FOSS MARITIME COMPANY

CAMPBELL FOSS

HYBRID RETROFIT
FINAL REPORT

Rick McKenna

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EXECUTIVE SUMMARY

Background

In June 2010, the California Air Resources Board awarded the Port of Long Beach a $1,000,000 grant from the Air Quality Improvement Program (AQIP) through Assembly Bill 118 (AB 118) to demonstrate the feasibility to modify an existing harbor tugboat with a hybrid propulsion system that would bring about significant reductions in the criteria pollutant emissions Oxides of Nitrogen (NOx), Particulate Matter (PM) and Carbon Monoxide and Dioxide (CO and CO2), and considerable improvements in fuel economy. Subsequently the Port of Long Beach contracted with Foss Maritime Company to retrofit an existing conventionally-powered ship assist tug to a hybrid propulsion system. The project officially kicked off in November 2010, and was originally scheduled to be completed by June 30, 2012. However, due to unforeseen events during the project's implementation, Foss and the Port of Long Beach requested and received an extension for project completion of one year to May 30, 2013.

Project Summary

The candidate tugboat for this project was the ***Campbell Foss***, a conventional sister tug of the first new build hybrid tugboat, the ***Carolyn Dorothy***, which assists ocean-going vessels in the San Pedro Bay. Foss teamed with Aspin, Kemp and Associates (AKA) to develop the hybrid retrofit design, based on a simplified version of the design that Foss and AKA developed for the ***Carolyn Dorothy*** in 2007. The Foss/AKA team selected batteries from Corvus Energy, a Canadian company developing the latest generation of lithium-polymer batteries for the maritime industry. The ***Campbell Foss*** was retrofitted with motor generators, batteries, and control systems at Foss shipyard in Rainier, Oregon from August to December 2011. Upon completion of the modifications, the ***Campbell Foss*** was vigorously tested, commissioned and re-entered service at Long Beach in late January 2012. Within the first month of operation, the ***Campbell Foss*** suffered a clutch failure which required a redesign and retrofit of the clutch actuation system. The tugboat continued to work in non-hybrid mode until the new clutch actuation system was installed. Final emissions testing was performed in July 2012, and the tugboat continued to work as a hybrid until August 20, 2012, when a fire occurred in the battery compartment. Although no one was injured, the ***Campbell Foss*** was out of service for approximately three months for an extensive forensic investigation and repair. The tugboat has been repaired and is currently operating in San Pedro harbor in hybrid mode, but with the battery system disabled. Foss is planning to reinstall batteries with the required system modifications once they have been fully designed and vetted.

Project Results

Emissions reductions: 31% NOx, 30% CO/CO2, 29% PM

Fuel savings: 25-30% reduction in fuel consumption

Schedule: The project took approximately 3 months longer than planned to complete, due to a combination of delay in starting (due to ship-assist work needs), shipyard resource sharing, and issues with the clutches and their actuation systems.

Cost: Final cost of the project $2,307,437 – project estimate was $2,391,240, so the project came in under budget by approximately $80,000.

Operation: The ***Campbell Foss*** met all operational goals. It had better bollard pull than prior to retrofit, cruise speed on one generator was greater than six knots, and the crew reported the hybrid system works seamlessly and well. Aside from the issues with the clutch actuation and the battery compartment fire, Foss Operations was very pleased with the final product.

1. Design

Design for this project was broken into two portions, “Hybrid Design” and “Tugboat Modification” which are discussed in greater detail below. In general, AKA was responsible for the Hybrid Design, with input from and review by Foss. The Tugboat Modification design was done by Foss based on physical requirements of the hybrid components and ancillary equipment.

Hybrid Design

This task covered the detailed design of the hybrid electrical systems and controls, the fabrication of the electrical control panels and switchboard, and the sizing and purchase of the hybrid electrical equipment. The Foss contract with AKA included the following:

- Finalizing hybrid equipment sizing and requirements.
- Finalizing installation drawings, electrical one-line diagrams, Functional Design Specifications, purchase specifications and other design deliverables to Foss per their quotation.
- Purchase of the following equipment:
    - 500 kW Motor/Generators (M/G’s)
    - Variable Frequency Drives (VFD’s)
    - Active Front End drives (AFE’s)
    - DC/DC converters
- Fabricating, testing and delivery of the hybrid switchboard, controllers and Programmable Logic Controller (PLC) cabinets.

The final hybrid design Functional Design Specification is included with this report as Appendix A and provides a detailed description of the hybrid system operation.

Tugboat Modifications

This task covered the design of the modifications required to the tugboat’s structural, mechanical and electrical systems to accommodate the hybrid propulsion system. It also covered the purchase of the new generator set, shaft drivelines and appurtenances required by the hybrid propulsion system.

Foss, with support from vendors and subcontractors, performed the following modifications:

- Design of the new machinery space layout
- Design of modifications to the structure to accommodate the new and relocated equipment
- Design of the battery support structure, battery compartment and battery ventilation system, including fire suppression system
- Design of a new propulsion shaft drive line to allow for the installation of the M/G’s in the driveline

- Specification, purchase and delivery of the following equipment:
    - 350 kW diesel generator set
    - Main engine clutches
    - Propulsion shaft drive-line components (shafts, universal joints, couplings, etc.)
    - Grid coolers for hybrid electronics and new generator set
    - Electrical cabling for hybrid system connection
    - Hydraulic Power Units (HPU's) for propulsion drive-line clutches
    - Batteries – Lithium Polymer from Corvus Energy

Foss had originally planned to use Absorbed Glass Mat (AGM) lead acid batteries for this project, similar to those used on the ***Carolyn Dorothy***. However, during detailed design, Foss chose to go with new Lithium Polymer batteries designed and packaged by Corvus Energy. These batteries were state-of-the-art units with internal sensing, cooling and alarming functions, had 2 - 4 times the expected life, were smaller for the same amount of power, and could be cycled significantly more than the equivalent AGMs. Unfortunately, as discussed later in this report, the control system for these batteries was the source of a fire in the battery compartment after the ***Campbell Foss*** had been placed back into service as a hybrid.

Design Challenges

As this was the second hybrid tug built by Foss and AKA, the design process went smoothly and without many challenges. The system installed on the ***Campbell Foss*** was significantly less complicated and had fewer components than the first system installed the ***Carolyn Dorothy***, which helped to reduce the design challenges associated with implementing the hybrid system.

Still, there were significant challenges associated with this retrofit, especially since Foss was modifying an existing tugboat rather than building a new, hybrid-specific tugboat, as was done on the ***Carolyn Dorothy***. The biggest challenge with this project was to fit all the required equipment into the already crowded engine room of an existing Dolphin-class tugboat. From a constructability perspective, designing all the hybrid equipment such that it would fit through the planned access opening was a challenge for AKA.

The Foss/AKA team implemented "lessons-learned" from the ***Carolyn Dorothy*** project in the design of this project, such as using water-cooled energy transfer equipment (Active Front Ends, Variable Frequency Drives, etc.) to reduce component size and susceptibility to overheating; reduced scope of battery power; and consolidation/elimination of equipment where practicable. Foss also learned lessons from this ***Campbell Foss*** hybrid retrofit, which will be implemented on future hybrid installations to help refine, simplify and improve the efficiency and ruggedness of the hybrid system. The "lessons-learned" on this project include using an established hydraulic clutch system, simplifying the hybrid equipment cooling system, improving battery control and alarm software, and designing and installing battery compartment ventilation and explosion suppression systems. All of these "lessons-learned" are discussed in more detail in other areas of this report.

2. Construction

Construction on the ***Campbell Foss*** was performed at the Foss shipyard in Rainier, Oregon, the same shipyard that originally built the ***Campbell Foss*** in 2005. Due to ship assist work load in Long Beach, the tugboat departed approximately two weeks later than originally scheduled. Once arriving at the Rainier yard, the start of the retrofit project was again delayed to allow the ***Campbell Foss*** to perform ship assist work on the Columbia River.

Actual work began at the end of July 2011. The delay in starting the project allowed another vessel to occupy the large marine railway for an extended period of time, which ended up causing delays in getting the ***Campbell Foss*** out of the water for the work required to her underwater hull. This in turn caused a delay of approximately one month in completing the modifications.

Removals

The first month of the yard period was devoted mainly to removals required to gain access into the tugboat and make space for the new hybrid equipment. Foss, with support from vendors and subcontractors, performed the following tasks:

- Removed top of port stack and engine exhaust for access to machinery spaces
- Removed deck plates and deck plate supports as needed
- Cleaned and gas-freed machinery spaces and oil tanks
- Removed port generator set
- Removed miscellaneous equipment (water pressure set, water heater, air tanks, bilge and fire pumps, etc.)
- Disassembled ship's service main switchboard; retained for reuse
- Removed and retained auxiliary switchboard

Installations

The next three months of the yard period were devoted mainly to installing the new hybrid components and systems, and to restoring the existing systems and equipment to fit the new configuration. Foss, with support from vendors and subcontractors, performed the following tasks required for installations:

- Made structural modifications, including:
    - Modified foundations to support new M/G installation
    - Fabricated and installed structure for new 350 kW genset
    - Created structural foundation for new hybrid switchboard
    - Fabricated battery compartment and support rack, and their structural foundations
    - Hull penetrations for new grid coolers
- Installed new equipment, including:
    - Hybrid switchboard (from AKA)

    - M/G's
    - Batteries
    - Shaft lines (clutches, shafts, couplings, etc.)
    - 350 kW generator set and its exhaust system
    - Clutch Hydraulic Power Units (HPUs)
    - Grid coolers on outside of hull
- Ran new and modified existing electrical and communications cabling to connect hybrid components and integrate into existing electrical system
- Made all electrical connections, including battery jumpers
- Reinstalled previously removed equipment (such as potable water tank, bilge pumps and air compressors)into their new locations
- Re-ran piping disturbed by modifications; installed piping to new equipment as needed
- Reinstalled stack and engine exhaust
- Cleaned and painted all interior and exterior areas disturbed by retrofit work
- Performed initial equipment operational testing
- Performed initial electrical connectivity testing

Construction Challenges

In addition to the schedule challenges noted above, there were also typical construction challenges associated with a shipyard project of this scope, such as coordinating work, rigging large objects through small openings and tight quarters, and installing intricate piping and electrical systems in a small engine room. Over and above these typical issues, Foss encountered several challenges that required considerable work to overcome:

- **Clutch Actuation (Clutch Issue #1)**—Based on assurances from the clutch manufacturer, Foss decided to install air-actuated clutches between the main engines and the M/G sets. This was a design change from the hydraulic clutches on the ***Carolyn Dorothy***, and was thought to be a simpler, cleaner, reduced maintenance solution. Unfortunately, during initial testing of the M/G sets in November 2011, both clutches failed due to excessive heat in the air seal units. Investigation showed the issue was that the tight clearance required to seal the air in the clutch did not allow for the thermal expansion of the shaft, causing the stationary seal material to contact the rotating shaft. The clutch manufacturer, Logan, agreed that the clutch actuation needed to switch back to hydraulic, where the clearances could be enlarged and a fluid medium would always flow between the seal and the shaft. Foss had to ship the damaged clutch assemblies back to Logan's shop in Cleveland, Ohio, where they were reworked for hydraulic installation. Logan worked with a hydraulics vendor in the Portland, Oregon, area to develop the required hydraulic actuation package (pump, reservoir, piping and control valves). This was installed along with the rebuilt clutches in mid-December and appeared to work correctly. This entire process caused an additional 3 week delay to the project.

- **Shaftline Components**—The misalignment and torsional couplings on the shaft lines between the main engines and the motor generators were supplied by Centa Corporation, an industry leader in these components. The challenge for Centa was to provide flexibility to allow for the movement and vibration of the main engine (which is mounted on springs), and to not bind the M/G set (which is bolted directly to the steel foundation) while still transmitting 2500 HP. The Centa design was a proven one – it is the same system used on the ***Carolyn Dorothy***. However, the Centa components were delivered late, were in some cases incorrectly assembled (requiring Foss to disassemble/reassemble), and in some cases included wrong components. The bolted "Centa-link" connections came with bolts that were too short, causing one of them to strip out the threads in the mating Centa-supplied torsional coupling. Foss was able to work through these issues and the final installation worked as planned, but it cost considerable time and work to remedy.

- **Switchboard Cooling System**—As part of the design improvements implemented on this project, AKA changed their AC/DC conversion equipment from air cooled to water cooled. This reduced the size of the equipment considerably, and made the equipment much less susceptible to overheating in the engine room. The challenge to using water cooling is that it requires an additional cooling water system be installed. As we didn't have a full 3-D CAD model of the tugboat when the design was started, this system was not fully designed and required significant work to fit all the valves, manifolds, heat exchangers, pumps and tubing into the very confined area below the switchboard. The end result of having a reliable water-cooled system, however, far outweighed the difficulties in getting the cooling water system installed.

3. Testing and Commissioning

After completion of the hybrid system modifications, the ***Campbell Foss*** drove up river to Portland, Oregon to perform a Bollard Pull test. In this test, the tugboat is attached to a strong point on the shore (a bollard) by a 300' high-strength synthetic rope, and pulls as hard as it can in both directions (forward and astern). This test took place on December 21, 2011, and the results were surprising in that the ***Campbell Foss*** pulled harder in every hybrid mode than it did in non-hybrid mode. Foss/AKA theorized that this increase in pull is due to the electrical power flow to/from the M/Gs acting to even out the loading on the shafts, allowing them to provide more consistent, linear torque to the propellers. In a non-hybrid boat, during bollard pull, each shaft momentarily provides a little more thrust than the other as the boat is constantly weaving slightly under the extreme load – on the hybrid, the M/Gs dampened this weaving by causing both shafts to provide a similar, consistent torque. The Bollard Pull test results were as follows:

- Non-Hybrid Mode: ~62 short tons (124,000 lbs)
- Hybrid Mode w/o Batteries: ~63 short tons (126,000 lbs)
- Hybrid Model w/ Batteries: ~65 short tons (130,000 lbs)

A copy of the ABS Bollard Pull Report is included as Attachment B to this report.

After this test, the tugboat returned to the Rainier shipyard for final outfit and preparation to depart to Long Beach for final hybrid system testing and commissioning. The tugboat departed Rainier on December 31, 2011. However, on Sunday, January 1, 2012, the ***Campbell Foss*** reported that the starboard clutch had overheated, and the tugboat proceeded to Eureka, California for repairs.

Clutch Issue #2

In Eureka, Foss and Logan Clutch engineers worked with the tugboat's chief engineer to disassemble the shaft line and remove the starboard clutch. They initially expected that the seal overheated again, as seen during construction. What they found was that the roller bearings in the clutch unit had bound and overheated. This was eventually traced to the bearing being clamped into place too tightly during initial installation, which caused the bearing to bind and overheat after extended periods of operation. Logan reassembled the clutch with new bearings and disassembled and inspected the port clutch as well, ensuring all bearings were pre-tensioned correctly. The tugboat was in Eureka for 8 days while repairs were made and the system tested.

At this point, Foss decided to take the tugboat to San Francisco for final hybrid system testing and commissioning. From January 11 through January 20, 2012, Foss and AKA performed a full set of operational, endurance, and failure mode tests. In general, these tests went smoothly.

The test procedures are included as Appendix C to this report. During this testing, the clutches were cycled often, and engaged and disengaged as required, but their operation was inconsistent. Times for engagement and disengagement varied and sometimes the clutches needed multiple attempts to engage. This continued to be a concern for the crew and Foss engineering; therefore arrangements were made for ongoing hydraulic system improvement.

4. Post Delivery

The ***Campbell Foss*** performed her first ship assist job in San Francisco bay on January 21, 2012. She continued to work in the San Francisco bay for approximately one week due to ship-assist work needs, and then headed to Long Beach, California and re-entered ship assist service in the end of January.

The tugboat began a full workload of ship assist work as the second hybrid tug in the San Pedro harbor. Initial indication from the crew was that the system worked very well, and they were happy to work on the ***Campbell Foss*** and enjoyed having her run as a hybrid. Unfortunately, after being in full service for only two weeks, the port clutch failed.

Clutch Issue #3

Logan Clutch again dispatched their field engineers to investigate the cause of the failure. They found the clutch had failed due to excessive heat caused by the clutch plates not fully disengaging for approximately 1 minute after the signal to disengage. This is equivalent to "riding the clutch" on a manual transmission car. The reason the clutch did not disengage was due to the design of the hydraulic actuation system. Logan replaced the damaged clutch, checked the other clutch, and the tugboat went back into service in Non-Hybrid mode (in Non-Hybrid mode, the clutches are always fully engaged, so the disengagement problem was not an issue). Logan researched a solution to the actuation system problem – they needed a system that would bleed off the hydraulic pressure from the clutch immediately upon getting the "open clutch" signal. The installed system had a large number of valves and hoses, all of which kept residual pressure on the clutch while the hydraulic fluid drained away. Logan hired a hydraulics expert to review the situation and develop a solution. The final solution involved a much simpler system that uses aircraft-quality hydraulic components to drop pressure off the clutch almost instantaneously. The system was shop tested at the Logan facility, and then installed and tested onboard the ***Campbell Foss*** on May 14 - 16, 2012. The system has operated without further incident since the implementation of this final clutch solution, and Foss believes the system now to be rugged and reliable.

After some additional updating of the hybrid system software and testing, the tugboat returned to full hybrid service in the end of May. The tugboat worked through mid-August without incident, and the crew confirmed that the hybrid system worked well. University of California-Riverside performed their final 1000 hour emissions testing in June, and the final emissions report is attached as Appendix D.

Battery Fire

On August 20, 2012, while pushing on a ship at a dock, the crew of the tugboat heard a loud bang along with a shudder through the hull. Black smoke started coming from the engine room vents and alarms sounded. The crew immediately activated the fire suppression system, which

closed the fire dampers, shut off the vent fans and released fire suppression gas into the engine room. The battery compartment had its own fire suppression system which activated automatically via a heat sensor.

Foss, in conjunction with AKA and the battery manufacturer Corvus, performed an exhaustive incident investigation. The report of this investigation is included as Appendix E. The findings of this investigation indicated that a single battery (1 of 10) exploded due to overheating caused by consistent overcharging. The battery control system supplied by Corvus monitors the health and status of each battery, and has multiple levels of safety features and alarms to prevent overcharging. The system has a function that monitors each element for "over voltage" and "over temperature", and is designed to open the charging switches (and stop charging) if it detects any of these signals. However, during detailed design and commissioning, AKA and Corvus inadvertently disabled this function while troubleshooting a fix to electrical signal interferences between the battery control system and other electrical systems, including the AKA energy management system. Additionally, the batteries had been providing "nuisance" alarms for non-essential items for several months; however, Corvus had indicated these were not critical and could be ignored. This led the crew to assume the recurring alarms were of the same nature as the previously investigated alarms, which created an atmosphere of complacency. When other, more critical alarms indicated that one of the batteries was damaged, they were also ignored, as there was no obvious indication what the alarm was for (checking the cause of the alarm requires accessing the battery controller with a laptop computer).

On the mechanical side, the battery compartment held tight during the explosion and ensuing fire, and the fire suppression system self-activated and closed the ventilation dampers as designed. However, the ventilation system downstream of the battery compartment was made from plastic as it was seen as a non-critical system since it was separated from the battery compartment by the fire damper. However, the fire damper did not close immediately during the initial explosion and blast of hot gasses, so this blast entered the plastic ducting, causing it to melt and setting on fire adjacent material in the engine room.

After approximately 3 months of investigation and repair, Foss has completed repairs to the ***Campbell Foss*** and it is back up in service in Long Beach harbor. However, it is currently not using batteries and will continue to operate without batteries until the recommendations and additional fail-safe measures noted in the investigation report can be fully designed and implemented. Foss hopes to implement these measures and return batteries to service in the hybrid system this summer.

5. Emissions Testing

Foss teamed with University of California – Riverside (UC-R) to perform the emissions testing on the ***Campbell Foss***. UC-R performed the emissions testing on the ***Carolyn Dorothy*** and implemented a similar approach to the ***Campbell Foss***. The testing consisted of four phases:

1. Pre-modification testing – Pre-modification testing was performed in Long Beach, California, in June 2011, prior to the tugboat's departure to the shipyard for hybridization. UC-R installed instrumentation on the exhaust stacks of the old port genset (the one that would be replaced as part of the retrofit) and the port main engine. UC-R then brought in a load bank to connect to the genset and let the engine run at full power while they recorded the exhaust emissions . Next UC-R ran the tugboat at full power against a bulwark and took emissions readings from the port main engine (this test was done as a verification of the engine emissions, since the main engines were 6 years old).

2. 0-Hour Testing – After the tugboat had returned to service as a hybrid tugboat, and the new 350 kW genset had run for a minimum of 300 hours for break-in, UC-R again brought a load-bank and ran the new generator at full power, measuring the exhaust emissions. This testing took one full day to complete. The morning was used for equipment testing set up and the testing was completed in the afternoon.

3. 30-day Monitoring—After the 0-hour testing was complete, UC-R installed monitoring equipment on the tugboat and in the hybrid system to monitor how long the tugboat ran in each discrete mode of operation.

4. 1000-Hour Testing – Once the new genset had accumulated 1000 operating hours, UC-R performed the same test as the 0-hour test, to confirm that there had been no change in the emissions as the genset got more use.

The purpose of the emissions testing was to determine the level of emissions reductions after retrofit. The pre-modification testing was completed to establish a baseline. The 0-Hour Testing established the baseline of the new genset after the required "de-greening" period. The 30-day test was performed to establish the percentage of time in each operating mode. The 1,000 hour test is a durability test to determine if there had been any significant changes in the emissions profiles of the engines since the baseline testing. For more details on the testing, please refer to Appendix D.

The final emissions report from UC-R is attached as Appendix D.

6. Results and Summary

Quantitative Results of Emission Reductions from the Hybridization of the Campbell Foss

*(*Carolyn Dorothy *results shown for comparison)*

Emissions Reductions:	NOx	CO/CO2	Particulate Matter
Campbell Foss	31%	30%	29%
Carolyn Dorothy	51%	27%	73%

Fuel Consumption:

Campbell Foss	25% Reduction
Carolyn Dorothy	25% Reduction

Performance:	***Campbell Foss***	***Carolyn Dorothy***
Bollard Pull – no batteries	63 Tons	62 Tons
Bollard Pull – w/batteries	65 Tons	64.5 Tons
Speed on 1 Genset	6 knots	6.5 knots
Speed on 2 Gensets	8 knots	8.5 knots

Financial: Total cost of project was $2,307,437

$83,803 under budget

Comparison of Emissions Results

Comparing the overall emissions results of this study with the earlier ARB study "Evaluating Emission benefits of a Hybrid Tugboat" from October 2010 shows some similarities and some significant differences. These differences can be explained and are brought about by:

1) The changes in the activity revealed from data logging. For example, the time in the *Assist* mode was increased from 22% to 33%. This was mainly due to the fact that the ***Campbell Foss*** was spending more time in moving barges because of the new travel restrictions due to the Helm Bridge project.

2) The change in emissions due to engines from different manufacturers. In the repower study, the same main propulsion engine was used so there are no differences in emissions from the main engine. However, the first study, *Evaluating Emission Benefits of a Hybrid Tugboat* (2010) was of a conventional tugboat with a Caterpillar 3512 engine and a hybrid with a Cummins QSK50-M engine. While both engines complied with the overall weighted emission factors for US EPA Tier 2, the individual model emissions differed significantly.

3) Table 3-9 shows the emissions differences in grams per hour at different loads. About 30% of the difference is due to the size of the engine as the Caterpillar was rated at 1902 kW and the Cummins was rated at 1342 kW. Still, as the tugboats showed similar histograms, it is clear that the Cummins on the hybrid was a much cleaner engine at the lower operating modes in which the tug mainly operates; thus resulting in the 72% PM benefit in that study and 28% in this study. For this project, the conventional and retrofitted hybrid tugboat had the same main engine so benefits from engine manufacturer cannot be realized.

Table 6-1: Difference in NOx and $PM_{2.5}$ Emission Rates across Load Points

Engine Load	CAT 3512C	Cummins QSK50-M	CAT 3512C	Cummins QSK50-M
	NO_x (g/hr)		$PM_{2.5}$ (g/hr)	
7%	2439	1035	6.3	9.5
25%	4867	2674	94	9.8
50%	7781	5374	195	50
75%	9450	7921	97	58
100%	14124	10215	173	54

Considering specific cases, the NOx emission reduction of the earlier study was 51% and for this study was 31%. This difference can be partially explained by the change in modal activity in the histograms and overall weighting factor for the two cases. Table 6-2 uses the activity factors from the earlier study and the NOx reduction of this study would be boosted from the 31% reported in Section 3.4 to 42%, a value closer to the earlier study. The remainder of the difference is due to benefits of the cleaner Cummins engine at low loads as described above.

Similarly for the PM some of the differences are due to the higher time in the *Assist* mode. As Table 3-10 indicates, the PM benefits would increase from 28% to 34%. However, it is the near

ten-fold differences for PM grams per hour at low loads that the Cummins engine provided in the earlier comparison and boosted the benefit to near 70%. Even operating the Cummins AE provided PM benefits over the John Deere AE.

Table 6-2: Modal and Overall Emission Reductions based on Operating Weighting Factors are obtained from ARB study

Operating Modes	Weighing factors		NOx (g/hr)		% Reduction	CO_2 (kg/hr)		% Reduction	$PM_{2.5}$ (g/hr)		% Reduction
	Conv.	Hybrid	Conv.	Hybrid		Conv.	Hybrid		Conv.	Hybrid	
SHORE POWER	0.01	0.18	0.0002	0.0002	0%	0.002	0.002	0%	0.00013	0.00013	0%
STOP	0.54	0.35	133	38	71%	11.4	4.4	61%	4.6	1.4	70%
IDLE	0.07	0.07	338	25	93%	13.0	2.8	78%	2.2	0.7	70%
TRANSIT	0.16	0.18	1261	391	69%	79.5	39.3	51%	11.2	7.5	33%
ASSIST	0.22	0.22	1653	1494	10%	101.7	85.4	16%	15.4	12.4	20%
Overall	1.00	1.00	3385	1948	**42%**	206	132	**36%**	33.4	21.9	**34%**

Summary

Setting aside the major issue of the battery fire, Foss was able to successfully modify an existing harbor tugboat with a hybrid propulsion system that would bring about significant reductions in fuel consumption and emissions. The hybrid system on the ***Campbell Foss*** is less complicated than its predecessor, the ***Carolyn Dorothy***, and has received great reviews from those who operate and maintain the tugboat.

The major mechanical issues Foss had with the implementation of this modification all dealt with the clutches. While they are critical to the success of the tugboat, they had minimal impact on the hybrid system itself and have effectively been resolved.

The battery fire provides a reminder that the implementation of new technology carries risk. Fortunately no one was hurt, and damage to the tugboat was minimized due to the quick actions of the crew and the installed safety systems. However, all future installations of this technology, especially when utilizing batteries, need to have significant risk assessment and controls implemented.

Looking forward, Foss continues to embrace and promote hybrid technology on tugboats. In the summer of 2013, Foss is planning to reinstall batteries on the ***Campbell Foss*** once all system improvements have been designed, tested and vetted. Foss is also currently scheduled to retrofit another Foss Dolphin-class tugboat, the ***Alta June***, to a hybrid propulsion system starting in January of 2014.

APPENDIX A

HYBRID FUNCTIONAL DESIGN SPECIFICATION

FOSS

Campbell Foss

Hybrid Marine Power System

FUNCTIONAL SPECIFICATION (HIGH LEVEL)

REVISION STATUS - AKA INTEGRATED DOCUMENTATION SYSTEM
VERSION
1
17 JAN
2011

xero point hybrid

Document Reference: 110117-SPEC-CMBLFOSS-2228B(HighLevel).doc

ENGINEERING INNOVATIVE SOLUTIONS

DOCUMENTATION SYSTEM CONTROL

REVISION CONTROL LOG

Version	Description	Date
1	First Issue	January 17, 2011
2	Second Issue	March 23, 2011

SPECIFICATION

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SPECIFICATION

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1 FUNCTIONAL DESIGN SPECIFICATION (HIGH LEVEL)

This preliminary high level FDS and electrical one-line is intended to provide Foss Maritime the opportunity to comment on the high level aspects of the design. Approval will allow AKA to continue with the detailed electrical and control design which will culminate in the necessary schematics and drawings to begin manufacture of the hybrid system components and development of the system control logic.

1.1 SYSTEM OVERVIEW

The Campbell Foss Hybrid will maintain her Caterpillar 3512D main diesel engines rated at 2540 HP @ 1800 RPM, shafted to Rolls Royce UL 205 Azimuthing Stern Drives (ASDs) through new Foss supplied Logan air clutches. TECO-Westinghouse Propulsion Motor/Generators (M/Gs) rated for 670 HP (500 KW) will be fitted between the main diesels and the ASD's. The M/Gs will function either as motors to provide propulsive power to the ASD's, or as generators providing electrical power back to the system.

The M/G's will be controlled by water cooled Vacon Variable Frequency Drives (VFD's). Steering and lubrication for the RR ASD's is provided by shaft driven (belt drive) Hydraulic Power Units (HPU's).

