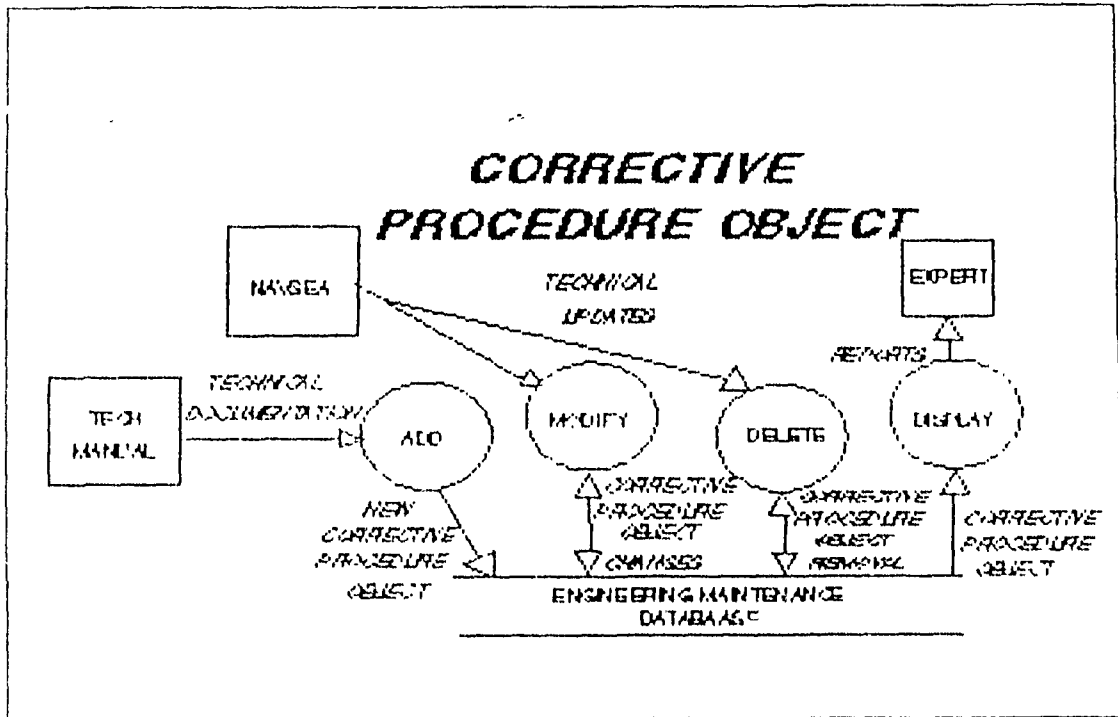


Figure C5 The Corrective Procedure Object Dataflow Diagram

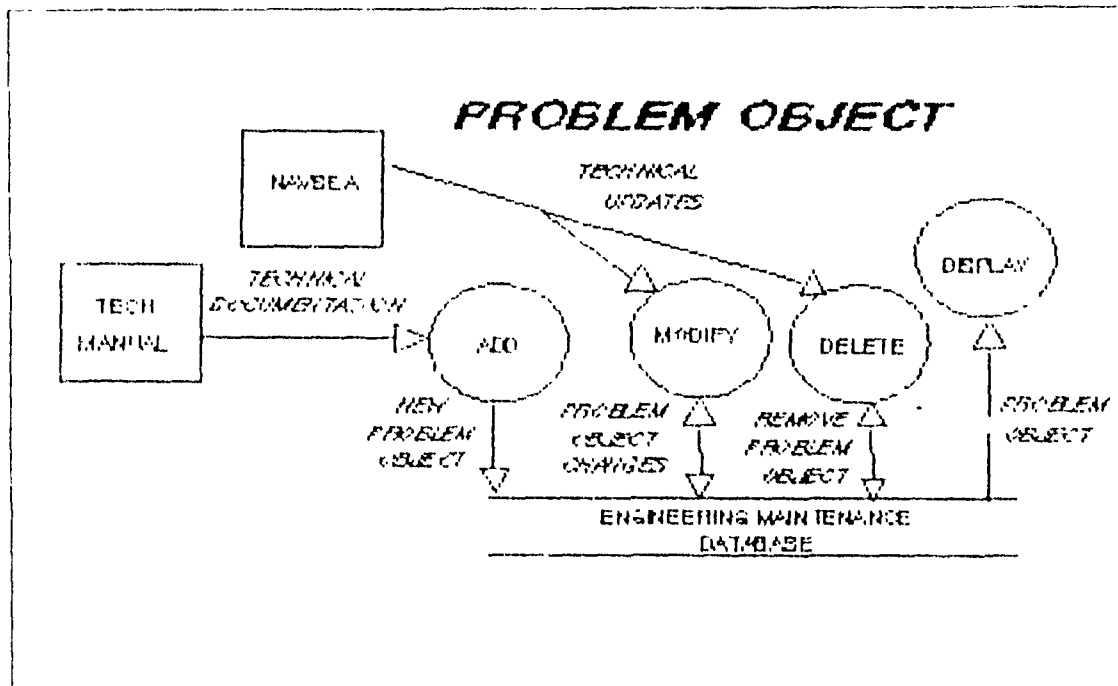


Figure C6 The PROBLEM Object Dataflow Diagram.

IV. UPDATE, DISPLAY AND CONTROL MECHANISMS

A. LEADING PETTY OFFICER APPLICATION

1. Update Mechanisms

a. Add *EQUIPMENT, SYSTEM, CORRECTIVE PROCEDURE, and PROBLEM Data*

- (1) Inputs. New equipment technical manuals.
- (2) Outputs. New *EQUIPMENT, SYSTEM, CORRECTIVE PROCEDURE*, and *PROBLEM* object instances in database.
- (3) Frequency. As new equipment arrives.

b. Edit *EQUIPMENT, SYSTEM, CORRECTIVE PROCEDURE, and PROBLEM Data*

- (1) Inputs. Technical updates from NAVSEA.
- (2) Outputs. Modified object instances in the database.
- (3) Frequency. As updates are received.

2. Display Mechanisms

a. Query on *EQUIPMENT, SYSTEM, CORRECTIVE PROCEDURE, and PROBLEM*

- (1) Output Description. Forms showing all object data.
- (2) Source Data. Objects; equipment, system, corrective procedure, or problem names keyed in by user.
- (3) Processing Notes. Used by LPO, CPO, or DIVO.
- (4) Frequency. As required.

b. *Equipment Technical Manual List*

- (1) Output Description. A report showing all *EQUIPMENT* object instances and their respective technical manuals.
- (2) Source Data. *EQUIPMENT* object; keyed request for equipment report.
- (3) Processing notes. Used to validate technical library.
- (4) Frequency. Quarterly.

