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VAPOR COMPRESSION DISTILLATION SUBSYSTEM (VCDS) COMPONENT ENHANCEMENT, TESTING AND EXPERT FAULT DIAGNOSTICS DEVELOPMENT

FINAL REPORT

Volume II

by

E.S. Mallinak

December, 1987

Prepared Under Contract NAS9-16374

by

Life Systems, Inc.
Cleveland, OH 44122

for

LYNDON B. JOHNSON SPACE CENTER
National Aeronautics and Space Administration

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DEVELOPMENT OF AN ADVANCED PREPROTOTYPE VAPOR COMPRESSION DISTILLATION SUBSYSTEM (VCDS) FOR WATER RECOVERY

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FOREWORD

The development work described herein was conducted by Life Systems, Inc. during the period June, 1984 to December, 1987. The Program Managers were Ed Zdankiewicz who completed the major portion of the program followed by Ed Mallinak completing the expert fault diagnostic development and final efforts. Technical support was provided by the following:

Personnel	Responsibility
Jeff Birkel	Electrical Software Design
David Case	Electrical Technician
James Chu	Mechanical Design and Testing
Steve Czernec	Mechanical Technician and Test Support
John O. Jessup	Electrical Hardware Design and Fabrication
Licia S. Kovach	Testing Analysis and Documentation
Earl Linaburg	Hardware Fabrication and Purchasing
Ed Mallinak	Expert Fault Diagnostics Development and Program Management
Dave Novak	Mechanical Design
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Bob Roski	Hardware Fabrication and Purchasing
Dorothy Ruschak	Contract Administration
Franz H. Schubert	Product Technology
Lowell Wolfe	Chemical Analysis and Testing
Dan Walter	Mechanical Design
Rob Werner	Mechanical Design
Rick A. Wynveen, Ph.D.	Business Manager, Cost and Schedule Conformance
Ed Zdankiewicz	Mechanical Design, Fabrication, Testing and Program Management

The Final Report consists of two stand-alone documents. This document is Volume II. It describes the work performed in expert fault diagnostic development for the Vapor Compression Distillation Subsystem.

The Final Report is submitted to the National Aeronautics and Space Administration Johnson Space Center as required by Statement of Work Task 15.2e of Life Systems, Inc.'s Program Plan, TR-471-22D, dated September 13, 1985. The Technical Monitor of the program was Mr. Don F. Price, Crew Systems Division, National Aeronautics and Space Administration, Johnson Space Center, Houston, TX.

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APCCS	Atmosphere Pressure and Composition Control System
ARS	Air Revitalization System
C/M I	Control/Monitor Instrumentation
ECLSS	Environmental Control and Life Support System
EFD	Expert Fault Diagnostic
EVA	Extravehicular Activity
FMEA	Failure Mode and Effects Analysis
MCV	Microbial Check Valve
ORU	Orbital Replacement Unit
PCA	Pressure Control Assembly
PL/M	Programming Language/Microcomputers
THCS	Temperature and Humidity Control System
VCD	Vapor Compression Distillation
VCDS	Vapor Compression Distillation Subsystem
VCD2B	Vapor Compression Distillation, Enhanced Advanced Preprototype Configuration
VPI	Valve Position Indicator
WMS	Water Management System
WRS	Water Reclamation System

SUMMARY

A wide variety of Space Station functions will be managed via computerized controls. Many of these functions are at the same time very complex and very critical to the operation of the Space Station. The Environmental Control and Life Support System is one group of very complex and critical subsystems which directly affects the ability of the crew to perform their mission. Failures of the Environmental Control and Life Support Subsystems are to be avoided and, in the event of a failure, repair must be effected as rapidly as possible. Due to the complex and diverse nature of the subsystems, it is not possible to train the Space Station crew to be experts in the operation of all of the subsystems. By applying the concepts of computer-based expert systems, it may be possible to provide the necessary expertise for those subsystems in dedicated controllers. In this way, an expert system could avoid failures and extend the operating time of the subsystems even in the event of failure of some components, and could reduce the time to repair by being able to pinpoint the cause of a failure when one cannot be avoided.

A study was undertaken by Life Systems, Inc. to investigate the application of expert system concepts to fault diagnosis on Environmental Control and Life Support subsystems. An operating water recovery subsystem, Vapor Compression Distillation, was used as the specific example in the study. A detailed fault analysis was prepared and methods of applying expert system concepts were developed. An auxiliary computer was used in a demonstration of these concepts with an operating Vapor Compression Distillation Subsystem. Six examples were successfully executed with the subsystem, illustrating that all of the areas of fault diagnosis could be addressed with a computer-based expert system. The demonstration examples were recorded on video tape. Finally, an analysis of the potential application of these expert fault diagnostic concepts to other Environmental Control and Life Support Subsystems was performed. It showed that there is a great deal of similarity among the subsystems and, therefore, an anticipated high degree of applicability to all the subsystems in that group.

INTRODUCTION

The subsystems being developed for the Environmental Control and Life Support System (ECLSS) of the Space Station are designed to be low maintenance, long life, self-regulating units which would require little attention by the crew in normal operation. As a result, the crew would be ill-prepared to deal with extraordinary occurrences that could be potentially mission-threatening.

The complexity of the subsystems makes fault diagnosis and repair a job for an expert. Rather than trying to train a crew to be experts on all such subsystems, artificial intelligence in the form of an Expert Fault Diagnostic (EFD) system would be a preferred alternative. Such a system could constantly monitor the processes and recognize faults, or potential fault conditions, and apply the knowledge of a process expert to avoid, mitigate or at least pinpoint the cause of such faults. In the area of ECLSS, extension of operating time in the face of component failures can be especially important.

Project Goals

The program was set up to study the possible application of expert system concepts to fault diagnosis on a Vapor Compression Distillation Subsystem (VCDS). The subsystem was to be analyzed to incorporate the VCDS developer's fault diagnostic knowledge into a set of expert rules. Application of these rules could then improve the reliability, efficiency and maintainability of the VCDS. In addition, an analysis of the applicability of generic portions of the VCDS expert rules to another ECLSS was to be performed.

Program Accomplishments

A detailed analysis of the Vapor Compression Distillation (VCD) process (see Figure 1), its components and failure modes, resulted in a series of fault trees identifying more than 500 specific faults. From these fault trees, expert rules were developed specifying the logic used by an expert in avoiding, preventing, detecting, isolating, correcting and tolerating each type of fault. A demonstration of these expert rules was developed on an auxiliary computer interfacing in real time with an operating VCDS. Six examples were selected and successfully implemented to illustrate the application of the EFD concept at every level of fault management. A video tape of the examples was prepared.

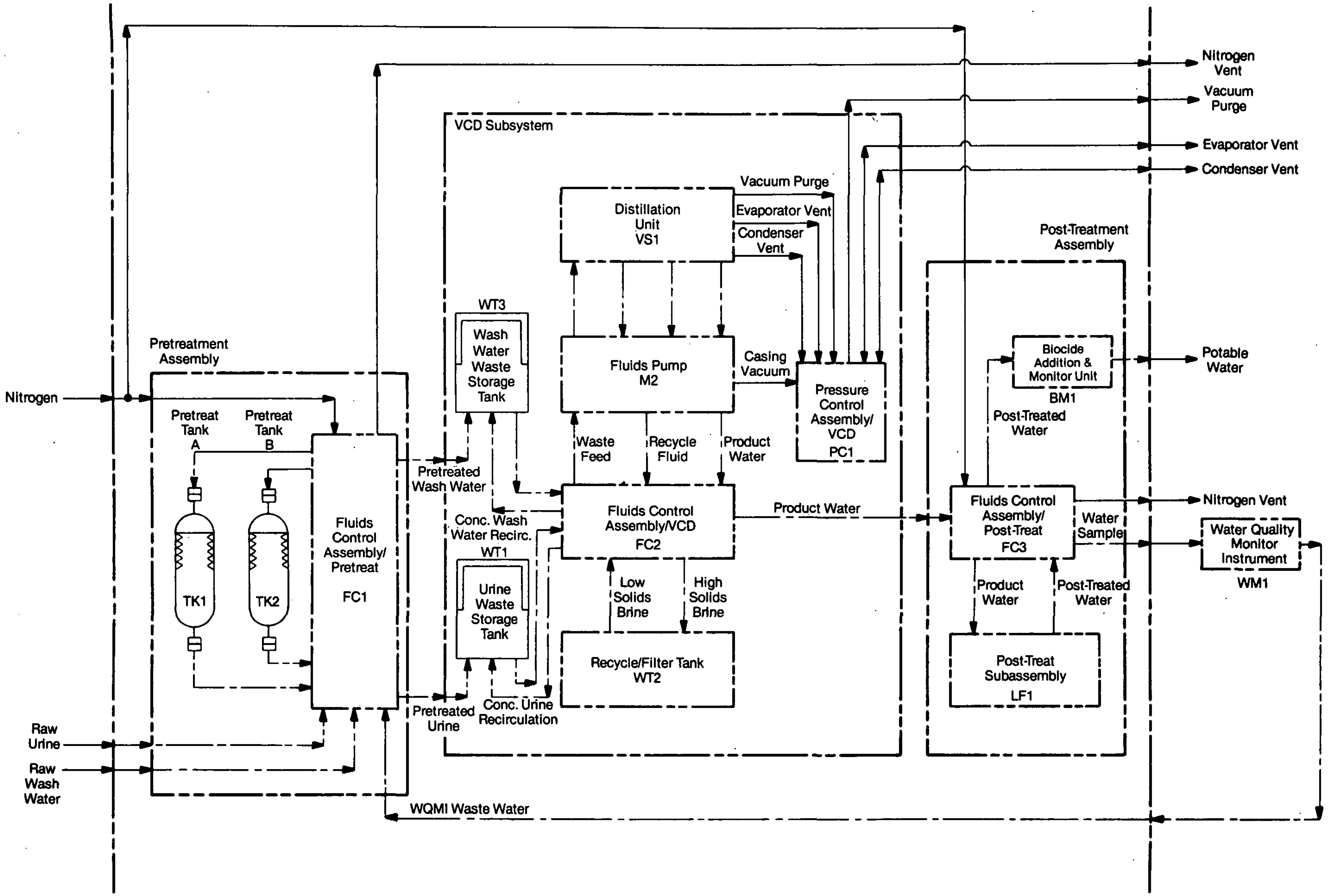
Other subsystems of the ECLSS were analyzed to identify components similar to those on the VCDS where the developed expert rules could also be applied. Such components were found in every ECLSS, showing that the EFD concept has wide applicability. Additional analyses were done in regard to the implementation of this concept on existing controllers on the ECLSS and within the hierarchy of Space Station controllers. The results of these analyses are included in this report.

Final Report

This report is organized into five major sections. The first presents background information on the VCD subsystem under study and expert systems and fault diagnostics in general. The second section covers the fault analysis prepared on the VCDS. The third section deals with issues that must be addressed when considering the application of expert systems to a process. The fourth section describes the demonstration experiment and the examples chosen to illustrate the EFD concepts, and the last section presents the results of the analyses concerning the extension of the concept to other subsystems of the ECLSS.

BACKGROUND

Objectives of this study were an analysis of a subsystem of the ECLSS group of the Space Station for application of expert systems' concepts to the area of fault diagnostics and the demonstration of those concepts with an operating subsystem. The subsystem used in this study was a VCDS, designated Vapor Compression Distillation, Enhanced Advanced Preprototype Configuration (VCD2B), developed under previous portions of this contract.



(a) Based upon Vapor Compression Distillation

FIGURE 1 PHASE CHANGE WATER RECOVERY SYSTEM[(a)] MECHANICAL SCHEMATIC AT THE ORU LEVEL

Expert Systems

The term "expert systems" refers to an area of artificial intelligence which attempts to capture the knowledge of an expert, organize that knowledge, and make it available to others. It is this concept that is to be applied to the VCDS and the problem of fault diagnosis.

There are some general guidelines that can be used when trying to determine whether an expert system can be applied to a particular problem. If there are just a few individuals with special knowledge, if there is a significant and narrowly focused problem, and if the problem involves heuristics and judgment then expert systems can generally be applied to good advantage. In this case, the question is the application of expert systems to a VCDS and specifically to the area of fault diagnostics. Following the above guidelines, this would seem to be a good candidate for an expert system application. One final guideline in applying expert systems is whether the expert knowledge can be integrated into the target system. At first glance, this may seem to be a trivial or even nonsensical question, but in fact, it is very important. If the knowledge of the expert cannot be brought to bear on the problem in a practical way and in the environment in which it is required, then the resulting system will be useless. The demonstration experiment developed as part of this study answers this question for the VCDS.

Many previous studies of expert systems as applied to an ECLSS have used process simulations as a test article in the demonstrations. While some of these have achieved a high degree of fidelity, they are nonetheless simulations of processes and not actual subsystems. In this study, an actual operating VCDS is used as a test vehicle for demonstrating expert systems concepts.

Fault Diagnostics

For any given subsystem, the area of fault diagnostics covers a wide variety of fault handling methods (see Table 1). Expert system concepts can be applied to some degree at each level. Table 2 lists the types of expert knowledge that would be applied using an expert system at each level of fault diagnostics. The demonstration developed in conjunction with this study illustrates each of these concepts using an operating ECLSS, specifically, the VCDS.

Vapor Compression Distillation Subsystem

The VCDS is a phase change water recovery process developed for the Water Management System (WMS) of the Space Station ECLSS (see Figure 2). Its purpose is to recover potable water from onboard generated wastewater. It has been shown to be a highly efficient, low-specific energy consumption technique for accomplishing such water recovery. Figure 3 diagrams the VCD concept. The VCD process achieves its high efficiency by recovering the latent heat of vaporization from the evaporation-condensation cycle. It does this by compressing the vapor and condensing it on a surface in thermal contact with the evaporator. This process is carried out at a low temperature by

TABLE 1 FAULT DIAGNOSTIC LEVELS[a]

Operational Implementation Level	Function	Brief Description
1	Fault Avoidance	Design to avoid faults, e.g., - Prevent human errors - Eliminate weak links - Monitor interfaces
2	Fault Prediction	Predict fault will occur or is beginning
3	Fault Detection	Detect failure or symptom of failure
4	Fault Isolation	Identify what specifically failed
5	Fault Correction (or Correction Instructions)	Correct fault or provide detailed instructions to enable correction
6	Fault Tolerance	Tolerate faults without human intervention

(a) First for specific operating modes (steady-state) and later during mode transitions.

TABLE 2 EXPERT SYSTEM CONCEPTS APPLIED TO FAULT DIAGNOSTICS[a]

Function	Brief Description
Fault Avoidance	Knowing how to prevent a fault from occurring (recurring)
Fault Prediction	Knowing how to recognize that a fault is beginning
Fault Detection	Knowing how to recognize that a fault has occurred
Fault Isolation	Knowing how to identify specifically the failed component
Fault Correction	Knowing how to correct a fault or provide instructions for correction
Fault Tolerance	Knowing when and how to ignore faults and continue safe operation

(a) The demonstration illustrates each of these concepts using an operating ECLSS, specifically VCDS.

