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The E-STREAM Control System: Modular, Integrated, Extensible

Abstract

The US Navy has introduced a new family of Underway Replenishment (UNREP) systems, known as E-STREAM, that significantly improves throughput, operability, supportability, and total ownership cost compared to legacy equipment. D&K Engineering designed, built, and commissioned the control systems for the two solid cargo transfer stations and one liquid cargo station now in operation. One solid cargo station and the liquid cargo station are installed at the Navy's UNREP test site in California. The second solid cargo station is now in its fourth year of operation on a USNS underway replenishment ship. Another solid cargo station is in the pipeline. The control systems for this equipment consist of two types of electronics enclosures. The "brains" consists of low-power (120 VAC) enclosures that provide operator controls, data communication, and computing, based on Programmable Logic Controller (PLC) technology. The "brawn" consists of high-power (480 VAC) enclosures that energize and control the winches and other deck machinery using Variable Frequency Drive (VFD) technology. Brains and brawn are linked by digital communications networks, based on ControlNet technology by Rockwell Automation. This architecture is **modular** in that a handful of basic enclosure types (master power panel, master control console, local control panel, PLC, I/O, load center, VFD) is exploited mix-and-match style to populate the system. It is **integrated** in that common mechanical, electronic, and software solutions are used throughout the system. The end result is a control system readily **extensible** to other applications that require proven robust control of shipboard machinery. This paper describes the mechanical, electrical, and software building blocks of the E-STREAM control system.

Introduction

D&K Engineering was approached by the Underway Replenishment Division at Port Hueneme in late 2000 to look into methods to improve the operability of the suite of solid cargo transfer deck equipment known as Navy Standard. Due to limitations in the design of the Navy Standard system, it takes a highly skilled operator to land a load between ships in daylight under the best of conditions. At night, in weather and high seas, the job is much more difficult.

Couldn't modern electronics be used to sense the travel of the load from ship to ship and to automatically bring it to a smooth stop when it reached its destination? The answer was yes, of course. Over the next several years D&K developed a system for automatic landing of solid cargo loads, demonstrating it at the Underway Replenishment Test Site in Port Hueneme in 2007.

In 2008 the Navy increased the scope of the project. The underway replenishment community needed to eliminate three sources of increasingly severe maintenance and support headaches:

- Hauling winch air clutches, used to provide for variable torque of the winch drums, required frequent replacement, at great expense.
- Variable-speed hydrostatic transmissions incorporated in both hauling and highline winches were very expensive to maintain and qualified personnel to maintain them were becoming increasingly scarce. Furthermore, these transmissions had become obsolete, manufactured only at great cost by reluctant suppliers. There would be a time when these transmissions couldn't be procured at any reasonable price.
- Multi-speed AC induction motors used to power the sliding block were also becoming obsolete, and hence increasingly expensive and hard to source.

Could variable frequency drive (VFD) technology be used to eliminate these headaches? Once again the answer was yes. Over the next five years, engineers at D&K Engineering and Rockwell Automation worked under the supervision of Navy engineers at Port Hueneme to design, manufacture, and install the E-STREAM control system, culminating in the 2013 installation of the E-STREAM solid cargo station aboard ship. D&K Engineering is responsible for the design and manufacture of the E-STEAM control system, with Rockwell Automation as a key subcontractor and design partner. See References 1 and 2 for a history of underway replenishment equipment development leading up to E-STREAM, and a detailed description of the operational and logistic features and benefits of the new system.

The design team's marching orders were explicit. Paraphrasing Reference 1, they were:

1. Eliminate known high maintenance and repair items in the Navy Standard system.

2. Design for fail-operability. That is, don't allow the failure of any small, low cost component prevent the system from accomplishing its mission.

3. Maintain the look and feel of the legacy system, while achieving the improved controllability made possible by modern electronics.

4. Maintain physical and procedural compatibility with existing UNREP delivery and receiving systems, not changing how UNREP is performed in any significant way.

5. Port Hueneme engineers would provide design direction. Upon completion, all drawings would have NAVSEA numbers, owned and maintained by the Navy.

6. Maximize the use of common components throughout the system, to minimize the logistics footprint.

How the E-STREAM control system achieves these objectives in a **modular**, **integrated**, and **extensible** fashion occupies the balance of this paper.

The equipment under control

Figures 1 and 2 illustrate the E-STREAM Replenishment At Sea (E-RAS) station. The deck machinery consists of the highline winch, inhaul winch, outhaul winch, sliding block (which moves the transfer head up and down on the kingpost), and three anti-slack devices (ASDs), one for each winch. Operator controls and indicators are located in the master control booth (Figure 3) and at local control panels mounted on deck near each winch (Figure 4).

Each winch consists of a winch drum driven through a gearbox by a variable-speed electric motor. An electrically released spring set brake mounted on the winch holds the drum against wire rope tension when the motor is de-energized.

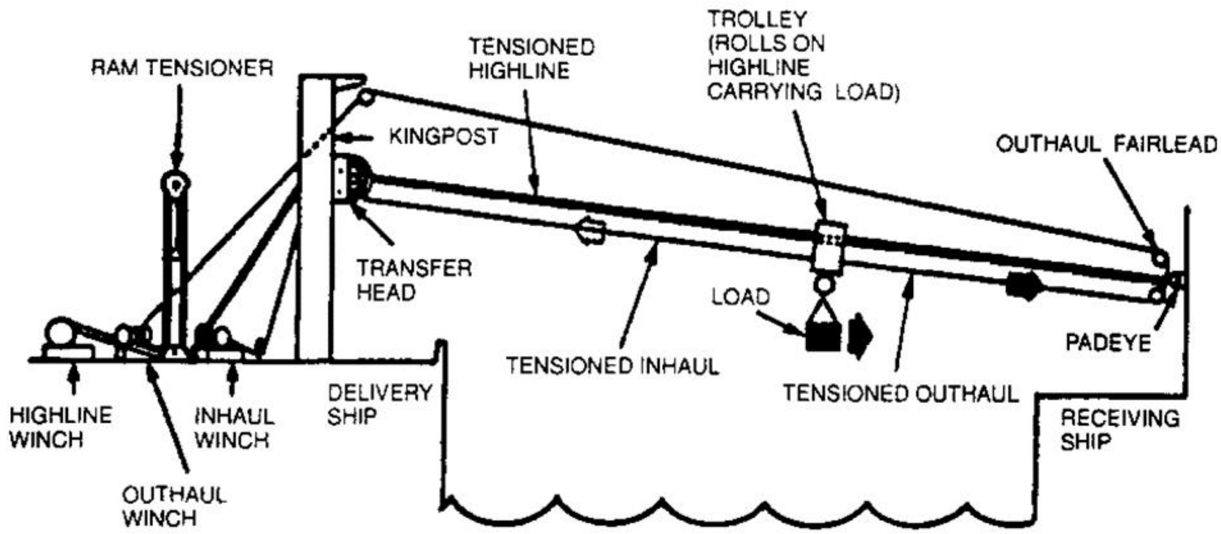


Figure 1. E-STREAM Replenishment at Sea (Solid Cargo)

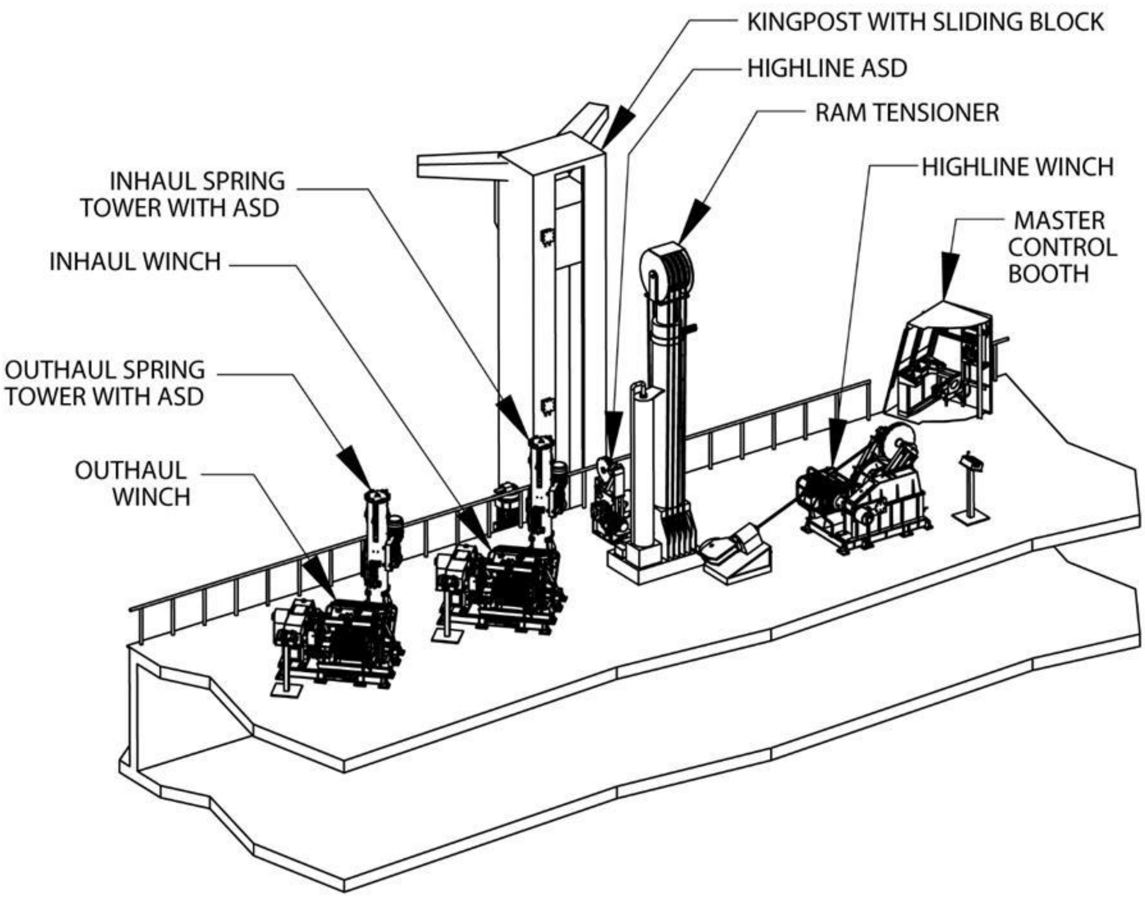


Figure 2. E-STREAM Replenishment at Sea Station (Solid Cargo)