3. Control Mechanism - access by password.

B. TROUBLESHOOTING APPLICATION

1. **Update Mechanisms** - none.

2. **Display Mechanisms**

a. **Query on EQUIPMENT, SYSTEM, CORRECTIVE PROCEDURE, and PROBLEM**

(1) Output Description. Forms showing all object data.

(2) Source Data. Objects; equipment, system, corrective procedure, or problem names keyed in by user.

(3) Processing Notes. Used by LPO, CPO, or DIVO.

(4) Frequency. As required.

b. **Problems by Symptom Report**

(1) Output Description. A report showing all problems for a given symptom and their corrective procedure tasks.

(2) Source Data. CORRECTIVE PROCEDURE and PROBLEM objects; keyed request for problems by symptom report.

(3) Processing Notes. Used by maintenance technician for troubleshooting equipment.

(4) Frequency. As required to troubleshoot.

c. **Problems by System Report.**

(1) Output Description. A report showing all problems for a given system and their corrective procedure tasks.

(2) Source Data. SYSTEM, CORRECTIVE PROCEDURE and PROBLEM objects; keyed request for problems by system report.

(3) Processing Notes. Used by maintenance technician for troubleshooting equipment.

(4) Frequency. As required to troubleshoot.

d. **Corrective Procedure Report**

(1) Output Description. A report showing the corrective procedure for a problem.

(2) Source Data. CORRECTIVE PROCEDURE and PROBLEM objects; keyed request for corrective procedure report.