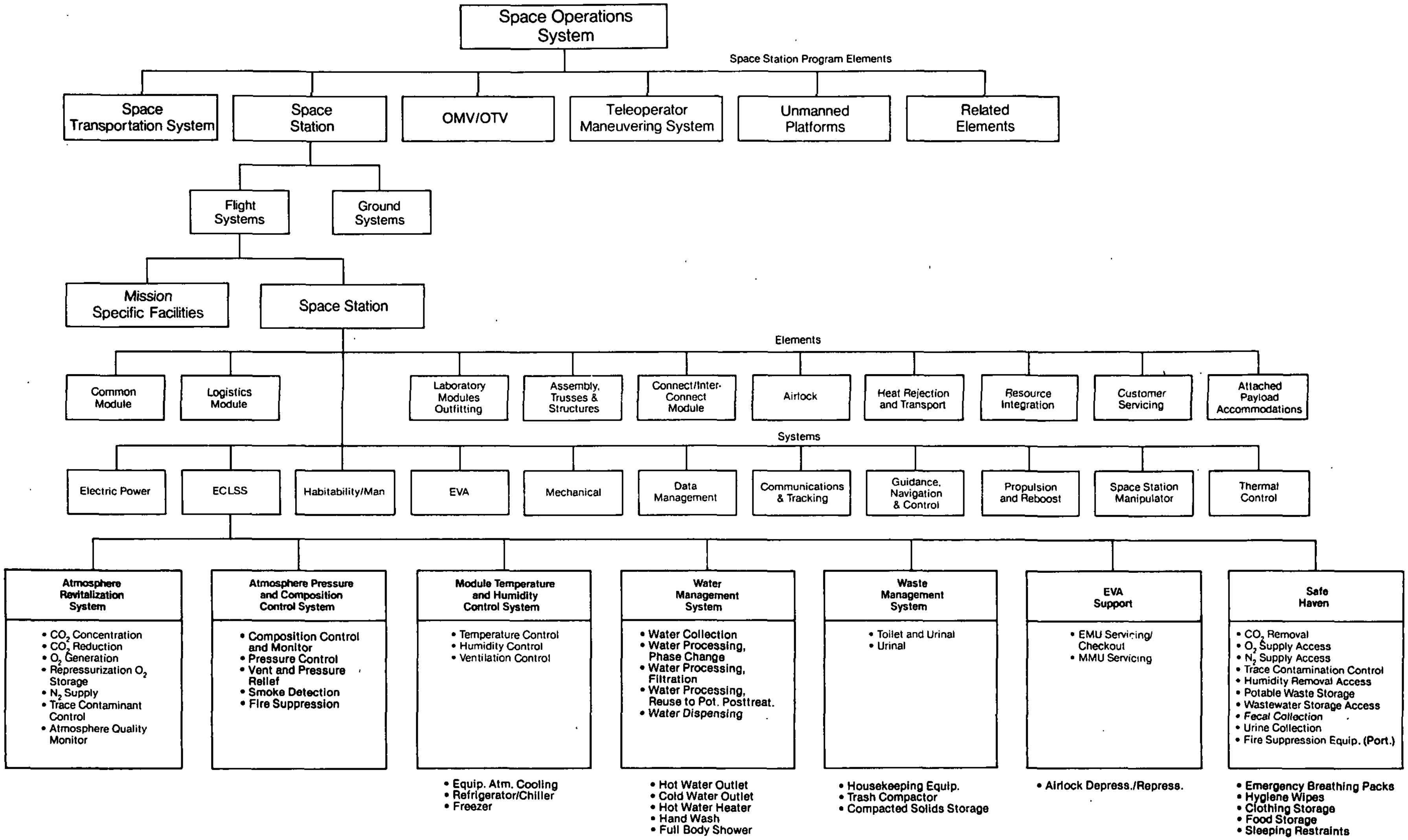


FIGURE 2 SOS AND SPACE STATION FUNCTIONAL BOUNDARIES

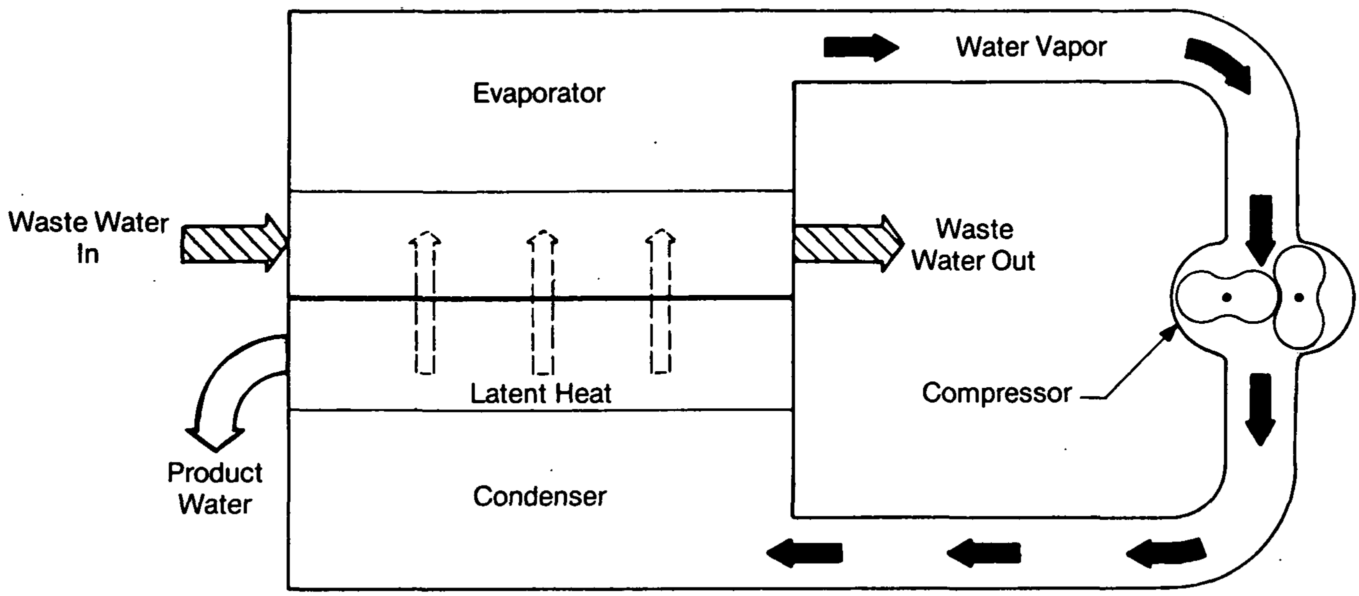


FIGURE 3 VAPOR COMPRESSION DISTILLATION CONCEPT

maintaining the condenser and evaporator at a very low pressure. Figure 4 shows the detailed mechanical schematic for the VCDS. The subsystem draws pretreated wastewater from the waste storage tank through the waste feed valve, labeled V1, and into the distillation unit where the evaporation-condensation process occurs. The fluids pump provides positive circulation for all fluids in the system. Excess wastewater is pumped from the evaporator section back to the waste storage tank for recycling or alternately through the recycle filter tank for removal of concentrated solids. The required low pressure in the distillation unit is maintained by periodic purging through the purge valve V3. Condensate is removed by the fluids pump and delivered to the post-treatment facility. If the product water quality is not adequate, then the output stream is redirected through valve V2 and reprocessed through the distillation unit. Due to the zero-gravity design requirement, the evaporator, condenser and condensate collector are rotated to provide the desired phase separation and liquid control. Figures 5 and 6 show the actual VCD mechanical hardware.

VAPOR COMPRESSION DISTILLATION FAULT ANALYSIS

The first step in implementing an expert system is to obtain the knowledge of the expert which relates to the problem to be addressed. The failures of the VCDS were analyzed in two ways: (1) by reviewing past VCD test programs and the failures which occurred during that testing, and (2) by doing a complete and detailed fault analysis of all of the components which make up the VCDS.

Past Vapor Compression Distillation Faults

Eight different sources of historical data on the VCDS were reviewed covering the period from April, 1983 through December, 1986. Three categories of VCDS failure were identified: a decrease in the water production rate, a less-than-acceptable water quality, and a decrease in the process efficiency. The process efficiency decrease could manifest itself either as an increase in the specific energy of the subsystem, an increase in the power consumption of the subsystem and/or a water production rate decrease. In all, 13 distinct faults were classified and these are listed in Table 3. For each of these faults the logic used in identifying and classifying it was specified and from that logic EFD rules for each fault diagnostic level were developed. Table 4 lists an example of the fault diagnostic rules developed based on past faults. It is clear by the low number of past faults identified that an expert system could not be based on this information alone. As a result, a detailed analysis of the failure modes of the VCDS was undertaken.

Vapor Compression Distillation General Fault Analysis

In organizing the fault analysis, a series of generic categories were identified. Figure 7 illustrates the breakdown of all possible faults on the subsystem into these categories. As can be seen from Table 5, the past VCD faults that were identified can be related to the generic fault descriptions.

