Automation of the Environmental Control and Life Support System

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Abstract

The objective of the Environmental Control and Life Support System (ECLSS) Advanced Automation Project is to recommend and develop advanced software for the initial and evolutionary Space Station Freedom (SSF) ECLS system which will minimize the crew and ground manpower needed for operations. Another objective includes capturing ECLSS design and development knowledge for future missions.

This report summarizes our results from Phase I, the ECLSS domain analysis phase, which we broke down into three steps: 1) Analyze and document the baselined ECLS system, 2) envision as our goal an evolution to a fully automated regenerative life support system, built upon an augmented baseline, and 3) document the augmentations (hooks and scars) and advanced software systems which we see as necessary in achieving minimal manpower support for ECLSS operations.

In addition, Phase I included development of an advanced software life cycle plan inpreparation for phase II and III, the development and integration phases, respectively. Automated knowledge aquisition, engineering, verification, and testing tools will be used in the development of the software. In this way, we can capture ECLSS development knowledge for future use, develop more robust and complex software, provide feedback to the KBS tool community, and insure proper visibility of our efforts.

Introduction Description

The overall goal of the ECLSS Advanced Automation Project is to help develop a fully autonomous Environmental Control and LifeSupport System for the Space Station Freedom and future manned missions. We have broken this goal into the following more practical objectives:

> 1) Analyze and document the ECLSS for automation candidates which, when deployed, would minimize crew and ground ECLSS operations.

> 2) Propose and document a fully automated ECLSS by augmentation of the baselined design with advanced software. Present software hooks and hardware scars which will enable migration of the advanced software to the flight station.

> 3) Develop, test, and demostrate on ECLSS hardware the most promising automation candidates using tools which maximize productivity in the acquiring, engineering,and storage of ECLSS knowledge.

Our approach is to break the project into phases; analysis, development, and integration:

> Phase I/FY89   Analyze and document ECLSS Advanced Automation candidates, approach, and hooks and scars.

> Phase II/FY90   Aquire tools and ECLSS knowledge, develop prototype software, and test in a simulated environment.

> Phase III/FY91   Integrate the advanced software into the ECLSS advanced development testbed for concrete demonstrations of the advantages of knowledge-based systems diagnosis.

The Johnson Research Center of the University of Alabama in Huntsville has completed the Phase I analysis of the ECLSS.
Boeing Computer Services Artificial Intelligence Center (BCS/AIC) was brought on board late in FY89 as the engineering development contractor in Phases two and three. The AIC has taken part in, and reviewed the UAH work, and developed a detailed software life cycle plan for prototype development and integration.

This presentation summarizes Phase I, gives status of Phase II, and presents a general look at our future plans.
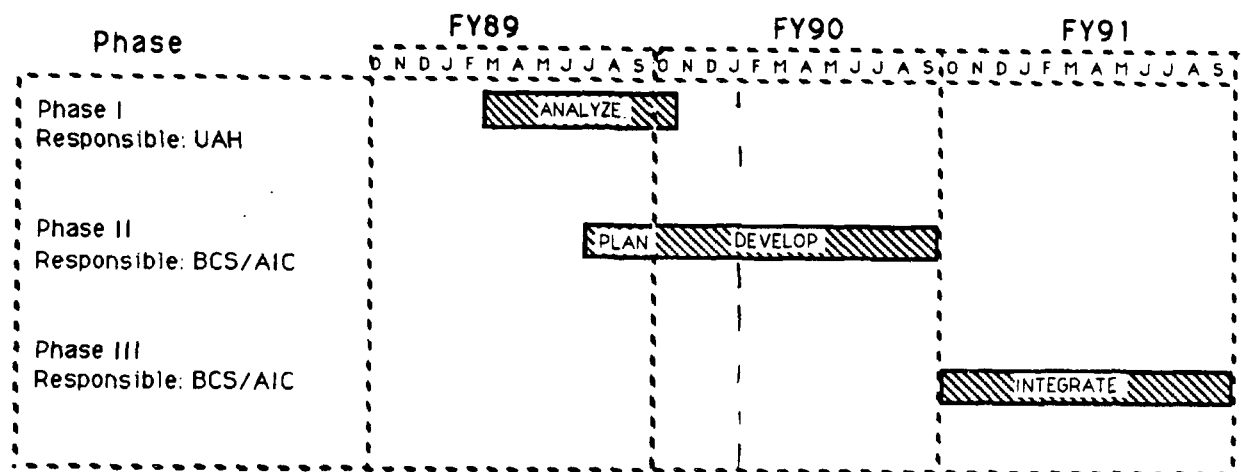
Introduction

- Project Goal:

    A fully automated Environmental Control and Life Support System.for the Evolutionary Freedom Station

- Practical Objectives:

    1) Analyze and document the baselined ECLSS

    2) Document automated ECLSS: augmentation of baseline

    3) Develop prototype software and integrate with hardware

- Approach

Phase	FY89 O N D J F M A M J J A S	FY90 O N D J F M A M J J A S	FY91 O N D J F M A M J J A S
Phase I Responsible: UAH	ANALYZE		
Phase II Responsible: BCS/AIC		PLAN DEVELOP	
Phase III Responsible: BCS/AIC			INTEGRATE

