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EBR-II COVER GAS CLEANUP SYSTEM UPGRADE

DISTRIBUTED CONTROL & FRONT END COMPUTER SYSTEMS

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ABSTRACT

The Experimental Breeder Reactor II (EBR-II) Cover Gas Cleanup System (CGCS) control system was upgraded in 1991 to improve control and provide a graphical operator interface. The upgrade consisted of a main control computer, a distributed control computer, a front end input/output computer, a main graphics interface terminal, and a remote graphics interface terminal. This paper briefly describes the Cover Gas Cleanup System and the overall control system; gives reasons behind the computer system structure; and then gives a detailed description of the distributed control computer, the front end computer, and how these computers interact with the main control computer. The descriptions cover both hardware and software.

INTRODUCTION

Cover Gas Cleanup System

The EBR-II reactor primary tank has an argon cover gas blanket over the liquid sodium coolant. This blanket becomes contaminated with highly radioactive xenon and krypton from the gas plenums in experimental fuel pins that breach during reactor operation. This radioactivity must be reduced for continued reactor operation and the contaminated cover gas analyzed to identify the subassembly that contains the breached fuel.

The Cover Gas Cleanup System cleans and analyzes the primary tank cover gas. The CGCS consists of a main cleanup loop and a gas analysis loop. The cleanup loop, called the main loop, takes argon cover gas from the primary tank, runs it through a cryogenic distillation column to clean it, and returns the clean gas to the primary tank. The gas analysis loop, called the tag system, takes a portion of gas from the cleanup loop, concentrates the xenon impurities in the gas through a cryogenic adsorption/desorption

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process, and runs the gas through a mass spectrometer to determine the ratios of the xenon isotopes in the cover gas.

A simplified view of the CGCS is shown in Figure 1. The main loop is shown in the lower part of the figure and the tag system is shown in the upper part. The main loop consists primarily of a supply valve, a flow sensor, six compressors, two pressure sensors, a distillation cleanup column, a flow sensor, and a return valve. The tag system consists primarily of two compressors, three bed paths, a vacuum system, a sample vial, a mass spectrometer, and miscellaneous valves, heaters, flow sensors, and pressure sensors. Each bed path consists of a primary tag bed, a secondary tag bed, and supporting and interconnecting valves and pipes. The vacuum system consists of two cryogenic vacuum pumps with associated pipes, valves, and vacuum sensors. The beds, vial, and vacuum pumps are cooled with liquid nitrogen. Heating is done with internal resistance heaters.

