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EVOLUTION OF THE DDG 51 MACHINERY CONTROL SYSTEM TO SUPPORT SSGTG LOCAL CONTROLLER UPGRADES

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ABSTRACT

The US NAVY DDG 51 Class Machinery Control System (MCS) provides control and monitoring capability of the ship's auxiliary, damage control, electrical, and propulsion systems. As part of its electrical capability, MCS interfaces with the ship's power generation and electrical distribution system. This paper focuses on MCS' interface with the ship's power generation equipment and how the interface has evolved since the class' inception.

The DDG 51 class has been in-service for nearly 2 decades and consists of over 60 ships. Over this period, a number of enhancements have been made to equipment on the ship to increase its functionality, enhance its operator interfaces, and address obsolescence issues. The Ship's Service Gas Turbine Generator (SSGTG) local controller is one such piece of equipment that has evolved throughout the years. Each SSGTG local controller upgrade has provided an opportunity for MCS to evolve to provide additional capability and data to the end user.

INTRODUCTION

The Machinery Control System (MCS) on board the US Navy DDG 51 Class ships provides centralized, remote monitoring and control of the propulsion plant, electric plant, and auxiliary support systems. The legacy MCS architecture is comprised of 5 major consoles. This includes three (3) consoles in Central Control Station (CCS) for remote monitoring and control: Propulsion and Auxiliary Control Console (PACC), Electric Plant Control Console (EPCC), and Engineering Officer of the Watch / Logging Unit (EOOW/LU)). There is a single Shaft Control Unit 1 (SCU1) in Main Engine Room1 (MER1) and there is a single Shaft Control Unit 2 (SCU2) in Main Engine Room 2 (MER2) (Figure 1 in Appendix A).

Each of the consoles operates a specific software executable designed for its intended functionality. The front of the consoles have a vertical panel and a sloping panel surface for mounting operating controls, indicator lights, and meters. Plasma displays are mounted to the vertical panel and a keyboard is mounted to the horizontal surface.

Displays on the consoles provide the operator with software based system status information including machinery status, alarm status, alarm reset status, and alarm acknowledge status. The operator uses the keyboard to generate requests to view demand display and summary group data from throughout the MCS.

While the MCS is modified slightly to align with unique configurations of each hull, there are several major re-designs of the MCS. From DDG 51 through 82 the MCS is based on an AN/UYK-44 real time processor and Standard Electronic Modules (SEMs) for signal and software processing. For DDGs 83 through 110, the MCS is based on a Versa Module Eurocard (VME) standard architecture. The SEMs are replaced by VME based input/out Circuit Card Assemblies (I/O CCAs). For DDG 111 and follow on hulls, the MCS remained VME based, however, the I/O is distributed amongst the machinery spaces in standalone cabinets instead of being located in the EPCC and SCUs. For DDG 111, the operator consoles are multi-function workstations, meaning they are capable of controlling any system within MCS vice being system specific consoles. The DDG 111 architecture is also being Back Fit on hulls that are being modernized.

In addition, the electric plant also saw the introduction of the Electric Plant Computer Processing Unit (EPCPU) for DDGs 79 through 110 which provided a remote operator interface for

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the Redundant Independent Mechanical Start System (RIMSS). The RIMSS is a newly introduced small turbine starting system for the SSGTG, replacing the legacy high pressure start air system.

The shipboard network that interconnects the MCS consoles is the copper-based Data Multiplex System (DMS). The network is used to transfer status and command messages between the MCS consoles. Figure 1 illustrates the interface between MCS and DMS. The network was upgraded to the Fiber Optic Data Multiplex System (FODMS) for hulls DDG 79 through 110 and upgraded further to the Giga-bit Ethernet Data Multiplex System (GEDMS) for hull DDG 111 and follow on ships. The GEDMS is also being implemented on DDGs that are being modernized through the Back Fit effort.

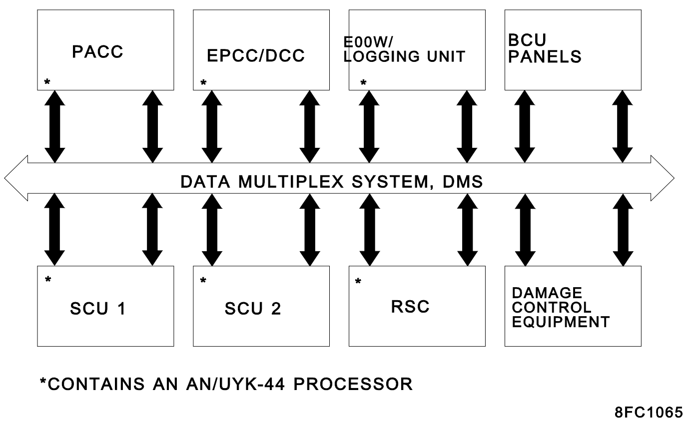


Figure 1-MCS to DMS Interface

Overview of the Machinery Control System

The following presents a brief overview of each of the consoles that comprise the MCS.

The EOOW/LU is a console located in the CCS. The console panels have no dedicated instruments or controls. It contains two plasma displays and a switchable keyboard that the EOOW uses to monitor the other MCS consoles and to perform bell and data logging. The unit is also used to modify alarm set, reset, and time delay values for the software operating on the other MCS consoles.

There are two (2) SCU consoles, one located in MER1 and one located in MER2. Each of these consoles interfaces with two General Electric (GE) LM2500 propulsion gas turbine modules (GTM) and their associated engine controller (EC). The starboard shaft is driven by the propulsion engines in MER1 and is controlled and monitored by SCU1. The port shaft is driven by the propulsion engines in MER2 and is controlled and monitored by SCU2. The SCU provides localized control and monitoring.