(3) Processing Notes. Used by maintenance technician for troubleshooting equipment.

(4) Frequency - as required to troubleshoot.

III. RELATIONAL DIAGRAM

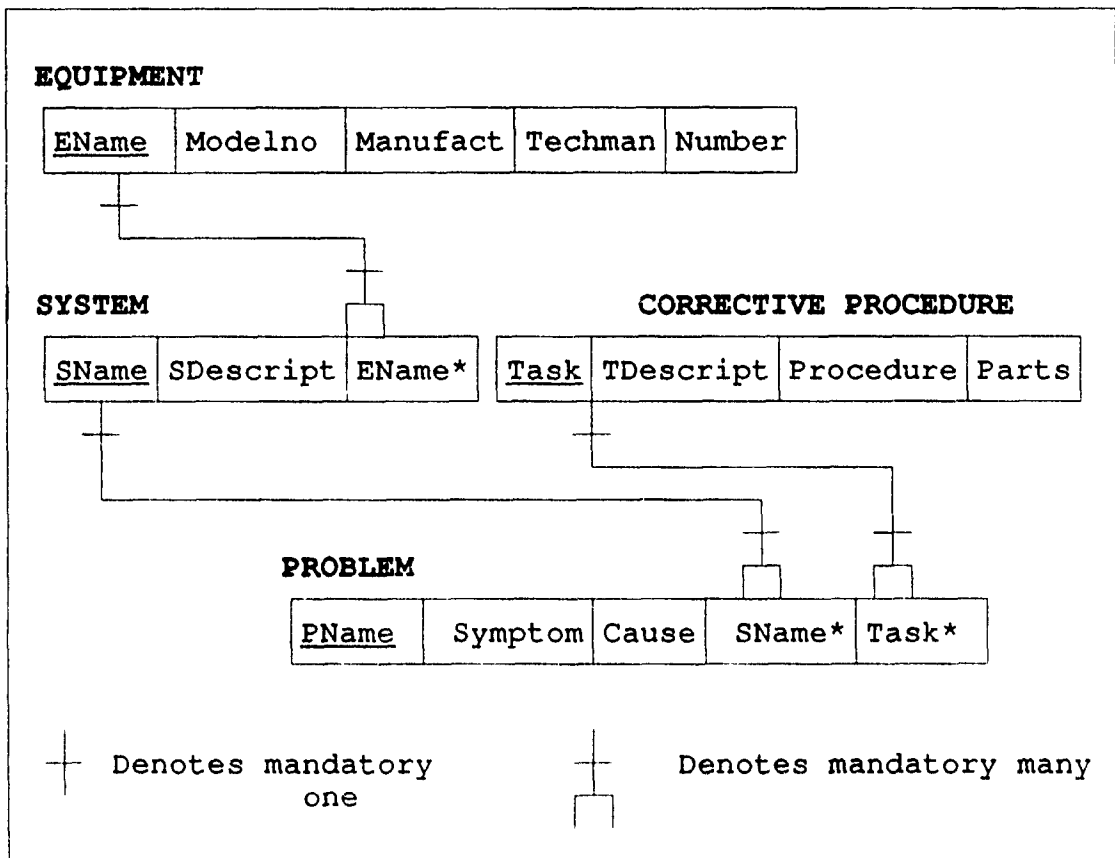


Figure C7 Engineering Maintenance Database System

Table C1. Relation Definitions

EQUIPMENT			SYSTEM			CORRECTIVE PROCEDURE			PROBLEM		
Item	L	T	Item	L	T	Item	L	T	Item	L	T
EName	30	t	SName	30	t	Task	30	t	PName	50	t
Modelno	15	t	SDescript	250	t	TDescript	100	t	Symptom	100	t
Manufact	30	t	EName	30	t	PName	50	t	Cause	100	t
Techman	16	t	PName	50	t	Procedure	U	m	Task	50	t
Number	2	n				Parts	100	t	SName	30	t