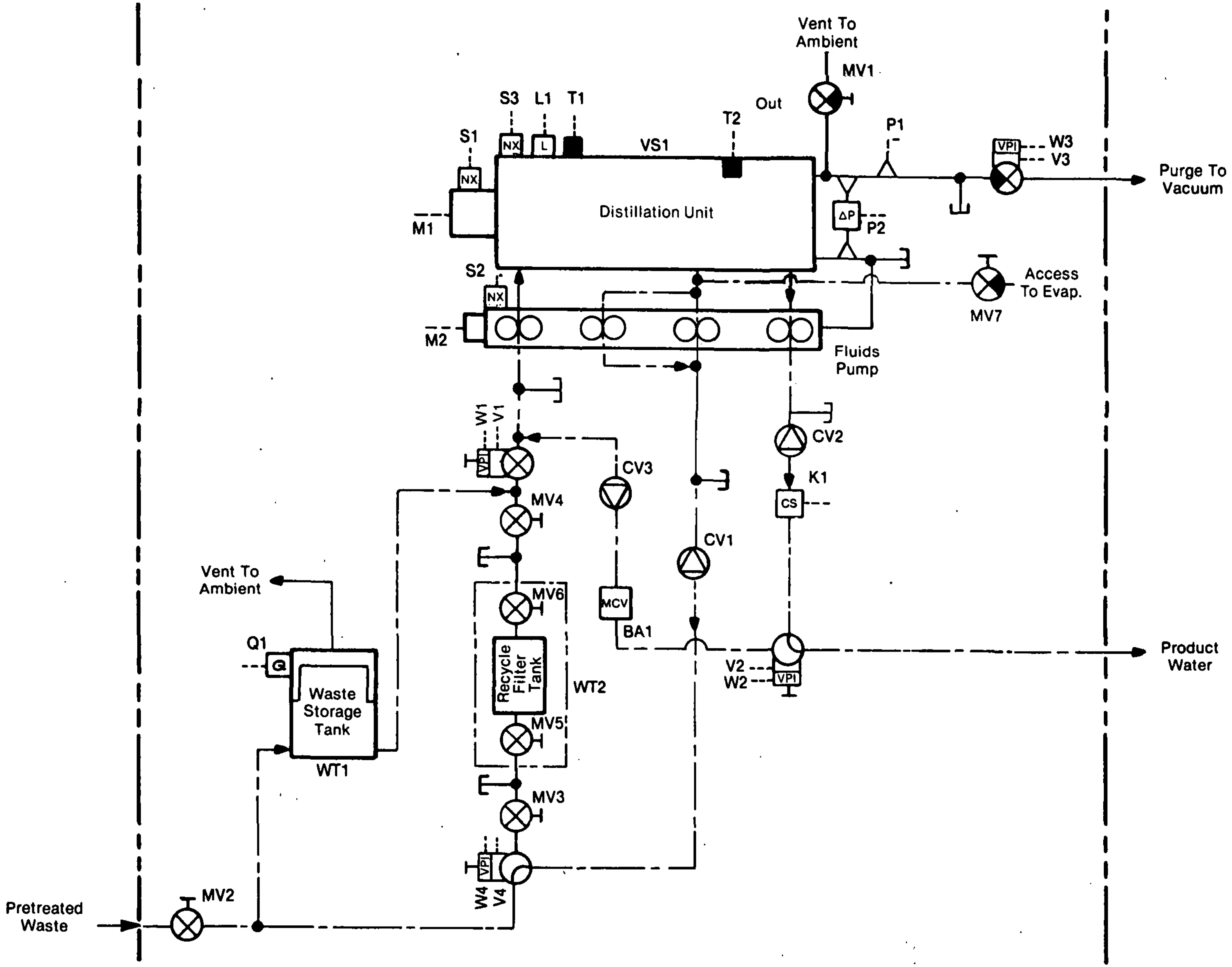


FIGURE 4 ADVANCED PREPROTOTYPE VCDS MECHANICAL SCHEMATIC WITH SENSORS

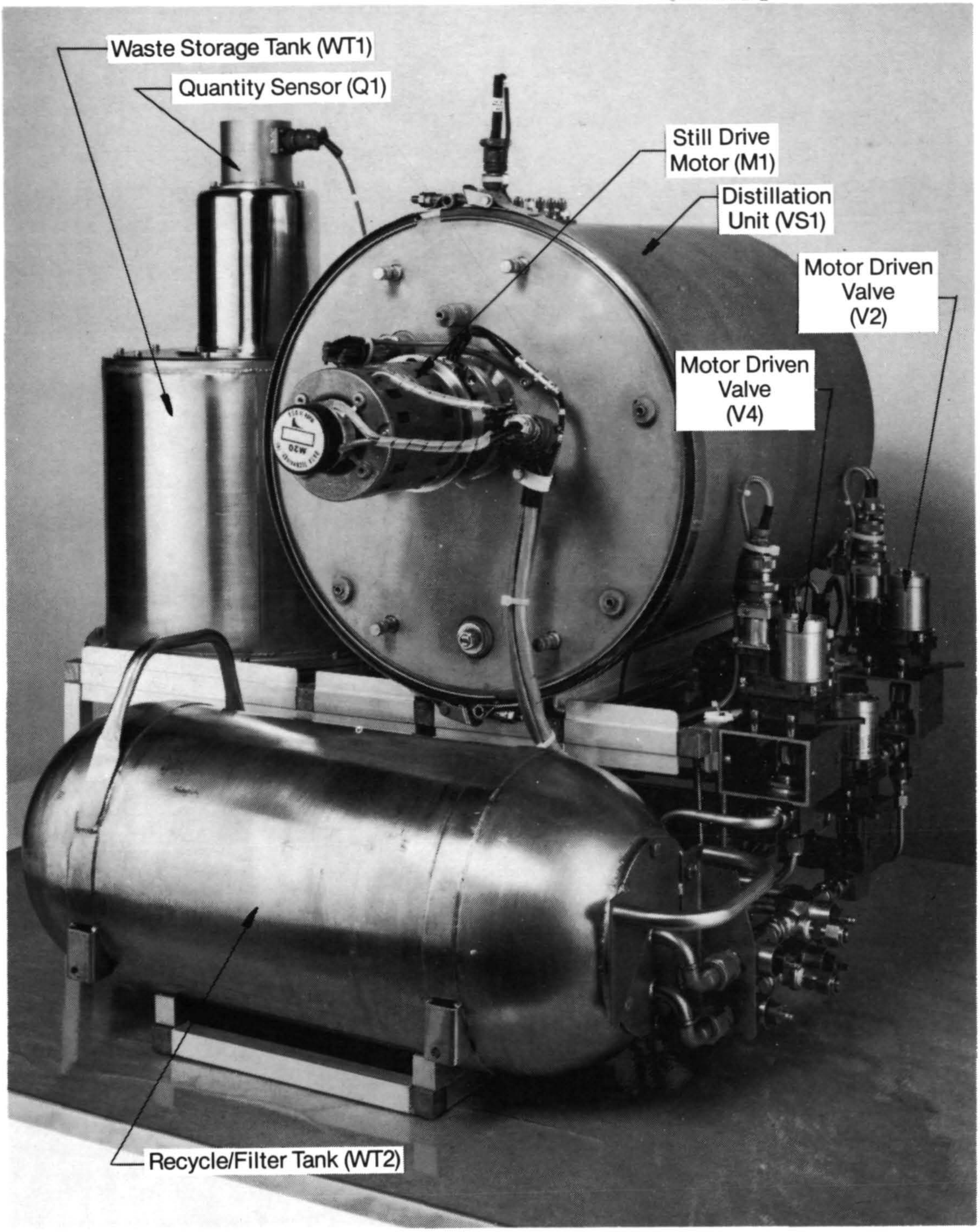


FIGURE 5 ADVANCED PREPROTOTYPE VCDS, FRONT VIEW

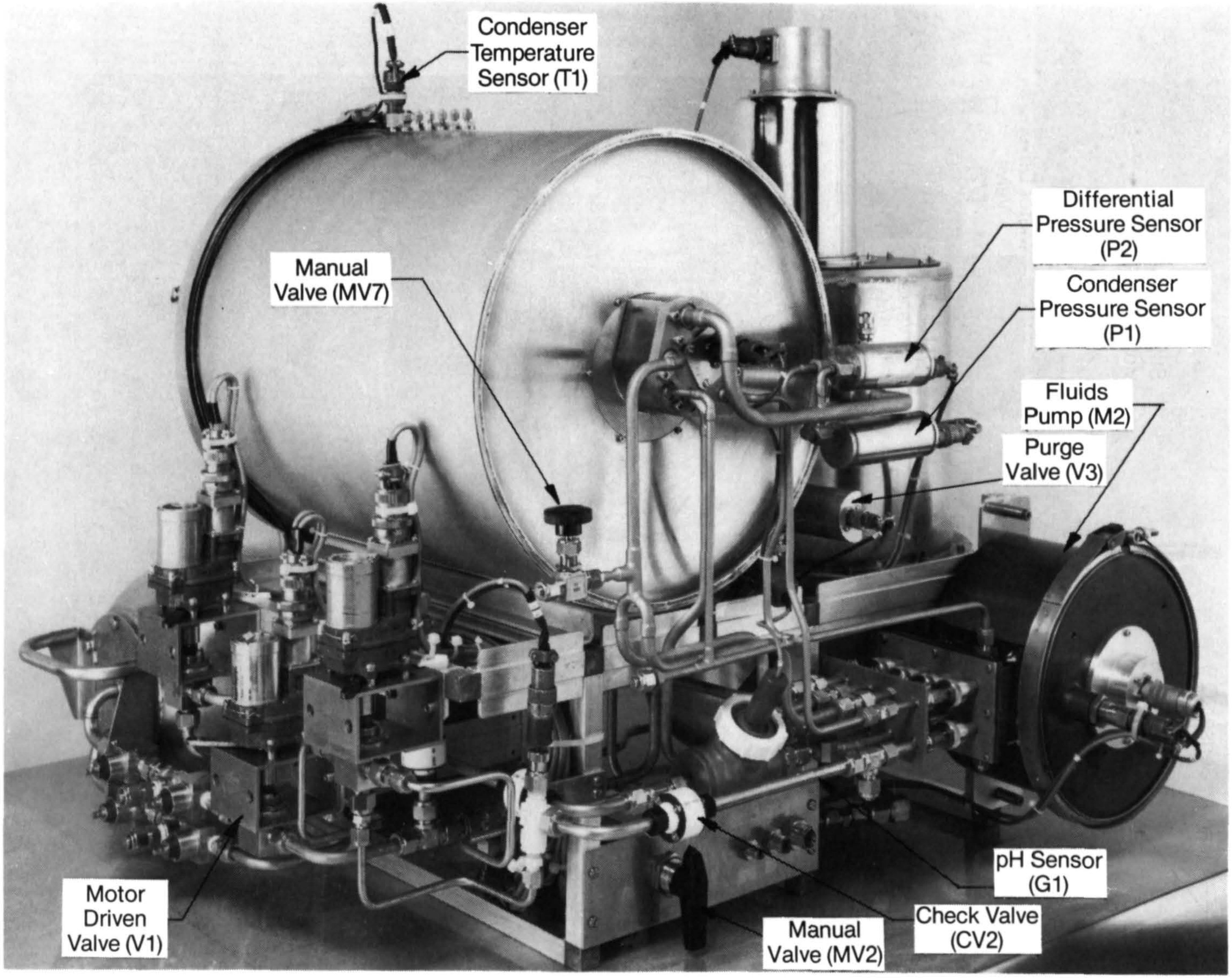


FIGURE 6 ADVANCED PREPROTOTYPE VCDS, BACK VIEW

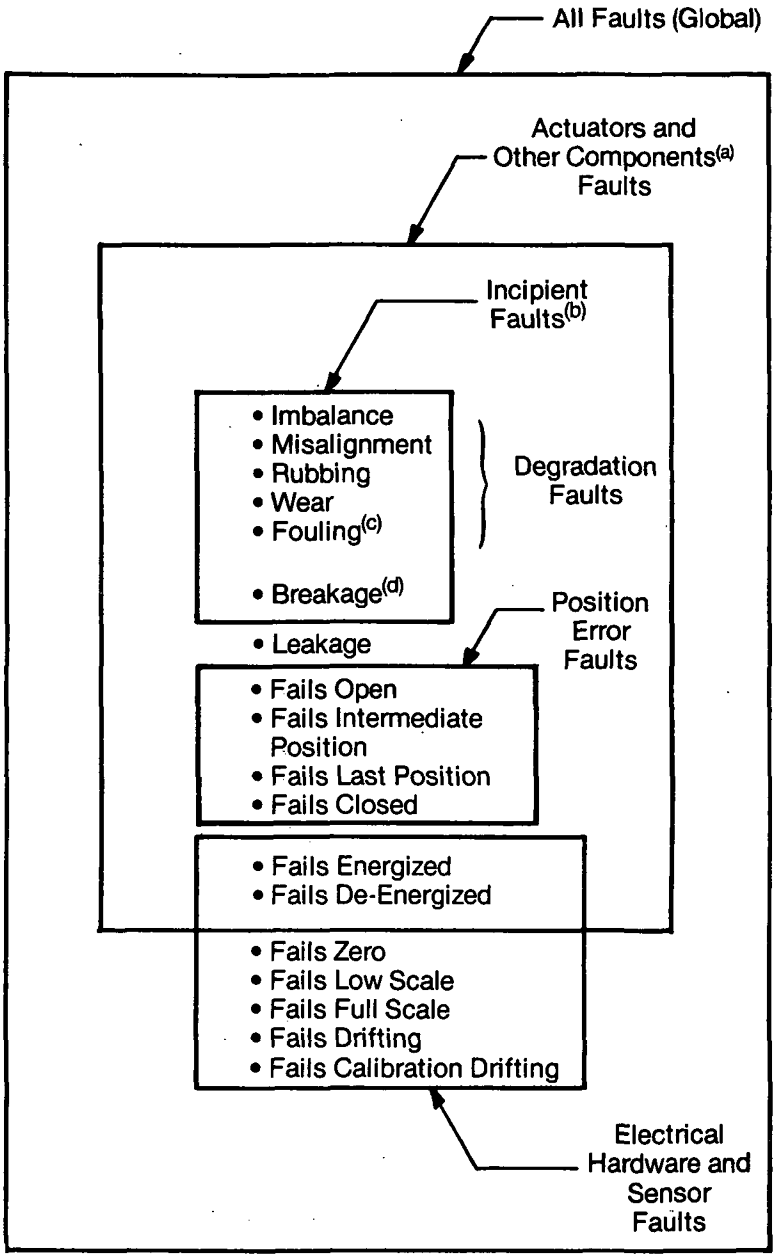
TABLE 3 SUMMARY OF PAST VCD SUBSYSTEM FAILURES FROM ALL PREVIOUS DEVELOPERS

- C/M I Internal Power Supply
- Q1 Sensor/Diaphragm Sticking
- Motorized Valve Sticking
- Fluids Pump Gearbox Fouling
- Centrifuge Timing Belt Breakage
- Centrifuge O-Ring Belt Breakage
- Centrifuge O-Ring Belt Slippage
- Centrifuge Bearing Fouling
- Magnetic Drive Delamination and Decoupling
- Fluids Pump Recycle Tubing Wear
- Check Valve Sticking
- Conductivity Sensor Signal Conditioning
- C/M I Overheating and Software Failure

(a) Eliminating those faults due to building power, TSA and operator error.

TABLE 4 EXAMPLE OF VCD EXPERT FAULT DIAGNOSTIC ROUTINE DESCRIPTIONS BASED ON PAST FAULTS

Fault	Diagnostic Level	Description
Fluids Pump Recycle Tubing Wear	Avoidance	Replace pump tubing at regular maintenance intervals
	Prediction	Partial drydown cycles occurring at more frequent intervals
	Detection	Repeated cycling to partial drydown
	Isolation	Increasing fluids pump speed corrects the problem, decreasing it causes problem to return
	Correction	Replace pump tubing
	Tolerance	Cycle waste feed valve open and closed periodically (5 min/2 min) to limit intake of water while still pump out some fluid (intermittant partial drydown) or increase fluids pump speed



(a) Mechanical components which are not sensors or actuators such as filters or storage tanks.
(b) Faults which can be identified at their initial occurrence.
(c) Includes solids precipitation sludge formation, blockage, plugging and sticking failures.
(d) Subdivided into mechanical breakage and performance failure or "breakage."

FIGURE 7 GENERIC FAULT CLASSIFICATION

TABLE 5 GENERIC EQUIVALENT OF PAST VCDS FAULTS

Past VCDS Fault	Generic Fault Description	Faults Peculiar to VCDS	Faults Generic to ECLSS
C/M I Computer Power Supply	C/M I Failed De-Energized	-	X
Q1 Sensor/Diaphragm Sticking	Tank Degradation (Alignment)	X	-
Motorized Valve Sticking	Valve Degradation (Fouling)	-	X
Fluids Pump Gearbox Fouling	Gearbox Degradation (Fouling)	-	X
Centrifuge Timing Belt Breakage	Drive Motor Subassembly Breakage	-	X
Centrifuge O-Ring Breakage	Drive Motor Subassembly Breakage	-	X
Centrifuge O-Ring Belt Slippage	Drive Motor Subassembly Degradation (Rubbing)	-	X
Centrifuge Bearing Fouling	Centrifuge Degradation (Fouling)	-	X
Magnetic Drive Delamination/ Decoupling	Drive Motor Subassembly Breakage	-	X
Fluids Pump Recycle Tubing Wear	Pump Tubing Degradation (Wear)	X	-
Check Valve Sticking	Check Valve Degradation (Fouling)	-	X
Conductivity Sensor S/C	C/M I Failed Drifting	-	X
C/M I Overheating and Software Failure	C/M I Failed De-Energized and C/M I Loss of Programmed Control	-	X
Totals		2	11

The format used in performing the analysis was a series of fault trees. Figure 8 represents the fault tree for the VCDS using Orbital Replacement Units (ORUs) as the lowest level component. In order to utilize an expert system in the areas of fault tolerance and fault correction, it is necessary to isolate failures down to a component level rather than an ORU level. Only by identifying individual components would it be possible to determine the action to be taken in tolerating or correcting any failures.

The VCDS was examined in detail, including both the pretreat and post-treat assemblies, and 109 individual components were identified. Failure modes of each component were identified and a total of 536 possible faults were listed for all of the components of the VCDS. Out of this number, 55 distinct types of faults were identified and, using the generic fault classifications, 30 distinct generic types were listed. Due to the size of the analysis and quantity of data, Table 6 shows only a representative portion of a fault tree defined for the VCDS components.

As had been done following the analysis of the past VCD faults, the logic used in analyzing each fault type was again specified. From this fault tree analysis and the expert logic, the generic fault diagnostic routines to be used by the expert system were once again identified. Tables 7, 8 and 9 represent this progress from the fault tree to the expert fault diagnostic routines for one particular example failure. Similar descriptions were developed for each of the 30 classified generic types of faults.

A thorough analysis of the possible subsystem faults is critical to a successful implementation of EFDs. Without such an analysis it is not possible to formulate the rules which are at the heart of such a system. The VCD general fault analysis, thus, stands as the basis for the expert system implementation and the rules which govern its operation.

APPLICATION CONSIDERATIONS

In implementing an expert system, it is necessary not only to examine the knowledge that an expert uses in approaching a problem, but also the methods employed in dealing with situations. A review of the methods that a subsystem developer might use in analyzing a failure can significantly influence the structure of the system rules and knowledge base in the implementation.

Fault Analysis by a Subsystem Expert

In general, a subsystem developer approaches the failure of the system in three phases. First is detection of the failure. Here, he might observe abnormal operation, in this case, decreases in water production rate or water quality or process efficiency. He might also be aware of warning or alarm messages issued by the subsystem controller, or sensor readings which deviate from the normal range. In isolating a fault, he might additionally look at actuator positions compared to their normal positions, as well as sensor readings compared to the associated actuator position. He may also perform a detailed analysis of each possibility and, if necessary, a component-by-component verification. Finally, to determine the ultimate cause of the

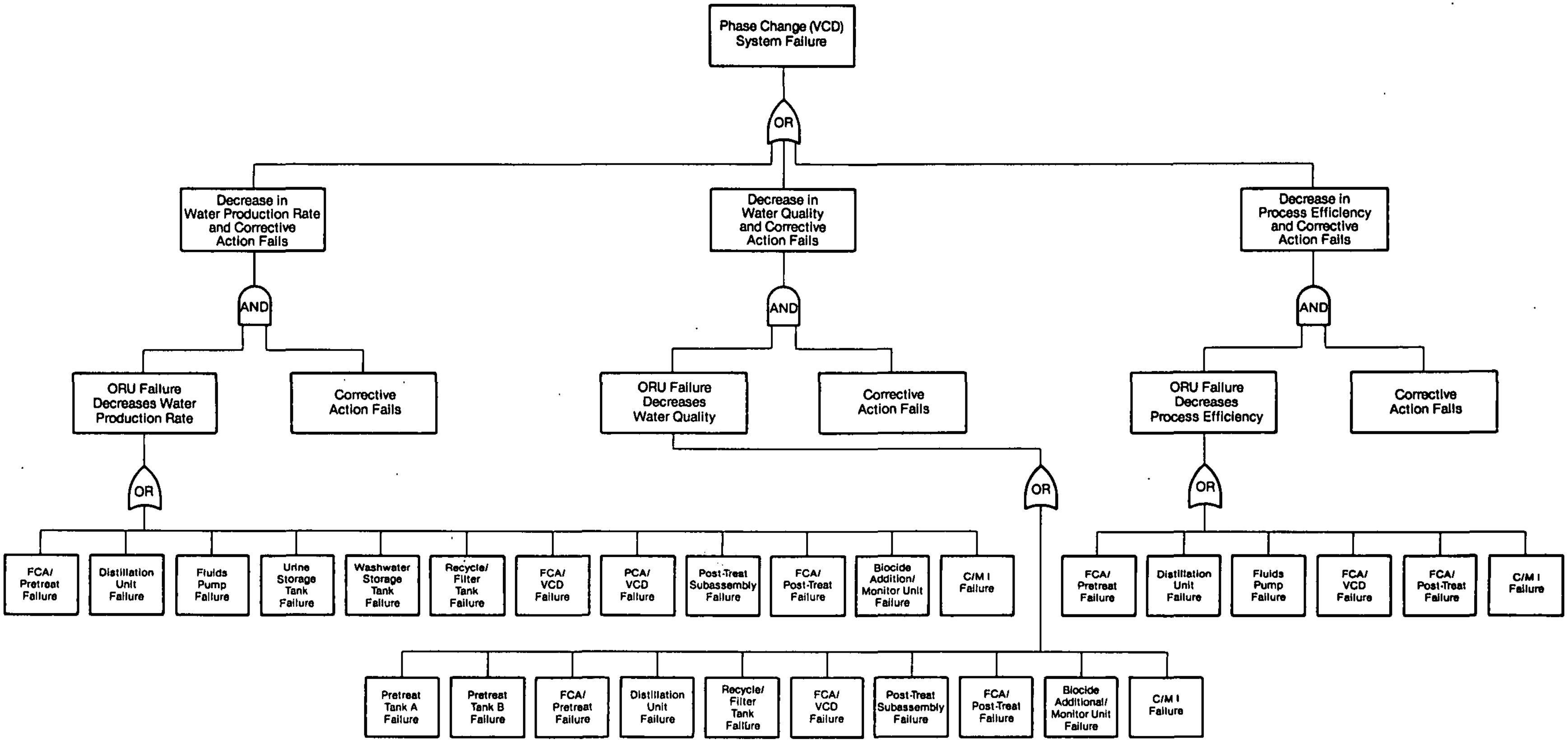


FIGURE 8 PHASE CHANGE (VCD) SYSTEM FAULT TREE AT THE ORU LEVEL

TABLE 6 DISTILLATION UNIT FAULT DEFINITION FOR PHASE CHANGE (VCD) SYSTEM

Generic Component	Component Qty.	Fault Description: Generic	Fault Description: Specific	Fault Qty.
Distillation Assembly	1	Centrifuge Breakage	Mechanical	1
		Centrifuge Degradation	• Imbalance	1
			• Misalignment	1
			• Rubbing	1
			• Wear	1
			• Evaporator Fouling	1
		Centrifuge Drive[(a)] Breakage	Mechanical	1
		Centrifuge Drive Degradation	• Imbalance	1
			• Misalignment	1
			• Rubbing	1
			• Wear	1
		Compressor Breakage	Mechanical	1
		Compressor Degradation	• Imbalance	1
			• Misalignment	1
			• Rubbing	1
			• Wear	1
			• Fouling	1
		Outer Shell Leakage	• Waste Water	1
			• Product Water	1
			• Vacuum	1
Drive Motor Subassembly	1	Drive Motor Breakage	Mechanical	1
		Drive Motor Degradation	• Imbalance	1
			• Misalignment	1
			• Rubbing	1
			• Wear	1
		Drive Motor Electrical Failure	• Fails De-Energized	1
			• Fails Low Speed	1
			• Fails Drifting Speed	1
			• Fails High Speed	1
		Magnetic Coupling Breakage	• Mechanical	1
			• Performance[(b)]	1
		Magnetic Coupling Degradation	• Imbalance	1
			• Misalignment	1
			• Rubbing	1

continued-

(a) Two-stage belt drive for speed reduction.
(b) Decoupling.

Table 6 - continued

Generic Component	Component Qty.	Fault Description: Generic	Fault Description: Specific	Fault Qty.
Temperature Sensor	2	Sensor Breakage	Mechanical	2
		Sensor Degradation	Fouling	2
		Sensor Leakage	Vacuum	2
		Sensor Electrical Failure	• Fails De-Energized	2
			• Fails Zero	2
			• Fails Low Scale	2
			• Fails High Scale	2
			• Fails Drifting	2
			• Fails Calibration Drifting	2
Speed Sensor	2	Sensor Breakage	Mechanical	2
		Sensor Degradation	Fouling	2
		Sensor Leakage	Vacuum	2
		Sensor Electrical Failure	• Fails De-Energized	2
			• Fails Zero	2
			• Fails Low Scale	2
			• Fails High Scale	2
			• Fails Drifting	2
			• Fails Calibration Drifting	2
Liquid Level Sensor	1	Sensor Breakage	Mechanical	1
		Sensor Degradation	Fouling	1
		Sensor Leakage	Vacuum	1
		Sensor Electrical Failure	• Fails De-Energized	1
			• Fails Zero	1
			• Fails Low Scale	1
			• Fails High Scale	1
			• Fails Drifting	1
			• Fails Calibration Drifting	1
Motor Current Sensor	1	Sensor Breakage	Mechanical	1
		Sensor Electrical Failure	• Fails De-Energized	1
			• Fails Zero	1
			• Fails Low Scale	1
			• Fails High Scale	1
			• Fails Drifting	1
			• Fails Calibration Drifting	1
Total Generic Faults Possible	8		Total Specific Faults Possible	86

TABLE 7 EXAMPLE OF FAULT TREE ANALYSIS

Generic Component	Component Qty.	Fault Description: Generic	Fault Description: Specific	Fault Qty.
Liquid Filter	1	Filter Degradation	Fouling	1
		Filter Leakage	Product Water	1

TABLE 8 EXAMPLE OF EXPERT LOGIC

Fault Type	Logic Description
Filter Degradation	Flow rate decreases over time
	Upstream pressure increases over time
	Time since last maintenance approaches or exceeds scheduled maintenance interval
	Physical inspection shows fouling
	Replacement returns operation to normal

TABLE 9 EXAMPLE OF GENERIC EXPERT FAULT DIAGNOSTIC ROUTINES

Fault	Diagnostic Level	Description
Filter Degradation	Avoidance	Replace filter at regular maintenance intervals
	Prediction	Flow rate has decreased significantly from original value Pressure has increased significantly from original value Time since last maintenance is approaching the maintenance inverval
	Detection	Flow rate is low
	Isolation	Bypassing filter increases flow rate Replacing filter increases flow rate Inspection of filter shows fouling
	Correction	Replace filter
	Tolerance	(None)

failure, the developer might be required to disassemble and inspect the subsystem components suspected of causing the failure, or replace a component and retest the subsystem in order to verify the actual cause of failure. Figure 9 represents graphically the order in which a subsystem developer might approach the analysis of a fault.

An expert system would have to be able to mimic the expert, in both his data gathering and his logical reasoning, to perform similar functions. Direct observation of the subsystem operation can be performed using electromechanical sensors to take the place of the human senses used by the expert. The senses of vision, hearing, touch, taste and smell can be replaced by corresponding sensors which might record the temperature, pressure, flow, vibration, noise and other comparable quantities. It should be noted, however, that totally replicating a human expert's senses would require a substantial increase in the number of subsystem sensors required. Table 10 illustrates how a great number of additional sensors, above those normally on the subsystem, would be required on the VCD in order to replicate what a human expert might observe on the system. In most cases, all of these sensors would not be required. Readings from some of the sensors might be able to be deduced by readings taken elsewhere on the system. Also, when reviewing the actual expert rules implemented in a particular subsystem, many of these sensors would not be required to support those rules. The sensor complement of any subsystem being considered for expert applications must be reviewed for the addition of sensors required by the expert system rules. Generally, additional sensors will be required above those normally used for fault detection and safety shutdown alone.