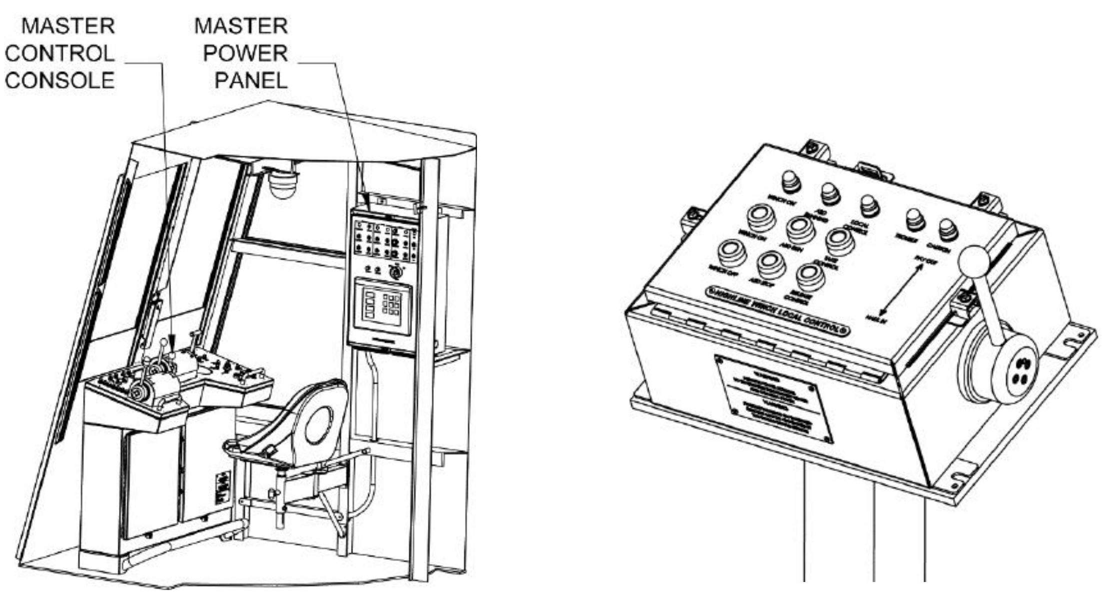


Figure 3. Master Control Booth

Figure 4. Winch Local Control Panel

Each winch also has an anti-slack device (ASD). While the system is being rigged, this device grips the wire rope and pulls on it so as to strip it off the drum, not hard enough to overcome the winch motor or brake, but hard enough to maintain tension in the rope so it doesn't foul on the drum (birdcage). Once the rope is tensioned between the ships, the ASD is disengaged.

The highline winch is used to tend the highline, a tensioned rope which supports the cargo as it travels between ships. The highline is reeved multiple times through sheaves at either end of a large hydraulic cylinder and rod, called the ram tensioner. The ram tensioner acts as a gas spring to maintain relatively constant tension in the highline as the replenishment stations on the two ships move toward and away from each other due to ship motion.

To achieve automatic tending of the highline, a feature of the Navy Standard system, draw wire encoders continuously report the position of the tensioning ram. Using this information the control system operates the highline winch to pay out or haul in as necessary to keep the ram away from its travel limits.

The hauling winches, inhaul and outhaul, pull the trolley back and forth between the ships. Rotary encoders mounted on the hauling winches report the rotation of the hauling winch drums and of sheaves the hauling ropes are reeved through, providing rope payout information. These feedbacks enable the control system to compute the location of the trolley between the two ships, and hence to achieve automated soft landing of cargo loads.

The highline and hauling ropes are reeved through the transfer head, which is attached to the sliding block, a carriage that rides up and down on the kingpost. The sliding block motor raises and lowers the sliding block, thereby raising and lowering the trolley and its load when they are at the UNREP ship. There are rotary encoders in the sliding block chain drive mechanism and travel limit switches on the kingpost, allowing the control system to automatically bring the sliding block to a soft stop at the ends of its allowed travel.

The solid cargo stations installed at Port Hueneme and aboard ship are a special version of the E-RAS station, denoted Heavy E-STREAM Replenishment At Sea (E-HRAS). (Strictly speaking these are *prototype* E-HRAS control systems. The final E-HRAS design described here is the result of design work that incorporated lessons learned from the first two installations.)

The E-HRAS station is identical to E-RAS, with the exception that it is sized to provide the higher rope tensions required to transfer loads of up to 12,000 lb., twice the capacity of E-RAS. It is configurable using a selector switch to set Navy Standard or Heavy rope tensions. The ability to configure the rope tensions, and hence load capacity, is needed because only aircraft carriers and some UNREP ships will be outfitted with receiving stations capable of sustaining Heavy rope tensions. Henceforth, references to E-RAS can be understood to include E-HRAS, unless otherwise indicated.

System architecture - data flow

Figure 5 is a simplified block diagram of the E-RAS control system. It can be thought of as a large wiring harness that carries data between electronics enclosures and various deck-mounted sensors and actuators.

The central computer of this system is located in the PLC Enclosure. It consists of a pair of identical mutually redundant Rockwell Automation ControlLogix programmable logic controllers (PLCs). One PLC operates the system while the other stands by. If the first malfunctions, the second takes over seamlessly. Together these two PLCs are called the Main PLC.

The Main PLC communicates with the rest of the system via ControlNet, a fully redundant high speed data communications network. It consists of pairs of coaxial cables wired in parallel between network nodes. Both cables carry the same data. If either of the two cables between nodes is damaged, the other keeps the network functioning, while system software issues a warning.

Since the Main PLC communicates via ControlNet, components must exist to interface ControlNet with both (1) operator inputs and indicators and (2) deck-mounted sensors and actuators. These interface components are contained in two types of electronic enclosures: input-output (I/O) enclosures and drive enclosures.

There is an I/O enclosure for each of the four subsystems: highline winch, inhaul winch, outhaul winch, and sliding block. Each of these enclosures contains I/O modules that interface ControlNet with the discrete 24 VDC circuits associated with local control panel operator inputs and indicators and with sensors in the deck machinery, such as rope payout, sliding block position, and ram position encoders.

There is also a drive enclosure for each of the four subsystems. While the drive enclosures exist to energize and control motors and brakes, they also contain I/O modules to interface with certain 24 VDC discrete circuits, such as from the travel limit switches at either end of sliding block travel.