Both SCUs monitor and control the propulsion plants for their respective shaft including auxiliary machinery such as start air, bleed air, fuel service, propeller hydraulics, and lube oil. Control levers mounted on the SCU provide thrust and propeller pitch control. There are separate levers for lockout manual and computer assisted (programmed) control modes.

The SCUs are similar physically, but differ electrically because of the number and types of signals entering the console for processing. Signals to and from the plant are hardwired directly to the console through a cable entry panel.

The PACC is located in CCS and provides centralized control and monitoring for both shafts including the propulsion engines (4), the reduction gears (2), propellers (2), and engine auxiliaries. The PACC also monitors and controls start air, bleed air, fuel service, propeller hydraulics, lube oil, and sea water pumps. Programmed control levers mounted on the PACC provide computer assisted (programmed) thrust and propeller pitch control. The PACC does not interface directly to the plant. The SCU provides the physical interface to the plant and communicates plant information to the PACC over the network.

The EPCC console is located in CCS and provides centralized monitoring and control of the three Ship's Service Gas Turbine Generators (SSGTG 1, SSGTG 2, and SSGTG 3) and electric plant switchboards (three in total). The SSGTGs and switchboards are located in different spaces throughout the ship. The EPCC is physically hardwired to the electric plant. Signals to and from the plant are connected directly to the console through a cable entry panel.

The EPCC contains signal transducers and digital meters for processing and displaying each SSGTG's current, voltage, frequency, and power. There are controls to lower or raise the voltage or frequency of the SSGTG's output. A bus voltage meter, selector switch, and synchroscope are also on the vertical panel. The sloping panel has the push buttons and indicators for power distribution, shore power circuit breaker open control, load shedding, and remote starting of the SSGTGs.

Many of the indicators and pushbutton switches used for control of the electric plant are hardwired directly to the local SSGTG controller, bypassing the EPCC processor. The system was designed in this manner so that the electric plant could still be safely operated in the event that the EPCC processor became unavailable.

DDGs 51 through 77 have a single plasma display mounted to the vertical panel of the console. DDG78 through 110 EPCCs also have the EPCPU touch screen computer mounted on the vertical panel. A keyboard is mounted to the horizontal surface.

SSGTG LOCAL CONTROL

The primary function of the SSGTG local controller is to provide control and monitoring of the SSGTG. This includes start/stop sequencing along with alarm and shutdown processing to allow for safe turbine operation. The US NAVY DDG 51 class currently employs the Full Authority Digital Controller (FADC) to serve this purpose on all its hulls. However, that has not always been the case. The class was first delivered with a SSGTG Local Control Panel (LOCOP). The LOCOP performed the necessary functions using a 301 Sequencer, Allison Speed/Temp Box, and a GT400 Closed-Loop Governor. The Closed Loop Governor utilizes a Piston-Liquid Fuel Valve and Electro-Hydraulic Governor-Actuator to perform its primary function. The LOCOP provided the means to interface with the MCS. This includes receiving commands from and providing feedback to the MCS. A total of 47 signals of varying types (see table 1) are provided to the EPCC from the LOCOP and the SSGTG skid through a common interface box. These signals are hardwired to the EPCC through three (3) multi-pair cables. Although there are additional signals that the LOCOP could provide to the EPCC, the set of 47 that were chosen were deemed the most pertinent data to provide to the operator given the total number of signals that the three interface cables could accommodate. This physical I/O cable limitation not only restricted the amount of data that the end user could currently obtain, it also impacted future expansion of the system as a whole.

Table 1-EPCC/LOCOP Interface Signal Types

Signal/Measurement Type	Quantity
4 to 20 mA	10
RTD	3
Discrete Commands to LOCOP from EPCC	6
Discrete Indications from LOCOP to EPCC	28

The FADC was introduced to the US NAVY DDG 51 class starting with DDG 86 and has since been retrofitted to all hulls within the class. While the FADC served as a form, fit, function replacement of the LOCOP with respect to EPCC, it represented a major controller enhancement when it was introduced to the class. The LOCOP was a strict gauge and indicator system driven by the underlying 301 Sequencer. The FADC was a software based system that utilized a NETCON digital controller to perform all of the start/stop sequencing and alarm and shutdown processing that was necessary. The FADC also introduced a PC based, touch screen human machine interface (HMI) that was installed on the FADC enclosure. The FADC HMI was developed using the commercially available Intellution Fix software package. Subsequent to the introduction of the FADC, the NETCON digital controller was upgraded to a MICRONET digital controller which provided Ethernet communication capability. The NETCON and MICRONET systems from the Woodward Governor Company utilize their Graphical Application Programmer (GAP) programming environment. GAP not only provides a means to create, edit, and view the digital controller's software but also provides the end user with advanced troubleshooting tools such as on-line code monitoring, variable monitoring, and data logging. All these functions are part of an advanced feature set that provide more capability and insight to the local end user. The ability to troubleshoot issues with the local controller or the SSGTG skid itself is greatly improved. These features allow for greater ability to incorporate improvements to the local controller and significantly reduce the time required to implement improvements. With the introduction of Ethernet communications with the MICRONET controller, the interface to the remote end user became easily expandable. No longer was the remote end user limited by the restricted amount of physical I/O cables. A tremendous window of opportunity and possibility was opened for the DDG modernized MCS.