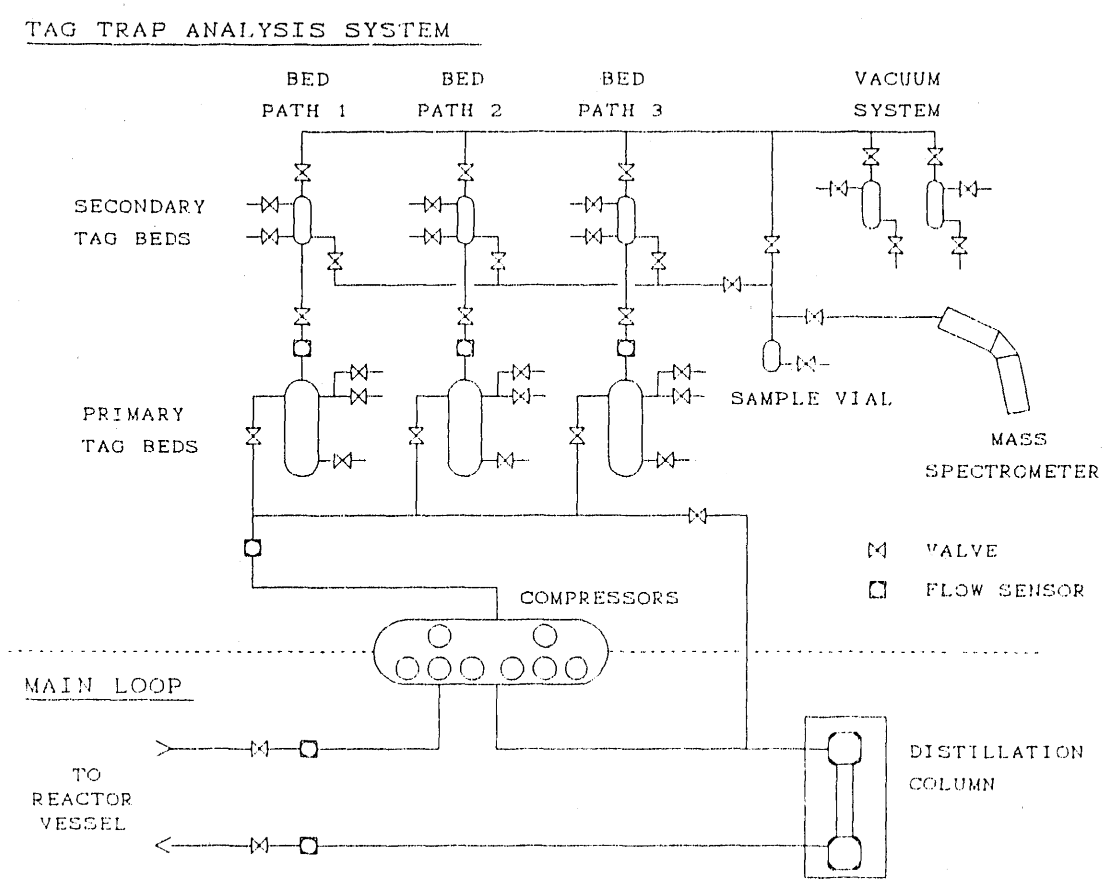


Figure 1. Cover Gas Cleanup System

During operation the main loop removes entrained sodium from the cover gas; removes the xenon, krypton, and other condensable impurities by means of a cryogenic distillation process in the distillation column; and then returns the cleaned argon to the primary tank.

The tag system takes a portion of gas from the main loop before it reaches the distillation column, concentrates the gas in a chilled primary tag bed, chills the secondary bed, heats the primary bed and the gas flows from the primary bed to the secondary bed, chills the sample vial, heats the secondary bed and the gas flows to the sample vial. The sample vial is heated and the gas flows to the mass spectrometer where it is analyzed. Since argon, krypton, and xenon adsorb and desorb at different temperatures the use of bed temperature control and venting at specific points removes the argon and krypton and concentrates the xenon as the gas progresses through the beds to the sample vial.

The mass spectrometer collects data on ten specific xenon isotopes. The xenon isotopes originate from experimental fuel in reactor core subassemblies. The fuel is tagged with xenon gas in specific isotope ratios so that experimental subassemblies whose fuel pins breach during reactor operation can be identified.

Control System Upgrade

Prior to the control system upgrade, the tag system was controlled by a number of discrete controllers and alarm units that were in turn controlled by a Data General Nova computer. The main loop was controlled by discrete controllers. The operator interface to the system was through graphics panels with meters, indicating lights and switches. The Nova computer ran a program that stepped through a sequence of states. At each state-transition point controllers, alarm units and valves would be given setpoints or position commands appropriate for the operation of the state. Periodically through the state certain parameters would be checked and compared to verify proper operation. When the mass spectrometer was being run, the Nova essentially relinquished monitoring and control of the rest of the system to the discrete controllers and alarm units and ran the mass spectrometer control program. The Nova computer basically functioned as a single tasking system with interrupt handlers to handle certain types of events. The system was unreliable and high maintenance, it was difficult to work with the Nova computer, and many of the 300 plus components were becoming obsolete.

The system was upgraded to provide a CRT based graphical user interface in the reactor control room and in the CGCS building in place of the meters, indicating lights and switches; to replace the Nova computer with a more state of the art computer system; to control the system directly, not through discrete controllers; to improve reliability and reduce maintenance; and to provide a system that allowed the CGCS to be monitored and controlled in a more timely, safe, and accurate manner. The upgrade consisted primarily of a new computer control system.

DESCRIPTION OF COMPUTER CONTROL SYSTEM

Overall Computer System

The layout of the CGCS computer control system is shown in Figure 2. The system consists of three computers: a main control computer consisting of a Concurrent Computer Corporation MC6450 with RTU, Concurrent's real-time UNIX operating system; a main loop distributed control computer; and a tag system front end computer. The main operator interfaces with the system are through two 19 inch color graphics terminals. The main loop computer drives a main loop backup control terminal and the tag system computer drives a printer and an optional maintenance terminal. The main loop and tag system computers communicate with the main control computer through serial fiber optic links. The main control room graphics terminal directly connects to the main control computer and the remote graphics terminal, an X-terminal, connects to the main control computer through a fiber optic ethernet.

The main control computer with its associated console terminal is located in a computer room directly below the EBR-II control room. The X-terminal, main loop computer, tag system computer, main loop backup terminal, and the tag system printer are located in the CGCS building. The CGCS building is located on the opposite side of the EBR-II reactor containment building from the EBR-II power plant building that houses the EBR-II control room.