A subsystem expert might also make use of high level or composite views of the subsystem in monitoring its performance. An expert system could also implement the same function by generating composite sensors. These sensors would be combinations of the normal sensor complement on the subsystem which would give a single value representative of the quality of operation of a given aspect of the subsystem. Tables 11 and 12 give examples of composite sensors that might be implemented on the VCDS and those faults which could be identified using those sensors.

The logical reasoning of an expert that is used in analyzing a fault can also be duplicated in an expert system. Logic programming can reason from rules listed in a rule base similar to the heuristic rules that a human expert might use when approaching a problem. If the rules of experience are not successful in pinpointing a problem, an expert generally resorts to reasoning from the theory of operation. This could also be implemented in the rule base of an expert system. While it may not be possible for an expert system to actually do the detailed tear down and inspection or substitution and verification, it would be possible for an expert system to recommend probable causes and suggest a course of action for repair. In this way, an expert system could duplicate virtually all of the functions of an expert in analyzing a subsystem failure.

Finally, an expert system should be able to easily add to its knowledge base when new rules and new failure modes are identified. Rules could be added to the knowledge base not only to assist in identifying future failures more easily, but also to improve performance of the system during normal operation.

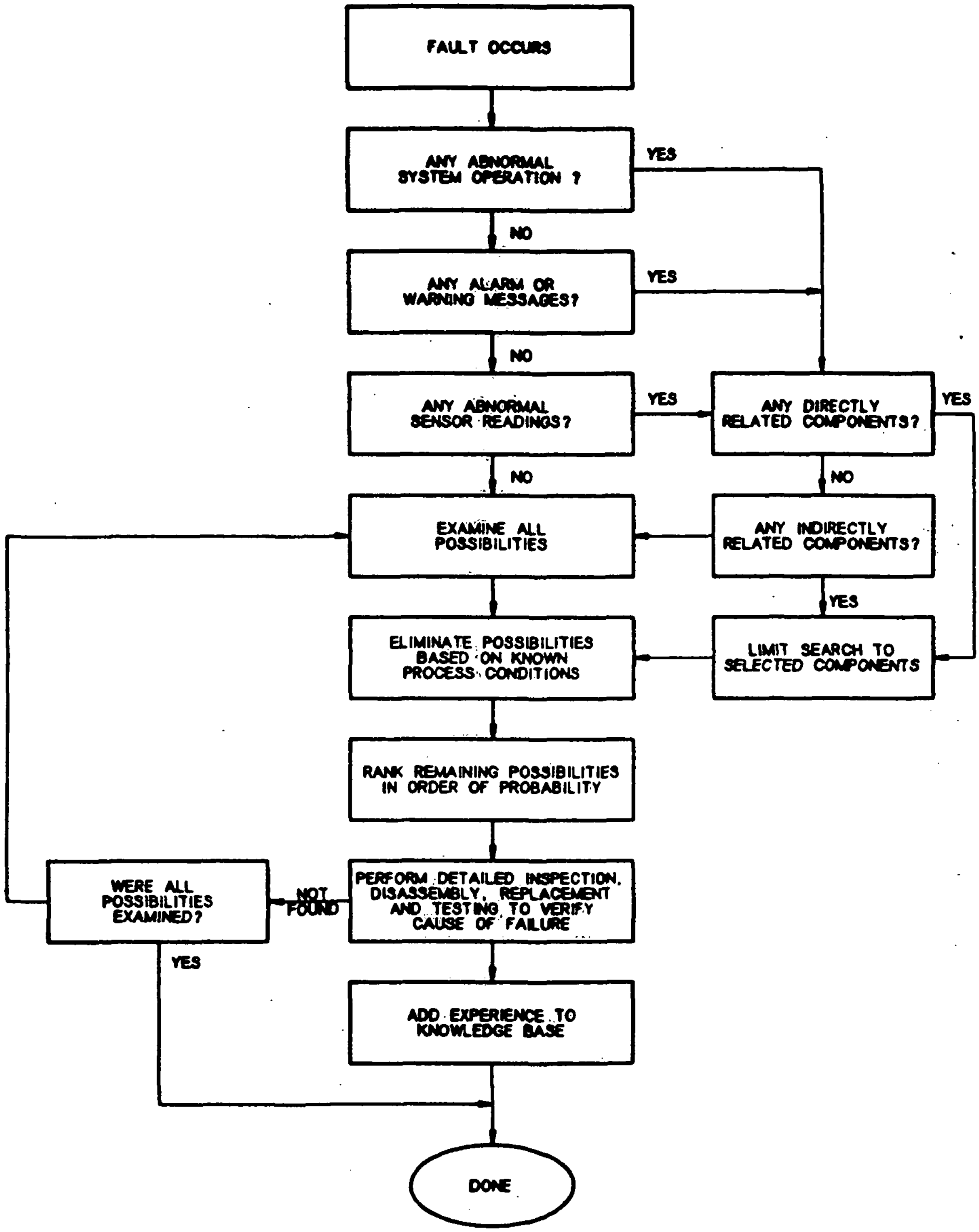


FIGURE 9 DEVELOPER'S LOGIC IN ANALYZING A FAULT TYPE

TABLE 10 ADDITIONAL SENSORS REQUIRED ON VCDS TO PROVIDE INFORMATION EQUIVALENT TO HUMAN EXPERT

	VCD Subsystem ORUs													
Sensor Type	Pret. Tank A	Pret. Tank B	FCA/ Pret.	Urine Stor.	Wash. Stor.	Fluids Pump	Distl. Unit	FCA/ VCD	PCA/ VCD	Recycle Tank	FCA/Post-Treat	Post-Treat Subassy.	BAMU	Total
Temperature	-	-	2	-	-	1	1	-	-	-	-	-	-	4
Flow	1	1	2	1	1	3	-	3	-	1	3	2	1	19
Vibration	-	-	2	-	-	1	1	-	-	-	1	-	-	5
Noise	-	-	2	-	-	1	1	-	-	-	1	-	-	5
Concentration	1	1	-	-	-	-	-	-	-	1	-	-	-	3
Current	-	-	2	-	-	1	1	-	-	-	1	-	-	5
Voltage	-	-	2	-	-	1	1	-	-	-	1	-	-	5
Liquid Level	1	1	1	1	1	1	1	1	1	1	1	1	1	13
Pressure	-	1	-	-	-	1	-	-	-	-	-	-	-	2
	3	4	13	2	2	10	6	4	1	3	8	3	2	61

TABLE 11 POTENTIAL VCDS COMPOSITE SENSOR LIST

Composite Sensor Name	Composite Sensor Symbol	Participating Sensors	Participating Sensors Symbols
Condenser saturation condition	KS1	Condenser pressure	P1
		Condenser temperature	T1
Evaporator pressure	KS2	Compressor delta P	P2
		Condenser pressure	P1
Gross liquid level	KS3	Liquid level	L1
		Still drive current	I1
Evaporator saturation condition	KS4	Condenser pressure	P1
		Compressor delta P	P2
		Evaporator temperature	T2
Distillation unit drive condition	KS5	Centrifuge speed	S3
		Still drive speed	S1
		Still drive current	I1
		Condenser temperature	T1
		Liquid level	L1
		Time in normal mode	Z5
Fluids pump drive condition	KS6	Pump speed	S2
		Pump drive current	I2
		Time on fluids pump	Z11
		Liquid level	L1
		Waste storage quantity	Q1, Q2
Recycle loop solids level	KS7	Waste storage quantity	Q1, Q2
		Time in normal mode	Z5
		Total time on recycle tank	Z12
		Condenser temperature	T1
Centrifuge delta T	KS8	Condenser temperature	T1
		Evaporator temperature	T2

TABLE 12 VCDS FAULTS ISOLATED BY COMPOSITE SENSORS

Composite Sensor Name	Composite Sensor Symbol	VCDS Fault(s) Isolated
Condenser saturation condition	KS1	• High condenser pressure due to faulty purge valve V3 • Out-of-tolerance water production rate
Evaporator pressure	KS2	• Used in computing evaporator saturation condition KS4 • Out-of-tolerance water production rate
Gross liquid level	KS3	• Waste feed valve (V1 or V6) failure to close during partial drydown • Loss of C/M I control
Evaporator saturation condition	KS4	• High evaporator pressure due to distillation unit vacuum leak • Out-of-tolerance water production rate
Distillation unit drive condition	KS5	• Drive subassembly breakage • Drive subassembly degradation • Centrifuge breakage • Centrifuge degradation • Compressor breakage • Compressor degradation • Casing process fluid leakage • Casing vacuum leakage • Fluids pump breakage[a] • Fluids pump degradation[b]
Fluids pump drive condition	KS6	• Fluids pump breakage • Fluids pump degradation • Pump casing vacuum leakage • Pump drive subassembly breakage • Pump drive subassembly electrical

continued-

(a) Loss of fluids pump drive such that recycle loop pumping capability is lost.
(b) Pump recycle loop tubing wear.

Table 12 - continued

Composite Sensor Name	Composite Sensor Symbol	VCDS Fault(s) Isolated
Fluids pump drive condition - continued	KS6	• Pump tubing breakage • Pump tubing degradation
Recycle loop solids level	KS7	• Impending high solids fouling of VCDS • Recycle/filter tank changeout
Centrifuge Delta T	KS8	• Loss of waste feed fluid • Waste storage tank degradation[a] • Tank quantity sensor failure

(a) Such as rolling diaphragm sticking.

Expert System Automation

In applying an expert system for fault diagnostics on any particular subsystem, it is important that an analysis be done specifically for the expert system application. The normal analyses performed in designing and building a subsystem generally do not address those issues that are directly related to the EFD system. A typical Failure Mode and Effects Analysis (FMEA) may identify certain failure modes of the subsystem and their effects, but the form of the data is such that it would make expert system construction very difficult. The fault analysis used in this study (i.e., fault trees) lends itself far more readily to translation into the expert system rules and the reasoning logic.

The complement of sensors on the subsystem is also a critical item and this needs to be addressed likewise, specifically for the expert systems implementation. It is recommended that a second analysis of subsystem sensors be performed after the rules are formulated for the expert system so that the desired degree of expert implementation, as well as the types of failures to be detected, can influence the types and quantities of sensors required. As mentioned earlier, it is often possible to derive the value of certain subsystem parameters in a number of ways using different types of sensors. Once the expert systems analysis has been completed, the selection of the actual subsystem sensor list can take into account both the requirements of the operating control and fault detection as well as the expert systems requirements.

The response time of an expert system when used in a fault diagnostic application is especially critical. In order to safely avert a shutdown of the subsystem, the expert system must be able to analyze a situation, identify the fault, isolate the cause, and effect corrective action within the time frame normally allowed before a safety shutdown of the subsystem. In most cases this is only a matter of a few seconds. Systems which consist of a large number of rules will need very fast processors to maintain an adequate response time. Similarly, slower processors would limit the amount of expert knowledge which could be applied to a subsystem. The demonstration system was found to respond adequately in spite of the additional communications delay resulting from the implementation being in an auxiliary processor, separate from the subsystem controller, however, the rule base for this system was quite restricted.

The rule base for an expert system can use up a great deal of the available storage in a typical subsystem controller. When adding expert knowledge at that level, this situation must be considered. Either additional storage must be made available, or the rule base will have to be restricted to some degree.

The subsystem rules that are identified and are to be implemented for a particular subsystem can be implemented a number of different ways. The initial formulation of the rules should be independent of the implementation and should not directly rely on a particular coding scheme or a particular language of implementation. The demonstration system developed under this study takes advantage of that situation by using an implementation that closely relates to the current architecture of the subsystem controller. The rules that were formulated could just as well have been implemented using a higher-level, more traditional artificial intelligence language.

EXPERT DEMONSTRATION SYSTEM

Once the fault analysis of the VCDS was completed and the rules governing the implementation of that knowledge were formulated, it was then possible to select examples from that rule base which could be demonstrated using an operating VCDS. Six such examples were selected from among the EFD rules which were developed. These six examples illustrate the application of expert system concepts to all the operational levels of fault diagnostics.

Overview

An auxiliary computer was selected to implement the expert demonstration system. This was done to simplify the development work of the expert system by isolating any interaction between it and the normal control logic in the subsystem controller to a simple communications interface. Another advantage of this organization was a much clearer demonstration due to the additional color graphic displays which were available on the auxiliary computer. It was also possible to more easily separate the expert system logic from the normal subsystem controls and, thereby, contrast the difference in operation of the subsystem with and without the expert logic being activated. Also, there was an existing interface for communications between the controller and an auxiliary computer. No modification to the subsystem control software was necessary in order to add the expert demonstration system to the VCDS. No changes to the control algorithms were made, nor was any allowance made concerning response time of the expert system. In all cases, the subsystem controller reacted exactly as it has been configured, except for those instances when the expert system issued commands to override sensors or actuators. Any and all such commands used by the expert system were already available and understood by the subsystem controller.

Figure 10 illustrates the overall organization of the demonstration system. The mechanical hardware of the VCDS interacts with the subsystem controller through the sensors and actuators. A RS-232C communications channel links the auxiliary computer with the subsystem controller. Through this communications link, the auxiliary computer can update itself with the current status of the subsystem sensors and actuators, as well as issue commands to the subsystem controller to take action when the expert system requires it. An additional significant note is the use of Intel 8086 family processors in both the subsystem controller and the expert demonstration system. The software for this expert system was also coded in the same programming language, Programming Language/Microcomputers (PL/M), that is used in the subsystem controller. The selection of PL/M as the implementation language allowed the use of an existing library of low level interface routines for both the Control/Monitor Instrumentation (C/M I) communications and the color graphic displays. In addition, the compiler for PL/M is highly optimized and generates efficient native code for the Intel processors

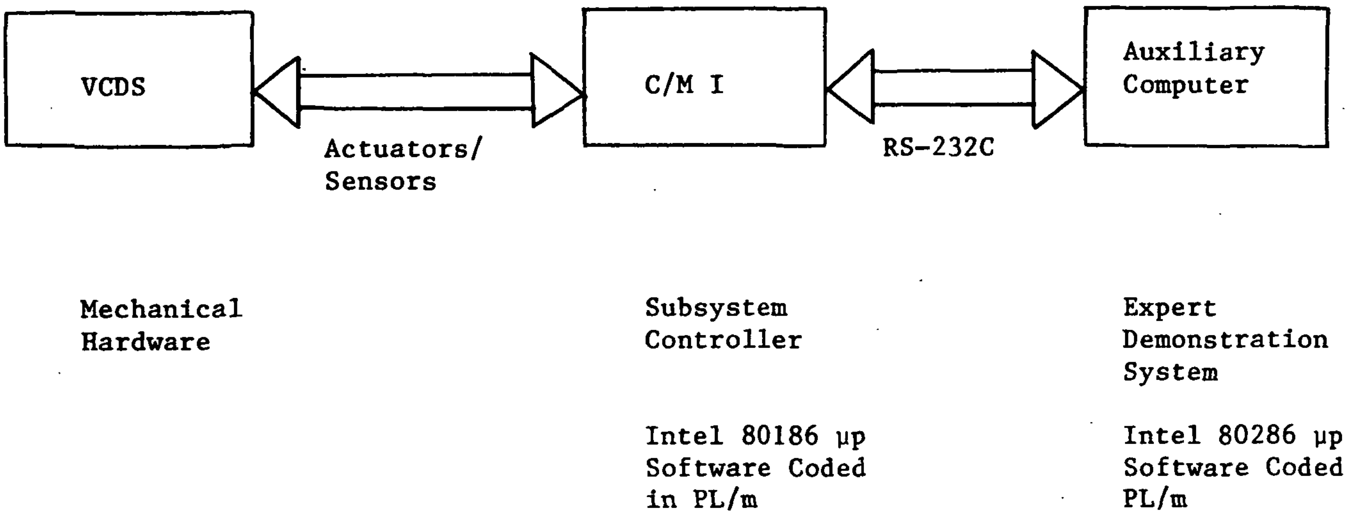


FIGURE 10 ORGANIZATION OF DEMONSTRATION

yielding a high execution speed which can be critical in an expert system implementation. The fact that the same family of microprocessors is used in both the auxiliary computer and the subsystem controller means that the expert system logic developed in this separate machine could be transported fairly easily and incorporated into the control software of the existing subsystem controller. The demonstration, therefore, not only would illustrate how expert system concepts can be applied to an existing subsystem, but also that they could be applied using existing subsystem controllers.

Selected Examples

Figure 11 shows a sample display screen developed for the expert demonstration system. This screen is the initial startup screen where one of the six examples can be selected for operation. All of the screens used in the expert demonstration system have the same general format. The bar at the top of the screen provides the current date and time, as well as the current status, of the subsystem, either normal, warning or alarm. This bar will actually change colors depending upon the status of the subsystem, being green for normal, yellow for warning or red for alarm. The area of the screen labeled "comments" is used for a narrative on the progress of the selected example. Any messages appearing in this area are generated by the supervisory routines and not by the actual expert system rules. The section of the screen labeled "advisory" contains those messages which are actually generated by the expert system rules themselves. It is this portion of the screen which will provide the operator with the fault correction, detection, isolation and other messages issued by the expert system. The final portion of the screen is used in various ways depending on the situation at hand. In some cases, it will contain a graphic representation of the subsystem itself where faulty components are highlighted for identification to the operator. In other cases, it may be used to show the trend of data over a period of time to explain to the operator why a certain action is required or why the expert system is taking a particular course of action at that time.