EPCC Architecture

Just as the SSGTG local controller has seen upgrades through its life cycle, so has the MCS. The Flight I EPCC (DDG 51 class hulls 51 through 82) is a processor based operator's console running a computer software program that is stored on non-volatile bubble memory units. The computer software program contains all the logic to process all inputs and outputs to the console both internally (i.e. pushbuttons/indicators/plasma display) and externally. The MCS Computer Program (CP) is executed on an AN/UYK-44 real time computer processor.

A plasma display provides the visual interface while a keyboard and pushbuttons on the console allow the operator to interact with the console and electric plant. All inputs and outputs are signal conditioned as they enter/leave the console through the use of SEMs. There are a variety of SEM types that facilitate the conversion of different real world input types to a digital format that can be utilized by the computer software program. Each SEM is designed to perform a single function but can accommodate several circuits allowing for multiple signal paths through a single SEM. Due to this design, it may take several SEMs to signal condition a single signal from physical units to a digital format. The SEMs are housed in either the Input Output Multiplexer (I/O Mux) section or the Panel Distributor section of the console. The complete signal routing once the signal enters the console is made via a wire wrapped backplane. The LOCOP interface to the EPCC is made via hardwire means at the EPCC cable entry.
Figure 2 illustrates a representative signal path from the LOCOP to the AN/UYK-44. Figure 2 in Appendix A provides a more detailed signal flow diagram.

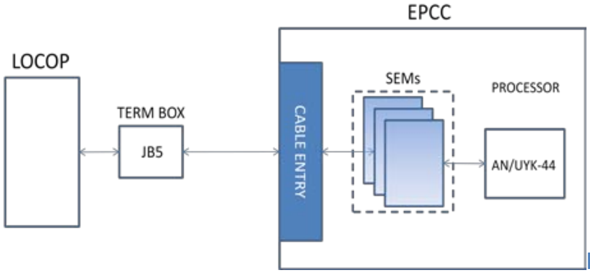


Figure 2-Elementary Signal Path

The EPCC provides very limited SSGTG control capability and is essentially restricted to the most basic SSGTG functions including starting, stopping, bleed air control, and start air selection. The EPCC also provides the capability to remotely release primary and reserve fire fighting agents in the event of a SSGTG module fire.

From a SSGTG indication standpoint, the EPCC provides the operator with measurements such as Engine RPM, Turbine Inlet Temperature, Engine and Generator Lube Oil pressure, Generator Bearing Temperatures, and Stator Temperatures. These measurements are received directly from the LOCOP itself. For measurements such as Generator output voltage, the EPCC obtains the data from a potential transformer in the associated switchboard rather than from the SSGTG or the LOCOP.

For the MCS on DDG 51 class hulls 83 through 110 (commonly referred to a Flight II), the SEMs are replaced by VME based Input/Out Circuit Card Assemblies (I/O CCAs). The AN/UYK-44 computer is replaced by two VME based processor CCAs, the Control processor CCA and the GUI processor CCA. The Control processor CCA contains the software for processing I/O and performing control of the field systems. It uses a Wind River VxWorks Operating System (OS). The other processor CCA contains the software for the Graphical User Interface (GUI) screens used on the console display for operator information. The GUI processor uses a Windows NT Operating System.

The bubble memory software storage device of the Flight I console is replaced with a Personal Computer Memory Card International Association (PCMCIA) card that inserts directly into the Control processor CCA. The panel distributor is replaced by the VME based card cage and I/O CCAs. The signal path from cable entry to the VME processor is done via ribbon cables vice the wire wrap of the Flight I. The FADC interface to the Flight II EPCC remains through the cable entry as was the case for the Flight I EPCC. As Figure 3 illustrates, the technology upgrades to MCS for DDGs 83 through 110 do not affect the interface between the FADC and EPCC.

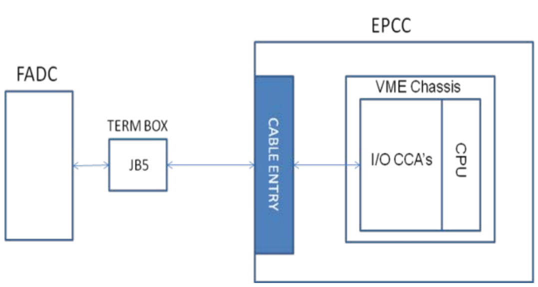


Figure 3-Flight II Architecture

One other EPCC upgrade worth touching on was introduced with DDG 79. Beginning with DDG 79, the High Pressure Air Compressor (HPAC) systems for the generator spaces were removed. The HPAC was used as the initial/emergency starting system for the SSGTGs. The HPAC was replaced with the Redundant Independent Mechanical Starting System (RIMSS). The RIMSS is essentially a small turbine that is mechanically coupled to the SSGTG to start it. The RIMSS itself is started by battery vice forced air, allowing for a more robust starting system. Due to the physical I/O cabling restrictions between the FADC and EPCC, the RIMSS required a separate interface that integrates with both the local FADC and the EPCC. This interface consists of an Electric Plant Input Output Unit (EPIOU) dedicated to each RIMSS and FADC and a single EPCPU to interface with all three EPIOUs. The EPCPU uses a Windows NT operating system.

The EPIOU consists of four GE Fanuc Genius series I/O blocks. Two are analog modules and two are discrete modules. The Genius I/O blocks are self-contained, configurable I/O modules. The modules are programmed to interface directly with the FADC which contains the command and control logic for the RIMSS. The interface between the EPIOU and the FADC consists of multipair cables containing the RIMSS based signals. However, the interface between the EPIOU and the EPCPU is a combination of hardwired and serial communication cables. Figure 3 of Appendix A illustrates the interfaces. The EPCPU provides three hardwired emergency stops, one per RIMSS, to the appropriate EPIOU. All other command and status signals are transmitted between the EPCPU and the three EPIOUs in a serial bus switching architecture. The serial connection is daisy chained between each EPIOU and the link is completed back to the EPCPU by the first and third EPIOU. In addition, the link has a primary and a backup bus which are provided by separate cables to each EPIOU and the EPCPU. Figure 4 of Appendix A represents the EPCPU to EPIOU serial connections. The hardwired emergency stop commands and the two serial links are all separate cables to all units.