L=LENGTH T=TYPE t=Text n=Numeric U=Unlimited m=Memo

VI. FORMS, REPORTS AND MENUS

EQUIPMENT DATA		
XXXXXXXXXXXXXXXXXXXXX NAME	XXXXXXXXXXXXXXXXXXXXX MODEL NUMBER	XXXXXXXXXXXXXXXXXXXXX MANUFACTURER
XXXXXXXXXXXXXXXXXXXXX TECHNICAL MANUAL	XXX NUMBER ONBOARD	
SYSTEM DATA		
XXXXXXXXXXXXXXXXXXXXX NAME	XXX DESCRIPTION	
CORRECTIVE PROCEDURE DATA		
XXXXXXXXXXXXXXXXXXXXX TASK	XXX DESCRIPTION	
XXXX PROCEDURE (MEMO)	XXX PARTS	
PROBLEM DATA		
XXXXXXXXXX*XXXXXXX NAME	XXXXXXXXXXXXXXXXXXXXX SYMPTOM	XXXXXXXXXXXXXXXXXXXXX CAUSE

Figure C8 Leading Petty Officer Update Forms.

Enter name of **EQUIPMENT** to delete: XXXXXXXXXXXXXXXXXXXXXXXX

This is the record for the equipment:

XXXXXXXXXXXXXXXXXXXXX XXXXXXXXXXXXXXXX XXXXXXXXXXXXXXXXXXXXXXXX
Equipment name Model number Technical manual

Is this the correct equipment to delete? (Y/N)

Figure C9 Form for Deleting EQUIPMENT.

<u>PROBLEMS BY SYSTEM</u>		
<u>SYSTEM</u>	<u>PROBLEM</u>	<u>CORRECTIVE PROCEDURE</u>
<u>PROBLEMS BY SYMPTOM</u>		
<u>SYMPTOM</u>	<u>PROBLEM</u>	<u>CORRECTIVE PROCEDURE</u>

Figure C10 Troubleshooting Reports of Problems

TASK:
DESCRIPTION:
PROBLEMS CORRECTED:
PROCEDURE:
PARTS REQUIRED:

Figure C11 Troubleshooting Corrective Procedure Report.

Table C2. Database Schema.

DATA \ APPLICATION	LEADING PETTY OFFICER	TROUBLESHOOTING
EQUIPMENT	X	
SYSTEM	X	X
CORRECTIVE PROCEDURE	X	X
PROBLEM	X	X

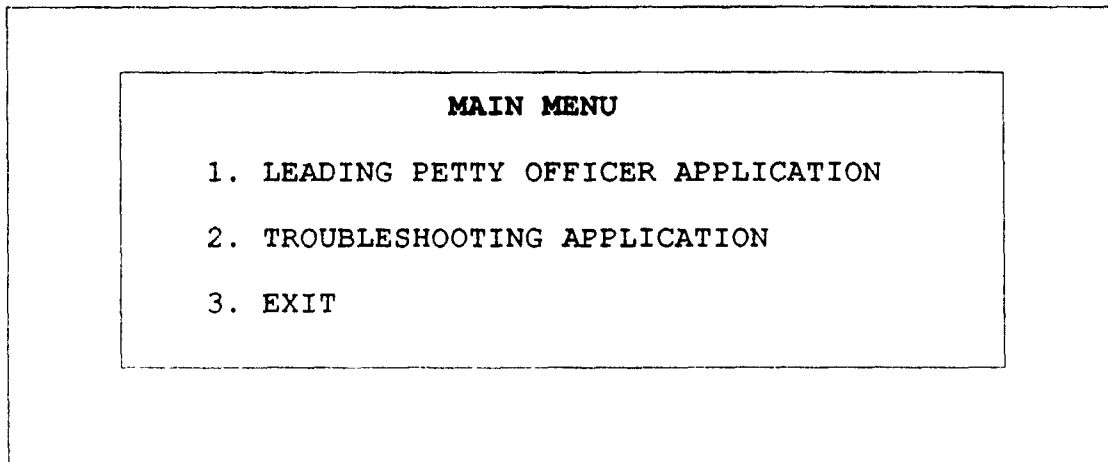


Figure C12 The Engineering Maintenance Database Main Menu.