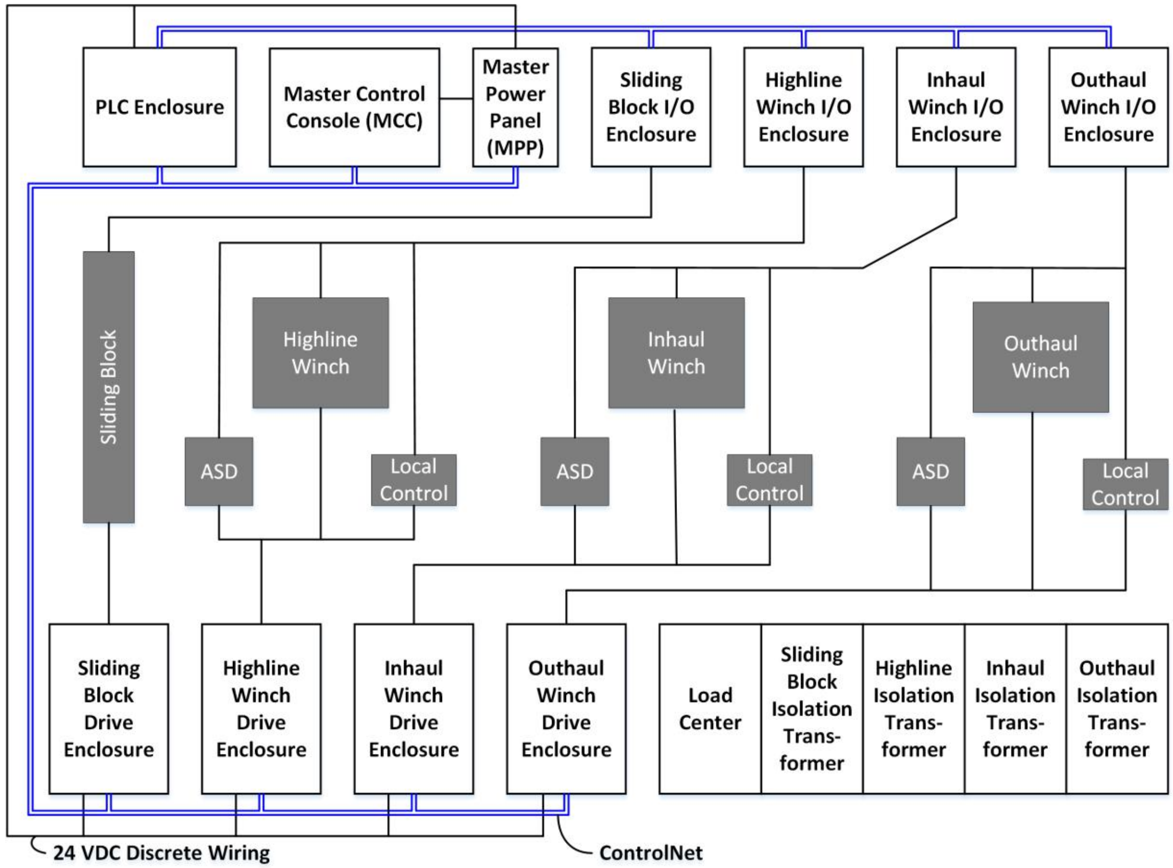


Figure 5. E-RAS Data Flow

The Master Control Console (MCC), located in the Master Control Booth, provides all the controls and indicators needed to operate the station. These include system status and warning lamps, control handles for the sliding block and the three winches, and selector switches to establish mode of operation – such as rigging versus transferring cargo.

The lower bay of the MCC amounts to an additional I/O enclosure because it contains I/O modules to interface control booth controls and indicators with ControlNet.

The Master Power Panel (MPP), also located in the Master Control Booth, is modeled on the STREAM Power Panel of the Navy's legacy equipment. The legacy panel has ON/OFF push buttons to power up single speed AC induction motors. Corresponding ON and OFF push buttons exist on the E-STREAM MPP. However what they actually do is enable and disable variable frequency drives, which remain powered up in any case. That is, when the ON lamp for a given motor is lit, the corresponding drive is enabled and hence capable of responding to commands from software, even though the motor isn't necessarily under power. When that lamp is OFF, the drive is powered up but disabled, making it physically unable to deliver energy to the motor, regardless of software commands. Discrete 24 VDC circuitry, based on safety-rated relays and monitored by system software, ensures that this enable/disable function is extremely reliable.

The MPP also has a touch screen display, which is used to provide status information, including the nature of any warnings issued by control system software. It also provides engineering access, such as to calibrate encoders and to test overload slip clutches. Finally it provides backup input in case a simple input device, such as a selector switch, fails.

Like the Main PLC, the touch screen display is a programmable object. Software in the Main PLC and in the touch screen display starts up as soon as the PLC Enclosure and touch screen display have power. Once they establish communication, the display presents a status screen that indicates that the station is ready for operation.

Purchased as a commercial component, the touch screen display is not EMC qualified. A transparent conductive mesh and other shielding components are added to the commercial unit, so as to satisfy the Navy's EMC requirements.

A local control panel is mounted on deck near each winch. It has a control handle to operate the winch drum and pushbuttons to provide for manual RUN/STOP operation of the anti-slack device. It also has winch motor ON/OFF pushbuttons which duplicate the functions of identical buttons on the MPP. In the interest of safety, the control system will only allow a given winch to have one active control handle at a time. To transfer control to the local handle, the operator sets a switch on the MCC to LOCAL. Lamps on the MCC and the local control panel start blinking. The operator then presses the TAKE CONTROL push button at the local panel. The lamps stop blinking and indicate that the local handle is active. A similar procedure using the RELEASE CONTROL push button returns control to the MCC.

System architecture - power flow

Figure 6 shows the power delivery structure of the E-RAS control system. Power is drawn by the system from ship mains in two forms: three-phase 60 Hz 480 VAC main power and single-phase 60 Hz 120 VAC heating and lighting power. Main power is distributed to the drive enclosures via delta-delta wound isolation transformers, one for each drive enclosure. Heating and lighting power is distributed to individual control system enclosures. Because this power energizes anti-condensation heaters in the electronics and deck machinery, it is intended to be active 24/7. In contrast, 480 VAC main power may be switched off when the station is not in use.

The load center also provides a second source of single-phase 60 Hz 120 VAC power, called control system power, which it generates from main power via a step-down transformer. Control system power is filtered to reduce electrical noise, which could interfere with the functioning of digital electronics. It is delivered to the PLC Enclosure, which then further distributes it to 24 VDC power supplies in the other low-power electronics enclosures.

Drive enclosures contain the variable frequency drives (VFDs) that energize and control the motors. There is one drive enclosure for each major subsystem: highline winch, inhaul winch, outhaul winch, and sliding block. Each enclosure has a large (235 HP or 600 HP) liquid-cooled drive for the winch or sliding block motor. These are referred to as the main drive and main motor, respectively. In the case of the winches, there is also a 15 HP air cooled drive for the ASD motor. Additional circuits provide DC power to energize the service brake in each subsystem.

All drives (main and ASD) are equipped with special DriveLogix drive control cassettes that provide PLC functionality, making them essentially drive-mounted PLCs. These are called drive PLCs to distinguish them from the Main PLC. The drive PLC incorporated in the main drive is called the main drive PLC. I/O modules in each drive enclosure are wired to the main drive PLC, which then provides interface to ControlNet as required.

The presence of drive PLCs makes the drive enclosures semi-autonomous. That is, while high-level motion commands come from the Main PLC, they are implemented via detailed instructions to motor and brake – such as for torque proving – orchestrated by software running in the drive PLCs.

This architecture enables a key feature of the E-STREAM control system, called Emergency Run. The Navy was concerned that a casualty to the Main PLC or a ControlNet network could completely disable an E-STREAM station. Emergency Run mode mitigates this possibility by allowing the motors and drives to achieve minimal functionality in the case of Main PLC or ControlNet failure, so at least the rig can be recovered.

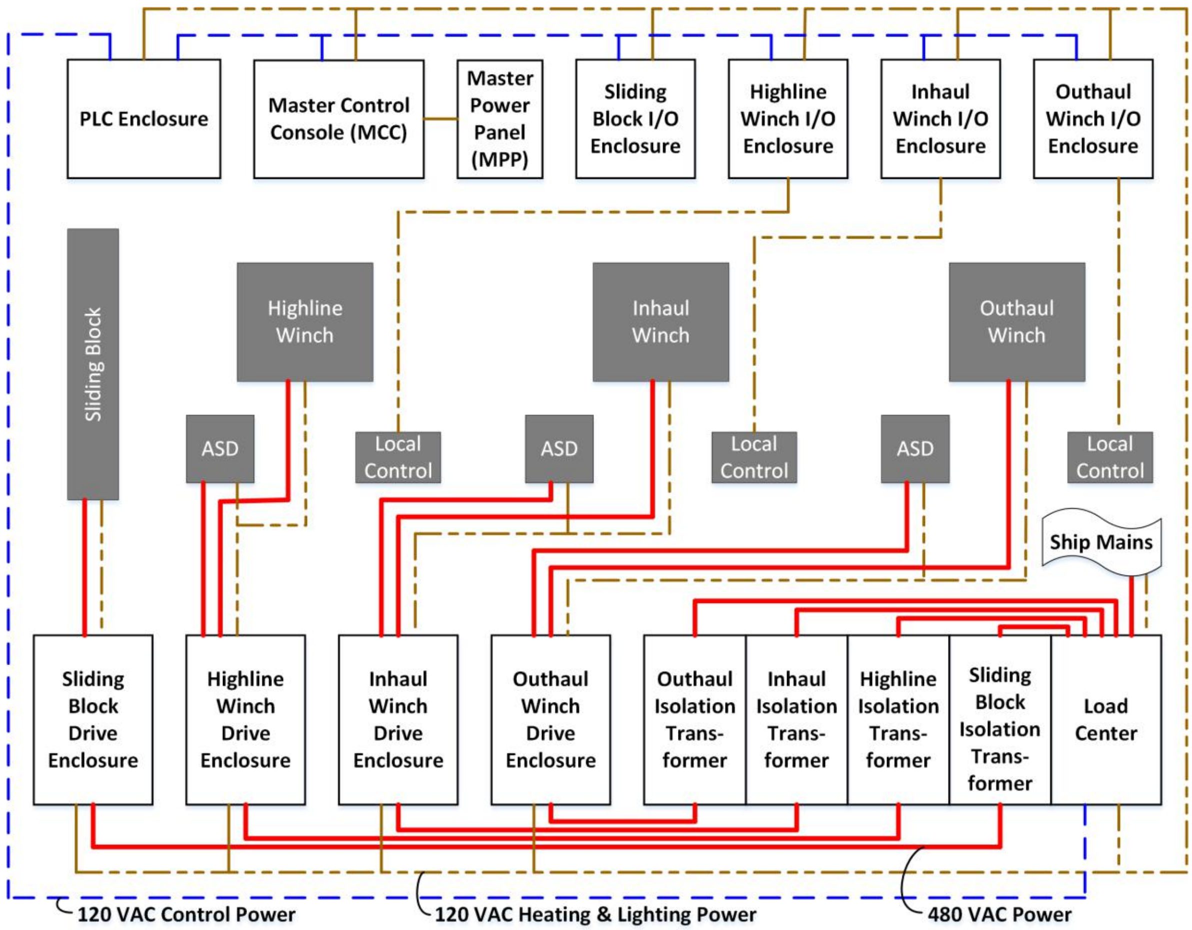


Figure 6. Power Delivery Structure of the E-RAS Control System

Inside each drive enclosure is a switch that can be set to Emergency Run. This cannot be done casually, because the enclosure must be powered down and multiple bolts loosened in order to open the drive door. Once it is set to Emergency Run and returned to service, the drive enclosure ignores ControlNet communications. In fact, only the drive enclosure at hand need be powered up. The rest of the control system may be powered down.