The main control computer controls the tag system through the front end computer and supervises the main loop distributed control computer. The main control computer contains four main tasks: the operator interface task that handles the main graphics terminal and the X-terminal, the process control task that controls the tag system, the mass spectrometer task that controls the mass spectrometer and analyzes the data it collects, and the communications task that handles the communications with the EBR-II DAS, the main loop and the tag system computers. The operator interface task with its associated graphical interface is described in a paper by Jeffery D. Staffon and Gregory G. Peters entitled "EBR-II Cover Gas Cleanup System Upgrade Graphical Interface Design"[1]. The main control computer hardware, system software, process control task, mass spectrometer task, and communications task are described in a paper by Reed B. Carlson and Jeffery D. Staffon entitled "EBR-II Cover Gas Cleanup System Upgrade Process Control System Structure"[2].

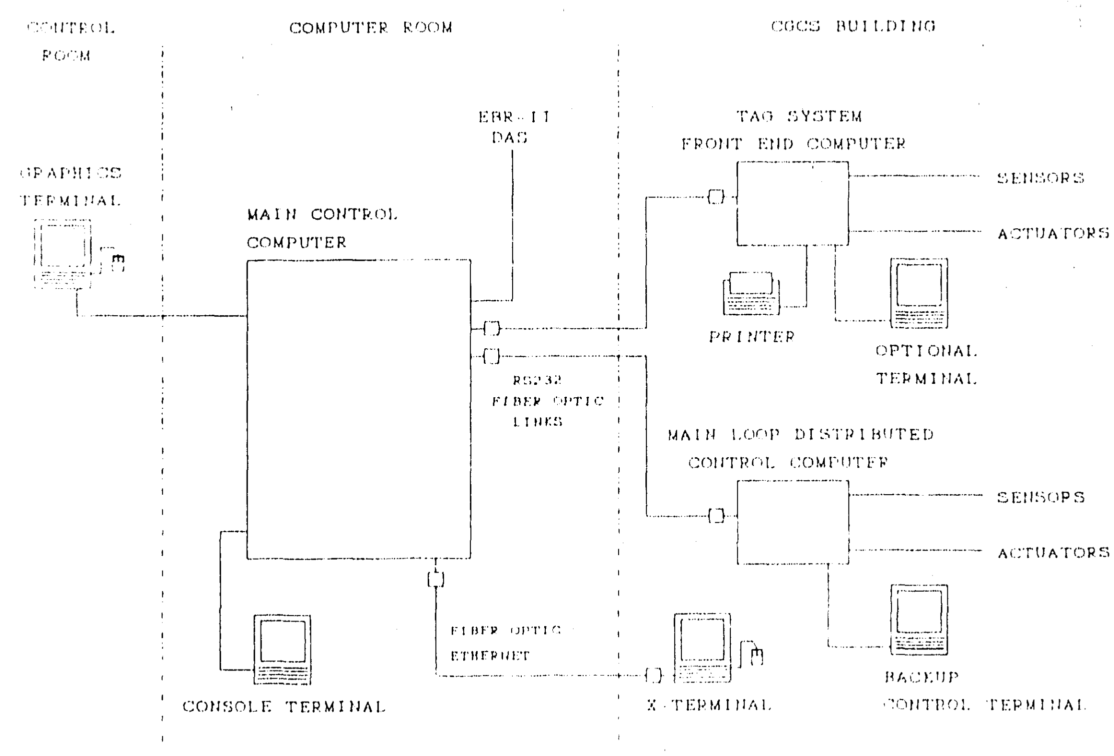


Figure 2. CGCS Computer Control System

Main Loop Distributed Control Computer

The main loop distributed control computer controls the main cleanup loop portion of the CGCS and is supervised by the main control computer. The computer has a backup operator interface terminal that allows the main loop to be monitored and controlled if the main control computer is down.

Tag System Front End Computer

The tag system front end computer acts as a main control computer I/O front end for the tag system portion of the CGCS. The computer drives a printer that prints out the results of mass spectrometer analysis and can optionally drive an alphanumeric maintenance terminal.

REASONS FOR COMPUTER SYSTEM STRUCTURE

The computer system is configured into a three computer system for three main reasons: distance, reliability, and I/O hardware availability.

Distance

Due to space limitations the main control computer could not be installed in the CGCS building. As a result the computer was installed in a computer room in the EBR-II power plant near the EBR-II control room. The distance between the CGCS building and the power plant was great enough that it was unreasonable to consider extending the sensor and control wiring into the power plant.

Reliability

The main loop was required to be operational as much as possible, potentially during times of main control computer maintenance, backup, or repair. STD bus based computers with no moving parts, operating system, or disk have proven to be very reliable in embedded control installations at EBR-II. The main control computer with its complex real-time operating system and hardware, hard disk, cooling fans, and graphics terminal was judged to be less reliable than the STD bus based computers. It was, therefore, decided that the main loop needed to be controlled in a separate more reliable STD bus based computer.