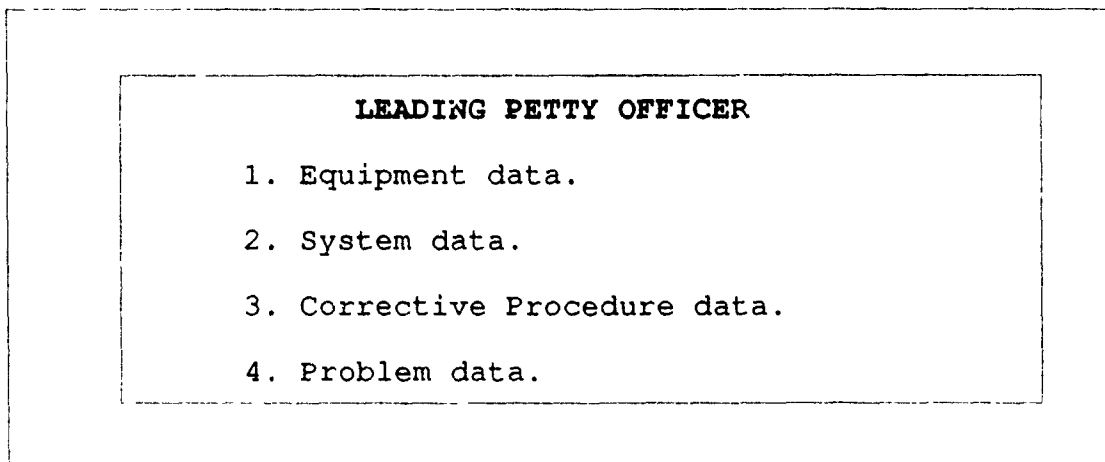


Figure C13 The Leading Petty Officer First Level Menu.

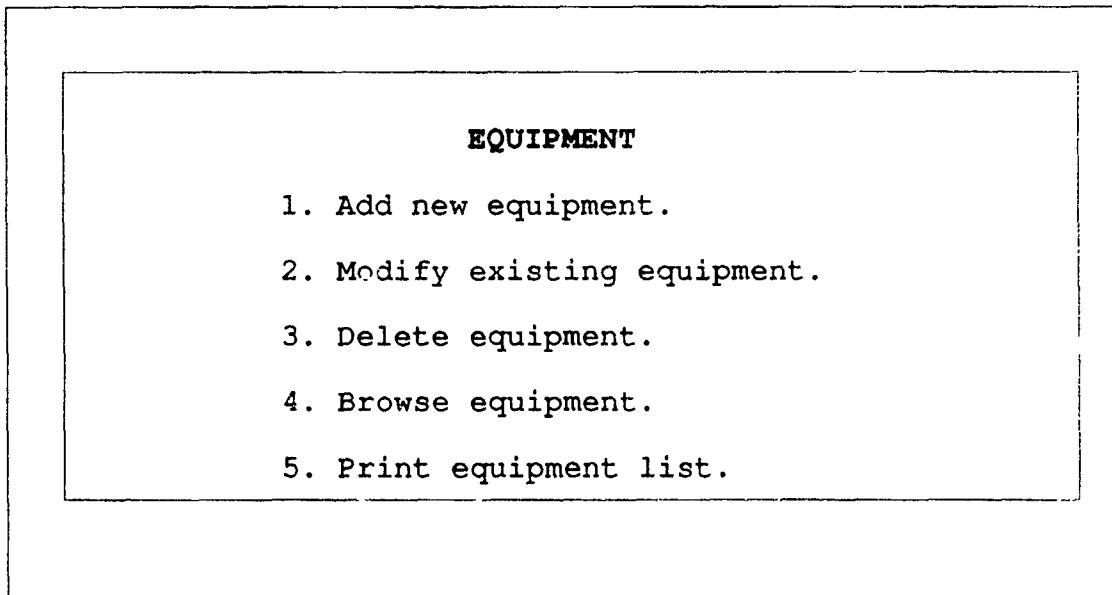


Figure C14 The Leading Petty Officer Second Level Menu for Equipment.