Due to the communications protocol between the EPCPU and EPIOU being proprietary, the EPCPU is required to be a separate computer from the EPCC. Even though the EPCPU is physically embedded into the EPCC and its display is next to the EPCC display, the EPCPU converts the RIMSS data to RS-232 serial protocol for communication to the EPCC software. The EPCC then displays the RIMSS status and alarm information within its software to provide a complete electric plant overview to the operator from a single display.

It should be noted that the interface between the EPCPU and the EPCC does not change with the introduction of the VME-based EPCC beginning with DDG 83.

DDG MODERNIZATION

The DDG Modernization program represents design changes made to the ships control system to address obsolescence issues and provide the warfighter with an advanced set of tools to perform his/her duties. The program is divided into two parts: new construction initiatives and in service Back Fit applications. Each program has its share of similarities and disparities with each other. For the purposes of this paper, however, the similarities outweigh the differences and, as such, the differences will be ignored and the Modernization effort will be discussed as a whole rather than its parts.

Architecture Overview

The Modernization program represents a major change in the overall architecture of the Machinery Control System and the equipment with which it interfaces. The most noticeable design change is the replacement of the single, dedicated function consoles like PACC and EPCC with Universal Control Consoles (UCCs). The user can select what function at the UCC he/she is to perform (i.e. PACC, EPCC, EOOW, SCU1, or SCU2). While the UCC acts as the user interface to the system, the signal conditioning and logic applied to inputs/outputs are performed at the Data Interface Units (DIUs). The introduction of the DIU represents another one of the changes that constitutes the modernized system. The DIUs utilize a VME based architecture that employs a primary & secondary Central Processor Unit (CPU) card along with IO CCAs. The computer software program runs on the CPU while the CCA's provide the signal conditioning of all ships I/O. On the surface this may not seem to be a departure from the legacy DDG 83 through 110 VME MCS system, however, there are two (2) distinct features that differentiate the modernized system from the legacy: the CCAs are multifunction and the user interface, software, and signal conditioning do not reside in a single enclosure.

The multifunction CCA allows conditioning of different signal types on a single card. This allows for less VME card cage slot usage, increased expandability, and simplified logistics.

The elimination of a single enclosure represents the first steps toward a fully distributed I/O system. The DIU and UCC are now networked together via the ship's GEDMS which enables UCCs to not only be multifunction but also location independent. But it goes further. Other intelligent equipment can also utilize the distributed architecture to interface with the MCS through the GEDMS network.

Figure 5 in Appendix A contains a representation of how the modernized system looks.

FADC and Modernization

The introduction of a network based architecture allowed the FADC to eliminate the three (3) cables that served as the hardwired interface to the EPCC in the legacy system. The hardwired interface was no longer a restriction in communication between the FADC and the MCS. Instead, the GEDMS network acts as the communication interface between the two.

The FADC utilizes TCP/IP MODBUS to interface with GEDMS in the modernized architecture. GEDMS then provides the interface between the FADC and an Electric Plant DIU.

The adoption of a network based interface for the FADC resulted in the ability to send and receive more data to/from MCS than before. Where once an acceptable limit of 47 signals was used, messaging allows for maximum values of 118 analogs and 1888 discrete signals in both command and status messages. Currently, for the DDG modernized system, the number of signals that the FADC and DIU exchange via the network is approximately 145. The majority of this data are indications from the FADC to MCS providing the operator with more information about the state of the SSGTG and RIMSS. The information that was previously provided to the EPCC through the EPCPU and the EPIOU is now provided directly by the FADC through the GEDMS network. Although the network interface has changed how much data is exchanged between the FADC and MCS, the amount of control that MCS has remains relatively unchanged. However, with so much bandwidth leftover in the current modernized network communication scheme, expansion of data exchanged and control capabilities are easily expandable compared to the legacy systems.

As an example, an Engineering Change Proposal has been recently introduced for both the MCS and FADC for Modernization. SSGTG motor-related problems have demonstrated the need for improved control of SSGTG local and remote motoring. The changes will provide improved control of local and remote SSGTG motoring operations for both. The MCS software changes will provide the operator a more detailed display of actual SSGTG motoring status and UCC motor command logic will be based on actual SSGTG motoring status feedback. These MCS software changes will be implemented in conjunction with a FADC software modification, The FADC software change will include the ability to stop remote and local motoring by pressing any UCC stop button or the FADC stop button.

All of these modifications can be implemented strictly through software changes. No hardware or wiring changes are required between the MCS, the FADC, or the SSGTG. Instead, the additional data required to make these updates will be extracted from the existing network messages that are exchanged by the MCS and FADC through the GEDMS network.

Electric Plant DIUs

The modernized MCS still utilizes a function called EPCC which reflects the control and monitoring capability that existed in the legacy MCS. However, the implementation is quite different. Rather than having a single EPCC console located in CCS with all three (3) FADCs hardwired to it, three Electric Plant DIUs have taken its place. Each of these DIUs resides in the same space as the FADC with which it interfaces. This architecture adoption eliminates long signal I/O cable runs and provides increased survivability.

Using the additional data that is now available, the UCC provides graphical and textual data from each SSGTG for the EPCC operator to use for operations and troubleshooting purposes.

