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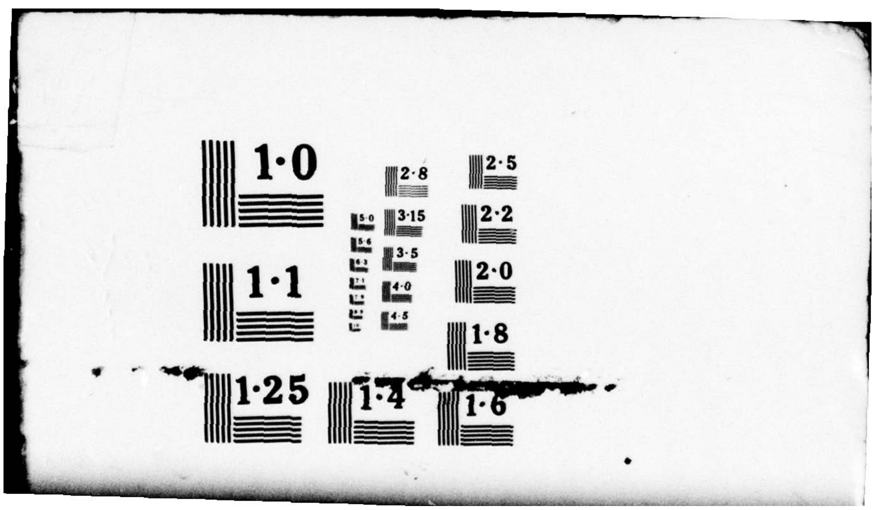
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ADVANCED INSTRUMENTATION DEVELOPMENT FOR A WATER PROCESSING PILOT PLANT FOR FIELD ARMY MEDICAL FACILITIES

TECHNICAL REPORT

by

P.Y. Yang, J.Y. Yeh,

J.D. Powell and R.A. Wynveen

May, 1978

Project Officers:

Major Walter P. Lambert and William J. Cooper

Environmental Protection Research Division

US Army Medical Bioengineering

Research and Development Laboratory

Ft. Detrick, Frederick, MD 21701

Supported by

US Army Medical Research and Development Command

Ft. Detrick, Frederick, MD 21701

Contract DAMD17-76-C-6063

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An automatic control and monitor instrumentation for an integrated water processing system pilot plant has been developed. The water processing system is designed to treat nonsanitary wastewaters of the U.S. Army field hospitals, either for nonconsumptive reuse or for surface discharge to the environment. In addition, it can also be used to purify natural fresh or brackish waters for potable use.

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This report presents the results and concepts of the development of the automatic instrumentation unit to automate the operation of the complex water treatment/purification unit processes. Because of the unique requirements of the Army field medical facility, the instrumentation unit is required to provide the water processing system with reliable operation, maximum performance, minimum operator skill level requirement, reduction of operator errors and simple operation of the complex system. The instrumentation is characterized by its computerized, automatic process control, automatic operating mode control, operating mode transitions, setpoint modifications, fault detection and isolation analysis, system performance trend analysis, interactive operator/system interface, automatic data transmission to a data acquisition system and the backup of a semiautomatic instrumentation and manual override.

The instrumentation unit is designed with a 16-bit minicomputer and 16K words of computer memory. It is designed to interface with 64 analog inputs, 5 analog outputs, 128 digital inputs and 80 digital outputs. The packaged unit is 21 x 21 x 28.5 in. It weighs about 250 lb and consumes approximately 750 W of electrical power.

ER-314-7-4

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Prepared Under Contract DAMD17-76-C-6063

by

LIFE SYSTEMS, INC.
Cleveland, Ohio 44122

for

U.S. Army Medical Research and Development Command
Ft. Detrick, Frederick, MD 21701

EXECUTIVE SUMMARY

The U. S. Army Medical Research and Development Command has been developing wastewater reuse technology applicable for use in the Army field environment. The system is called the Water Processing Element. The interim objective of the wastewater reuse technology development is to recycle nonsanitary wastewaters of Army medical facilities for nonconsumptive field usage. The ultimate objective is reuse for potable as well as nonconsumptive requirements in the Army field environment. Under Contract No. DAMD17-76-C-6063, Life Systems, Inc. designed and fabricated a wastewater reuse pilot plant and delivered it to the U. S. Army Medical Bioengineering Research and Development Laboratory, Fort Detrick, Frederick, MD.

This report presents the results and concepts of the development of the automatic control and monitor instrumentation for the Water Processing Element pilot plant. The Water Processing Element is an integration of many complex water treatment/purification unit processes. Because of the unique requirements of the Army field medical facilities, the automatic instrumentation unit is required to provide the Water Processing Element with reliable operation, maximum performance, minimum operator skill level requirement, reduction of operator errors and simple operation of the complex system.

As a part of the development effort, a Data Acquisition System was designed and fabricated. The Data Acquisition System is designed to collect the pilot plant data through the automatic instrumentation unit. The automatic instrumentation is designed to control and monitor six unit processes of the Water Processing Element automatically and to communicate with the operator and the Data Acquisition System. The automatic instrumentation is characterized by:

- Computerized, automatic process parameter control
- Automatic operating mode control
- Automatic operating mode transition control
- Automatic setpoint modification
- Fault detection and isolation analysis
- System performance trend analysis
- Interactive operator/system interface
- Automatic data transmission to Data Acquisition System
- Semiautomatic instrumentation and manual override backup

The operator/system interface, consisting of a control panel, a system status summary display panel, an alphanumeric message display unit, an operator command keyboard and a recessed manual override panel, is designed for ease in operating the Water Processing Element. The message display and keyboard panel provides the operator with a convenient way of communicating with the system. Parametric data, fault detection and trend analysis messages, operator error messages and control/monitor setpoints can be examined and displayed on the message panel. Control/monitor setpoints, scale factors, allowable ranges and control constants can be modified by an authorized operator easily from the front panel keyboard interface. The system operation, including different operating modes, mode transitions and auxiliary maintenance modes, is simplified considerably with the automatic instrumentation unit.

The automatic control/monitor instrumentation unit is designed with a 16-bit minicomputer and 16K words of computer memory. It is designed to interface with 64 analog inputs, 5 analog outputs, 128 digital inputs and 80 digital outputs. The packaged unit is 21 x 21 x 28.5 in. It weighs about 250 lb and consumes approximately 750 W of electrical power.

FOREWORD

The development of the advanced instrumentation was conducted for the U. S. Army Medical Research and Development Command, Fort Detrick, Frederick, MD, under Contract DAMD17-76-C-6063. The Program Manager was Dr. R. A. Wynveen. Technical effort was completed by Dr. P. Y. Yang, Dr. J. Y. Yeh, J. D. Powell, Jr., Dr. M. K. Lee, G. G. See, J. O. Jessup and D. C. Walter. Administrative and documentation support was provided by J. W. Shumar, B. A. Ginunas, R. H. Kohler, C. A. Lucas and M. Prokopcak.

Mr. W. J. Cooper and Maj. W. P. Lambert, Environmental Protection Research Division, U. S. Army Medical Bioengineering Research and Development Laboratory, Fort Detrick, Frederick, MD, were the Technical Monitors of this program. The technical contributions, assistance and program guidance offered by Lt. Col. L. H. Reuter, Capt. B. W. Peterman and Mr. M. J. Small are greately acknowledged.

Results of this study are published in six reports as follows:

Title	Report No.
Pilot Plant Development of an Automated, Transportable Water Processing System for Field Army Medical Facilities	ER-314-7-1
Water Treatment Unit Development for Field Army Medical Facilities	ER-314-7-2
Water Purification Unit Development for Field Army Medical Facilities	ER-314-7-3
Advanced Instrumentation Development for a Water Processing Pilot Plant for Field Army Medical Facilities	ER-314-7-4
UV/Ozone Oxidation Technology Development for Water Treatment for Field Army Medical Facilities	ER-314-7-5
Data Acquisition, Monitor and Control System Development for Field Army Medical Facilities	ER-314-7-6

The first report, ER-314-7-1, outlines in brief the overall program for the pilot plant development of the Water Processing System. The succeeding reports present further details on the subsystem developments of the Water Processing System pilot plant. The pilot plant consists of four subsystems: (1) a water treatment unit, (2) a water purification unit, (3) a UV/ozone oxidation unit and (4) an automatic instrumentation unit. This report describes development of the Water Purification Unit.

TABLE OF CONTENTS

continued-

Table of Contents - continued

LIST OF FIGURES

LIST OF TABLES

ACRONYMS

A/D	Analog/Digital
C/M I	Control/Monitor Instrumentation
COD	Chemical Oxygen Demand
CRT	Cathode-Ray Tube
DAMCS	Data Acquisition Monitor and Control System
DAS	Data Acquisition System
DDC	Direct Digital Control
DF/IE	Depth Filtration/Ion Exchange
DSC	Digital Supervisory Control
EP	Equalization/Prescreening
FDIA	Fault Detection and Isolation Analysis
HC	Hypochlorination
IE	Ion Exchanger
I/O	Input/Output
LED	Light Emitting Diode
MUX	Multiplexer
O_3/UV	UV-Activated Ozone Oxidation
PCB	Printed Circuit Board
PSCMC	Process Sequence Control Micro-Command
RO	Reverse Osmosis
RTC	Real-time Clock
RTE	Real-time Executive
TOC	Total Organic Carbon
TTL	Transistor-transistor Logic
UF	Ultrafiltration
USAMBRDL	U.S. Army Medical Bioengineering Research and Development Laboratory
USAMRDC	U.S. Army Medical Research and Development Command
WPE	Water Processing Element
WPS	Water Processing System
WPU	Water Purification Unit
WTU	Water Treatment Unit

INTRODUCTION

The wastewater reuse technology applicable to Army field medical facilities has been under development by the U. S. Army Medical Bioengineering Research and Development Laboratory (USAMBRDL) of the U. S. Army Medical Research and Development Command (USAMRDC). As a continued effort in this research area, a Water Processing System (WPS) pilot plant, also known as the Water Processing Element (WPE), for Army field medical facilities was designed, fabricated and delivered to USAMBRDL, Fort Detrick by Life Systems, Inc. The WPS Pilot Plant was designed with six unit processes and an automated Data Acquisition, Monitor and Control System (DAMCS). The WPS Pilot Plant with the DAMCS was designed to permit experimentation leading to the complete mechanical, hydraulic, electrical and instrumentation design of a fully-operational, automatically-controlled WPS prototype for the field Army medical facilities.

The purpose of this report is to describe the design, configuration and operation of the automatic Control/Monitor Instrumentation (C/M I) unit of the WPS Pilot Plant. This report is intended to be supplementary to Life Systems' Final Report entitled "Pilot Plant Development of an Automated, Transportable Water Processing System for Field Army Medical Facilities."(1)

Background

The American life-style is reflected in an American soldier. A typical American soldier is one who is used to flush toilets, daily showers and frequent changes of clothing. He does not question the quality of the water that comes out of a tap. For morale purposes and the fighting man's well-being, it is paramount that the waste disposal and water supply not be a nuisance or cause adverse health effects. This is true for general Army field facilities and especially so for Army field medical facilities.

The Army in the field under combat conditions does face special water supply and waste disposal problems. Some of these special factors are: the possibility of world-wide military operations, water deficient areas, poor quality water sources, water distribution systems that entail numerous transfer and storage stages of the water from its point of treatment to the point of consumption, and requirements for the same equipment to operate on highly variable environmental or geographical conditions. Therefore, the direct recycle and reuse of wastewaters is an attractive goal which would enhance tactical flexibility and capabilities. However, no Army equipment or commercial equipment is available off-the-shelf which will meet requirements of the WPS for Army field medical facilities. Thus, the USAMRDC has been conducting research and development on wastewater treatment and purification systems for the field hospitals.

(1) References cited in parentheses are listed at the end of this report.

Water Processing System

The mechanical portion of the WPS Pilot Plant consists of six unit processes:

1. Equalization/Prescreening (EP) Unit Process
2. Ultrafiltration (UF) Unit Process
3. Depth Filtration/Ion Exchange (DF/IE) Unit Process
4. Reverse Osmosis (RO) Unit Process
5. Ultraviolet Activated Ozone Oxidation (O_3/UV) Unit Process
6. Hypochlorination (HC) Unit Process

Figure 1 shows the WPS block diagram. Figure 2 shows the WPS in a more descriptive flow diagram.

The WPS has two primary modes of operation: namely, the Reuse Mode and the Potable/Discharge Mode. In the Reuse Mode the WPS treats and purifies nonsanitary hospital wastewaters for nonconsumptive reuse. In the Potable/Discharge mode it simultaneously treats wastewaters for discharge to the environment while treating natural fresh or brackish water sources for potable use. In addition to these two primary modes of operation, there are two secondary modes and four auxiliary modes. The secondary modes are potable only and discharge only. The auxiliary modes are those designed for scheduled maintenance; namely, UF cleaning, Ion Exchanger (IE) regeneration, RO cleaning/coating and system drain.

The function of the EP unit process is to settle and screen gross suspended solids and to equalize hydraulic loading and concentration variations so that a uniform flow is fed to the UF process. The EP process is also designed so that bad actor waste such as the laboratory waste with high refractory organic concentration is separately collected and equalized in the bad actor tank before being allowed to overflow to the mixing compartment. Sludge formed and accumulated at the bottom of the EP tank is removed automatically once every day during the four-hour maintenance period.

The UF unit process is designed to separate the suspended and dissolved solutes with a molecular weight greater than about 15,000 to minimize the fouling and maintenance of the RO membranes.

The DF/IE unit process consists of depth filtration, carbon adsorption and ion exchange processes. Its function is to pretreat natural fresh or brackish sources to prevent the precipitation of calcium and magnesium carbonate, bicarbonate and sulfate salts in the RO unit process when external water sources are used.

The function of the RO unit process is to remove most of the dissolved organic or inorganic solutes with molecular weights of 150 to 15,000.

The O_3/UV unit process is required to reduce the concentration of organic solutes in the process water to meet water reuse or surface discharge specifications. The O_3/UV is needed only when refractory organic solutes exist in the process water.

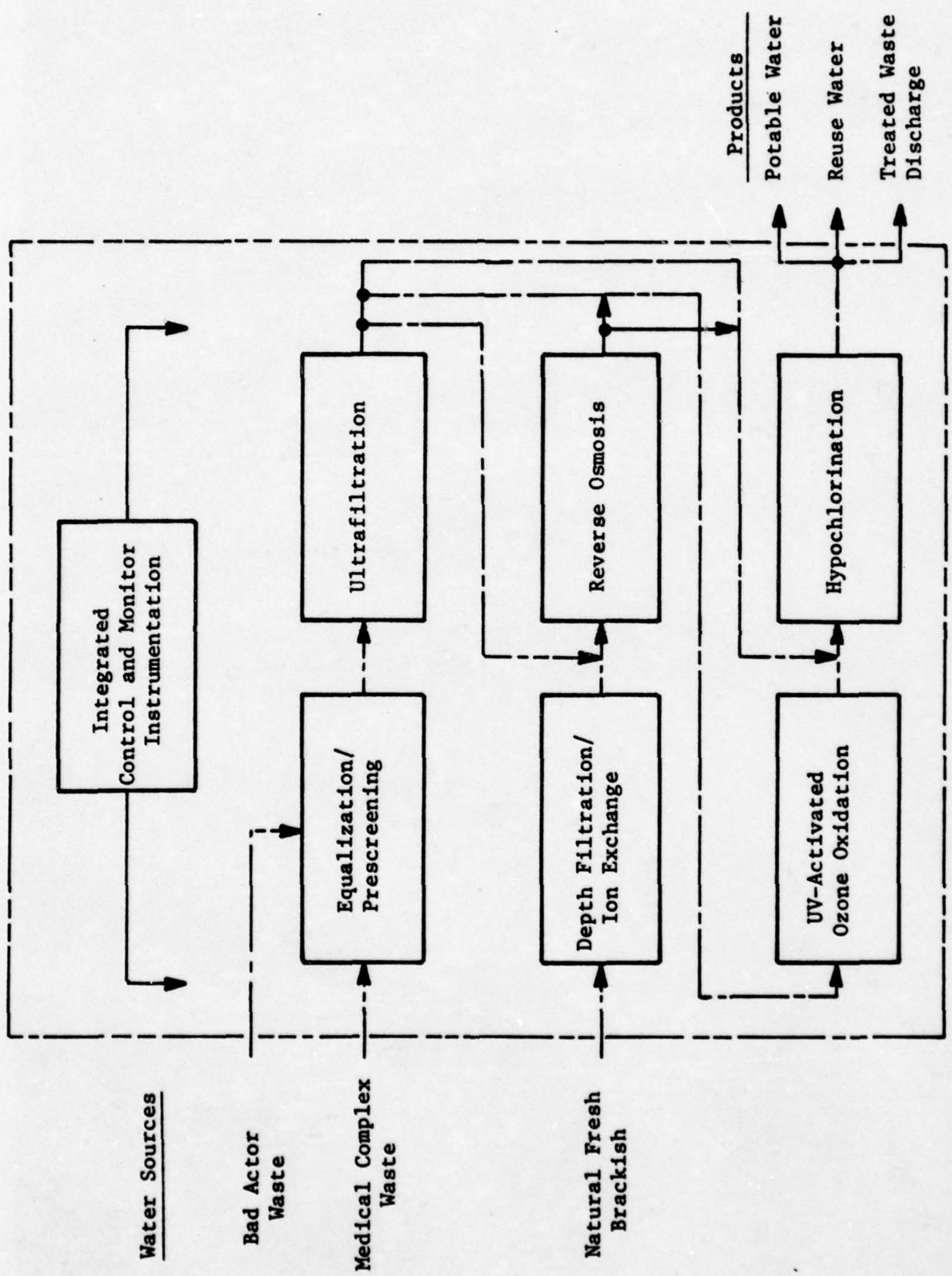


FIGURE 1 WATER PROCESSING SYSTEM BLOCK DIAGRAM

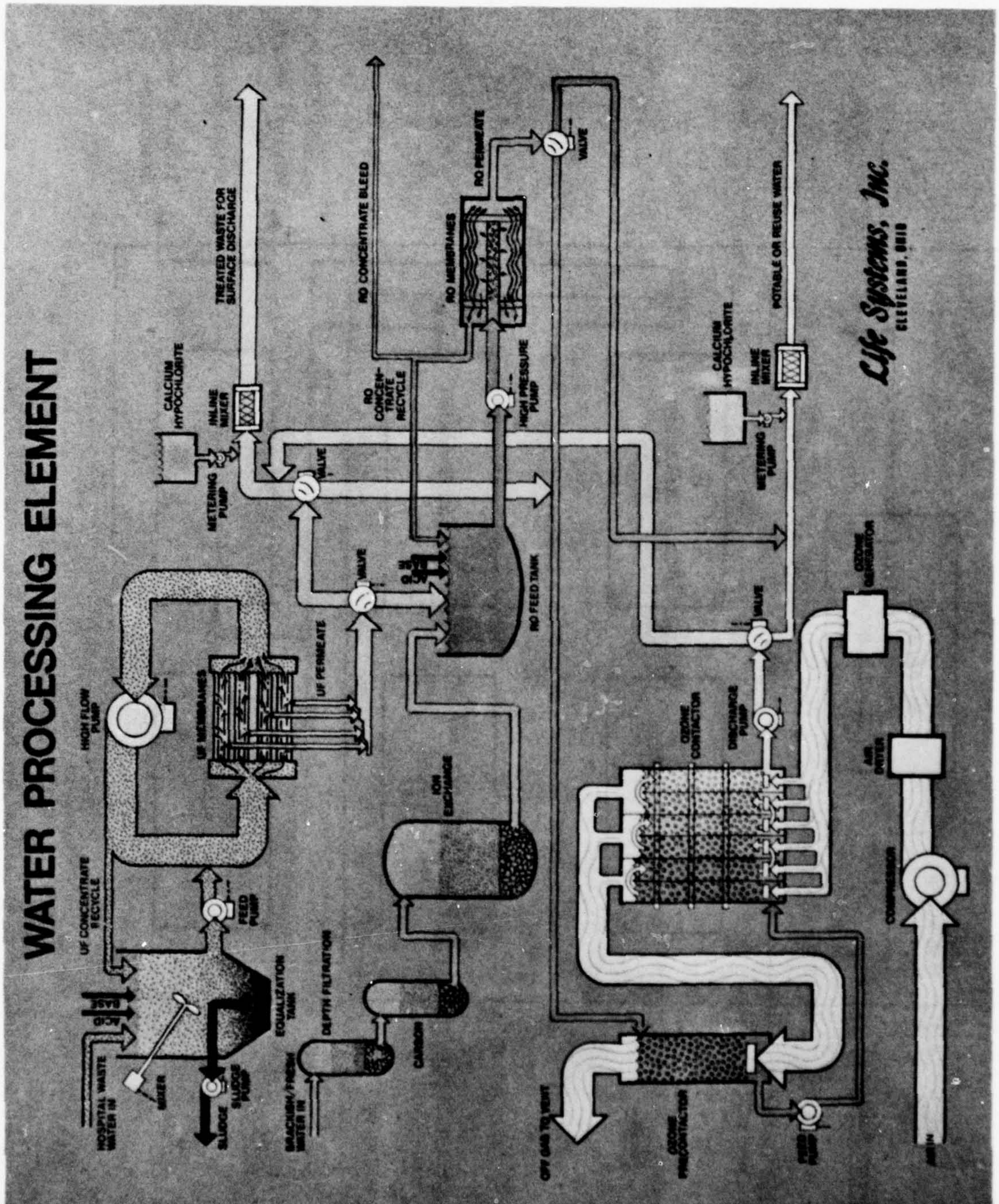


FIGURE 2 WATER PROCESSING SYSTEM FLOW DIAGRAM

The HC unit process is designed to provide a residual chlorine for the effluent waters from the WPS. The product water specifications require a 5 mg/l residual chlorine for reuse and potable waters and a 2 mg/l residual chlorine after 20 minutes of contact time for surface discharge wastewaters.

In the Reuse Mode nonsanitary hospital wastewaters such as operating room, kitchen, x-ray, laboratory, shower and laundry wastewaters are fed through the following unit processes: EP, UF, RO, O_3/UV and HC. The overall recovery of water is at least 85% of the inflow water in this mode.