Additionally, the Campbell Foss will have two diesel generator sets (auxiliary generators) one existing John Deere rated at 168 HP (125 Kw) and one new Detroit Diesel rated at 470 HP (350 Kw) to supply electrical power for propulsion, hotel services for the boat, and to charge the batteries as required. One or both auxiliary generators can provide propulsive power. The number of generators in operation will be determined by the operator based on the mode chosen. Energy for low power requirements and for 'riding-through' transient demands is provided by the storage battery.

To ensure additional redundancy the vessel can be operated in a strictly non-hybrid mode of operation, bypassing all hybrid components and control.

2 ELECTRICAL DESIGN PHILOSOPHY

The hybrid system will at a minimum, provide the same or better level of reliability/redundancy as a conventional Dolphin in regards to electrical supply. The system via the driveline configuration will provide additional redundancies in regards to get home propulsion, as compared to a conventional dolphin.

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2.1 OVERVIEW

- Refer to: One-line Drawing - CAM -010-P4190100K Model (1)

The hybrid electrical system will be centered on a common ~800V DC bus. The DC bus is the preferred bus for all major electrical loads. This bus is supported by two water cooled Vacon Active Front End (AFE) converters each fed by its respective 125 KW and 350 KW auxiliary generators. Either or both of these generators can be engaged to support the DC bus. This arrangement eliminates the need for synchronization of the generators. Through Vacon Variable Frequency Drives (VFDs) the DC bus will provide a 480 VAC, 3-phase supply to the propulsion motor/generators. These drives also allow the MG's to provide energy back to the bus when they are being driven by the main engines. Even at idle the main engines via the MG's will provide significant power to supply the hotel load of the vessel. This energy flow will be controlled through the VFD's according to the requirements of the energy management system (EMS). Finally, the Lithium battery bank will be connected to the ~800V DC bus using DCDC converters capable of operating bi-directionally. It is possible to charge the battery arrays from the DC bus or, alternatively, discharge them to the DC bus as required.

The DC bus will be fitted with a bi-directional 140 KW water cooled AFE to supply the existing 480 VAC distribution.

The existing shore power connection via the bi-directional AFE will allow the DC bus to be powered from shore side resources. This will allow the batteries to be charged from the grid and/or alternative energy sources.

2.2 SUPPLY OF THE EXISTING 480 VAC SWITCHBOARD

The main supply to the existing 480 distribution will be via a water cooled 140 KW AFE located within the main DC switchboard. This AFE is sized to provide the hotel load of the vessel including the winch. The AFE acts as an electronic generator. In addition to the AFE, either of the auxiliary generators can connect directly to the AC bus – See "Emergency Supply to AC Switchboard"

2.3 SHORE POWER

The shore power connection will remain on the existing 480 VAC bus. The hotel AFE is bi-directional which allows the DC bus to be supported via shore power allowing the batteries to be charged.

To ensure shore power is not connected to a live bus, both phase rotation protection and dead bus protection will be provided. During connection the vessel will momentarily go "black ship" as now occurs on a conventional Dolphin.

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2.4 EMERGENCY SUPPLY TO AC SWITCHBOARD

In the event that the hotel load AFE or DC bus should fail the 125 KW gen will automatically start (if not already running) and connect to the AC bus, a momentary black ship condition would occur.

NOTE: In comparison to a conventional Dolphin, a generator failure would also cause a black ship condition, with the difference being that the second generator would need to be started manually and then connected, taking more time than our proposed design.

NOTE: Either the 125 KW or 350 KW gen will be capable of being manually connected to the AC bus when the vessel is in non-hybrid mode.

2.5 GENERATOR MONITORING

In normal operation (Hybrid Mode) the generator monitoring will always be available on the new DC switchboard section (SB02). In the instance where either generator connects directly to the AC bus (as in non-hybrid mode) the monitoring will revert to the existing AC switchboard (SB01).

2.6 WINCH SUPPLY

As requested by Foss Maritime the winch will remain on the AC bus.

2.7 ELECTRICAL STORAGE

For this design we are anticipating the use of the Corvus Lithium Polymer 48 VDC batteries. We have allowed for a hotel load of 25 KW and duration of 2 hours (50 KW/hrs of energy storage). Corvus has indicated a single string of 10 batteries will provide these needs. The Corvus quote provides additional detail.

This string will be connected to the DC bus through a single DCDC convertor. The battery management and monitoring system will fall within the scope of Corvus Energy. Our Energy Management System will be designed to communicate with the Corvus system to ensure appropriate limits of charge and discharge are respected. For clarification, the AKA EMS will dictate when the batteries charge or discharge based on system power requirements and mode of operation.

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2.8 24 VDC SUPPLY

A stand-alone 24 VDC redundant power supply for the supplied hybrid system will be provided. This system will be comprised of two 24 vdc power supplies and a battery charger each fed from the existing 120 vessel service bus. A set of AGM batteries will provide an uninterrupted power supply to the system. The power supplies and battery charger will be located in the base of the control section of the hybrid switchboard. In addition, 2 – 225 watt Solar panels will be connected to the AGM batteries for additional charging. The vessel's existing 24 VDC supply and distribution will remain independent of this system.

2.9 HYBRID CONTROL AND MONITORING

System Control and Energy Management will be developed using Siemens Step 7 software. The Siemens PLC will be located in the control section of the SWBD and be supplied with a 24 VDC UPS (as described earlier). A function block diagram of the PLC logic will be included in the final documentation set.

2.10 HYBRID SYSTEM INTERFACE

The system will include 2 touch screen HMI's, one fitted within its own cabinet for placement in the Engine Room and the other in the wheelhouse. A hybrid control panel will also be located in the wheelhouse. The HMI's will only display hybrid related information. The existing alarm and monitoring system for the vessel will remain independent of the hybrid system.

The hybrid control panel will provide the operator with the ability to choose "hybrid" or "non - hybrid" modes of operation. In hybrid, a selector switch will provide the operator the ability to choose between; Stop, Idle, Transit 1, Transit 2 and Assist. The panel will also include an alarm acknowledgement button, a hybrid system in command indicator light, a lamp test button, and a dimmer switch. The panel will also include main engine start buttons that will also be hard wired to close the clutches.

An additional stainless steel wheelhouse panel will be provided that holds E-stops for each motor/generator as well as the hybrid alarm.

Existing Wheelhouse Emergency Stop controls for the engines and generators will be retained.

Hybrid system alarms, both visual and audible will be indicated on the HMI's. The hybrid control panel will have visual indication and audible alarms will be installed in the Engine Room, Galley and Wheelhouse. Alarms can be acknowledged at the HMI's and hybrid control panel. Clearing of the alarms will only be from the E/R Location.

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2.11 CLUTCH OPERATION

The Campbell Foss hybrid tug will use Logan air clutches between the diesel and the motor/generator. AKA will provide a 24 VDC supply to the clutch solenoids to control the open/close function based on mode. AKA will also provide clutch control panels that will provide the option for remote (hybrid control) or local control of the clutch. Additionally, the clutches will be able to be closed from the bridge position when the vessel is in “non-hybrid” mode.

2.12 STEERING

The Campbell Foss hybrid tug will use the same RR 205 azimuthing stern drives (ASD’s) as a conventional Dolphin. The hydraulics for clutch and steering are powered as a conventional Dolphin, via the propulsion shaft through a belt driven pump. As the shaft RPM will operate below the main engine idle speed an electrically driven hydraulic pump will be fitted within the hydraulic circuit. This unit fitted with a pressure switch will automatically start if pressure drops below a preset value ensuring pressure for lubrication, clutch engagement and steering is always available. When pressure exceeds a preset maximum, this auxiliary hydraulic pump will automatically shut down. The supply and installation of these units will be within the scope of Foss Maritime. These electric pumps will be supplied via AKA supplied VFDs from the DC bus.

2.13 COOLING WATER SYSTEM

The cooling water manifolds, pressure and temperature sensors and flow meters will be located within the base of the DC switchboard. Two cooling water circuits will be required, one supplying the port side converters and one for the starboard side convertors and hotel AFE. A cross over connection between circuits will be required, with each circuit sized to handle the cooling requirements of both sides. The supplied DC switchboard will have an inlet and outlet connection for each cooling circuit.

AKA will supply the drive side circulating pumps and heat exchangers. Foss will be responsible for supplying and plumbing all cooling water piping as well as the supply and design of the seawater side of the cooling circuit.

3 MODES OF OPERATION

As with the Carolyn Dorothy, the system will be designed with “hybrid” and “non-hybrid” modes of operation.

In “hybrid” the operator will be provided the following modes of operation. These modes can only be selected when the throttles are in their idle position.

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3.1 STOP

For use when the vessel is secured. The throttles are disabled. Power is supplied via the batteries, with the 125 KW gen starting automatically when batteries reach a preset minimum SOC. If shore power is available the DC bus can be shut down for maintenance. Electrical distribution is via the existing 480 AC bus.

3.2 IDLE

For use when the vessel is stopped at sea. The throttles are enabled. Power is supplied via the batteries, with the 125 KW generator starting automatically and connecting to the DC bus when batteries reach a preset minimum SOC. Minor station keeping can be performed.

3.3 TRANSIT 1

Transit 1 Mode is for transit speeds of 6 kts or less. Selecting Transit 1 will automatically start the 350 KW generator and connect it to the DC bus. The Logan clutches will open (if closed) and all other running engines will shut down after a preset cool down period.

The batteries will be connected to the DC bus via the DCDC converter. The batteries will be charged if SOC is below a set limit and can be used to support the DC bus if required.

3.4 TRANSIT 2

Transit 2 Mode is for transit speeds up to approximately 7.5 kts or less. Selecting Transit #2 will automatically start the 350 KW generator (if not already running) and the 125 KW generator and connect them both to the DC bus. The Logan clutches will open (if closed) and the main engines will shut down (if running) after a preset cool down period.

The batteries will be connected to the DC bus via the DCDC converter. The batteries will be charged if SOC is below a set limit and can be used to support the DC bus if required.

3.5 ASSIST

Selecting Assist mode will cause both main engines to start and the Logan clutches to close. The MG VFD's will begin supporting the DC bus and the generators (if running) will be disconnected from the DC bus by first opening their contactors. The 350 KW gen (if running) will shut down after a preset cool down period. The 125 KW gen will remain running (or if not running will be

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automatically started) and be available to connect to the AC bus via a dead bus relay should power from the DC bus be lost.

AKA will provide the option for this functionality to be removed (via the HMI) if future confidence in the system precludes the need to have the 125 gen running during Assist Mode. It should be noted however that the EMS will always start and connect the 125 KW generator to the AC bus during any mode of operation where the DC bus feed to the existing AC SWBD is lost.

The batteries will be connected to the DC bus via the DCDC converter. The batteries will be charged if SOC is below a set limit and can be used to support the DC bus if required.

3.6 NON - HYBRID

Selecting the “non-hybrid” position is undertaken if the DC bus needs to be shut down or the EMS is not functioning.

In the “non-hybrid” position both main engines will need to be started manually (if not already running) and the engine clutches will need to be closed manually. (Investigation is ongoing as to the ability for the clutches to fail in the closed position if 24 vdc is lost). These operations can be achieved either locally at the engine and clutch control panels or using the hard-wired emergency controls from the wheelhouse hybrid panel. Either generator can be started (if not already running) and manually connected to the ac bus (if not already connected).Generator monitoring will revert to the SB01 location. Interlocks between the “Generator Junction Boxes” will prevent both generators from ever being connected to the AC bus.

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APPENDIX B

ABS BOLLARD PULL TEST REPORT

ABS Consulting
RISK CONSULTING DIVSION / MARINE SERVICES

ABSG CONSULTING INC.
16855 NORTHCHASE DRIVE
HOUSTON, TEXAS 77060-6008
OFFICE: (281) 673 2769
FAX: (281) 673-2960

BOLLARD PULL TEST DATA FORM
(SECTION A)

Project ID No.: 2730383	**Report No.: WA-9597**	**Office: Gig Harbor, Washington**

Bollard Pull Test Location and Personnel Data	
Survey Date	21 December 2011
Location	Port of Portland, Oregon
Vessel Name	**"CAMPBELL FOSS"**
Marine Surveyor	S. P. Smith, ABS Consulting/Marine Service representatives
Others In Attendance	Joel Altus, Foss Maritime Mark J. Suryan, P.E., Dynamark Engineering, Inc. Mr. Rick McKenna, Foss Maritime Mr. Tim Stewart, Foss Maritime

General Comments

Due to the vessel being placed into service in the Port of LA/LB the criteria for the ports of San Francisco, Los Angeles/Long Beach, CA were adhered to for all of the ahead and astern pulls. Their criteria are in excess of the criteria shown in this report format. The ultimate bollard pulls, ahead and astern shown in tons in the sections below were determined from the recorded data captured over a period of time in excess of 15 minutes as witnessed throughout by the undersigned representative of ABS Consulting.

Testing was performed on 21 December 2011. The vessel was tested in four (4) separate propulsion modes both ahead and astern as per:

1st Mode Conventional main engine power with diesel generators providing hotel service load.

2nd Mode DC power bus regulation without batteries; main engines providing propulsion and hotel load via motor/generators.

3rd Mode DC power bus regulation with batteries; main engines providing propulsion power, hotel load via motor/generators.

4th Mode Super Assist, with batteries and motor-generator sets contributing to shaft power.

The test bollard at the Swan Island Shipyard, Portland, OR precluded positioning of the load cell on the pier end of the hawser being very difficult to manipulate and monitor for the ahead and astern pulls therefore the dynamometer was positioned on the vessel for all of the ahead and astern pulls. The load cell was monitored throughout both the astern and ahead pulls from the vessel and remained unobstructed and horizontal throughout both pulls.

Load Cell Data	
Load Cell Manufacturer's Name	Washington Chain Service
Load Cell Model/Type	250 Ton/500,000 Pound, S/N WC 101
Load Cell Last Calibration Date	8 December 2011
Recording Device (Computer)	Yes
Recording Device Manufacturer/Model/Type	Agilent, Model 34970A Data Acquisition System w/ Graphtec GL220, calibrated on 8 December 2011.
Load Cell Operator's Name and Company	Mr. Mark J. Suryan, P.E., Dynamark Engineering, Inc.
Comments: The operator was at the monitoring location in the vessels mess throughout the astern and ahead pulls observing both the loadcell readout and computer input. Copies of the bollard pull printouts remain on file. The +15 minute data are consistent with the visual readings noted during the test periods.	

Ahead 1st Mode	**Bollard Pull Test Data**		
Clock Time	Minute Number	Average Indicated Steady Bollard Pull	
Start: 1130	0	Slack Tide	Slack tide
	1	124,160	
	2	125,200	
	3	125,200	
	4	124,270	
End of Fifth Minute:	5	124,450	
Average Steady Bollard Pull Rating **Ahead**		124,656	**62.33 Short Tons**

Ahead 2nd Mode	**Bollard Pull Test Data**		
Clock Time	Minute Number	Average Indicated Steady Bollard Pull	
Start: 1210	0	Slack Tide	Slack tide
	1	126,860	
	2	127,290	
	3	127,250	

	4	126,570	
End of Fifth Minute:	5	126,750	
Average Steady Bollard Pull Rating **Ahead**		126,944	**63.47 Short Tons**

Ahead 3rd Mode	**Bollard Pull Test Data**		
Clock Time	Minute Number	Average Indicated Steady Bollard Pull	
Start: 1250	0	Slack Tide	Slack tide
	1	129,360	
	2	130,220	
	3	131,150	
	4	130,270	
End of Fifth Minute:	5	130,300	
Average Steady Bollard Pull Rating **Ahead**		651,300	**65.13 Short Tons**

Ahead 4th Mode	**Bollard Pull Test Data**		
Clock Time	Minute Number	Average Indicated Steady Bollard Pull	
Start: 1310	0	Slack Tide	Slack tide
	1	129,860	
	2	130,600	
	3	131,250	
	4	129,570	
End of Fifth Minute:	5	130,750	
Average Steady Bollard Pull Rating **Ahead**		130,406	**65.20 Short Tons**

Astern 1st Mode	**Bollard Pull Test Data**		
Clock Time	Minute Number	Average Indicated Steady Bollard Pull	
Start: 1415	0	Slack Tide	Slack tide
	1	135,790	
	2	134,790	
	3	135,850	
	4	135,570	
End of Fifth Minute:	5	136,750	

Average Steady Bollard Pull Rating **Astern**	135,750	**67.88 Short Tons**

Astern 2nd Mode	**Bollard Pull Test Data**		
Clock Time	Minute Number	Average Indicated Steady Bollard Pull	
Start: 1415	0	Slack Tide	Slack tide
	1	136,750	
	2	137,500	
	3	137,350	
	4	136,550	
End of Fifth Minute:	5	137,700	
Average Steady Bollard Pull Rating **Astern**		137,170	**68.59 Short Tons**

Astern 3rd Mode	**Bollard Pull Test Data**		
Clock Time	Minute Number	Average Indicated Steady Bollard Pull	
Start: 1500	0	Slack Tide	Slack tide
	1	136,900	
	2	137,780	
	3	137,950	
	4	136,970	
End of Fifth Minute:	5	137,950	
Average Steady Bollard Pull Rating **Astern**		137,510	**68.76 Short Tons**

Astern 4th Mode	**Bollard Pull Test Data**		
Clock Time	Minute Number	Average Indicated Steady Bollard Pull	
Start: 1555	0	Slack Tide	Slack tide
	1	137,890	
	2	138,650	
	3	137,550	
	4	138,510	
End of Fifth Minute:	5	138,750	
Average Steady Bollard Pull Rating **Astern**		138,270	**69.14 Short Tons**

REMARKS

☒ The load cell used for the test had been calibrated within the preceding 12 months by a certified testing laboratory. The last certificate was available for review and a copy is retained on file.

☒ The load cell provided a continuous readout.

☒ A device for recording the bollard pull graphically, as a function of the time, was connected to the load cell.

☒ 2-Way voice communication was maintained between dock and tug during the course of this test.

☒ During the test there was one Surveyor located in the vessel's mess, pilothouse and engine room observing vessel operations.

Surveyor With Load Cell:

Print Name: Stan Smith

Company: ABS Consulting / Marine Services

Load Cell Operator:

for

Print Name: Mark J. Suryan

Company: Dynamark Engineering Inc.

BOLLARD PULL TEST DATA FORM
(SECTION B)

Project ID No.:	**Report No.: WA-9697**	**Office: Gig Harbor, Washington**

Bollard Pull Test Location and Personnel Data	
Survey Date	21 December 2011
Test Location	**Port of Portland, OR**
Vessel Name	**"CAMPBELL FOSS"**
Marine Surveyor	S. P. Smith

Vessel Particulars	
Registered Name	**"CAMPBELL FOSS" (Hybrid)**
Official Number	1177724
Port of Registry/Flag	Long Beach/USA
Year Built / At	2005/Rainier, Oregon
Classification Society	N/A
Load Line Assigned	No

Registered Tonnages	Gross: 160	Net: 109	
Length Overall	78.0’		
Registered Dimensions	Length 73.4’	Breadth 34.0’	Depth 19.5’
Main Propulsion As appropriate, include the following: • Number of Engines • Engine Manufacturer • Engine Model Numbers • Continuous HP Rating @ Specific RPM • Number of Gearboxes/Reduction Gears • Gearbox Manufacturer • Gearbox Model Numbers • Forward/Astern Reduction Ratios • Number of Propeller Shafts • Number of Engines per Shaft	Two (2) Caterpillar 3512D Marine Diesel engines each driving through a Rolls-Royce / Ulstein Aquamaster Azimuth Thruster Z Drive. One (1) MTU Series 60 Marine Diesel engine driving one (1) 350 KW generator and one (1) John Deere Marine Diesel engine driving (1) 125 kW generator that are selectively operated during mode 4 “Super Assist”, powering two (2) TECO-Westinghouse electric drive motors, one (1) each shaft.		
Propulsion Arrangement	Conventional ☐	Tractor ☐	Tractor Plus ☒ **Hybrid**
Propulsion System Manufacturer	Rolls-Royce Z-Drive/**Hybrid**		
Propeller(s) used for Test	Diameter 94”	Pitch 82.8”	No. of Blades 4

Comments Pertaining To Vessel / Vessel Personnel

The M/V **CAMPBELL FOSS** although built as a conventional ship-handling tug during 2005, was converted during 2011 into a **Diesel-Electric Hybrid tug**. Its power is derived from either direct diesel, diesel-electric with power supplied by the generators, or solely by battery banks. The vessel’s crew and support staff were cooperative and very professional throughout the bollard pulls.

Bollard Pull Test Situation

Water Depth @ Test Site	43’	
Water Current @ Test Site (Kts.)	Slack tide, light flood tide, current < 1Kt.	
Wind Direction / Speed (MPH)	Northeast < 5 knots.	
Approximate Air Temperature	40 Degrees F.	
Vessel's Drafts	Forward: 16.50’	Aft: 16.50’
Towing Hawser	Synthetic, Double Braid, 8” Spectra	
Hawser Length (*Vessel to Bollard*)	425’	

Bollard Pull Test - Vessel Operations Data

Main Engine Data	Port Engine:	Center Engine:	Starboard Engine:
Max Cont RPM - Rated/During Test	1800/1826		1800/1819
Rated Continuous BHP @____RPM	1,800		1,800
Overspeed RPM Settings	110%		110%

Max. Lube Oil Pressure/Temperature	/	/	/
Max. Cooling Water Temperature	In: /Out:	In: /Out:	In: /Out:
Manifold Air Temperature			
Reduction Gear Ratio			
Reported Propeller Material			
Reported No. of Propeller Blades	4		4
Reported Propeller Diameter / Pitch	94”/82.8”	/	94”/82.8”

Comments Pertaining To Vessel Systems / Machinery During Test
Vessel just completed Sea Trials following conversion to Hybrid technology. All normal systems, pumps and auxiliaries were in operation throughout all bollard pulls.

REMARKS

☒ The test **was** carried out with the vessel’s trim and/or displacement corresponding to applicable Load Line requirements and/or Letter of Stability.

☒ Auxiliary equipment (i.e., pumps, generators, etc), which are driven from the main engines or propeller shafts during normal operation of the vessel, **were** connected during the test.

☒ The Z-Drive units fitted on the vessel during the test **are** the same as those reportedly used when the vessel is in normal operation.

☒ Water depth under the keel **was** twice the vessel's depth at midship.

☒ Water current **did not** exceed 1.0 Knot and was not conducted both upstream and downstream.

☒ Wind speed **did not** exceed 10 Miles per hour.

☒ Towline length **was** at least twice the length of the vessel from stern/bow to fixed bollard.

☒ 2-Way voice communication **was** maintained during the course of this test.

Surveyor Observing Vessel Operation.

Print Name: Stan Smith

Company: ABS Consulting / Marine Services

APPENDIX C

HYBRID CUSTOMER ACCEPTANCE TEST PROCEDURES

JOB NUMBER 2228	**TESTING DOCUMENTATION**	DOCUMENT REFERENCE 111104 - CAT Test Procedure 1-CAM-2228-24 VDC System-Rev02.docx
INSTALLATION Campbell Foss		PROJECT MANAGER John Eldridge
TESTING HELD AT Richmond, Ca		DESIGN ENGINEER Chris Wright

Customer Acceptance Test Procedure

ID	Test Description	Result	Signature of AKA	Signature of Client
PREPARATION (Dock Trials)				
1	Power up 24 VDC system as per operating procedure.			RM
TEST 24 VDC SYSTEM				
2	Power on Power Supply #1 and record voltage – no load.	~~26.1~~ 27		RM
3	Power on Power Supply #2 and record voltage – no load.	27.1 / 27.5 ~~26.1 / 26.9~~		RM
4	Power on Battery Charger and record voltage – no load.	26.1 / 26.5 ~~25.4 / 24.9~~		RM
5	Connect Batteries and record voltage – no load.	~~24.9 / 24.1~~ 25.8 / 26.1		RM
6	Connect all 24 VDC loads and confirm power up at device and HMI.			RM
7	Record PS#1 voltage and amps with load.	26.1 / 9.5a		RM
8	Record PS#2 voltage and amps with load.	26.1 / 26.9 / 8.5a		RM
9	Record Battery Charger voltage and amps with load, compare with HMI.	25.4 / 24.9, 9a		RM

JOB NUMBER 2228	**TESTING DOCUMENTATION**	DOCUMENT REFERENCE 111104 - CAT Test Procedure 2-CAM-2228-Hybrid Environmental-Rev01
INSTALLATION Campbell Foss		PROJECT MANAGER John Eldridge
TESTING HELD AT Richmond, Ca		DESIGN ENGINEER Chris Wright

Customer Acceptance Test Procedure

ID	Test Description	Result	Signature of AKA	Signature of Client
PREPARATION (Dock Trials)				
1	Vessel to be placed in Non-Hybrid Mode, with VSS supplied direct from shore power.			RM
2	Ensure breakers supplying AC feed to SB02 are closed.			RM
TEST LIGHTS & HEATERS Note: Fans will be checked when DC bus is up				
3	SB02 Port Section - verify light turns on when door opens.			RM
4	SB02 Port Section - increase temperature on thermostat until heater starts. Reset temperature.			RM
5	SB02 Aft Section - verify light turns on when door opens.			RM
6	SB02 Aft Section - increase temperature on thermostat until heater starts. Reset temperature.			RM
7	SB02 Starboard Section - verify light turns on when door opens.			RM
8	SB02 Starboard Section - increase temperature on thermostat until heater starts. Reset temperature.			RM
9	SB02 Forward Section - verify light turns on when panel removed.			RM
10	SB02 Forward Section - increase temperature on thermostat until heater starts. Reset temperature.			RM
11	DCDC Cabinet - verify light turns on when door opens.			RM

JOB NUMBER 2228	**TESTING DOCUMENTATION**	DOCUMENT REFERENCE 111104 - CAT Test Procedure 2-CAM-2228-Hybrid Environmental-Rev01
INSTALLATION Campbell Foss		PROJECT MANAGER John Eldridge
TESTING HELD AT AKA PEI, PEI		DESIGN ENGINEER Chris Wright

Verification Procedures and Factory Acceptance Test

ID	Test Description	Result	Signature of AKA	Signature of Client
12	DCDC Cabinet - increase temperature on thermostat until heater starts. Reset temperature.	HRS old style strip with AKA to swap out too not!		RM
13	Port Motor Heaters - turn motor heaters on at Control Section: verify amber indicator light illuminated and heaters functioning.			RM
14	Starboard Motor Heaters - turn motor heaters on at Control Section: verify amber indicator light illuminated and heater functioning.			RM

JOB NUMBER 2228	TESTING DOCUMENTATION	DOCUMENT REFERENCE 111104 - CAT Test Procedure 3-CAM-2228-DC Bus Operations - Rev01
INSTALLATION Campbell Foss		PROJECT MANAGER John Eldridge
TESTING HELD AT Richmond, Ca		DESIGN ENGINEER Chris Wright

Customer Acceptance Test Procedure

ID	Test Description	Result	Signature of AKA	Signature of Client
PREPARATION (Dock Trials)				
1	Vessel to be placed in Hybrid Stop Mode, with shore power connected. Maintenance Key Switch to be in the on position to allow access to SWBD.			RM
BRING UP THE DC BUS				
2	Bring up the DC bus as per operating procedure. Verify with the client that the procedure is accurate and clear.	Need instruction for DC Bus up on shore power		RM
3	Verify bus came up via shore power.			RM
4	Verify that the "red" bus hot indicator lights are on at the SWBD and DCDC converter cabinet.			RM
5	Verify port cooling pump is running via HMI. Starboard cooling pump should be off. Note: additional testing of the cooling water system will be done in a separate section.			RM
6	Verify all fans are operating and blowing air "out" of each SWBD section and the DCDC cabinet.			RM
7	Verify HMI and meter readings			RM
VERIFY DC BUS E-STOPS				
8	E-Stop the bus using the main E-stop on SB02. Re-arm the E-Stop switch and bring the bus back up.			RM
9	With the Maintenance Key in the off position, verify the Bus E-Stops when the Port Section door is opened. Bring the bus back up.			RM

JOB NUMBER 2228		DOCUMENT REFERENCE 111104 - CAT Test Procedure 3-CAM-2228-DC Bus Operations - Rev01
INSTALLATION Campbell Foss	**TESTING DOCUMENTATION**	PROJECT MANAGER John Eldridge
TESTING HELD AT Rainier, Or		DESIGN ENGINEER Chris Wright

Customer Acceptance Test Procedure

ID	Test Description	Result	Signature of AKA	Signature of Client
10	With the Maintenance Key in the off position, verify the Bus E-Stops when the Aft Section door is opened. Bring the bus back up.			RM
11	With the Maintenance Key in the off position, verify the Bus E-Stops when the Forward Section panel is opened. Bring the bus back up.			RM
12	With the Maintenance Key in the off position, verify the Bus E-Stops when the DCDC Cabinet door is opened. Bring the bus back up.			RM

JOB NUMBER 2228	**TESTING DOCUMENTATION**	DOCUMENT REFERENCE 111104 - CAT Test Procedure 4-CAM-2228-Stop Mode Functionality (Shore Power Connected) - Rev01
INSTALLATION Campbell Foss		PROJECT MANAGER John Eldridge
TESTING HELD AT Richmond, Ca		DESIGN ENGINEER Chris Wright