Challenges with the Modernized Architecture

Although not implicitly discussed in previous sections, the legacy interface between EPCC and the FADC was limited by the number of spare cable pairs available in a cable and the number of spare channels of any particular signal type in the EPCC. To summarize, the biggest challenge facing this implementation was hardware based.

The modernized architecture certainly does not suffer from the hardware restrictions of its predecessors. However, there are a number of challenges that impact it. Two of the most notable are:

- Network implementation to increase survivability
- Lack of hardwired signals results in total network dependence

These items have been looked at throughout the design and testing phases and will continue to be evaluated as the system is installed in the fleet.

What does the Future Hold?

It can easily be seen that the core functionality of the interface between MCS and the SSGTG controller has not differed drastically through the lifecycle of the class. However, technology insertion has played a large role in how that function is performed and will continue to do so in the future. Recently, changes have been proposed and are being tested that improve the information and control provided to the MCS operator for the SSGTG via the FADC. These improvements take advantage of the increased bandwith for data exchange provided by using a network communication architecture instead of a hardwired signal exchange.

Looking at potential areas of improvement/advancement in the future, one has no choice but to look at how network communications are performed and the functions that MCS can perform. In terms of communications, adopting schemes that lower CPU utilization, on both sides, and decreasing bandwidth are areas to focus on.

In terms of EPCC function expansion, utilizing the abundant data from the SSGTG controller about the SSGTG and itself, can open doors to condition based maintenance, advanced system diagnostics, and increased integrated system troubleshooting.

In a network based system, it is feasible that each FADC can talk with each other allowing for opportunities such as load balancing/sharing between the SSGTGs. Introduction of a distributed, networked architecture opens endless opportunity as technology increases allowing for system designers to provide more advanced systems for the warfighter to use in completing their mission.

ACKNOWLEDGMENTS

Thanks to Brian Connery, US NAVY for providing his subject matter expertise related to the SSGTG Local Controllers.