Table 13 lists the six examples which were selected for the demonstration. It also indicates the areas of fault diagnostics which are illustrated using each particular example. As can be seen from the Table, the fault detection and isolation logic are required by the expert system for virtually every operation. Before fault correction action can be taken or before a decision can be made on tolerating a fault, the expert system must first determine the actual component which has failed. Thus, some of the examples illustrate a number of levels of fault diagnostic application. The six examples were chosen so that all six levels of fault diagnostics can be illustrated in this demonstration.

Figures 12 through 17 and Tables 14 through 19 provide the details of each individual example. In each instance, each situation was demonstrated with the expert system disabled and then again with the expert system enabled. The resulting effects on the subsystem in each case are recorded for each example.

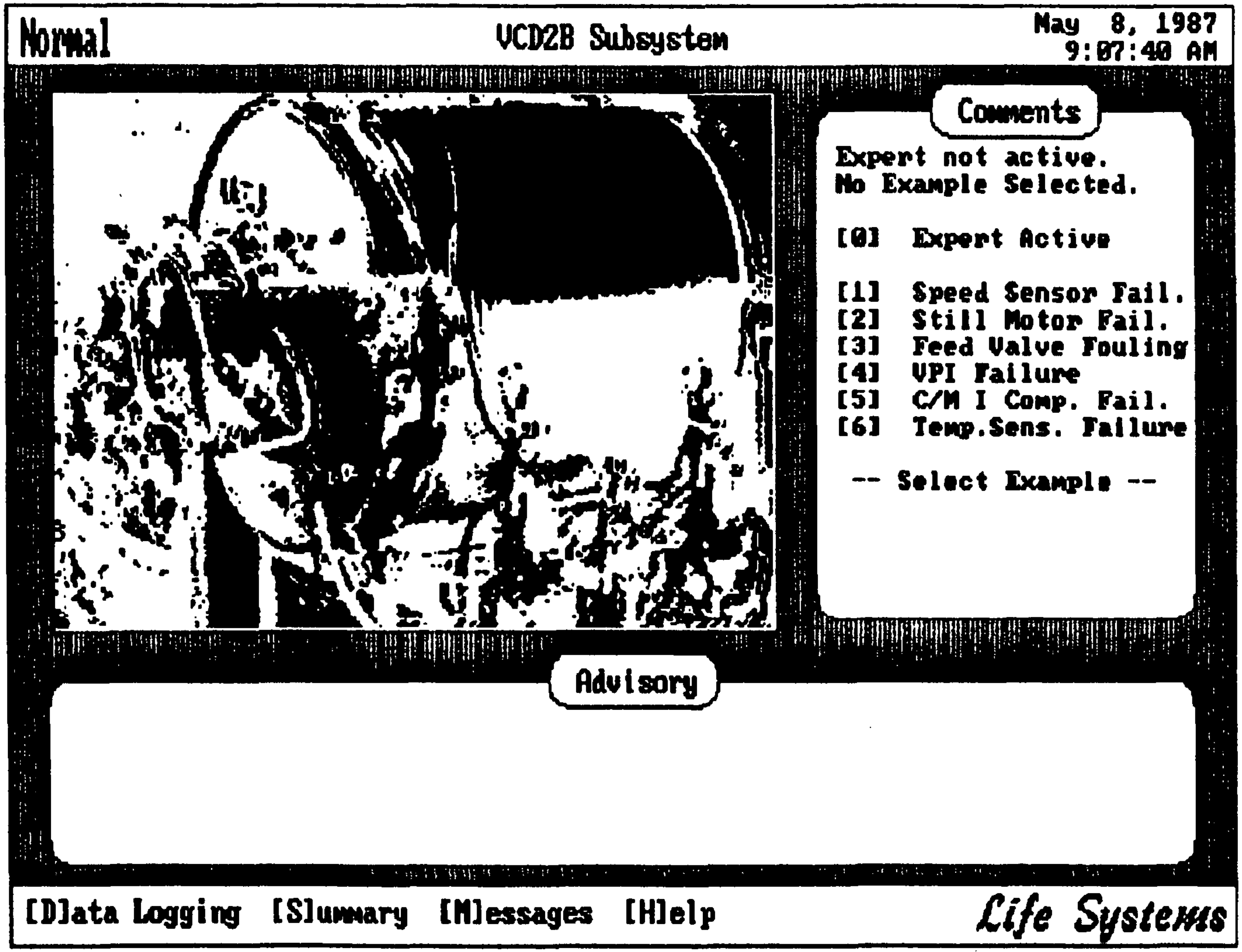


FIGURE 11 EXPERT DEMONSTRATION SAMPLE SCREEN - STARTUP SCREEN

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TABLE 13 EXAMPLES OF EXPERT SYSTEM CONCEPTS

No.	Description	Fault Avoidance	Fault Prediction	Fault Detection	Fault Isolation	Fault Correction	Fault Tolerance	Action
1	Speed Sensor Failure			X	X		X	Substitute derived value for failed sensor to avoid shutdown
2	Still Drive Motor Failure			X	X			Identify failure and suggest corrective action
3	Waste Feed Valve Fouling	X		X	X	X		Correct fault condition and perform periodic preventive maintenance
4	VPI Failure			X	X		X	Identify failure and substitute derived value for failed sensor
5	C/M I Component Failure		X					Predict impending fault allowing time to correct failure condition
6	Temperature Sensor Failure			X	X		X	Identify failure and permit continued operation for a limited period of time based on historical trend

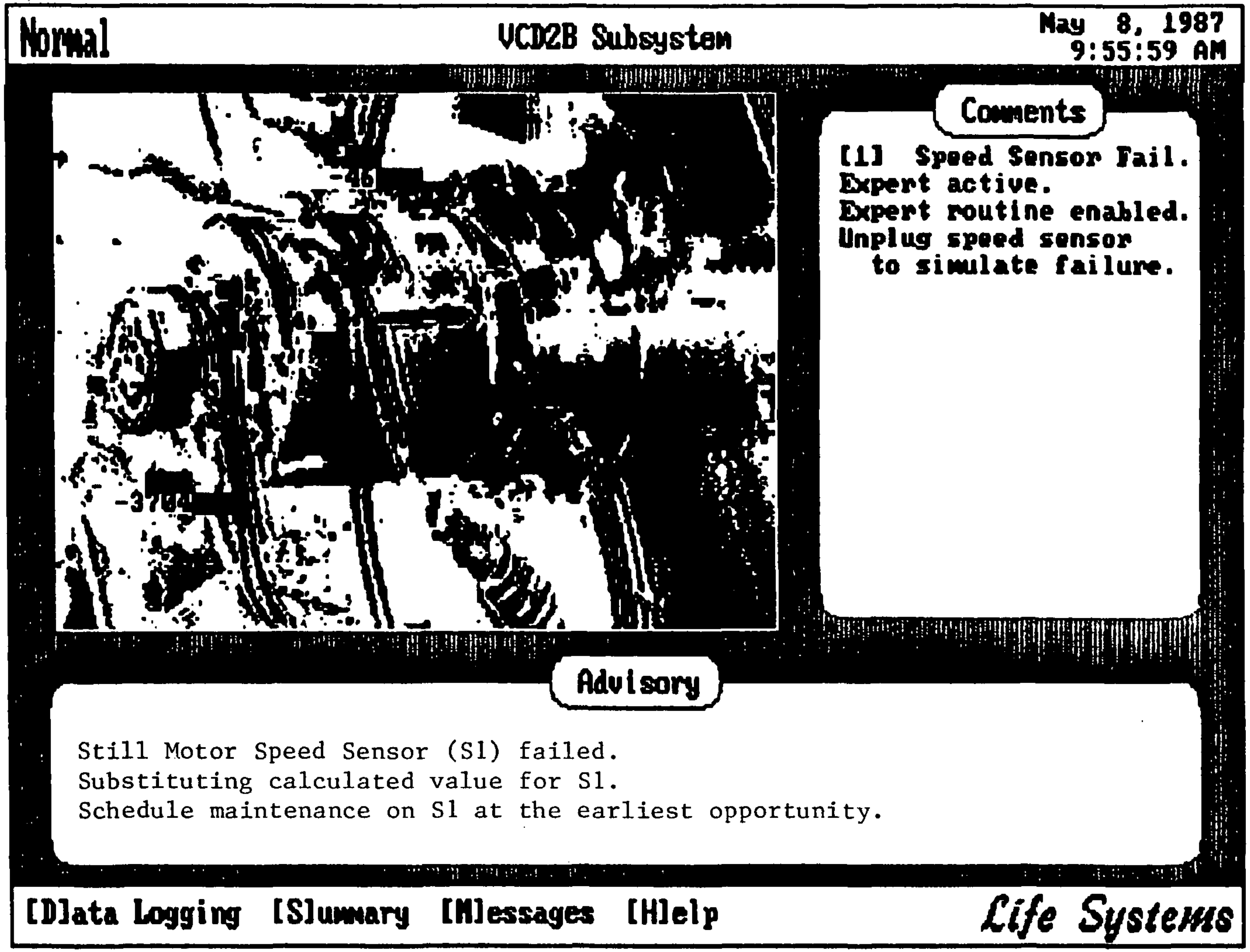

FIGURE 12 EXPERT DEMONSTRATION SAMPLE SCREEN - EXAMPLE 1

TABLE 14 EXAMPLE 1 - SPEED SENSOR FAILURE

Description:

Speed Sensor, S1, is disconnected to simulate a failure of the sensor.

Demonstrates:

How an expert can recognize the failure and continue operation by deriving a value for S1 from sensor S3 reading and known interrelation of S1/S3.

Without Expert:

S1 low alarm indication.

Subsystem shuts down immediately.

With Expert:

Speed sensor is identified as failed. Subsystem continues normal operation.

Value for S1 is substituted by calculation using S3 reading.

Control loop for still motor speed continues to function with no specific knowledge of a fault.

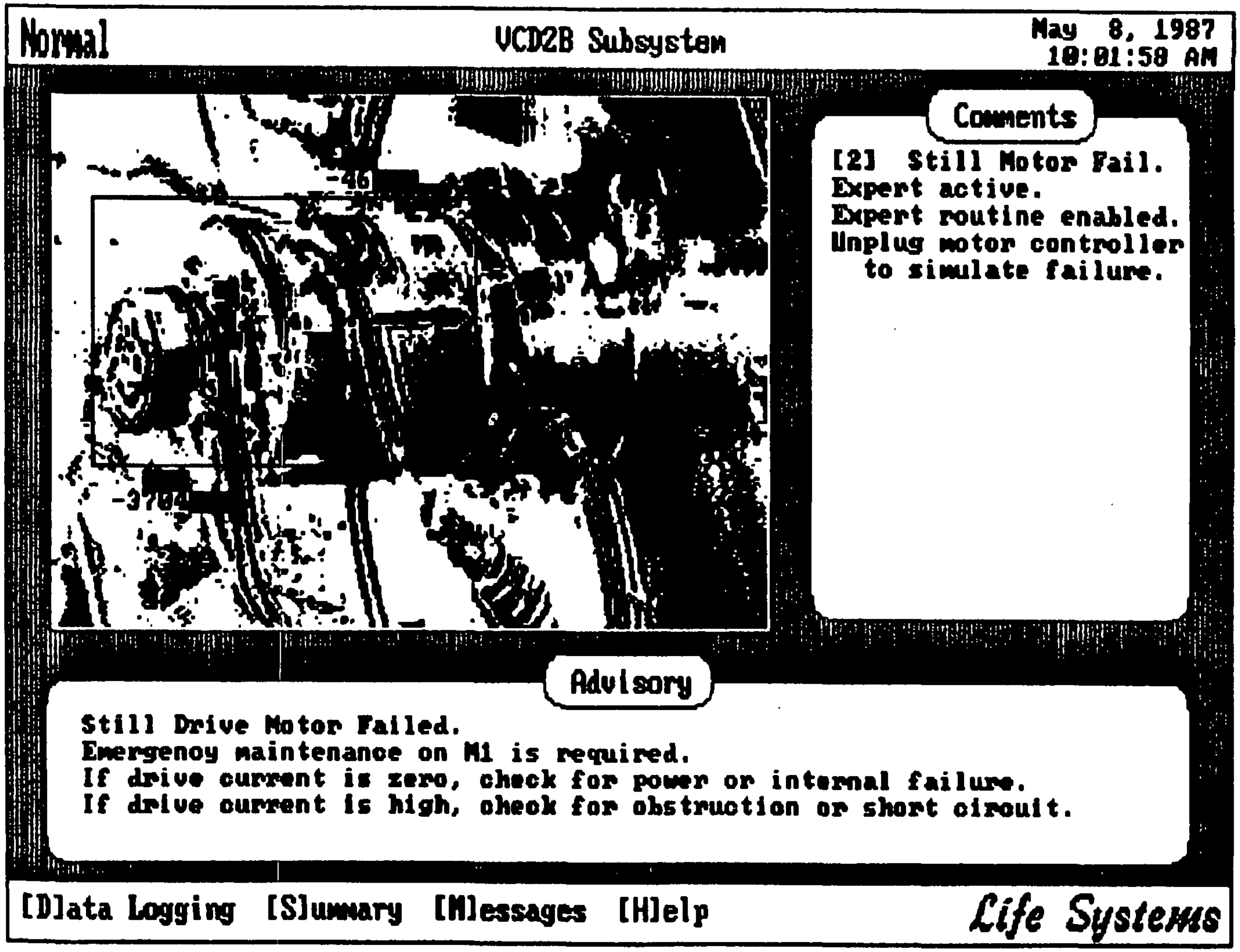

FIGURE 13 EXPERT DEMONSTRATION SAMPLE SCREEN - EXAMPLE 2

TABLE 15 EXAMPLE 2 - STILL DRIVE MOTOR FAILURE

Description:

Drive Motor is disconnected to simulate the failure of the motor.

Demonstrates:

How expert knowledge of the subsystem components can be used to more effectively identify and isolate the source of the failure, reducing the time to repair. Also shows how expert suggestions and recommendations can be incorporated into fault diagnostic logic.

Without Expert:

Subsystem shuts down immediately with only a single alarm message indicating Low S1 reading.

With Expert:

Low S1 reading is verified by comparable Low S3 reading, eliminating speed sensor failure as cause, identifying drive motor as failed component.

Suggestions for verification of type of motor failure are presented, based on current being drawn by motor.

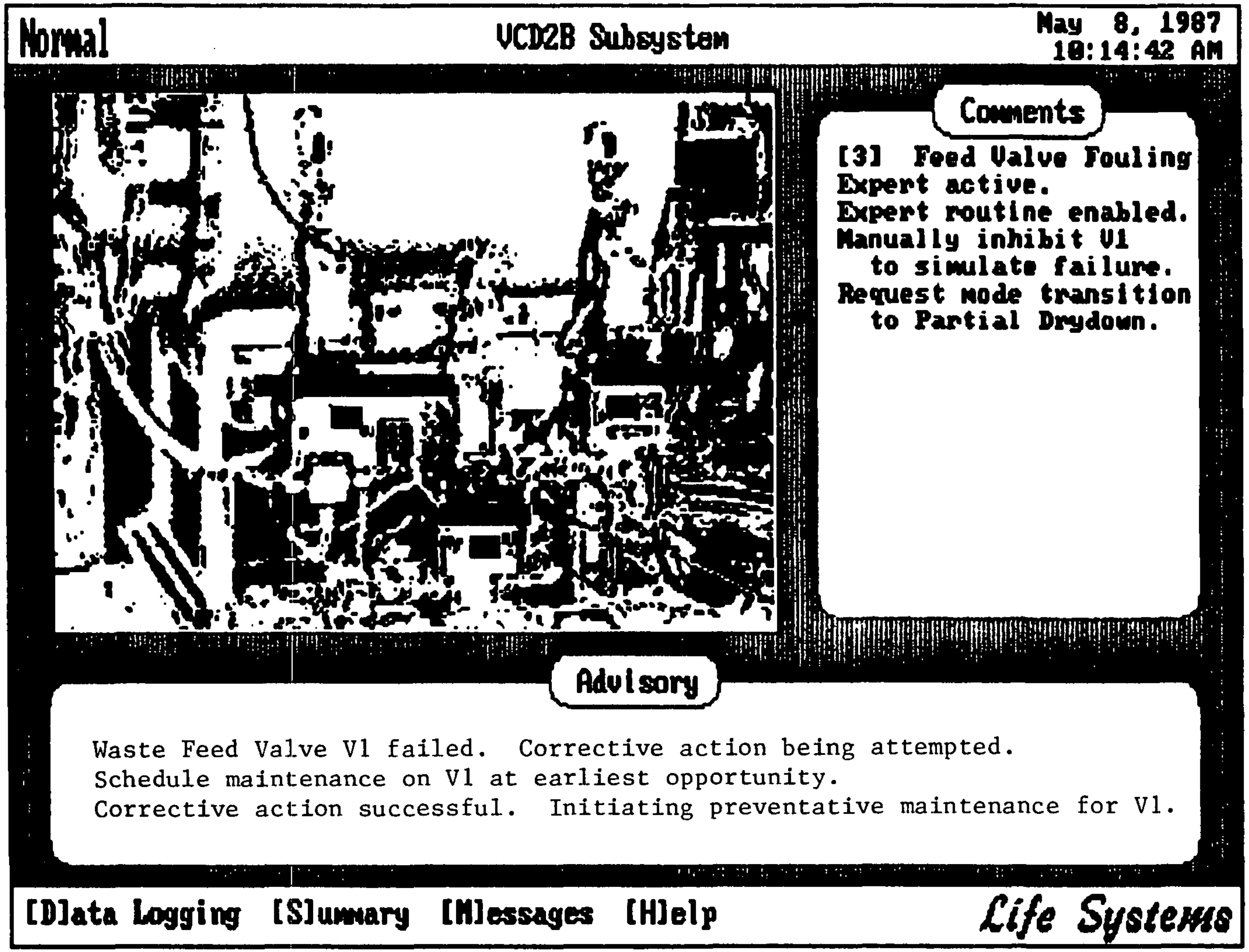

FIGURE 14 EXPERT DEMONSTRATION SAMPLE SCREEN - EXAMPLE 3

TABLE 16 EXAMPLE 3 - WASTE FEED VALUE FOULING

Description:

Waste Feed valve is physically inhibited from reaching a new position.