Customer Acceptance Test Procedure

ID	Test Description	Result	Signature of AKA	Signature of Client
PREPARATION (Dock Trials)				
1	Vessel is to be placed in Hybrid Stop Mode with shore power connected and battery bank below its maximum SOC set point. Bring up the DC bus as per operating procedures.			RM
2	Verify that the procedure is accurate and that DC bus is up on Shore Power.			RM
TEST BATTERY CHARGING				
3	Verify that the DCDC converter is in buck mode and charging batteries.	In Buck, but HMI Reads Boost		RM
4	Verify that charging stops at the upper SOC limit.			
5	Record upper/lower limit set points.			
6	Verify HMI and meter readings.	HMI reads "BOOST"		
7	Verify throttles are disabled.	*		RM

* Throttles were disabled, however HMI shows ASD clutches engaged due to HMI reading throttle position

JOB NUMBER 2228	**TESTING DOCUMENTATION**	DOCUMENT REFERENCE 111104 - CAT Test Procedure 5A-CAM-2228-Stop Mode Functionality-no Batteries (Shore Power Disconnected) - Rev01
INSTALLATION Campbell Foss		PROJECT MANAGER John Eldridge
TESTING HELD AT Richmond, Ca		DESIGN ENGINEER Chris Wright

Customer Acceptance Test Procedure

ID	Test Description	Result	Signature of AKA	Signature of Client
PREPARATION (Dock Trials)				
1	Vessel is to be placed in Hybrid Stop Mode with shore power disconnected, dead ship condition. DC bus should come up via starboard generator.		[illegible]	RCM
2	Bring up the DC bus with the key switch and confirm the starboard generator auto-starts, the bus pre-charges and the island AFE supports the AC bus.		[illegible]	RCM
3	Verify throttles are disabled.	* disabled, but HMI shows as in	[illegible]	RCM
4	Verify HMI and meter readings	* Island AFE shows incorrect kW	[illegible]	RCM

JOB NUMBER 2228	**TESTING DOCUMENTATION**	DOCUMENT REFERENCE 111104 - CAT Test Procedure 5-CAM-2228-Stop Mode Functionality (Shore Power Disconnected) - Rev01
INSTALLATION Campbell Foss		PROJECT MANAGER John Eldridge
TESTING HELD AT Richmond, Ca		DESIGN ENGINEER Chris Wright

Customer Acceptance Test Procedure

ID	Test Description	Result	Signature of AKA	Signature of Client
PREPARATION (Dock Trials)				
1	Vessel is to be placed in Hybrid Stop Mode with shore power disconnected, dead ship condition. DC bus is brought up from batteries.			RM
2	Verify throttles are disabled.			RM
TEST BATTERY CHARGING				
3	Allow bank voltage to drop to lower set point. (this can be set high for demonstration). Confirm that the small gen auto-starts at the lower limit, connects to the bus and that the DCDC converter automatically goes into buck mode.	Batteries in ~~Boost~~ Buck but HMI reads ~~Buck~~ Boost		RM
4	Allow small gen to charge bank, verify that the small gen disconnects at the SOC upper limit (this can be reduced in the PLC for demonstration purposes) and that the DCDC converter goes into Boost mode with power transferred seamlessly.			RM
5	Confirm that the small gen shuts down after 5 minute cool down period.			RM
6	Verify HMI and meter readings			RM
7	Reset (if necessary) and record lower and upper limit set points.	30 & 95		RM

JOB NUMBER 2228	**TESTING DOCUMENTATION**	DOCUMENT REFERENCE 111104 - CAT Test Procedure 6A-CAM-2228-Idle Mode Functionality-no Batteries-Rev01
INSTALLATION Campbell Foss		PROJECT MANAGER John Eldridge
TESTING HELD AT Richmond, Ca		DESIGN ENGINEER Chris Wright

Customer Acceptance Test Procedure

ID	Idle Mode	Result	Signature of AKA	Signature of Client
PREPARATION (Dock Trials)				
1	Vessel to be placed in Hybrid Stop Mode, with shore power disconnected and DC bus up on the small generator. All devices should be in remote.		JE	RM
TEST IDLE MODE FUNCTIONALITY – NO BATTERIES				
2	Confirm all modes available as indicated by LEDs and HMI.		JE	RM
3	Choose "Idle Mode" and confirm successful transition at bridge console, HMI and ER.		JE	RM
4	Verify throttles are enabled.		JE	RM
5	Verify HMI and meter readings		JE	RM
6	Return system to Stop Mode		JE	RM

JOB NUMBER 2228	**TESTING DOCUMENTATION**	DOCUMENT REFERENCE 111104 - CAT Test Procedure 6-CAM-2228-Idle Mode Functionality-Rev01
INSTALLATION Campbell Foss		PROJECT MANAGER John Eldridge
TESTING HELD AT Richmond, Ca		DESIGN ENGINEER Chris Wright

Customer Acceptance Test Procedure

ID	Idle Mode	Result	Signature of AKA	Signature of Client
PREPARATION (Dock Trials)				
1	Vessel to be placed in Hybrid Stop Mode, with shore power disconnected and DC bus up on batteries. All devices should be in remote.			
TEST IDLE MODE FUNCTIONALITY				
2	Confirm all modes available as indicated by LEDs and HMI.			
3	Choose "Idle Mode" and confirm successful transition at bridge console, HMI and ER.			
4	Verify throttles are enabled.			
TEST TRANSITION FROM BATTERIES TO SMALL GEN				
5	Allow batteries to be reduced to the minimum SOC. This can be accelerated by turning the props or setting the low limit high in the PLC.			
6	Verify that the small gen starts and connects to DC bus.			
7	Verify the DCDC converter goes to buck.	*		
8	Verify HMI and meter readings			
9	Return system to Stop Mode			

JOB NUMBER 2228	**TESTING DOCUMENTATION**	DOCUMENT REFERENCE 111104 - CAT Test Procedure 7A-CAM-2228-Transit 1 Mode Functionality-no Batteries-Rev01
INSTALLATION Campbell Foss		PROJECT MANAGER John Eldridge
TESTING HELD AT Richmond, Ca		DESIGN ENGINEER Chris Wright

Customer Acceptance Test Procedure

ID	Test Description	Result	Signature of AKA	Signature of Client
PREPARATION (Dock Trials)				
1	Vessel to be placed in Hybrid Stop Mode, with shore power disconnected and DC bus up on the starboard generator. All devices should be in remote.		JE	RM
TEST TRANSIT #1 MODE FUNCTIONALITY – NO BATTERIES				
2	Confirm all modes available as indicated by LEDs and HMI.		JE	RM
3	Choose "Transit #1 Mode" and confirm successful transition at bridge console, HMI and ER.		JE	RM
4	Verify that the large gen starts and connects to the DC bus.		JE	RM
5	Verify that the small gen disconnects form the DC bus and shits down after a 5 minute cool down period.		JE	RM
6	Verify throttles are enabled.		JE	RM
7	Verify steering for responsiveness.		JE	RM
8	Verify propulsion by providing throttle.		JE	RM
9	Verify HMI and meter readings		JE	RM
10	Return system to Stop Mode		JE	RM

JOB NUMBER 2228	**TESTING DOCUMENTATION**	DOCUMENT REFERENCE 111104 - CAT Test Procedure 7-CAM-2228-Transit 1 Mode Functionality-Rev01
INSTALLATION Campbell Foss		PROJECT MANAGER John Eldridge
TESTING HELD AT Richmond, Ca		DESIGN ENGINEER Chris Wright

Customer Acceptance Test Procedure

ID	Test Description	Result	Signature of AKA	Signature of Client
PREPARATION (Dock Trials)				
1	Vessel to be placed in Hybrid Stop Mode, with shore power disconnected and DC bus up on batteries. All devices should be in remote. Batteries should be below maximum SOC.			
TEST TRANSIT #1 MODE FUNCTIONALITY				
2	Confirm all modes available as indicated by LEDs and HMI.			
3	Choose "Transit #1 Mode" and confirm successful transition at bridge console, HMI and ER.			
4	Verify that the large gen starts and connects to the DC bus.			
5	Verify that the DCDC converter begins charging the batteries			
6	Verify throttles are enabled.			
7	Verify steering for responsiveness.			
8	Verify propulsion by providing throttle.			
9	Verify HMI and meter readings	HMI-360 meter-350		
10	Return system to Stop Mode			

JOB NUMBER 2228	**TESTING DOCUMENTATION**	DOCUMENT REFERENCE 111104 - CAT Test Procedure 9A-CAM-2228-Transit 2 Mode Functionality-no Batteries-Rev01
INSTALLATION Campbell Foss		PROJECT MANAGER John Eldridge
TESTING HELD AT Richmond, Ca		DESIGN ENGINEER Chris Wright

Customer Acceptance Test Procedure

ID	Test Description	Result	Signature of AKA	Signature of Client
PREPARATION (Dock Trials)				
1	Vessel to be placed in Hybrid Stop Mode, with shore power disconnected and DC bus up on the starboard generator. All devices should be in remote.			RM
TEST TRANSIT #2 MODE FUNCTIONALITY – NO BATTERIES				
2	Confirm all modes available as indicated by LEDs and HMI.			RM
3	Choose "Transit #2 Mode" and confirm successful transition at bridge console, HMI and ER.			RM
4	Verify that the port generator starts and connects to the DC bus.			RM
5	Verify throttles are enabled.			RM
6	Verify steering for responsiveness.			RM
7	Verify propulsion by providing throttle.			RM
8	Verify HMI and meter readings			RM
9	Return system to Stop Mode			RM

JOB NUMBER 2228	**TESTING DOCUMENTATION**	DOCUMENT REFERENCE 111104 - CAT Test Procedure 9-CAM-2228-Transit 2 Mode Functionality-Rev01
INSTALLATION Campbell Foss		PROJECT MANAGER John Eldridge
TESTING HELD AT Richmond, Ca		DESIGN ENGINEER Chris Wright

Customer Acceptance Test Procedure

ID	Test Description	Result	Signature of AKA	Signature of Client
PREPARATION (Dock Trials)				
1	Vessel to be placed in Hybrid Stop Mode, with shore power disconnected and DC bus up on the batteries. All devices should be in remote.			RM
TEST TRANSIT #2 MODE FUNCTIONALITY				
2	Confirm all modes available as indicated by LEDs and HMI.			RM
3	Choose "Transit #2 Mode" and confirm successful transition at bridge console, HMI and ER.			RM
4	Verify that the both generators start and connect to the DC bus.			RM
5	Verify that the DCDC converter begins charging the batteries.			RM
6	Verify throttles are enabled.			RM
7	Verify steering for responsiveness.			RM
8	Verify propulsion by providing throttle.			RM
9	Verify HMI and meter readings	Stbd gauge - 110 HMI 125 meter		RM
10	Return system to Stop Mode			RM

JOB NUMBER 2228	**TESTING DOCUMENTATION**	DOCUMENT REFERENCE 111104 - CAT Test Procedure 10A-CAM-2228-Assist Mode Functionality-no Batteries-Rev01
INSTALLATION Campbell Foss		PROJECT MANAGER John Eldridge
TESTING HELD AT Richmond, Ca		DESIGN ENGINEER Chris Wright

Customer Acceptance Test Procedure

ID	Test Description	Result	Signature of AKA	Signature of Client
PREPARATION (Dock Trials)				
1	Vessel to be placed in Hybrid Stop Mode, with shore power disconnected and DC bus up on the starboard generator. All devices to be in remote mode.			RM
TEST ASSIST MODE FUNCTIONALITY				
2	Confirm all modes available as indicated by LEDs and HMI.			RM
3	Choose "Assist Mode" and confirm successful transition at bridge console, HMI and ER.			RM
4	Verify that both main engines started.			RM
5	Verify that the ME clutches engaged.			RM
6	~~Verify that starboard generator started.~~ Starbgen stops!			RM
7	Verify that the MG's are supporting the DC bus.			RM
8	Verify throttles are enabled.			RM
9	Verify steering for responsiveness.			RM
10	Verify propulsion by providing throttle.			RM
11	Verify HMI and meter readings			RM
12	Return system to Stop mode			RM

JOB NUMBER 2228	TESTING DOCUMENTATION	DOCUMENT REFERENCE 111104 - CAT Test Procedure 10-CAM-2228-Assist Mode Functionality-Rev01
INSTALLATION Campbell Foss		PROJECT MANAGER John Eldridge
TESTING HELD AT Richmond, Ca		DESIGN ENGINEER Chris Wright

Customer Acceptance Test Procedure

ID	Test Description	Result	Signature of AKA	Signature of Client
PREPARATION (Dock Trials)				
1	Vessel to be placed in Hybrid Stop Mode, with shore power disconnected and DC bus up on batteries. All devices to be in remote mode. Batteries should be below maximum SOC.		[illegible]	RM
TEST ASSIST MODE FUNCTIONALITY				
2	Confirm all modes available as indicated by LEDs and HMI.		[illegible]	RM
3	Choose "Assist Mode" and confirm successful transition at bridge console, HMI and ER.	slow w/multiple reclutches	[illegible]	RM
4	Verify that both main engines started.		[illegible]	RM
5	Verify that the ME clutches engaged.	1st time clutches took awhile 2nd time came fast	[illegible]	RM
6	~~Verify that starboard generator started.~~	NO - no genset for Assist	[illegible]	
7	Verify that the MG's are supporting the DC bus.		[illegible]	RM
8	Verify that the DCDC converter is charging the batteries.		[illegible]	RM
9	Verify throttles are enabled.		[illegible]	RM
10	Verify steering for responsiveness.		[illegible]	RM
11	Verify propulsion by providing throttle.		[illegible]	RM
12	Verify HMI and meter readings		[illegible]	RM

OK w/ FOD

JOB NUMBER 2228	TESTING DOCUMENTATION	DOCUMENT REFERENCE 111104 - CAT Test Procedure 10-CAM-2228-Assist Mode Functionality-Rev01
INSTALLATION Campbell Foss		PROJECT MANAGER John Eldridge
TESTING HELD AT Richmond, CA		DESIGN ENGINEER Chris Wright

Customer Acceptance Test Procedure

ID	Test Description	Result	Signature of AKA	Signature of Client
13	Return system to Stop mode			

JOB NUMBER 2228	**TESTING DOCUMENTATION**	DOCUMENT REFERENCE 111104 - CAT Test Procedure 11A-CAM-2228-Mode Transitions-no Batteries-Rev01
INSTALLATION Campbell Foss		PROJECT MANAGER John Eldridge
TESTING HELD AT Richmond, Ca		DESIGN ENGINEER Chris Wright

Customer Acceptance Test Procedure

ID	Test Description	Result	Signature of AKA	Signature of Client
PREPARATION (At Dock Trials)				
1	Vessel to be placed in Hybrid Stop Mode, with shore power disconnected and DC bus up on the starboard generator.		[illegible]	RM
TEST MODE TRANSITIONS				
2	Confirm all modes available as indicated by LEDs and HMI.		[illegible]	RM
3	Test "Stop" to "Idle" to "Stop" confirm successful transitions at bridge console, HMI and E/R.	3 secs 2 secs	[illegible]	RM
4	Test "Stop" to "Transit #1" to "Stop" and confirm successful transitions at bridge console, HMI and E/R.	6 secs 2 secs	[illegible]	RM
5	Test "Stop" to "Transit #2" to "Stop" and confirm successful transitions at bridge console, HMI and E/R.	5 secs 2 secs	[illegible]	RM
6	Test "Stop" to "Assist" to "Stop" and confirm successful transitions at bridge console, HMI and E/R.	35 secs 1 sec	[illegible]	RM
7	Test "Idle" to "Transit #1" to "Idle" and confirm successful transition at bridge console, HMI and E/R.	5 sec 2 sec	[illegible]	RM
8	Test "Idle" to "Transit #2" to "Idle" and confirm successful transitions at bridge console, HMI and E/R.	7 secs 1 sec	[illegible]	RM
9	Test "Idle" to "Assist" to "Idle" and confirm successful transitions at bridge console, HMI and E/R.	31 sec 1 s	[illegible]	RM
10	Test "Transit #1" to "Transit #2" to "Transit #1" and confirm successful transitions at bridge console, HMI and E/R.	5 sec 2 s	[illegible]	RM

JOB NUMBER 2228	TESTING DOCUMENTATION	DOCUMENT REFERENCE 111104 - CAT Test Procedure 11A-CAM-2228-Mode Transitions-no Batteries-Rev01
INSTALLATION Campbell Foss		PROJECT MANAGER John Eldridge
TESTING HELD AT Richmond, Ca		DESIGN ENGINEER Chris Wright

Customer Acceptance Test Procedure

ID	Test Description	Result	Signature of AKA	Signature of Client
11	Test "Transit #1" to "Assist" to "Transit #1" and confirm successful transitions at bridge console, HMI and E/R.	✓ 2 sec		RM
12	Test "Transit #2" to "Assist" to "Transit #2" and confirm successful transitions at bridge console, HMI and E/R.	28 s 3 s		RM

JOB NUMBER 2228	**TESTING DOCUMENTATION**	DOCUMENT REFERENCE 111104 - CAT Test Procedure 11-CAM-2228-Mode Transitions-Rev01
INSTALLATION Campbell Foss		PROJECT MANAGER John Eldridge
TESTING HELD AT Richmond, Ca		DESIGN ENGINEER Chris Wright

Customer Acceptance Test Procedure

ID	Test Description	Result	Signature of AKA	Signature of Client
PREPARATION (At Dock Trials)				
1	Vessel to be placed in Hybrid Stop Mode, with shore power disconnected and DC bus up. Batteries should be below maximum SOC.			RM
TEST MODE TRANSITIONS				
2	Confirm all modes available as indicated by LEDs and HMI.			RM
3	Test "Stop" to "Idle" to "Stop" confirm successful transitions at bridge console, HMI and E/R.			RM
4	Test "Stop" to "Transit #1" to "Stop" and confirm successful transitions at bridge console, HMI and E/R.			RM
5	Test "Stop" to "Transit #2" to "Stop" and confirm successful transitions at bridge console, HMI and E/R.			RM
6	Test "Stop" to "Assist" to "Stop" and confirm successful transitions at bridge console, HMI and E/R.	13 secs		RM
7	Test "Idle" to "Transit #1" to "Idle" and confirm successful transition at bridge console, HMI and E/R.	4sec		RM
8	Test "Idle" to "Transit #2" to "Idle" and confirm successful transitions at bridge console, HMI and E/R.	7sec 4sec		RM
9	Test "Idle" to "Assist" to "Idle" and confirm successful transitions at bridge console, HMI and E/R.	42sec 4sec		RM
10	Test "Transit #1" to "Transit #2" to "Transit #1" and confirm successful transitions at bridge console, HMI and E/R.	6sec gen running 4sec		RM
11	Test "Transit #1" to "Assist" to "Transit #1"	Took awhile, 42 secs		RM

JOB NUMBER 2228	TESTING DOCUMENTATION	DOCUMENT REFERENCE 111104 - CAT Test Procedure 11-CAM-2228-Mode Transitions-Rev01
INSTALLATION Campbell Foss		PROJECT MANAGER John Eldridge
TESTING HELD AT Rainier, Or		DESIGN ENGINEER Chris Wright

Customer Acceptance Test Procedure

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OK

ID	Test Description	Result	Signature of AKA	Signature of Client
	and confirm successful transitions at bridge console, HMI and E/R.	3sec ~~stop pont sent~~ stayed in tmx,		Ron
12	Test "Transit #2" to "Assist" to "Transit #2" and confirm successful transitions at bridge console, HMI and E/R.	37 secs 3 secs		Ron

JOB NUMBER 2228	**TESTING DOCUMENTATION**	DOCUMENT REFERENCE 111104 - CAT Test Procedure 12-CAM-2228-Non Hybrid Mode Selection-Rev01
INSTALLATION Campbell Foss		PROJECT MANAGER John Eldridge
TESTING HELD AT Richmond, Ca		DESIGN ENGINEER Chris Wright

Customer Acceptance Test Procedure

ID	Test Description	Result	Signature of AKA	Signature of Client
PREPARATION (At Dock Trials)				
1	Vessel to be placed in Hybrid Stop Mode, with shore power disconnected and DC bus up on batteries.			RM
STOP MODE TO NON-HYBRID (PLC OPERATIONAL)				
2	Confirm all modes available as indicated by LEDs and HMI.			RM
3	As per procedures, choose "Non- Hybrid Mode" and confirm successful transition at bridge console, HMI and ER.			RM
4	Verify that the Island AFE contactor opens, vessel should go black ship.			RM
5	Verify that the starboard gen starts and connects to AC bus.			RM
6	Verify that both main engines can be started from the wheelhouse panel.			RM
7	Verify that the ME clutches engage.			RM
8	Verify throttles are enabled.			RM
9	Verify steering for responsiveness.			RM
10	Return system to Hybrid Stop mode			RM
IDLE MODE TO NON-HYBRID (PLC OPERATIONAL)				
11	Place system in Idle Mode on batteries.			RM

JOB NUMBER 2228	TESTING DOCUMENTATION	DOCUMENT REFERENCE 111104 - CAT Test Procedure 12-CAM-2228-Non Hybrid Mode Selection-Rev01
INSTALLATION Campbell Foss		PROJECT MANAGER John Eldridge
TESTING HELD AT Rainier, Or		DESIGN ENGINEER Chris Wright

Customer Acceptance Test Procedure

ID	Test Description	Result	Signature of AKA	Signature of Client
12	As per procedures, choose "Non- Hybrid Mode" and confirm successful transition at bridge console, HMI and ER.			RM
13	Verify that the Island AFE contactor opens, vessel should go black ship.			RM
14	Verify that the starboard gen starts and connects to AC bus.			RM
15	Verify that both main engines can be started from the wheelhouse panel.			RM
16	Verify that the ME clutches engage.			RM
17	Verify throttles are enabled.			RM
18	Verify steering for responsiveness.			RM
19	Return system to Hybrid Stop mode			RM
TRANSIT #1 MODE TO NON-HYBRID (PLC OPERATIONAL)				
20	Place system in Transit #1 Mode			RM
21	As per procedures, choose "Non- Hybrid Mode" and confirm successful transition at bridge console, HMI and ER.			RM
22	Verify that the Island AFE contactor opens, vessel should go black ship.			RM
23	Verify that port gen contactor opens and gen shuts down after 5 minute cool down period.			RM
24	Verify that the starboard gen starts and connects to AC bus.			RM
25	Verify that both main engines can be started			RM

JOB NUMBER 2228	TESTING DOCUMENTATION	DOCUMENT REFERENCE 111104 - CAT Test Procedure 12-CAM-2228-Non Hybrid Mode Selection-Rev01
INSTALLATION Campbell Foss		PROJECT MANAGER John Eldridge
TESTING HELD AT Richmond, Ca		DESIGN ENGINEER Chris Wright

Customer Acceptance Test Procedure

ID	Test Description	Result	Signature of AKA	Signature of Client
	from the wheelhouse panel.			
26	Verify that the ME clutches engage.			
27	Verify throttles are enabled.			
28	Verify steering for responsiveness.			
29	Return system to Hybrid Stop mode			
TRANSIT #2 MODE TO NON-HYBRID (PLC OPERATIONAL)				
30	Place the system in Transit Mode #2.			
31	As per procedures, choose "Non- Hybrid Mode" and confirm successful transition at bridge console, HMI and ER.			
32	Verify that the Island AFE contactor opens, vessel should go black ship.			
33	Verify that the starboard gen contactor opens and that the gen connects to AC bus.			
34	Verify that the port generator contactor opens and the generator shuts down after 5 minute cool down period.			
35	Verify that both main engines can be started from the wheelhouse panel.			
36	Verify that the ME clutches engage.			
37	Verify throttles are enabled.			
38	Verify steering for responsiveness.			

JOB NUMBER 2228	**TESTING DOCUMENTATION**	DOCUMENT REFERENCE 111104 - CAT Test Procedure 12-CAM-2228-Non Hybrid Mode Selection-Rev01
INSTALLATION Campbell Foss		PROJECT MANAGER John Eldridge
TESTING HELD AT Rainier, Or		DESIGN ENGINEER Chris Wright

Customer Acceptance Test Procedure

ID	Test Description	Result	Signature of AKA	Signature of Client
39	Return system to Hybrid Stop mode			RM
ASSIST MODE TO NON-HYBRID (PLC OPERATIONAL)				
40	Place the system in Assist Mode.			RM
41	As per procedures, choose "Non- Hybrid Mode" and confirm successful transition at bridge console, HMI and ER.			RM
42	Verify that the Island AFE contactor opens, vessel should go black ship.			RM
43	Verify that the starboard gen starts (if not already running) and connects to AC bus.			RM
44	Verify throttles are enabled.			RM
45	Verify steering for responsiveness.			RM
46	Return system to Hybrid Stop mode			RM

JOB NUMBER 2228	**TESTING DOCUMENTATION**	DOCUMENT REFERENCE 111104 - CAT Test Procedure 13-CAM-2228-AFE Failure, All Modes-Rev02.docx
INSTALLATION Campbell Foss		PROJECT MANAGER John Eldridge
TESTING HELD AT Richmond, Ca		DESIGN ENGINEER Chris Wright

Customer Acceptance Test Procedure

ID	Test Description	Result	Signature of AKA	Signature of Client
PREPARATION (DOCK TRIALS)				
1	Vessel to be placed in Hybrid Stop Mode, with shore power disconnected and DC bus up on batteries. All devices should be in remote and all Modes should be available.			RM
TEST AFE FAILURE WHILE IN STOP MODE The loss of the Island AFE will result in loss of AC bus support. The vessel will go black ship during the time it takes for the stbd generator to auto-start and connect direct to the AC bus. NOTE: Once a generator connects direct to the AC bus, the vessel should be switched to non-hybrid mode when it is safe to do so.				
2	Place the vessel in Stop Mode.			RM
3	Simulate AFE failure by stopping the drive or opening its line contactor.			RM
4	Verify system alarm.	Alarms not yet installed		
5	Verify that the stbd gen auto-starts and connects, restoring AC power.	No - this doesn't happen in "stop"		
6	Record time to recover.	"		
7	Restart Island AFE and return system to normal configuration.			RM
TEST AFE FAILURE WHILE IN IDLE MODE The loss of the AFE will result in loss of AC bus support. The vessel will go black ship during the time it takes for the stbd generator to auto-start and connect direct to the AC bus. Propulsion will still be available via the batteries. NOTE: Once a generator connects direct to the AC bus, the vessel should be switched to non-hybrid mode when it is safe to do so.				
8	Place the vessel in Idle Mode.			RM

JOB NUMBER 2228	TESTING DOCUMENTATION	DOCUMENT REFERENCE 111104 - CAT Test Procedure 13-CAM-2228-AFE Failure, All Modes-Rev02.docx
INSTALLATION Campbell Foss		PROJECT MANAGER John Eldridge
TESTING HELD AT Richmond, Ca		DESIGN ENGINEER Chris Wright

Customer Acceptance Test Procedure

ID	Test Description	Result	Signature of AKA	Signature of Client
9	Simulate AFE failure by stopping the drive or opening its line contactor.			RM
10	Verify system alarm.	N/A		RM
11	Verify that the stbd gen auto-starts (if not running) and connects, restoring AC power.			RM
12	Record time to recover.	10sec		RM
13	Verify propulsion and steering.			RM
14	Restart Island AFE and return system to normal configuration.			RM

TEST AFE FAILURE WHILE IN TRANSIT #1 MODE

The loss of the AFE will result in loss of AC bus support. The vessel will go black ship during the time it takes for the stbd generator to auto-start and connect direct to the AC bus.

Propulsion will still be available.

NOTE: Once a generator connects direct to the AC bus, the vessel should be switched to non-hybrid mode when it is safe to do so.

15	Place the vessel in Transit #1 Mode.			RM
16	Simulate AFE failure by stopping the drive or opening its line contactor.			RM
17	Verify system alarm.	N/A		RM
18	Verify that the stbd gen auto-starts and connects, restoring AC power.	9s		RM
19	Record time to recover.	9sec		RM
20	Verify propulsion and steering.			RM

JOB NUMBER 2228	TESTING DOCUMENTATION	DOCUMENT REFERENCE 111104 - CAT Test Procedure 13-CAM-2228-AFE Failure, All Modes-Rev02.docx
INSTALLATION Campbell Foss		PROJECT MANAGER John Eldridge
TESTING HELD AT Richmond, Ca		DESIGN ENGINEER Chris Wright

Customer Acceptance Test Procedure

ID	Test Description	Result	Signature of AKA	Signature of Client
21	Restart Island AFE and return system to normal configuration.			RM

TEST AFE FAILURE WHILE IN TRANSIT #2 MODE

The loss of the AFE will result in loss of AC bus support. The vessel will go black ship during the time it takes for the stbd generator to disconnect from the DC bus and reconnect to the AC bus.

Propulsion will still be available.

NOTE: Once a generator connects direct to the AC bus, the vessel should be switched to non-hybrid mode when it is safe to do so.