ANNEX A

APPENDIX A

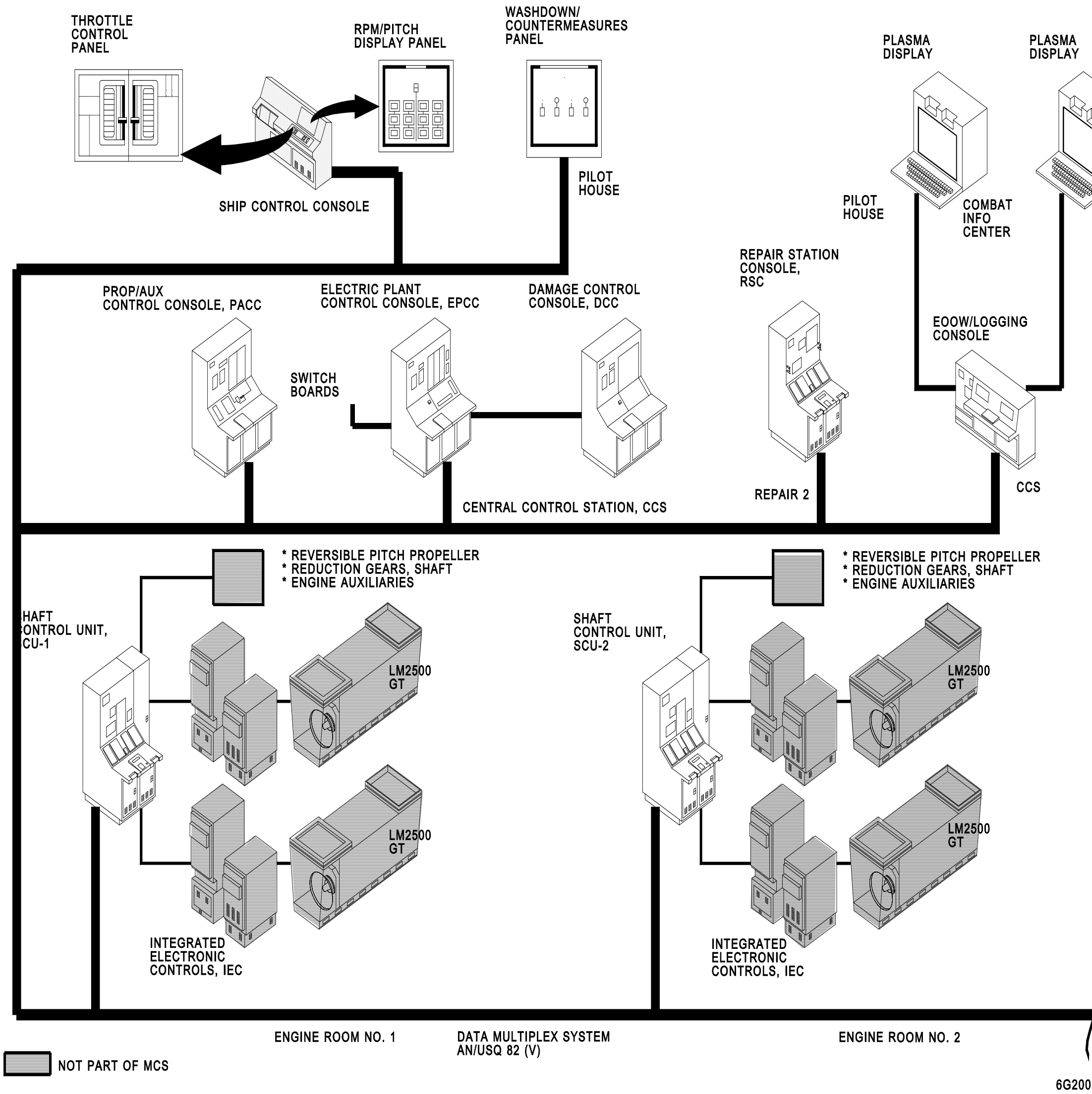

THROTTLE CONTROL PANEL
RPM/PITCH DISPLAY PANEL
WASHDOWN/ COUNTERMEASURES PANEL
PLASMA DISPLAY
PLASMA DISPLAY
SHIP CONTROL CONSOLE
PILOT HOUSE
PILOT HOUSE
COMBAT INFO CENTER
REPAIR STATION CONSOLE, RSC
PROP/AUX CONTROL CONSOLE, PACC
ELECTRIC PLANT CONTROL CONSOLE, EPCC
DAMAGE CONTROL CONSOLE, DCC
EOOW/LOGGING CONSOLE
SWITCH BOARDS
REPAIR 2
CCS
CENTRAL CONTROL STATION, CCS
* REVERSIBLE PITCH PROPELLER
* REDUCTION GEARS, SHAFT
* ENGINE AUXILIARIES
* REVERSIBLE PITCH PROPELLER
* REDUCTION GEARS, SHAFT
* ENGINE AUXILIARIES
SHAFT CONTROL UNIT, SCU-1
SHAFT CONTROL UNIT, SCU-2
LM2500 GT
LM2500 GT
LM2500 GT
LM2500 GT
INTEGRATED ELECTRONIC CONTROLS, IEC
INTEGRATED ELECTRONIC CONTROLS, IEC
ENGINE ROOM NO. 1
DATA MULTIPLEX SYSTEM AN/USQ 82 (V)
ENGINE ROOM NO. 2
NOT PART OF MCS
6G200