The tag system portion of CGCS needed to be assured that valves and heaters would go to their fail safe states on main control computer failure. In order to guarantee fail safe operation a separate computer was needed. The main control computer could not be guaranteed to put its outputs fail safe if it failed.

I/O Hardware

EBR-II already had a number of embedded control systems that utilized the STD bus I/O boards. The software drivers for the boards had already been developed for these systems. The maintenance technicians were familiar with many of the boards and the boards were stocked as spare parts.

DETAILED DESCRIPTION

The remainder of the paper describes the main loop distributed control computer and the tag system front end computer in detail. Details common to both computers are given first, the computers are then individually described, and the description ends with intercomputer communication details.

Common Hardware Details

The main loop and tag system computers are both STD bus based. They each consist of a rack mountable STD bus chassis; a 6.144 MHz Z80 CPU board with three programmable counter/timers, two serial ports, and up to 64 Kbytes of memory; a watchdog board; 12 bit analog input boards; TTL digital input boards; reed relay output boards; open collector digital output boards; and 12 bit analog output boards. The STD bus chassis are mounted in equipment cabinets in the CGCS building. The counter/timers provide repetitive timer interrupts which initiate operation of the real-time software routines. The serial ports are used to communicate with the main control computer and with the local terminal or printer. The Universal Asynchronous Receiver Transmitter (UART) chip that controls the serial ports provides communications transmit and receive interrupts that initiate operation of the communications software routines. The 64 Kbytes of memory is divided into EPROM for the application software and battery backed RAM for read/write variables and stack space. The I/O boards provide the interface between the computer control system and the CGCS main loop and tag system.

The watchdog board provides a hardware or software fail detection capability. The board receives power from the STD bus and a 1 Hz pulse from a digital output board. The pulse is output by a real-time software function that runs every 1/2 second. As long as there is power on the bus and the pulses are received, a solid state relay that supplies power to the computer is energized. If the bus power to the watchdog board fails or the pulses stop the watchdog board deenergizes the relay which, in turn, powers down the computer. When the bus powers down all the outputs go to their fail safe state.

Common Software Details

The software structure of the two computers are similar. They both operate without operating systems, their real-time software runs in response to hardware interrupts generated by the counter/timers or the UART, and their local terminal or printer functions operate when the real-time software is not running. They each have similar main control computer message receive and transmit functions, I/O board handling functions, and error handling functions.

The software is written in C with a few assembly language functions for microprocessor initialization, low level interrupt handling, and where optimum speed is important. The software is highly modularized by function so that lower level and I/O functions could be written once and adapted to both systems.

Main Loop Distributed Control Computer

The main loop distributed control computer controls the main cleanup loop independently of the main control computer. The operator interface with the computer is via the main control computer graphics terminals. The operator can monitor the main cleanup loop, change setpoints, initiate certain special operations, and turn compressors on or off. If the main control computer is down or the graphics terminals are not available, the main loop backup terminal is used as the operator interface.

The computer communicates with the main control computer through a serial port operating at 9600 baud. The second serial port is used to drive the backup terminal. For I/O the computer contains one relay output board, one dual stepper motor control board, one 56 circuit digital output board, one four channel 12 bit analog output board, one 112 circuit digital input board, and one 16 channel 12 bit analog input board. The computer has the following inputs and outputs:

7 valve position inputs
6 compressor starter status inputs
2 flow sensor inputs
2 pressure sensor inputs
12 miscellaneous digital and analog inputs

6 compressor on/off control outputs

2 stepping motor on/off outputs
2 stepping motor position control outputs
6 alarm outputs
10 relay outputs
1 flow mismatch analog output

The real-time I/O and control functions operate in response to a CPU board counter/timer interrupt that occurs every 1/2 second. In response to the interrupt, the digital inputs and analog inputs are read, the analog inputs are averaged and converted to engineering units, the digital inputs are debounced, the digital inputs and engineering units are checked against alarm limits, the valve flow control functions are run, and the digital, relay, analog, and stepper motor outputs are written. See Figure 3 for a simplified software function diagram. The timer interrupts are precise and predictable enough to allow operations to be scheduled to the microsecond. This allows a certain amount of digital filtering. For instance; 60Hz is filtered out of the 5 main loop analog inputs by reading the five inputs 8 times spaced evenly over a 16.667 millisecond period, delaying for 6.25 milliseconds, and then reading the 8 inputs again over a 16.667 millisecond period. The 16 readings are then averaged to eliminate any 60Hz interference.