22	Place the vessel in Transit #2 Mode.			RM
23	Simulate AFE failure by stopping the drive or opening its line contactor.			RM
24	Verify system alarm.	N/A		
25	Verify that the stbd gen disconnects from the DC bus and reconnects to the AC bus, restoring AC power.			RM
26	Record time to recover.	3s		RM
27	Verify propulsion and steering.			RM
28	Restart Island AFE and return system to normal configuration.			RM

JOB NUMBER 2228	TESTING DOCUMENTATION	DOCUMENT REFERENCE 111104 - CAT Test Procedure 13-CAM-2228-AFE Failure, All Modes-Rev02.docx
INSTALLATION Campbell Foss		PROJECT MANAGER John Eldridge
TESTING HELD AT Richmond, Ca		DESIGN ENGINEER Chris Wright

Customer Acceptance Test Procedure

ID	Test Description	Result	Signature of AKA	Signature of Client
TEST AFE FAILURE WHILE IN ASSIST MODE				
The loss of the AFE will result in loss of AC bus support and therefore winch control. The vessel will go black ship during the time it takes for the stbd generator to auto-start and connect to the AC bus.				
Once AC power is lost, the clutch may disengage due to loss of pressure, therefore an open signal will be sent to the clutch to ensure it does not re-engage at high engine RPM (when AC is restored). The captain will be required to bring the throttles back to the "0" position for the clutch to re-engage.				
NOTE: Once a generator connects direct to the AC bus, the vessel should be switched to non-hybrid mode when it is safe to do so.				
29	Place the vessel in Assist Mode.		[illegible]	RM
30	Simulate AFE failure by stopping the drive or opening its line contactor.		[illegible]	RM
31	Verify system alarm.	N/A	[illegible]	RM
32	Verify that the stbd gen auto-starts and connects to the AC bus, restoring AC power.		[illegible]	RM
33	Record time to recover.	13 s	[illegible]	RM
34	Verify propulsion, clutch and steering.		[illegible]	RM
35	Restart Island AFE and return system to normal configuration.		[illegible]	RM

JOB NUMBER 2228	**TESTING DOCUMENTATION**	DOCUMENT REFERENCE 111104 - CAT Test Procedure 14-CAM-2228-DC Bus Failure, All Modes-Rev02.docx
INSTALLATION Campbell Foss		PROJECT MANAGER John Eldridge
TESTING HELD AT Richmond, Ca		DESIGN ENGINEER Chris Wright

Customer Acceptance Test Procedure

ID	Test Description	Result	Signature of AKA	Signature of Client
PREPARATION (DOCK TRIALS)				
1	Vessel to be placed in Hybrid Stop Mode, with shore power disconnected and DC bus up. DC Bus to be supported by batteries. All devices in remote mode and all modes should be available.			
TEST DC BUS FAILURE WHILE IN STOP MODE The loss of the DC Bus will result in loss of AC bus support. The vessel will go black ship during the time it takes for the stbd generator to auto-start and connect direct to the AC bus. The PLC's will remain operational.				
2	Place the vessel in Stop Mode.			
3	Simulate DC Bus failure by E-stopping the Bus.			
4	Verify system alarm.			
5	Verify that the stbd gen auto-starts and connects, restoring AC power.			
6	Record time to recover.			
7	Restart DC Bus and return system to normal configuration.			

Boat goes black ship - genset does NOT come on by design

JOB NUMBER 2228	TESTING DOCUMENTATION	DOCUMENT REFERENCE 111104 - CAT Test Procedure 14-CAM-2228-DC Bus Failure, All Modes-Rev02.docx
INSTALLATION Campbell Foss		PROJECT MANAGER John Eldridge
TESTING HELD AT Richmond, Ca		DESIGN ENGINEER Chris Wright

Customer Acceptance Test Procedure

ID	Test Description	Result	Signature of AKA	Signature of Client
TEST DC BUS FAILURE WHILE IN IDLE MODE The loss of the DC BUS will result in loss of propulsion and AC bus support. The vessel will go black ship during the time it takes for the stbd generator to auto-start and connect direct to the AC bus. The PLC's will remain operational. The vessel will need to be switched to non-hybrid and the main engines will need to be started and clutches engaged from the WH position.				
8	Place the vessel in Idle Mode.		[illegible]	RM
9	Simulate DC Bus failure by E-Stopping the bus.		[illegible]	RM
10	Verify system alarm.	N/A	[illegible]	RM
11	Verify that the stbd gen auto-starts and connects, restoring AC power.	N/A	[illegible]	RM
12	Switch to Non-Hybrid and confirm main engine start and clutch engagement.		[illegible]	RM
13	Verify throttle and steering control.		[illegible]	RM
14	Record time to recover.	~ 15 s	[illegible]	RM
15	Restart DC Bus and return system to normal configuration.		[illegible]	RM

JOB NUMBER 2228	TESTING DOCUMENTATION	DOCUMENT REFERENCE 111104 - CAT Test Procedure 14-CAM-2228-DC Bus Failure, All Modes-Rev02.docx
INSTALLATION Campbell Foss		PROJECT MANAGER John Eldridge
TESTING HELD AT Richmond, Ca		DESIGN ENGINEER Chris Wright

Customer Acceptance Test Procedure

ID	Test Description	Result	Signature of AKA	Signature of Client
TEST DC BUS FAILURE WHILE IN TRANSIT #1 MODE				
The loss of the DC Bus will result in loss of propulsion and AC bus support. The vessel will go black ship during the time it takes for the stbd generator to auto-start and connect direct to the AC bus. The PLC's will remain operational.				
The vessel will need to be switched to non-hybrid and the main engines will need to be started and clutches engaged from the WH position.				
The port generator will remain running and can be shut down manually once the AC bus is being supported by the stbd gen.				
16	Place the vessel in Transit #1 Mode.		[illegible]	RM
17	Simulate DC Bus failure by E-stopping the bus.		[illegible]	RM
18	Verify system alarm.	N/A	[illegible]	RM
19	Verify that the stbd gen auto-starts and connects, restoring AC power.		[illegible]	RM
20	Switch to Non-Hybrid and confirm main engine start and clutch engagement.		[illegible]	RM
21	Verify propulsion and steering.		[illegible]	RM
22	Record time to recover.	75 secs for AC Bus	[illegible]	RM
23	Restart DC Bus and return system to normal configuration.		[illegible]	RM

JOB NUMBER 2228	TESTING DOCUMENTATION	DOCUMENT REFERENCE 111104 - CAT Test Procedure 14-CAM-2228-DC Bus Failure, All Modes-Rev02.docx
INSTALLATION Campbell Foss		PROJECT MANAGER John Eldridge
TESTING HELD AT Richmond, Ca		DESIGN ENGINEER Chris Wright

Customer Acceptance Test Procedure

ID	Test Description	Result	Signature of AKA	Signature of Client
TEST DC BUS FAILURE WHILE IN TRANSIT #2 MODE The loss of the DC Bus will result in loss of propulsion and AC bus support. The vessel will go black ship during the time it takes for the stbd generator to disconnect from the DC bus and re-connect direct to the AC bus. The PLC's will remain operational. The vessel will need to be switched to non-hybrid and the main engines will need to be started and clutches engaged from the WH position. The port generator will remain running and can be shut down manually once the AC bus is being supported by the stbd gen.				
24	Place the vessel in Transit #2 Mode.		[illegible]	RM
25	Simulate DC Bus failure by E-stopping the bus.		[illegible]	RM
26	Verify system alarm.	N/A		
27	Verify that the stbd gen disconnects from the DC bus and reconnects to the AC bus, restoring AC power.		[illegible]	RM
28	Switch to Non-Hybrid and confirm main engine start and clutch engagement.		[illegible]	RM
29	Verify propulsion and steering.		[illegible]	RM
30	Record time to recover.	1-2 s	[illegible]	RM
31	Restart DC Bus and return system to normal configuration.		[illegible]	RM

JOB NUMBER 2228	**TESTING DOCUMENTATION**	DOCUMENT REFERENCE 111104 - CAT Test Procedure 14-CAM-2228-DC Bus Failure, All Modes-Rev02.docx
INSTALLATION Campbell Foss		PROJECT MANAGER John Eldridge
TESTING HELD AT Richmond, Ca		DESIGN ENGINEER Chris Wright

Customer Acceptance Test Procedure

ID	Test Description	Result	Signature of AKA	Signature of Client
TEST DC BUS FAILURE WHILE IN ASSIST MODE The loss of the DC Bus will result in loss of AC bus support. The vessel will go black ship during the time it takes for the stbd generator to auto-start and connect direct to the AC bus. Once AC power is lost, the clutch may disengage due to loss of pressure, therefore an open signal will be sent to the clutch to ensure it does not re-engage at high engine RPM (when AC is restored). The captain will be required to bring the throttles back to the "0" position for the clutch to re-engage. No other hybrid modes will be available. The vessel must be placed in non-hybrid mode when safe to do so.				
32	Place the vessel in Assist Mode.			RCM
33	Simulate DC Bus failure by E-stopping the bus.			RCM
34	Verify system alarm.			RCM
35	Verify that the stbd gen auto-starts and connects to the AC bus, restoring AC power.			RCM
36	Verify propulsion, clutch and steering.			RCM
37	Record time to recover.	8 secs		RCM
38	Restart DC Bus and return system to normal configuration.			RCM

JOB NUMBER 2228	TESTING DOCUMENTATION	DOCUMENT REFERENCE 111104 - CAT Test Procedure 15-CAM-2228-Hybrid Battery System Failure-Rev01
INSTALLATION Campbell Foss		PROJECT MANAGER John Eldridge
TESTING HELD AT Richmond, Ca		DESIGN ENGINEER Chris Wright

Customer Acceptance Test Procedure

ID	Test Description	Result	Signature of AKA	Signature of Client
PREPARATION (Dock Trials)				
1	Vessel to be placed in Idle Mode, with shore power disconnected and DC bus up and supported by batteries.			RM
TEST LOSS OF HYBRID SYSTEM BATTERIES IN IDLE MODE Loss of batteries could be DCDC failure, Loss of Pack Controller or blown fuse. In all other modes the DC bus is being supported by additional resources, therefore the bus will remain stable.				
2	Simulate battery loss by opening switch on Corvus Pack Controller. Dead ship condition should momentarily occur.			
3	Verify system alarm	N/A		
4	Verify that the starboard gen starts and restores the DC bus.			
5	Verify that Island AFE supports the AC bus, restoring AC power.			
6	Verify throttles are enabled.			
7	Verify steering for responsiveness.			

No, system goes to "non-hybrid" w/ stbd genset supporting AC bus. operator can then go to hybrid-Idle on genset.

- confirmed dropping batteries in Transit!
- No problems

JOB NUMBER 2228	**TESTING DOCUMENTATION**	DOCUMENT REFERENCE 111104 - CAT Test Procedure 16-CAM-2228-Transit 1 Gen Failure - with Batteries -Rev01
INSTALLATION Campbell Foss		PROJECT MANAGER John Eldridge
TESTING HELD AT Richmond, Ca		DESIGN ENGINEER Chris Wright

Customer Acceptance Test Procedure

ID	Test Description	Result	Signature of AKA	Signature of Client
PREPARATION (Sea Trials)				
1	Vessel to be placed in Transit #1 and making way at available full power.			RM
TEST LOSS OF PORT GEN WHILE IN TRANSIT #1 MODE On the loss of the port gen the DCDC converter should go into auto boost to support the DC bus. This should be a seamless transition (no black or grey out should occur), however propulsion power will be reduced. If the batteries reach their preset minimum SOC, the stbd gen will auto-start and connect.				
2	Simulate the gen failure by manually opening its AFE line contactor.			RM
3	Verify that the DCDC converter goes to boost and supports the bus.			RM
4	Verify a seamless transition (no black or grey out)			RM
5	Verify throttles are enabled.			RM
6	Verify steering for responsiveness.			RM

JOB NUMBER 2228	**TESTING DOCUMENTATION**	DOCUMENT REFERENCE 111104 - CAT Test Procedure 17-CAM-2228-Transit 1 Gen Failure - without Batteries -Rev01
INSTALLATION Campbell Foss		PROJECT MANAGER John Eldridge
TESTING HELD AT Richmond, Ca		DESIGN ENGINEER Chris Wright

Customer Acceptance Test Procedure

ID	Test Description	Result	Signature of AKA	Signature of Client
PREPARATION (Sea Trials)				
1	Vessel to be placed in Transit #1 Mode, with batteries disconnected. Vessel to be making way or pushing at full available power.			RM
TEST LOSS OF PORT GEN WITH BATTERIES DISABLED If the battery bank is not available, it will still be possible to operate the boat in hybrid mode, however the loss of the port gen will result in loss of propulsion and AC power. This test will verify that the starboard gen auto-starts and connects. The available power will be significantly less and the captain may choose to go to non- hybrid should this situation occur. It may also be prudent to always transit in the #2 position to avoid a single point failure.				
2	Simulate the gen failure by manually opening its AFE line contactor. Vessel should go black.			
3	Verify that the starboard gen starts and connects to the DC bus.			
4	Verify that AC power is reconnected.			
5	Verify propulsion returns.			
6	Verify steering for responsiveness.			

Boat goes to "Non-hybrid" — Stbd gen comes up & goes to AC Bus

JOB NUMBER 2228	**TESTING DOCUMENTATION**	DOCUMENT REFERENCE 111104 - CAT Test Procedure 18-CAM-2228-Transit 2 Port Gen Failure - with Batteries -Rev01
INSTALLATION Campbell Foss		PROJECT MANAGER John Eldridge
TESTING HELD AT Richmond, Ca		DESIGN ENGINEER Chris Wright

Customer Acceptance Test Procedure

ID	Test Description	Result	Signature of AKA	Signature of Client
PREPARATION (Sea Trials)				
1	Vessel to be placed in Transit #2 Mode. Vessel to be making way or pushing at full available power.			RM
TEST LOSS OF PORT GEN WHILE IN TRANSIT MODE #2 The loss of the port gen should result in a loss of propulsion power, however the plant should survive without a black or grey out.				
2	Simulate loss of the port gen by opening its AFE line contactor.			RM
3	Verify system alarm.	N/A		RM
4	Verify that the plant survives without black or grey out.			RM
5	Verify propulsion.			RM
6	Verify steering for responsiveness.			RM
7	Reconnect port gen AFE line contactor to bring vessel back to normal operation.			RM

JOB NUMBER 2228	**TESTING DOCUMENTATION**	DOCUMENT REFERENCE 111104 - CAT Test Procedure 19-CAM-2228-Transit 2 Port Gen Failure - without Batteries -Rev01
INSTALLATION Campbell Foss		PROJECT MANAGER John Eldridge
TESTING HELD AT Richmond, Ca		DESIGN ENGINEER Chris Wright

Customer Acceptance Test Procedure

ID	Test Description	Result	Signature of AKA	Signature of Client
PREPARATION (Sea Trials)				
1	Vessel to be placed in Transit #2 Mode, with batteries disconnected. Vessel to be making way or pushing at full available power.			RM
TEST LOSS OF PORT GEN WHILE IN TRANSIT MODE #2, WITHOUT BATTERIES The loss of the port gen should result in a loss of propulsion power, however the plant should survive without a black or grey out. Propulsion power though significantly reduced should be equally distributed on the throttles. Without the batteries to provide additional support to the DC bus the small stbd gen must be able to survive the sudden increase in load caused by the failure of the larger port generator.				
2	Simulate loss of the port gen by opening its AFE line contactor.			RM
3	Verify system alarm.	N/A		RM
4	Verify that the plant survives without black or grey out. — stbd AFE Alarms and loses prop power for a second or two - DIDN'T lose AC Bus			RM
5	Verify propulsion.			RM
6	Verify steering for responsiveness.			RM
7	Reconnect port gen AFE line contactor to bring vessel back to normal operation.			RM

JOB NUMBER 2228	**TESTING DOCUMENTATION**	DOCUMENT REFERENCE 111104 - CAT Test Procedure 20-CAM-2228-Transit 2 Stbd Gen Failure - with Batteries -Rev01
INSTALLATION Campbell Foss		PROJECT MANAGER John Eldridge
TESTING HELD AT Richmond, Ca		DESIGN ENGINEER Chris Wright

Customer Acceptance Test Procedure

ID	Test Description	Result	Signature of AKA	Signature of Client
PREPARATION (Sea Trials)				
1	Vessel to be placed in Transit #2 Mode. Vessel to be making way or pushing at full available power.			RM
TEST LOSS OF STBD GEN WHILE IN TRANSIT MODE #2 The loss of the stbd gen should result in a loss of propulsion power, however the plant should survive without a black or grey out. Propulsion power though reduced should be equally distributed on the throttles. Due to the size of the stbd gen its loss should have minimal impact on propulsion, unlike the loss of the larger port gen, additionally batteries are available to support any sudden drop in DC bus voltage.				
2	Simulate loss of the stbd gen by opening its AFE line contactor.			RM
3	Verify system alarm.	N/A		RM
4	Verify that the plant survives without black or grey out.			RM
5	Verify propulsion.			RM
6	Verify steering for responsiveness.			RM
7	Reconnect stbd gen AFE line contactor to bring vessel back to normal operation.			RM

JOB NUMBER 2228	**TESTING DOCUMENTATION**	DOCUMENT REFERENCE 111104 - CAT Test Procedure 21-CAM-2228-Transit 2 Stbd Gen Failure - without Batteries -Rev01
INSTALLATION Campbell Foss		PROJECT MANAGER John Eldridge
TESTING HELD AT Rainier, Or		DESIGN ENGINEER Chris Wright

Customer Acceptance Test Procedure

ID	Test Description	Result	Signature of AKA	Signature of Client
PREPARATION (Sea Trials)				
1	Vessel to be placed in Transit #2 Mode, with batteries disconnected. Vessel to be making way or pushing at full power setting.		[illegible]	RM
TEST LOSS OF STBD GEN WHILE IN TRANSIT MODE #2, BATTERIES DISCONNECTED The loss of the stbd gen should result in a loss of propulsion power, however the plant should survive without a black or grey out. Propulsion power though reduced should be equally distributed on the throttles. Due to the size of the stbd gen its loss should have minimal impact on propulsion. Without batteries the port gen alone must be able to survive the sudden additional loading.				
2	Simulate loss of the stbd gen by opening its AFE line contactor.		[illegible]	RM
3	Verify system alarm.	N/A	[illegible]	RM
4	Verify that the plant survives without black or grey out.		[illegible]	RM
5	Verify throttles are enabled.		[illegible]	RM
6	Verify steering for responsiveness.		[illegible]	RM
7	Reconnect stbd gen AFE line contactor to bring vessel back to normal operation.		[illegible]	RM

JOB NUMBER 2228	**TESTING DOCUMENTATION**	DOCUMENT REFERENCE 111104 - CAT Test Procedure 22-CAM-2228-Sea Trials -Assist Mode VFD Failure - without Batteries -Rev01
INSTALLATION Campbell Foss		PROJECT MANAGER John Eldridge
TESTING HELD AT Richmond, Ca		DESIGN ENGINEER Chris Wright

Customer Acceptance Test Procedure

ID	Test Description	Result	Signature of AKA	Signature of Client
PREPARATION (Sea Trials)				
1	Vessel to be placed in Assist Mode and at full power with high loading on the AC fed Winch. The batteries are to be disconnected.			RM
TEST LOSS OF MG VFD WHILE IN ASSIST MODE The system can operate without the batteries connected. This is to ensure the vessel can operate in hybrid mode if issues require the batteries to be removed from service. On the loss of a single VFD the remaining MG will need to continue to support the DC bus. Due to the relatively low AC loads propulsion power should not be affected (assuming boost mode is not selected). This test will ensure the plant remains stable (no black or grey out should occur).				
2	Simulate a VFD failure by manually stopping the drive at the keypad.			RM
3	Verify that the plant remains stable.			RM
4	Verify propulsion capability.			RM
5	Verify steering.			RM

JOB NUMBER 2402	**TESTING DOCUMENTATION**	DOCUMENT REFERENCE 111104 - CAT Test Procedure 23-CAM-2228-Hybrid PLC Failure, All Modes-Rev01
INSTALLATION Campbell Foss		PROJECT MANAGER John Eldridge
TESTING HELD AT Richmond, Ca		DESIGN ENGINEER Chris Wright

Customer Acceptance Test Procedure

ID	Test Description	Result	Signature of AKA	Signature of Client
PREPARATION (DOCK TRIALS)				
1	Vessel to be placed in Stop Mode, with shore power disconnected and DC bus up. All modes should be available.			
TEST HYBRID PLC FAILURE WHILE IN IDLE MODE The loss of the Hybrid PLC will automatically place the system in "non-hybrid" mode. Mode selection will not be available. The AC bus will be temporarily lost while the starboard generator auto-starts and connects to the AC bus. Propulsion and steering will be available via the DC bus being supported by the batteries or by the starboard generator if it was already supporting the bus prior to the incident. The operator will need to start the main engines before battery state of charge degrades to the point it cannot support the DC bus. Once the main engines are started and the AC bus is supported by the secondary generator, the DC bus can be shut down via the key switch. This procedure does not test the start of the main engines or clutch engagement. These functions are tested in earlier procedures.				
2	Place the vessel in Idle Mode			RM
3	Simulate Hybrid PLC failure by stopping the PLC using the small switch on CPU module.			RM
4	Verify system alarm.	N/A		
5	Verify that the DC bus is maintained via batteries.			RM
6	Verify secondary generator auto-starts and connects to the AC bus.			RM
7	Verify propulsion	No propulsion per design		RM
8	Verify steering	"		RM
9	Return vessel to Stop Mode and re-start Hybrid PLC.			RM
TEST HYBRID PLC FAILURE WHILE IN TRANSIT MODE #1 The loss of the Hybrid PLC will automatically place the system in "non-hybrid" mode. Mode selection will				

ID	Test Description	Result	Signature of AKA	Signature of Client

not be available. The AC bus will be temporarily lost while the secondary generator disconnects from the DC bus and connects to the AC bus. P~~ropulsion and steering will be available via the DC bus being supported by the primary generator. The~~ system will stay in this mode until the operator manually starts the main engines and shuts down the DC bus.

This procedure does not test the change-over of the steering or the manual start of the main engines. These functions are tested in earlier procedures.

same as above

10	Place the vessel in Transit Mode #1.			
11	Simulate Hybrid PLC failure by stopping the PLC using the small switch on CPU module.			
12	Verify system alarm.			
13	Verify that the DC bus is maintained.			
14	Verify secondary generator connects to the AC bus.			
15	Verify propulsion			
16	Verify steering			
17	Return vessel to Stop Mode and re-start Hybrid PLC.			

TEST HYBRID PLC FAILURE WHILE IN TRANSIT MODE #2

The loss of the Hybrid PLC will automatically place the system in "non-hybrid" mode. Mode selection will not be available. The AC bus will be temporarily lost while the secondary generator disconnects from the DC bus and connects to the AC bus. Propulsion and steering will be available via the DC bus being supported by the primary generator and battery support, as well as the center main engine. The system will stay in this mode until the operator manually starts the outboard main engines and shuts down the DC bus.

This procedure does not test the change-over of the steering or the manual start of the main engines. These functions are tested in earlier procedures.

JOB NUMBER 2402	TESTING DOCUMENTATION	DOCUMENT REFERENCE 111104 - CAT Test Procedure 23-CAM-2228-Hybrid PLC Failure, All Modes-Rev01
INSTALLATION Campbell Foss		PROJECT MANAGER John Eldridge
TESTING HELD AT Richmond, Ca		DESIGN ENGINEER Chris Wright

Customer Acceptance Test Procedure

ID	Test Description	Result	Signature of AKA	Signature of Client
18	Place the vessel in Transit Mode #2.			
19	Simulate Hybrid PLC failure by stopping the PLC using the small switch on CPU module.	same as Ex Ole		
20	Verify system alarm.			
21	Verify that the DC bus is maintained.			
22	Verify secondary generator connects to the AC bus.			
23	Verify propulsion			
24	Verify steering			
25	Return vessel to Stop Mode and re-start Hybrid PLC			

TEST HYBRID PLC FAILURE WHILE IN ASSIST MODE

The loss of the Hybrid PLC will automatically place the system in "non-hybrid" mode. Mode selection will not be available. The AC bus will be temporarily lost while the secondary generator auto-starts and connects to the AC bus. Propulsion and steering will be available via the DC bus being supported by batteries~~, as well as the center main engine~~. The system will stay in this mode until the operator manually starts the outboard main engines and shuts down the DC bus.

This procedure does not test the change-over of the steering or the manual start of the main engines. These functions are tested in earlier procedures.

26	Place the vessel in Assist Mode.			
27	Simulate Hybrid PLC failure by stopping the PLC using the small switch on CPU module.			
28	Verify system alarm.			

JOB NUMBER 2402	TESTING DOCUMENTATION	DOCUMENT REFERENCE 111104 - CAT Test Procedure 23-CAM-2228-Hybrid PLC Failure, All Modes-Rev01
INSTALLATION Campbell Foss		PROJECT MANAGER John Eldridge
TESTING HELD AT Richmond, CA		DESIGN ENGINEER Chris Wright

Customer Acceptance Test Procedure

ID	Test Description	Result	Signature of AKA	Signature of Client
29	Verify that the DC bus is maintained.			
30	Verify secondary generator connects to the AC bus.			
31	Verify propulsion			
32	Verify steering			
33	Return vessel to Stop Mode and re-start Hybrid PLC			

During Assist, DC Bus stayed up but Generator did not switch over to AC Bus initially

On 2nd try it worked and system acted like "non-hybrid

JOB NUMBER 2402	TESTING DOCUMENTATION	DOCUMENT REFERENCE 111104 - CAT Test Procedure 24-CAM-2228-Incomer PLC Failure, All Modes-Rev01
INSTALLATION Campbell Foss		PROJECT MANAGER John Eldridge
TESTING HELD AT Richmond, CA		DESIGN ENGINEER Chris Wright

Customer Acceptance Test Procedure

ID	Test Description	Result	Signature of AKA	Signature of Client
PREPARATION (DOCK TRIALS)				
1	Vessel to be placed in Stop Mode, with shore power disconnected and DC bus up. All modes should be available.			

TEST INCOMER PLC FAILURE WHILE IN IDLE MODE

The loss of an incomer PLC will prevent the corresponding generator from responding to system requests. If that generator is supporting the DC Bus then it's corresponding AFE will stop and it will no longer transfer power to the DC bus. If the generator was previously running then it will continue to run. If the generator was not previously running then it will be automatically started when the PLC is lost. The DC bus will then revert to battery support.

Propulsion and steering will be available. When safe to do so the crew should go to non-hybrid. It will be necessary to manually switch the generators at the change-over junction box, making them available to the existing AC switchboard for manual connection. Once a generator is connected to the AC bus the DC bus can be powered down via the key switch. If the DC bus is not manually "switched off" it will eventually fail as battery state of charge deteriorates.

2	Place the vessel in Idle Mode, with the primary generator supporting the DC bus.			
3	Simulate the primary Incomer PLC failure by stopping the PLC using the small switch on the CPU module.			
4	Verify system alarm.			
5	Verify that the DC bus is maintained via batteries.			
7	Verify propulsion			
8	Verify steering			
9	Return vessel to Stop mode and re-start Incomer PLC			

JOB NUMBER 2402	TESTING DOCUMENTATION	DOCUMENT REFERENCE 111104 - CAT Test Procedure 24-CAM-2228-Incomer PLC Failure, All Modes-Rev01
INSTALLATION Campbell Foss		PROJECT MANAGER John Eldridge
TESTING HELD AT Richmond, Ca		DESIGN ENGINEER Chris Wright

Customer Acceptance Test Procedure

ID	Test Description	Result	Signature of AKA	Signature of Client

TEST HYBRID PLC FAILURE WHILE IN TRANSIT MODE #1

The loss of an incomer PLC will prevent the corresponding generator from responding to system requests. The generators corresponding AFE will stop and it will no longer transfer power to the DC bus, however the generator will continue to run.

The loss of an incomer PLC has no effect on the performance of the other incomer function. If both incomers were supporting the DC Bus then the opposite generator will continue to provide support.

Propulsion and steering will be available however propulsion power will be diminished. When safe to do so the crew should go to non-hybrid. It will be necessary to manually switch the generators at the change-over junction box, making them available to the existing AC switchboard for manual connection. Once a generator is connected to the AC bus the DC bus can be powered down via the key switch. If the DC bus is not manually "switched off" it will eventually fail as battery state of charge deteriorates.

This procedure does not test the change-over of the steering or the manual start of the main engines. These functions are tested in earlier procedures.

10	Place the vessel in Transit Mode #1.			
11	Simulate an Incomer PLC failure by stopping the PLC using the small switch on the CPU module.			
12	Verify system alarm.			
13	Verify that the DC bus is maintained and stable.			
15	Verify propulsion			
16	Verify steering			
17	Return vessel to Stop Mode and re-start the Incomer PLC.			

TEST INCOMER PLC FAILURE WHILE IN TRANSIT MODE #2 – worst case

The loss of the primary incomer PLC will prevent the corresponding generator from responding to system requests. The generators corresponding AFE will stop and it will no longer transfer power to the DC bus, however the generator will continue to run.

JOB NUMBER 2402	TESTING DOCUMENTATION	DOCUMENT REFERENCE 111104 - CAT Test Procedure 24-CAM-2228-Incomer PLC Failure, All Modes-Rev01
INSTALLATION Campbell Foss		PROJECT MANAGER John Eldridge
TESTING HELD AT Richmond, CA		DESIGN ENGINEER Chris Wright

Customer Acceptance Test Procedure

ID	Test Description	Result	Signature of AKA	Signature of Client
The loss of an incomer PLC has no effect on the performance of the other incomer function. Propulsion and steering will be available via the DC bus being supported by re-gen from the center main engine/MG combination and battery support if necessary. When safe to do so the crew should go to non-hybrid. It will be necessary to manually switch the generators at the change-over junction box, making them available to the existing AC switchboard for manual connection. Once a generator is connected to the AC bus the DC bus can be powered down via the key switch. If the DC bus is not manually "switched off" it will eventually fail as battery state of charge deteriorates. This procedure does not test the change-over of the steering or the manual start of the main engines. These functions are tested in earlier procedures. Same as switching off AFE				
18	Place the vessel in Transit Mode #2.		[illegible]	RM
19	Simulate the primary Incomer PLC failure by stopping the PLC using the small switch on the CPU module.		[illegible]	RM
20	Verify system alarm.	N/A	[illegible]	
21	Verify that the DC bus is maintained and is stable.		[illegible]	RM
23	Verify propulsion		[illegible]	RM
24	Verify steering		[illegible]	RM
25	Return vessel to Stop Mode and re-start the incomer PLC.		[illegible]	RM

TEST HYBRID PLC FAILURE WHILE IN ASSIST MODE — NO INCOMERS

The loss of an incomer PLC will prevent the corresponding generator from responding to system requests. Modes requiring the generator will not be available. The generators corresponding AFE will stop initiating an auto-start of the associated generator.