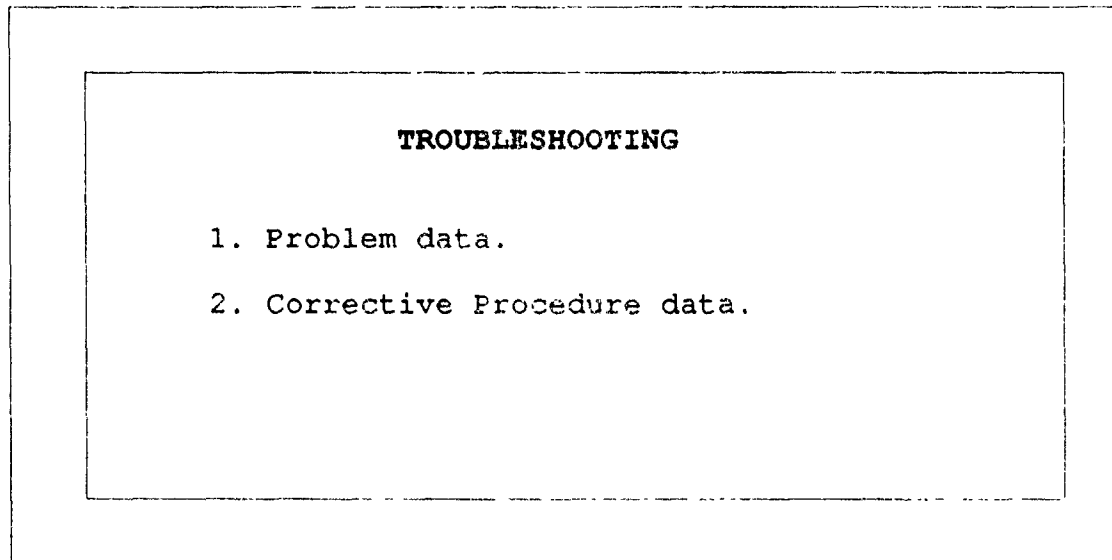


Figure C15 The Troubleshooting Application First Level Menu

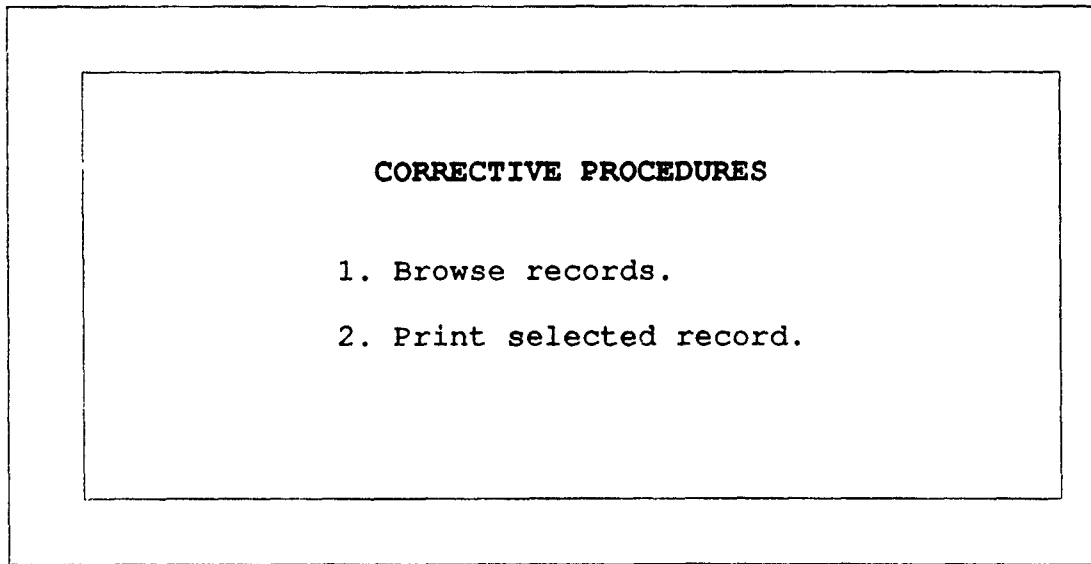


Figure C16. The Second Level Troubleshooting Menu for Corrective Procedures.