- Presentation Overview
    - Phase I Analysis Approach
    - ECLSS Software Domain Overview
        - Detailed FDIR Description
        - Detailed Water Quality Monitor Description
    - Automation Application Analysis
    - Overview of Major Hooks and Scars Analysis and Results
    - Phase II Development Status and Future Plans
    - Conclusion

Phase I Analysis Approach Description

The Phase I analysis report was generated by UAH in a manner similar to that depicted on the graph. We began by analyzing the ECLSS domain . As the ECLSS is currentlyin the preliminary design stage, our knowledge was generated from three general sources:
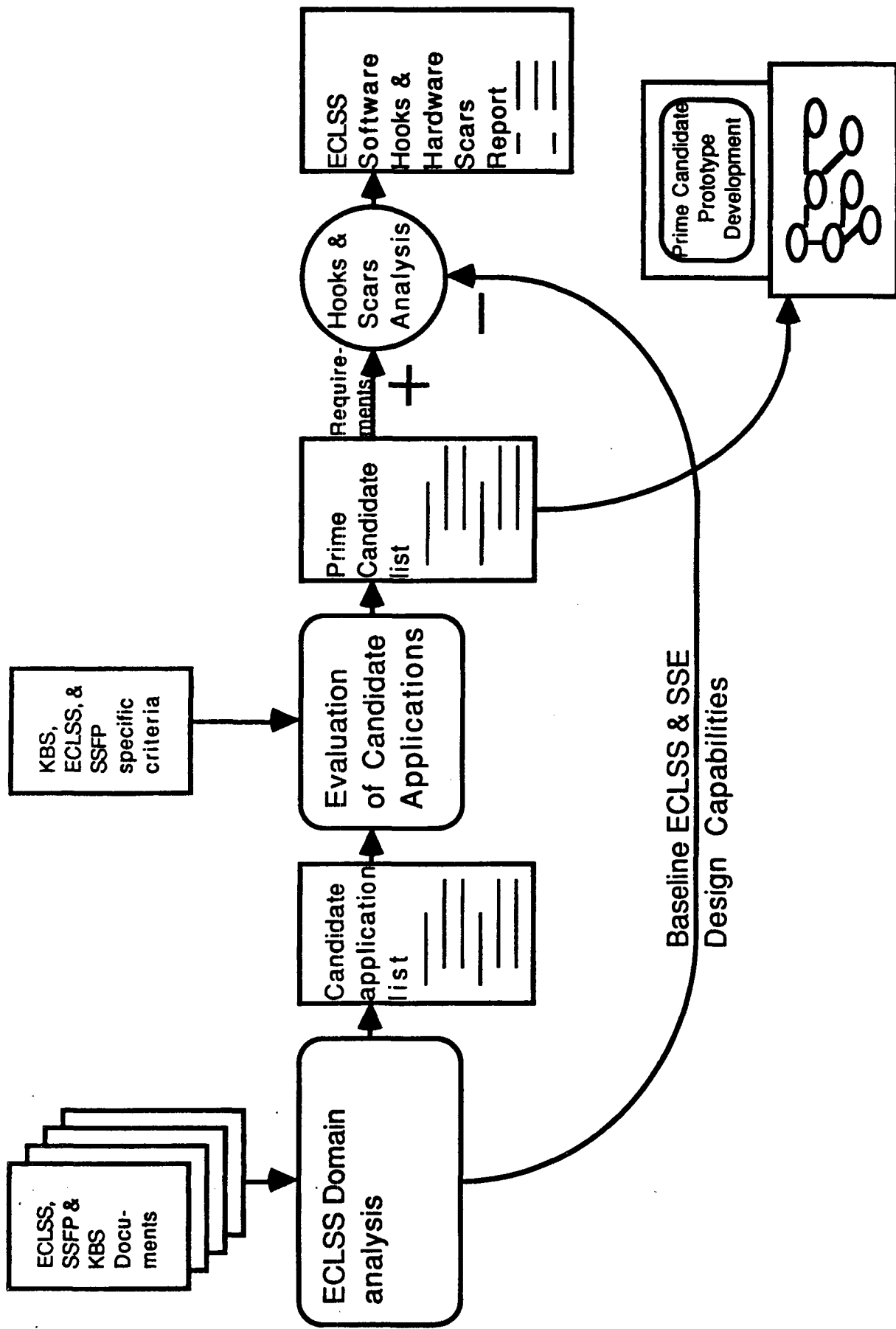
- Applicable Space Station Freedom documentation such as the ECLSS, DMS, OMS, Architecture Control Documents (ACD's), Contract End Item Specifications, ECLSS component test plans, and design review presentations

- Conference reports which discussed control of environmental processes using knowledge-based systems.

- Interviews with ECLSS test and design engineers, scientists, and doctors

The UAH team, consisting of environmental, chemical, process control, and artificial intelligence engineers, gathered some 140 documents and presentations (an appendix to the Phase I report lists these references). They then analyzed each document, determining areas in need of advanced automation and the resulting hooks and scars.

Those software processes which were seen to be candidates for automation (and some new applications, not in the baseline) were listed.
Evaluation criteria was generated and applied to each candidate in order to methodically discuss and document the pros and cons of development of each KBS application.

From the prime candidate list, an application was picked for rapid prototyping, in order todevelop a feel for the resource requirements (speed and memory) and operating system functional interface required. We prototyped a CLIPS based system which monitors and diagnoses faults in the Potable Water Recovery Subsystem. We found we that more than a production system tool was needed for adequate automation of our system (more on this in the results section).