During Emergency Run operation the drive enclosure responds to jog switches located in the local control handle mechanism of the winch it controls (or in the case of the sliding block, the master control handle). One jog switch closes when the control handle is full forward, the other when it is full back. These switch closings are interpreted as commands to jog slowly, forward or reverse. In the case of the sliding block, additional inputs are used by the drive during Emergency Run operation: Limit switches at the ends of travel allow the drive to prevent end crashes. During Emergency Run operation, anti-slack devices are controlled manually, using local control panel RUN/STOP push buttons.

Common features - low power enclosures

Low power enclosures above deck consist of the Master Power Panel (MPP), Master Control Console (MCC), and local control panels. Below deck there are the PLC Enclosure and I/O enclosures. These enclosures share several common design features, although not every enclosure has every feature:

- Dual mutually redundant 24 VDC power supplies
- Redundant ControlNet communications
- Unified control handle design
- Totally enclosed 316 stainless steel construction, powder coated gray
- Hinged doors with weather and EMI gaskets
- 120 VAC anti-condensation heaters
- 120 VAC low temperature heaters

Figure 7 shows the highline winch I/O enclosure, which exhibits all of these features, except the control handle.

Power supplies are widely known to be potential source of failure. So dual redundant 24 VDC power supplies are a critical element of the control system's fail-operable design. In normal operation, two identical supplies share the load. However each is rated to supply full system load. If one fails, the other takes over and notifies system software to provide a warning.

ControlNet is another key fail-operable element of the E-STREAM system design. And, of course, in the PLC Enclosure the ControlNet networks are managed by mutually redundant PLCs.

A single control handle design is used throughout the E-STREAM control system, shown in Figure 8. It is bidirectional and spring centered, with at least two IP-65 rated absolute position encoders to track handle position. Control handle input is interpreted as a velocity command, increasing in magnitude continuously as the handle is moved away from center.

Multiple encoders provide for output certainty and for fail operability. There must be two encoders that agree with each other for system software to treat the control handle as working correctly. If the control handle would otherwise be a single point of failure, a third encoder is provided. If one encoder fails, the other two can keep the system running, while the system raises a warning. The control handle mechanism, made almost entirely of stainless steel, is built to last under demanding conditions. Based on testing for tens of millions of cycles, it has a calculated MTBF of over 7 lifetimes.

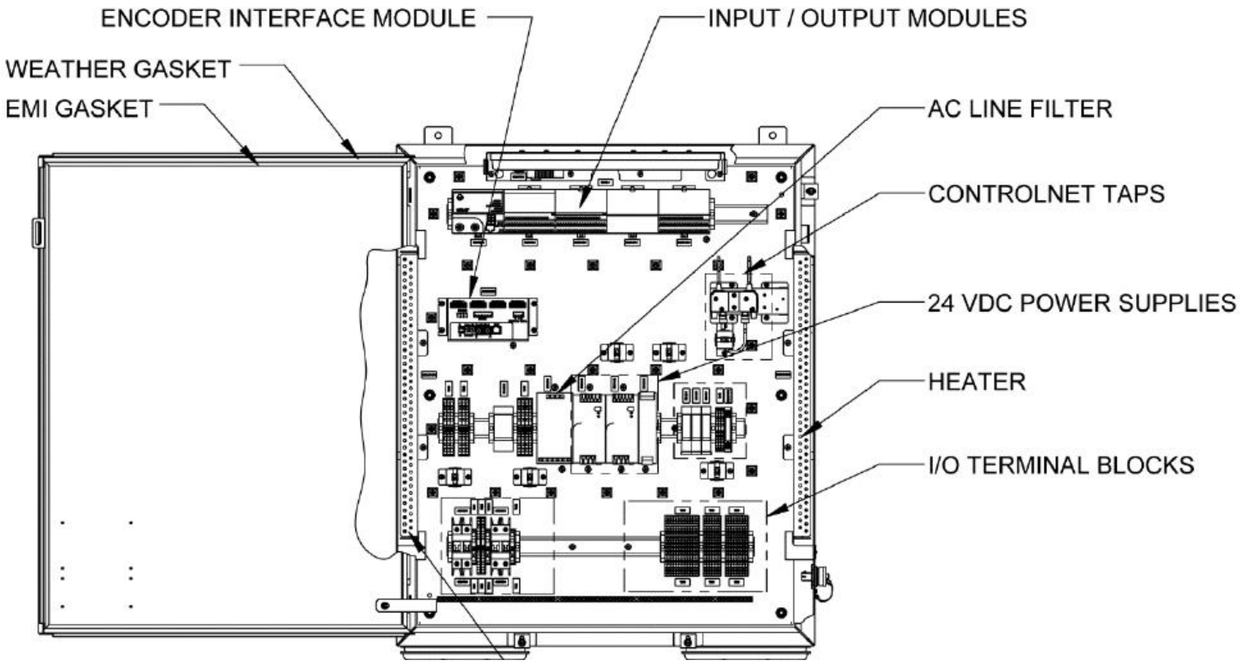


Figure 7. Highline Winch I/O Enclosure

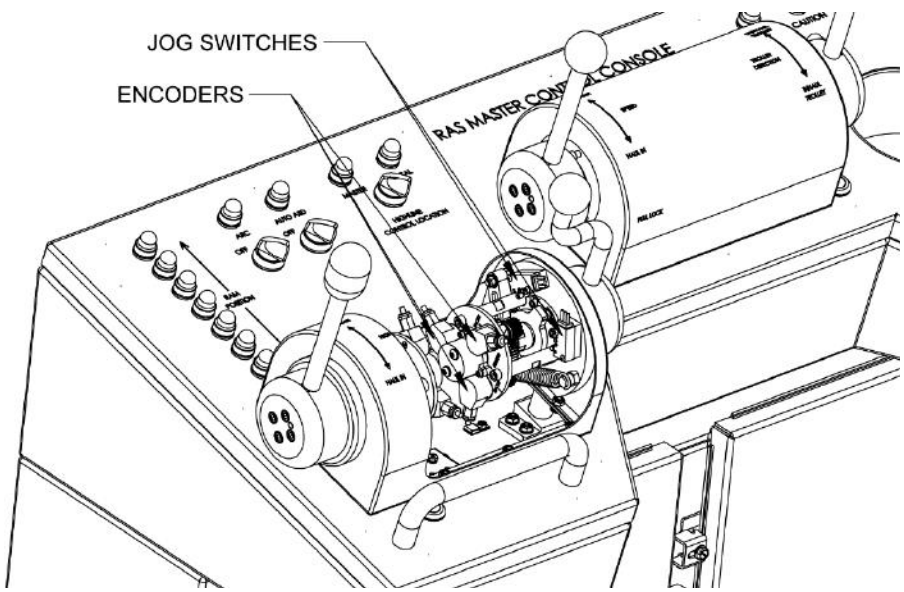


Figure 8. Control Handle Mechanism

Encoders used in control handles and in deck machinery, such as sliding block position encoders and hauling rope payout encoders, communicate with encoder interface modules in corresponding I/O enclosures, which interface these signals with ControlNet. The link from encoder to interface module uses Synchronous Serial Interface (SSI) communications, also known as the Stegmann interface. This is a robust message-based point-to-point communication protocol that transmits encoder data with high reliability. Each message contains absolute position information and is checked for error. So if a message is corrupted, this is detected. The prior information is held valid until the next good message is received, catching up with correct information. If too much information is corrupted, the control system can take appropriate action.

While the below-deck enclosures are likely to be placed in conditioned spaces, all low power enclosures are designed for service in unconditioned spaces.

Anti-condensation heaters operate 24/7 to protect the electronic components and circuits from condensation damage. Each heater has a built-in thermostat set in the factory, which operates autonomously, not connected to the control system. The set point is high (95 °F) so as to turn the heater off only when continued heat input could harm the electronics. There are also cold weather heaters sized to keep the interior temperature from falling below the operating range of the electronics. Their built-in thermostats are set at a low value (10 °F).

Common features - high power enclosures

Figure 9 illustrates the E-RAS load center and isolation transformer enclosures. These enclosures are designed to be installed in climate controlled spaces below deck, joined to each other in a line-up as shown or installed individually if necessary to comport with ship design. They are vented and the transformers are fan ventilated, so as to transfer their cooling load to ship air conditioning.

The load center has manual disconnects for 480 VAC and 120 VAC power coming from ship mains. Protective circuits in the load center protect ship circuits from isolation transformer inrush currents. Also, there are ground fault check features (push button and lamp) for 480 VAC main power, for 120 VAC heating and lighting power, and for 120 VAC control power.