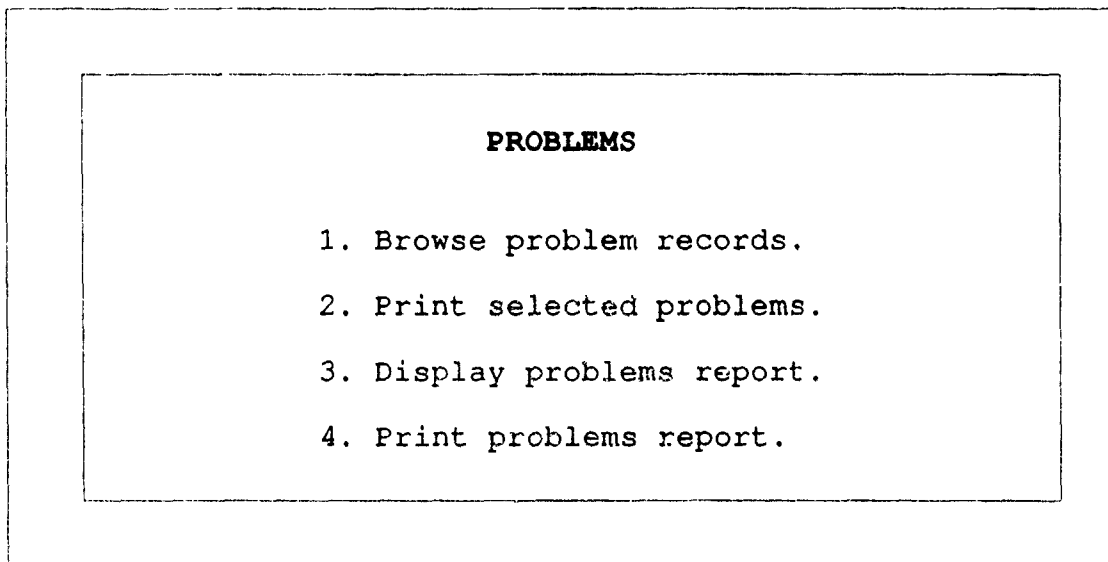


Figure C17 The Second Level Troubleshooting Menu for Problems.

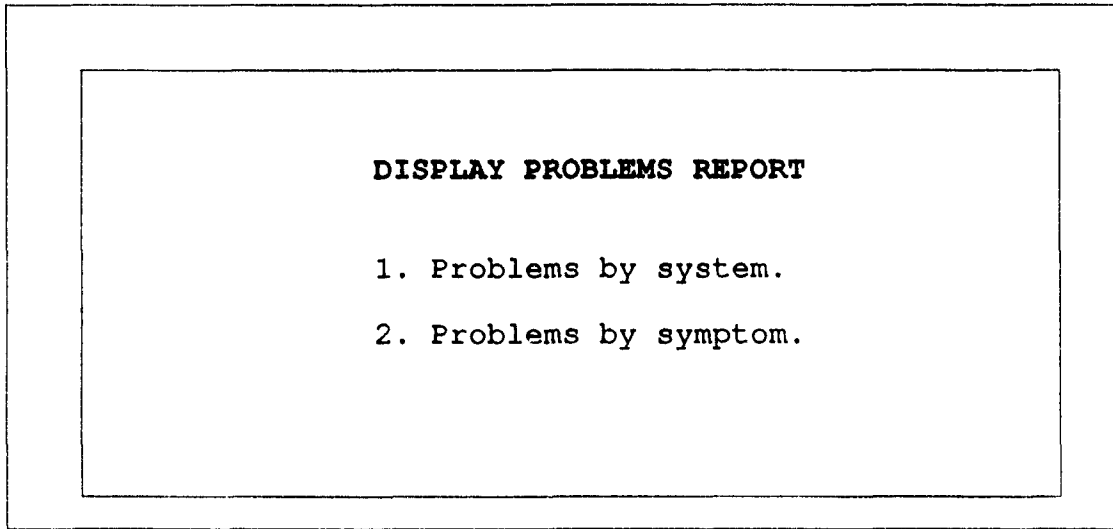


Figure C18. The Third Level Troubleshooting Menu for Display Problems Report.

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