Propulsion and steering will be available. When safe to do so the crew may go to non-hybrid. It will be necessary to manually switch the generators at the change-over junction box, making them available to the existing AC switchboard for manual connection. Once a generator is connected to the AC bus the DC bus can be powered down via the key switch.

JOB NUMBER 2402	TESTING DOCUMENTATION	DOCUMENT REFERENCE 111104 - CAT Test Procedure 24-CAM-2228-Incomer PLC Failure, All Modes-Rev01
INSTALLATION Campbell Foss		PROJECT MANAGER John Eldridge
TESTING HELD AT Richmond, Ca		DESIGN ENGINEER Chris Wright

Customer Acceptance Test Procedure

ID	Test Description	Result	Signature of AKA	Signature of Client
26	Place the vessel in Assist Mode.			
27	Simulate the primary Incomer PLC failure by stopping the PLC using the small switch on the CPU module.			
28	Verify system alarm.			
29	Verify that the DC bus is maintained and stable.			
30	Verify corresponding generator auto-starts			
31	Verify propulsion			
32	Verify steering			
33	Return vessel to Stop Mode and re-start the Incomer PLC.			

same as tripping VFD's

JOB NUMBER 2402	**TESTING DOCUMENTATION**	DOCUMENT REFERENCE 111104 - CAT Test Procedure 25-CAM-2228-Propulsion PLC Failure, All Modes-Rev01
INSTALLATION Campbell Foss		PROJECT MANAGER John Eldridge
TESTING HELD AT Richmond, Ca		DESIGN ENGINEER Chris Wright

Customer Acceptance Test Procedure

ID	Test Description	Result	Signature of AKA	Signature of Client
PREPARATION (DOCK TRIALS)				
1	Vessel to be placed in Stop Mode, with shore power disconnected and DC bus up. All modes should be available.			

TEST PROPULSION PLC FAILURE WHILE IN IDLE MODE

The loss of a propulsion PLC will cause its corresponding motor generator VFD to stop and propulsion will be lost on its associated thruster. The failure of a propulsion PLC does not impact the functionality of the remaining propulsion PLC's. Therefore, the vessel will be able to maintain propulsion and manoeuvrability on the remaining thrusters. When safe to do so the crew should go to non-hybrid. It will be necessary to manually switch the generators at the change-over junction box, making them available to the existing AC switchboard for manual connection. Once a generator is connected to the AC bus the DC bus can be powered down via the key switch.

This procedure does not test the change-over of the steering or the manual start of the main engines. These functions are tested in earlier procedures.

2	Place the vessel in Idle Mode.			
3	Simulate a Propulsion PLC failure by stopping the PLC using the small switch on the CPU module.			
4	Verify system alarm.			
5	Verify that the DC bus is maintained via batteries.			
7	Verify propulsion			
8	Verify steering			
9	Return vessel to Stop mode and re-start the propulsion PLC			

TEST PROPULSION PLC FAILURE WHILE IN TRANSIT MODE #1

The loss of a propulsion PLC will cause its corresponding motor generator VFD to stop and propulsion will

ID	Test Description	Result	Signature of AKA	Signature of Client
be lost on its associated thruster. The failure of a propulsion PLC does not impact the functionality of the remaining propulsion PLC's. Therefore, the vessel will be able to maintain propulsion and manoeuvrability on the remaining thrusters. When safe to do so the crew should go to non-hybrid. It will be necessary to manually switch the generators at the change-over junction box, making them available to the existing AC switchboard for manual connection. Once a generator is connected to the AC bus the DC bus can be powered down via the key switch. This procedure does not test the change-over of the steering or the manual start of the main engines. These functions are tested in earlier procedures.				
10	Place the vessel in Transit Mode #1.			RM
11	Simulate a Propulsion PLC failure by stopping the PLC using the small switch on the CPU module.			RM
12	Verify system alarm.	N/A		
13	Verify that the DC bus is maintained and stable.			RM
14	Verify propulsion side NOT tripped →	one side only		RM
15	Verify steering	"		RM
16	Return vessel to Stop Mode and re-start the propulsion PLC.			RM

TEST CENTER PROPULSION PLC FAILURE WHILE IN TRANSIT MODE #2

The loss of the center PLC will cause the center VFD to stop, and re-gen will not be available. Propulsion power to the outboard thrusters will be reduced, but will still be available via the power provided via the primary generator. The failure of a propulsion PLC does not impact the functionality of the remaining propulsion PLC's. Therefore, the vessel will be able to maintain propulsion and manoeuvrability via the center main engine and the outboard thrusters. When safe to do so the crew should go to non-hybrid. It will be necessary to manually switch the generators at the change-over junction box, making them available to the existing AC switchboard for manual connection. Once a generator is connected to the AC bus the DC bus can be powered down via the key switch.

This procedure does not test the change-over of the steering or the manual start of the main engines.

ID	Test Description	Result	Signature of AKA	Signature of Client
These functions are tested in earlier procedures.				
17	Place the vessel in Transit Mode #2.			
18	Simulate the center propulsion PLC failure by stopping the PLC using the small switch on the CPU module.			
19	Verify system alarm.			
20	Verify that the DC bus is maintained and is stable.			
21	Verify propulsion			
22	Verify steering			
23	Return vessel to Stop Mode and re-start the propulsion PLC.			
TEST OUTBOARD PROPULSION PLC FAILURE WHILE IN TRANSIT MODE #2 The loss of an outboard propulsion PLC will cause its associated VFD to stop, and propulsion will be lost on that thruster. The failure of a propulsion PLC does not impact the functionality of the remaining propulsion PLC's. Therefore, the vessel will be able to maintain propulsion and manoeuvrability on the remaining thrusters. When safe to do so the crew should go to non-hybrid. It will be necessary to manually switch the generators at the change-over junction box, making them available to the existing AC switchboard for manual connection. Once a generator is connected to the AC bus the DC bus can be powered down via the key switch. This procedure does not test the change-over of the steering or the manual start of the main engines. These functions are tested in earlier procedures.				
24	Place the vessel in Transit Mode #2.			
25	Simulate an outboard propulsion PLC failure by stopping the PLC using the small switch on			

ID	Test Description	Result	Signature of AKA	Signature of Client
	the CPU module.			
26	Verify system alarm.			
27	Verify that the DC bus is maintained and is stable.			
28	Verify propulsion			
29	Verify steering			
30	Return vessel to Stop Mode and re-start the propulsion PLC.			

TEST PROPULSION PLC FAILURE WHILE IN ASSIST MODE

The loss of a propulsion PLC will cause its corresponding motor generator VFD to stop and re-gen will not be available on that shaft line. The failure of a propulsion PLC does not impact the functionality of the remaining propulsion PLC's. Therefore, the two remaining MG's will be able to provide re-gen to the DC bus. These two MG's should provide sufficient power to maintain the DC bus, with batteries available for additional support. When safe to do so the crew can go to non-hybrid. It will be necessary to manually switch the generators at the change-over junction box, making them available to the existing AC switchboard for manual connection. Once a generator is connected to the AC bus the DC bus can be powered down via the key switch.

This procedure does not test the change-over of the steering or the manual start of the main engines. These functions are tested in earlier procedures.

31	Place the vessel in Assist Mode.			
32	Simulate the center propulsion PLC failure by stopping the PLC using the small switch on the CPU module	same as closing VFD		
33	Verify system alarm.			
34	Verify that the DC bus is maintained and stable.			

JOB NUMBER 2402	**TESTING DOCUMENTATION**	DOCUMENT REFERENCE 111104 - CAT Test Procedure 25-CAM-2228-Propulsion PLC Failure, All Modes-Rev01
INSTALLATION Campbell Foss		PROJECT MANAGER John Eldridge
TESTING HELD AT Richmond, Ca		DESIGN ENGINEER Chris Wright

Customer Acceptance Test Procedure

ID	Test Description	Result	Signature of AKA	Signature of Client
35	Verify propulsion			
36	Verify steering			
37	Return vessel to Stop Mode and re-start the propulsion PLC.			

JOB NUMBER 2228	**TESTING DOCUMENTATION**	DOCUMENT REFERENCE 111104 - CAT Test Procedure 28-CAM-2228-Sea Trials-Cooling Water System-Rev01
INSTALLATION Campbell Foss		PROJECT MANAGER John Eldridge
TESTING HELD AT Richmond, Ca		DESIGN ENGINEER Chris Wright

Customer Acceptance Test Procedure

ID	Test Description	Result	Signature of AKA	Signature of Client
PREPARATION (Sea Trails)				
1	Vessel to be placed in Transit 2 Mode. This mode requires the most power from the drives. Vessel should operate at full available power until readings stabilize.	SYSTEM TESTED		
VERIFY PORT COOLING WATER SYSTEM		IN EUREKA		
2	Verify pump is running. Check HMI.			
3	Record pump speed at key pad.	TO SATISFACTION		
4	Record flow through Port AFE	OF FOSS		
5	Record flow through Port VFD			
6	Record flow through Island AFE			
7	Record port circuit pressure			
8	Record supply temperature			
9	Record discharge temperature reading			
VERIFY STARBOARD COOLING WATER SYSTEM				
10	Verify pump is running. Check HMI.			
11	Record pump speed at keypad.			
12	Record flow through starboard AFE via HMI.			
13	Record flow through starboard VFD			

ID	Test Description	Result	Signature of AKA	Signature of Client
14	Record starboard circuit pressure			
15	Record supply temperature reading			
16	Record discharge temperature reading			
TEST CROSS OVER CIRCUIT - PORT PUMP FAILURE				
17	Open cross over valves and stop port pump.			
18	Record port AFE flow			
19	Record port VFD flow			
20	Record Island AFE flow			
21	Record port supply temperature reading			
22	Record port discharge temperature			
23	Record port system pressure			
24	Record starboard AFE flow			
25	Record starboard VFD flow			
26	Record stbd supply temperature			
27	Record stbd discharge temperature.			
28	Record starboard system pressure			

JOB NUMBER 2228	**TESTING DOCUMENTATION**	DOCUMENT REFERENCE 111104 - CAT Test Procedure 28-CAM-2228-Sea Trials-Cooling Water System-Rev01
INSTALLATION Campbell Foss		PROJECT MANAGER John Eldridge
TESTING HELD AT Richmond, Ca		DESIGN ENGINEER Chris Wright

Customer Acceptance Test Procedure

ID	Test Description	Result	Signature of AKA	Signature of Client
TEST CROSS OVER CIRCUIT - STBD PUMP FAILURE				
29	Re-start port pump and stop starboard pump.			
30	Record port AFE flow			
31	Record port VFD flow			
32	Record Island AFE flow			
33	Record port supply temperature			
34	Record port discharge temperature			
35	Record port system pressure			
36	Record starboard AFE flow			
37	Record starboard VFD flow			
38	Record stbd supply temperature			
39	Record stbd discharge temperature			
40	Record stbd system pressure			
41	Restart stbd pump and close cross over valves			

APPENDIX D

U.C. RIVERSIDE

FINAL

EMISSIONS

REPORT

Evaluation of Hybrid Retrofit System for a Tugboat

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Disclaimer

This report was prepared as the result of work sponsored by the *Air Resources Board* (ARB) and carried out with Foss Maritime Company. As such the report does not necessarily represent the views of ARB and Foss Maritime Company. Further the collective participants, its employees, contractors and subcontractors make no warrant, express or implied, and assume no legal liability for the information in this report; nor does any party represent that the uses of this information will not infringe upon privately owned rights. This report has neither been approved nor disapproved by the collective group of participants nor have they passed upon the accuracy or adequacy of the information in this report.

Acknowledgements

Authors would like to thank *Air Resources Board's* Air Quality improvement Program for their financial support without which this project would not have been possible. The authors acknowledge the support from Foss crew members during emissions testing. A special thanks to *US Environmental Protection Agency (*USEPA), Office of Transportation and Air Quality, in the preparation of the test plan for this project. Authors also acknowledge *Air Resources Board's* Stationary Source Division for their 2010 study "Evaluating Emission Benefits of the Hybrid Tugboat" which was the base of this project. The authors acknowledge John Elderidge and Ed McCain from *Aspin Kemp* & *Associates* and *Foss Maritime Company*, respectively. The authors also thanks to Kathalena Cocker, Jesus Sahagun and Kurt Bumiller from UC Riverside for test preparation and analysis of filter sample media.

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Executive Summary

Background: Hybrid technology is becoming a prevalent solution to reduce emissions. Emissions from harbor craft account for significant proportion of criteria pollutants and greenhouse gases from port activities, and this report is about the application of hybrid technology to a harbor tugboat. In an earlier project, significant emission reductions up to 73% for $PM_{2.5}$, 51% for NOx and 27% for CO_2 were observed when a conventional and newly built hybrid tugboat were compared. The goal of this study was to evaluate the criteria emissions reduction and fuel economy benefits by retrofitting an existing tug, the *Campbell Foss* with hybrid technology.

Methods: This demonstration project was conducted in three phases. In the first phase emissions were measured for the main engines (ME) and auxiliary engines (AE) of the *Campbell Foss* prior to the retrofit to a hybrid. The next phase involves the development of the activity of the hybrid *Campbell Foss* and emissions testing of the new repower AE engine according to ISO 8178 D2 and in-use testing based on activity data. A data-logging system, capable of simultaneously monitoring and reporting the status of the power sources was installed for a period of over one month. Four gigabytes of data were analyzed to determine the weighting factors, i.e., the fraction of time spent by the tug in the six discrete operating modes *Shore Power*, *Stop*, *Idle*, *Transit 1*, *Transit 2* and *Assist*. Further engine histograms for all four engines on the tug at these operating modes were established. The third and final phase of the work involved the retesting of the new repowered engine at 1000 hours of operation to ensure durability of emissions profile and combining the activity and emissions data to calculate the overall in-use emissions from the tug prior and after retrofit.

Results: The first phase of the study was conducted to ensure that the main (ME) and auxiliary engines (AE) on the conventional tug are representative of engines in their category and emissions are within certification limits (Table ES-1). Emission results confirmed that NOx, CO and $PM_{2.5}$ emissions levels are below standards. ISO 8178 protocols were used to evaluate emissions and are presented in section 3.1.

The second phase of the study was to confirm that emissions from the new AE were within certification limits (Table ES-2) and to establish weighting factors for the operating modes of the hybrid *Campbell Foss* in total. The weighting factors were found to be 0.13 for Shore Power, 0.38 for Stop, 0.02 for Idle, 0.14 for Transit (includes Transit 1& Transit 2) and 0.33 for Assist (includes barge move). The weighting factors were assumed to be same for conventional *Campbell Foss* as above. Detailed engine histograms are presented in the section 3.3.

Table ES 1: Comparison of measured and EPA Tier 1 standards for various pollutants

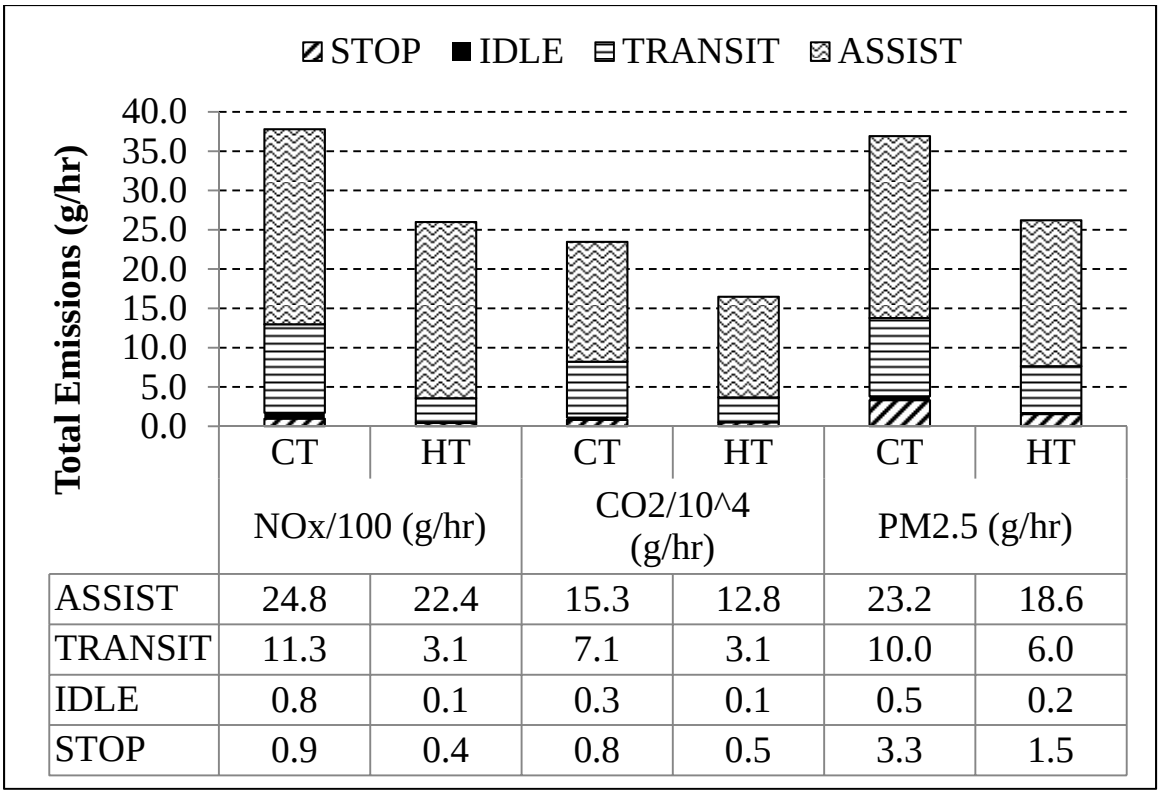
Pollutants	NO_x	CO	CO_2	THC	$PM_{2.5}$	EC	OC
	g/kW-hr						
Auxiliary Engine on Conventional Campbell Tug JD 6081							
Wt. Avg.	7.1	1.6	870.1	0.2	0.4	0.3	0.1
EPA Tier 1	9.2	11.4			0.54		
Main Engine on Conventional Campbell Tug CAT 3512 C							
Wt. Avg.	8.2	1.8	648.6	0.1	0.1	0.0	0.1
EPA Tier 1	9.2	11.4			0.54		

Table ES 2: Comparison of measured and EPA Tier 2 standards for various pollutants

Pollutants	NO_x	NO_x+NMHC	CO	CO_2	THC	$PM_{2.5}$	EC	OC
	g/kW-hr							
MTU/Detroit Series 60 (0 hour Emission Measurements)								
Weighted Avg.	6.7	6.8	0.42	776	0.08	0.08	0.04	0.04
Tier 2	–	7.2	5.0	–	–	0.20	–	–
MTU/Detroit Series 60 (1000 hour Emission Measurements)								
Weighted Avg.	6.2	6.9	0.67	752.9	0.68	0.13	0.09	0.07
EPA Tier 2	–	7.2	5.0	–	–	0.20	–	–

The third phase of the project involved retesting of new AE, manufactured by MTU, after 1000 hours of operation to ensure durability of the engine. Table ES-2 shows the emissions profile from the MTU engine after 1000 hours of operation are within Tier 2 standards. Figure ES 1 shows the overall in-use emissions for the conventional and hybrid *Campbell Foss* based on the individual operating mode weighting factors.

Emission reductions with the hybrid technology were 28% for $PM_{2.5}$, 31% for NOx and 29% for CO_2. The diesel electric drive train on the hybrid tug that allows the use of auxiliary power for propulsion was the primary cause for the overall in-use emission reductions as opposed to the use of batteries. Operating with hybrid technology for the transit mode eliminated the need for using the main propulsion engines and this feature was the most significant contributor to the overall emission reductions. In previous ARB study[14], *Evaluating Emission Benefits of a Hybrid Tugboat* (2010), *Alta June* and *Carolyn Dorothy* spent more time during transit and idle operating mode, therefore, when their duty cycle was imposed on *Campbell Foss*, emission reductions with the hybrid technology would have been 34%, 42% and 36% for $PM_{2.5}$, NOx and CO_2, respectively.



	NOx/100 (g/hr)		CO2/10^4 (g/hr)		PM2.5 (g/hr)	
	CT	HT	CT	HT	CT	HT
ASSIST	24.8	22.4	15.3	12.8	23.2	18.6
TRANSIT	11.3	3.1	7.1	3.1	10.0	6.0
IDLE	0.8	0.1	0.3	0.1	0.5	0.2
STOP	0.9	0.4	0.8	0.5	3.3	1.5

Figure ES 1: Overall in-use emissions based on the individual Tug Operating Modes Weighting Factors

1 Introduction

The last decade has seen an increasing interest in reducing the emissions from marine sources. Several studies[1-6] have shown that emissions from ports significantly affect the air quality and present a substantial health hazard to the communities near to the ports. The sources in the ports include ships, harbor-craft, cargo-handling equipment, trucks and locomotives. Ships are the largest contributors to the total port emissions. Emissions from harbor-craft, though smaller, still form a significant part of the total port emissions[7, 8]. Harbor crafts include ferries, excursion boats, tugboats, towboats, crew and supply vessels, work boats, fishing boats, barges and dredge vessels.

Corbett's study[9] on waterborne commerce vessels in the United States revealed that in several states ~65% of the marine nitrogen oxides comes from vessels operating in inland waterways. Since harbor craft (e.g., barges and tow-boats) are the most common commercial vessels operating in inland waterways[10], hybridization of tugboats could have significant effects on the air quality of inland areas as well.

Harbor-craft are typically powered by marine compression ignition engines which are regulated by United States Environmental Protection Agency's (U.S. EPA) code of federal regulation title 40 parts 85-94[11]. Emission studies[12, 13] on these vessels have predominately focused on older engines operating on high sulfur fuels. Only a few studies have evaluated emissions from harbor craft operating on ultra-low sulfur diesel (ULSD) fuel.

Future regulations on diesel engines are geared towards simultaneous reduction of toxic air contaminants, criteria pollutants and green-house gas emissions to address the issues of air quality and global warming. One prevalent solution to achieve this goal is called hybrid technology. In hybrid technology, two or more distinct power sources are used to provide the mechanical energy for vessel operation. A common application of this technology today is passenger cars.

This technology is not new to the marine world. Diesel electric submarines have been prevalent for over sixty years. The propeller (usually single) on these submarines is driven by an electric motor which derives energy from diesel generators or batteries. The diesel generators were also used to charge batteries.

Based on the encouraging results from a previous project that created a new-build hybrid tug boat, the Foss Maritime Company (Foss) and their Canadian partners, Aspin Kemp & Associates (AKA) have retrofitted a tug by the addition of motor generator sets, an energy management system, batteries and other design enhancements. It has 10 Lithium Polymer batteries providing a total of 65 kW-hr of energy in a single bank. The batteries are typically charged by the AEs but have the capability to be charged from shore power. All four engines (two main and two auxiliary) and the batteries are coupled and

controlled by an energy management system. Therefore, the energy from the batteries and the auxiliary engines can also be used for propulsion in the hybrid tugboat.

2 Test Protocol and Test Plan

Test plan is similar to that reported in the ARB report[14], *Evaluating Emission Benefits of a Hybrid Tugboat* (2010), and developed in conjunction with US EPA, Office of Transportation and Air Quality.

2.1 Overview

The primary objective of this project was to determine emission benefits of using a hybrid retrofit system on an existing tugboat. For this purpose, a "Dolphin class" tugboat from Foss' fleet was retrofitted with the hybrid systems in addition to repowering one of the auxiliary engines to a larger auxiliary engine to provide sufficient power for propulsion while transiting.

Listed below is a brief description of the procedure adopted to determine the in-use emission benefits of the hybrid retrofitted tugboat.

a) Engine, GPS and battery data were logged for 37 days. This data was analyzed to determine the activity and engine histograms for each operating mode of a hybrid tugboat.
b) Activity of conventional tugboat (before repowering engine and addition of batteries to *Campbell Foss*) was assumed to be the same as the activity of hybrid tugboat. However, engine histograms for each operating mode of a conventional tugboat were obtained from the ARB study.
c) Emission measurements were made from one main and one auxiliary engine before the tugboat was retrofitted and hybridized. After retrofitting the tugboat, emissions were measured from the new auxiliary engine at 0 hr operation and after 1000 hr operation to ensure durability of new AE over time. These engines were analyzed to determine the gaseous (CO, CO_2, NO_x and THC) and particulate matter ($PM_{2.5}$) emissions for each engine across that engine's entire operating range.
d) Activity and engine histogram data coupled with the emissions data were used to determine the total in-use emissions in g/hr for the tugboat before and after the hybrid retrofit.
e) These total in-use emissions were then used to calculate the reduction of the gaseous and particulate matter species with the hybrid retrofit system.

A detailed description of the approach, test schedule, measurement and analyses techniques used to determine the emission reduction potential of the hybrid retrofit system are provided below.

2.2 Approach

The emission benefits of a hybrid tug can be calculated as follows

$$\boldsymbol{Emission\ Reduction}\ \% = \frac{\boldsymbol{TE_c - TE_h}}{\boldsymbol{TE_c}} \times \mathbf{100}$$ **--------- Equation 2-1**

where,

TE_c total in-use emissions for conventional tugboat in g/hr

TE_h total in-use emissions for hybrid tugboat in g/hr

The total in-use emissions of any gaseous or particulate matter species, is determined using the following equation:

$$\boldsymbol{TE} = \sum_{\boldsymbol{i=1}}^{\boldsymbol{n}} [\boldsymbol{W_i} \sum_{\boldsymbol{j=1}}^{\boldsymbol{m}} (\boldsymbol{E_{ij}})]$$ **--------- Equation 2-2**

where,

TE total in-use emissions in g/hr

n total number of operating modes (Section 2.5.1)

m the total number of power sources on the tug (Section 2.3)

W_i weighting factor for i^{th} operating mode (See Equation 2-3)

E_{ij} total in-use emissions in g/hr from the jth power source for the ith operating mode (See Equation 2-4)

The weighing factors for each operating mode are calculated as follows:

$$\boldsymbol{W_i} = \frac{\boldsymbol{t_i}}{\boldsymbol{t_{total}}}$$ **--------- Equation 2-3**

where,

W_i weighting factor for the ith operating mode

t_i time spent by the tug in the ith operating mode

t_{total} total sample time for the tug

As mentioned earlier, tugboats typically have four engines, two for propulsion and two auxiliary generators. To determine the total in-use emissions from each of these engines/power sources the following equation can be used:

$$\boldsymbol{E_{ij} = \sum_{k=1}^{p}[WL_{ijk}\, EL_{jk})]} \qquad \text{———Equation 2-4}$$

where,

E_{ij} total in-use emissions in g/hr from the jth power source/engine for the ith operating mode

p total number of operating modes for the jth power source (marine diesel engine). there are twelve operating modes for the engine based on the percentage of maximum engine load: off, 0 to <10%, 10% to <20%, 20% to <30%, and so on until 90% to <100% and 100%.

WL_{ijk} fraction of time spent by the jth power source/engine at its kth operating mode during the ith tug boat operating mode. This value can be obtained from the engine histograms

EL_{jk} emissions in g/hr for the jth power source/engine at its kth operating mode

While developing engine histograms for the hybrid tugboat it is important to ensure that the state of charge of the battery at the start and end time of each sample period chosen for the calculation of the engine histogram are the same. This would eliminate any biases in emissions resulting from operation of the auxiliary generators for charging the batteries. The protocol was adopted after reviewing the hybrid testing protocol adopted by the Society of Automotive Engineers[15] (SAE) and California Air Resources Board [16](CARB) for testing hybrid electric vehicles.

2.3 Test Tugboat

The primary objective of this project was to determine emission benefits of using a hybrid retrofit system on a tugboat. For this purpose, one of the tugboats (*Campbell Foss*) belonging to Foss' fleet operating in the Ports of Los Angeles and Long Beach was retrofitted with hybrid components in addition to the repowering one of the auxiliary engines. Originally, *Campbell Foss* was equipped with EPA Tier 1 marine main and auxiliary diesel engines. During the hybrid retrofit process, one of the auxiliary engines was replaced by an EPA Tier 2 marine auxiliary engine. Details of power sources on the *Campbell Foss* tugboat are described below.

The conventional *Campbell Foss* was powered by two 1902 kW CAT 3512C main engines and two 125 kW John Deere (JD) 6081 auxiliary engines (Table 2-1). This tugboat has two Azimuthing stern drives (ASD) for propulsion units. Each main engine was connected through a mechanical drive shaft to each ASD.