Transformer windings have thermostats to detect overheating. Each isolation transformer also has a ground fault check feature for the 480 VAC power delivered to the drive.

Figures 10 and 11 show the E-RAS highline winch and inhaul winch drive enclosures, which are typical of drive enclosures with 235 HP and 600 HP main drives, respectively. These drives have considerably more power capability than the motors they control – 130 HP and 240 HP respectively. This is in order to provide the high currents that are required intermittently in worst-case operating and test scenarios. In particular, the hauling winch motors are permanent magnet brushless (PMBL) motors, also known as brushless DC motors. In normal operation they can be called upon to exert full load torque – and hence current – while completely stalled. This places an unusually severe demand for continuous current in a single phase of the three phase power leads.

Common features of all drive enclosures include:

- Manual disconnects for 480 VAC main power and 120 VAC heating and lighting power
- Input line filtering for the 480 VAC and 120 VAC heating and lighting power
- Step-down transformer to provide 120 VAC drive enclosure control power (distinct from the 120 VAC control system power generated in the load center and distributed to low power enclosures.)
- Dual mutually redundant 24 VDC power supplies
- Rockwell PowerFlex 700L liquid cooled main drive with active front end (AFE)
- Rockwell PowerFlex 700S air cooled ASD drive
- Motor shaft velocity feedback from redundant incremental encoders or from a resolver (hauling winch motors)
- Circuits to energize the service brake with DC (rectified AC) power
- I/O modules wired to the main drive PLC
- Enable/disable circuitry based on safety-rated relays and safe off technology
- Redundant ControlNet communications
- Totally enclosed 316 stainless steel construction, powder coated gray
- Hinged doors with weather and EMI gaskets
- Liquid cooled heat exchanger
- Cabinet heater
- Leak detector

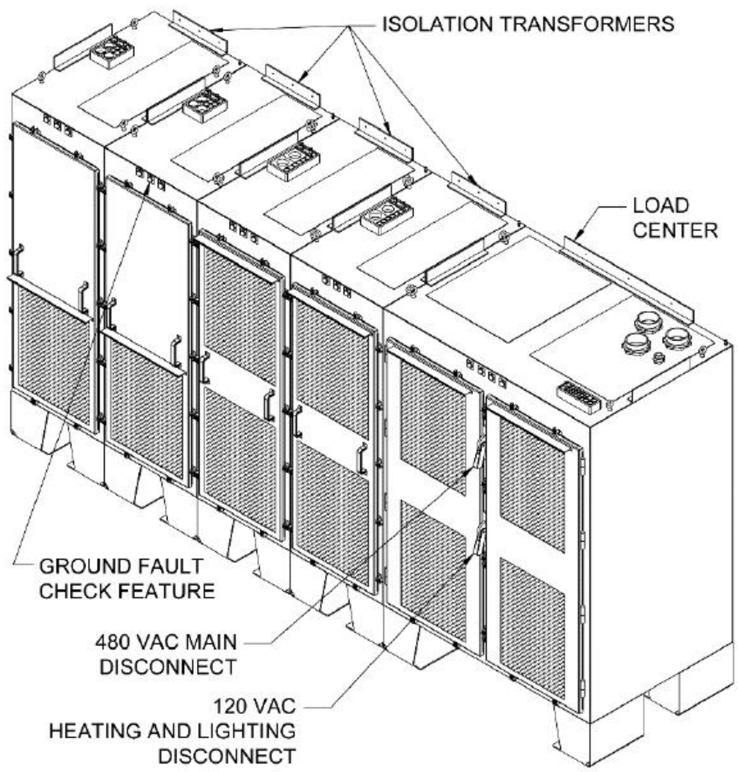


Figure 9. E-RAS Load Center and Isolation Transformers

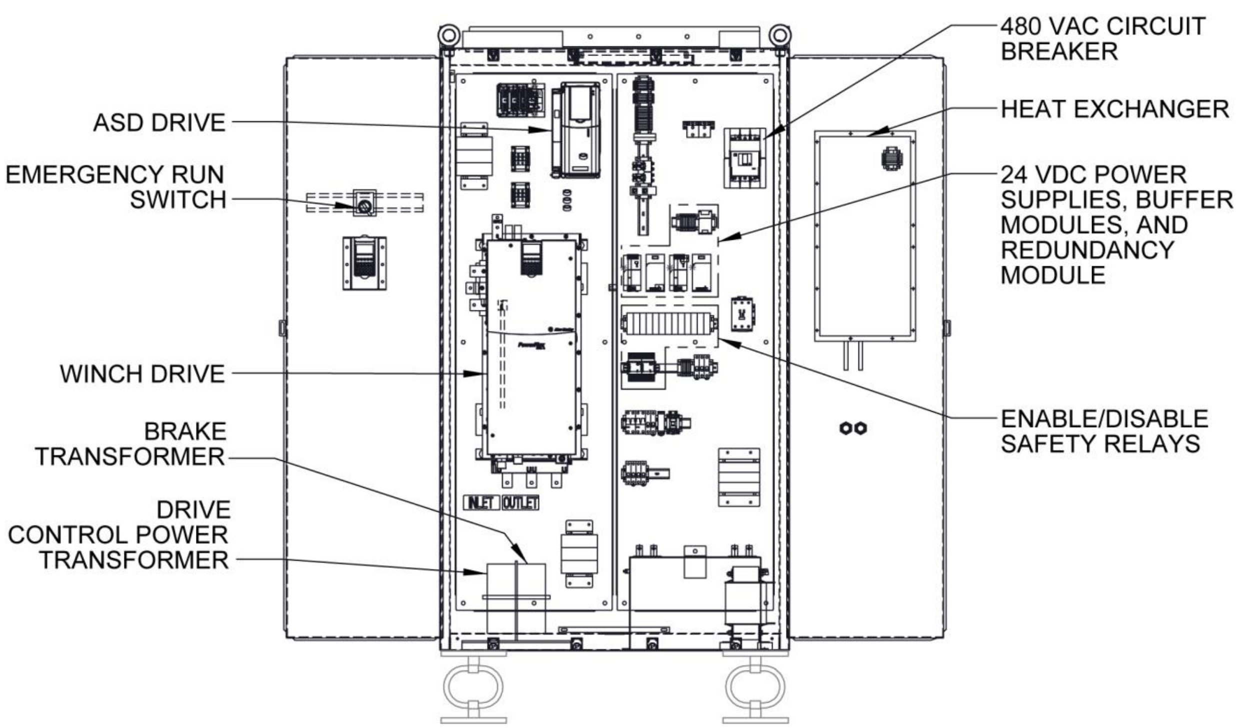
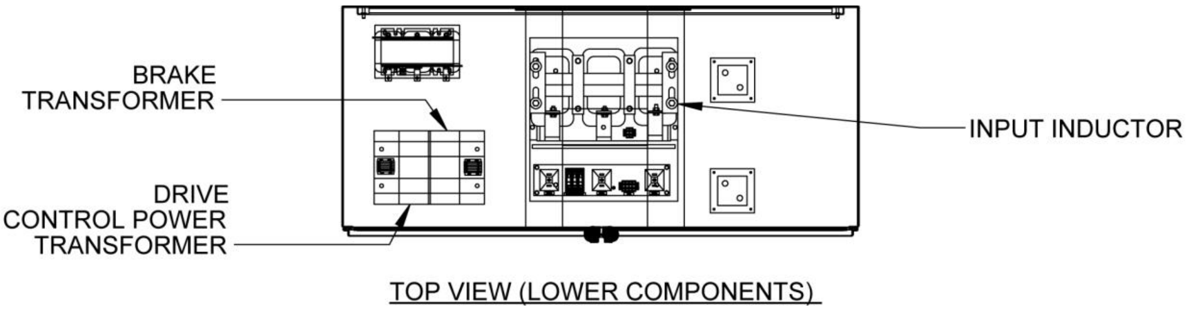