The baselined ECLSS design was compared with the requirements of our candidateadvanced automation systems in order to drive out a list of hooks and scars.

ECLSS
Software
Hooks &
Hardware
Scars
Report

Hooks &
Scars
Analysis

Prime Candidate
Prototype
Development

Require-
ments

+

−

Prime
Candidate
list

KBS,
ECLSS, &
SSFP
specific
criteria

Evaluation
of Candidate
Applications

Baseline ECLSS & SSE
Design Capabilities

Candidate
application
list

ECLSS,
SSFP &
KBS
Docu-
ments

ECLSS Domain
analysis

Phase I Analysis Approach

ECLSS Software Domain Overview Description

The ECLSS Station Manager, 1.0) contains four functional software components which: 1.1) Maintain ECLSS configuration data, 1.2) coordinate the ECLSS among elements and, 1.3) control O2N2 pressure. O2N2 Pressure Control, Number 1.3) is an ACS function which is included in the ECLSS station manager software because it must monitor atmosphere constituents throughout the Station.

1.2) coordinating the ECLSS among elements requires expert knowledge of the ECLS System. This function is responsible for Inter-Module Ventilation (IMV), inter-module cabin air, and inter-module potable and hygiene water control. The inter-module air flow problem should be solved during Expanded ECLSS testing when a "race track" of element mockups will be used to make sure no instabilities exist in controlling the blowers and valves which semi-independently push air around the station. The function coordinating the ECLSS among elements function will be defined in greater detail during testing.

2.0), the ECLSS Element Supervisor contains many candidate automation processes. It includes 2.1), distributed subsystem control, a generic name for those subsystem functions which require distribution throughout the lab, such as Fire Detection sensor monitoring and verification, Avionics air cooling and distribution control, etc.... The process control software loops for these functions will reside in the ECLSS Element Supervisor.

2.2) Inter-subsystem flow control is similar to 1.2) ECLSS coordination among elements in that the total responsibilities of this function will be derived during testing. Its responsibilities will include control of CO_2 transfer from the 4BMS to the Bosch, venting from the Bosch to the TCC, water transfer from the Bosch and the THC assembly to the potable water processor's raw water tank, and hygiene water transfer from the hygiene water processor to the water electrolysis unit.

2.3) Off-line subsystem FDIR is a monitoring and diagnosis function. It will be explained later as a prime candidate for an advanced automation approach.

2.4) Component performance and trend analysis is in the ground ECLSS sustaining engineering environment, though some of its functions will migrate on-board as DMS resources permit. This function records and analyzes trend data on the performance of ECLSS pumps, valves, heaters, and filters which will be used to predict faults, maintain system health, and schedule maintenance procedures. Research in chemical and microbial interactions may allow this function to predict and maintain proper chemical and microbial balances throughout the regenerative life support system.

3.0) Real-time Process Control Software consists of process control algorithms in each subassembly, real-time fault detection, and built in tests (BIT) for each subassembly.
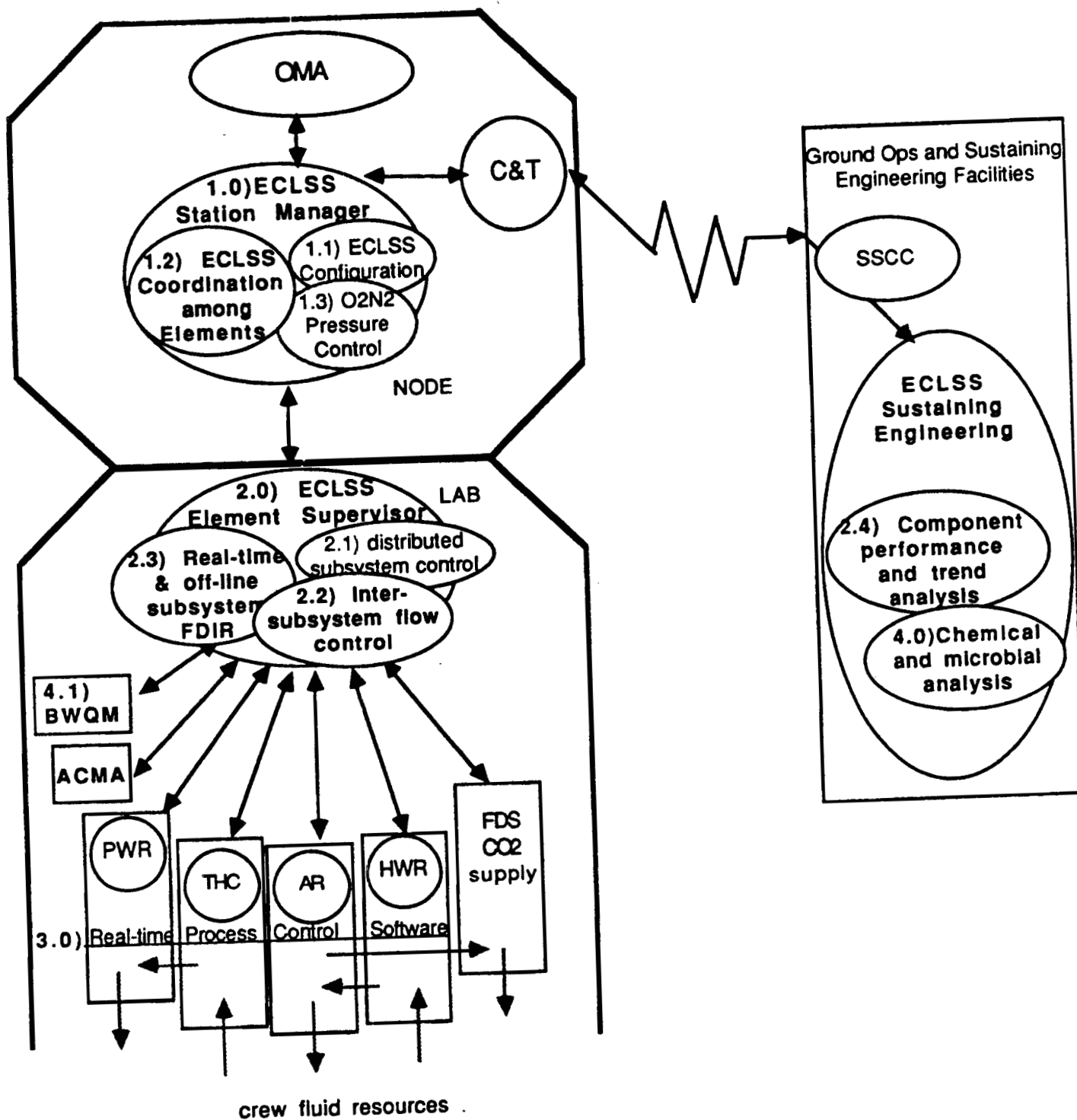
ECLSS Software Domain Overview