Table 2-1: Engine Specifications for *Campbell Foss*

	Main Engine (ME)	**Auxiliary Engine (AE)**
Manufacturer /Model	CAT 3512	John Deere 6081
Manufacture Year	2005	2005
Certification Standard	Tier 1	Tier 0
Technology	4-Stroke Diesel	4-Stroke Diesel
Max. Power Rating	1902 kW	125 kW
Rated Speed	1800 rpm	1800 rpm
# of Cylinders	8	8
Displacement	58.6 liters	8.1 liters

The retrofit hybrid *Campbell Foss* is powered by the original MEs and one of the two original AEs. The other AE was repowered with a new Tier 2 engine (Table 2-2). It also has 10 Lithium Polymer batteries providing a total of 65 kW-hr of energy in a single bank. The batteries are typically charged by the AEs but can be charged from shore power.

Table 2-2: Repowered AE engine Specifications for *Campbell Foss*

	Auxiliary Engine (AE)
Manufacturer /Model	MTU/Detroit Diesel Series 60
Manufacture Year	2011
Technology	4-Stroke Diesel
Certification Standard	Tier 2
Max. Power Rating	350 kW
Rated Speed	1800 rpm
# of Cylinders	6
Displacement	14 liter

In the case of the conventional *Campbell Foss* the main engines were linked mechanically to the propellers through a drive shaft. Therefore both main engines had to be operated for moving and maneuvering the boat. The auxiliary engines were only used for hoteling, lighting, air conditioning and operating the winch motor. However, in case

of the hybrid retrofit *Campbell Foss*, there is a motor-generator unit mounted in the shaft line between each engine and ASD. An additional clutch was also fitted between the main engine and motor-generator. With the clutch open, the motor-generator uses electrical power from the batteries and auxiliary engines to drive the shaft for propelling the boat.

With the clutch engaged, the motor-generator is able to produce from the shaft using the main engines or freewheeling propeller (regenerative power). This power is used for charging the batteries, driving the winch and other hoteling activities of the tug. This means that AE's are not required to be running when the main engines are providing propulsion.

The batteries on the *Campbell Foss* are predominately charged using the power from the auxiliary engines drawn through the DC bus. In the previous ARB[14] study, auxiliary engines in the hybrid tugboat were of higher power rating than conventional tugboat so that they can be used for charging batteries and propelling the tugboat. Therefore, in *Campbell Foss*, one of the JD 6081's was replaced by an engine with a higher power rating.

The hybrid *Campbell Foss* is equipped with an energy management system that manages the power sources and the drive train. A schematic of the diesel electric drive train is shown in Figure 2-1. The captain on the hybrid tug uses a switch in the wheelhouse to communicate the desired operating mode of the tug to the energy management system. The signal from this wheelhouse switch helps the energy management system in making decisions regarding the number of power sources required to operate the tug. Further details of this wheelhouse switch are provided is Section 2.5.2.

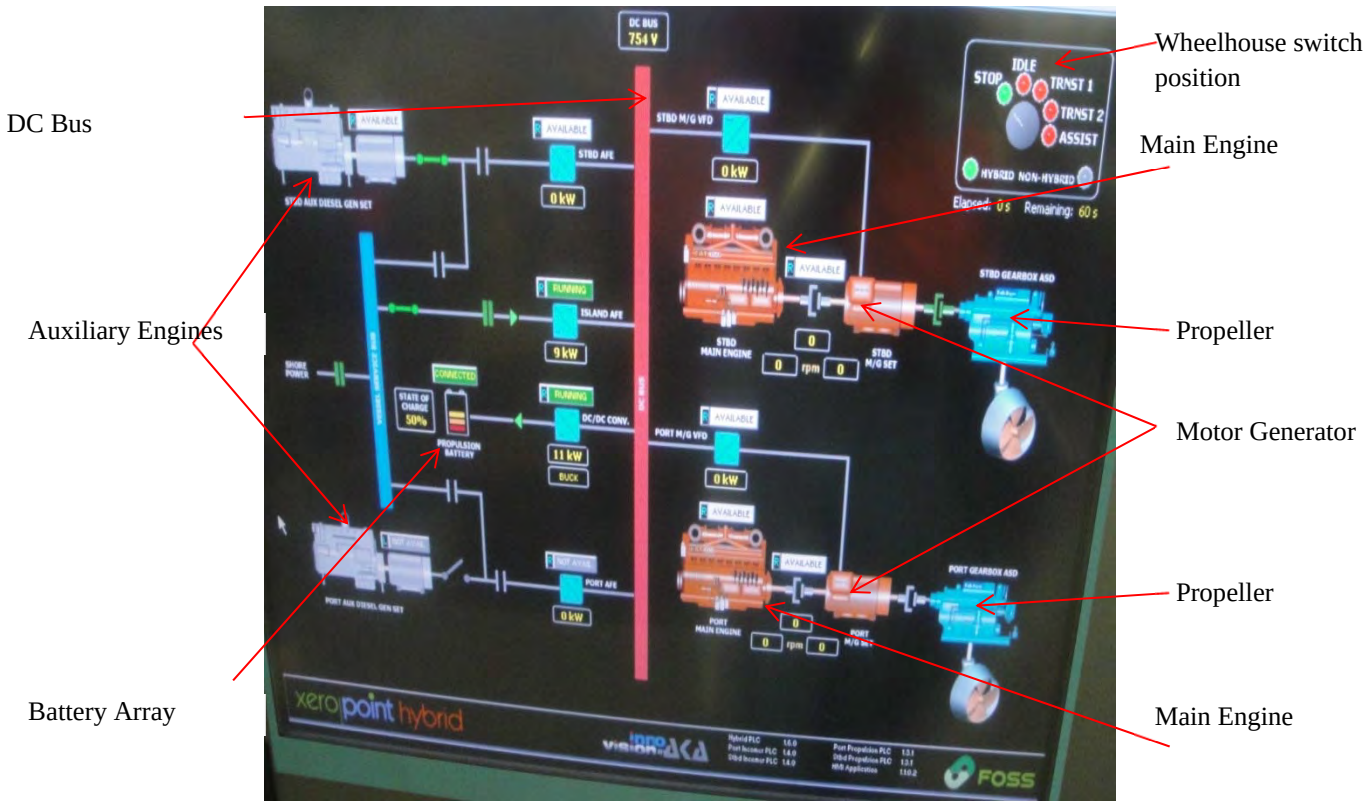


Figure 2-1: Diesel Electric Drive Train on the Hybrid *Campbell Foss*

2.4 Test Schedule

The testing program was conducted over the period of 13 months which included data logging for 37 days to determine the activity of the hybrid tugboat and emissions measurement from main and auxiliary engines.

According to the test plan, activity of the tugboat was to be logged for at least continuous 30 days. However, due to technical issues with the hybrid tugboat and data logger, data was obtained intermittently for nine to nineteen days period. Thus, activity data was logged for more than 30 days to ensure that the logged activity is representative of tugboat operation. Table 2-3 shows the schedule for data logging on the hybrid tugboat. Details of the data logging procedure and analysis to determine the tugboat activity are provided in section 2.5.

Table 2-3: Data Logging Test Schedule

Tugboat	Start Date	Stop Date
Hybrid Campbell	5/25/2012	6/6/2012
	6/9/2012	6/17/2012
	6/21/2012	7/9/2012

Emissions testing of main and auxiliary engines were performed in three phases. A brief description of these phases is provided below. Test schedules for Phase *I*, *II* and *III* are

provided in Table 2-4. Further details on emissions testing and analysis are presented in section 2.6.

Phase I involves testing one ME and one AE from the *Campbell Foss* tug prior to retrofit following the load points in the ISO 8178 E3 (ME), ISO 8178 D2 (AE) and the in-use load points determined in the previous ARB report[14].

Phase II involves the testing of the new repowered AE engine according to ISO 8178 D2 and in-use load points.

Table 2-4: Test Schedules for Emissions Testing *Phase I*, *II* and *III*

Phase	Tugboat	Engine	Date
I	Conventional	CAT 3512C	6/27/2011
		JD 6081	6/28/2011
II	Hybrid	MTU/Detroit Series 60	3/21/2012
III	Hybrid	MTU/Detroit Series 60	7/12/2012

Phase III involves retesting the new retrofit AE engine after the 1000 hour operation according to ISO 8178 D2 test cycle and in-use load points. This test was required to show the durability of the new engine over time.

2.5 Determining Tugboat Activity

The following sections describe the typical operating modes of the tug boat, procedure for data collection and analysis to establish the weighing factors for each operating mode as well as development of engine histograms for all four engines on the tugboat.

2.5.1 Tug Operating Modes

There are five operating modes pre-determined for the hybrid *Campbell Foss*. These operating modes are *Stop*, *Idle*, *Transit 1*, *Transit 2* and *Assist*. In addition to these modes, *Shore Power* was determined from in-use activity data.

Shore Power: The tug is at the dock plugged into shore power for its utilities. None of the engines are operating during this mode. The hybrid boat spends considerable amount of time plugged into shore power. The conventional boat also spends similar amount of time plugged into shore power when at dock. During this time, batteries can be charged.

Stop: During this operation the tug boat is at the dock (shore power is unavailable) with batteries or one auxiliary engine supplying power for the lights and air-conditioning on the boat. On the conventional tug one auxiliary engine is always on at *Stop*. The hybrid tug switches between one auxiliary engine and batteries during this mode. If the state of charge (SOC) of the battery arrays reduce to 20% the 125 kW auxiliary engine will turn

on to charge the batteries and provide hoteling power for the tug. As soon as the batteries are charged to a SOC of 95% the engine turns off and the batteries discharge providing hoteling power.

Idle: In this mode the tug is idling at sea waiting for a vessel to arrive or a call from the dispatch office to start or transit to a job. The conventional tug operates two main propulsion engines and one auxiliary generator during *Idle*. As in the case of *Stop* the hybrid tug switches between the batteries and one auxiliary engine.

Transit 1: The mode refers to the movement of the tug between jobs and to and from different docks. The conventional tug boat operates two main engines and one auxiliary engine during transit. The hybrid boat operates its 350 kW auxiliary engine for transit at <6.0 knots within the port. The auxiliary engine also provides power for battery charging and hotel loads.

Transit 2: This mode is available to provide transit speeds up to approximately 7.5 knots. In this mode the 350 kW and 125 kW auxiliary engines provide power for propulsion, battery charging and hotel load. Main engines are rarely operated during *Transit 2* in the hybrid tugboat.

Assist: Tug boats typically perform two kinds of jobs in the ports – a) assisting ships from berth to sea and vice-versa b) moving barges from one location to another. In this study, both jobs are considered under *Assist* as both main engines are operating irrespective of job nature. The conventional tug operates two main engines and one auxiliary engine during this mode. The hybrid boat operates both main engines. A 350 kW auxiliary engine rarely operates during *Assist*.

Tables 2-5 and 2-6 show the operating details for the conventional and hybrid tug boats during each mode.

Table 2-5: Operating modes of conventional tugboat

Operational Modes	ME#1 CAT 3512C	ME#2 CAT 3512C	AE#1 JD 6081	AE#2 JD 6081
Shore Power	Off	Off	Off	Off
Stop	Off	Off	On	Off
Idle	On	On	On	Off
Transit 1	On	On	On	Off
Transit 2	On	On	On	Off
Assist	On	On	On	Off

Table 2-6: Operating modes of hybrid tugboat. **ME**: *Main Engine*; **AE:** *Auxiliary Engine*

Operational Modes	ME#1 CAT 3512C	ME#2 CAT 3512C	AE#1 DETROIT	AE#2 JD 6081	Battery
Shore Power	Off	Off	Off	Off	Off
Stop	Off	Off	Off	On (as needed)	On
Idle	Off	Off	Off	On (as needed)	On
Transit 1	Off	Off	On	Off	Off (Charging)
Transit 2	Off	Off	On	On	Off (Charging)
Assist	On	On	Off	Off	On (as needed)

To determine the activity of the hybrid tug, GPS, and engine and battery data had to be logged continuously for a period of over one month. For this purpose, a Labview program was developed that was capable of interfacing with the four engine electronic control modules (ECMs), a GPS and batteries to retrieve the required information continuously on a second by second basis and write it into a comma separated value (CSV) file. Each line in the CSV file generated by the code represents one second. The program automatically creates a new file after 65500 seconds thereby ensuring that the CSV file is not too large for Microsoft Excel to handle. This Labview program was installed and operated on the data-logger which is a computer with Windows XP operating system. The Labview program was incapable of logging ECM signals from two different Society of Automotive Engineers (SAE) protocols (J1939 and J1708). Therefore, MTU/Detroit diesel engine which was compatible with J1708 protocol was recorded separately on the laptop with the same Labview program. Table 2-7 lists all the parameters that were logged from the tugboat along with the devices used for interfacing between the power sources and the data-logger.

Schematic of the data-logger set up on the hybrid tugboat is provided in Figures 2-2. The data-logger and the laptop were placed on the workbench in the engine room of tug boat. Data from the ECMs on the two main propulsion engines and the two auxiliary engines were obtained using four Dearborn Protocol Adapters that convert the J1939 and 1807 signals to serial/RS-232 signals. Power for the Dearborn adapters was obtained from the batteries used for engine startup.

A Garmin GPS that provides data on location, speed and course of the tug at any second during the sample time was placed at the top of the mast on the tug boat to ensure that it receives a clear signal. Serial cables were run from GPS to the data-logger.

The hybrid tug has a switch in the wheelhouse that is used by the captain for operating the boat. This wheelhouse switch communicates with an energy management system to determine how many power sources will be required for that operation. The wheelhouse

switch has five positions which indicate the mode of operation of the tug. These are listed below:

1 - Stop Tug switches between the batteries and one auxiliary engine.

2 - Idle Tug switches between the batteries and one auxiliary engine.

3 - Transit 1 Tug uses one auxiliary engine (JD 6081 – 125kW).

4 – Transit 2 Tug uses both auxiliary engines.

5 - Assist Tug uses both main and the batteries (if needed) for a job.

AKA provided us with five digital signals, indicating the operating mode of the hybrid tugboat. They also provided us with three analog signals that give information on the operation of the battery array

1 - State of Charge of Battery Array

2 - Voltage of Battery Array

3 - Current for Battery Array

The wireless network on the boat was not strong enough for file transfer. Therefore the port engineer uploaded the CSV files on a weekly basis to a file transfer protocol (FTP) site.

	HT	Devices Used	Parameters Logged
GPS	√	• Garmin GPS 18 PC receives wireless signal from satellite and transmits it through a serial port to the data-logger	Date, time, latitude, longitude, speed and course
Two main propulsion engines and two auxiliary engines	√	• 4 Dearborn Protocol Adapters Model DG-DPAIII/i that receive J1939 and 1708 signal from engine electronic control modules (ECM) • 4 Dearborn Protocol Adapter cables (DG-J1939-04-CABLE) that convert the J1939 signal to serial/RS232 signal, • One USB2-4COM-M that receives 4 serial signals and transmits them through one USB port to the data-logger	Engine speed (rpm), engine load (percentage of maximum load at the engine speed), instantaneous fuel flow rate (cc/min), inlet manifold temperature (°F) and pressure (kPa)
Wheelhouse Switch	√	• 5 Philmore 86-124 (24 vDC, 10 A) SPDT relays convert the signals from wheelhouse switch to digital voltage signals. • Omega's USB-1608FS box receives these five digital signals from the relays and transmits them through a single USB cable to the data-logger.	Operating Modes: Stop, Idle, Transit 1, Transit 2 and Assist
Battery Array	√	• Omega's USB-1608FS box that receives three analog signals from the battery array and transmits them through a single USB cable to the data-logger.	State of charge, voltage in volts and current in amps from battery array.

Table 2-7: Details of Data-Logger

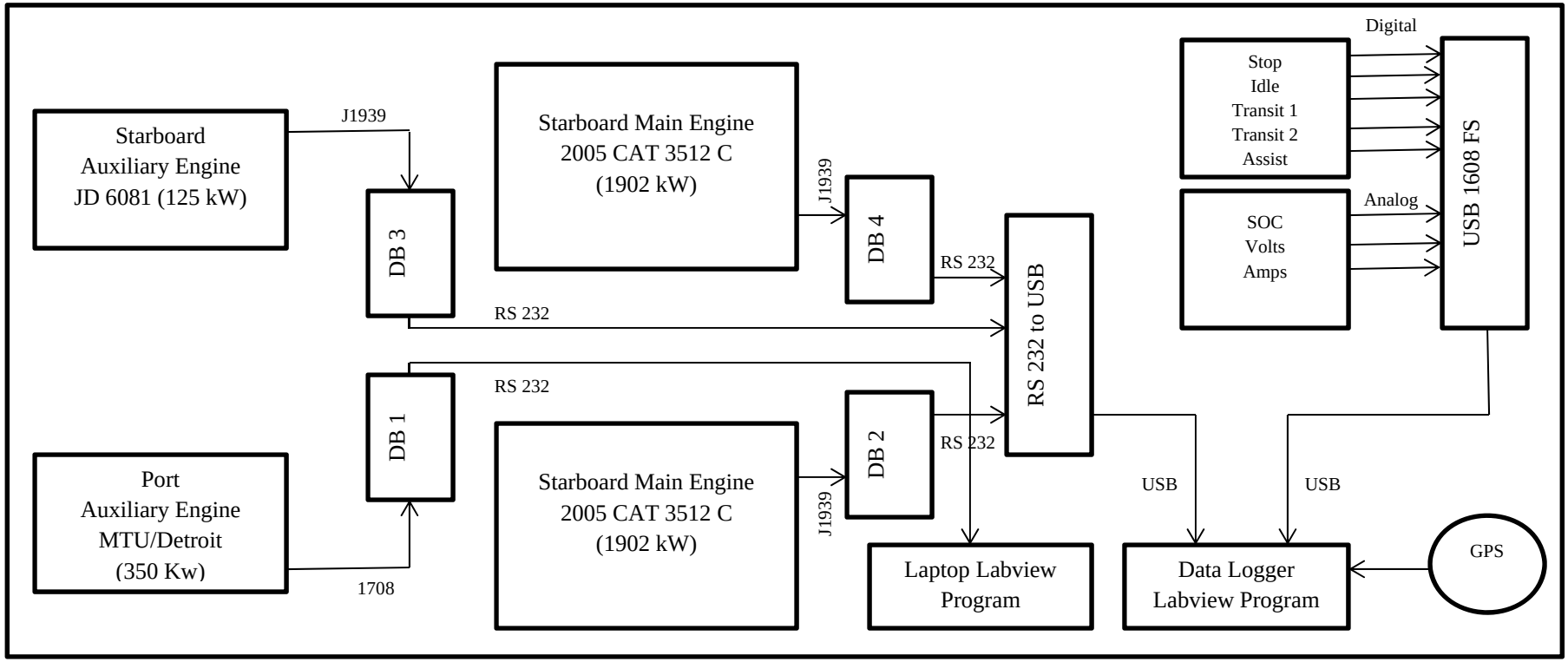


Figure 2-2: Schematic of Data-logging system on a Hybrid Tugboat

2.5.2 Establishing Weighting Factors for Tugboat Operating Modes

The weighting factor for each operating mode was calculated as the ratio of the time spent by the tug in that mode to the total sample time (Equation 2-3). The CVS files obtained from data logger have five columns which represent five (*Stop*, *Idle*, *Transit 1*, *Transit 2*, *Assist*) operating modes of the tugboat. Depending upon the mode that tugboat is in; digital signals from Energy Management System will feed a value "1" to the data logger and "0" for rest of the operating modes. For example, when tugboat is in *Assist* mode, *Assist* column in the CVS file will be represented by "1" and rest of modes will be represented by "0". Therefore, in each CVS file, sum of individual operating modes represents the time spent by tug in those operating modes. Hence, weighting factor for each operating mode was obtained as the ratio of the time spent by the tug in that mode to the total sample time. Please note that the weighting factors for the conventional tugboat (prior to retrofit) are assumed to be same as hybrid tugboat.

2.5.3 Developing Engine Histograms

Engine histograms are basically graphs showing the amount of time the engine spends at different loads. In this project, engine histograms have to be developed for all four engines for each tug operating mode. During the data logging procedure, the engine speed in rpm and engine load as a percentage of the maximum load at that speed were retrieved from the engines' ECMs and written into the CSV files. For the auxiliary engines which are constant speed diesel generators, the percent load from the ECM has to be multiplied by the maximum rated load of the engine in kW to get the load on the engine. The main propulsion engines are variable speed engines. Therefore, at any given speed the maximum attainable load in kW was obtained from the engines' lug curve and multiplied by the percent load retrieved from the ECM to determine the load on the engine. The Lug Curve for the main engine was obtained from the ARB[14] study, *Evaluating Emission Benefits of a Hybrid Tug Boat* (2010).

The ratio of the carbon-dioxide emissions to the load on the engine is an indication of its thermal efficiency. This efficiency tends to be relatively constant across the entire range of engine operation. Therefore, we would expect a straight line relationship between the engine load and the CO_2 emissions in kg/hr. Any significant deviation from the straight line relationship will indicate an error in the load readings provided by the ECM. Figure 2-3 to 2-5 shows plots of ECM load versus the measured CO_2 emissions in kg/hr for the main engine and auxiliary engines tested for emissions.

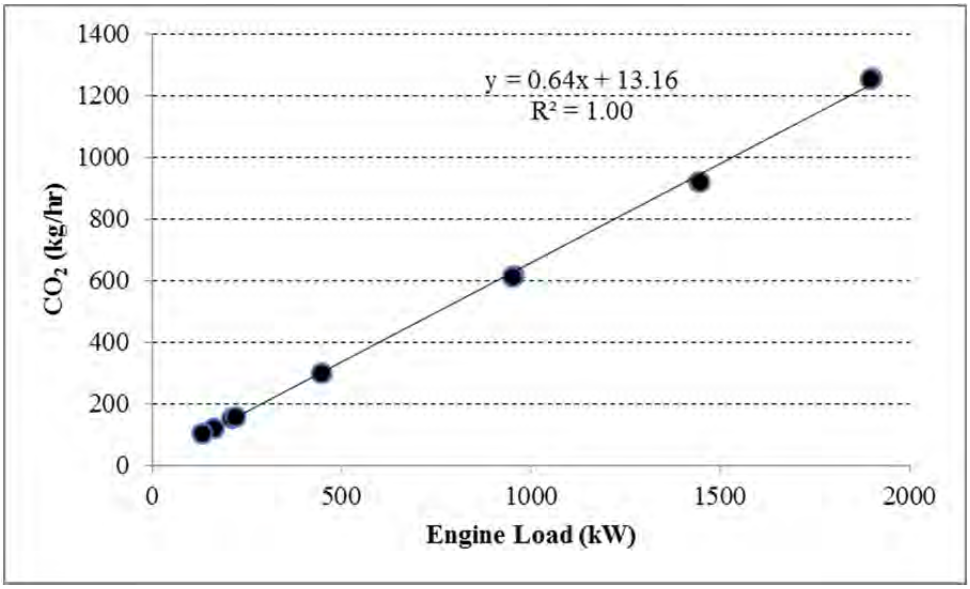


Figure 2-3: ECM load versus CO_2 emissions for the main engine (CAT 3512 C)

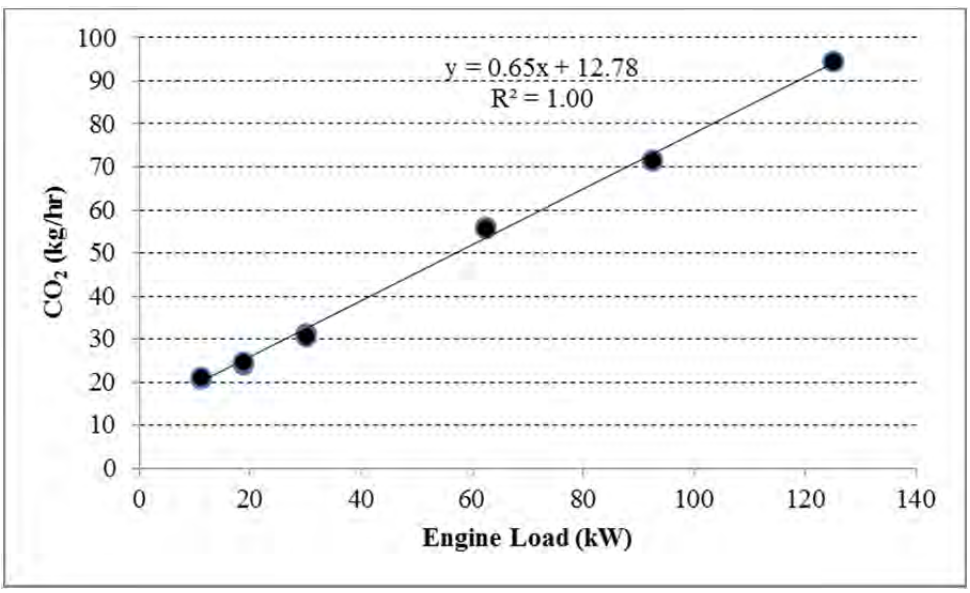


Figure 2-4: ECM load versus CO_2 emissions for the auxiliary engine (JD 6081)

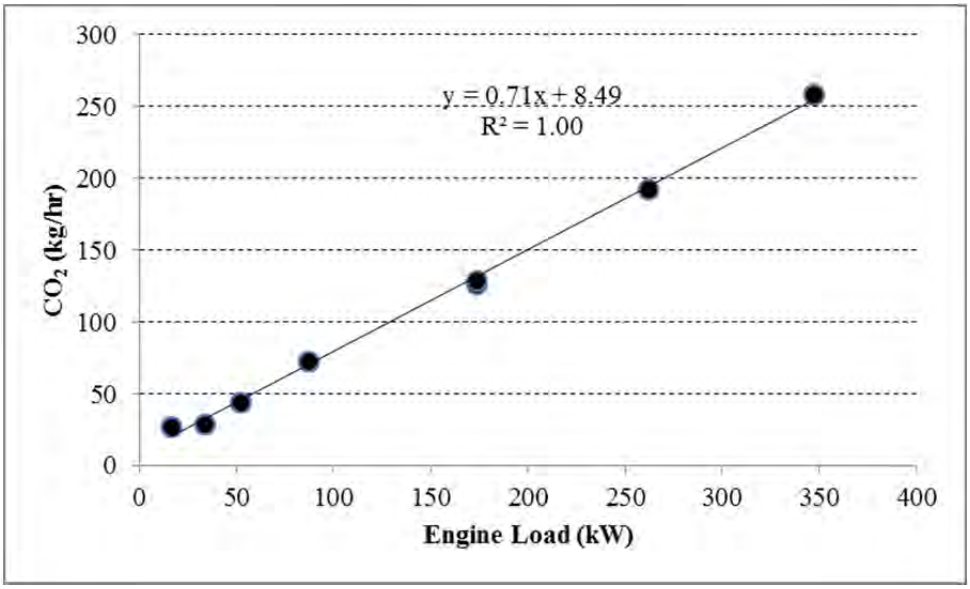


Figure 2-5: ECM load versus CO_2 emissions for the auxiliary engine (MTU/Detroit)

Within each CVS file, five more spreadsheets were added to represent five operating modes of the tugboat. Based on the digital value of "1" obtained from energy management system to indicate the engaged operating mode, data in CVS file was filtered and added to the respective operating mode spreadsheet. Within each operating mode spreadsheets, engine loads were split into twelve bins for all four engines as shown in Table 2-8.

Bin	Load Range	no. of data points in each Bin
Bin 0	0%	Bin 0
Bin 1	<10%	Bin 1 - Bin 0
Bin 2	10% to <20%	Bin 2 - Bin 1
Bin 3	20% to <30%	Bin 3- Bin 2
Bin 4	30% to <40%	Bin 4- Bin 3
Bin 5	40% to <50%	Bin 5- Bin 4
Bin 6	50% to <60%	Bin 6- Bin 5
Bin 7	60% to <70%	Bin 7- Bin 6
Bin 8	70% to <80%	Bin 8- Bin7
Bin 9	80% to <90%	Bin 9- Bin 8
Bin 10	90% to <100%	Bin 10- Bin 9
Bin 11	<101%	Bin 11- Bin 10

Table 2-8: Twelve bins for dividing engine load range

Using this data the fraction of time spent by the engine in any bin for a particular operating mode was calculated. This was then plotted in the form of engine histograms. The engine histograms developed from the CSV files are used to calculate the total emissions from a tug. Therefore it is important to ensure that the state of charge of the battery at the start and end time of each sample period chosen for the calculation of the engine histogram are the same. This would eliminate any biases in emissions resulting from the use of the auxiliary engine for charging the batteries. This protocol was adopted based on the guidelines in the SAE[15] and ARB[16] testing protocols for hybrid electric vehicles.

2.6 Emissions Testing Procedure

2.6.1 Test Engines

Conventional *Campbell Foss* was powered by two main propulsion engines and two auxiliary engines/generators. The main engines (ME) CAT 3512 Tier 1 marine diesel engines while the auxiliary engines (AE) John Deere 6081 diesel engines (Table 2-9). The MEs were used for propulsion and the AEs were used for hoteling, lighting, air conditioning and to operate the winch motor.

Table 2-9: Engine Specifications for Conventional *Campbell Foss*

	Main Engine (ME)	**Auxiliary Engine (AE)**
Manufacturer /Model	CAT 3512	John Deere 6081
Manufacture Year	2005	2005
Certification Standard	Tier 1	Tier 0
Technology	4-Stroke Diesel	4-Stroke Diesel
Max. Power Rating	1902 kW	125 kW
Rated Speed	1800 rpm	1800 rpm
# of Cylinders	8	8
Displacement	58.6 liters	8.1 liters

The retrofit hybrid *Campbell Foss* is powered by the original MEs and one of the two original AEs. The other AE was repowered with a new Tier 2 engine (Table 2-10).