In the Potable/Discharge Mode the WPS performs two independent functions: (1) potable water production from natural fresh or brackish source and (2) hospital wastewater treatment prior to surface discharge to protect the environment. The function of potable water production requires the following unit processes: DF/IE, RO and HC. The wastewater treatment for surface discharge function requires the following processes: EP, UF, O_3/UV and HC. The O_3/UV process in the surface discharge function is used only for certain wastewaters with high organic loading such as kitchen, laboratory, x-ray and composite wastewaters. Note that there are two separate HC unit processes in the WPS. This allows the two functions described above to be independent from each other and, therefore, can either run separately or simultaneously.

The WPS Pilot Plant mechanical hardware is divided into three units: a Water Treatment Unit (WTU), a Water Purification Unit (WPU) and a O_3/UV Unit.[1,2,3] The WTU consists of the EP, UF and HC unit processes. The WPU consists of the DF/IE, RO and HC unit processes. Because of the present physical size of the O_3 contactor and the O_3 generator, the O_3/UV unit process is packaged as a separate unit. Functionally, the O_3/UV is a part of the WTU. The ultimate packaging goal is to incorporate the O_3/UV into the WTU package. The physical dimensions (length x width x height) of the three units are as follows:

- WTU: 12 x 8.75 x 6.75 ft
- WPU: 9.75 x 5 x 6.75 ft
- O_3/UV: 10 x 8.5 x 6.75 ft

Figures 3 through 5 are photographs of the three mechanical units of the WPS Pilot Plant.

The WPS has a nominal product water capacity of 13,200 liters (3,500 gal) per 20-hour day with four hours available for daily maintenance. It is capable of treating or purifying a number of different water sources such as shower, operating room, laundry, laboratory, x-ray, kitchen and composite wastewaters as well as natural fresh or brackish water sources.

Program Objectives

The overall objective of Contract No. DAMD17-76-C-6063 was the development of a fully-operational WPS Pilot Plant incorporating an automated DAMCS to allow testing leading to the complete mechanical, hydraulic, chemical and electrical design of a fully-operational, automatically-controlled WPS for the Army field medical facilities. The specific objectives of the WPS Pilot Plant instrumentation development program were to design, fabricate, install and debug an

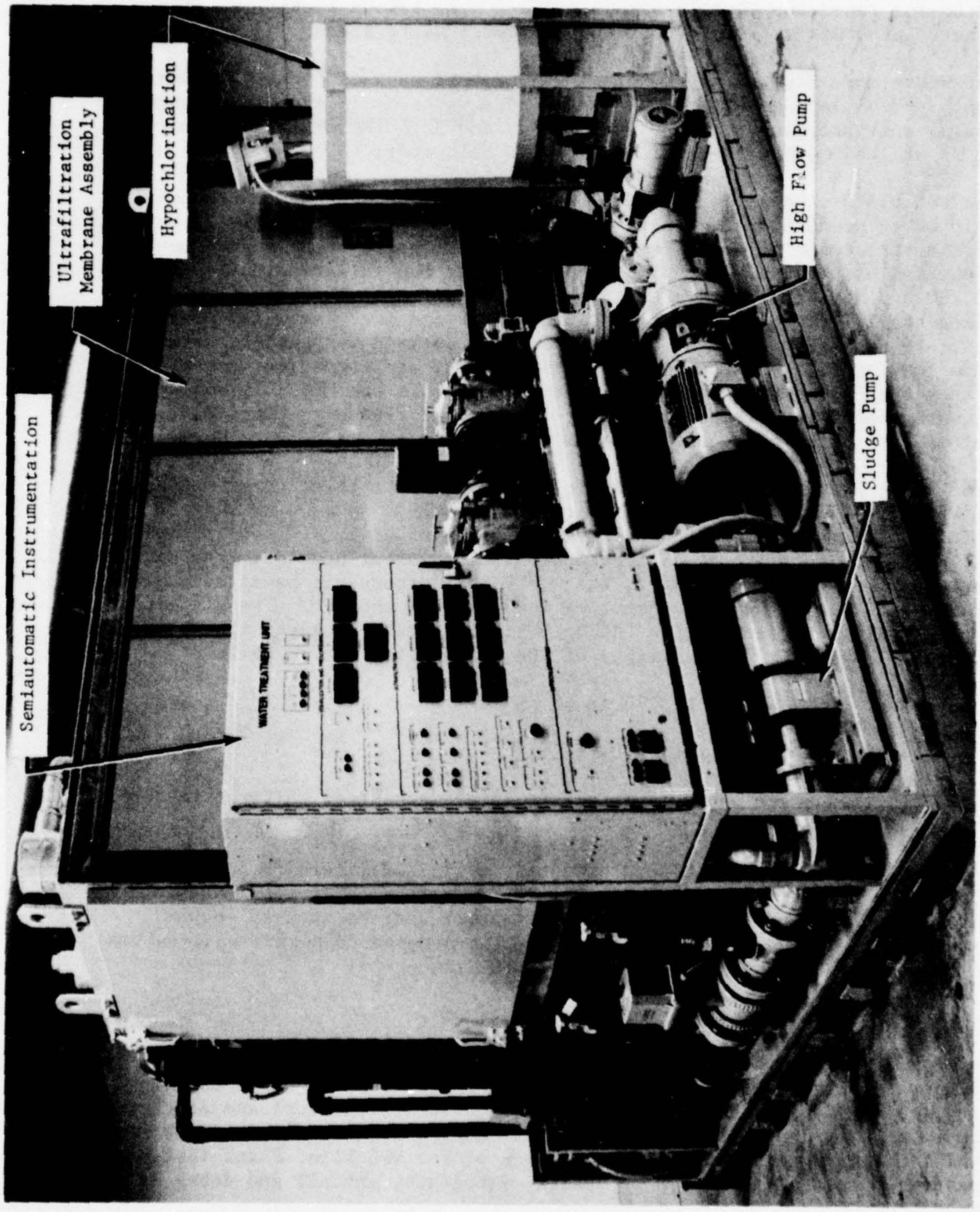


FIGURE 3 WATER TREATMENT UNIT

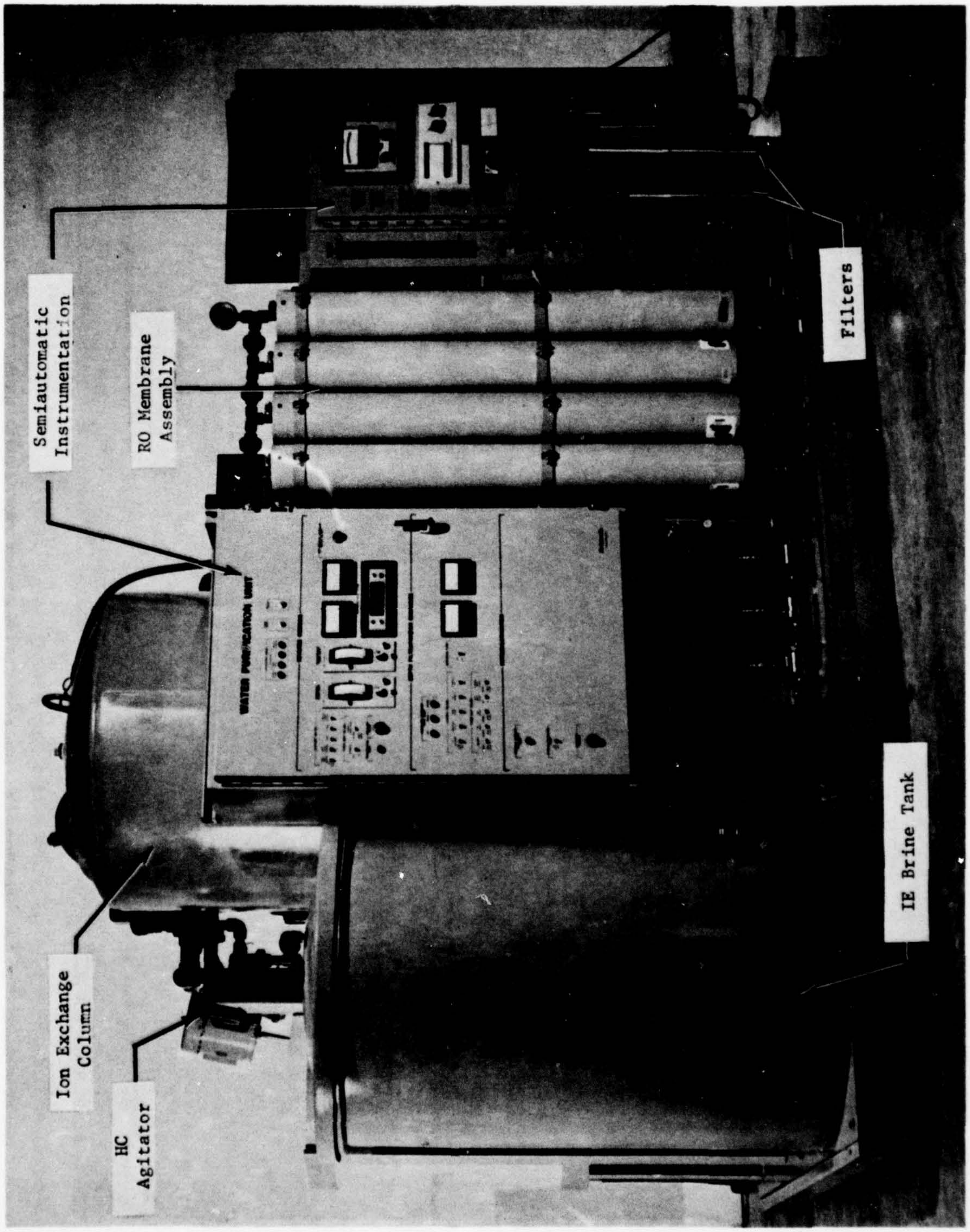


FIGURE 4 WATER PURIFICATION UNIT

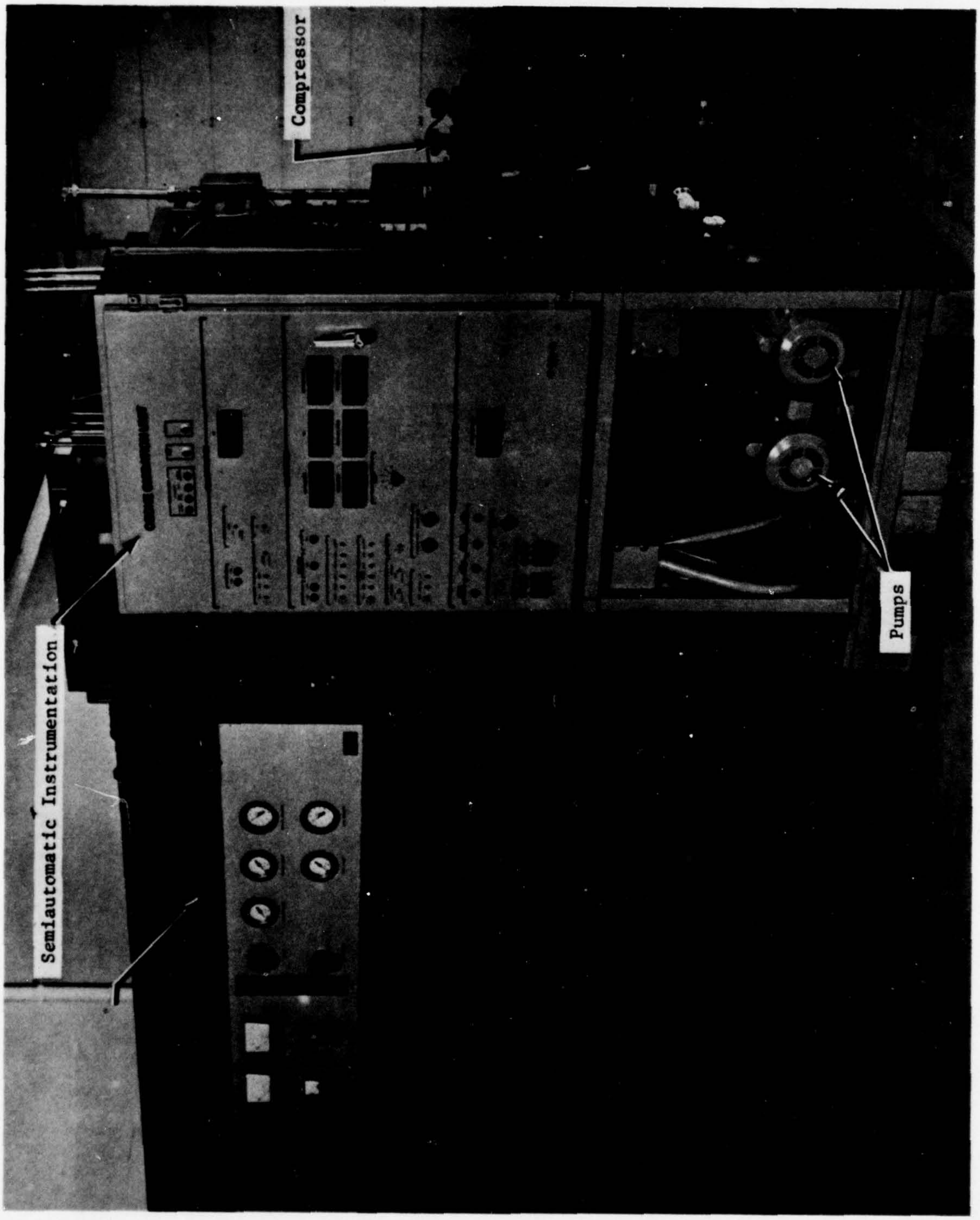


FIGURE 5 UV-ACTIVATED OZONE OXIDATION UNIT

automatic instrumentation unit to simplify the system operation, minimize system downtime, minimize requirements of operator skill level, increase system operation reliability, increase system maintainability, increase system flexibility and provide data acquisition capability.

INSTRUMENTATION CONFIGURATIONS

During the pilot plant phase of the WPS, two types of instrumentation were designed for the water processing system: a semiautomatic instrumentation and an automatic instrumentation. The semiautomatic and automatic instrumentation could be converted back and forth rapidly in the WPS Pilot Plant. This enabled the project engineers to perform unit process testing under semiautomatic operation and integrated system testing under automatic instrumentation. In addition, a Data Acquisiton, Monitor and Control System was also incorporated to collect the pilot plant data. The block diagram of the WPS with DAMCS is shown in Figure 6.

The semiautomatic instrumentation, as a backup to the automatic instrumentation, is characterized by:

- Automatic process parameter control
- Manual startup and shutdown sequences
- Manual selections of valve positions according to operating mode
- Automatic alarm shutdown
- Switches, meters, gauges and status indicators for operator/system interface

The basic design concepts of the semiautomatic instrumentation were to implement process parameter control loops and the alarm shutdown logic into automatic operation so that the system would be in automatic operation with protection against possible damages once it reached steady-state. The only manual operations needed in the semiautomatic instrumentation were during the transitions and mode selections. The semiautomatic instrumentation units were physically packaged into the three mechanical units (WTU, WPU and O_3/UV). They are discussed with the mechanical hardware in other Life Systems' reports.[1-4] The DAMCS is also discussed in a separate document.[5] In this report, only the automatic instrumentation unit is discussed.

The automatic instrumentation is characterized by:

- Computerized automatic parameter control
- Automatic operating mode control
- Automatic operating mode transition control
- Automatic setpoint modification

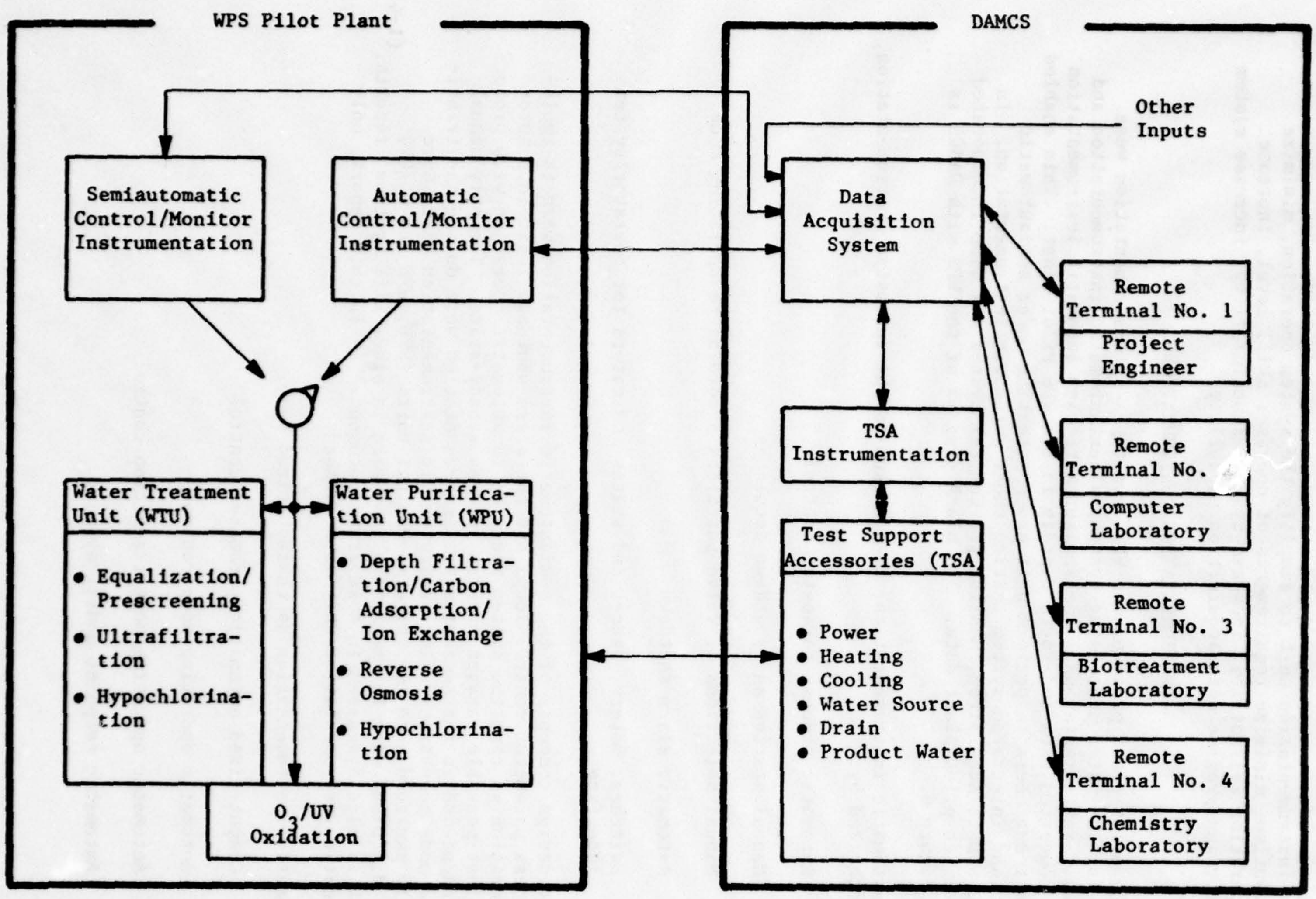


FIGURE 6 WPS/DAMCS PILOT PLANT BLOCK DIAGRAM

- Fault detection and isolation analysis
- System performance trend analysis
- Interactive operator/system interface

Hardware Description

Figure 7 shows the WPS automatic instrumentation. Table 1 summarizes the design characteristics of the automatic instrumentation unit. The unit is designed to control six unit processes of the WPS automatically and communicate with the operator and data acquisition system computer as shown on the block diagram in Figure 8.

On the operator/system interface side the operator is provided with a front panel consisting of a control panel, a message display, a keyboard panel and a recessed manual override panel. The control panel provides the operator with pushbutton switches and lamp indicators for ease of selecting:

- Product/Source
- Auxiliary Operating Mode
- System Operating Mode

The complex operation of the WPS operating modes and transitions are simplified considerably. The message display and keyboard panel provides the operator with a convenient way of communicating with the system. Parametric data, fault detection and trend analysis messages, operator error messages, and control/monitor setpoints, scale factors and allowable ranges can be modified by the operator easily from the front panel keyboard switches. The manual override panel is recessed behind the control panel. The operator can override the system quickly and easily by this recessed panel designed for system checkout and maintenance.

There are two communication links between the automatic instrumentation and the Data Acquisition System (DAS). One link is through the distributed input/output channel to the DAS Foreground Computer for on-line data communication and the other link is through the communication switch of the DAS to remote terminals for troubleshooting and debugging.[5]

On the process side an analog and digital interface board was designed for the automatic control/monitor instrumentation. The analog and digital interface was designed to handle 64 analog sensors, 8 analog actuators, 128 digital sensors and 64 digital actuators. The interface has expansion capabilities for more sensors and actuators.

Software Description

The software of the instrumentation can be divided into two portions: (1) control and monitor modules and (2) communication modules for operator/system interface and data acquisition functions.