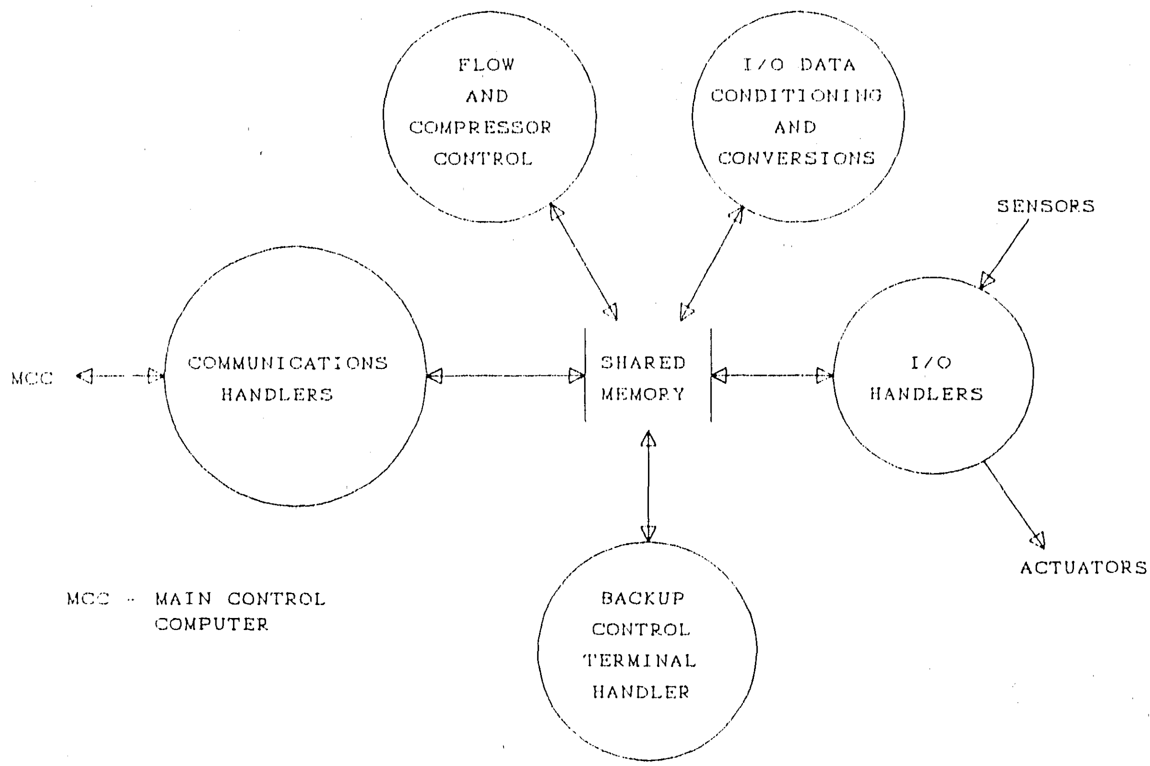


Figure 3. Main Loop Computer Simplified Software Function Diagram

The real-time communications functions operate in response to receive and transmit character interrupts. In response to a receive interrupt, a receive message handler is called. This handler checks for receive hardware errors, checks for beginning and end of message conditions, keeps track of position of the character in the message, and sets a flag when a complete message has been received. When a message is complete a function is called that calculates a message checksum and compares it to an appended checksum, stores the message information in shared memory, builds a response message, calculates and appends a checksum to the message, and initiates transmission of the message back to the main control computer. In response to a transmit character interrupt a transmit message handler is called. This handler checks for transmit hardware errors, checks for end of message conditions, and initiates transmission of the next message character.

During operation a message containing all commands and setpoints is received from the main control computer every second. In response to this message, the main loop computer sends back a message containing all the data received on its inputs, the calculated engineering units values, any additional calculated values, any new setpoints or on/off commands that were entered at the backup alphanumeric terminal, and alarm condition information. The main control computer to main loop computer message is 16 bytes long and the returned message is 60 bytes long.

When the real-time functions are not running the computer is running the backup terminal handling functions. The terminal handling is done continuously and the real-time functions run in response to interrupts that interrupt the terminal handling. The backup terminal allows the operator to monitor and control the main loop via text screens. The terminal handler software normally has the screen blank and is waiting for a return to be entered. In response to a return at the terminal keyboard a main menu is displayed. The menu appears as follows:

(start of screen)

CGCS Main Loop Menu

1 Compressor control

2 Flow control/status

3 Limit and floating head tank (FHT) bypass status

4 Control tune

5 Mismatch to isolation time delay test

6 Digital to analog board calibration

7 Valves 211 & 248 manual operation

8 FHT slope calculation

Enter selection and press return:

Note: Press <ESC> to clear screen

(end of screen)

The operator selects the appropriate item from the menu list depending on what is to be monitored or controlled. In response to a selection a new screen is displayed showing the status of the item selected and, as appropriate, the operator is prompted for control actions. For example if 2 is selected the following screen is displayed:

(start of screen)