FIGURE 1

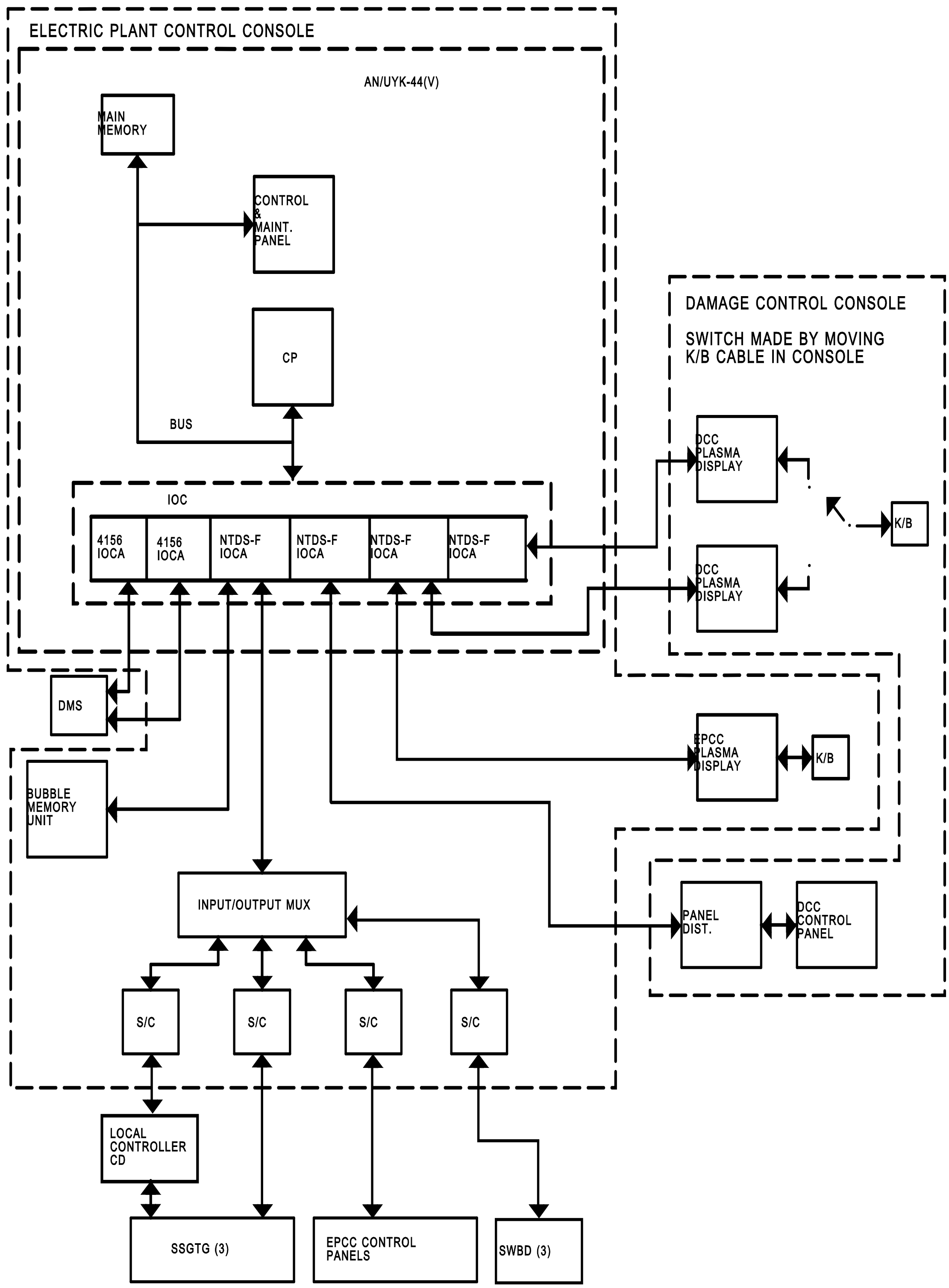

ELECTRIC PLANT CONTROL CONSOLE
AN/UYK-44(V)
MAIN MEMORY
CONTROL & MAINT. PANEL
CP
BUS
IOC
4156 IOCA
4156 IOCA
NTDS-F IOCA
NTDS-F IOCA
NTDS-F IOCA
NTDS-F IOCA
DAMAGE CONTROL CONSOLE
SWITCH MADE BY MOVING K/B CABLE IN CONSOLE
DCC PLASMA DISPLAY
K/B
DCC PLASMA DISPLAY
DMS
EPCC PLASMA DISPLAY
K/B
BUBBLE MEMORY UNIT
INPUT/OUTPUT MUX
PANEL DIST.
DCC CONTROL PANEL
S/C
S/C
S/C
S/C
LOCAL CONTROLLER CD
SSGTG (3)
EPCC CONTROL PANELS
SWBD (3)

FIGURE 2

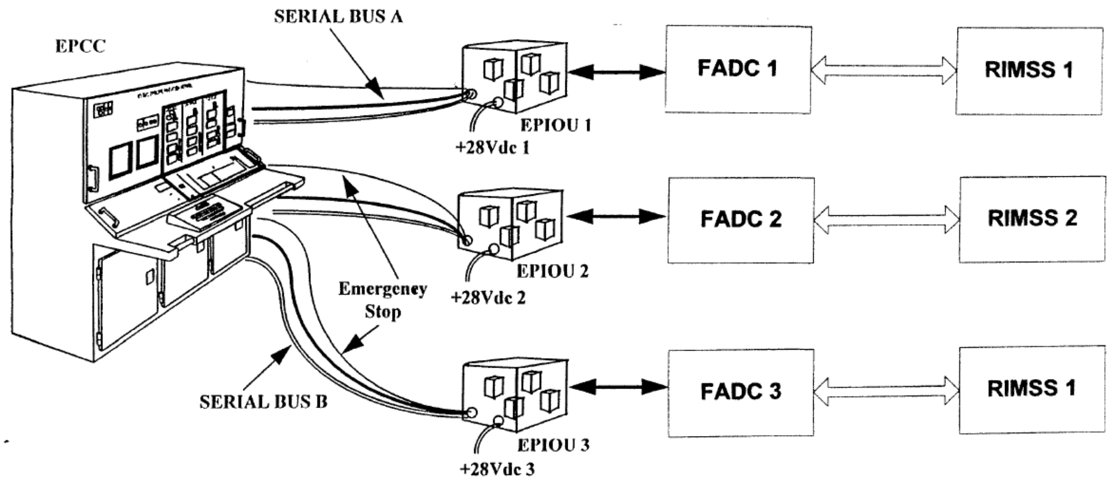
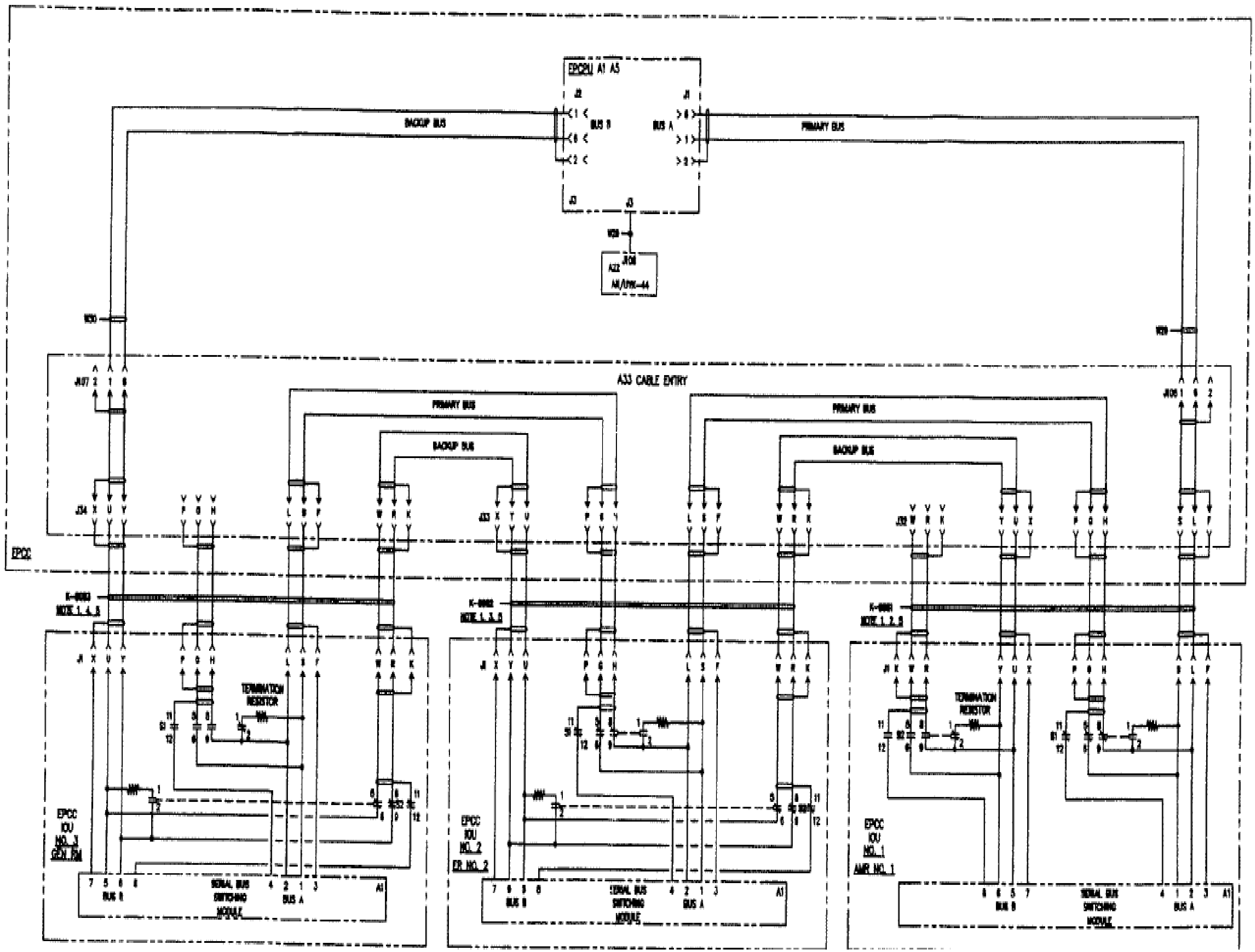