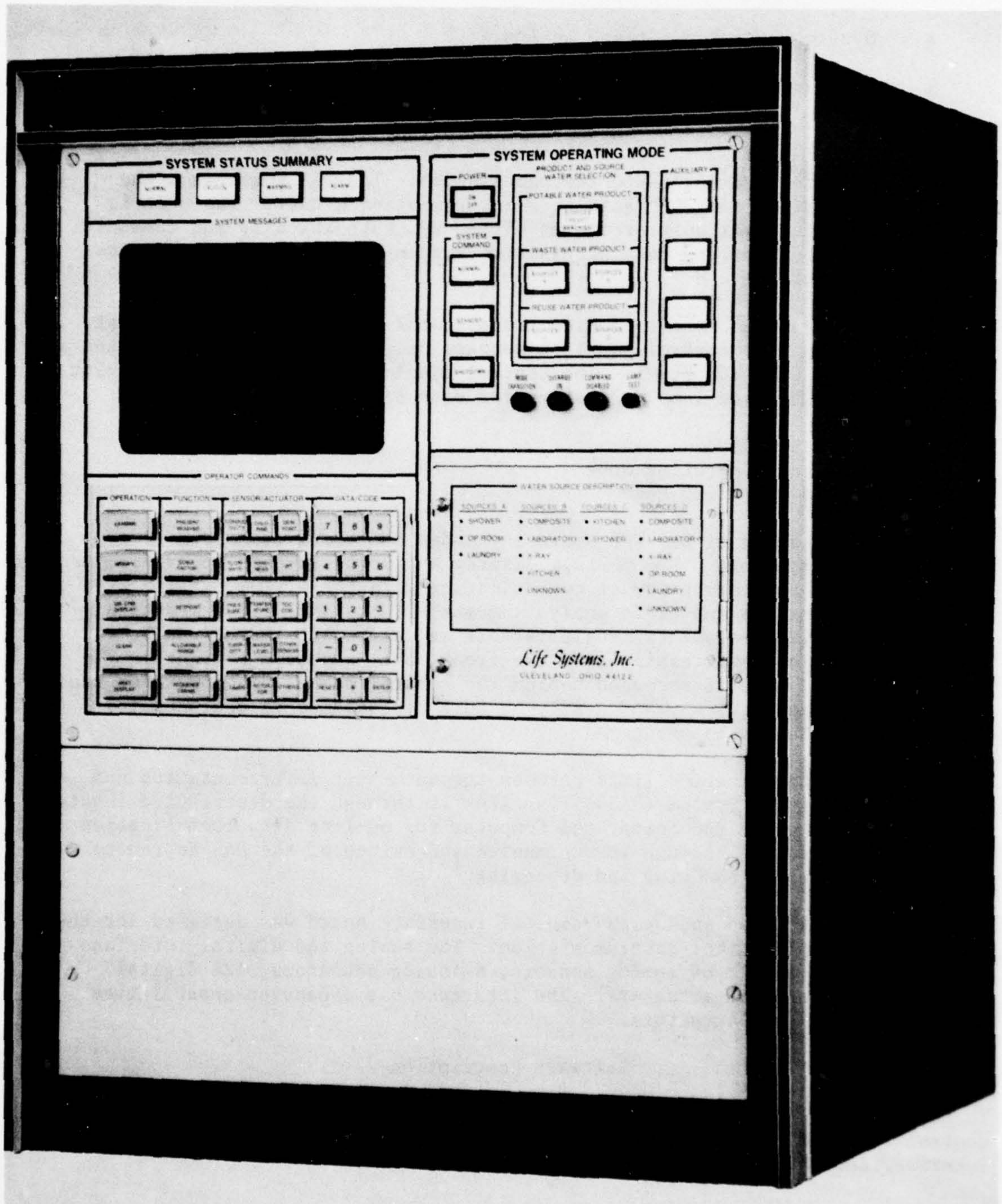


FIGURE 7 AUTOMATIC CONTROL/MONITOR INSTRUMENTATION

TABLE 1 WPS AUTOMATIC CONTROL/MONITOR INSTRUMENTATION DESIGN CHARACTERISTICS

Parameter	Specification or Reference
Dimensions (L x W x H), in	21 x 21 x 28.5
Weight, kg (lb)	110 (250)
Power Consumption, W	750
Line Voltage, V	115
Line Frequency, Hz	60
Input Sensor Signal Range, VDC	0 to 5
Output Actuator Signal Range, VDC	0 to 5
Processor	
CPU	LSI-2/20
Word Size, bits/word	16
Memory Size, words	16,384
Memory Speed, nsec	1,200
Input/Output	
Number of Analog Inputs	64
Number of Analog Outputs	5
Number of Digital Inputs	128
Number of Digital Outputs	80
Front Panel	
Command Inputs	Pushbutton Switches
Message Display	Color-coded Indicators and a CRT Display
Display Panel Capacity, characters	1,920 (80 x 24)
Number of Manual Overrides	39
Operating Modes	
Number of Primary Operating Modes	2
Number of Product/Source Modes	5
Number of Auxiliary Modes	4
Number of System Modes	4
Number of WPS Mode Transitions	7

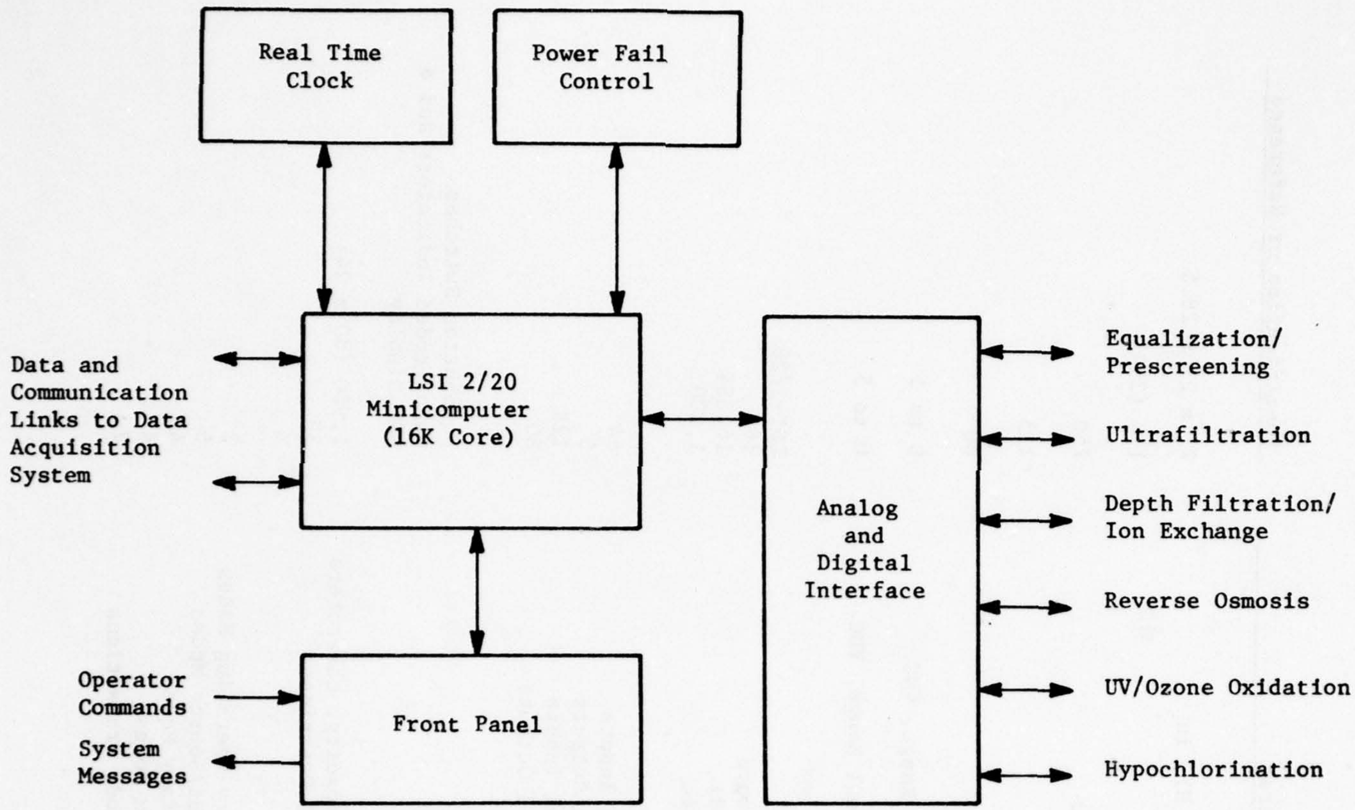


FIGURE 8 WPS AUTOMATIC CONTROL/MONITOR INSTRUMENTATION HARDWARE BLOCK DIAGRAM

The software structure is shown in Figure 9. The control and monitor modules run under a real-time executive (RTE). The software RTE handles the automatic scheduling of the input/output modules, unit process control modules, operating mode control and mode transition modules, parameter control modules, fault detection, isolation and trend analysis modules and dynamic trend analysis module.

The process parameters of the WPS are under direct digital control of the automatic C/M I. These parameters include pH, temperature, water level, hypochlorite dosage and O_3 dosage. The process parameters monitored for system performance trend analysis include pH, turbidity, temperature, pressure, flow rate, conductivity, hardness and total organic carbon (TOC)/chemical oxygen demand (COD). The performance trend analysis includes both the static trend analysis and the dynamic trend analysis. The static trend analysis compares a parameter reading with setpoints indicating Caution, Warning, and Alarm thresholds. Visual displays indicating whether a parameter is in Normal, Caution, Warning or Alarm range are provided in the instrumentation. The dynamic trend analysis module calculates the rate of change of a parameter and predicts a fault condition based on the rate of change of the parameter.

The process operating mode control is a complicated operation. It includes selection of different unit processes, selection of valve positions, sequencing of actuators and checking parametric conditions as the transition proceeds. The process operating mode control module is implemented in such a way that the parameter, its functions, time constants, conditions, etc. are tabulated and microcoded. The microcoded transition tables are translated into system operations by a software microcode interpreter which decodes and implements the functions specified in the microcode commands. This provides ease of change in the process control sequences. Whenever a new control sequence is desired a programmer simply defines the new control sequence in the microcode table, links the new control sequence to the C/M I software and loads the new code into the control memory.

Operation

The automatic C/M I provides the WPS with advanced operation features. It controls the integrated WPS systems operations automatically by providing the WPS system with automatic operating mode and mode transition control, and process parameter control. Therefore, minimum operator intervention is required.

The computer-based instrumentation provides the WPS with maximum flexibility to add, delete or change functions. The unit process control routines and parameter control loops were implemented in modular forms for ease of modifications. The real-time constant settings for control/monitor routines and the process control parameter setpoints were implemented in tabular forms for flexible operations. The table-driven implementation facilitates the on-line adjustments of control and monitor functions.

The monitor functions include fault detection and trend analysis. These functions safeguard the WPE against possible damages to system and personnel. It also gives an early warning of any pending failures so that corrective maintenance can be performed quickly and effectively.

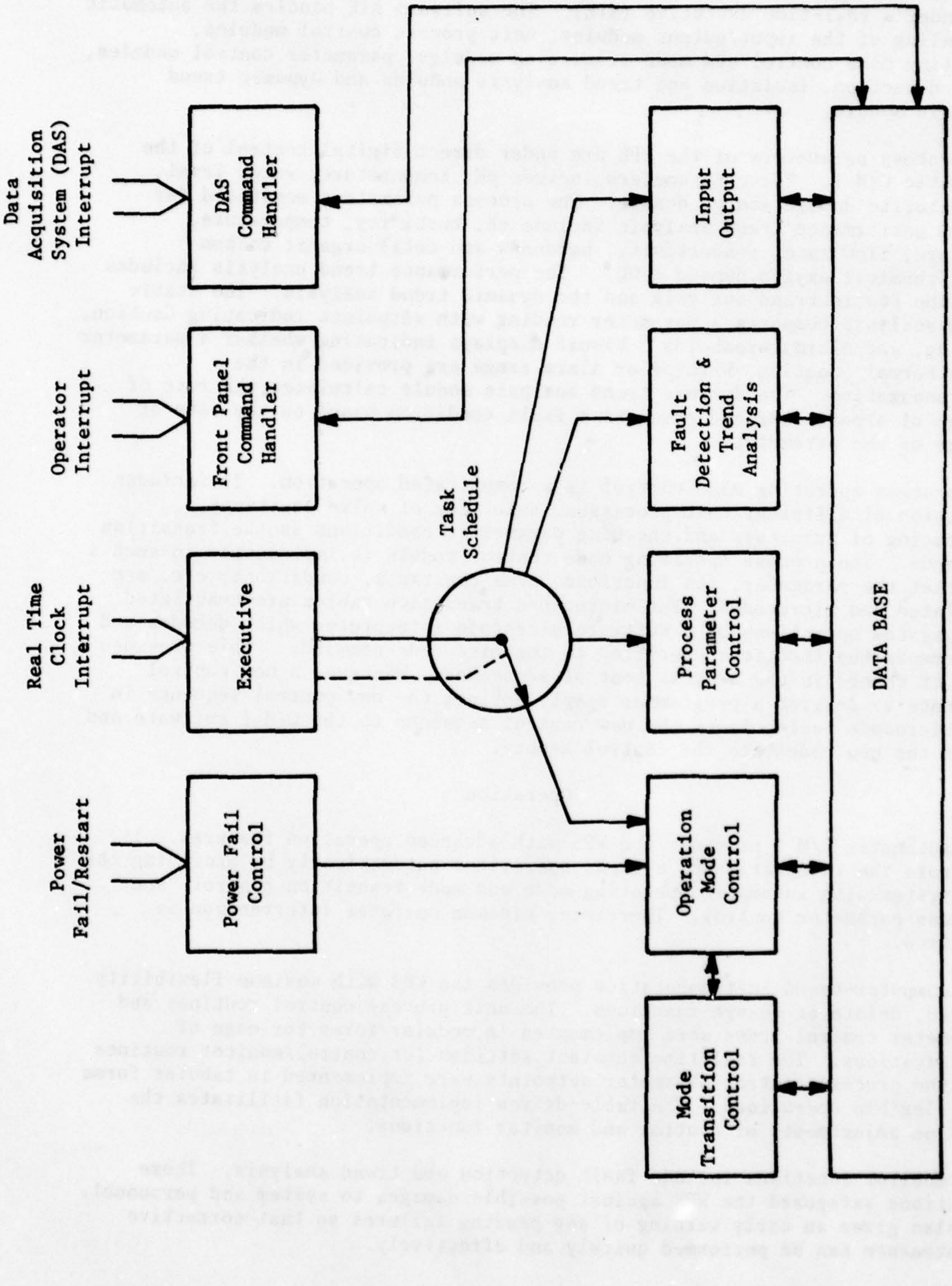


FIGURE 9 WPS AUTOMATIC CONTROL/MONITOR INSTRUMENTATION SOFTWARE BLOCK DIAGRAM

The communication functions employ the minicomputer's hardware interrupt capability to provide an interface of the WPS with the outside world at minimum overhead. The WPS accepts operator commands either directly from the front panel or remotely from the DAS. The communication is interactive and capable of on-line displaying, examining and modifying parameters and setpoints.

AUTOMATIC CONTROL/MONITOR INSTRUMENTATION DESIGN

The design specifications and the unique requirements for the WPS Pilot Plant are presented in this section. The design of instrumentation architecture, system input/output, control strategies, monitor functions, operator/system interface and data acquisition interface is described in detail.

Design Specifications

Detailed design specifications of the WPS Pilot Plant are introduced in a separate report.[1] A synopsis of the WPS specifications related to the instrumentation design is given in Table 2. The unique requirements for the WPS instrumentation design are: (1) limited allowance on size, including weight, volume and electrical power consumption, (2) minimum maintenance for unskilled operators, (3) pilot plant capabilities with semiautomatic instrumentation and manual override backup for performance evaluation and (4) data acquisition capability for scientific data collection.

Table 3 summarizes the WPS Pilot Plant automatic instrumentation design specifications. The design characteristics were shown in Table 1. In light of the specifications cited, one can visualize the automatic instrumentation unit as an intelligent electronics enclosure which accepts valid commands from an authorized operator through the use of an operator/system interface panel, implements the operator commands (operating mode, source/product selection, auxiliary mode, system mode and operator/system interface commands), collects sensor data from the pilot plant, converts the data into engineering units, performs flexible control strategies, monitors system performance, alerts the operator when failures occur, provides maintenance aids and transmits sensor data to a DAS.

Instrumentation Approach and Architecture

The selection of an instrumentation approach and architecture is typically based on system complexity, flexibility, reliability, maintainability and cost.[6] The integrated WPS is a very complex system consisting of over 100 actuators and 100 sensors. It is a mission-oriented system intended for Army field applications. Rapid startup/shutdown, reliable operation and minimum downtime are only a few of the critical requirements of the WPS operation. The design specifications of the WPS Pilot Plant instrumentation require that the system be automated with maintenance aids and the routine maintenance and operation of the pilot plant instrumentation be performed by one person. Previous studies by Life Systems, Inc. in the general areas of process control and monitor instrumentation, as well as the specific areas of water processing instrumentation, indicate that to achieve the WPS development goals the pilot plant instrumentation should be designed based on a

TABLE 2 SYNOPSIS OF WPS SPECIFICATIONS RELATED TO PILOT PLANT INSTRUMENTATION DESIGN

A. Pilot Plant Phase

Item	Specification
General Requirements	• Small size (weight, volume and power consumption) • Minimum maintenance skill level requirement • Semiautomatic and manual override backup • Data acquisition provision
Water Sources	• Natural fresh/brackish • Medical complex wastewaters (shower, operating room, kitchen, laboratory, x-ray, laundry and composite)
Water Products	• Reuse (nonconsumptive) • Potable • Surface Discharge
Operating Modes	• Two primary modes (reuse and potable/discharge) • Four auxiliary modes (UF cleaning, IE regeneration, RO cleaning/coating and system drain) • Four system modes (power off, shutdown, standby and normal)
Operating Time, hr/d	20

continued-

Table 2 - continued

B. Production Phase

Item	Specification
Mean-Time-Between-Failure	560 hr for a mission of 240 hr
Mean-Time-to-Repair	60 min on-site
Setup Time	30 min
Shelf Life	10 years
Dimensions (LxWxH)[a]	
Expanded, ft	11.5 x 9.5 x 6.75
Transportable, ft	11.5 x 6.5 x 6.75
Dry Weight, lb	12,000
Power, kW	30

(a) Each ward container. The WPE will be packaged in two ward containers.

TABLE 3 SYNOPSIS OF WPS PILOT PLANT AUTOMATIC INSTRUMENTATION DESIGN SPECIFICATIONS

- Must produce information necessary for the design of a fully-automated WPS prototype
- When applicable, should conform to the same industrially-recognized instrumentation compatibility standard
- Should be accompanied by easily-used standards for calibration and diagnostics
- Routine maintenance and operation of pilot plant instrumentation can be performed by one person
- All readouts and controls will be accessible to one operator
- Convert standard sensor signals to engineering units
- Perform diagnostics to insure the integrity of transmitted signals, the validity of transmitted data values
- Easily expandable to twice the original number of sensors
- Command at least 50 control points easily expandable to at least 100
- Capable of fully-automatic operation of the WPS pilot plant as an automatic system with maintenance aids
- Amenable to easy transfer of control, monitor and maintenance aid intelligence to a microprocessor-implemented WPS instrumentation prototype
- Rapidly modify, create, or override control and monitor functions of the mainframe computer with the generation of an automatic log of the operator-initiated control actions
- Capable of interfacing with a DAS which will query, store, retrieve and report sensor data

minicomputer but structured for easy transfer of control, monitor and maintenance aids intelligence to a microprocessor-implemented WPS instrumentation prototype.(6-10)

Figure 10 is a detailed block diagram of the WPS Pilot Plant automatic instrumentation unit.

Table 4 shows the instrumentation design considerations for the WPS Pilot Plant. Among the options of instrumentation architecture (distributed design, hierarchical design, centralized design and centralized design with redundancy), the centralized design with redundancy was selected for the WPS automatic instrumentation.(6) In the pilot plant phase, however, no instrumentation redundancy was implemented. The redundancy instrumentation design could readily be incorporated during the prototype phase after the centralized automatic instrumentation unit is proven and fine tuned during the pilot plant phase.

When designing the pilot plant sensor and actuator input/output, consideration must be given to (1) packaging the signal conditioners with the mechanical units or packaging the signal conditioners with the automatic instrumentation unit and (2) multiplexing sensor signals at low signal levels, multiplexing sensor data at high signal levels or no multiplexing. Among these options the one with signal conditioners packaged with mechanical units and high level signal multiplexing was selected and implemented. Signal conditioners were packaged with mechanical units because the mechanical hardware was physically located at a distance of approximately 6 to 10 m (20 to 30 ft) from the automatic instrumentation unit during the pilot plant experiment. Packaging the signal conditioners at the mechanical units reduced the electromagnetic interference (EMI) considerably. High level multiplexing of the sensor signals was implemented for the same reason (less EMI) in addition to economic reasons (high level multiplexing costs less than no multiplexing).

Among the available command/data entry techniques and system display techniques, the one with a custom-made keyboard and a black and white Cathode Ray Tube (CRT) display unit was selected and implemented. It was concluded during the evaluation period that such a design is the best trade-off between human factors and the cost of design and manufacturing.

Included in Table 4 are system protection considerations, operational simplicity considerations and instrumentation packaging considerations. Further discussions are provided in the following sections.