Real Time and Off Line FDIR Description

There is a duplication of Potable Water Recovery (PWR), Hygiene Water Recovery (HWR), and Air Revitalization (AR) subsystems for redundancy. There are actually four of these subsystems, two in the Habitation Module, and two in the Laboratory Module. Two of the four are running in nominal operations to support an eight man crew.

2.3) Real-time and Off-line FDIR has been split into its two components, 2.3.1) Real-time Subsystem Fault Detection, and 2.3.2) OfflineSubsystem Fault Isolation & Recovery.
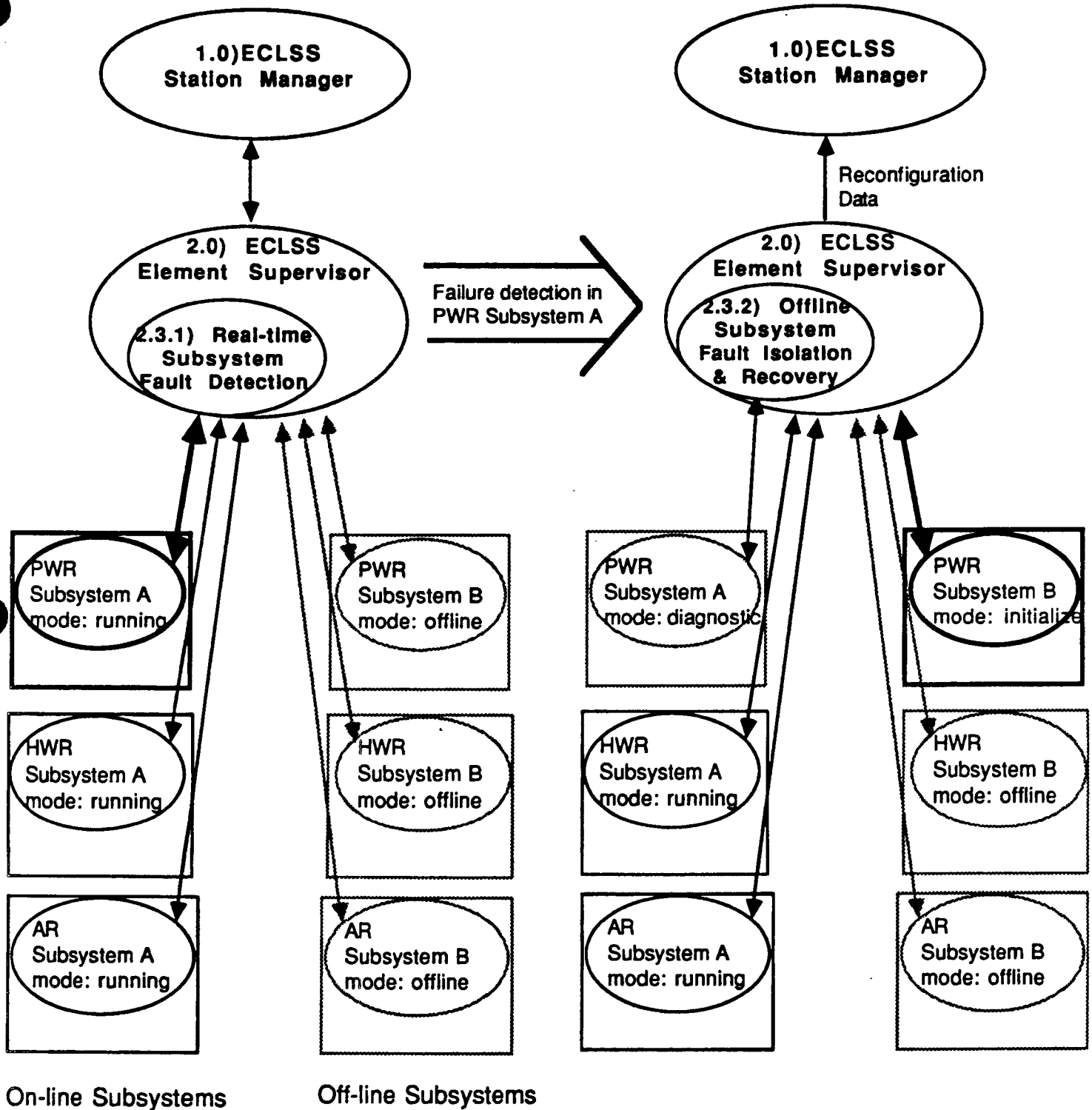
The schenario depicted is a failure in PWR subsystem A. This failure is detected by 2.3.1) Real-time subsystem fault detection, which monitors the sensor values of the running PWR subsystem and compares these to expected values. This system is to be developed as part of the baseline using algorithms implemented in Ada with the support of ground personel. 2.3.1) detects the fault and informs 2.0) the ECLSS Element Supervisor which instructs PWR subsystem B to initialize and PWR subsystem A to change modes to diagnostics. The ECLSS Element Supervisor also starts another software process, 2.3.2) Offline Subsystem Fault Isolation and Recovery, passing it the name of the subsystem to diagnose.