Figure 10. E-RAS Highline Winch Drive Enclosure



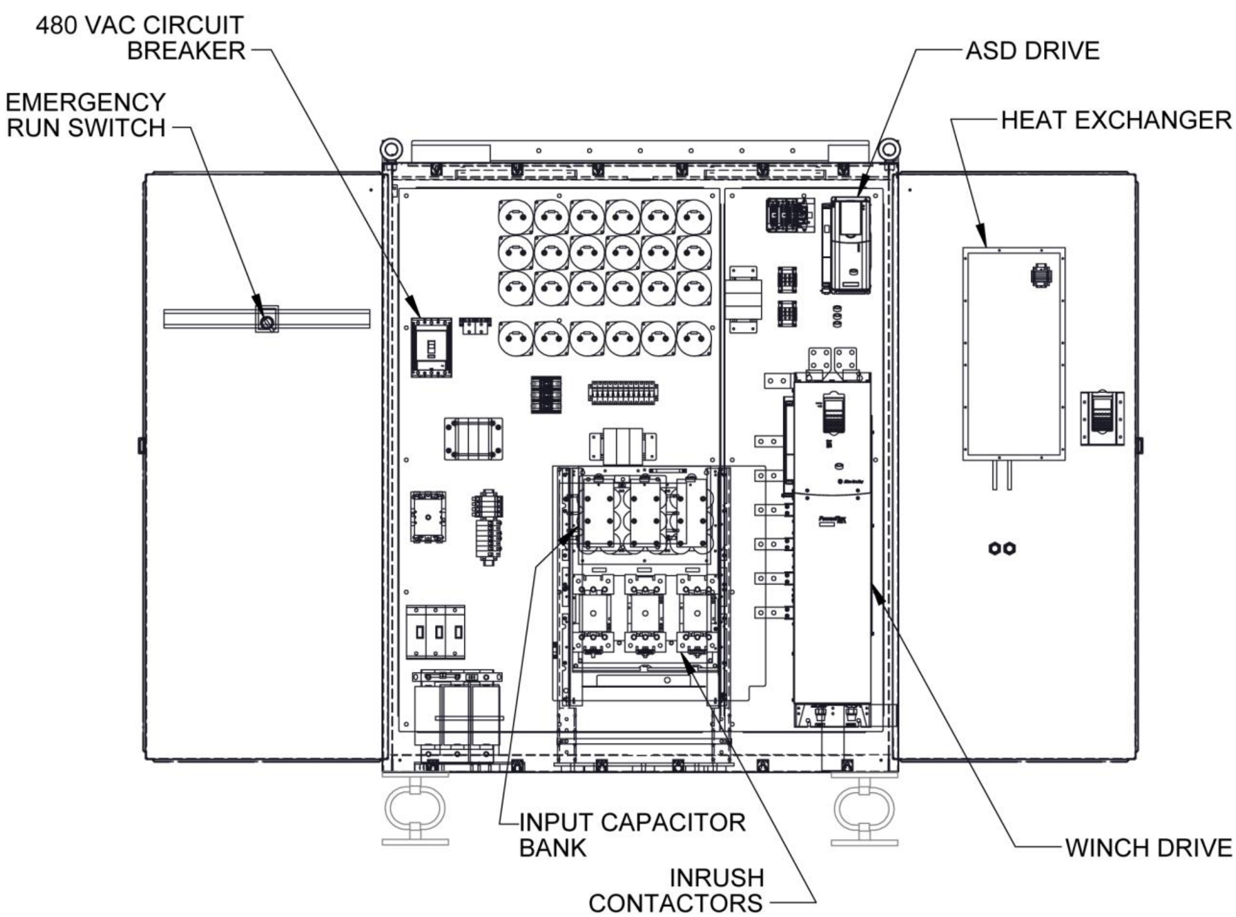


Figure 11. E-RAS Inhaul Winch Drive Enclosure

Drive enclosures contain extensive line filtering circuits to suppress the high level of electromagnetic noise intrinsic to VFDs. Incoming 480 VAC main power is filtered by a line reactor, a capacitor bank, and an RFI line filter. There are also protective resistor circuits to prevent excessive inrush currents. Incoming 120 VAC heating and lighting power also passes through an RFI line filter.

As a result of this filtering, along with other design measures, all E-STREAM drive enclosures, as well as all other control system enclosures, meet emission and susceptibility requirements defined by MIL-STD-461.

The dual mutually redundant 24 VDC power supplies are the same as those in the low power enclosures. They normally share the load, but if one fails the other takes over for both and a warning is raised.

The liquid cooled main drive is equipped with an active front end (AFE), which converts input main power from AC to DC, energizing a 650 VDC capacitor bank called the DC bus. The drive energizes the motor by inverting bus energy back to three phase AC, at controlled voltage and frequency. This energy conversion is bidirectional. So when the motor is absorbing energy (braking) the absorbed energy is delivered to the DC bus, and ultimately regenerated back into the AC mains. There are no braking resistors.

The ASD drive is also powered bidirectionally by the main drive DC bus. It does not have its own AFE, nor braking resistors. The ASD drive is controlled by the main drive PLC. That is, rather than receiving commands from the Main PLC, the ASD drive receives velocity commands from the main drive PLC, in the form of an analog voltage signal.

The sliding block subsystem does not have an ASD. So sliding block drive enclosures, which are otherwise identical to winch drive enclosures, do not have the ASD drive and related circuitry.

All AC induction motors are equipped with incremental magnetic encoders having a single magnetic disk and dual read heads. The read heads contain alarm circuits that detect impending failure, information that is passed on to the Main PLC. In addition the drives have encoder failure detection circuitry. If failure of the primary encoder is detected, the alternate encoder is selected and a warning is raised.

Each hauling winch motor is equipped with a single-turn resolver, which is a rotary transformer that intrinsically senses absolute shaft angle. This angle is needed in order to commutate the permanent magnet motor. PowerFlex drives do not support redundant resolvers, so this feedback channel is a single point of failure. The reliability of resolver feedback was deemed adequate to not require a redundant alternative feedback solution.

The winch brake is powered by a dual output step down transformer that converts 480 VAC main power to 115 VAC and 44 VAC outputs, which are in turn rectified to 96 VDC and 36 VDC respectively. The 96 VDC power is applied to release the brake. Voltage is reduced two seconds later to 36 VDC to hold the brake in the released condition.

The main drive PLC receives external and internal discrete signals via I/O modules. External signals include motor enable/disable and ASD RUN/STOP push button input, brake set/released status, motor thermostat status, sliding block limit switch status, etc. Internal signals report the status of various components inside the drive enclosure, such as the redundant power supplies, brake control contactors, the leak detector, and so on.

A key feature of the E-STREAM control system is the reliability of enable/disable circuits. Of particular concern is that OFF means OFF. If an unexpected circumstance calls for a motor to be brought to a sudden stop, this must occur without fail once an OFF push button is pressed. The logic described conceptually in Figure 12 accomplishes this task.

The ON and OFF push buttons for a given motor – in the Master Control Booth and at local control panels – are treated as equals. That is, at any time a push button at either location can be used to enable or disable the corresponding drive. When a push button is pressed, the signal goes to a safety rated relay, which sends it off in two directions. First, it goes to another safety-rated relay with immediate output to a digital input of the drive and a delayed output to a drive safe off enable input. (Safe off is a feature of the drive that makes sure it cannot deliver energy in the absence of a valid enable signal.)

Second, it is sent via an I/O module to the main drive PLC, which relays it to the Main PLC. In the case of an ON push button, the drive becomes enabled once the delayed signal from the safety relay, and a confirming enable from the Main PLC, are received by the (safe off) drive enable input. In the case of an OFF push button, the drive responds to the digital input by bringing the motor to a controlled emergency stop and setting the brake. After a short time interval, the delayed OFF signal arrives at the drive enable input, disabling it entirely regardless of software command and ensuring that the brake is indeed set. So OFF means that the drive will soon be disabled and the brake set. But first there will be a controlled stop.

If the drive enclosure is set to Emergency Run, the enable/disable circuitry is bypassed, keeping the drives enabled as long as power is supplied to the drive enclosure. This design feature ensures that if the enable/disable circuitry itself suffers a casualty, the equipment can be still be operated to recover the rig.

ControlNet communication allows both the main drive and the ASD drive to communicate directly with the Main PLC. In the case of the ASD drive, this communication is limited to status information, because the main drive PLC is generally in charge of ASD operation.

Like the low power enclosures, drive enclosures are made of 316 stainless steel, sealed, and have hinged doors with weather and EMI gaskets. Chilled coolant supplied by the ship cools the liquid cooled drive directly, and circulates in an air-to-liquid heat exchanger that removes heat developed in other components. A cabinet heater provides 24/7 anti-condensation heating, controlled by a combined temperature and humidity sensor.

The leak detector has a rope-like sensor that lies along the bottom of the enclosure. If moisture is detected, a pair of relay contacts closes, signaling the control system. An additional set of contacts allows for connection to external circuits provided by the ship, so that moisture can be detected even if the control system is powered down. To that end, the water leak detector is powered by 120 VAC heating and lighting power, which is intended to be energized 24/7.