Flow Control/Status

	Setpoint	Status	LS	Control Output	Enter New Setpoint
Valve 211	4.00 CFM	4.01 CFM	O	1452	
Valve 248	3.90 CFM	3.92 CFM		843	
Flow Mismatch	2.0 CFM	0.08 CFM			
FHT Signal	-0.231 mmm	bypassed			
FHT Effect	100 %	0.00 CFM			
FHT Position	391 mm				
Control Status		loc211sp: 4.00		loc248sp: 3.90	

PT 213: 9.9 PSIA PT 309: 10.4 PSIA

To change setpoint enter new value and hit <RET>
To retain current setpoint hit <RET> without entering a value

Note: Press <ESC> to exit
(end of screen)

The other main menu functions allow the compressors to be monitored and controlled, allow miscellaneous inputs to be monitored, allow flow control valve proportional-integral control to be monitored and tuned, allow I/O boards to be calibrated, allow certain tests and special calculations to be run, and allow flow control valves to be manipulated for maintenance purposes.

The software on the main loop computer consists of 75 functions that vary in size from 3 lines of assembly code to a single C function listing that takes eleven 8 1/2" X 11" pages. Twenty-one of the functions are written in assembly language and the remainder are in C. The total software listing for the computer is 122 pages long. Of the total listing space approximately 40 percent is function and file header english language descriptions, in line comments, and white space for readability.

Tag System Front End Computer

The tag system front end computer provides the input/output interface between the main control computer and the tag system process. The operator interface with the computer is via the main control computer graphics terminals. If the main control computer or communications link with the main control computer goes down the front end computer takes the system fail safe. The vacuum system portion of the tag system has a requirement that the vacuum pumps not be left in a high vacuum state when they go off. The front end computer will take the vacuum system through a two hour heatup and off gas operation if the main control computer is not available before taking the vacuum system fail safe.

The computer communicates with the main control computer through a serial port operating at 9600 baud. The second serial port is used to drive the tag system printer and, optionally, an alphanumeric terminal that is used for maintenance. For I/O the computer contains one relay output board, one 56 circuit open collector digital output board, two four channel 12 bit analog output boards, one 112 circuit digital input board, five 16 channel 12 bit analog input boards, and one 8 channel 16 bit analog input board. The computer has the following inputs and outputs:

54 valve position inputs
2 compressor starter status inputs
1 set of vacuum sensor BCD inputs
33 thermocouple inputs
8 level sensor inputs
4 flow sensor inputs
6 pressure sensor inputs
3 mass spectrometer electrometer 16 bit analog inputs
3 miscellaneous inputs

48 valve control outputs
2 compressor on/off outputs
9 heater control outputs
1 16 bit magnet control output
5 alarm outputs
4 relay outputs
4 flow control outputs
1 miscellaneous output

The real-time I/O and control functions operate in response a CPU board counter/timer interrupt that occurs every 1/10 of a second. Every five interrupts (1/2 second) the digital and 12 bit analog inputs are read, the analog inputs are averaged, the digital inputs are debounced, and the digital, relay, and analog outputs are written. See Figure 4 for a simplified software diagram. Every 1/10 of a second interrupt, a command may be written to control the mass spectrometer magnet, the three 16 bit analog electrometer input channels may be read, and a duty cycle heater control function may be run. Mass spectrometer magnet control, reading of the mass spectrometer electrometer, and control of the heaters are only done when commanded by the main control computer.

The real-time communications functions operate in response to receive and transmit character interrupts. In response to a receive interrupt, a receive message handler is called. This handler checks for receive hardware errors, checks for beginning and end of message conditions, keeps track of the position of the character in the message, and sets a flag when a complete message has been received. When a message is complete a function is called that calculates a message checksum and compares it to an appended checksum, stores the message information in shared memory, builds a response message, calculates and appends a checksum to the message, and initiates transmission of the message back to the main control computer. In response to a transmit character interrupt, a transmit message handler is called. This handler checks for transmit hardware errors, checks for end of message conditions, and initiates transmission of the next message character. The main control computer to tag system STD bus message is 39 bytes long and the returned message is 137 bytes long.

During operation the main control computer sends a message every second containing all output for valves, heaters, and flow control setpoints. In response to this message the tag system computer sends back a message containing all the data received on its inputs, any calculated data, and alarm condition information. When mass spectrometer analysis results are to be printed on the local CGCS printer a special message is sent from the main control computer containing the data. When the mass spectrometer is to be controlled and its output read a special message is sent with magnet control and read electrometer input commands. In response to a mass spectrometer control command an electrometer data message is sent back after the electrometer has been read the required number of times. These special messages are in addition to the normal one second messages.