2.3.2), The off-line fault isolation and recovery process inpects the status of the offline (not running but in diagnostic mode) PWR subsystem, sends commands and inspects the responses of the faulty subsystem if the failure is not immediately apparent. The off-line fault isolation and recovery procedure may instruct the faulty PWR subsystem to perform built in tests, or more advanced tests. With the help of ground support and maybe some manual crew procedures, the fault is isolated and a recovery recommendation is formulated and sent to the ECLSS Station Manager through the ECLSS Element manager.

Advancements in the maturity of knowledge based real-time monitoring and diagnosis systems indicate that these software processes are prime candidates for advanced automation development. Autonomous ECLSS subsystem RT & OL FDIR processes could utilize an internal model of the subsystem under test. Implementation of FDIR processes based on internal causual models show strong promise in knowledge based systems for process control diagnosis. Model aqcuisition should start early in the design process, because later implementation may prove too costly.

Before Subsystem Fault is Detected   **After Subsystem Fault is Detected**

1.0)ECLSS
Station Manager

1.0)ECLSS
Station Manager

Reconfiguration
Data

2.0) ECLSS
Element Supervisor

2.3.1) Real-time
Subsystem
Fault Detection

Failure detection in
PWR Subsystem A

2.0) ECLSS
Element Supervisor

2.3.2) Offline
Subsystem
Fault Isolation
& Recovery

PWR
Subsystem A
mode: running

PWR
Subsystem B
mode: offline

PWR
Subsystem A
mode: diagnostic

PWR
Subsystem B
mode: initialize

HWR
Subsystem A
mode: running

HWR
Subsystem B
mode: offline

HWR
Subsystem A
mode: running

HWR
Subsystem B
mode: offline

AR
Subsystem A
mode: running

AR
Subsystem B
mode: offline

AR
Subsystem A
mode: running

AR
Subsystem B
mode: offline

On-line Subsystems   Off-line Subsystems

Real-Time and Offline FDIR

Water Quality Monitor Description

The second major automation candidate is the Water Quality Analysis processwhich includes the process control water quality monitor (PCWQM), not shown on this graph, 4.1) the batch water quality monitor (BWQM), and 4.0) the ground basedchemical and microbial analysis process which is not shown here but is on the ECLSS Domain Functional Schematic.

There are two types of water quality monitors, the PCWQM, and the batch water quality monitor (BWQM).There is a PCWQM associated with each potable, hygiene, and urine pretreatment system. The PCWQM gives near real-time continuous readings for pH, conductivity, iodine concentration, and total organic carbons (TOC) for the product (output) water of each system. If the product water does not match the required specifications for these values, it returns as raw, or input water to the systems.