System Input/Output

The system input/output (the "front-end" of the system) of the automatic instrumentation unit consists of the following components:

- Sensors
- Signal conditioner (sensor excitation, preamplification, noise filtering, signal calibration, curve shaping, temperature compensation and common mode voltage rejection)

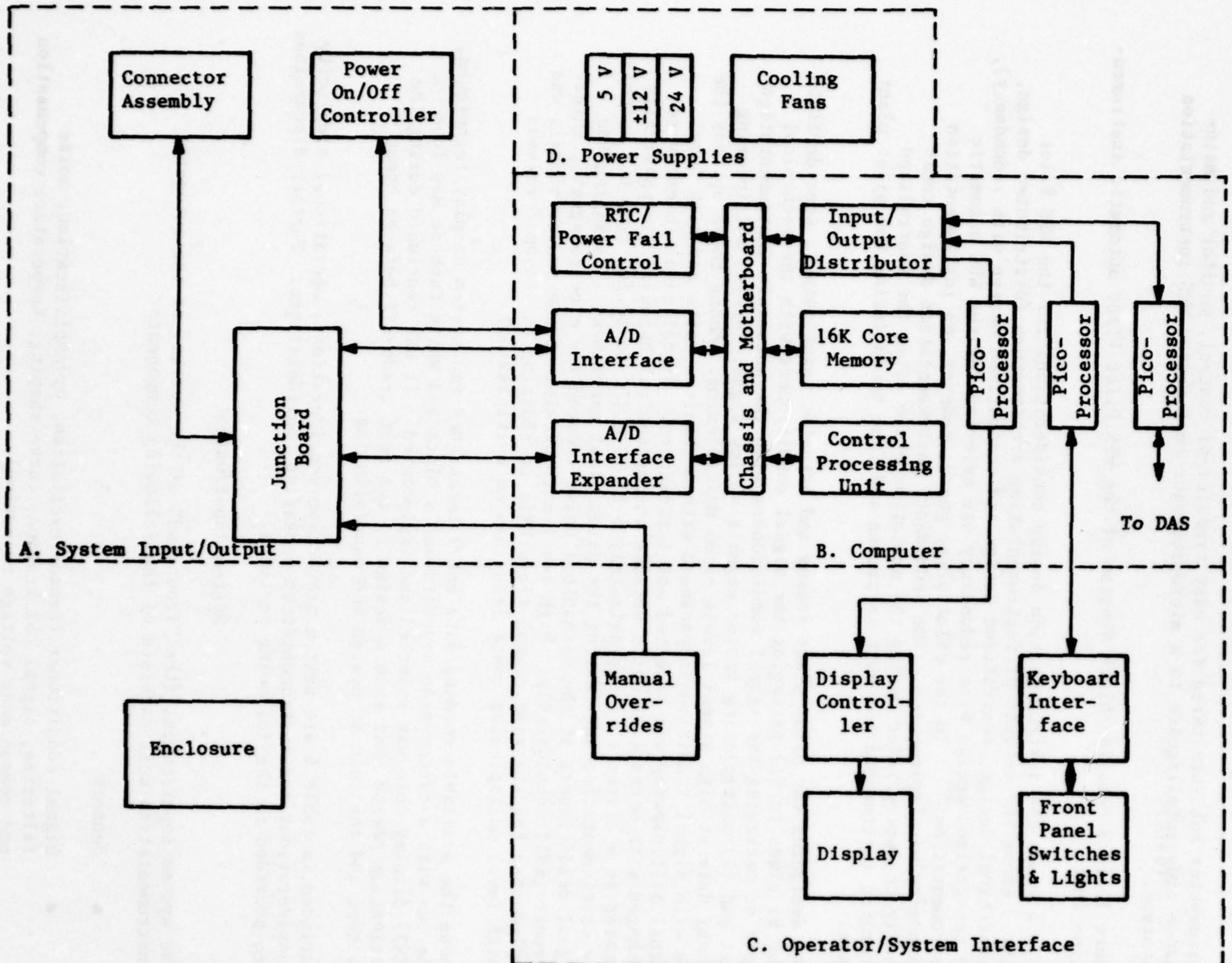


FIGURE 10 DETAILED WPS AUTOMATIC INSTRUMENTATION HARDWARE BLOCK DIAGRAM

TABLE 4 WPS PILOT PLANT AUTOMATIC INSTRUMENTATION DESIGN CONSIDERATIONS

- **Available Approaches**
  - Hardwired
  - Programmable Logic
  - Microprocessor
  - Microcomputer
  - Minicomputer
  - Large Scale Computer

- **Architectural Options**
  - Distributed design
  - Hierarchical design
  - Centralized design
  - Centralized design with redundancy

- **Input/Output Design Options**
  - Signal conditioners packaged with mechanical units
  - Signal conditioners with automatic instrumentation unit
  - High level multiplexing
  - Low level multiplexing
  - No multiplexing

- **Available Command/Data Entry Techniques**
  - Custom-made keyboard
  - Off-the-shelf 51-key typewriter-type keyboard
  - Off-the-shelf point-of-sale type keyboard
  - Thumbwheel switch/pushbutton switch combination

- **Available System Display Techniques**
  - Black and white CRT display
  - Colored CRT display
  - Gas discharge dot matrix display
  - Four level indicator light display
  - Illuminated graphic or message display switches

- **System Protection Considerations**
  - Front panel command disable provision
  - Operator identification password requirement
  - Command validity check
  - Built-in allowable ranges for setpoint modifications
  - Performance trend analysis with system shutdown upon alarm conditions

continued-

Table 4 - continued

- Operation Simplicity Considerations

  - Divisions of system command, product/source selection, and auxiliary modes
  - Definition of allowable mode changes
  - Definition of allowable combinations of modes
  - Indication of mode transition
  - Description of water sources
  - Division of manual override switches by unit processes and by type of actuators

- Instrumentation Packaging Considerations

  - Modular design of electronic circuits and assemblies for ease of maintenance
  - Mounting of the CRT display unit inside the cabinet for both equipment and personnel safety
  - Removable side panels, rear panels, top panel and front panel for ease of maintenance
  - Interchangeable computer front panel: (1) plain cover, or (2) programmer's panel
  - Performated bottom panel and louvered rear door for ventilation

- Amplifier (supplementary to signal conditions; scale all signals to 0-5 V)
- Multiplexer (relay or solid state switching and control logic)
- Analog to digital converter
- Digital signal interface with computer

Sensor Selection

In the WPS Pilot Plant there are 13 different types of sensors used for control, monitor and data acquisition purposes. They are:

- Chlorine
- Conductivity
- Dew Point (moisture)
- Flow (both flow rate and total flow quantity)
- Liquid Level
- Pressure (gauge pressure and differential pressure)
- pH
- Temperature
- Turbidity
- Water Hardness
- Total Organic Carbon/Chemical Oxygen Demand (TOC/COD)
- O_3-in-Air
- O_3-in-Water

In addition, there are valve position indicators (VPI) and UV lamp current sensors for fault isolation purposes.

Sensors present special challenges in wastewater applications because they often interface directly with a potentially damaging fluid and, therefore, are subject to continued fouling from solids deposition, slime-buildup and chemical precipitation.[11-14] In a recent survey by the U. S. Environmental Protection Agency it was concluded, from the field experience that the following sensors proved sufficient reliability for on-line use in wastewater treatment applications: level, flow, temperature, pressure, speed, weight, position, conductivity, rainfall, turbidity, pH, residual chlorine, free chlorine gas and free flammable gas. Most of the sensors judged as unsatisfactory in the survey were the analytical types.[11]

A sensor selection procedure typically consists of two steps.[8,15] First, the type of sensor monitoring technique has to be selected and then a specific field hardware is selected. Tables 5 and 6 show the criteria used in determining the monitor technique and field hardware of the WPS Pilot Plant sensors. For some sensors the monitor technique can be readily chosen, either because there are very few choices (e.g., pH, turbidity and conductivity monitoring techniques) or because of well established practices in industry (e.g., temperature and pressure monitoring techniques). For others, a thorough investigation is required in which the range, sensitivity, stability, response speed, interferences and common problems have to be studied. After

TABLE 5 SENSOR MONITORING TECHNIQUE SELECTION CRITERIA

Absolute Requirements

Adequate Monitoring Range
Adequate Sensitivity and Stability
Avoidance of Interferences
Adequate Speed of Response

Primary Considerations

Continuous versus Cyclic Analysis
Direct versus Indirect Indication
Sample Size
Reagent Requirement (when required, high reagent stability)
Degree of Specificity
Automation Possibility
Skill Level
Environmental Conditions

Temperature
Flow Rate
Pressure
Reagent Storage (if required)

Secondary Considerations

Reagent Volume
Analysis Time Sensitivity
Output Units
Sample Concentration Needed

TABLE 6 FIELD HARDWARE SELECTION CRITERIA

Absolute Requirements

- High Safety Level
- Applicable to Field Use
- Adequate Operating Life
- Adequate Functional Capability
- Low Cost
    - R&D (Minimize Development Risk)
    - Capital (Original Equipment)
    - Operating

Primary Considerations

- Weight (Hardware, Spares and Expendables)
- Power Requirements
- Volume (Hardware, Spares and Expendables)
- Low Logistical Support Requirements
    - Expendables
    - Spares
- Durability
- Reliability
- Transportability
- Operation
- Storage
- Maintainability
    - Operator Skill Level and Time
    - Minimum Servicing
    - Easy Replacement
    - Easy Repair
    - Maximum Time Between Servicing
- Low Noise Level
- Simplicity (Operation and Configuration)
- Quantity of Heating
- Quantity of Cooling (Heat Rejection)
- Availability of Equipment in Marketplace
- Number of Different Components and Total
- Number of Components Development Risk

Secondary Considerations

- Growth Potential
- Minimum Service Interfaces
- Flexibility to Other Available Reagents
- Weight of Individual Components

the type of sensor is selected, a particular field hardware can then be decided based primarily on its safety level, field applicability, operating life, capability, cost and size.

Chlorine Sensor. In the WPS, a chlorine sensor was designed for the HC unit process to monitor the hypochloride residual in the potable/reuse water stream. There are three types of chlorine sensors: (1) amperomatic flow through, (2) membrane electrode and (3) redox potential. Common problems of chlorine sensors are membrane fouling, sensitivity to pressure, pH and flow rate fluctuations, frequent calibration, flow response and memory effect in sensor response. A preliminary selection was made to use a membrane electrode type chlorine sensor. During the pilot plant phase of the development, actual incorporation of the chlorine sensor was postponed pending further investigation or development of a reliable sensor. However, the instrumentation (including the signal conditioner, interface and related computer software) is designed and ready for the update.

Conductivity Sensor. A conductivity sensor was required to monitor the RO permeate water quality to ensure that the RO permeate water was free of suspended and all but low molecular weight dissolved solids.

There are two types of conductivity sensors: (1) two electrodes and (2) four electrodes. Common problems of conductivity measurement are electrode poisoning and polarization, especially in high conductivity measurement. In the application of RO permeate conductivity monitoring, these problems are less likely to happen because of the lower conductivity of the RO permeate. A two-electrode conductivity meter was used in the WPE Pilot Plant.

Dew Point Sensor. A dew point (moisture) sensor was required to monitor the feed air to the O_3 generator in the O_3/UV unit process. This was needed to protect the O_3 generator from permanent damage caused by moisture in the air and for scientific data collection to evaluate the air dryer. A built-in moisture probe inside the O_3 generator was used to monitor the process air dew point in the pilot plant.

Flow Rate Sensor. Process water flow rates and gas flow rates are important parameters in all six unit processes of the WPE Pilot Plant. Flow rate sensors are used to monitor the UF concentrate flow rate, the UF permeate flow rate and total quantity, the RO concentrate flow rate, the RO permeate flow rate and total quantity, the O_3/UV water flow rate and the O_3 air supply gas flow rate. Flow sensors available on the market include variable head meters with differential pressure transducers (Venturi tubes, flow nozzle, orifice plate centrifugal section), variable area meters with displacement transducers (float, spring-restrained plug, hinged valve and cantilever vane), rotating meters (propeller or turbine), electromagnetic flow sensors, thermoelectric flow sensors and ultrasonic flow sensors.[16,17] Turbine type flow sensors are used in the WPS Pilot Plant for clean water flow rate monitoring. A magnetic flowmeter is used for the UF concentrate loop where the fluid is wastewater with a high concentration of suspended solids. Measuring clean water with turbine flow sensors has been very satisfactory with only minor problems such as defective material which causes bearing failure. Contamination of electrodes in electromagnetic sensors is a common problem.

However, as long as regular maintenance is performed, flow measurement with electromagnetic sensors is satisfactory.[15]

Liquid Level Sensors. Liquid level sensors were required in five water tanks of the WPS Pilot Plant: the EP tank, the UF feed tank, the RO feed tank, the O_3/UV precontactor and the product water storage tank. There are five categories (visual, float, probe, radiation and differential pressure) and a total of 27 types of liquid level sensors.[18] Some typical liquid level sensors include those employing buoyancy displacers, air bubblers, pressure transducers, microwave, cavity resonance, conductivity, nuclear radiation and sonic; multiple point magnetic switches and multiple point optical switches.

The float magnetic-switch type level detectors are used in the RO feed tank, the O_3/UV precontactor and the product water storage tank. The water in these three tanks is clean and free of suspended solids and the purpose of the water level sensors is to detect whether the tanks are full or empty. The process water in the EP tank and the UF feed tank is solid-bearing hospital wastewater. Contamination of float-switch level detectors in the EP and UF tanks is possible because of the sludges at the bottom of the tanks and scum on the surface of the water. Differential pressure liquid level sensors were used in these two tanks. Common problems reported were gravity and liquid density effects and vibration interference.

Bubbler-type level sensors were also evaluated. Because of the higher operating cost, more frequent maintenance, difficulty in calibration and lower reliability, the WPS Pilot Plant was designed with differential pressure type sensors rather than bubblers.

Pressure Transducer. There are two categories of pressure transducers used in the WPS Pilot Plant: (1) differential and (2) gauge/absolute pressure. The differential transducers were used to monitor the pressure drops across UF basket strainers, the UF membrane, the IE depth filter, the RO micron filter and the RO membrane. The gauge/absolute pressure transducers were used to monitor the UF module upstream pressure, the IE column pressure, the RO module pressure and the O_3 generator feed pressure.

Common problems reported on strain gauge pressure transducers are the vibration interference in the low pressure range reading and the contamination of the solids in the process water stream.[19] In places of the WPS system where the process water is highly contaminated with solids and corrosive chemicals, gauge protectors were used to physically isolate the sensor element from the potentially damaging fluids. Low pass filters were used in the signal conditioning circuits to minimize the possible interference due to vibration.

pH Sensor. The process water pH was controlled and monitored in the EP tank to induce precipitation and adjust the pH for more optimum performance of the membrane processes. In addition, the pH was controlled and monitored at the RO and O_3/UV unit processes for more optimal performances. Among the six pH sensors required in the WPE design, the one in the EP tank and the one in-line in the UF unit process are the two that are likely to have electrode fouling and sensor drifting problems caused by the contamination of soaps, detergents, greases and suspended solids in the hospital wastewater stream. In the UF unit process, because of the high flow rate of the process water at about 270 gpm or approximately 27 fps, the contamination problem is less likely to happen. For the pH electrode in the EP tank, an ultrasonic cleaner was incorporated to periodically clean the electrodes of the precipitate or of the solid contamination caused by the soap or greasy film.

Temperature Sensor. There are approximately 20 temperature sensors in the WPE Pilot Plant for control and monitor functions as well as scientific data collection. Temperature sensors have the least problem in chemical processing or waste treatment applications. Thermocouples were used in the design. There is no potential problem with these temperature sensors in the WPE Pilot Plant.[12]

Turbidity Sensor. Turbidity is an indication of the total suspended solids in the process water. In the WPS Pilot Plant, a turbidity meter was used in the EP unit process to monitor the influent wastewater turbidity and a second turbidity meter was used to monitor the UF permeate water turbidity level and, therefore, the performance of the UF unit process.

Common problems of turbidity sensors include contamination of windows by suspended solids and difficulties in the frequency of maintenance required. The contamination problem is more serious in the EP tank; therefore, a self-cleaning turbidity meter was used.

Water Hardness Sensor. There are three types of water hardness sensors: (1) conductivity or differential conductivity, (2) specific ion electrode and (3) batch processing colorimetric. Water hardness sensors are required to monitor the IE column water and effluent water hardness. The specific ion electrode and the colorimetric type analyzers are not suitable for the WPE application because of their range of measurements, response time, accuracy or the reagent requirement does not satisfy the application specifications of the WPS. A conductivity-type water hardness probe was used to monitor the change of the IE resin bed conductivity.

TOC/COD Sensor. The TOC/COD sensor is required to monitor the water quality of the O_3/UV unit process effluent. However, no on-line field applicable TOC/COD sensors are available off-the-shelf today. Such a field applicable water quality monitor is under development at the present time.[20-22]

Ozone Sensors. The O_3-in-air monitor, as well as the aqueous O_3 monitor, was used in the WPS Pilot Plant for scientific data collection only. These monitors are laboratory-type measuring devices which have long response times and require frequent maintenance.

Signal Conditioner

Most of the signal conditioners of the WPS Pilot Plant sensors are off-the-shelf design. A signal conditioning circuit typically includes sensor excitation, sensor signal preamplification, noise filtration, signal calibration, curve shaping, temperature compensation and common mode voltage rejection. In addition, all conditioned WPE sensor signals are amplified to 0 to 5 V signals.

The WPS is an electrically-noisy system because of the mixers, pumps, and compressors in the system. Low pass filters were incorporated in the signal conditioner design as a general rule. The signal conditioners and signal amplifiers were packaged physically at the WPS mechanical "pallets" to ensure a low noise/signal ratio before they are transmitted through 25 ft cables to the instrumentation unit.

Figure 11 illustrates the WPE system input/output configuration.

Analog and Digital Interface

In a minicomputer-controlled system an important design area is in the analog and digital interfacing requirements. Many types of analog and digital interface systems are available in either rack-mount form or a separate printed circuit card for analog input, analog output, digital input and digital output. The Life Systems' Analog and Digital (A/D) Interface board combines all of these functions into one printed circuit board (PCB) with an optional expander PCB available. Both of these boards have been designed to provide a complete analog and digital interface for the minicomputer used in the WPE Pilot Plant.

The analog interface features provide a choice of two input configurations: (1) 160 single-ended inputs or (2) 80 pairs of true differential inputs. The multiplexer (MUX) circuitry used in the Life Systems' A/D Interface is an advanced design. A break-before-make switching eliminates interchannel transients and feedback of switching spikes. Very low capacitance per channel minimizes source loading. Cross-talk, leakage and offsets have all been reduced to negligible levels for sources having recommended impedance levels. The MUX was designed to protect both itself and its signal sources from over-voltage failure and from fault currents due to power-off loading or MUX failure.

The full-scale range (FSR) of the analog input circuitry may be set by appropriate jumper interconnections of terminals to any of eight different standard ranges: (1) 0 to +10 V, (2) 0 to +10.24 V, (3) 0 to +5 V, (4) 0 to +5.12 V, (5) -10 to +10 V, (6) -10.24 to +10.24 V, (7) -5 to + 5 V and (8) -5.12 to +5.12 V. The 10.24 and 5.12 V levels are frequently convenient in that they yield conversion increments of exactly 5 mV per bit, 2-1/2 mV per bit or 1.25 mV per bit. The above ranges are adjustable by external gain trimming potentiometers on the rear of the printed circuit board. The output code of the converter is also jumper selectable to any of the following codes: unipolar binary, 2's complement, offset binary, 1's complement. All of these signal outputs are buffered to the computer data bus. The more distinct characteristics of the analog conversion input portion of the A/D PCB are described in Table 7.

Another important part of the A/D Interface is the analog output capability. The A/D PCB has been designed for a maximum of eight analog outputs, four outputs with eight bit resolution and four outputs selectable between 8, 10 and 12 bit resolutions. The scale of the output voltage is also selectable, -5 to +5 or 0 to +10. Table 8 presents the analog output characteristics.

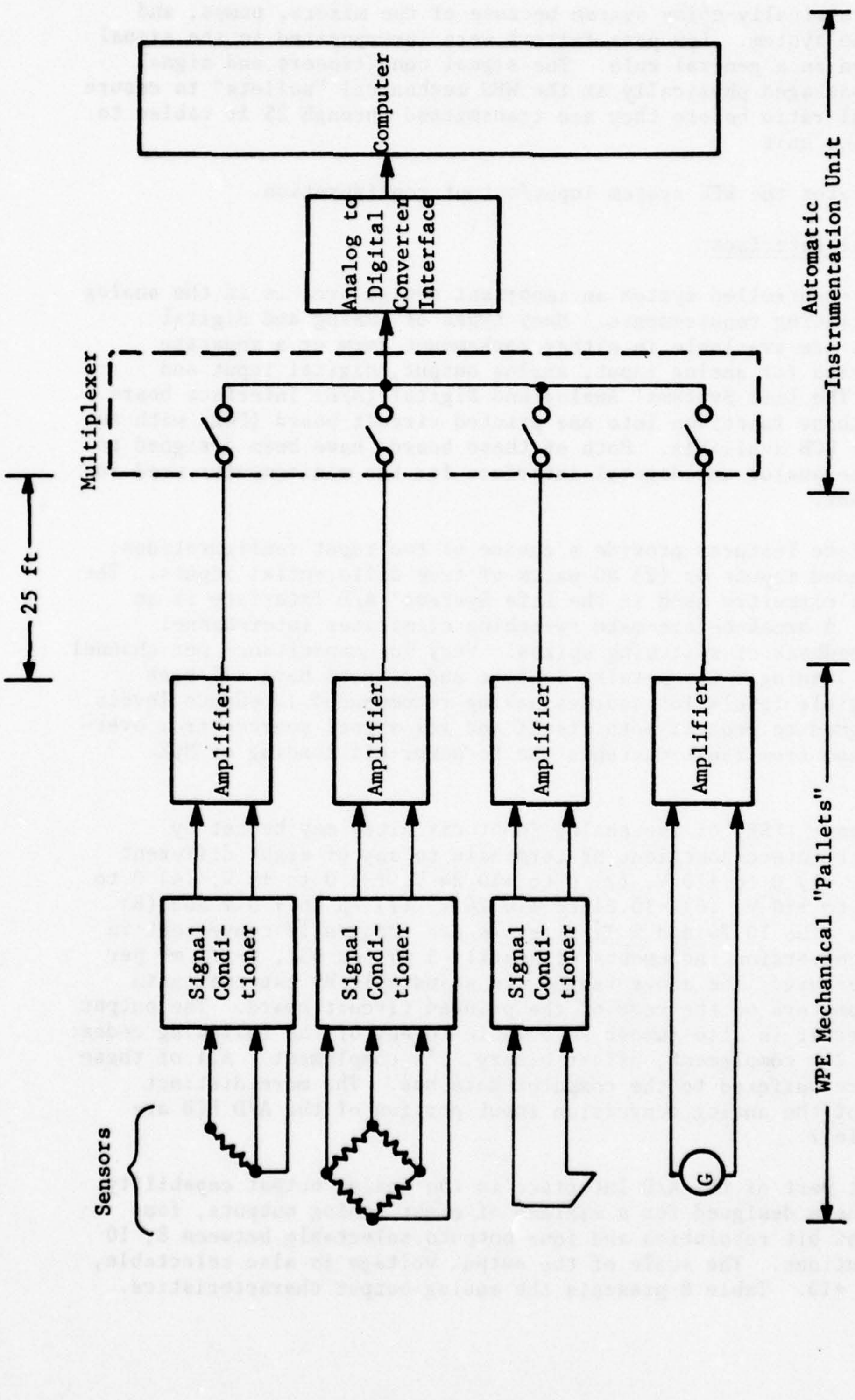


FIGURE 11 WPS SYSTEM INPUT/OUTPUT BLOCK DIAGRAM

TABLE 7 ANALOG INPUT CHARACTERISTICS

Number of Inputs	32 Minimum 160 Maximum by Increments of 32	
Input Voltage, V (Full Scale Range)	-10 to +10 0 to +10 -5 to +5 0 to +5	-10.24 to +10.24 0 to +10.24 -5.12 to +5.12 0 to +5.12
Maximum Input Voltage, V (Signal and Common Mode)	-10.24 to +10.24	
Input Current	<1 nA at 25 C; 20 nA at 60 C	
Input Impedence, megohms	>100	
Input Capacitance, pf	10 (Off Channel) 100 (On Channel)	
Resolution	12 Bits	
Accuracy	±0.25% FSR at 100 kHz Thru-put	
Quantizing Error, LBS	±1/2	
3 δ Noise, FSR	0.01%	
Thru-put to Memory, kHz	75	

TABLE 8 ANALOG OUTPUT CHARACTERISTICS

Number of Outputs	1 to 8	
Output Voltage, V	-5 to +5	0 to +10
Output Impedance, ohm	<0.1	
Resolution. Bits	8 to 12	
Scale Factor Accuracy, %	±0.1	
Settling Time, μ sec	5	
Linearity	±0.0125	
Thru-put from Memory, kHz	100	

On the digital side, the A/D PCB can input 128 digital channels such as switch contacts and output 64 digital signals of Transistor-Transistor Logic (TTL) levels. A tradeoff capability of outputting more TTL signals can be acquired by decreasing the number of analog outputs. For every analog output not required, eight additional TTL channels are available. See Table 9 for digital output characteristics.