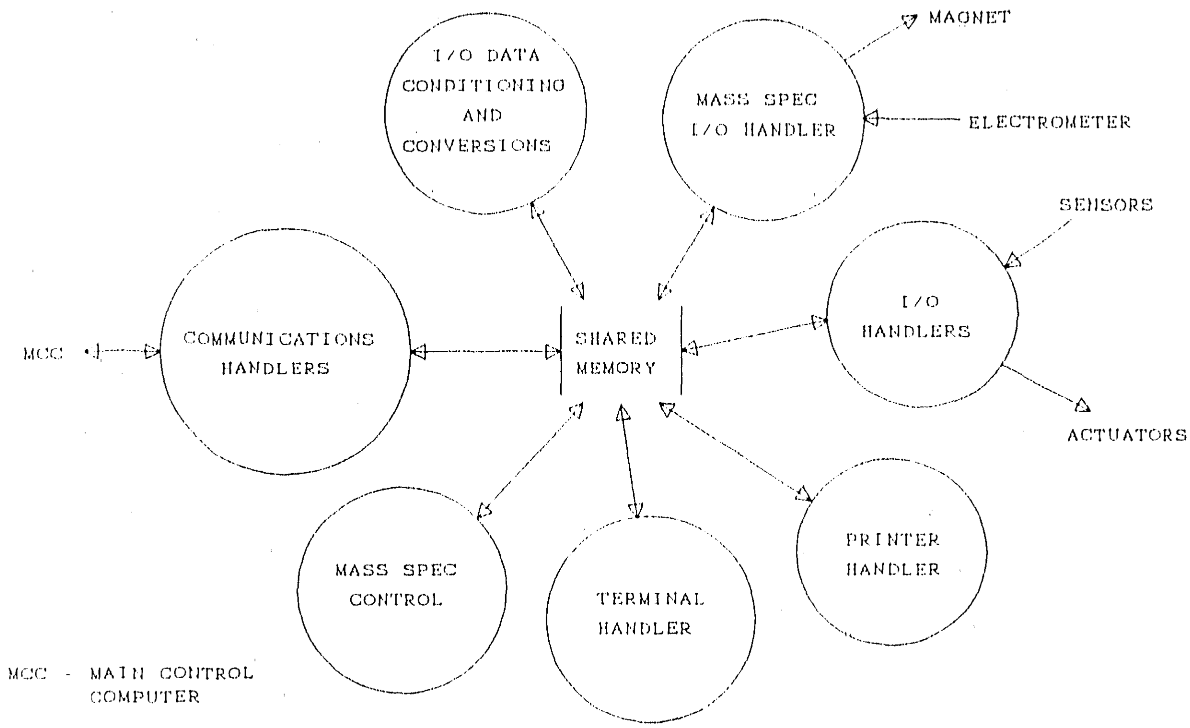


Figure 4. Tag System Computer Simplified Software Function Diagram

When the real-time functions are not running the computer is running the printer or, optionally, the terminal handling functions. The printer or terminal handling is done continuously and the real-time functions run in response to timer or communications interrupts.

For maintenance purposes a technician or engineer can interact with the tag system computer through the optional terminal. To use the terminal a switch that is read by the computer is switched to a maintenance position, the printer is disconnected from the serial port and the terminal connected. Changing the position of the switch directs the computer to bypass the printer handling software and run the terminal handling software. When the terminal return key is hit the main menu appears as follows:

(start of screen)

CGCS Tag System Menu

1 Analog to digital board calibration

2 Digital to analog board calibration

3 Electrometer amplifier board calibration

Enter selection and press return:

Note: Press <ESC> to clear screen
(end of screen)

The main menu functions allow the analog input boards, analog output boards, and a special mass spectrometer amplifier board to be calibrated. In response to a menu selection special calibration screens are displayed that allow a technician to see specific raw analog input data or to output keyboard entered values through specific analog output channels. The input data screens update in real-time so the results of any adjustments can be monitored.

The software on the tag system computer consists of 68 functions that vary in size from 3 lines of assembly code to a single C function listing that takes nine 8 1/2" X 11" pages. Twenty-four of the functions are written in assembly language and the remainder are in C. The total software listing for the computer is 79 pages long. Of the total listing space approximately 40 percent is function and file header english language descriptions, in line comments, and white space for readability.

Communications

The design of the communications between the computers had to consider efficiency, robustness, failure detection, fail recovery, and synchronization. The considerations were how to keep the messages short yet still convey needed information, how to detect bad messages and not lose information after a bad message, how to reestablish communications after a failure, and how to synchronize the receiver function with the message so that it knows when a message begins and when it ends.

For efficiency the messages are binary rather than ASCII. On/off type information is packed into bytes with up to seven on/off inputs assigned to a message byte. Raw analog input data and engineering unit data are sent in the minimum number of bytes needed to send the data. Floating point data is sent in its IEEE binary floating point form.