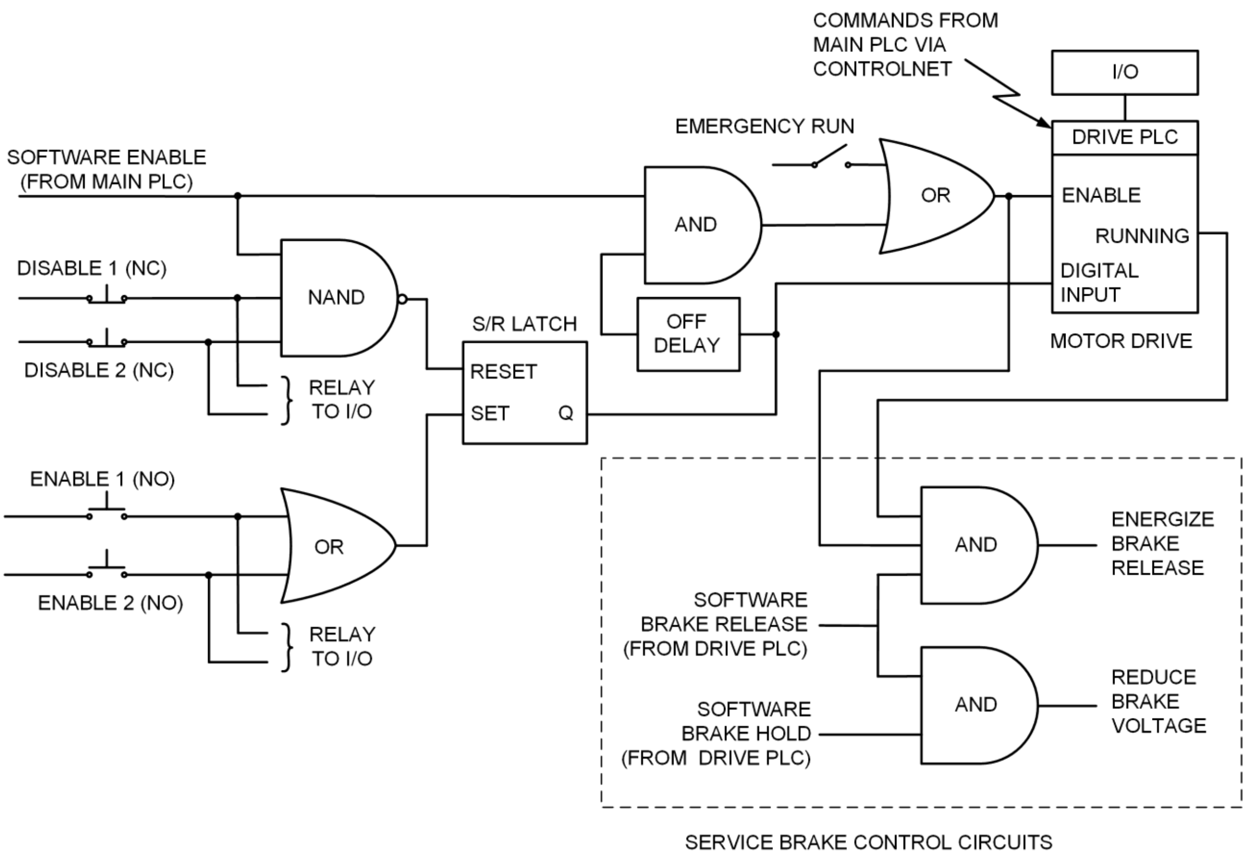


Figure 12. Enable/Disable Logic

Common features - software

The E-STREAM control system is built around a suite of complementary hardware and software products from Rockwell Automation, known as Integrated Architecture. Together these products provide a common development environment to integrate PLCs, drives, the touch screen display, network communications, and field devices. The ControlLogix PLCs that control the overall system as well as each of the drives share the same code base, providing the ability to maintain a consistent code base and to leverage proven solutions into new applications.

E-STREAM control system software takes full advantage of add-on instructions, a feature of the ControlLogix platform. An add-on instruction encapsulates code and data to create a custom PLC function, making it a standalone component that can execute in any application that calls it.

Commonly used algorithms, having been fully developed and tested, are encapsulated in this way and reused across the E-STREAM systems, promoting consistency and reliability. Notable examples of add-on instructions in the E-STREAM systems include:

- State machine initialization and sequencing
- PLC-level fault handling
- A custom ControlNet message handling protocol to provide detailed, plain English operator feedback via the touchscreen display
- Configuration of multi-channel encoder interface modules at power up
- Calculation of S-Curve trolley velocity profiles
- Winch slip clutch testing. The clutch test entails complex interactions between operator inputs and indicators, motion control, and monitoring of drive feedback. Using an add-on instruction to implement this test provides a universal test procedure for all the different pieces of deck equipment.
- Debouncing of push buttons and other discrete inputs
- Arbitration and failure handling of redundant inputs, such as from redundant encoders, multi-position selector switches, and dual-contact push buttons. Arbitration consists of determining which of multiple inputs are valid.
- Audible annunciation with standardized tone sequences to provide intuitive operator feedback

In addition to sharing common functionality using add-on instructions, software applications running on each PLC have been developed with consistency as a prime objective. To that end, all winch and sliding block drive PLCs share the same software. Similarly, so do all the ASDs. Upon power up, the software detects the ControlNet address of the drive PLC it is installed in and a unique software key (set of three dedicated digital inputs). It then "knows" what drive it has under control, say the sliding block drive, or the outhaul winch drive. The ASD drive software follows a similar approach.

Within each PLC, the application is divided into separable programs and routines. Each program has its own private memory space, allowing two virtually identical programs to co-exist without incident. For example, the inhaul and outhaul winch programs that run in the Main PLC are nearly identical. Commonality between the two simplifies code maintenance and ensures consistency.

Extension to other stations

As previously discussed, the E-HRAS station is nearly identical to its E-RAS counterpart. It is different only in the sizing of certain motors and drives and the ability to set rope tensions to Navy Standard or Heavy values.

The E-STREAM Fueling At Sea (E-FAS) station that has been built and installed at the Port Hueneme site has significant differences with the E-RAS and E-HRAS stations. However the E-FAS control system design leans heavily on the template laid down by E-RAS.

The E-FAS station (see Figures 13 and 14) has a spanwire winch, three saddle winches, and an ASD for the spanwire winch.

The spanwire winch and ASD are essentially identical to their E-RAS highline counterparts and perform the same function: providing a tensioned wire rope between ships. So all design elements associated with the E-FAS spanwire winch and ASD, namely the operator controls and displays, I/O enclosure, and drive enclosure, are also essentially identical to their E-RAS highline equivalents.

The E-FAS saddle winches are used to position the saddles that support fuel hoses suspended from the spanwire. They are unlike other E-STREAM winches in that they are less powerful (40 HP), do not have ASDs, and do not have local control panels. They are controlled exclusively by control handles at the Master Control Console.

This unique configuration of the saddle winches results in a unique I/O and drive architecture. As shown in Figure 15, the saddle winch drive enclosure has a single liquid cooled 300 HP active front end (AFE) drive, which does not power any motor directly. Instead, it energizes a DC bus and provides regenerative braking. Three air cooled 75 HP drives draw power from this DC bus bidirectionally to energize and control the saddle winch motors. Each saddle winch drive is equipped with a drive PLC, which is controlled directly by the Main PLC. No single drive PLC performs the role of “main drive PLC.”

There are independent I/O modules for each saddle winch, wired to corresponding drive PLCs. The saddle winches do not have I/O enclosures.

In Emergency Run mode, the three saddle winch drives also operate independently, responding to jog switch input from the control handles.

Aside from the features just described, the saddle winch drive enclosure has the same features as the other drive enclosures: manual disconnects, input line filtering, step down transformers, dual mutually redundant 24 VDC power supplies, rectified AC power circuits for the three service brakes, I/O modules, enable/disable circuits, ControlNet communication, totally enclosed 316 stainless steel construction with hinged doors and weather and EMI gaskets, a liquid cooled heat exchanger, anti-condensation heaters, and a leak detector.