Demonstrates:

How expert knowledge of the subsystem operation can be used to correct fault conditions and prevent shutdown. Further, such knowledge can be used to perform preventative maintenance on some components.

Without Expert:

Failure to reach position causes an immediate shutdown of subsystem with an alarm message indicating the failure.

With Expert:

Valve is cycled back and forth three times to attempt to free up the valve. When this succeeds, demonstrated by removing the impediment, a cycle of automatic preventative maintenance is instituted. The subsystem continues normal operation.

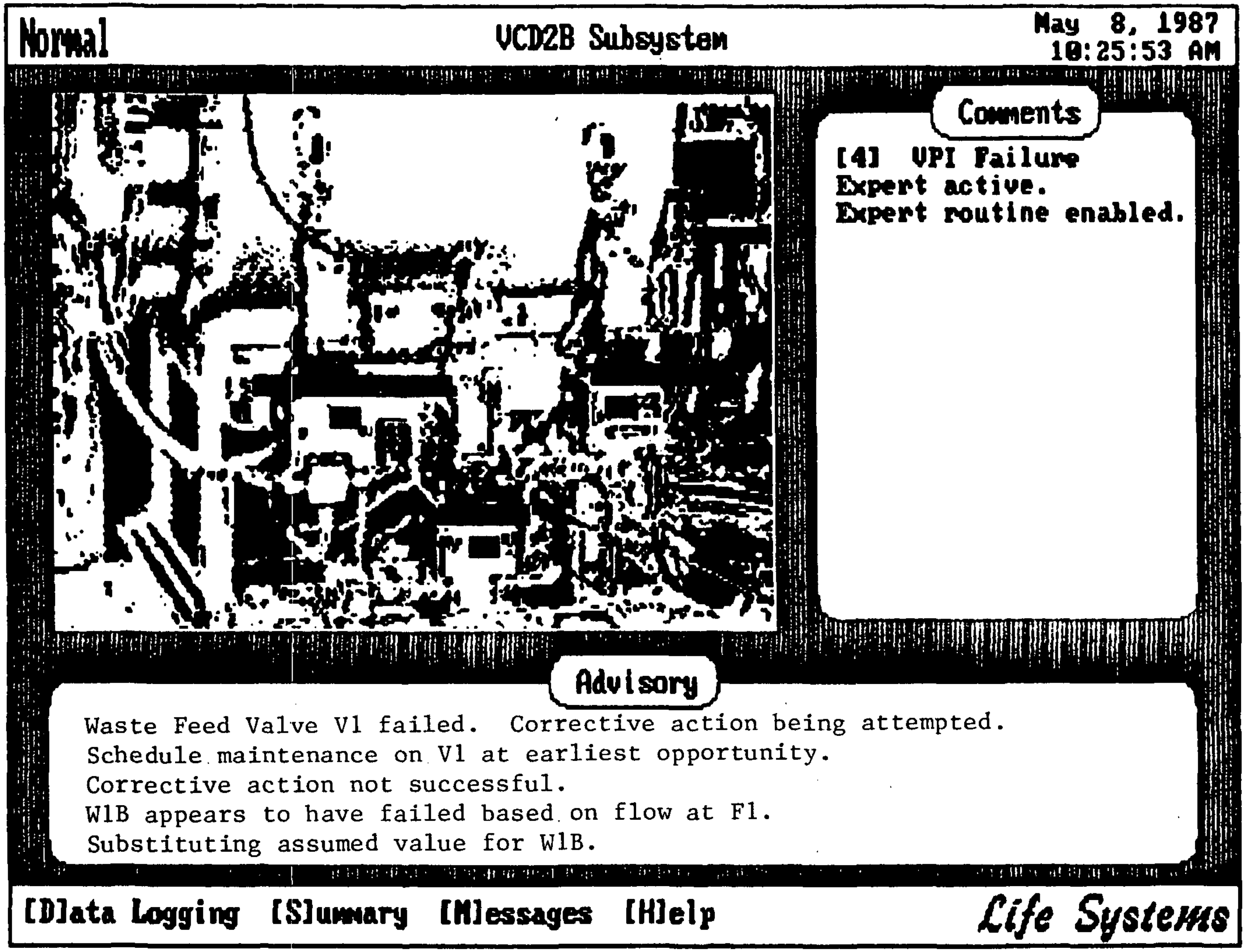

FIGURE 15 EXPERT DEMONSTRATION SAMPLE SCREEN - EXAMPLE 4

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TABLE 17 EXAMPLE 4 - VPI FAILURE

Description:

The failure of a valve position indicator is demonstrated by overriding the VPI sensor reading.

Demonstrates:

How multiple levels of expert knowledge can be applied to a failure. Also demonstrates how knowledge of the relations between sensors and actuators can be used to indirectly deduce the actual state of certain actuators (valves).

Without Expert:

Failure to reach position is detected (erroneously) and an immediate shutdown of the subsystem occurs.

With Expert:

A fouled valve is first suspected and that corrective logic is attempted first. When this fails, the operation of the VPI is verified using knowledge of flow at F1. The failed VPI is identified and a value for it is substituted based on the measured flow. A warning message is issued identifying the VPI failure, but the subsystem continues to function.

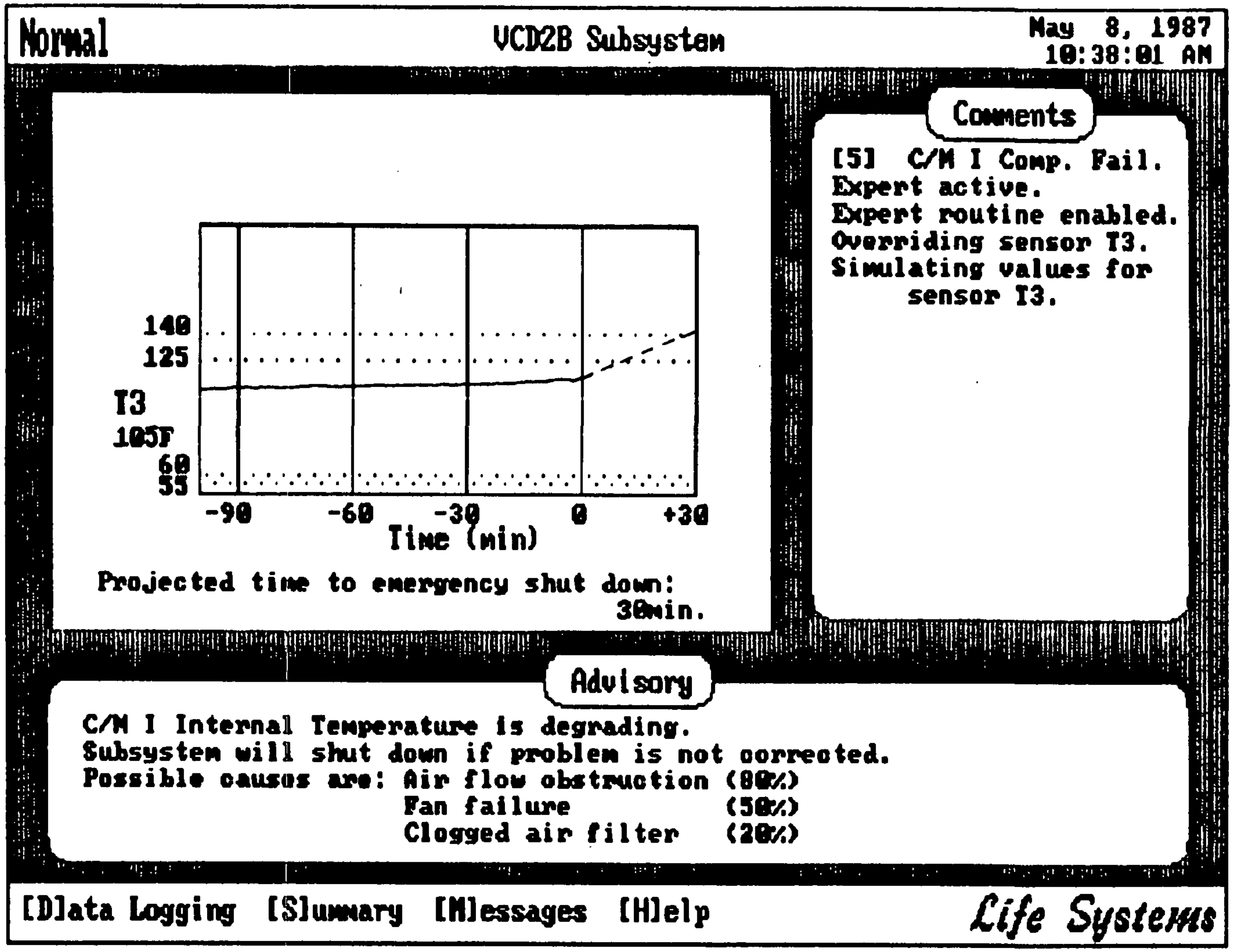

FIGURE 16 EXPERT DEMONSTRATION SAMPLE SCREEN - EXAMPLE 5

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TABLE 18 EXAMPLE 5 - C/M I COMPONENT FAILURE

Description:

Simulation of failure of C/M I cooling.

High temperature would eventually cause a failure in the integrated circuits and the subsystem would shut down before this point is reached.

Demonstrates:

How an expert can recognize an impending failure and provide warning that a condition is developing which, if not corrected, could result in shut down of the subsystem. Also shows how expert knowledge can suggest possible causes to assist in correcting the problem.

Without Expert:

Temperature rises with no advance warning until fault detection limits are encountered. Subsystem eventually shuts down.

With Expert:

Initial warning is given based on trend of temperature before fault detection limits are reached. This provides additional time to correct the problem. Possible causes are listed to aid in locating and correcting the problem.

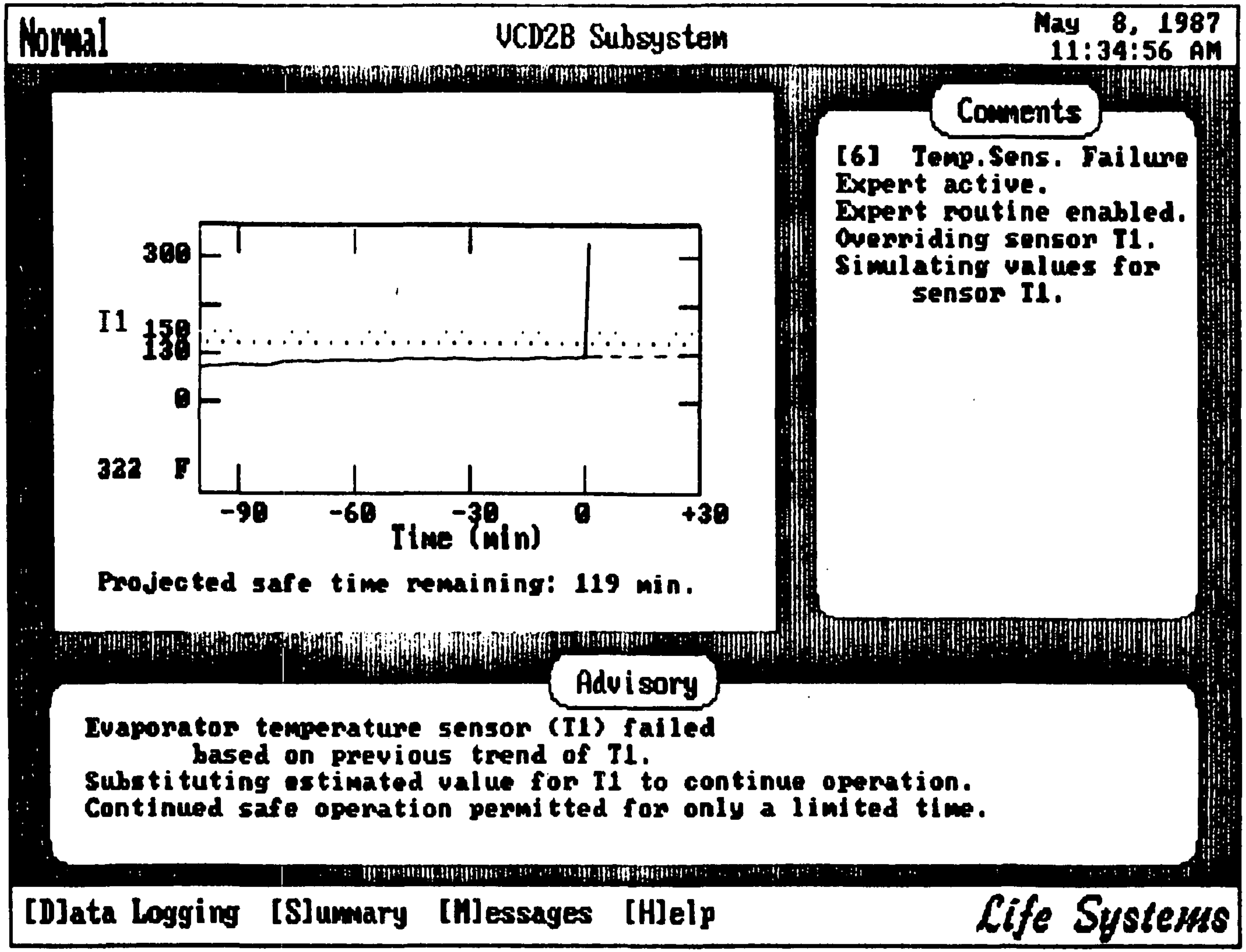

FIGURE 17 EXPERT DEMONSTRATION SAMPLE SCREEN - EXAMPLE 6

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TABLE 19 EXAMPLE 6 - TEMPERATURE SENSOR FAILURE

Description:

Failure of a temperature sensor is simulated by overriding the sensor reading.

Demonstrates:

How expert knowledge of the subsystem can identify invalid readings and can make a judgment concerning continuing operation.

Without Expert:

Subsystem shuts down immediately.

With Expert:

Instantaneous change in temperature reading is recognized as invalid and a result of sensor failure. No backup sensor is available, but based on theoretical maximum rate of change of temperature, subsystem is permitted to continue operation for a period of two hours, thus extending operating time and allowing more time for maintenance preparations.

The first example (Figure 12, Table 14) illustrates the failure of a sensor by manually disconnecting the speed sensor S1. This example is used to demonstrate the fault tolerance of a subsystem by recognizing the failure of the sensor and deriving a value from a known relationship with another sensor on the subsystem. In this case, operation of the subsystem can be continued without a shutdown. The expert system automatically substitutes a calculated value for the failed sensor and normal control algorithms within the subsystem controller continue without any interruption. Note also that an automatic maintenance scheduling algorithm can easily be implemented using an expert system. The fault detection and isolation mechanisms inherent in the EFD function makes such maintenance scheduling easy to implement. Note also that on the graphic display associated with this example the operator is presented with a picture of the subsystem where the failed component is highlighted so it may be easily located and repaired or replaced.

The second example (Figure 13, Table 15), that of still drive motor failure, is related to the first in that it illustrates how an expert system must be able to distinguish between a number of faults which may have similar symptoms. In this case, the failure of the still drive motor also results in a low reading on the speed sensor. In this case, however, the comparison between the two speed sensors can isolate for the expert system the fact that it is not a sensor failure in this case, but a failure of the drive motor. Note also that the advisories issued by the expert system provide the operator with additional information in determining the exact cause of the failure. In this case, the expert system itself cannot determine the absolute cause of the failure because it does not have access to a drive current sensor reading. Even in cases such as this, however, the expert system can provide additional diagnostic assistance by providing a check list to the operator which could be used to determine the ultimate cause of the subsystem fault.

The third example (Figure 14, Table 16) concerns a degradation in the operation of a valve on the subsystem. The condition simulated here was one that actually occurred during testing and was identified in the analysis of past VCD failures. Under certain conditions, deposits can build up on the valves which inhibit their operation. When this occurs, the valve may not reach the position that is requested of it by the subsystem controller. Ordinarily, this would cause an immediate shutdown of the subsystem. When this problem is encountered by an expert, it is generally alleviated by cycling the valve back and forth a number of times to free up the sticky mechanism. The expert system rules implemented in this case attempt to perform the same operation to free up the valve. This example also illustrates how an expert system can be set up to provide automatic preventive maintenance on various components. In this case, if the corrective action on the sticking valve is successful, the expert system then periodically cycles the valve back and forth to prevent such a buildup from occurring again.

The fourth example (Figure 15, Table 17) also relates to the valve operation and shows how various expert system rules can interact. In this example, the failure of the Valve Position Indicator (VPI) at first looks to the expert system as the same situation as the sticky valve in the previous example. As a result, the expert system first attempts the same corrective action, but when this fails, then looks further on into the system to try to determine whether it is a VPI that has failed. In this case, it uses the knowledge of flow in a particular line which is downstream of the valve to determine the actual position of the valve. Using this expert knowledge of the subsystem, it can then continue operation of the subsystem and avoid a shutdown in the event of this sensor failure.