EPCC
SERIAL BUS A
EPIOU 1
+28Vdc 1
FADC 1
RIMSS 1
EPIOU 2
+28Vdc 2
FADC 2
RIMSS 2
Emergency
Stop
SERIAL BUS B
EPIOU 3
+28Vdc 3
FADC 3
RIMSS 1

FIGURE 3



A33 CABLE ENTRY
PRIMARY BUS
BACKUP BUS
TERMINATION RESISTOR
SERIAL BUS SWITCHING MODULE
EPCC

FIGURE 4

DRAFT

Modernized DDG Engineering Hardware Architecture

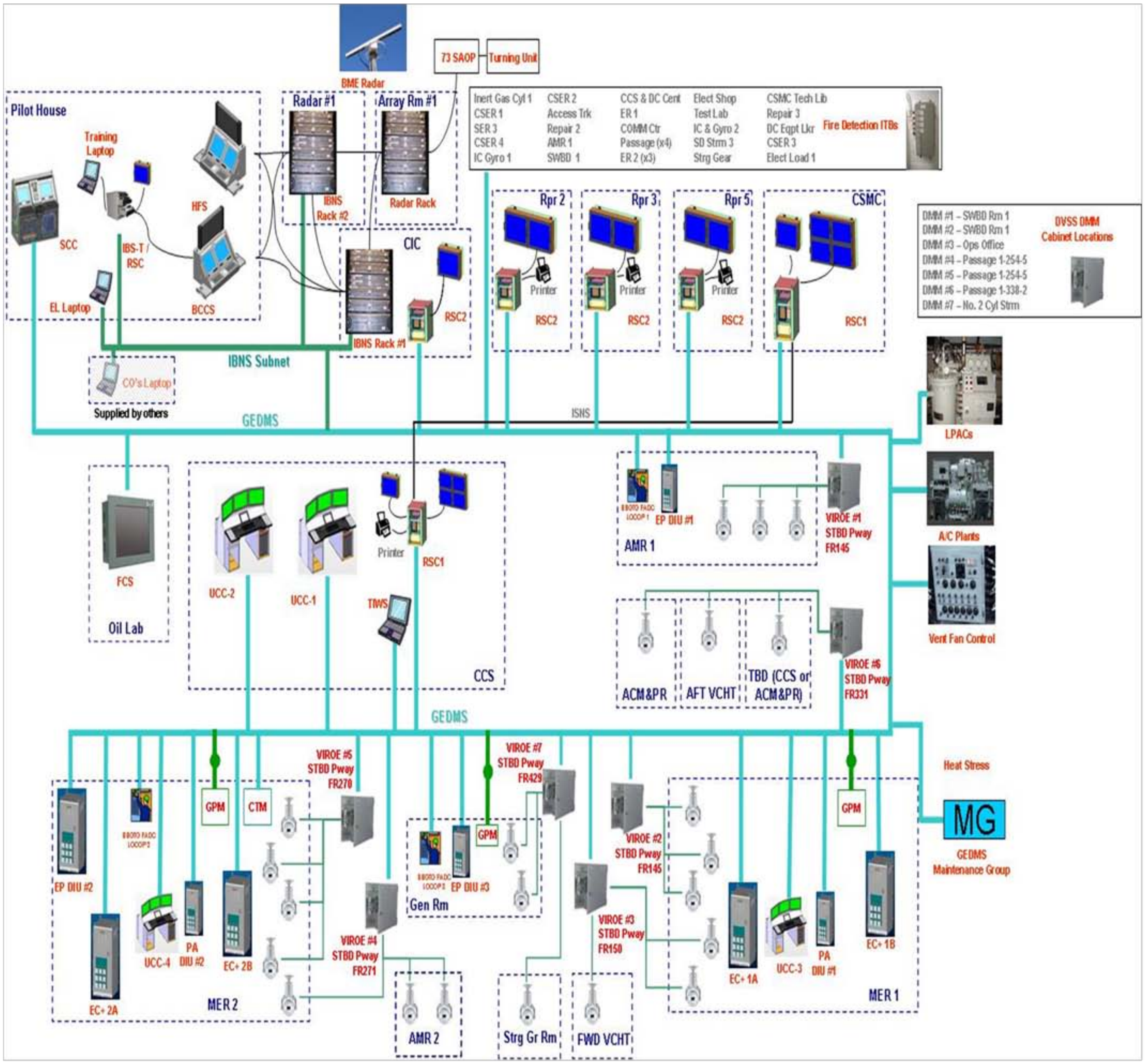


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FIGURE 5