It is important to understand the limitations of the PCWQM data.
The TOC readings detect the presence of organic compounds but cannot differentiate between compounds or determine their source.
Therefore, periodic manual water sampling and manual analysis will be necessary. The flight and ground batch water quality monitor (BWQM) will provide more complete water quality data.
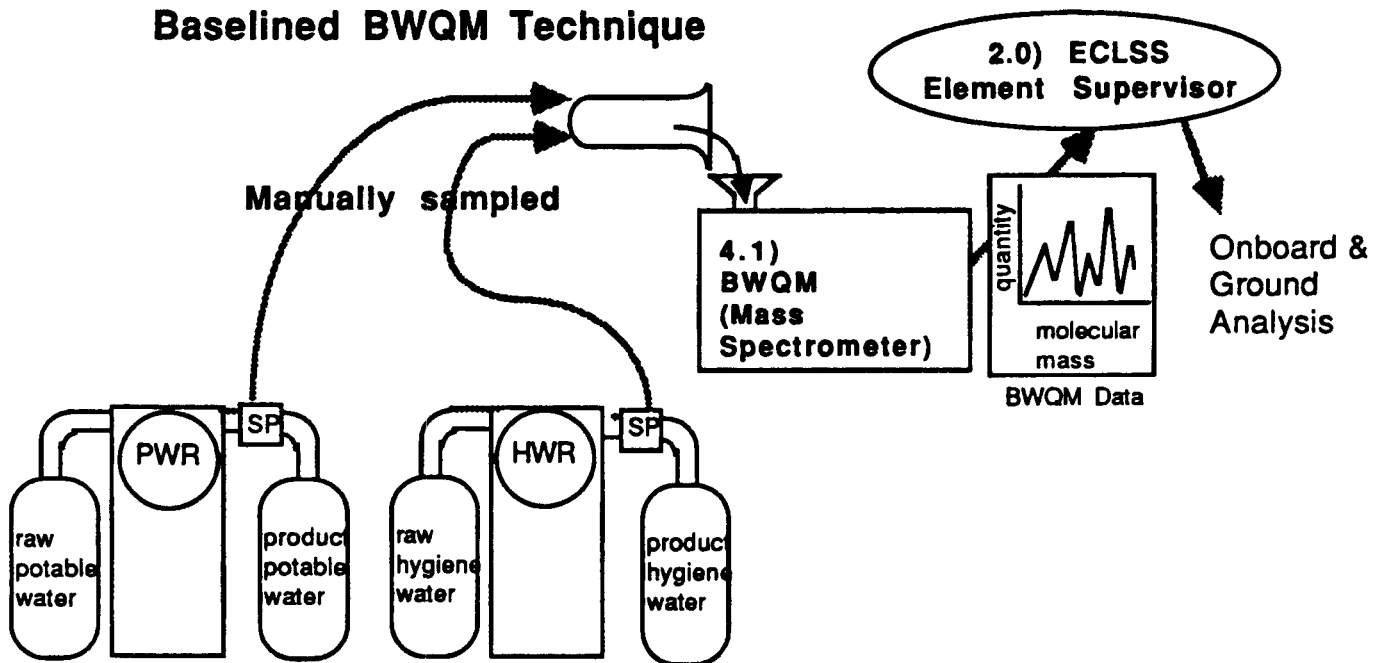
The batch water quality monitor is a mass spectrometer (developed by Perkin Elmer) which requires periodic manual sampling via manual sample ports (SP) in the potable and hygiene product water lines. The on-board BWQM allows the crew to perform tests more frequently than 90 days, when a shuttle flight will return samples for more extensive ground testing. Such testing will include culture growth, a visual inspection, and qualitive judgement by an expert using a microscope to check for various micro-organisms.

Data from the on-board BWQM will be available on the DMS for on-board processing and downlink. Currently, there are no plans to automate the sampling procedures or data analysis.
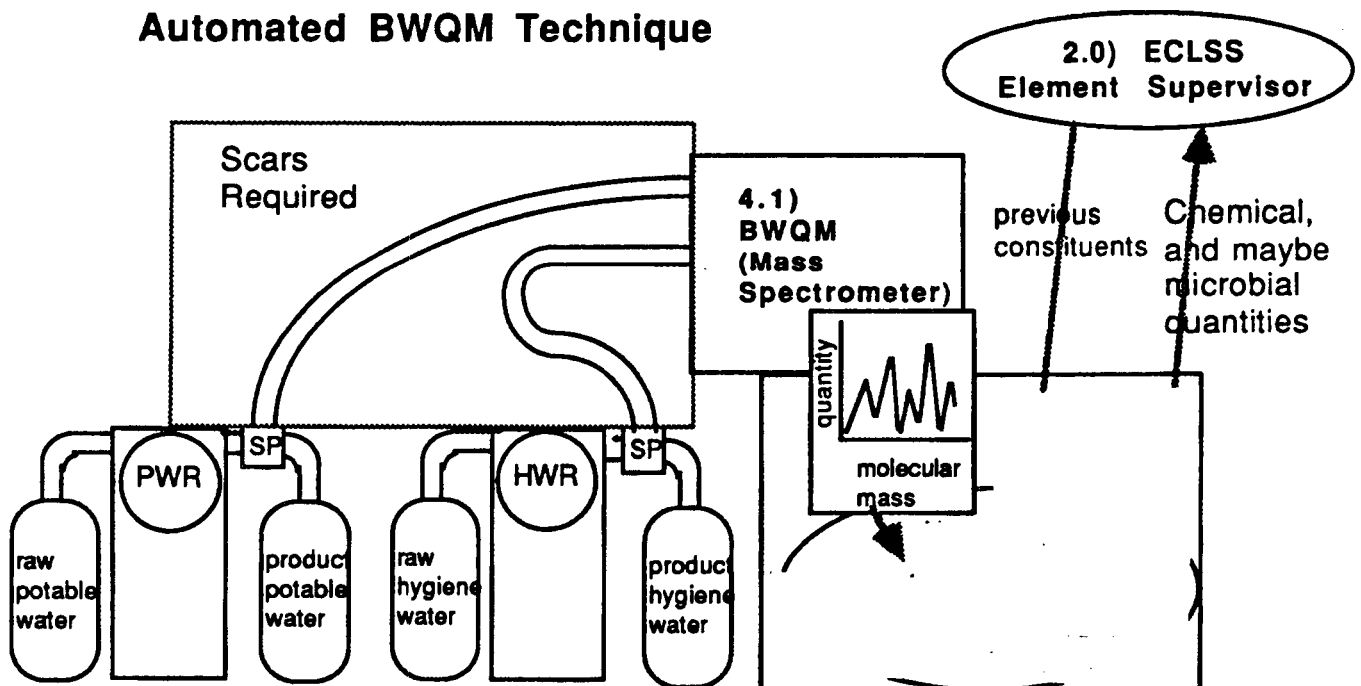
A technique may be needed in the future to automate BWQM sampling of potable and hygiene water. Further, research into automated analysis of mass spectrometer data may enable further automation of this process. This is required to be a real time analysis, on the order of seconds, to feed back into a more advanced control system which will use the data in adjusting a more flexible process control system. This information will also be used to decide if the water was drinkable or okay to wash with.