Table 2-10: Engine specifications of new Auxiliary Engine

	Auxiliary Engine (AE)
Manufacturer /Model	MTU/Detroit Diesel Series 60
Manufacture Year	2011
Technology	4-Stroke Diesel

Certification Standard	Tier 2
Max. Power Rating	350 kW
Rated Speed	1800 rpm
# of Cylinders	6
Displacement	14 liter

2.6.2 Fuels

The project used commercial On-Road #2 diesel fuel meeting specification requirements of the California Air Resources Board and the ASTM 975. Typically, the sulfur content in the fuel is < 10ppmw.

2.6.3 Test Cycle and Operating Conditions

Phase I: The primary goal of this phase of the testing program was to establish if the test engines meet their certification standards when in-use. Gaseous and $PM_{2.5}$ emission measurements on these engines were made based on the ISO 8178-1 protocol (Appendix A). Briefly, a partial dilution system with a venturi was used for $PM_{2.5}$ sampling (Appendix A). Carbon dioxide, nitrogen oxides and carbon monoxide were measured in both the raw and the dilute exhaust. The ratio of the concentration of carbon dioxide in the raw to the in the dilute was used to determine the dilution ratio for $PM_{2.5}$ sampling.

The main propulsion engines were tested following the steady state load points in the ISO 8178-4 E3 cycle. It has been found in the previous study that main engine spent significant amount of time at loads below 25%. Also, engine histogram (Figure 2-6) obtained from ECM clearly indicated that the main engine was operated under 25% load for approximately 80% of its time. Therefore, an additional measurement was made at the 15% and 10% of engine load. The auxiliary engines were operated at the steady state load points in the ISO 8178-4 D2 cycle and at 15% engine load. Details of the test cycles are provided in Appendix B.

Table 2-11: Test matrix of emissions testing of *Phase I*

Tug Boat	Engine	DATE	Engine Loads
Campbell	CAT 3512 C	6/27/2011	RT & ISO: 100%, 75%, 50%, 25%, 15%, 10%
Conventional	JD 6081	6/28/2011	RT & ISO: 100%, 75%, 50%, 25%, 15%, 10%

RT: Real Time Monitoring and Recording of Gaseous Emissions; ISO: Filter Samples taken in accordance with ISO 8178-4 E3/D2 cycles

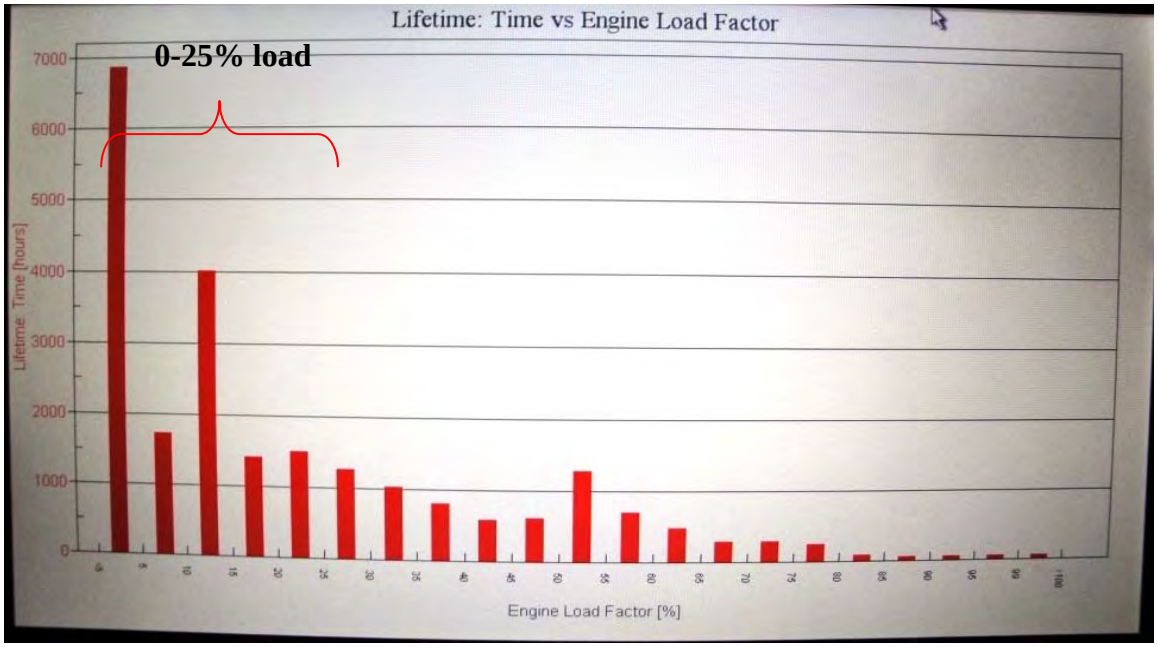


Figure 2-6: Engine Histogram Obtained from the ECM of the Main Engine on the *Campbell Foss*

The steady state load points on the main engine of the conventional tug were achieved while the tug pushed against the pier. Since the auxiliary generator on the conventional tug is not used for propulsion and the typical steady state load on this engine is 12% of its maximum load, a load bank had to be used to achieve the higher load points. Due to practical considerations, the actual engine load at each test mode on all four engines could differ by a factor of ±5% from the ISO target load. Table 2-11 lists the test matrix for Phase *I* of emissions testing.

At each steady state test mode the protocol requires the following:

- Allowing the gaseous emissions to stabilize before measurement at each test mode.
- Measuring gaseous and $PM_{2.5}$ concentrations for a time period long enough to get measurable filter mass
- Recording engine speed (rpm), displacement, boost pressure and intake manifold temperature in order to calculate the mass flow rate of the exhaust.

Phase II: It involves the emissions testing of new retrofit AE engine according to ISO 8178 D2 and in-use load points. Test matrix for *Phase II* is shown in Table 2-12.

Phase III: involves retesting the new retrofit AE engine after the 1000 hour operation at the harbor according to ISO 8178 D2 test cycle and in-use load points. This test was required to show the durability of the new engine over time. Test matrix for *Phase III* is shown in Table 2-12.

Table 2-12: Test matrix of emissions testing of *Phase II* and *III*

Phase	Tugboat	Engine	Date	Engine Loads
II	Hybrid	MTU/Detroit	3/21/2012	RT &ISO: 100%, 75%, 50%, 25%, 15%, 10%, 5%
III	Campbell	MTU/Detroit	7/12/2012	RT &ISO: 100%, 75%, 50%, 25%, 15%, 10%, 5%

RT: Real Time Monitoring and Recording of Gaseous Emissions; ISO: Filter Samples taken in accordance with ISO 8178-4 E3/D2 cycles

2.6.4 Sampling Ports

Only one sample port was available in the stack of each engine. A T- joint was installed at the end of the sample probe to provide raw gas sample for gaseous measurements and dilution for $PM_{2.5}$ sampling. Sample ports on both main and auxiliary engines were located before the muffler. For the main propulsion engines, the sample port was located just a few inches above the exhaust manifold while on the auxiliary engines it is several feet away from the manifold. The sampling probes used for emissions testing were 3/8th inch stainless steel tubing. These probes were inserted five inches into the main engine stacks (stack diameter: fourteen inches) and two in into the auxiliary engine stack (stack diameter: six inches). These distances were sufficiently away from any effects found near the stack walls. Figure 2-7 and Figure 2-8 show pictures of installed setup for sampling gaseous and particulate emissions from auxiliary and main engines of the conventional *Campbell Foss* tug.

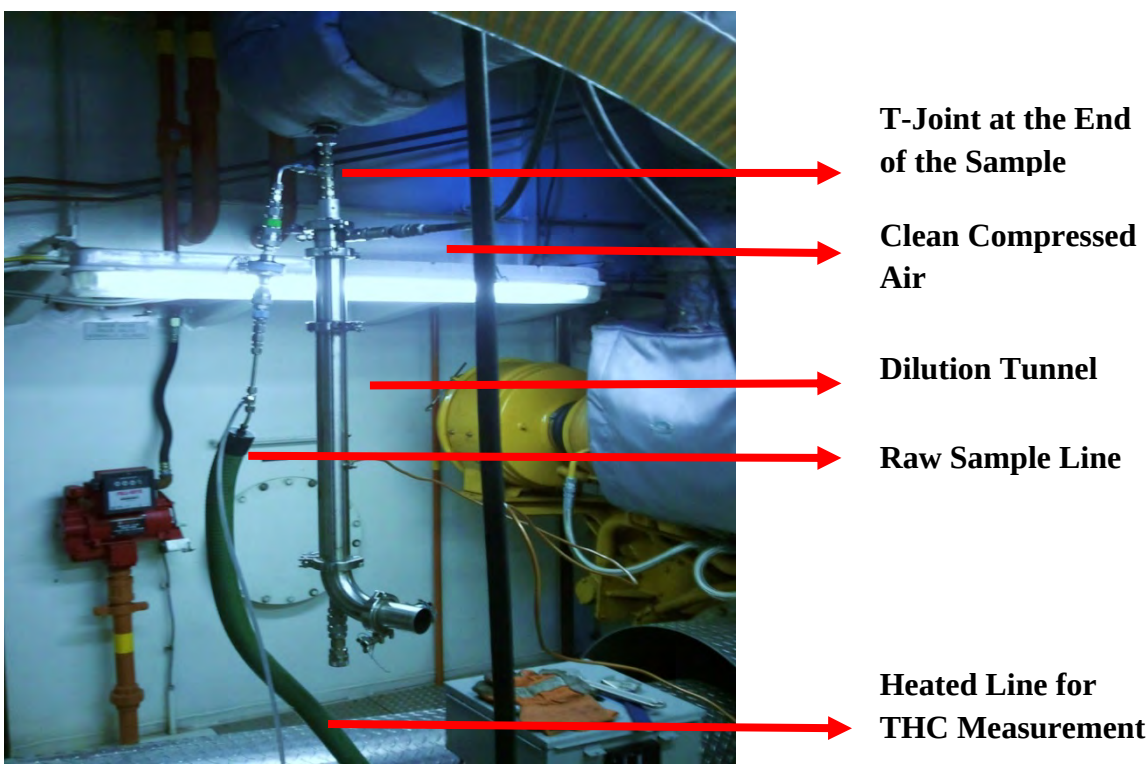


Figure 2-7 Sampling port for Auxiliary engine on conventional *Campbell Foss* tug boat

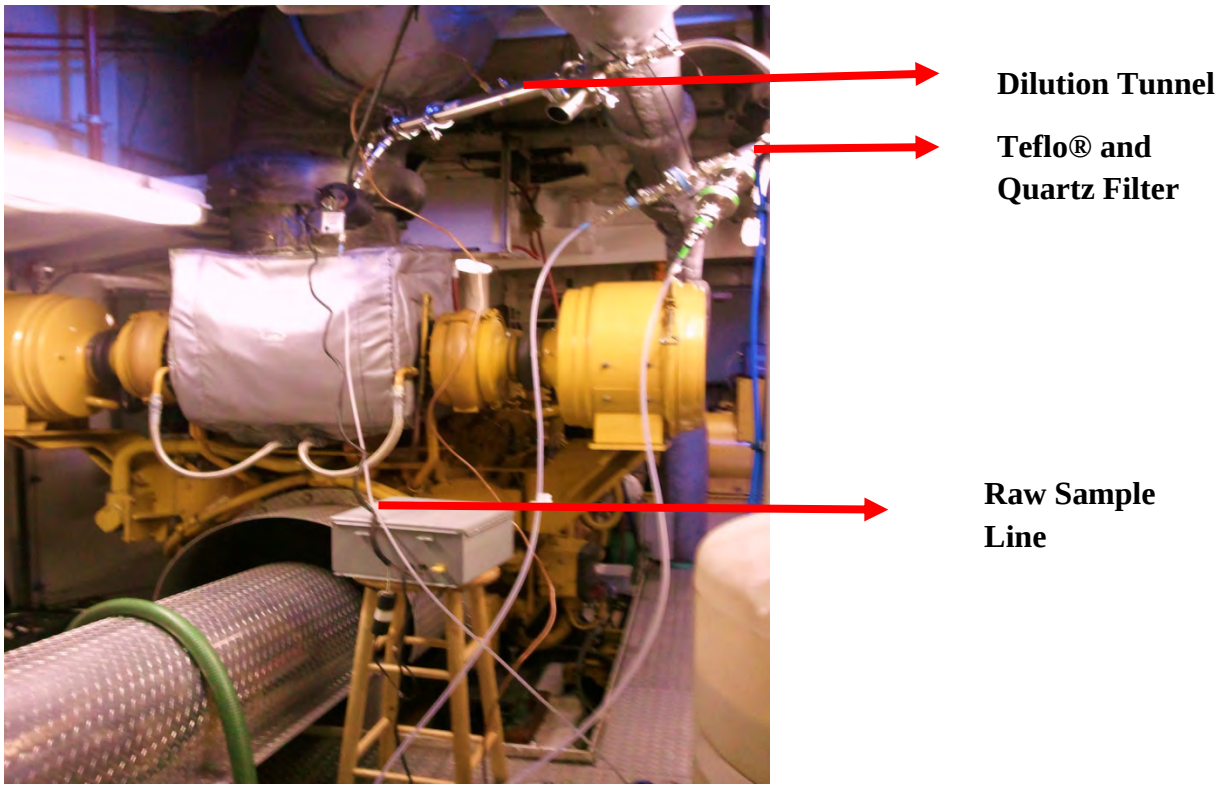


Figure 2-8 Sampling port for Main engine on conventional *Campbell Foss* tug boat

2.6.5 Measuring Gases and $PM_{2.5}$ emissions

The concentrations of carbon dioxide (CO_2), nitrogen oxides (NO_x) and carbon monoxide (CO) were measured both in the raw exhaust and the dilution tunnel with a Horiba PG-250 portable multi-gas analyzer. During Phase I particulate matter ($PM_{2.5}$) was sampled from the dilution tunnel on Teflo® and Tissuquartz filters. These filters were analyzed to determine the total and speciated $PM_{2.5}$ mass emissions.

2.6.6 Calculating Exhaust Flow Rates

Intake Air Method: An accurate calculation of the exhaust gas flow rate is essential for calculating emission factors. This method calculates the exhaust gas flow as equal to the flow of intake air. This method is widely used for calculating exhaust flow rates in diesel engines and assumes the engine is an air pump, so the flow of air into the engine will be equal to the exhaust flow out of the engine. The flow rate of intake air is determined from the cylinder volume, recorded engine speed, and the temperature and boost pressure. The method works best for four stroke engines or for two stroke engines where there the scavenger air flow is much smaller than the combustion air. All four test engines in this program were four stroke marine diesel engines.

Carbon Balance Method: The calculated emission factor is strongly dependent on the mass flow of the exhaust. Two methods for calculating the exhaust gas mass flow and/or

the combustion air consumption are described in ISO 8178-1 Appendix A[1]. Both methods are based on the measured exhaust gas concentrations and fuel consumption rate. The two ISO methods are described below.

Method 1, Carbon Balance, calculates the exhaust mass flow based on the measurement of fuel consumption and the exhaust gas concentrations with regard to the fuel characteristics (carbon balance method). The method is only valid for fuels without oxygen and nitrogen content, based on procedures used for US EPA and United Nation Economic Commission for Europe (UNECE) calculations.

Method 2, Universal, Carbon/Oxygen-balance, is used for the calculation of the exhaust mass flow. This method is applicable for fuels containing H, C, S, O and N in known proportions and does not apply here since the fuel contains mainly carbon and hydrogen and rest of the elements were insignificant.

The carbon balance methods may be used to calculate exhaust flow rate when the fuel consumption is measured and the concentrations of the exhaust components are known. In these methods, flow rate is determined by balancing carbon content in the fuel to the measured carbon dioxide in the exhaust. This method can only be used when the fuel consumption data are available.

For both main and auxiliary engine on the tug, fuel consumption rate was recorded from ECM. Fuel consumption rate was used in calculating exhaust flow rate by carbon balance method. Intake manifold temperature and boost pressure readings were obtained from the main engine ECM. These were used for the exhaust flow calculation based on the intake air method. Boost pressure was not retrievable from the auxiliary engine; therefore calculation based on the intake air method was not performed.

2.6.7 Calculation of Engine Load

The actual load on the engine at each test modes is required to calculate the modal and overall emission factors in g/kW-hr. The engine ECM provides engine speed and the percentage of the maximum engine load at that speed. For the main propulsion engines, this data was used along with the lug curve provided by the manufacturer for that engine family to determine the actual load in kW for each test mode. For the constant speed auxiliary engines the % of maximum engine load obtained from the engine ECM was multiplied by the engine's rated prime power to get the load on the engine in kW.

[1] *International Standards Organization, IS0 8178-1,* Reciprocating internal combustion engines - Exhaust emission measurement -Part 1: Test-bed measurement of gaseous particulate exhaust emissions, *First edition 1996-08-l5*

2.6.8 Calculation of Emissions in g/hr

Mass emissions of CO_2, NO_x and CO in g/hr were determined using the calculated exhaust flows and the measured concentrations in the exhaust. For $PM_{2.5}$ mass emissions the concentration in the dilute exhaust was calculated as a ratio of the measured filter weight to the total sample flow through the filter. This was then converted to a concentration in the raw exhaust by multiplying with the dilution ratio. The raw $PM_{2.5}$ concentration was used along with the exhaust flow to determine the mass emissions in g/hr.

2.6.9 Calculation of Emission Factors in g/kW-hr

The emission factor at each mode is calculated as the ratio of the calculated mass flow (g/hr) in the exhaust to the reported engine load (kW).

An overall single emission factor representing the engine is determined by weighting the modal data according to the ISO 8178 E3 or ISO 8178 D2 cycle requirements and summing them. The equation used for the overall emission factor is as follows:

$$\boldsymbol{EF_{WM}} = \frac{\sum_{i=1}^{n}(\boldsymbol{g_i} \times \boldsymbol{WF_i})}{\sum_{i=1}^{n}(\boldsymbol{P_i} \times \boldsymbol{WF_i})}$$

where:

EF_{WM}	Overall weighted average emission factor in g/kW-hr
n	Total number of modes in the ISO duty cycle
g_i	Calculated mass flow in g/hr for the ith operating mode
WF_i	weighing factor for the ith operating mode
P_i	Engine load in kW for the ith operating mode

3 Results and Discussions

3.1 Emissions Testing *Phase I*

The primary gaseous emissions measured during this test program include carbon dioxide (CO_2), nitrogen oxides (NO_x), and carbon monoxide (CO). Each of these gaseous species was measured using the ISO standard instrumentation (Appendix A, Section 4.6). In addition to gaseous emissions, the $PM_{2.5}$ mass emissions and the speciated $PM_{2.5}$ emissions as elemental carbon (EC) and organic carbon (OC) were measured. As described earlier, the PM mass in the raw exhaust was sampled using a partial dilution method and collected on filter media. A detailed list of the modal gaseous and $PM_{2.5}$ emissions in g/hr and g/kW-hr, for the two test engines are provided in Tables 3-1 and 3-2 respectively. In the previous study, activity data developed for the tug boat reflected that the tug spends significant amount of time while operating between 10-20% engine loads. Therefore, emissions at 15% load for auxiliary engine, and 10% and 15% for main engine were tested in addition to load specified in ISO 8178 for engine certification.

Duplicate measurements were made at steady state test mode. Each gaseous measurement was a three to seven minute average of one hertz data obtained from the instrument. The standard deviation of three to seven minute averages was <2% for CO_2. This indicates that the load on the engine while testing that mode was steady, thereby validating the measurement at each of those test modes. In the case of $PM_{2.5}$, each measurement refers to a filter sample. The range across these duplicate measurements is shown as error bars in the Figures 3-1 and 3-2.

Modal emissions data represented in Table 3-2 are helpful in developing emission inventories of tugboats. High emission factors are observed at loads 25% or below for both engines. This is consistent with our observations and the fact that brake-specific fuel consumption increases significantly at these load points.

Table 3-2 also lists the overall weighted average emission factors for both of the test engines. The overall weighted factors from both engines were also compared with EPA Tier 1 standards. The overall weighted average for auxiliary engine (JD 6081) is well below EPA Tier 1 standards for NO_x and $PM_{2.5}$. Moreover, EF_{CO} is comparatively very low which is typical of diesel engines. In case of Main engine (CAT 3512 C); overall weighted emission factors are also below EPA Tier 1 limit. $EF_{PM2.5}$ is significantly lower than standard which is similar to previous study. The speciated $PM_{2.5}$ data suggests that for both engines, organic fraction of total PM dominates at lower loads (≤ 25%) and elemental carbon at loads above 25%.

Overall, *Phase I* study concludes that the both engines are well maintained; their emissions are within certification limits and are representative of engines in their category.

Table 3-1: Results for *Phase I* of Emissions Testing in g/hr

Load		NO_x	CO	CO_2	THC	$PM_{2.5}$	EC	OC
Target	**Actual**	**g/hr**						
Auxiliary Engine on Conventional Campbell Tug JD 6081								
10%	9%	242	42	20920	9.2	8.6	0.8	4.6
15%	15%	278	39	24463	13	8.6	1.3	5.2
25%	24%	366	44	30950	7.7	17	6.4	5.7
50%	50%	372	88	55781	12	23	19	5.7
75%	74%	519	137	71380	16	37	22	11
100%	100%	753	296	94530	20	45	28	11
Main Engine on Conventional Campbell Tug CAT 3512 C								
10%	8%	2299	166	121606	63	10	1.6	5.0
15%	11%	2922	195	155143	63	6.7	3.2	5.7
25%	24%	4860	1252	300463	116	32	18	11
50%	50%	8638	2574	615489	155	101	56	28
75%	76%	11728	2571	922501	207	190	76	66
100%	100%	14078	2481	1257418	224	207	81	81

Table 3-2: Emission Factors in g/kW-hr from *Phase I* of Testing

Load		NO_x	CO	CO_2	THC	$PM_{2.5}$	EC	OC
Target	**Actual**	**g/kW-hr**						
Auxiliary Engine on Conventional Campbell Tug JD 6081								
10%	9%	21.5	3.75	1860	0.82	0.76	0.07	0.41
15%	15%	14.8	2.09	1305	0.69	0.46	0.07	0.28
25%	24%	12.2	1.46	1032	0.26	0.55	0.21	0.19
50%	50%	5.9	1.41	892	0.20	0.37	0.31	0.09
75%	74%	5.6	1.49	772	0.17	0.40	0.24	0.12
100%	100%	6.0	2.37	756	0.16	0.36	0.22	0.09
Wt. Avg.		7.1	1.59	870	0.20	0.42	0.25	0.13
EPA Tier 1		9.2	11.4			0.54		
Main Engine on Conventional Campbell Tug CAT 3512 C								
10%	8%	14.3	1.03	755	0.39	0.06	0.01	0.03
15%	11%	13.6	0.91	722	0.29	0.03	0.01	0.03
25%	24%	10.9	2.8	671	0.26	0.07	0.04	0.02
50%	50%	9.1	2.7	647	0.16	0.11	0.06	0.03
75%	76%	8.1	1.8	639	0.14	0.13	0.05	0.05
100%	100%	7.4	1.3	663	0.12	0.11	0.04	0.04
Weighted Avg.		8.2	1.80	649	0.14	0.12	0.05	0.05
EPA Tier 1		9.2	11.4			0.54		

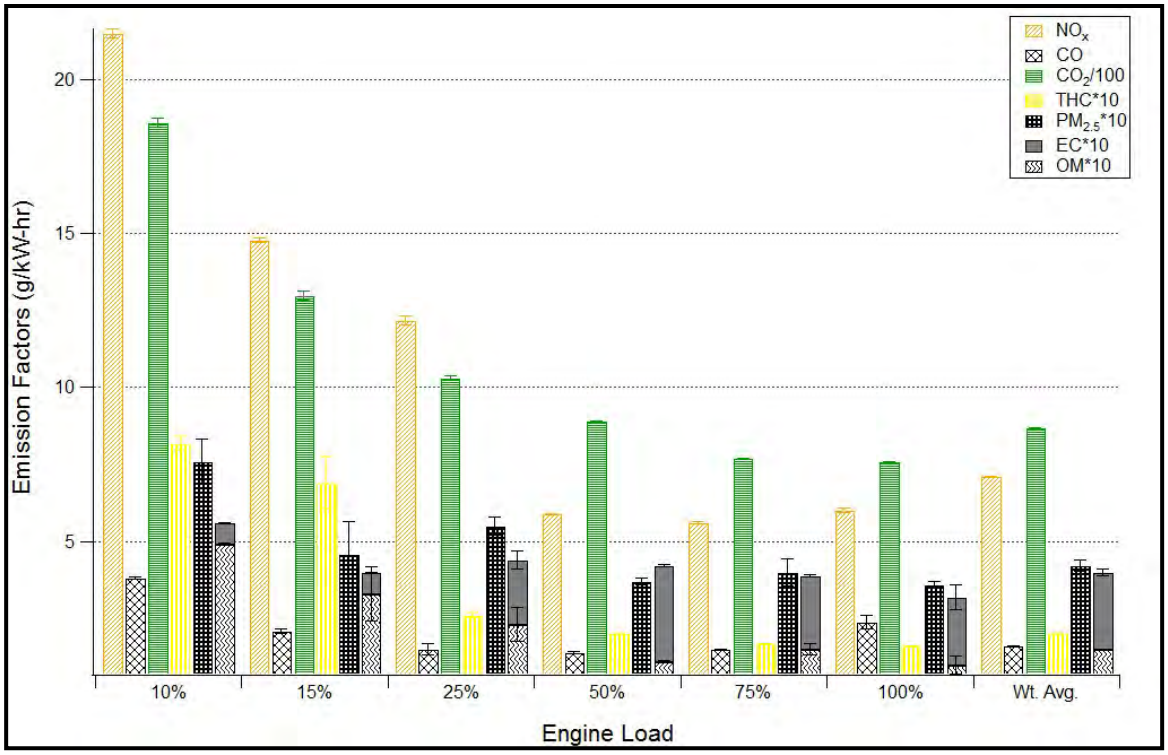


Figure 3-1: Modal Emission Factors for Auxiliary Engine on Conventional *Campbell Foss* Tug JD 6081

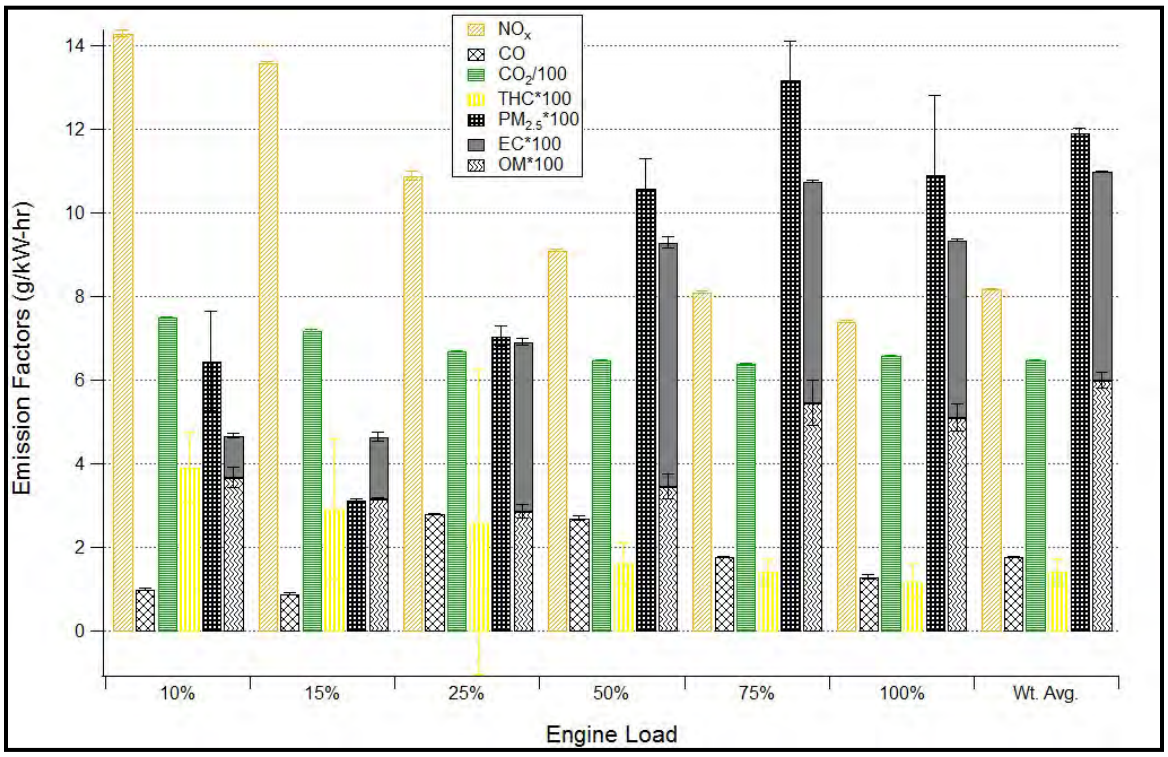


Figure 3-2: Modal Emission Factors for Main Engine on Conventional *Campbell Foss* Tug CAT 3512 C

Diesel particulate matter primarily consists of elemental and organic carbon. Figure 3-3 shows a plot of the $PM_{2.5}$ emissions in g/hr obtained from two separate methods – gravimetric measurements of $PM_{2.5}$ collected on Teflo® filters and total carbon analysis of $PM_{2.5}$ collected on parallel Tissuquartz filters by a thermal/optical carbon analyzer (±20% measurement uncertainty). Here, the total mass is represented as the sum of elemental carbon (EC) and organic mass (OM). The organic mass is equal to the organic carbon (OC) multiplied by a factor of 1.2 to account for hydrogen and oxygen attached to the carbon in the total PM. Overall, good agreement is observed between two different PM measurement methods.