In summary, the features of the Life Systems' A/D Interface PCB are: the capability for analog input, analog output, digital input and digital output on a single board; complete automatic interrupt channelled operation from the computer to sensor and actuator output; small size; low power; and high thru-put. Figure 12 shows the A/D Interface board and the expander board.

Control Strategies

The complexity of the WPS automatic control instrumentation is caused by the fact that the system contains multiple unit processes which are selected in different combinations depending on the product/source selections. Each operating mode has shutdown, standby and normal system modes. Transitions among these modes are complex because flow rates, liquid levels, pH, temperature, pressure and many other process parameters have to be controlled to go through a definite sequence of events. In addition, auxiliary modes for scheduled maintenance are automated to simplify the system operation.

The control strategies of the WPS automatic instrumentation are classified into two types:

- Procedure Control
- Process Parameter Control

The procedure control is used to automate system transitions and the auxiliary mode operations. The process parameter control is used to maintain system parameters at their setpoints.

Procedure Control

To implement procedure controls a Process Sequence Control Micro-Command (PSCMC) language was devised as part of the WPE automatic instrumentation software program.[23] The PSCMC was designed so that 27 standard procedures could be interpreted with a very simple coding scheme. These 27 standard procedures include the typical steps during a mode transition such as "increase a flow rate from 0 to a setpoint within a definite period of time," "turn on an actuator for a definite period of time," "compare a process parameter against a setpoint and wait for a certain period of time then take certain actions," etc. A complete listing of PSCMC commands is shown in Table 10.

With the PSCMC and the list of sensor and actuator locations, one can easily prepare a procedure control program within a short period of time and with minimal computer memory requirement. Table 11 presents such an example of UF membrane cleaning procedure. Figure 13 shows the corresponding PSCMC program listing.

TABLE 9 DIGITAL INPUT AND OUTPUT CHARACTERISTICS

Number of Inputs	4 to 128 TTL levels
Number of Outputs	8 to 64 TTL levels
Input Current	1 TTL load
Output Current	10 TTL loads
Thru-put to Memory	Same as analog input and output

FIGURE 12 A/D INTERFACE BOARD

TABLE 10 PSCMC COMMAND SUMMARY

Command Number	Operation
1	Activate an analog actuator and increment linearly to full scale in t seconds (t = specified time)
2	Activate an analog actuator to full scale
3	Decrease an analog actuator linearly from present state to 0 in t seconds
4	Set an analog actuator to 0
5	Turn off a digital actuator and wait t seconds
6	Turn off a digital actuator
7	Turn on a digital actuator and wait t seconds
8	Turn on a digital actuator
9	Check an analog sensor and wait t seconds then set condition flag
10	Check an analog sensor and set condition flag
11	Enable an analog sensor for FDIA but inhibit alarm function for t seconds
12	Check an analog sensor FDIA result, set flag if normal
13	Check a digital sensor, wait for t seconds then set condition flag
14	Check a digital sensor, set flag if true
15	Enable a digital sensor for FDIA but inhibit alarm for t seconds
16	Enable a digital sensor for FDIA
17	Mask off a digital actuator word (i.e., turn off a number of digital actuators)
18	Mask on a digital actuator word (i.e., turn on a number of digital actuators)

continued-

Table 10 - continued

Command Number	Operation
19	Set unit process sample rate to n x 100 msec (n = specified increment)
20	Set an analog actuator to the value specified
21	Set an analog actuator to the value specified (a redundant one of Command 20)
22	Turn off a digital actuator if conditions specified are true
23	Turn on a digital actuator if the conditions specified are true
24	Set completion flag and exit
25	Completion check
26	Disable analog sensors for FDIA
27	Disable digital sensors for FDIA

TABLE 11 UF CLEANING PROCEDURE

1. Drain the concentrated waste from the UF unit process by closing EP effluent valve (V102), opening the drain valve (V203) and sludge valve (V207), turning on the sludge pump (M102) and operating until the UF low alarm level setpoint is achieved.

2. Fill the feed tank with clean water by opening valve (V210) until the 60 inch water level is sensed (L201).

3. Flush clean water through the UF module at a low flow rate (20 gpm) for 15 minutes by operating the UF feed pump (M201) with the UF high flow pump (M202) off, valve X201 open and UF temperature control activated. The UF concentrate is recycled to the UF feed tank (valve V204 in position B).

4. Drain the feed tank to EP by switching valve V204 to position A and operating until low level shutdown is sensed.

5. Fill the feed tank with cleaning solution by opening V209 for four minutes.

6. Fill UF feed tank to a 60-inch water level by opening valve V210.

7. Circulate the UF cleaning solution for 30 minutes at a flow rate of 20 to 25 gpm and temperature 115 to 120 F with valve V204 in position B.

8. UF pump/drain down.

9. Fill the feed tank with clean water as in Step 2 above.

10. Flush the UF unit process with clean water for 20 to 30 minutes at a low flow rate as in Step 3 above.

11. UF pump/drain down.

12. Send a ready message to the system message display to signal the operator that the UF is now ready for manual cleaning with sponge balls, if required. Sponge balling is not required in every cleaning cycle (24-72 hours). If the operator elects to sponge ball the membranes he must manually remove each tubular assembly, insert a ball and connect a line from the portable pump and product storage tank to the assembly. Once connected, he must turn the pump on to force the ball through the assembly. This procedure is repeated until all assemblies are sponge balled. If sponge balling is not required the operator simply depresses the SHUTDOWN button and the system is ready for water production.

```
*    UF    SD-CLEANING   MICRO CODES
           DATA      :0000      EXEC
           DATA      :8001      #19, 100 MS CLOCK
           DATA      :2850      #6, CLOSE V102
           DATA      :3859      #8, V208 ON
           DATA      :3858      #8, V207 ON
           DATA      :3811      #8, M102 ON
           DATA      :4006      #9, CHECK L201
     M228  DATA      :0003      EVERY 3 SEC
           DATA      :8290      UNTIL UF LOW ALARM
           DATA      :2811      #6, M102 OFF
           DATA      :2858      #6, V207
           DATA      :2859      #6, V208
           DATA      :384E      #8, V210 ON
           DATA      :4006      #9, CHECK L201
     M229  DATA      :0005      EVERY 5 SEC
           DATA      :4990      UNTIL 60 IN
           DATA      :284E      #6, V210 OFF
           DATA      :2813      #6, M203 OFF
           DATA      :8D00      #20, X201 HALF OPEN
           DATA      :0080
           DATA      :0001      EXEC, TEMP CONTROL ON
           DATA      :3856      #8, V204 IN POSITION B
           DATA      :3012      #7, M201 ON
     M230  DATA      :0384      FOR 15 MIN
           DATA      :2856      #6, V204 IN POSITION A
           DATA      :4006      #9, CHECK L201 (TANK LEVEL)
     M231  DATA      :0002      EVERY 2 SEC
           DATA      :8290      UNTIL LOW ALARM
           DATA      :2812      #6, M201 OFF
           DATA      :3027      #7, V209 ON
     M232  DATA      :00F0      4 MIN
           DATA      :2827      #6, V209 OFF
           DATA      :384E      #8, V210
           DATA      :4006      #9, CHECK UF TANK LEVEL (L201)
     M233  DATA      :0005      EVERY 5 SEC
           DATA      :4990      UNTIL 60 IN
           DATA      :284E      #6, CLOSE V210
           DATA      :3856      #8, V204 IN POSITION B
           DATA      :3012      #7, M201 ON
     M234  DATA      :0708      #7, 30 MIN
           DATA      :2812      #6, M201 OFF
           DATA      :3859      #8, V208 ON
           DATA      :3858      #8, V207 ON
           DATA      :3811      #8, M102 ON
           DATA      :4006      #9, CHECK L201
     M235  DATA      :0003      #9, EVERY 3 SEC
           DATA      :8290      #9, UNTIL LOW ALARM
           DATA      :2811      #6, M102 OFF
           DATA      :2058      #5, V207 OFF
     M236  DATA      :0040      AND WAIT 1 MIN
           DATA      :2859      #6, V208 OFF
           DATA      :384E      #8, V210 ON
           DATA      :4006      #9, CHECK L201
     M237  DATA      :0005      EVERY 5 SEC
           DATA      :4990      UNTIL 60 IN
           DATA      :284E      #6, V210 OFF
           DATA      :3012      #7, M201 ON
     M238  DATA      :05DC      #7, FOR 25 MIN
           DATA      :2812      #6, M201 OFF
           DATA      :1800      #4, CLOSE X201
           DATA      :2856      #6, V204 IN POS. A
           DATA      :3859      #8, OPEN V208
           DATA      :3858      #8, OPEN V207
           DATA      :3811      #8, M102 ON
           DATA      :4006      #9, CHECK L201
     M239  DATA      :0003      EVERY 3 SEC
           DATA      :8290      UNTIL LOW ALARM
           DATA      :2811      #6, M102 OFF
           DATA      :2058      #5, V207 OFF
     M240  DATA      :0040      AND WAIT 1 MIN
           DATA      :2959      #6, V208 OFF
           DATA      :0         EXEC DIS CONTROLS
           DATA      :CC00      #25, TRANSITION COMPLETE
```

FIGURE 13 UF CLEANING PSCMC PROGRAM LISTING

Process Parameter Control

Digital computers can be used for process parameter control in a direct digital control (DDC) fashion or a digital supervisory control (DSC) fashion.[24,25] In a DDC system the computer receives information about the process from on-line sensors at regular intervals. From this data the computer performs a control action according to a programmed control strategy. In a DSC system the computer receives process information from on-line sensors, analyzes the data and determines the best operating setpoints for the process. The control strategies, however, are implemented with separate controllers in a DSC system. In most DSC systems the supervisory computer serves as an interface between the operator and a large number of distributed controllers. These controllers are typically hardwired although programmable controllers and DDC controllers can also be used for the distributed controllers under the supervision of a single computer.

The WPS automatic instrumentation unit is a DDC system. The DDC technique was selected because of the flexibility and physical size requirements of the WPS as well as the large number of logical decisions required to be made in the WPE control algorithms.

The WPS process parameter control routines consist of: (1) the feedback on/off control routines for pH, temperature, filter bank selection and water level, (2) the feedforward proportional control for HC dosage, and (3) the feedback/feedforward proportional control for O_3 dosage.

One of the primary goals of the WPS Pilot Plant is the study of the system dynamics of the six WPS unit processes and the development of appropriate control algorithms for various process parameter controls. The minicomputer-implemented automatic instrumentation provides an excellent tool for such a development.

Monitor Functions

Monitor functions required for the WPS are those designed for the protection of personnel and equipment against damage, the prevention of failures and shutdowns, the prediction, detection and isolation of faults and the provision of system maintenance aids. In general, monitor functions are the fault diagnostics functions including fault avoidance, fault prediction, fault detection, fault isolation, fault correction instructions and fault tolerance.[26]

Fault Avoidance

Fault avoidance capability is required to prevent human errors in causing faults. In the WPS automatic instrumentation unit the operator/system interface panel was designed with human factor considerations to reduce possible operator errors. An operator authorization code concept was also incorporated. These will be discussed later. In addition to the human factor considerations on the front panel design, the automatic instrumentation unit was designed with automatic cleaning capabilities of the turbidity sensor and the pH electrodes in the EP unit process. Sludge removal control was incorporated to allow automatic and periodic removal of EP tank sludge. These preventive measures are essential in avoiding failures.

Fault Prediction

Fault prediction is the function to predict process or component failures by performance trend analysis. This capability was incorporated into the WPS automatic instrumentation with the dynamic performance trend analysis technique which calculates first derivatives of system parametric data and predicts future projections based on the calculated rate of change and the current barometric data readings. This concept is illustrated in Figure 14. Fluctuations of a sensor reading within the normal limits are typically ignored. Once a sensor reading exceeds the normal limits, its future projection will be forecasted based on calculated slopes and the trend recognized after four consecutive and consistent estimates are encountered. The RO permeate water conductivity was used to predict the RO failure.

Fault Detection

Perhaps the most important monitor function is fault detection. When a failure has occurred, the fault detection function should immediately take action to prevent any equipment damage and to provide operator safety. The WPS automatic instrumentation was designed with a fault detection computer program which compares the WPS parametric data with their setpoints at a predetermined interval of 100 ms. There are a total of six setpoints for the monitor function in addition to two control setpoints and two allowable limits for all the setpoints mentioned above. The relationships among the setpoints are illustrated in Figure 15.

Control setpoints are usually set at the narrowest band; e.g., between 71 and 74 F. Next in the hierarchy is the caution band; where the temperature caution setpoints may be set at 70 and 75 F. Warning setpoints are next in the hierarchy; e.g., 68 and 77 F. Alarm setpoints are next; e.g., 66 and 79 F. All setpoints mentioned so far have to maintain their relative hierarchical relationship beginning from the control setpoints to the alarm setpoints. In addition, all these setpoints have to fall in the range of allowable alarm setpoints. The allowable range concept is designed to prevent an operator from mistakenly resetting any of the previously-mentioned setpoints to a level where it may exceed the physical limits or create hazards to a system. For example, the allowable range for the temperature sensor mentioned above may be from 60 to 85 F.

The fault detection program periodically checks the parametric status by comparing present readings against their setpoints and display the present status on the operator/system interface. Whenever a parametric data reading changes its status, a message of such a status change is displayed on the CRT display on the operator/system interface. A summary of the overall system status is displayed with a four-level status indicator (Normal, Caution, Warning and Alarm).

The fault detection program maintains an internal Sensor Control Word table which contains the information about previous fault detection results, whether

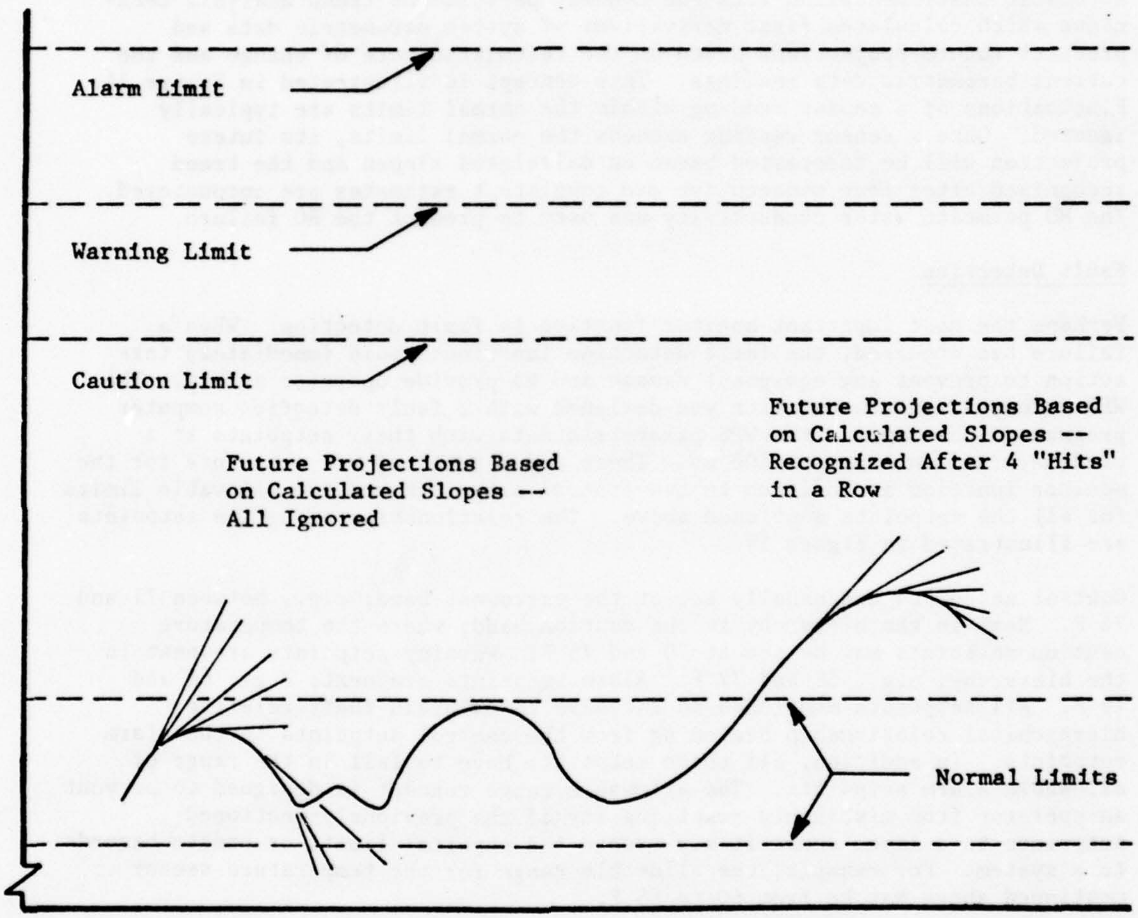
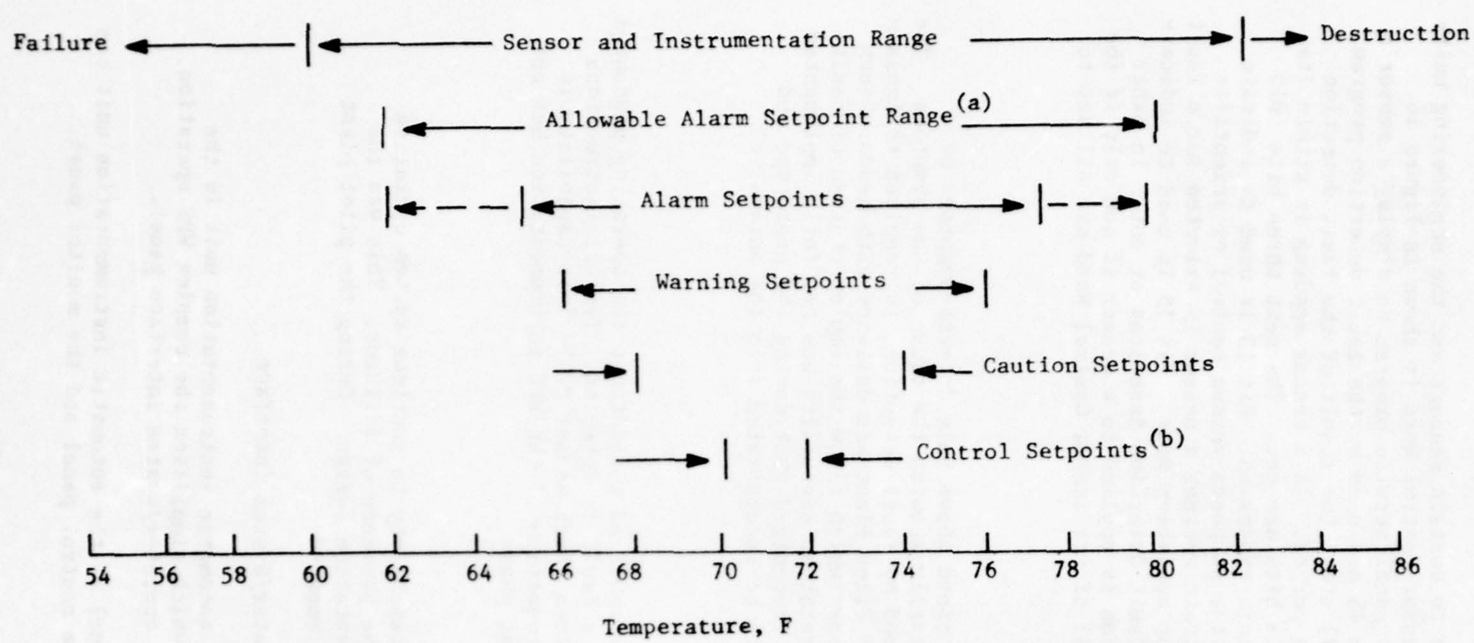


FIGURE 14 FAULT PREDICTION CONCEPT



(a) Software imposed limit on allowable modifications.
(b) Passwords needed to change setpoints -- different level, different authorization code.

FIGURE 15 MONITOR SETPOINTS AND THEIR RELATIONSHIP the fault detection is applicable to certain sensors and the engineering units of sensors. The format of the Sensor Control Word is shown in Figure 16. Bits 0 to 3 are used by the front panel service program to display a sensor's engineering unit. Bits 4 through 15 are used by the fault detection program. The first six bits (B4 through B9) store the result of the fault detection function during the last sampling period. If a sensor reading is within its normal limits then none of the six bits are set. The next three bits (B10 through B12) are reserved for future expansion. Bit 13 is used to indicate whether a sensor is used for monitor purposes versus control or scientific purposes. Bit 14 is used to indicate whether a sensor is selected for a fault detection function for the current operating mode. Bit 15 is used to indicate whether a sensor is enabled for fault detection functions or not. In other words, the fault detection function is applied to a sensor if and only if the first three bits (B13 through B15) of its Sensor Control Word are all set to one.