The fifth example (Figure 16, Table 18) illustrates how an expert system can be used to predict a fault before it actually occurs. In this case, the internal temperature of the subsystem controller is being monitored. An excessively high temperature could result in misoperation of the subsystem controller and loss of control of the subsystem. To avoid this, alarm limits are placed and automatic shutdown is initiated if this temperature goes too high. A failure of the cooling system is simulated in this instance causing a drastic increase in the temperature over time. By projecting the temperature at a future point in time, the expert system is able to give additional warning to the operator to allow him to correct the problem before shutdown of the subsystem is necessary. The expert system is also able to advise the operator as to the probable cause of this failure of the cooling system. Based on its knowledge of the subsystem, the historical trend of the temperature, and the maintenance history of the cooling system in particular, the expert system is able to provide a prioritized list of possible causes of the failure. The expert system is not able to automatically correct this problem, but it is able to guide the operator.

The last example (Figure 17, Table 19) also illustrates a problem with the temperature on the subsystem. The difference in this case is that the temperature changes dramatically in a very short period of time rather than as a longer-term trend. The expert system can, thus, recognize a failure of the temperature sensor due to the fact that it has knowledge of the maximum rate of change of this particular variable on the subsystem. Also illustrated in this example, is the concept of a safe operating time. While the expert system does not immediately shut down the subsystem, it also cannot permit the subsystem to continue operation indefinitely. The sensor which has failed, while not critical to the short-term operation of the system, is critical in a longer-term sense. Therefore, the expert system permits operation in this degraded mode for only a limited amount of time.

All of these examples illustrate how the concept of EFDs and an expert system implementation can extend the operating time of the subsystem or reduce the down time of a subsystem in the event of a critical failure. It can do this by making use of the knowledge of a subsystem expert and by communicating that knowledge to the system operator.

Conclusions

The expert demonstration system implemented under this study has shown that EFD concepts can extend the operating time of an ECLSS. It can also reduce the time to repair the subsystem by identifying the source of the failure to an operator. It has also shown that these concepts can be applied to existing subsystems by using an unmodified VCDS and subsystem controller to implement the expert system rules selected in this demonstration. Also, by using an architecture similar to that which exists on the current generation of subsystem controllers, it has demonstrated that the expert systems and EFD concepts illustrated here can be implemented using existing controllers.

APPLICATION TO OTHER ENVIRONMENTAL CONTROL AND LIFE SUPPORT SUBSYSTEMS

The demonstration with an operating VCDS has shown the practicality and effectiveness of an EFD system applied to one particular subsystem of the ECLSS. An analysis of the architecture and components of the other ECLSS was undertaken to assess the applicability of these concepts to other subsystems.

Implementation Within Existing Controllers

Figure 18 illustrates the software architecture of a typical subsystem controller of the ECLSS group. The operating system software has responsibility for all common functions to be performed, such as reading values of sensors and outputting commands to actuators. These operations can be tailored to individual subsystems by tables describing, for example, the sensor or actuator complement in the data base for each subsystem. The application software contains the custom processing required for a particular subsystem, such as control loop and device driver handling or special calculations. Table 20 shows some detail of this organization for a typical subsystem. This modular software architecture lends itself quite well to the addition of expert logic. Table 21 shows where expert systems could be implemented within such a controller. Note that the fault isolation, fault correction, fault prediction and fault tolerance modules have been reassigned from the operating system fault diagnostic group to the application side of the organization. This reflects the detailed knowledge of the subsystem expert that is used in developing the expert system rules. To properly perform these functions, detailed and specific subsystem knowledge is essential.

Thus, the software architecture of the ECLSS controllers can be seen to be compatible with the implementation of expert systems. Further, since the described organization is common to a number of ECLSS controllers, the application of expert fault logic to other ECLSSs should be a reasonable expectation.

Generic Faults Within Environmental Control and Life Support Subsystems

An investigation of all of the subsystems of the ECLSS group was conducted to identify those components which could be considered common, or generic, among all of the subsystems. Figure 19 shows the functional partitioning used in the analysis, and Table 22 lists the distribution of the generic faults previously identified from the VCDS study. It can readily be seen that this analysis also supports the idea of applying similar expert systems logic to all of the other groups of the ECLSS.

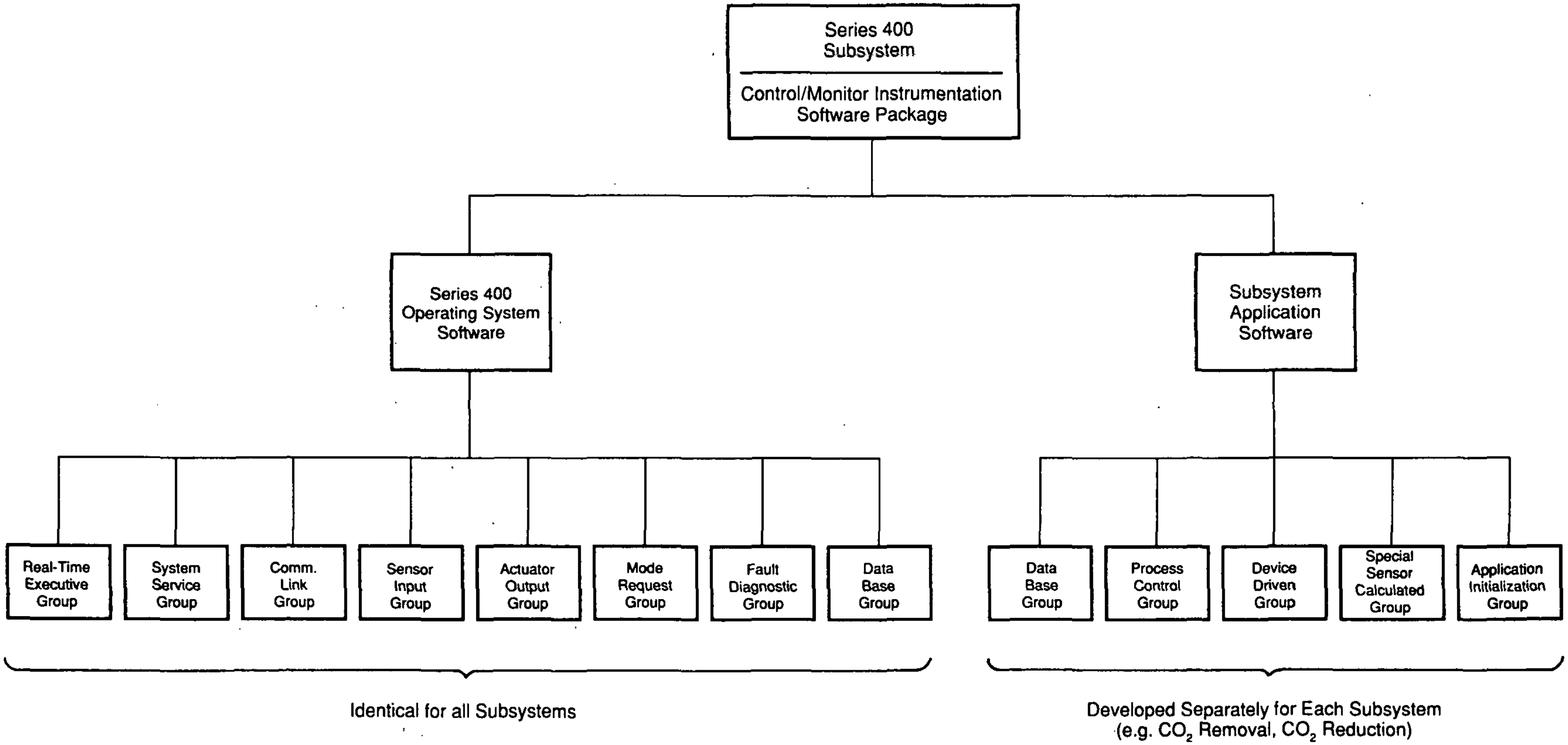

FIGURE 18 SERIES 400 SUBSYSTEM SOFTWARE ORGANIZATION

TABLE 20 EXPERT SYSTEM IMPLEMENTATION WITHIN EXISTING CONTROLLERS

Current Organization

Operating System		
	Fault Diagnostic Group	Fault Detection Fault Isolation Fault Correction[a] Fault Prediction[a] Fault Tolerance[b]
Application		
	Process Control Group	Pressure Control Recycle Control Quantity Control Quality Control Level Control Percent Solids Control
	Special Sensor Calculation Group	Solids Concentration Quantity Processed

(a) Not currently implemented.
(b) Triple redundant sensors only.

TABLE 21 EXPERT SYSTEM IMPLEMENTATION WITHIN EXISTING CONTROLLERS

	Future Organization	
Operating System		
Fault Diagnostic Group	- Fault Detection	
Application		
Fault Diagnostic Group	- Fault Isolation Fault Correction Fault Prediction Fault Tolerance	Expert Systems Implementation
Process Control Group	- Pressure Control Recycle Control Quantity Control Quality Control Level Control Percent Solids Control	
	Enhanced Control	Expert Systems Implementation
Special Sensor Calculation Group	- Solids Concentration	
	Quantity Processed Composite Sensors Sensor Substitution	Expert Systems Implementation

ECLSS

"Embodying regenerative concepts to minimize the use of expendibles."
RFP for Space Station

Atmosphere Revitalization System[(b)]

- CO_2 Concentration
- CO_2 Reduction
- O_2 Generation
- Repressurization O_2 Storage
- N_2 Supply[(e)]
- Trace Contaminant Control[(f)]
- Atmosphere Quality Monitor[(g)]

Atmosphere Pressure and Composition Control System[(b)]

- Composition Control and Monitor
- Pressure Control
- Vent and Pressure Relief
- Smoke Detection
- Fire Suppression

Module Temperature and Humidity Control System[(b)]

- Temperature Control[(h)]
- Humidity Control[(h)]
- Ventilation Control

- Equip. Atm. Cooling
- Refrigerator/Chiller
- Freezer

Water Management System[(c)]

- Water Collection[(i)]
- Phase Change Water Processing[(j)]
- Filtration Water Processing[(j)]
- Reuse to Potable Post-treatment
- Water Dispensing

- Hot Water Outlet
- Cold Water Outlet
- Hot Water Heater
- Hand Wash
- Full Body Shower

Waste Management System[(c)]

- Toilet and Urinal[(k)]
- Urinal[(l)]

- Housekeeping Equip.[(o)]
- Trash Compactor[(p)]
- Compacted Solids Storage[(p)]

EVA Support

- EMU Servicing/ Checkout[(m)]
- MMU Servicing[(m)]

- [(n)]

Safe Haven[(d)]

- CO_2 Removal
- O_2 Supply Access
- N_2 Supply Access
- Trace Contamination Control
- Humidity Removal Access
- Potable Water Storage
- Wastewater Storage Access
- Fecal Collection
- Urine Collection
- Fire Suppression Equipment (Portable)

- Emergency Breathing Packs
- Hygiene Wipes
- Clothing Storage
- Food Storage
- Sleeping Restraints

(a) Per Space Station Definition and Preliminary Design RFP, 09/15/84.
(b) Part of an Atmosphere Management Function (Group).
(c) Part of a Water and Waste (Liquid) Management Function (Group).
(d) Safe Haven provisions for food storage, health maintenance, personal hygiene (e.g., hygiene wipes, clothing storage), sleeping, communications and command/control are not included since assumed not part of ECLSS.
(e) Includes provisions for Module/Station leakage make-up and one complete Station repressurization.
(f) Including odor and microbial contamination control.
(g) Including microbial assessment.
(h) Controlled in each pressurized module.
(i) Including necessary pretreating of wastewater and segregation of the collected water as needed.
(j) Including necessary Post-Treatment, Water Quality Monitoring, Biocide Addition, Biocide Monitor and Concentrated Waste Liquid Storage.
(k) Assumes it contains provisions for disposing of or processing the material collected.
(l) Includes pretreatment as part of "flushing" function, e.g., urine will be processed in the Phase Change Water Processing subsystem.
(m) Within the Airlocks.
(n) Including Airlock Depressurization/Repressurization.
(o) Hygiene wipes and vacuum cleaner.
(p) ECLSS Related only.

FIGURE 19 FUNCTIONAL PARTITIONING OF SPACE STATION ECLSS[(a)]

TABLE 22 DISTRIBUTION OF GENERIC FAULTS WITHIN SPACE STATION ECLSS[(a)]

Generic Fault Description	ARS	APCCS	THCS	WMS	WRS	EVA Support	Safe Haven
Valve Motor Degradation	X	X	X	X	X	X	X
Valve Motor Breakage	X	X	X	X	X	X	X
VPI Failure	X	X	X	X	X	X	X
Check Valve Degradation	-	-	-	X	X	X	X
Valve Degradation	-	-	-	X	X	X	X
Valve Breakage	X	X	X	X	X	X	X
Valve Position Error	X	X	X	X	X	X	X
MCV Body Leakage	-	-	-	-	X	X	X
MCV Resin Depleted	-	-	-	-	X	X	X
MCV Resin Blockage (Degradation)	-	-	-	-	X	X	X
MCV Body Breakage	-	-	-	-	X	X	X
Sensing Element Leakage	-	X	-	X	X	X	X
Sensing Element Electrical	X	X	X	X	X	X	X
Sensing Element Degradation	X	X	X	X	X	X	X
Sensing Element Breakage	X	X	X	X	X	X	X
Pump Motor Electrical	-	-	-	X	X	X	X
Pump Motor Degradation	-	-	-	X	X	X	X
Pump Motor Breakage	-	-	-	X	X	X	X
Tank Leakage	-	-	-	-	X	X	X
Tank Degradation	-	-	-	-	X	X	X
Tank Breakage	-	-	-	-	X	X	X
Pump Degradation	-	-	-	X	X	X	X
Pump Breakage	-	-	-	X	X	X	X
Pump Casing Vacuum Leakage	-	-	-	X	X	X	X
Gearbox (Drive) Degradation	-	-	-	X	X	X	X
Gearbox (Drive) Breakage	-	-	-	X	X	X	X
Compressor (Pump) Breakage	-	-	-	-	X	-	X
Compressor (Pump) Degradation	X	X	-	-	X	X	X
Filter Blockage (Degradation)	X	X	X	X	X	X	X
Filter Leakage	X	X	X	X	X	X	X

(a) 01/09/86 Version.
Abbreviations:
APCCS = Atmosphere Pressure and Composition Control System
ARS = Air Revitalization System
EVA = Extravehicular Activity
MCV = Microbial Check Valve
THCS = Temperature and Humidity Control System
WMS = Waste Management System
WRS = Water Reclamation System

Table 23 describes the logic used in analyzing these generic faults. For this logic to be applied to a number of other subsystems, there must be a way to relate the general statements to the specific sensors and actuators used in each individual subsystem. In the context of expert systems, this means that the knowledge base developed must include specific relations between, and among, the individual sensors and actuators of each subsystem. The rule base would be specified in such a way as to describe the general relationships which are exploited in analyzing a particular fault. For example, in describing the logic involved in monitoring a filter, the rule base would contain statements such as:

Rule 1. If downstream flow rate for filter is less than 50% of original flow rate, then filter is degraded.

Rule 2. If upstream pressure for filter is greater than 150% of original pressure, then filter is degraded.

Rule 3. If time since last maintenance for filter is greater than 80% of maintenance interval, then filter is degraded.

The knowledge base would also contain specific facts concerning each subsystem such as:

Fact 1. VCD-FLTR is a filter
Fact 2. Downstream flow rate for VCD-FLTR is VCD-F1
Fact 3. Upstream pressure for VCD-FLTR is VCD-P3
Fact 4. Original flow rate for VCD-F1 is VCD-CALC2
Fact 5. Original pressure for VCD-P3 is VCD-CALC5
Fact 6. Time since last maintenance for VCD-FLTR is timer VCD-Z152
Fact 7. THCS-FLTR is a filter
Fact 8. Upstream pressure for THCS-FLTR is THCS-P6
Fact 9. Original pressure for THCS-FLTR is THCS-CALC8

Facts 1 to 6 relate specifically to the VCD filter, while facts 7 to 9 identify a filter in the THCS. The inference engine would then use the rule for finding a degraded (blocked) filter on either subsystem using the specific facts identifying individual sensors where required. In some cases, certain facts may not be available. For example, the THCS in this example does not have a downstream flow sensor. The expert system would have to deal with these variances. It would also be advisable to include in the system some certainty, or confidence, factors associated with each fact or rule. Rule 3, for example, is not necessarily strictly true, but represents a "good guess." Missing information, such as the THCS flow sensor, could also be handled with such a factor.