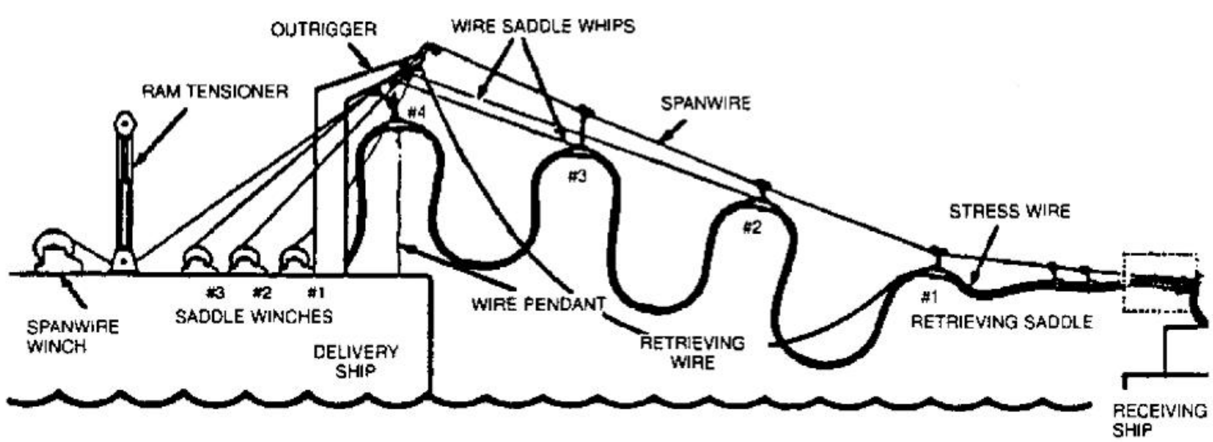


Figure 13. E-STREAM Fueling at Sea

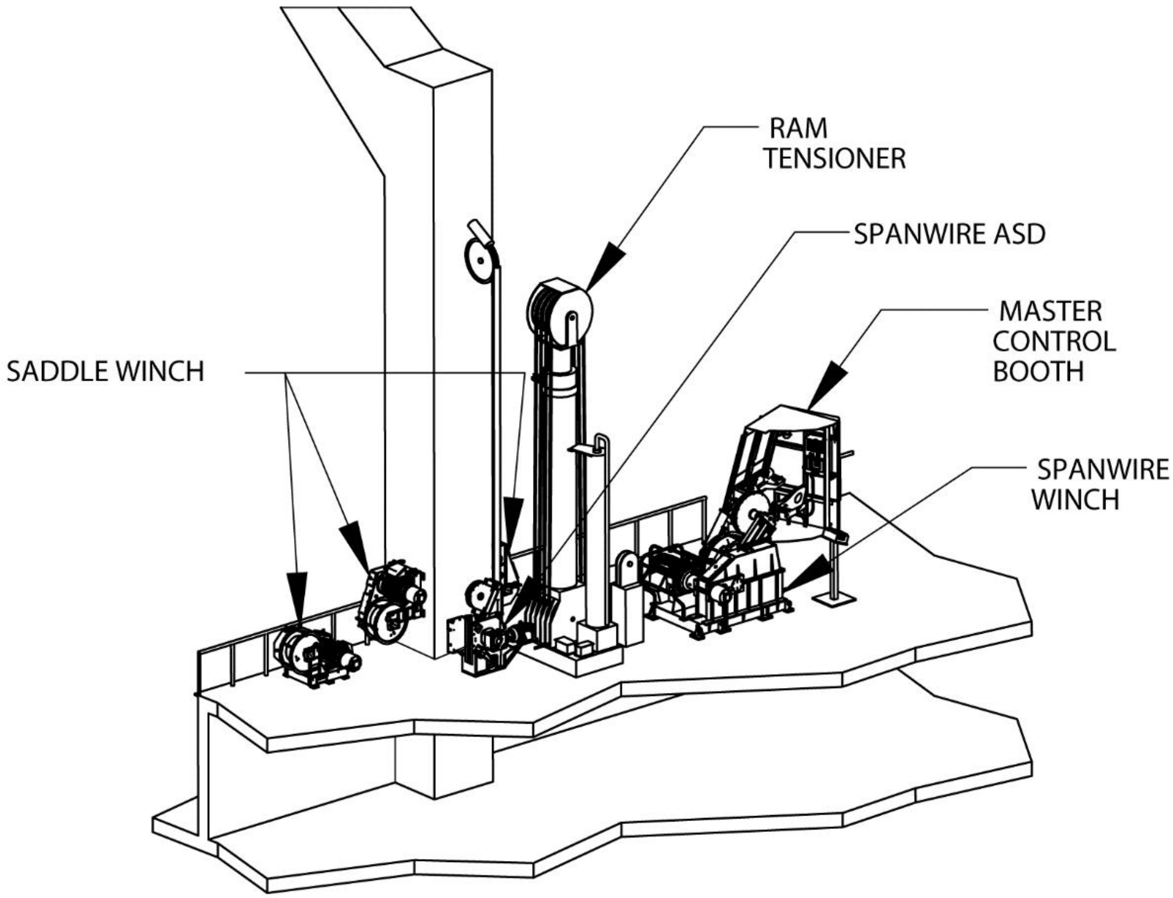


Figure 14. E-STREAM Fueling at Sea Station

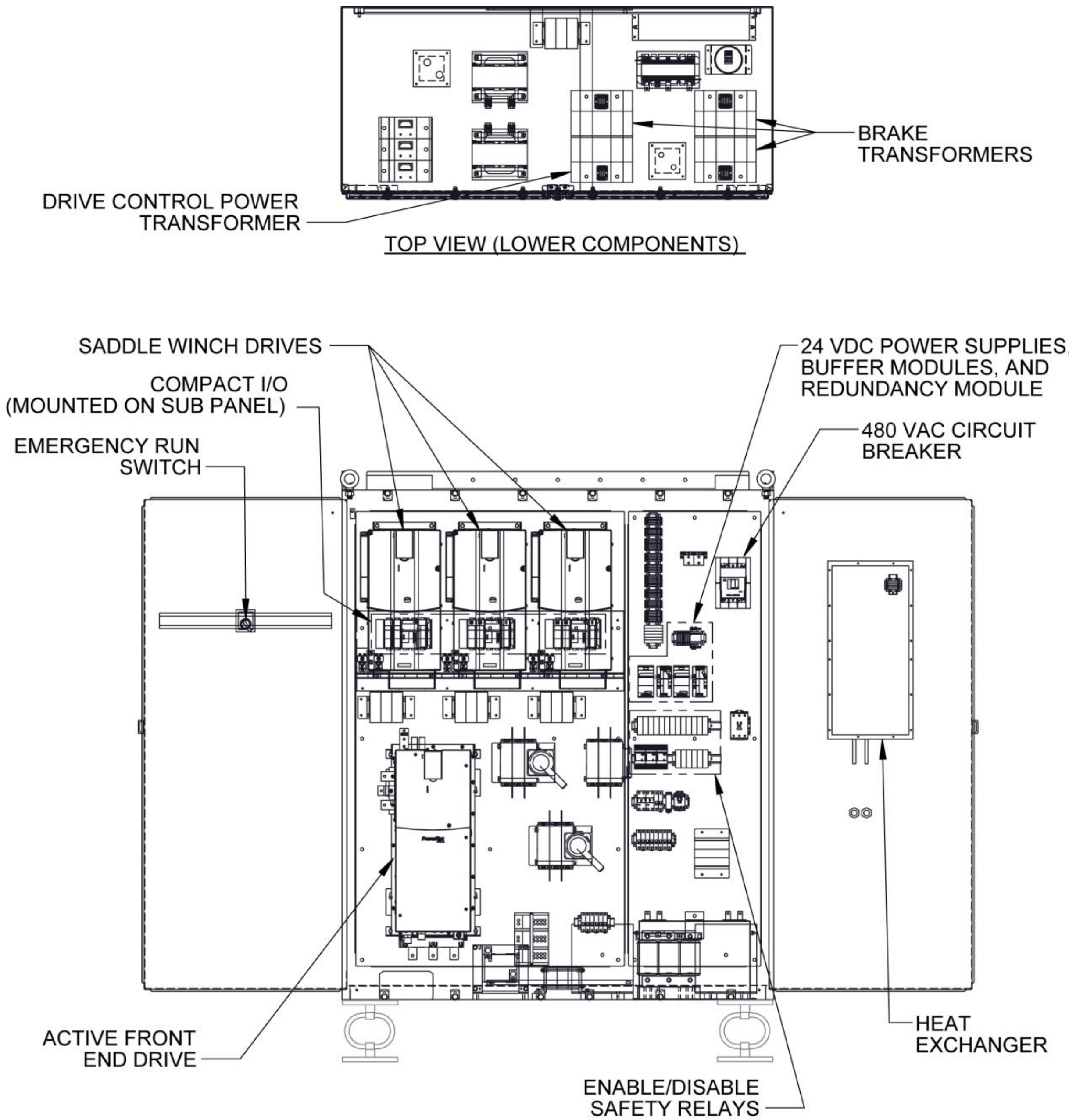


Figure 15. E-FAS Saddle Winch Drive Enclosure

Supplier commonality as a technical and logistic strategy

When the Navy adopted the design path that became E-STREAM, selecting an industry partner for the high power enclosures was a key decision. Ideally, these enclosures would be purchased off the shelf, or integrated by D&K in a straightforward fashion from commercial off the shelf components. But, given the Navy's particular requirements, such as for military environmental qualification, this was not a reasonable expectation. A partner was needed to design and build the power electronics.

The Navy chose Rockwell Automation for several reasons. First, Rockwell's marine group, located in Mayfield Heights, Ohio, is an established supplier of VFD-based installations on Navy ships.

Second, D&K's automatic landing software, which had already been demonstrated to the Navy, was written for Rockwell's ControlLogix PLC, which proved to have the raw computing power and rich programming language needed to perform the complex calculations – such as inverting cubic polynomials – required for soft landing of solid cargo loads. This software could be incorporated in the new system without translation.

More broadly, in PLC-based and VFD-based systems, coding details and the software development environment in which they are written are both tied to the hardware. This is particularly true in the case of high-capability code such as runs on the ControlLogix and DriveLogix PLCs. So it was very convenient for all the programmable hardware to come from a common supplier with a common software development environment. The link between hardware and software, and the common supplier for all programmable components, are major contributors to the integrated character of the E-STREAM control system and to the ultimate success of the program.

Besides a common software environment, additional desirable features available from Rockwell included the DriveLogix drive PLCs, redundant ControlNet networks, redundant PLCs, and redundant power supplies. It was clear that the entire control system, including low and high power enclosures, could be populated largely with Rockwell Automation and Allen-Bradley branded components, each used multiple times to reduce the number of different items requiring logistic support. Furthermore, many of these components are available in versions designed for extreme environments, adding design margin versus actual shipboard environments. Finally, Rockwell offered the world-wide support and support continuity over the long haul that only a large multi-billion-dollar-sales supplier can provide.

Conclusions

The E-STREAM control system is **modular** in that it exploits a limited number of different enclosure types, mixed and matched as needed for the different requirements of different replenishment stations. It is **integrated** in that the enclosures, and the software that animates them, embody a common set of linked hardware and software solutions that are applied over and over as needed. The modular and integrated nature of this system make it **extensible**, applying to both solid- and liquid-cargo underway replenishment stations, plus potentially to other applications not yet identified.

References

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Acknowledgements

The E-STREAM control system is the culmination of over a decade of work by talented engineers at D&K Engineering, Rockwell Automation, and the Naval Surface Warfare Center, Port Hueneme Division, too numerous to mention. They know who they are. We do wish to take particular note of the authors of References 1 and 2, who are the immediate past and current UNREP Engineering Branch Managers at Port Hueneme, respectively. They provided this effort with the steady guidance and support over the years that were crucial to its success.

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