Fault Isolation

The fault detection function described above only detects symptoms of component failures but not necessarily knowing the cause of the symptoms. The fault isolation function, triggered by fault detection, is required to isolate the causes of a symptom. The WPS Pilot Plant was designed with sensors such as VPI's and UV lamp current sensors which allow the implementation of fault isolation. Although the fault isolation capability was not fully implemented at the pilot plant stage, it was recognized that during the prototype and production phases it would have to be incorporated into the automatic instrumentation.

Fault Correction Instructions

Fault correction instructions are required to instruct the operating personnel on the maintenance actions after a fault is detected. Typical instructions are "check valve V1, if normal; then check sensor P2." This capability is essential for the prototype or production of the WPE instrumentation but not implemented during the pilot plant phase.

Fault Tolerance

Fault tolerance is the built-in capability to continue system operation without external assistance in the presence of failures. This was the ultimate goal of the WPS instrumentation design. During the pilot plant phase, however, this was not implemented.

Operator/System Interface

One of the major benefits of the automatic instrumentation unit is the operator/system interface panel which simplifies the complex WPS operation. Figure 17 is a photograph of the operator/system interface panel.

The operator/system interface panel of the automatic instrumentation unit can be divided into two portions: the control panel and the monitor panel.

System Enabled	Unit Process Selected	Monitor Sensor				High Alarm	High Warning	High Caution	Low Caution	Low Warning	Low Alarm	Engineering Unit Index			
B_{15}	B_{14}	B_{13}	B_{12}	B_{11}	$B_{1\emptyset}$	B_9	B_8	B_7	B_6	B_5	B_4	B_3	B_2	B_1	$B_\emptyset$

Sensor Control Word contains the following information for fault detection module:

Bit 15 is on when the sytem is in Normal Mode or when fault detection is required during transitions.

Bit 14 is on if this sensor is used in present operating mode.

Bit 13 is on if this is a monitor sensor.

Bit 9 is set if the previous result of fault detection is High Alarm.

Bit 8 is set if the previous result of fault detection is High Warning.

Bit 7 is set if the previous result of fault detection is High Caution.

Bit 6 is set if the previous result of fault detection is Low Caution.

Bit 5 is set if the previous result of fault detection is Low Warning.

Bit 4 is set if the previous result of fault detection is Low Alarm.

Bit 3 to Bit Ø is the index of Engineering Unit.

FIGURE 16 DEFINITION OF SENSOR CONTROL WORD

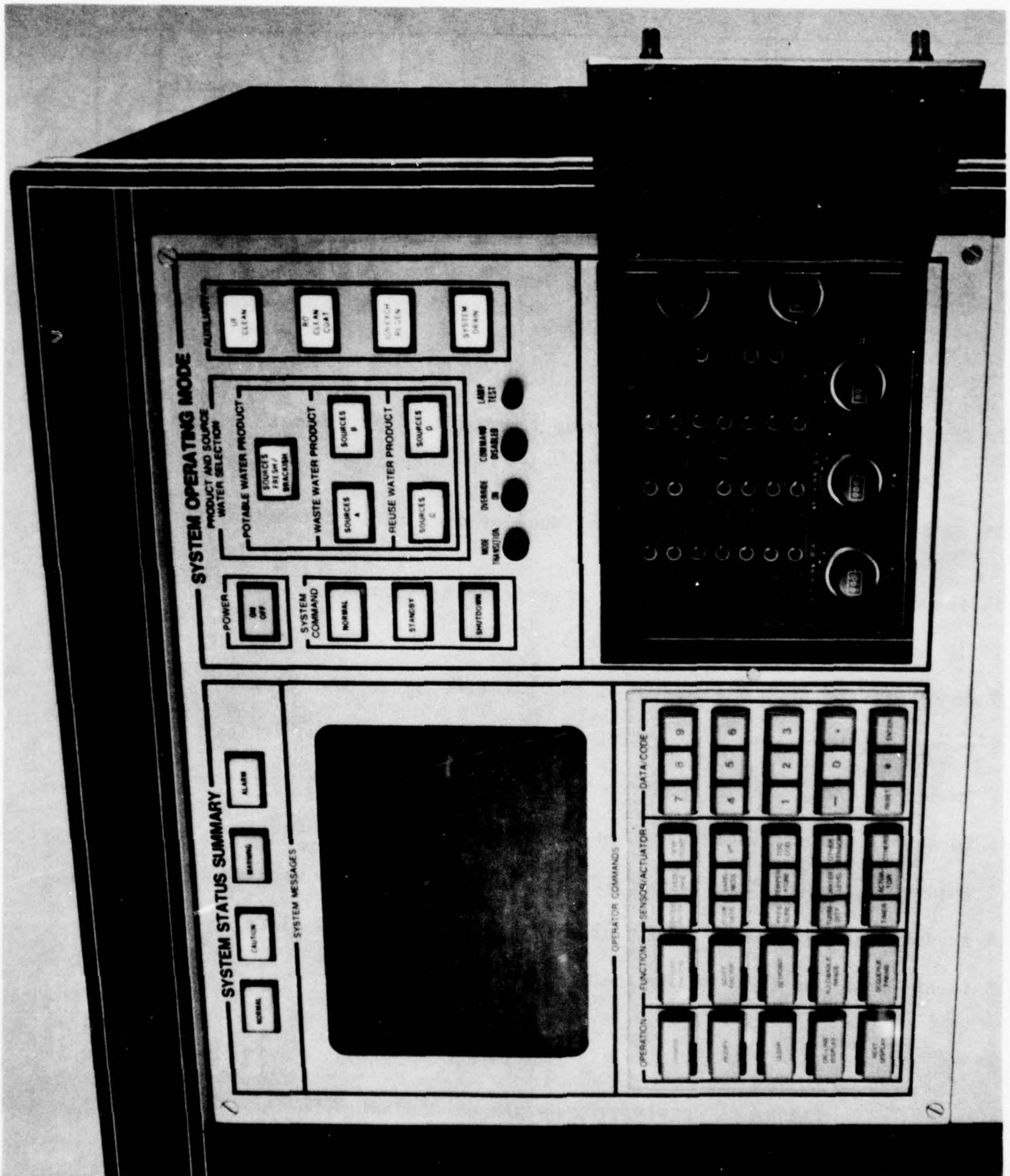


FIGURE 17 AUTOMATIC CONTROL/MONITOR INSTRUMENTATION FRONT PANEL AND RECESSED MANUAL OVERRIDE PANEL

The control panel, on the right-hand side of the picture, is used to select water source, water product, auxiliary modes and system operating modes. The monitor panel, on the left-hand side of the picture, is used to communicate with the system for parametric data examination, system message display, system status summary and for control/monitor parameter and setpoint modification.

Table 12 describes the components on the operator/system interface panel.

The system command pushbuttons are designed for the operator to control the WPS system modes. As shown in Figure 18, the WPS has four system operating modes (Unpowered, Shutdown, Standby and Normal) and seven allowable, programmable mode transitions. Direct transition from the Shutdown Mode to the Normal Mode is not allowed. In addition to the allowable, programmable transitions, it is possible for the WPS to go to the Unpowered Mode at any instance in time because of a power failure.

There are five Product/Source Operating Modes defined as follows:

- Potable Water Product from Sources Fresh/Brackish -- producing potable water from natural fresh or brackish water sources
- Wastewater Product from Sources A -- treating shower, operating room or laundry wastewaters for surface discharge
- Wastewater Product from Sources B -- treating hospital composite, laboratory, x-ray, kitchen or unknown wastewaters for surface discharge
- Reuse Water Product from Sources C -- processing kitchen or shower wastewaters for nonconsumptive reuse
- Reuse Water Product from Sources B -- processing composite, laboratory, x-ray, operating room, laundry or unknown wastewaters for nonconsumptive reuse

There are four Auxiliary Operating Modes for the WPE maintenance. They are designed for UF module cleaning, RO module cleaning/coating, IE module regeneration and WPE system water drain.

There are three Light Emitting Diodes (LED) on the front panel for the indication of Mode Transition, Override On and Command Disabled. A Lamp Test pushbutton is also provided for maintenance purposes.

Mode transitions are indicated by both the LED indicator and the color-coded system command pushbuttons. During a transition, the Mode Transition LED will be lit and the system command pushbutton which indicates the present operating mode will be illuminated in green and the future operating mode illuminated in amber. For example, if the WPE system is in the Standby Mode, the Standby button will be displayed in green. When the operator requests the system to go to the Normal Mode by pushing the Normal button, the system command buttons will show a green Standby and an amber Normal. At the same time the Mode Transition LED will be lit.

TABLE 12 AUTOMATIC CONTROL/MONITOR INSTRUMENTATION FRONT PANEL COMPONENTS

Component	Function
System Command	Pushbutton switches for mode transition request. Light displays indicate current mode (in green) or transition in process (in amber).
• ON/OFF	Power on/off request/indicator.
• SHUTDOWN	Shutdown mode request/indicator.
• STANDBY	Standby mode request/indicator.
• NORMAL	Normal mode request/indicator.
Product/Source Water Selection	Pushbutton switches activated in shutdown mode for product and source water selection. Green lights indicate current selection which may be cancelled by a second push or by selecting another mode. Validity is automatically checked.
• SOURCES FRESH/BRACKISH	Produce potable water from fresh source or brackish source.
• SOURCES A	Treat Sources A for waste discharge.
• SOURCES B	Treat Sources B for waste discharge.
• SOURCES C	Reuse Sources C for nonconsumptive purposes.
• SOURCES D	Reuse Sources D for nonconsumptive purposes.
Auxiliary	Activated in Shutdown Mode for auxiliary maintenance modes.
• UF CLEAN	UF module cleaning.
• RO CLEAN/COAT	RO module cleaning/coating.
• IE EXCH	IE module regeneration.
• SYSTEM DRAIN	Drain all water tanks.
Lamp Test	Lamp test pushbutton.
Manual Overrides	Switches and potentiometers on recessed panel for override.

continued-

Table 12 - continued

Component	Function
Manual Overrides	
• OVERRIDE ON	Indicator lit if any override switch is manually activated.
• Switches and Potentiometers	For manual override.
Mode Transition	Indicator lit when system in transition.
Command Disabled	Front Panel command pushbuttons inoperative.
Water Source Description	
• SOURCES A	Wastewater sources from shower, operating room and laundry.
• SOURCES B	Wastewater sources from composite, laboratory, x-ray, kitchen or unknown.
• SOURCES C	Wastewater sources from kitchen or shower.
• SOURCES D	Wastewater sources from composite, laboratory, x-ray, operating room, laundry or unknown.
System Status Summary	Summary of system status as indicated by the four lights.
• NORMAL	System normal.
• CAUTION	Cause of this status is explained on the monitor message panel.
• WARNING	Cause of this status is explained on the monitor message panel.
• ALARM	Cause of this status is explained on the monitor message panel.
System Messages	Display panel for system/operator communication. Total of 80 x 24 characters.
• FDIA Messages	First 6 lines of CRT display reserved for fault diagnostic messages.

continued-

Table 12 - continued

Component	Function
• On-Line Display	Next 8 lines reserved for selected sensor reading display (updated every minute)
• Operator Command Echo	One line reserved for operator command echo
• Operation Output and Data Input	Next 8 lines for EXAMINE and MODIFY interactive message display
• System to Operator Message	Last line of CRT display reserved for error message and other system message display
Operator Commands	Operators command to monitor for set-point modifications within allowable ranges and for display of data.
• OPERATION	Operator commands for EXAMINE, MODIFY, CLEAR, ON-LINE DISPLAY or NEXT DISPLAY operations.
- EXAMINE	Examines the present reading, scale factor, setpoint, allowable range, sequence timing of a component or the system.
- MODIFY	Modifies the scale factor, setpoint, allowable range, sequence timing of a component or the system. A valid password must be entered beforehand.
- CLEAR	Clears the CRT display and the password.
- ON-LINE DISPLAY	Displays present reading of a sensor and updates it every minute.
- NEXT DISPLAY	Advances the information on CRT display when there are more fault messages than the display capacity.
• FUNCTION	Operator commands for selection of data function.
- PRESENT READING	The present reading of the requested component in engineering units.
- SCALE FACTOR	Factors used to convert binary values to engineering units.
- SETPOINTS	System operational setpoints, two for control and six for monitor.

continued-

Table 12 - continued

Component	Function
- ALLOWABLE RANGE	The limits for system operational setpoints.
- SEQUENCE TIMING	The transition sequence timing constants for system operation.
• SENSOR/ACTUATOR	Type of sensor/actuator.
- SENSOR TYPE BUTTONS	There are 11 buttons available for different types of sensors in the system.
- TIMER	The software timers for WPE system, UF, RO and IE.
- OTHER SENSOR	Any sensors specified above.
- ACTUATOR	Status of digital/analog actuators.
• DATA/CODE	Data or code for the sensor/actuator selected.
- NUMBERS (0-9)	Part of the component code, data or password.
- MINUS (-)	Minus sign of a number or delete Operation for setpoint modifications.
- PERIOD (.)	Decimal point of a number or end of operation for MODIFY.
- ASTERISK (*)	Used to MODIFY operation to indicate NO CHANGE.
- RESET	Erases command/data just entered in case of typing error.
- ENTER	End of command/data, also used to change input modes.

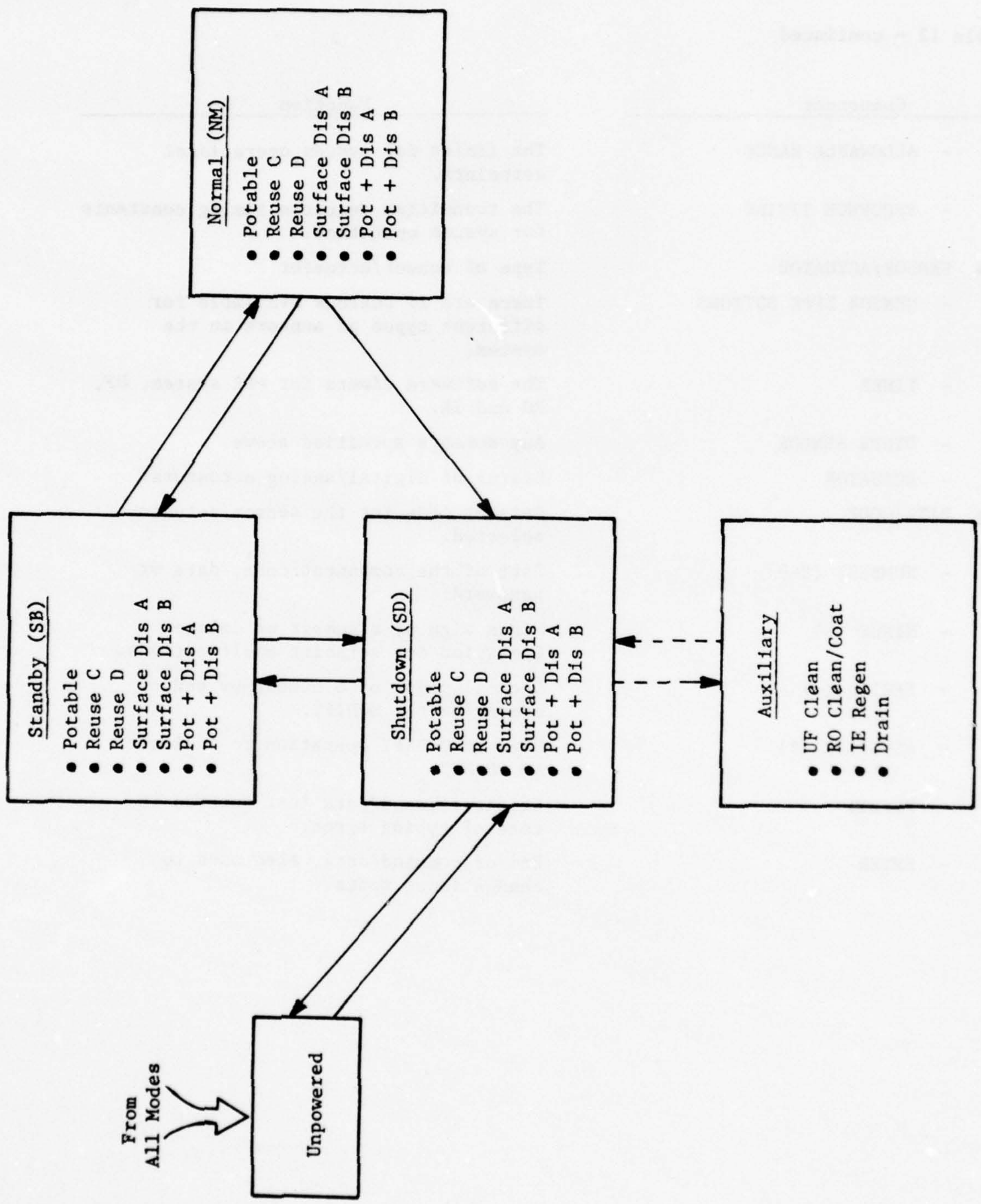


FIGURE 18 WPS OPERATING MODE/MODE TRANSITION BLOCK DIAGRAM

The Override On LED is lit when any of the manual override switches located in the recessed manual override panel is used to override the automatic instrumentation control of actuators.

The Command Disabled LED is lit when the front panel pushbuttons and the operator command keyboard are disabled. This is accomplished by placing a slide switch located at the rear panel to the Command Disable position. This is designed to prevent any unauthorized or accidental activation of any pushbuttons or keyboard switches.

The water source description printed on the front panel (see Figure 7) provides the operator with an in situ reference of the different combinations of water sources. This simplifies the WPE operation significantly.

The System Status Summary indicators are designed to give a quick summary of the system status at a glance. The operator can read the System Status Summary display from a distance and know whether the system is in Normal, Caution, Warning or Alarm state. Detailed Fault Detection and Isolation Analysis (FDIA) messages are displayed on the CRT display unit. The CRT display is partitioned horizontally into five different areas for human engineering considerations. The partition format of the CRT display is shown in Figure 19. Figure 20 shows an example of the types of messages displayed on the CRT.

The operator command keyboard consists of 40 keyboard switches. They are divided into four different groups as follows:

- Five operations -- Examine, Modify, On-line Display, Clear and Next Display
- Five functions -- Present Reading, Scale Factor, Setpoint, Allowable Range and Sequence Timing
- Fifteen sensor/actuator types -- Conductivity, chlorine, Dew Point, Flow Rate, Hardness, pH, Pressure, Temperature, TOC/COD, Turbidity, Water Level, Other Sensor, Timer, Actuator and Others
- Fifteen data/code entries -- numbers 0 through 9, minus sign, decimal point, Reset (to clear entry), asterisk (for no change during modification operation) and Enter (to indicate the end of a command sequence)

Both the command syntax and its semantic validity are checked automatically when the operator enters a sequence of operator commands. For example, "Examine, Present Reading, Conductivity, 400, Enter" is a correct sequence of operator commands both syntactically and semantically. A sequence of "Modify, Temperature, 101, Enter" is syntactically incorrect because the "function" command is missing. A sequence of "On-line Display, Present Reading, Turbidity, 605, Enter" is syntactically correct but semantically incorrect. It is syntactically correct because the sequence consists of all the necessary elements for a complete sentence: operation, function, sensor/actuator type and data/code. It is semantically incorrect because the sensor requested "Turbidity, 605" does not exist in the WPE system.

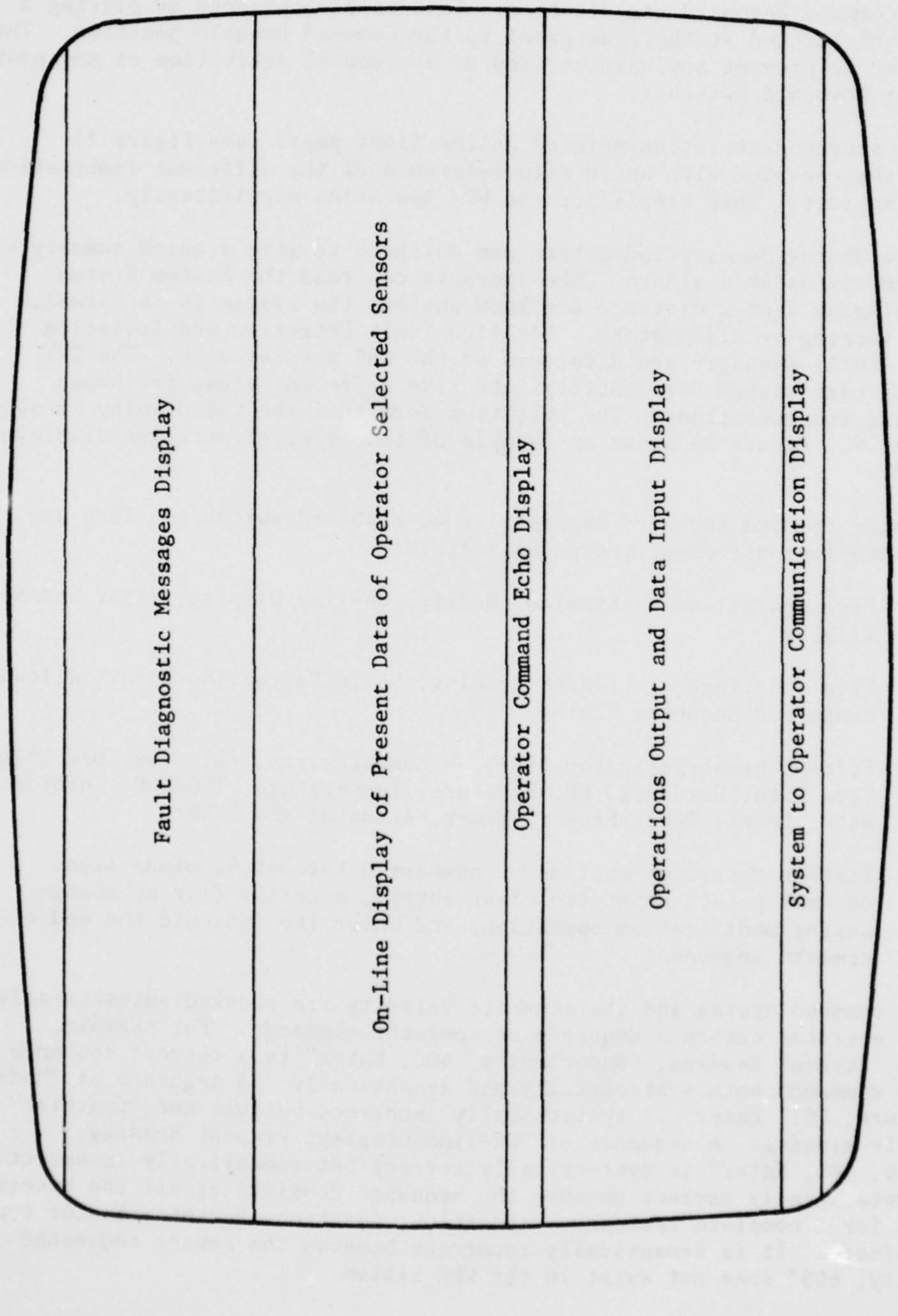


FIGURE 19 CRT DISPLAY FORMAT

```
T402 TEMPERATURE HIGH CAUTION
J201 TURBIDITY HIGH WARNING
C401 CONDUCTIVITY HIGH CAUTION

C401,UMHO/CM    READING=   12.0
P201,PSID       READING=    7.0
M301,DD/HH/MM ELAPSE TIMER = 00/02/38

OPERATOR COMMAND : MODIFY SETPOINT TEMPERATURE 201

I501,PH         INT.    =    2.0   SLOPE   =    0.225
T201,F          L-CNTRL=   85.0   H-CNTRL=   87.0   L-ALARM=  80.0  L-WARNI=  78.0
                L-CAUTI=   75.0   H-CAUTI=  140.0   H-WARNI=******  H-ALARM=******
T201,F          L-LIMIT=    0.0   H-LIMIT=  150.0
W401,GPM        READING=    3.5
A003,           DIGITAL BIT PATTERN  =  1000   0100   0010   0001
M221,HH:MM:SS   TIMING =00:01:20

(011)  OPERATOR PASSWORD?
```

FIGURE 20 CRT DISPLAY MESSAGE EXAMPLE

Table 13 is a summary of the WPS operator commands.