There has been effort in the medical industry to use many types of analysis including flow cytometry, solid state chemical sensors, and pattern recognition software to isolate specific organic constituents in real-time (the UAH report explores some of this promising research.

Baselined BWQM Technique

Manually sampled

2.0) ECLSS Element Supervisor

4.1) BWQM (Mass Spectrometer)

quantity

molecular mass

BWQM Data

Onboard & Ground Analysis

SP

PWR

SP

HWR

raw potable water

product potable water

raw hygiene water

product hygiene water

Automated BWQM Technique

Scars Required

4.1) BWQM (Mass Spectrometer)

2.0) ECLSS Element Supervisor

previous constituents

Chemical, and maybe microbial quantities

quantity

molecular mass

SP

PWR

SP

HWR

raw potable water

product potable water

raw hygiene water

product hygiene water

Automation Application Analysis Description

The objective of this analysis is to determine, based on specific criteria, which function in the ECLSS domain to automate.

1.2) ECLSS Coordination among elements and 2.2) Inter-subsystem flow control. These application are not well understood, expanded ECLSS testing will be required. The baseline application will be accomplished with enhanced instrumentation and traditional algorithmic architectures (Ada tasks and Unix operating system on a 80386-based computer.)

2.3) Real-time and off-line ECLSS subsystem FDIR functions meet all the criteria:
   • Implementation of an advanced automation approach to subsystem FDIR will reduce crew and ground maintenance times.
   • The processes can be implemented on ground and migrated on board.
   • These applications are well understood; the knowledge required is in the designs and models of the subsystems.
   • The processes cannot be accomplished with enhanced instrumentation and traditional algorithmic architectures.
   • A model oriented approach would minimize the use of sensors for subsystem FDIR and resolve the problem of bad or missing sensor data.
   • Technology for advanced automation approach is sufficiently mature due to the emerging capabilities of model based reasoning systems and tools. The subsystem control latencies are sufficiently long to allow implementation of real-time advanced fault analysis.

2.4) Component performance and trend analysis is already in the baseline for ground systems and will be migrated onboard after assembly complete. Some health maintenance functions may require a knowledge based approach. The application is not well understood at this time.

2.5) Automatic and semi-automatic fire suppression is already in the baseline.

4.0) Automatic chemical and microbial water analysis is not well understood. Research is required for this application. Technology does not yet exist for automated extensive analysis of mass spec data, and symbolic and/or neural net processing architectures onboard.

Automation Application Analysis

Criteria For Application Selection

A. Implementation of an advanced automation approach will reduce crew and ground maintenance times.

B. Process can be implemented on ground and migrated on board.

C. Application is well understood.

D. Cannot be accomplished with enhanced instrumentation and/or algoritmic architectures.

E. Technology for advanced automation approachis sufficiently mature.

Candidate Applications	Matching Criteria
1.2) ECLSS Coordination among elements	ABE
2.2) Inter-subsystem flow control	ABE
2.3) Real-time and off-line ECLSS subsystem FDIR	ABCDE
2.4) Component performance and trend analysis	ABDE
2.5) Automatic and semi-automatic fire suppression	CE
4.0) Chemical and microbial water analysis	ABD

Hooks and Scars Analysis Results Overview Description

The following are the major software hooks and hardware scars necessary for evolution to a more autonomous ECLSS. Prototype and baseline ECLSS development will produce more necessary augmentations.

- The advanced subsystem FDIR requires component sensors to be available from the Runtime Object Data Base (RODB) within 1 second with the assumption that the subsystem's control loops have a latency of 5-10 seconds. This allows real-time fault detection and fault preventive reconfiguration to use 3-8 seconds because communication with the ECLSS subassembly monitoring process is expected to take about 2 seconds.
  The software design of the RODB must meet the requirements of process location transparency and performance.
  Our analysis indicates that early capture of design knowledge using design knowledge capture tools such as AQUINAS and object oriented model-based reasoning tools such as KATE and ART/Ada would increase our automation proficiency. We suggest these tools be added to the SSFP Software Support Environment
  ECLSS leak detection can either be implemented using extensive leak detection instrumentation, or by designing subsystems using advanced engineering modeling and design tools which automate determination of optimal placement of leak detection sensors.
  Model-based reasoning approach to subsystem FDIR would allow minimal use of explicit leak detection sensors by inferring leaks using the baseline process control sensors.

- Advanced water quality monitoring will require scarring of the baseline design for future automatic transfer of potable and hygiene product water to the batch water quality monitor. This would be very expensive to implement without the scarring built in to the initial station.

- Research in automated analysis of Water Quality Monitor output is needed. Fast processing will be needed in order to implement real time chemical and/or microbial analysis in the life support control system and to quickly determine if the water is drinkable or okay to wash with.
  Intelligent instrumentation systems are needed for real time and inline chemical and microbial analysis.
  Onboard processing may require fast symbolic and/or neural net processing architectures.