For robustness every message from the main control computer contains all the control commands and setpoints used by the main loop or tag system computer. In this way if a message has a bad checksum and is rejected, all the information will be sent again one second later on the next normal command message. This ensures that no command information is lost. In the same manner every response message from the main loop or tag system computer sends all status and I/O input information. If one message is lost the main control computer will get the information one second later.

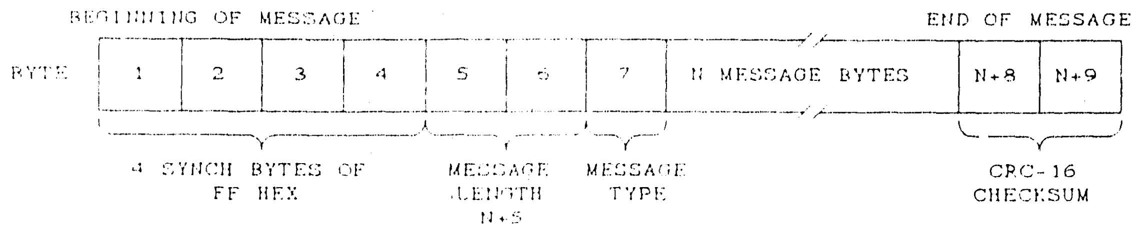
If a series of messages are received with bad checksums or a communications link goes down so no messages are received at all, communications timers will flag the communications as failed. Communications failure is indicated by alarms in the CGCS building and on the control room graphics terminal.

For failure detection a CRC-16 checksum is used for every message sent between the computers. The checksum is calculated for every message and appended to the message as the last two message bytes. When the message is completely received the CRC-16 checksum is calculated and must agree with the checksum appended to the message. If the checksums don't agree, the message is discarded.
The CRC-16 calculation function is implemented in software and is written in assembly language for speed.

If the computers are off, the communications link was down, or the main control computer was down but the main loop and tag system computers were operating, the control and display processes in the main control computer need to know the states of the inputs and setpoints on the other computers before calculating control outputs and giving control commands. In this situation the main control computer sets a particular bit in the outgoing message that tells the other computer to ignore any commands or setpoints in the message and to send its status and I/O data information.

To ensure that old command or data messages are not queued up in message buffers when a message link is not operational, the serial ports do not hardware or software handshake. When message transmission is initiated it completes regardless of the operational state of the receiving computer. This avoids the situation of a series of old command or data messages being sent when a communications link is reestablished.

For message synchronization purposes the messages have a particular structure where the message always starts with four bytes of ff hex. See Figure 5 for the standard message structure. The remainder of the message cannot have four consecutive bytes of ff hex. This is avoided by bit or byte stuffing with zero bits or bytes with values other than ff hex. This ensures that a partially received message, where the last part of the message was lost due to a transmitting computer or communications link failure, does not cause problems. Whenever the receiving computer sees four consecutive bytes of ff hex it throws away any partially received message and sets up to receive a new message.



MESSAGE LENGTH	2 BYTES WITH MOST SIGNIFICANT BYTE FIRST, 32,768 MAXIMUM
MESSAGE TYPE	1 BYTE, ANY VALUE FROM 0 TO 254
MESSAGE BYTES	ANY BINARY VALUES EXCEPT 4 ADJACENT BYTES OF FF HEX
CRC 16 CHECKSUM	CRC-16 RESIDUAL WITH LEAST SIGNIFICANT BYTE FIRST

Figure 5. Standard Message Structure

CONCLUSION

The control system with a main control computer, a main loop distributed control computer and a tag system front end computer has proven to be a good solution for the EBR-II CGCS upgrade. The system has allowed operators to be more aware of what is happening in the CGCS, to control the system even in a degraded mode, and to be assured that the system will go safe on a computer failure. The system is reliable, lower in maintenance, and much easier to work with than the old control system. The concept of driving alphanumeric terminals from the STD buses for maintenance and calibration has proven to be valuable. It adds a troubleshooting, maintenance, and control tuning capability that would have been more difficult to implement via the main control computer and that would not be available if the main computer was down.

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1. Jeffery D. Staffon and Gregory G. Peters, "EBR-II Cover Gas Cleanup System Upgrade Graphical Interface Design", *Proceedings of the 8th Power Plant Dynamics, Control & Testing Symposium*, Knoxville, TN, (1992).

2. Reed B. Carlson and Jeffery D. Staffon, "EBR-II Cover Gas Cleanup System Upgrade Process Control System Structure", *Proceedings of the 8th Power Plant Dynamics, Control & Testing Symposium*, Knoxville, TN, (1992).

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