Human Engineering Considerations

The operator/system interface was designed with significant human engineering considerations. They are summarized in Table 14.

The operator/system interface layout reflects the engineering effort in simplifying a complex operation by grouping command pushbuttons and switches according to their functions.

Instead of a typical "First In First Out" type CRT message display technique, the WPS automatic instrumentation was designed with a partitioned CRT message display which has a better human factor.

The color-coded system transition mode display was designed so that the operator could readily tell the system transition status. The additional Mode Transition LED indicator is designed so that even a colorblind person could operate the WPS automatic instrumentation.

The automatic operator command validity checking is an important feature. The types of validity checked include the following:

- Whether a transition requested is allowable
- Whether a combination of different product and source water selections is valid (potable water product and surface wastewater discharge product modes may be combined but the reuse water product mode cannot be combined with anyone else)
- Whether an operator command is syntactically correct
- Whether an operator command is semantically correct
- Whether an operator is authorized to operate the automatic instrumentation unit
- Whether an operator is authorized to modify setpoints
- Whether an operator is authorized to modify allowable ranges
- Whether the hierarchy of setpoints prevail (Caution, Warning and Alarm setpoints must be in the right order)

To protect the system from damages caused by unauthorized personnel, there are three levels of protection. The first level is a Command Disable switch located at the rear panel of the automatic instrumentation unit. This switch may be used to disable all the front panel pushbuttons and keyboard switches for protection against unauthorized usage. The second level is the authorization code (password) requirement when using the "Modify" operator command or the system control pushbuttons. A password is a four-digit number designed for an operator to identify himself. When this number, entered from

TABLE 13 SUMMARY OF OPERATOR COMMANDS

Operation	Function	Sensor/Actuator
EXAMINE	Present Reading Scale Factor Setpoint Allowable	Analog Sensors
EXAMINE	Present Reading	Timers Actuators Digital Sensors
EXAMINE	Sequence Timing	Timing Constants
ON-LINE DISPLAY	Present Reading	Digital Actuators Analog Sensors Timers
MODIFY	Scale Factor Setpoint Allowable Range	Analog Sensors
MODIFY	Sequence Timing	Timing Constants
CLEAR	-	-
NEXT DISPLAY	-	-

TABLE 14 HUMAN ENGINEERING CONSIDERATIONS ON OPERATOR/SYSTEM INTERFACE DESIGN

- Grouping of command pushbuttons by functions
- Partitioned CRT message display
- Color-coded status indicators
- Color-coded transition/steady-state displays
- Mode Transition LED indicator
- Automatic command validity checking
- Command Disable switch
- Operator authorization code
- Allowable range of setpoints
- Automatic setpoint hierarchy verification
- Recessed manual override panel
- In situ water sources description

the operator keyboard, matches one of the preprogrammed passwords in the computer memory, the operator is then allowed to perform operations for which he is authorized such as the modification of scale factors, setpoints, allowable ranges and sequence timing constants. During the modification of setpoints, the authorized operator must enter setpoints which prevail the setpoint hierarchy. It is also required that the new setpoints entered by the operator be within the allowable ranges. The relationship of the setpoints and the allowable ranges were shown in Figure 15.

Software and Data Base Structure

The WPS automatic instrumentation is a real-time control and monitor system. It is designed based on an interrupt-driven, table-driven and real-time clock (RTC) controlled software. The software block diagram was shown in Figure 9. The heart of the software is a RTE which operates based on a task table and a RTC time table. These two tables determine how often a software module is executed by the RTE. Therefore, each software module can run at a speed independent of the others. For example, the sensor data input module is executed once every 100 ms, but a fault detection module may run at a slower frequency such as one second or five seconds. In addition to the RTC interrupt, there are interrupts generated by the operator command keyboard, the data acquisition system and the power-fail/restart control circuit. These interrupts are running asynchronously with the RTC. The operator command interface interrupt activates the front panel service software modules. The DAS interrupt activates the data collection and tranmission modules. The power-fail/restart interrupt activates power-fail handler to ensure the recovery from a short-term power-fail or the fail-safe shutdown from a long-term power failure. Other than these three categories of software modules, the rest of them are all RTE controlled (in other words, RTC interrupt-driven). These include all control modules, fault detection modules, mode transition modules, input/output (I/O) modules and on-line display modules. The sensor data I/O and the display I/O are programmed in an automatic I/O fashion.[27] They are also interrupt-driven once set up by the RTE.

The automatic instrumentation data base consists of a number of tables:

- Analog/digital input buffer
- Temporary digital data buffer
- Temporary analog data buffer
- Unscaled sensor reading buffer
- Scaled sensor data table
- Analog/digital output buffer
- Control/monitor setpoint table

- Scale factor table
- Allowable range table
- Sensor control word table
- Sequence timing and system constant table
- Component identification table
- Sensor index directory

Figure 21 shows the WPS automatic instrumentation software data base and the relationships among the tables. Figures 22 through 28 show the procedure of the software design. They consist of the following steps:

- Instrumentation software block diagram design
- System tables, buffers and sensor definition design
- System definition, mnemonics, base page and pointers design
- System definition and data base creation
- Front panel service software design
- RTE, input/output and utility software design
- Control/monitor and operating mode control and intermode transitions software design

These figures illustrate the information and data flow from the system design personnel to the software design personnel.

Data Acquisition Interface

Data acquisition was a unique requirement of the WPE automatic instrumentation during the pilot plant developmental stage. Because the WPE automatic instrumentation unit is computerized instrumentation, digitized sensor data are already available in the automatic instrumentation unit. Therefore, to incorporate data acquisition capability, no further front-end instrumentation or analog-to-digital conversion interface are necessary.

The hardware interface between the automatic instrumentation unit and the DAS is a pair of general-purpose intelligent cables called "picoprocessors." A picoprocessor is a self-contained, high speed miniature digital processor, microprogrammed to provide standard controller functions such as data transfer, device control device status monitoring and interrupted generation.[28]

The software interface between the automatic instrumentation unit and the DAS is illustrated in Figure 29. As mentioned previously, the DAS may generate