- Certain aspects of inter-element coordination and inter-subsystem flow control are candidates for a production system approach. We also explored the use of a blackboard architecture to solve the problems of these functions. They will require expert system support functions in the Application Program Interface Definition (APID), expert system development tools in the SSE, and automated knowledge aquisition systems in the SSE.

Hooks and Scars Analysis Results Overview

• Requirements for advanced subsystem FDIR:

1) Component sensors available from the Runtime Object Data Base (RODB) within 1 second.
2) Software process location transparency.
3) Design knowledge capture tools and object oriented knowledge based system development tools available in the Software Support Environment (SSE).
4) Engineering modeling and design tools which automate determination of optimal placement of leak detection sensors.

• Requirements for advanced water quality monitoring:

1) Scarring for automatic transfer of potable and hygiene product water to the batch water quality monitor
2) Research in automated analysis of water quality monitor output
3) Research in realtime chemical and microbial analysis
4) Probable: symbolic and/or neural net processing architectures onboard

• Requirements for advanced ECLSS inter-element coordination

1) Expanded ECLSS domain testing.
2) Knowledge based system support functions in the Application Program Interface Definition (APID)
3) Knowledge based system development tools in the SSE.
4) Automated knowledge acquisition systems in the SSE.

• Requirements for inter-subsystem flow control:

1) Expanded ECLSS domain testing.
2) Blackboard software architecture application to the intersubsystem flow control problem.
3) Blackboard development tools in the SSE.
4) Automated knowledge acquisition systems in the SSE.

Development Status and Plans Description

Status

We have used Aquinas for knowledge acquisition on the potable water processor tradeoffs.

ART/Ada has been installed.

Development of the model based Water Recovery and Air Revitalization Diagnosis prototype using KATE is on-going.

Plans

Demonstration of the KATE based Water Recovery Diagnosis Prototype using a simulation of the Water Recovery Subsystem.in the summer of FY90.

Demonstration of the ART/Ada based Potable Water Recovery Diagnosis Prototype was scheduled for 2/90 but will be delayed until this spring. Possible use of TAE+ as the interface.

Phase III will demonstrate the Water Recovery Diagnosis Prototype using actual ECLSS Water Recovery Subsystem hardware.

Also in Phase III we will begin development of the Air Revitalization Diagnosis prototype which will contribute to the overall Regeneration Analysis and Diagnosis system.

A fourth Phase is needed to produce results on expanded ECLSS test data and to complete the Regeneration Analsys and Diagnosis system.

Development Status and Plans

Status

- Knowledge Acquistion

- ART/Ada beta test software installed

- Model based water recovery subsystem diagnosis development using KATE

Plans

Phase II

June/FY90	Demonstration of the Potable Water Recovery Diagnosis Prototype port to ART/Ada
August/FY90	Demonstration of the model based Water Recovery Diagnosis Prototype using a simulation of the Water Recovery Subsystem

Phase III

August/FY91	Demonstration of the model based Water Recovery Diagnosis Prototype using actual ECLSS Water Recovery Subsystem hardware
FY91	Development and integration of Air Revitalization Diagnosis with demonstrations using simulation and actual hardware Preliminary Integration of a Regeneration Analysis and Diagnosis system .

Phase IV

FY92	Results on expanded ECLSS test data Completion of the Regeneration Analsys and Diagnosis system.

Conclusion

<u>Phase I results</u>:

• ECLSS Advanced Automation Candidates.

• ECLSS hooks and scars analysis for growth to advanced automation.

• Prototype of the Potable Water Recovery FDIR Knowledge Based System.

• Advanced software life cycle plan for development and integration.

<u>Phase II Status</u>:

• Knowledge Acquisition using Acquinas.

• ART/Ada port of the CLIPS Water Recovery Diagnosis prototype in progress.

• KATE - Based Potable Water Recovery Diagnosis prototype

<u>Phase II Development</u>:

• Demonstrateion using simulation of the Water Recovery Subsystem.

• Continued ART/Ada beta testing.

<u>Phase III Plans</u>:

• Demonstration using Water Recovery Subsystem hardware in testbed.

• Integration of Air Revitalization Diagnosis knowledge

<u>Phase IV Plans</u>:

• Demonstration of Regeneration Analysis and Diagnosis system on expanded
    ECLSS test bed.

Conclusion Description

The results of Phase I of the ECLSS Advanced Automation project were discussed. These results include:

> Analysis and documentation ofthe ECLSS Advanced Automation Candidates which support our Phase II development, and baseline system design augmentations required for easier growth to automation.

> Development of a prototype Potable Water Recovery Diagnosis rule based system which helped in our requirements analysis and will be used as a starting point for future development.

Phase II development status was discussed and included the use of AQUINAS for knowledge acquisition. ART/Ada and KATE for development of the ECLSS Water Recovery and Air Revitalization Diagnosis software.

Phase II will produce a Water Recovery Diagnosis Prototype which will be demonstrated using a simulation of the Water Recovery Subsystem.

Phase III will demonstrate the Water Recovery Diagnosis Prototype using actual ECLSS Water Recovery Subsystem hardware. Also in Phase III we will begin development of the Air Revitalization which will contribute to the overall Regeneration Analysis and Diagnosis system.

A fourth Phase is needed to produce results on expanded ECLSS test data and to complete the Regeneration Analsys and Diagnosis system.