There are some situations which may have to be treated in a more specialized manner. For example, sensor breakage or degradation may not be able to be generalized for all sensors on all subsystems. However, it may be possible to treat all flow sensors, or all pressure sensors, the same. Further, there might be a class of rules applicable to all sensors, and then sets of rules which would apply only to certain types of sensors, such as flow or pressure

TABLE 23 SPECIFIC LOGIC USED IN ANALYZING A FAULT TYPE

Fault Type	Logic Description
Tank Breakage	Tank quantity does not change properly in relation to process operation. Loss of fluid outside of process is detected. Physical inspection shows serious mechanical failure of tank.
Tank Leakage	Tank quantity does not change properly in relation to process operation. Loss of fluid outside of process is detected. Physical inspection shows no serious mechanical failure of tank.
Tank Degradation	Tank quantity changes erratically or not at all in relation to process operation. No loss of fluid outside of process is detected. Physical inspection of bellows or rolling diaphragm shows fouling (sticking).
Sensor Breakage	Sensor reading is not changing with process or is reading highly suspect value. Physical inspection shows mechanical damage.
Sensor Degradation	Sensor reading in relation to process varies in one direction over period of time. Replacement returns operation to normal.
Sensor Electrical	Sensor reading is not changing with process or is reading erratic values. Sensor calibration values are extreme or erratic. Sensor reading in relation to process varies over time. Replacement returns operation to normal.
Sensor Leakage	Loss of fluid outside of process is detected. Physical inspection shows failure of seal on sensor mounting. Replacement or re-seating returns operation to normal.
Motor Breakage	Motor speed is erratic or zero. Motor sound changes characteristics. Motor vibration increases when running. Physical inspection shows mechanical damage.
Motor Degradation	Motor speed becomes erratic. Motor sound changes characteristics. Motor vibration increases when running. Physical inspection shows no mechanical damage. Replacement returns operation to normal.

continued-

Table 23 - continued

Fault Type	Logic Description
Motor Electrical	Unable to start or stop motor. Unable to adjust speed of motor. Motor speed varies over period of time.
Drive Breakage	Driven component's speed is erratic or zero. Driving motor is operating properly. Physical inspection shows mechanical damage.
Drive Degradation	Driven component's speed is erratic. Driven component's sound changes characteristics. Driven component's vibration increases when running. Physical inspection shows no mechanical damage. Replacement returns operation to normal.
Pump Breakage	Measured output is erratic or zero. Pump sound changes characteristics. Pump vibration increases when running. Physical inspection shows mechanical damage.
Pump Degradation	Measured output decreases or becomes erratic. Pump sound changes characteristics. Pump vibration increases when running. Physical inspection shows no mechanical damage. Replacement returns operation to normal.
Pump Leakage	Loss of fluid outside of process is detected. Physical inspection shows failure of seal. Replacement or re-seating returns operation to normal.
Valve Breakage	Loss of fluid outside of process is detected. Unable to change valve position. Physical inspection shows mechanical damage.
Valve Degradation	Flow rate decreases over time for a given open position or flow rate is not zero with valve closed. Valve does not respond to initial attempt to change position, but does respond after repeated attempts. Physical inspection shows no mechanical damage. Replacement returns operation to normal.
Valve Leakage	Loss of fluid outside of process is detected. Physical inspection shows failure of seal. Replacement or re-seating returns operation to normal.
Valve Position Error	Valve does not respond to attempt to change position. Physical inspection shows no mechanical damage. Replacement returns operation to normal.

continued-

Table 23 - continued

Fault Type	Logic Description
Valve Position Indicator Electrical	Indicated valve position does not reflect last requested position. Process measurements or observation confirm actual position of valve is requested position. Replacement returns operation to normal.
Check Valve Breakage	Loss of fluid outside of process is detected. Physical inspection shows mechanical damage.
Check Valve Leakage	Loss of fluid outside of process is detected. Physical inspection shows failure of seal. Replacement or re-seating returns operation to normal.
Check Valve Degradation	Forward flow rate decreases over time. Backward flow is non-zero when flow should be inhibited. Replacement returns operation to normal.
MCV Breakage	Loss of fluid outside of process is detected. Physical inspection shows mechanical damage.
MCV Leakage	Loss of fluid outside of process is detected. Physical inspection shows failure of seal. Replacement or re-seating returns operation to normal.
MCV Resin Breakthrough	Contamination of process is detected. Physical inspection shows breakthrough. Replacement returns operation to normal.
MCV Resin Degradation	Forward flow rate decreases over time. Contamination of process increases over time. Backward flow is non-zero when flow should be inhibited. Replacement returns operation to normal.
MCV Resin Depletion	Contamination of process is detected. Physical inspection shows no breakthrough. Replacement returns operation to normal.
Filter Degradation	Flow rate decreases over time. Upstream pressure increases over time. Time since last maintenance approaches maintenance interval. Physical inspection shows fouling. Replacement returns operation to normal.
Filter Leakage	Loss of fluid outside of process is detected. Physical inspection shows failure of seal. Replacement or re-seating returns operation to normal.

sensors. Substitution for failed sensors might be handled generally in some cases, or individually by special cases where general rules cannot be applied either due to a lack of the necessary sensors for substitution or the use of specialized sensors.

Table 24 lists the identified generic faults and the areas within the Space Station ECLSS where the associated fault diagnostic routines could be applied.

In general, it appears that the EFDs developed here will be easily applicable to a number of other ECLSSs. Both the general approach, as well as some of the specific rules formulated could be transferred to new applications.

Location of Expert Logic

This analysis has identified six specific types of expert systems routines that may be located within the Space Station ECLSS. They are fault avoidance, fault prediction, fault detection, fault isolation, fault correction, and fault tolerance. Fault avoidance attempts to prevent faults from occurring. This can be accomplished by monitoring the maintenance intervals required on the subsystems' components and ensuring that proper maintenance is performed, and also by preventing erroneous actions either by a human operator or by subsystem interaction. Fault prediction routines monitor the subsystems in an attempt to predict when a fault condition is beginning or when it might occur in the future. Fault detection routines monitor the subsystem for an imminent failure or symptoms of a failure as it is occurring. Fault isolation routines then attempt to determine specifically which component caused the failure. Fault correction routines attempt to maintain system operation by correcting the cause of the error. This may be accomplished by substituting for failed units or by entering an alternate operating mode which then corrects the condition of the subsystem which was detected as a fault. Fault tolerance is related to fault correction but it is not an attempt to actually correct the fault. Fault tolerance routines instead would attempt to continue operation of the subsystem, perhaps in a degraded mode, by bypassing the faulty components in some manner.

Figure 20 illustrates the hierarchy of controllers which is the current Space Station automation concept. Within this hierarchy there are a number of locations where expert system routines might be applied. At the lowest level is the subsystem controller which provides localized control over individual subsystems such as oxygen generation or wastewater recovery. At a higher level is the system controller which monitors an entire family of subsystems. This controller provides a centralized, supervisory form of control. Above the system controller is the module controller which has responsibility for an entire module of the Space Station. This controller again would operate in a supervisory control mode providing high level commands to the individual system controllers and, from there, to the subsystems. Some types of expert system routines could be located in any one of the levels of control within the Space Station.

TABLE 24 APPLICATION OF GENERIC FAULT ROUTINES WITHIN SPACE STATION ECLSS

Fault Type	Application
Tank Breakage Tank Leakage Tank Degradation	All subsystems; any storage tank or temporary fluid reservoir having a level sensing element.
Sensor Breakage Sensor Degradation Sensor Electrical	All subsystems; any sensing elements.
Sensor Leakage	All subsystems which have fluid flow; any sensing elements related to fluid flow.
Motor Breakage Motor Degradation	All subsystems; any electrical motor controlled by the subsystem having a speed sensor and/or sound/vibration sensors.
Motor Electrical	All subsystems; any electrical motor controlled by the subsystem having a speed or on/off sensor.
Drive Breakage Drive Degradation	All subsystems containing components which are driven through a power transfer system (gears, belts, pulleys, etc.); any power transfer assembly with associated speed, motor condition and/or sound/vibration sensors.
Pump Breakage Pump Degradation	All subsystems which have fluid pumps or compressors; any pump or compressor which has output sensors, and/or input and sound/vibration sensors.
Pump Leakage	All subsystems which have fluid pumps or compressors; any pump or compressor which has an external fluid loss sensor.
Valve Breakage Valve Position Error Valve Position Indicator Electrical	All subsystems; any valve, controlled by a subsystem, which has position sensors or fluid flow sensors.
Valve Leakage	All subsystems; any valve which has an external fluid loss sensor.
Valve Degradation	All subsystems containing corrosive or contaminated fluids; any valve, controlled by a subsystem, which has position sensors or fluid flow sensors.
Check Valve Breakage Check Valve Leakage	Any check valve which has associated flow rate sensors and/or external fluid loss sensor.

continued-

Table 24 - continued

Fault Type	Application
Check Valve Degradation	Any check valve which has associated flow rate sensors.
MCV Breakage MCV Leakage	Any MCV having an external fluid loss sensor.
MCV Resin Degradation	Any MCV having associated contamination sensors and/or flow rate sensors.
MCV Resin Breakthrough MCV Resin Depletion	Any MCV having associated contamination sensors.
Filter Degradation	All subsystems; any filter having an associated pressure and/or flow rate sensor.
Filter Leakage	All subsystems; any filter having an external fluid loss sensor.

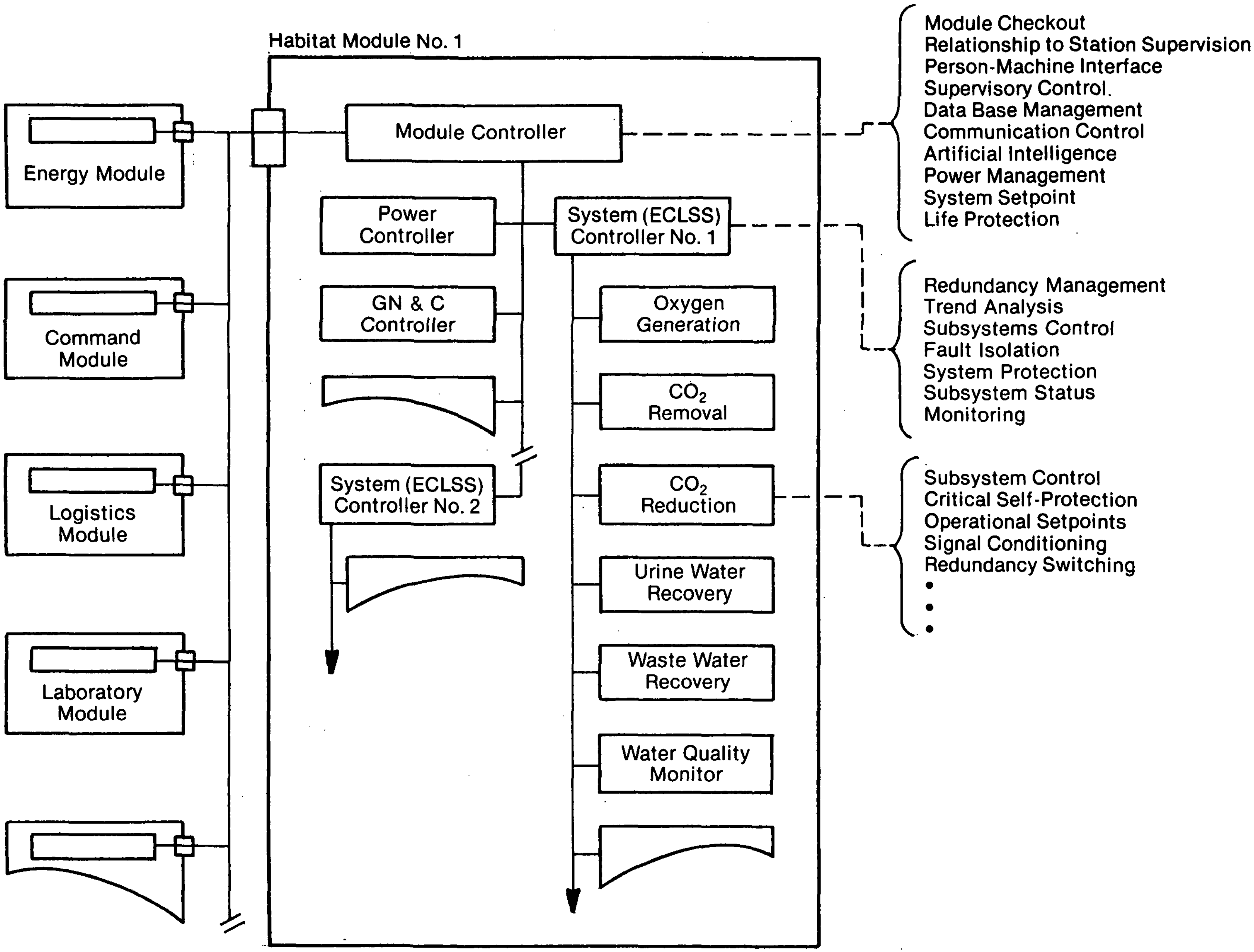

FIGURE 20 SPACE STATION AUTOMATION CONCEPT

Location of expert system routines within the individual subsystems has some advantages. Localized expert routines could be made specific to the individual subsystem, rather than being stated generally. These routines can then employ a detailed knowledge of the subsystem operation. Without the delays inherent in the communications from the higher level controllers, these localized routines can also afford faster response to situations than those located in the higher level controllers. Localized routines would also be easier to test and verify, since there would be no interactions or conflicts among the routines in different subsystems.

Centralized locations for expert system routines also afford some advantages. Located in the higher level controller these routines could provide supervisory functions that would not be possible if located in the subsystem controller. With a global view of the situations, the higher level controllers could apply the expert logic across subsystem boundaries. In some cases this may be the only way to properly identify faults which occur near the interfaces between subsystems. Fault avoidance routines include maintenance scheduling, external command verification, and management of interactions between subsystems. These functions would most appropriately be handled by a central controller. Since none of these functions require a high speed response, the additional communications delay from a higher level controller to the subsystem would not be a factor. Fault prediction routines, which tend to apply long term trend analysis in forecasting possible failures, also do not require short response time and, therefore, can also be centrally located.

For other situations the choice of local versus central location is not so clear cut. Fault detection routines generally require a high speed response to prevent possible subsystem damage. For this reason, fault detection routines should in general be located locally within the subsystem controller. For detection of faults which may occur at subsystem boundaries or between subsystems, a central location for some of these fault detection routines would be necessary. Likewise, some fault isolation routines would need to be centrally located as well. Fault isolation routines in general do not have a high speed response requirement, and all of these could be located in a central controller. However, fault correction and fault tolerance routines may require high speed response to prevent a subsystem shutdown and they, in turn, may depend on rapid isolation of a fault. Therefore, some of the fault isolation routines may need to be located locally within the subsystem controller. Fault correction and fault tolerance routines which prevent subsystem shutdown require high speed response and need to be located within the subsystem controller. Those fault correction and fault tolerance routines which operate at the interfaces between subsystems need to be located in the higher level controller. Such routines might make use of sensors in one subsystem to substitute for failed sensors in an adjacent subsystem.

It appears, therefore, that a combination of locations for the expert system routines, both localized and centralized, provides for the best application of the expert systems concept within the Space Station ECLSS.

CONCLUSIONS

A thorough study of fault diagnostics on a VCDS has shown how the concepts of EFD systems can extend the operating time of an ECLSS. An actual demonstration using an operating VCDS confirmed this and also illustrated how aspects of such an expert system could also reduce the time required to repair a subsystem following a failure. Furthermore, this demonstration showed that existing subsystems could be enhanced with EFD logic and that this logic could be implemented in the current generation of subsystem controllers.

An analysis of other ECLSSs has shown both similar controller architecture and similar complements of components leading to the conclusion that all ECLSSs are viable candidates for the addition of EFD logic. A study of the Space Station controller hierarchy with a view to the implementation of expert knowledge systems concluded that these concepts can and should be implemented both centrally, in higher level controllers, and locally, in the subsystem controllers, to most effectively apply the expert knowledge.

Costs and Benefits

Implementing an expert system can result in significant additional costs when developing a subsystem. Additional time will be required for analysis, additional sensors may need to be added to the subsystem, and additional testing will be required due to the more complex implementation and integration. The benefits of having such a system, however, can be substantial and dramatic. Improved process efficiency, through enhanced control and fewer subsystem shutdowns, as well as shorter downtime when repairs are required, can more than make up for additional costs of development.

Lessons Learned

During the course of this study a number of important lessons were learned. Anyone attempting to implement an EFD system should be aware of the following items.

- The fault tree and definition of expert routines are the top level "assembly drawings" of the EFD blueprint package.
- Application of expert systems will tend to increase the number of subsystem sensors desired.
- An analysis of the subsystem must be performed specifically for EFD applications. The required information and insight does not "fall out" of other subsystem analyses (e.g., FMEA).
- Response time is of critical importance for fault correction and fault tolerance applications intended to prevent shutdown of a subsystem. This may affect the location and degree of EFDs when implemented.

- Knowledge acquisition is the most important and time consuming aspect of expert system applications.
- Basing expert systems only on past experience may result in a system with very limited capability.
- While fault isolation need only be performed to the ORU level for maintenance and repair, advanced EFD implementations require isolation to component level.

Recommendations

In order to further promote the addition of EFD logic in ECLSSs, it is recommended that a set of guidelines be developed for performing an analysis of a subsystem and applying the expert knowledge which is collected. Other subsystems of the ECLSS should be analyzed in detail for EFD and knowledge bases developed for each. Presently, subsystem developers are on their own in determining in what areas and to what extent expert knowledge of a subsystem is incorporated. Management of failures is generally limited to fault detection and safe shutdown of the subsystem.

One possible way to ease the addition of expert knowledge might be to develop a traditional expert system (inference engine and rule base) that would be compatible with existing controller architecture and that could be easily included in the controllers. Such a system might be developed in a transportable software language such as "C" or "Ada." Availability of such a package would reduce the implementation and testing costs associated with the addition of expert knowledge, since the rules themselves would be the only component needing verification.

In any event, it has been shown that EFD systems are beneficial to the long-term reliability of the Space Station systems. The form of implementation is not important. It is not necessary to wait for traditional artificial intelligence machines or languages to be trimmed down to subsystem controller size. Nor, is it necessary to add expert knowledge only on large machines and at a high level. Some restrictions on the degree of expertise included may result from limitations of equipment or expenditure, but these concepts, at least to some degree, can and should be added to the next, if not the current, generation of subsystem controllers.

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