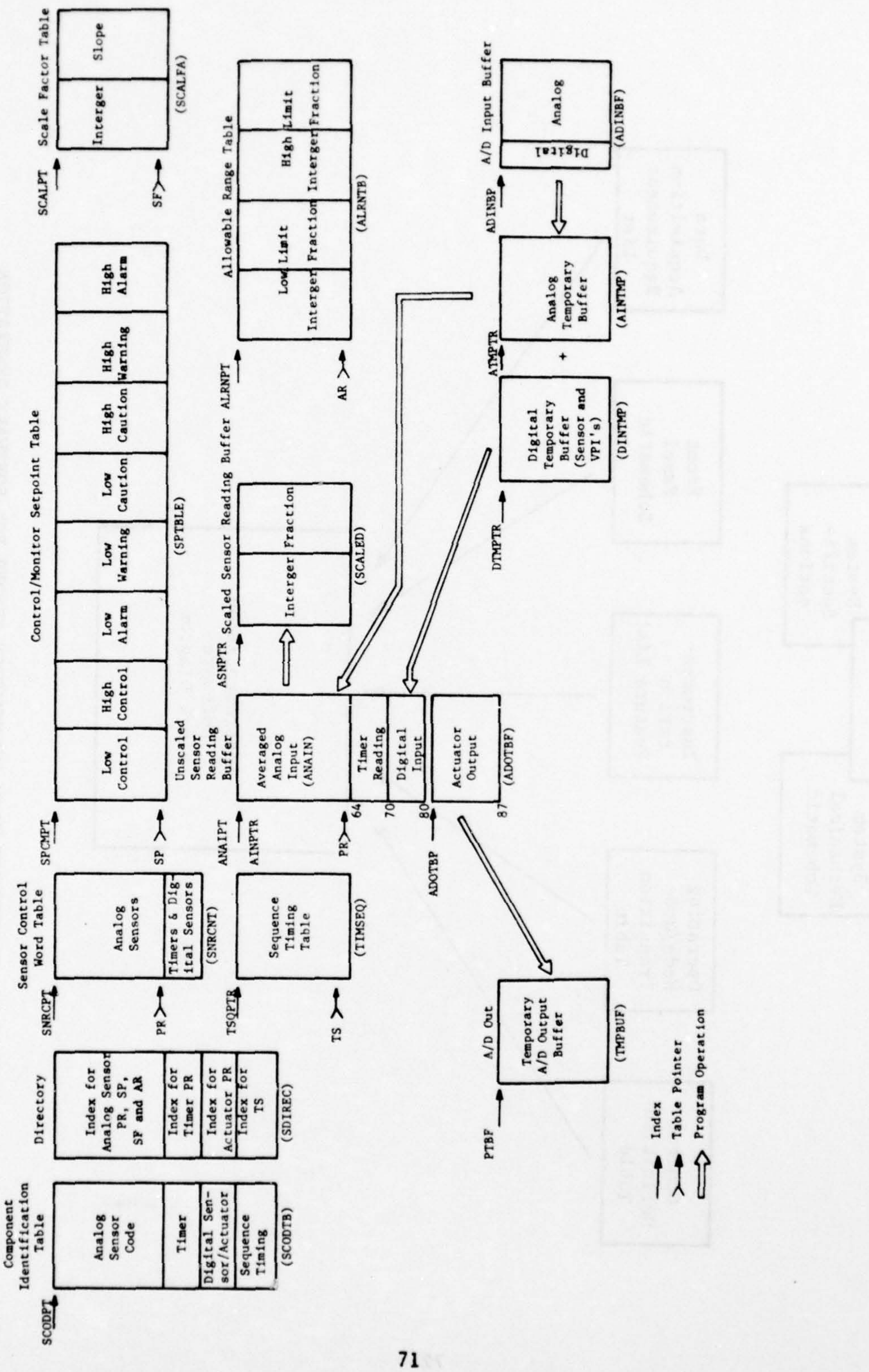


FIGURE 21 WPS AUTOMATIC CONTROL/MONITOR INSTRUMENTATION DATA BASE STRUCTURE

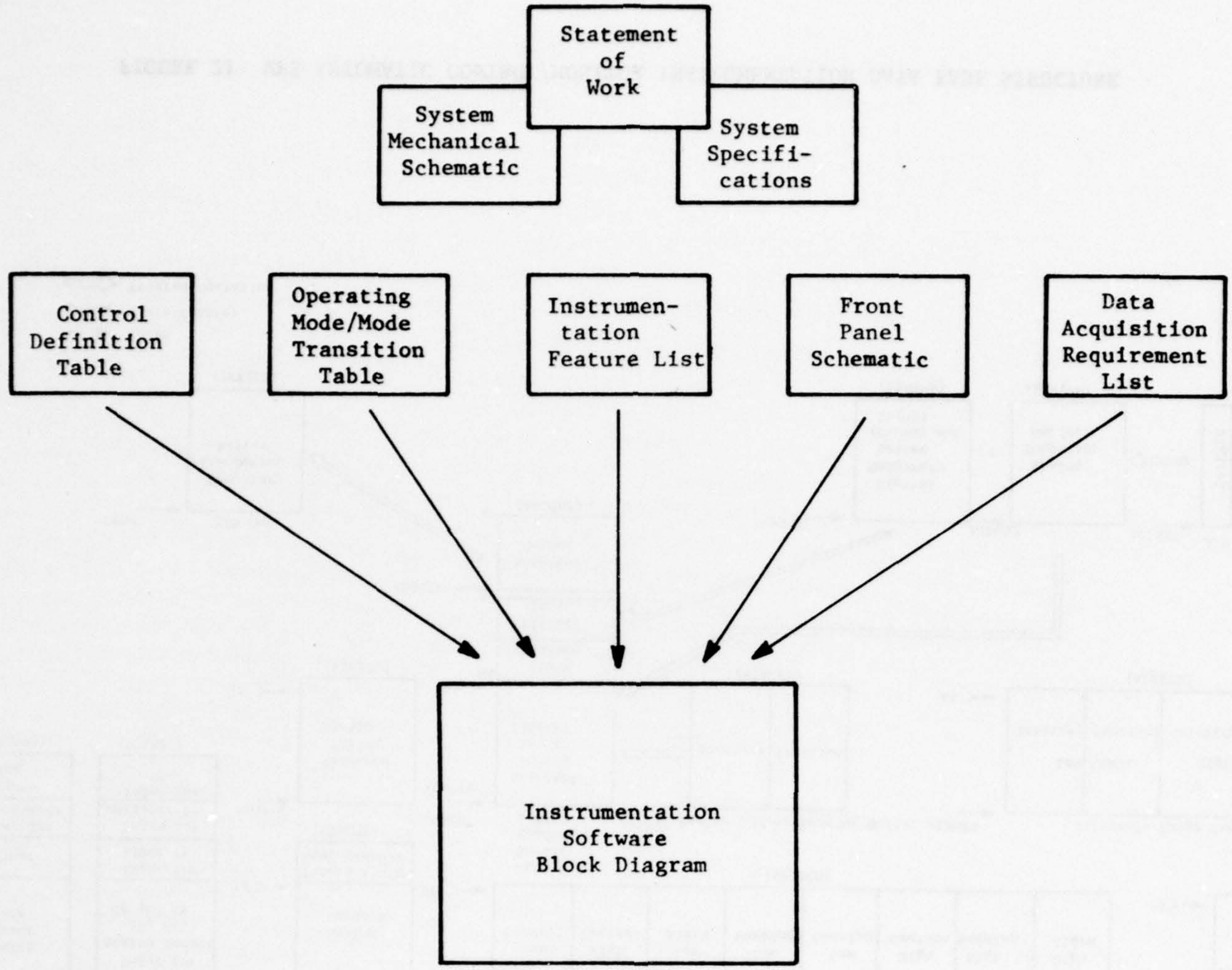


FIGURE 22 INSTRUMENTATION INFORMATION NEEDED FOR SOFTWARE GENERATION

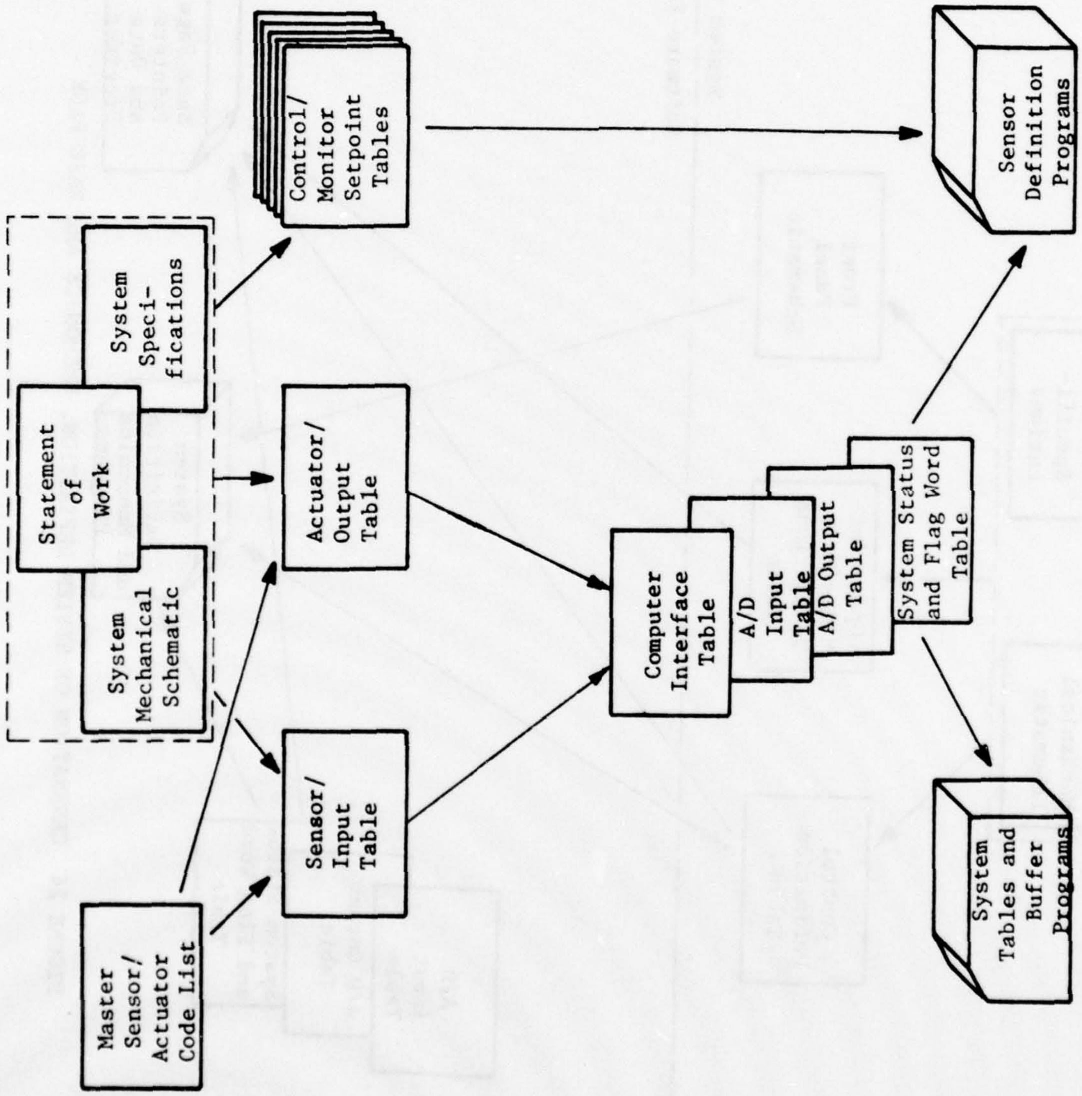


FIGURE 23 GENERATION OF SYSTEM TABLES, BUFFERS AND SENSOR DEFINITION

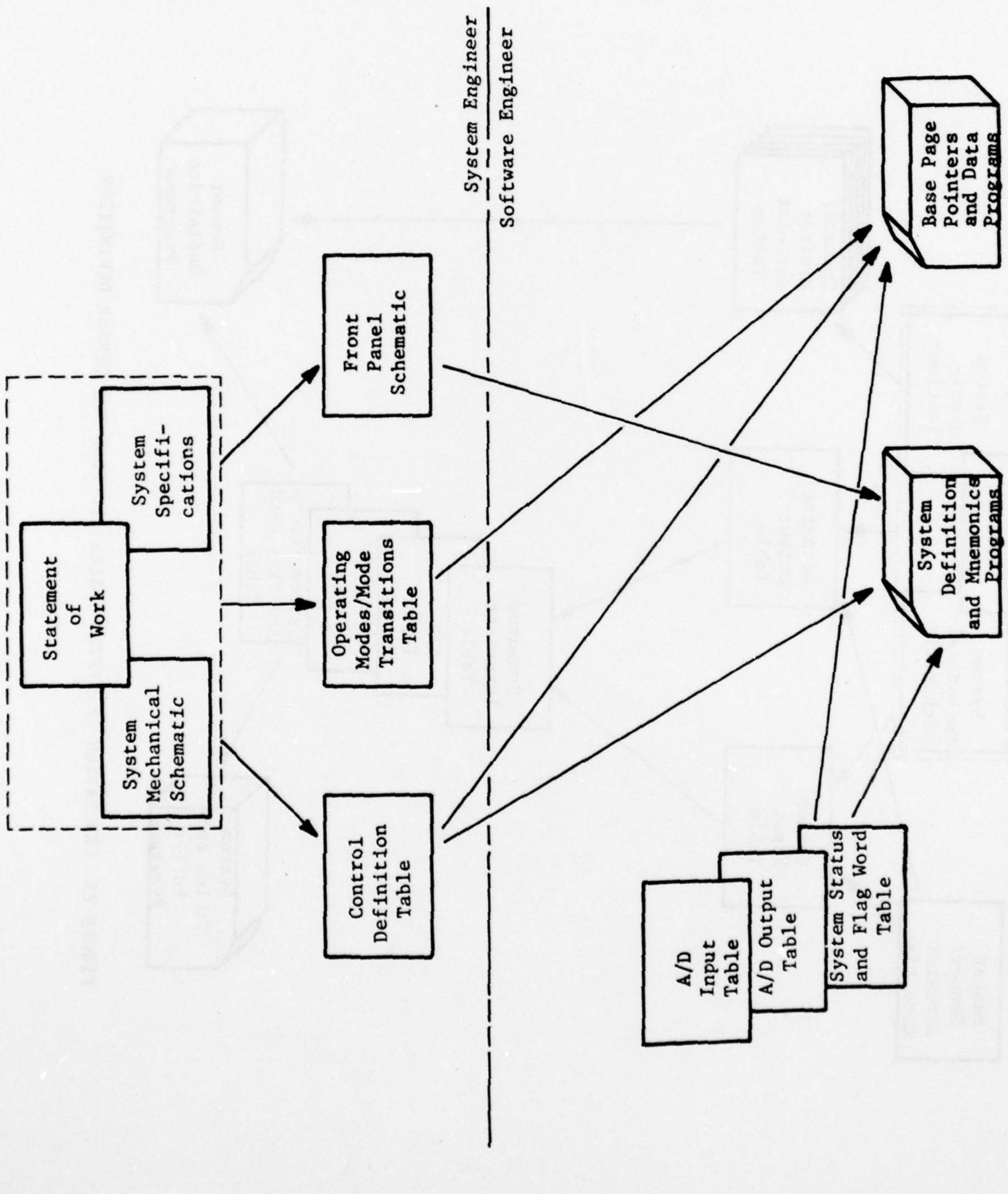


FIGURE 24 GENERATION OF SYSTEM DEFINITION, MNEMONICS AND BASE PAGE

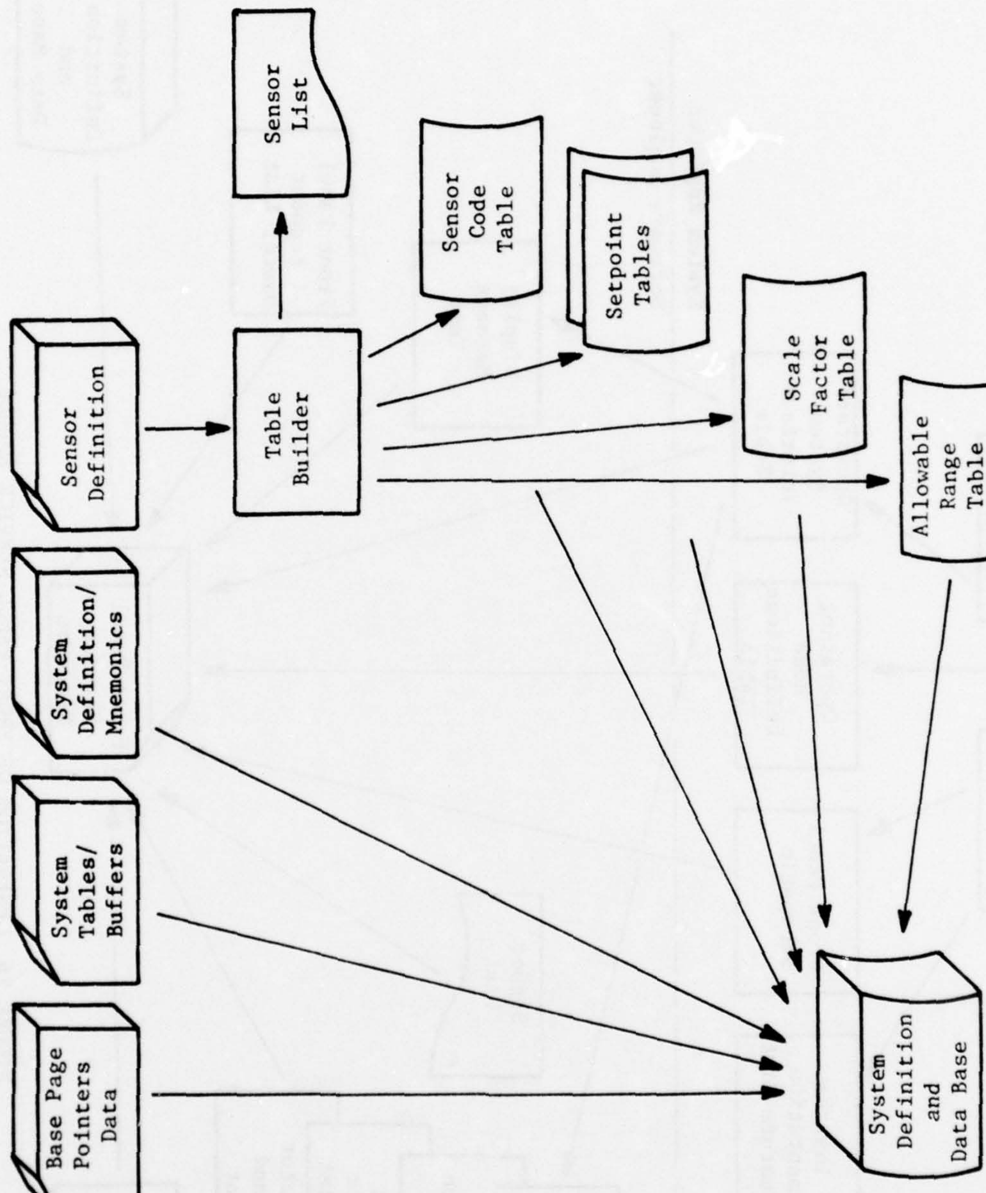


FIGURE 25 GENERATION OF SYSTEM TABLES AND DATA BASE

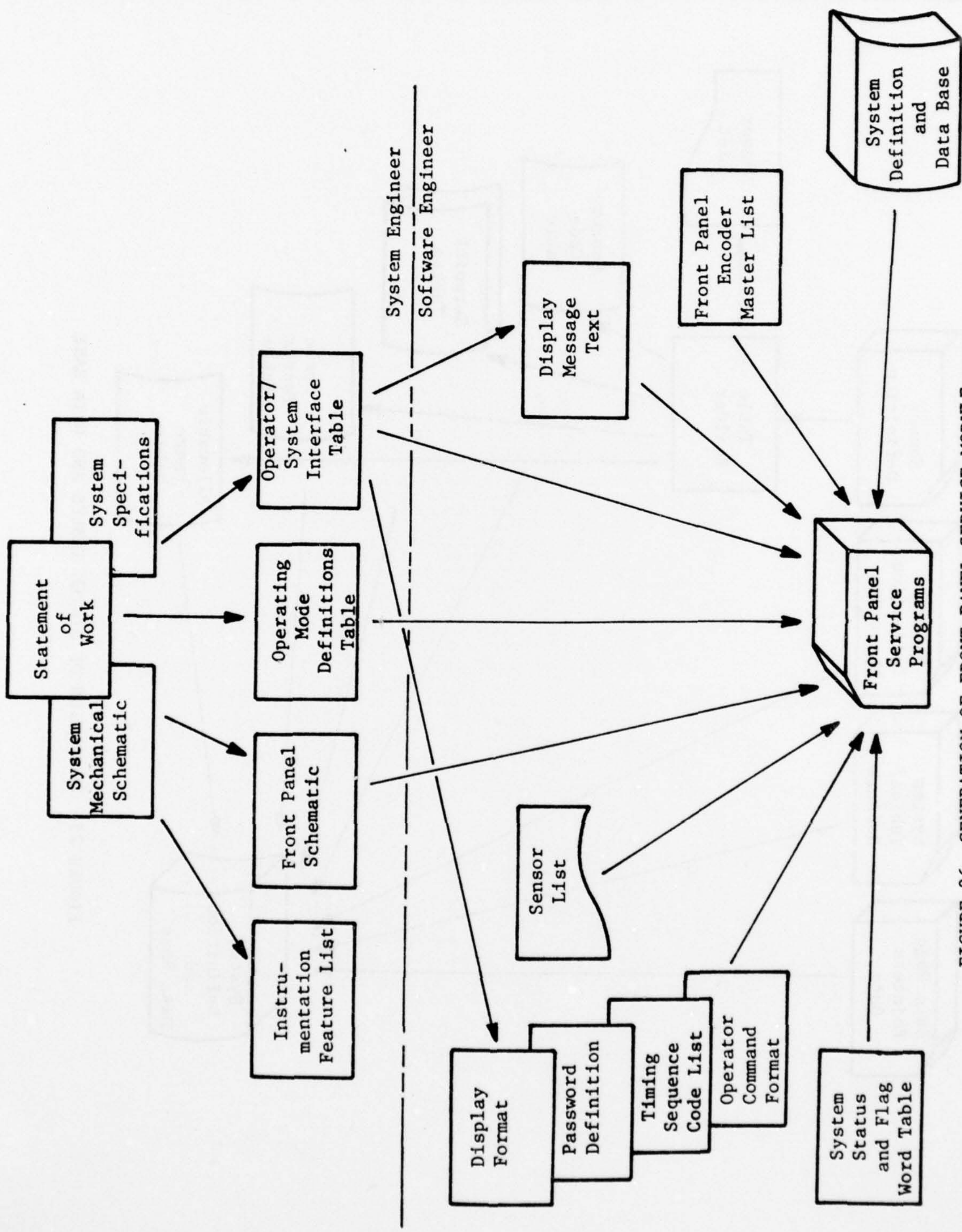


FIGURE 26 GENERATION OF FRONT PANEL SERVICE MODULE

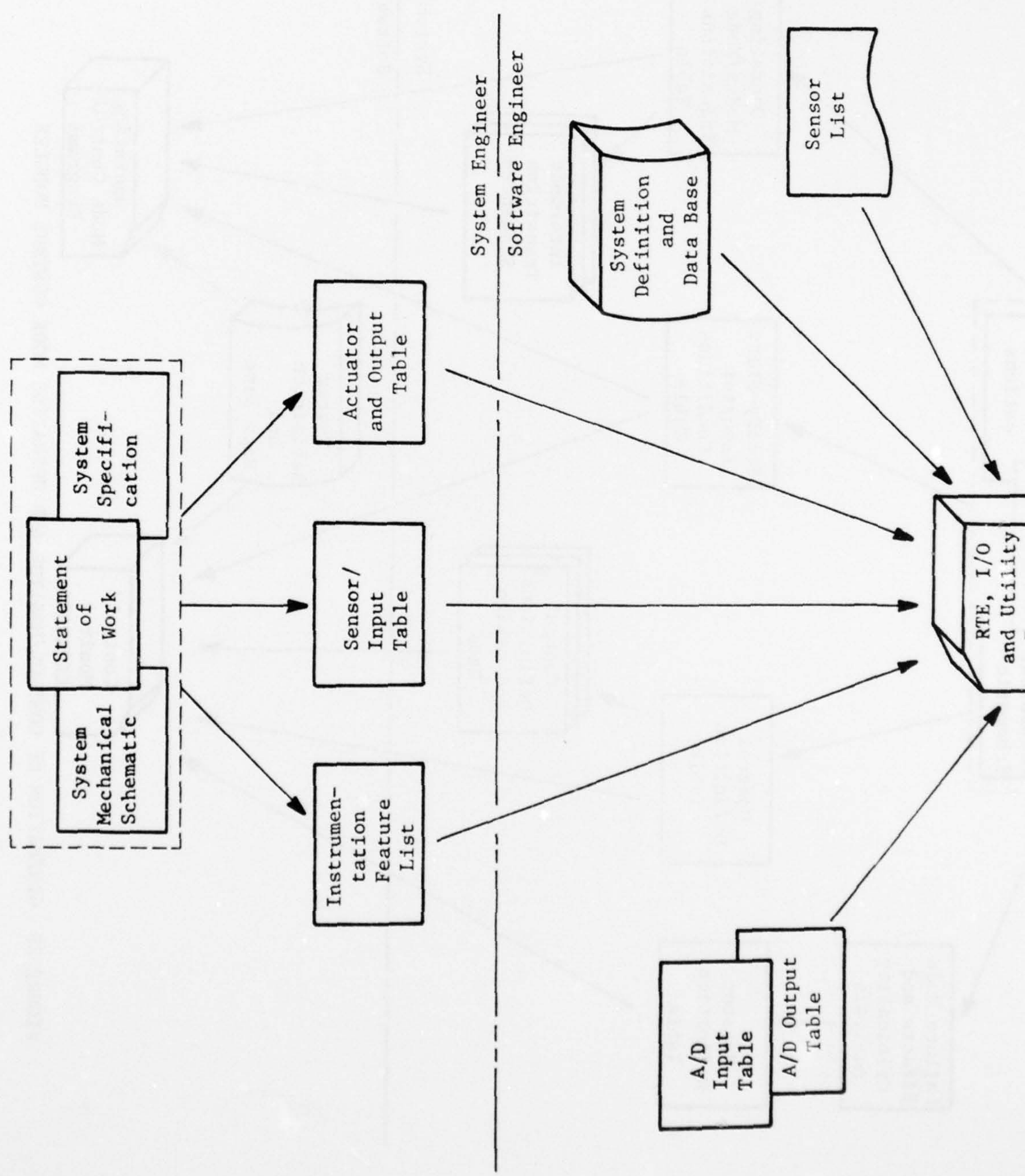


FIGURE 27 GENERATION OF REAL-TIME EXECUTIVE, I/O AND UTILITIES

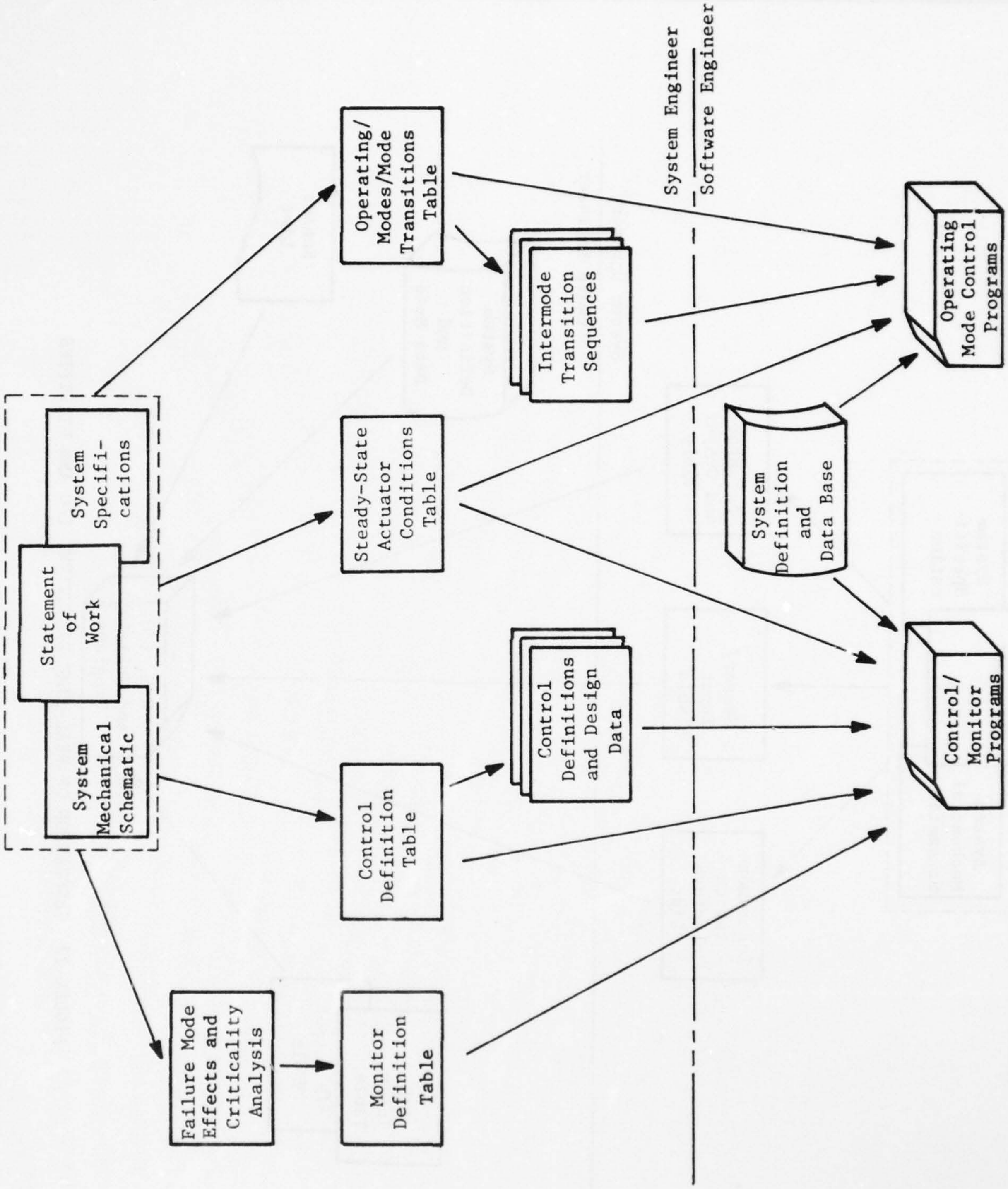
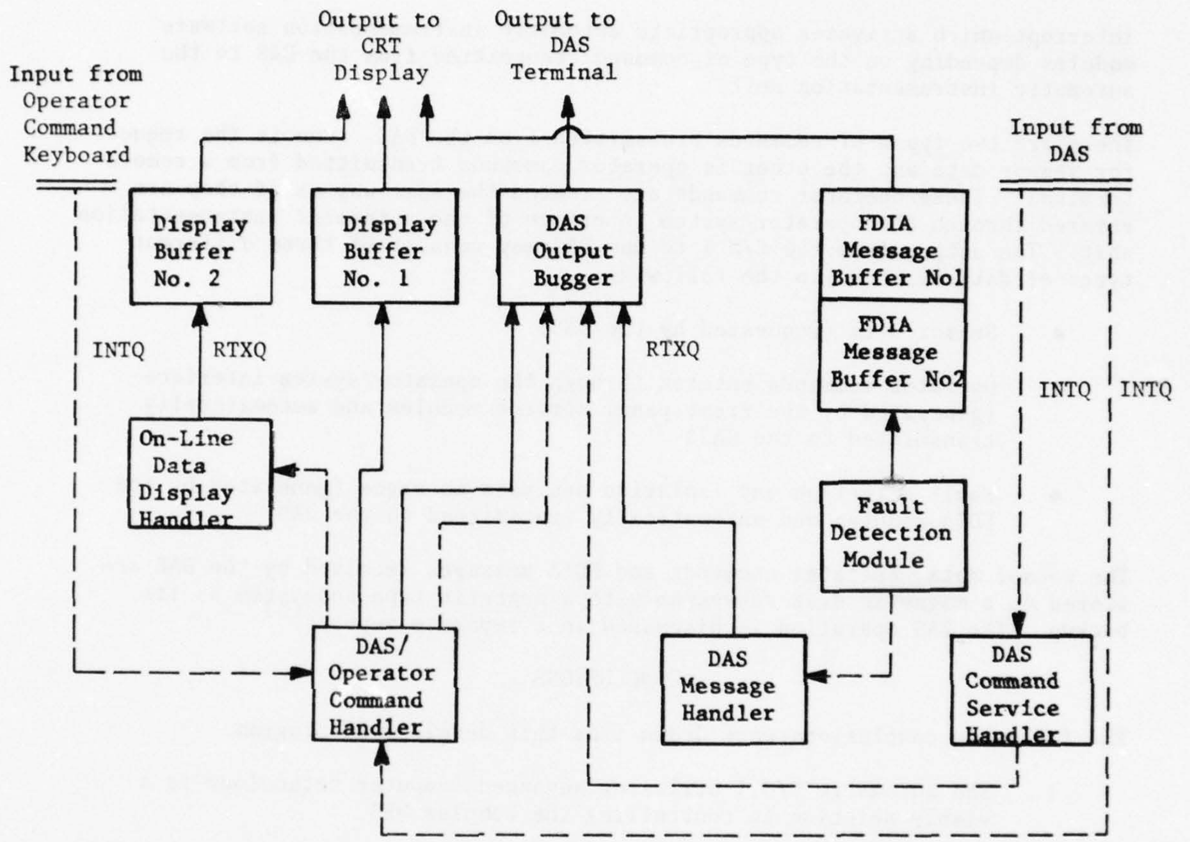


FIGURE 28 GENERATION OF CONTROL/MONITOR AND OPERATING MODE CONTROL MODULES



Legend

- - - -▶ Transactions without Buffer Handler
——▶ Transactions with Buffer Handler

INTQ: DAS or Operator Command Interrupt Request
RTXQ: RTE Interrupt Request

FIGURE 29 DAS AND C/M I SOFTWARE INTERFACE interrupt which activates appropriate automatic instrumentation software modules depending on the type of command transmitted from the DAS to the automatic instrumentation unit.

There are two types of commands transmitted from the DAS. One is the request for sensor data and the other is operator commands transmitted from a remote terminal. These operator commands are treated the same way as if they are entered through the operator/system interface of the automatic instrumentation unit. The output from the C/M I to the DAS may consist of three different types of data as shown in the following:

- Sensor data (requested by the DAS)
- Operator commands entered through the operator/system interface (generated by the front panel service modules and automatically transmitted to the DAS)
- Fault detection and isolation analysis messages (generated by the FDIA modules and automatically transmitted to the DAS)

The sensor data, operator commands and FDIA messages received by the DAS are stored on a magnetic disk subsystem with a magnetic tape subsystem as its backup. The DAS operation is discussed in a separate report.[5]

CONCLUSIONS

The following conclusions were drawn from this development program:

1. The automatic C/M I utilizing advanced computer technology is a viable solution to controlling the complex WPS.
2. The advanced operator/system interface panel simplifies the complex operation of WPS. The WPS can be operated by one single operator with minimal amount of training.
3. The use of a minicomputer-based advanced instrumentation provides flexibility during the pilot plant phase and ease of transferring the algorithms into a smaller microcomputer-based instrumentation in subsequent stages of development.

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