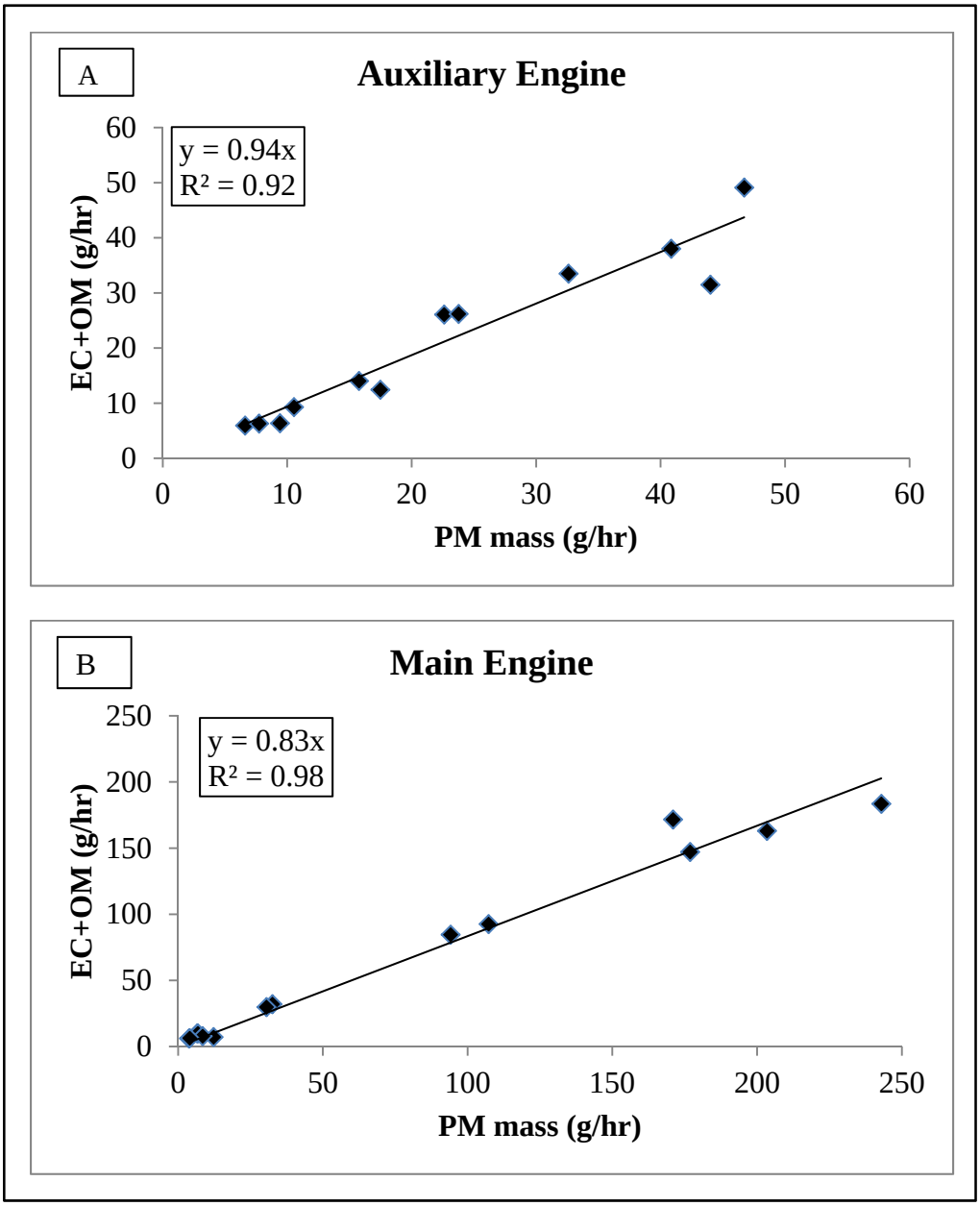


Figure 3-3: $PM_{2.5}$ Mass Balance for A) Auxiliary Engine JD 6081 and B) Main Engine CAT 3512C

3.2 Emissions Testing *Phase II* & *III*

Second and third phase of the emissions testing involved emission measurement from the new AE on the hybrid *Campbell Foss* at 0 hour and 1000 hours of operation, respectively. In both phases, emissions were measured at load points illustrated in ISO 8178 D2 test cycle and at 15% and 5% engine load where engine spends significant amount of time. Similar to *Phase I*, duplicate measurements were made at each load point. Table 3-3 and 3-4 shows gaseous and particulate emissions in g/hr and g/kW-hr, respectively.

Table 3-3: Emission Rates in g/hr for *Phase II* & *III* of Emissions Testing

Load (%)		NOx	CO	CO_2	THC	$PM_{2.5}$	EC	OC
Target	**Actual**	**g/hr**						
MTU/Detroit Series 60 (0 hour Emission Measurements)								
100	93	2507	116	259240	20.5	24.5	15.4	51.9
75	73	1879	73	194126	13.1	12.6	6.6	3.9
50	51	1075	63	129138	11.1	15.4	9.6	3.1
25	25	506	63	77094	11.8	10.9	6.0	3.9
15	15	305	71	48804	12.8	7.7	3.0	3.5
10	10	174	60	29843	11.7	6.0	1.6	3.7
5	5	144	73	26111	15.4	6.2	0.7	4.4
MTU/Detroit Series 60 (1000 hour Emission Measurements)								
100	99	2155	293	258404	166	40.2	24.6	36.1
75	75	1813	129	192278	127	32.6	16.0	20.8
50	50	1001	111	127348	100	19.4	20.2	10.0
25	25	466	76	72713	102	14.3	12.9	4.8
15	15	272	85	43997	118	8.9	4.8	2.0
10	10	169	71	28879	117	6.5	2.5	1.6
5	5	131	142	26394	13	3.2	0.9	1.6

The primary objective of emission measurements from MTU engine was to ensure that the emissions are within the Tier 2 standards and the tested engine is the representative of engines in their class.

Table 3-4 also lists the overall weighted average emission factors for MTU engine from both phases of testing. It also shows the EPA Tier 2 standard for that each test engine family. The overall weighted averages for MTU AE at 0 & 1000 hours are below EPA Tier 2 standards for NO_x and $PM_{2.5}$. Moreover, EF_{CO} is comparatively very low which is typical of diesel engines. The percentage difference between EF_{NOx} and EF_{CO2} measured at 0 hour and 1000 hours emissions testing are 7.8% and 3.0%, respectively which reflects good durability of the engine and robust emission measurements. Note that the emissions measured at 1000 hours are used in calculating in-use emissions from MTU engine.

Table 3-4: Emission Factors in g/kW-hr for *Phase II* & *III* of Emissions Testing

Load (%)		NOx	NOx+NHMC	CO	CO_2	THC	$PM_{2.5}$	EC	OC
Target	**Actual**	**g/kW-hr**							
MTU/Detroit Series 60 (0 hour Emission Measurements)									
100	93	7.7	7.7	0.35	793	0.06	0.07	0.05	0.16
75	73	7.4	7.4	0.29	762	0.05	0.05	0.03	0.02
50	51	6.1	6.1	0.35	729	0.06	0.09	0.05	0.02
25	25	5.8	5.9	0.72	886	0.14	0.13	0.07	0.04
15	15	5.8	6.0	1.34	927	0.24	0.15	0.06	0.07
10	10	5.0	5.3	1.72	861	0.34	0.17	0.05	0.11
5	5	8.2	9.1	4.18	1492	0.88	0.35	0.04	0.25
Weighted Avg.		6.7	6.8	0.42	776	0.08	0.08	0.04	0.04
Tier 2		–	7.2	5.0	–	–	0.20	–	–
MTU/Detroit Series 60 (1000 hour Emission Measurements)									
100	99	6.2	6.7	0.84	745	0.48	0.12	0.07	0.10
75	75	6.9	7.4	0.49	734	0.48	0.12	0.06	0.08
50	50	5.8	6.3	0.64	732	0.58	0.11	0.12	0.06
25	25	5.4	6.5	0.87	836	1.17	0.16	0.15	0.05
15	15	5.3	7.5	1.55	846	2.27	0.13	0.09	0.04
10	10	5.0	8.4	2.08	849	3.45	0.19	0.07	0.05
5	5	8.7	9.4	8.47	1553	0.75	0.19	0.06	0.09
Weighted Avg.		6.2	6.9	0.67	753	0.68	0.13	0.09	0.07
Tier 2		–	7.2	5.0	–	–	0.20	–	–

The rates in g/hr as a function of engine load for gaseous and particulate emissions coupled to the engine histograms (section 3.3) are used to calculate total emissions from each engine at the different tugboat operating modes.

3.3 Activity

3.3.1 Weighting Factors for Tug Operating Modes

Figure 3-4 shows the overall weighting factors for the hybrid tugboat. Total sample times used for the determined these weighing factors were 37 days for the hybrid tugboat. The figure shows that the dolphin class tug spends about 51% of its total operating time at Stop (includes *Shore Power*), ~2% in *Idle* ~14% in *Transit* (*Transit 1* and *Transit 2*), and ~33% in *Assist* (includes barge moves). Note that the overall weighting factors for the conventional *Campbell Foss* are assumed to be same as hybrid *Campbell Foss*.

Overall, 37 days of activity data was collected in three intervals of time period. Table 3-5 represents weighting factors for these three intervals. Clearly, no significant variation in operating modes was observed between three intervals.

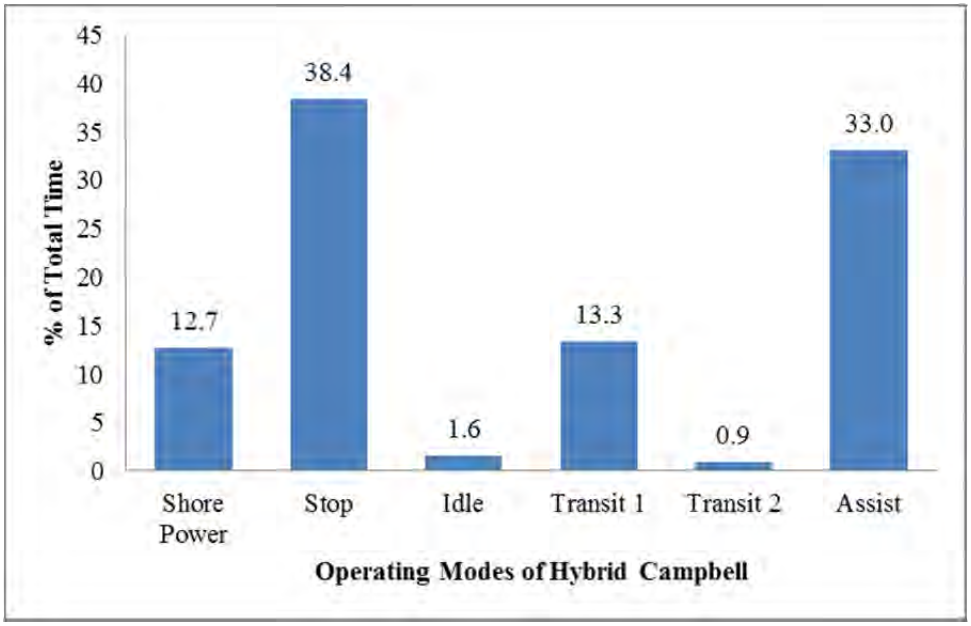


Figure 3-4: Overall Weighing Factors for Hybrid Tugboat Operating Modes

Table 3-5: Weighting factors for small intervals of time period

Time Period	Stop	Idle	Transit 1	Transit 2	Assist
05/25/12-06/06/12	50.6%	2.1%	14.8%	0.7%	31.7%
06/09/12-06/17/12	48.7%	3.7%	15.1%	1.2%	31.3%
06/21/12-09/07/12	52.2%	0.6%	11.7%	1.0%	34.5%

Tugboat operations in the port of Los Angeles and Long Beach consist primarily of docking and undocking ocean going vessels such as containerships and bulkers providing tanker escorts and moving bunkering barges in the harbor. The barge movements provide bunker fuel to ocean going vessels while they are berthed at various facilities in the Long Beach and Los Angeles ports.

The bunker barges are loaded at the Vopak fueling facility at Berth 187 in Los Angeles and Foss tugs are berthed at Pier D Berth 49. In between Long Beach Berth 49 and Los Angeles Berth 187 there is the Schuyler Heim drawbridge over the Cerritos Channel. Until January 2012 the horizontal clearance under this bridge was 142 feet which meant the tugs moving barges could move freely under this drawbridge. However, there is currently a Caltrans project underway to replace the aging Schuyler Heim drawbridge for seismic upgrades. In January 2012, two trestles were constructed adjacent to the existing bridge, which resulted in a horizontal restriction of 75 feet between the trestles. The Foss bunker barges are 290 feet in length, 62 feet in breadth with a molded depth of 18.5 feet. The tugs which are secured alongside the barge are 34 to 40 feet in breadth with an additional three feet of fenders between the tug and barge. This tug barge combination

cannot physically navigate through this newly restricted channel. This construction project is expected to continue for five years at which point the trestles will be removed and the horizontal clearance will return to pre-construction clearance.

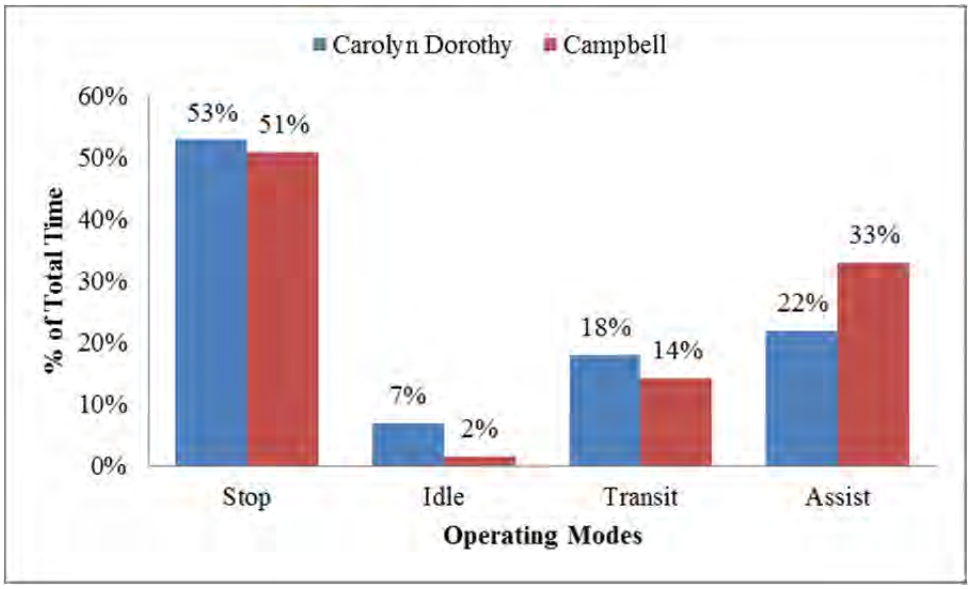


Figure 3-5: Comparison of Overall Weighting Factors for Hybrid *Carolyn Dorothy* and *Campbell Foss*

The practical result of this restricted waterway is that to service customers located at the majority of the terminals in the Port of Long Beach, Foss tugs with barges must now travel all the way through the Port of Los Angeles and enter the Port of Long Beach from the Outer Harbor instead of staying within the Inner Harbor of the Port of Long Beach (Appendix D). Between February and mid-November 2012, Foss tugs with barges have diverted over 1,800 miles due to this bridge construction project.

The ARB[14] study conducted in 2010, developed a duty cycle analysis for the Foss tugs *Carolyn Dorothy* (CD) and *Alta June* (AJ), sister vessels to the *Campbell Foss.* All three vessels operate from Long Beach Berth 49 and typically do the same mix of work in the ports of Los Angeles and Long Beach. The 2010 report showed both the *Carolyn Dorothy* and *Alta June* spent 22% of their time in "*Assist*" mode doing either ship assist or barge moves. The 2012 study of the *Campbell Foss* which was conducted between May and July of 2012 (after the channel restriction) showed this vessel spent 33% of its time in the "*Assist*" mode (Figure 3-5). One explanation for this variance is that this channel restriction and attendant navigational deviation means the *Campbell Foss* spent more time in the *Assist* mode because of the more time spent in moving barges for greater distance.

3.3.2 Engine Histogram for Conventional Campbell Foss

Alta June and *Campbell Foss* belongs to the same class of tugboats. Prior to the hybrid retrofit for *Campbell Foss*, both tugboats had same MEs and AEs. Therefore, engine histograms obtained for *Alta June* in the ARB study are assumed to be same for the conventional *Campbell Foss*.

The conventional *Campbell Foss* had only one of the two auxiliary engines working for all tug operating modes, except *Shore Power*. This auxiliary engine always operated at 10-12% of its maximum load. Therefore an engine histogram of the auxiliary engine would show a 100% bar at the 10-12% load with no bars at all other load points. The main engines on the conventional tugboat are off when the tugboat is at *Stop* or plugged into *Shore Power*. During the Idle mode these engines are idling with an engine load of about 5-7% of the maximum rated power. Figure 3-6 and 3-7 shows engine histograms for both main engines on the conventional *Campbell Foss* for *Transit* and *Assist* operating modes.

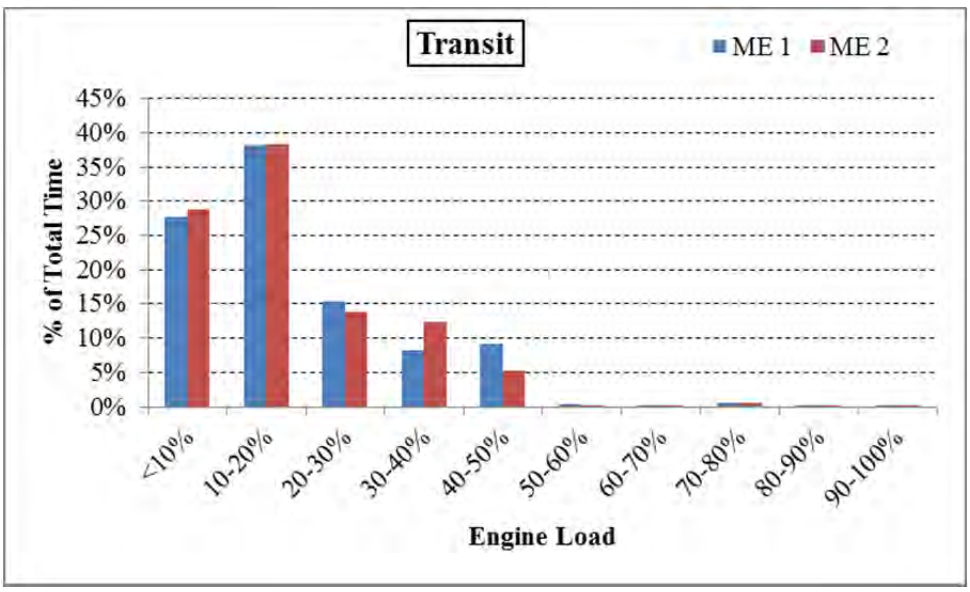


Figure 3-6: Main Engine Histogram during *Transit* Mode for Conventional *Campbell Foss*

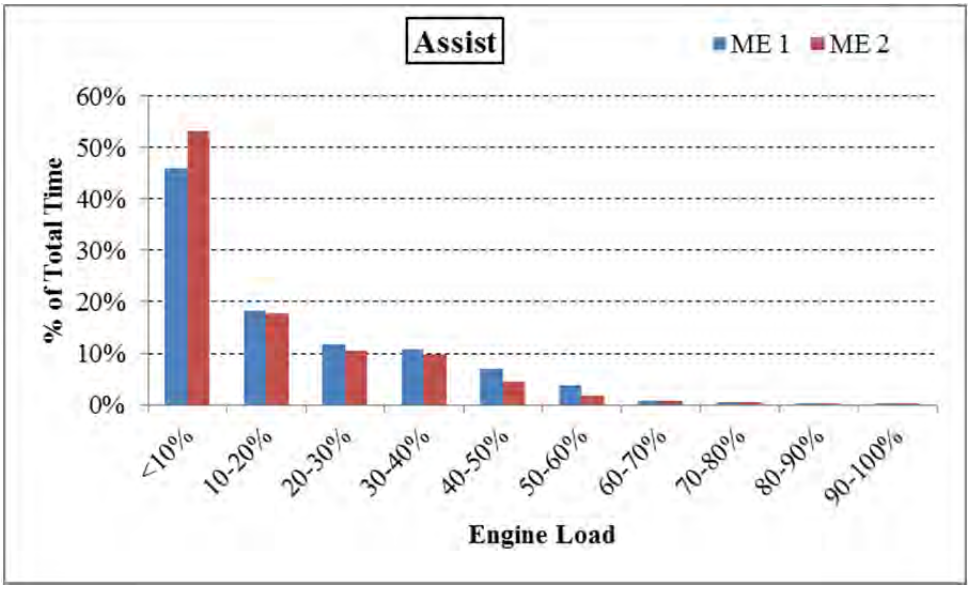


Figure 3-7: Main Engine Histogram during *Assist* Mode for Conventional *Campbell Foss*

3.3.3 Engine Histograms for Hybrid Campbell Foss

Engine histograms for hybrid *Campbell Foss* was obtained from the activity logged for 37 days during this study.

***Stop* Mode:** In this mode, both main engines are off similar to conventional *Campbell Foss*. Energy required for hoteling purposes are either extracted from the JD AE or batteries. The MTU AE is rarely operated during *Stop* mode as shown in Figure 3-8. For the case of the conventional *Campbell Foss*, only one AE was always operated at 10-12% engine load. Therefore, some emissions benefits are expected on using hybrid tugboat during *Stop* mode.

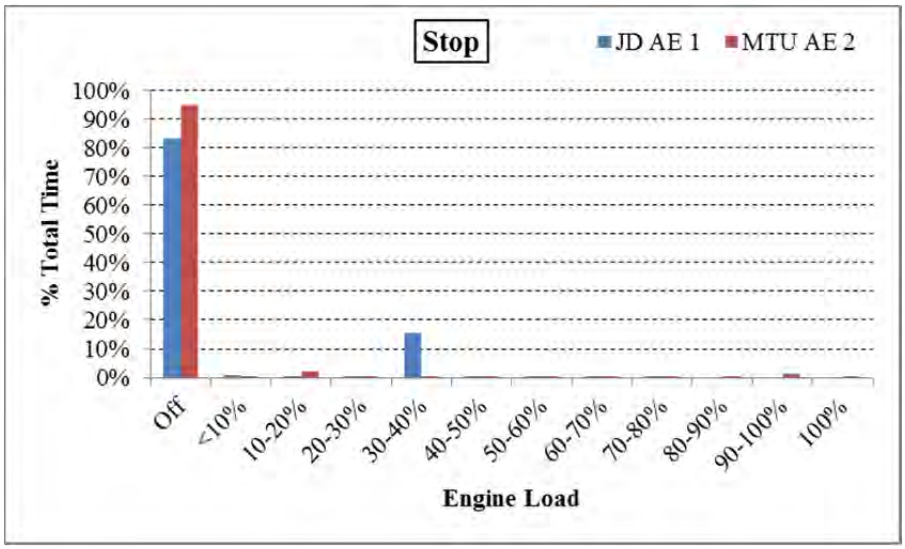


Figure 3-8: AEs histogram during *Stop* mode for Hybrid *Campbell Foss*

***Idle* Mode:** In this mode, both main engines are off in the hybrid design, whereas in the case of the conventional *Campbell Foss*, main engines are always operated (95% of total time) at 5% engine load. Both AEs and batteries switched between each other during *Idle* mode. AEs histogram for hybrid *Campbell Foss* is shown in Figure 3-9. Only one AE was always operated at 10-12% of maximum engine rated power in conventional *Campbell Foss*. Due to above differences in MEs and AEs operation, emission benefits are expected on using hybrid tugboat during *Idle* mode.

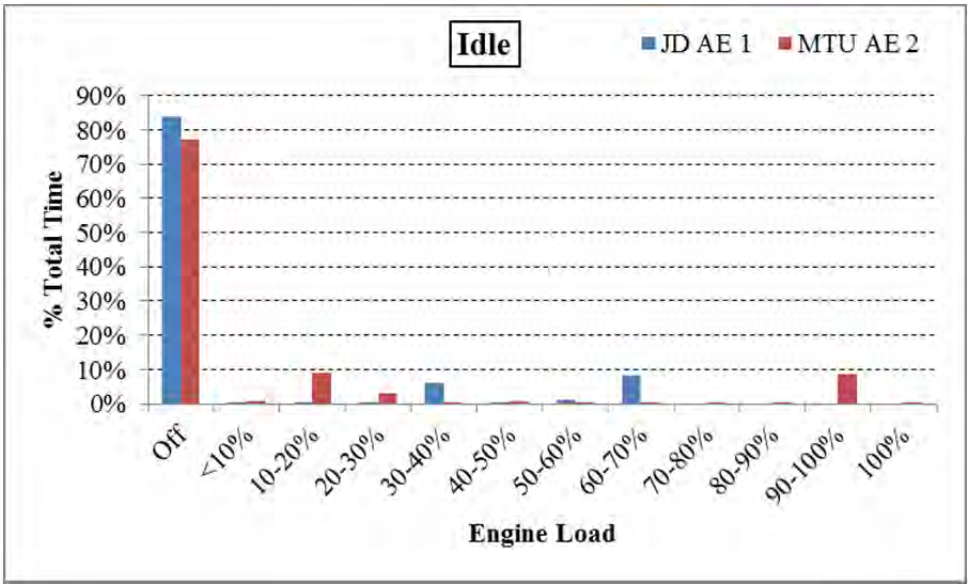


Figure 3-9: AEs histogram during *Idle* mode for Hybrid *Campbell Foss*

***Transit* Mode:** This mode is the combination of *Transit 1* and *Transit 2* mode of the hybrid tugboat. MEs are rarely operated during Transit mode in hybrid tugboat. However, MEs in the conventional *Campbell Foss* were always operating during this mode (Figure 3-10). In the hybrid *Campbell Foss*, either one AE or both AEs are operated in *Transit* mode depending upon the speed requirement. Conventional *Campbell Foss* utilized one AE for hoteling purposes during *Transit* mode. As hybrid *Campbell Foss* are propelled by AEs instead of MEs (which are much higher in power), significant emission benefits are expected during *Transit* mode on operating hybrid *Campbell Foss*.

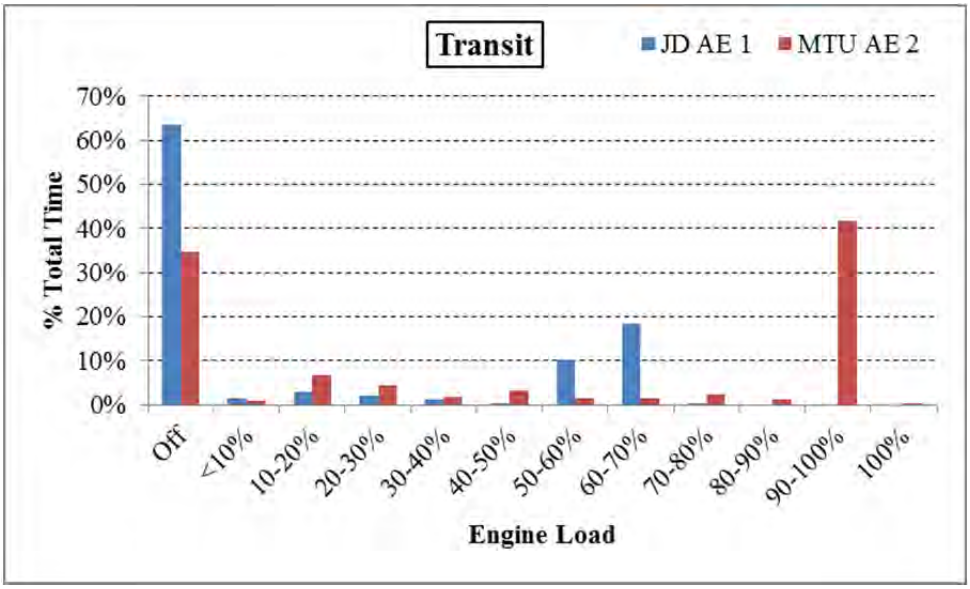


Figure 3-10: AEs histogram during *Transit* mode for Hybrid

***Assist* Mode:** Both MEs are in operation for conventional and hybrid *Campbell Foss* during *Assist* mode. MEs histogram during *Assist* mode is shown in Figure 3-11. AEs in the hybrid *Campbell Foss* are rarely operated whereas one AE was always in operation for conventional *Campbell Foss* during *Assist* mode.

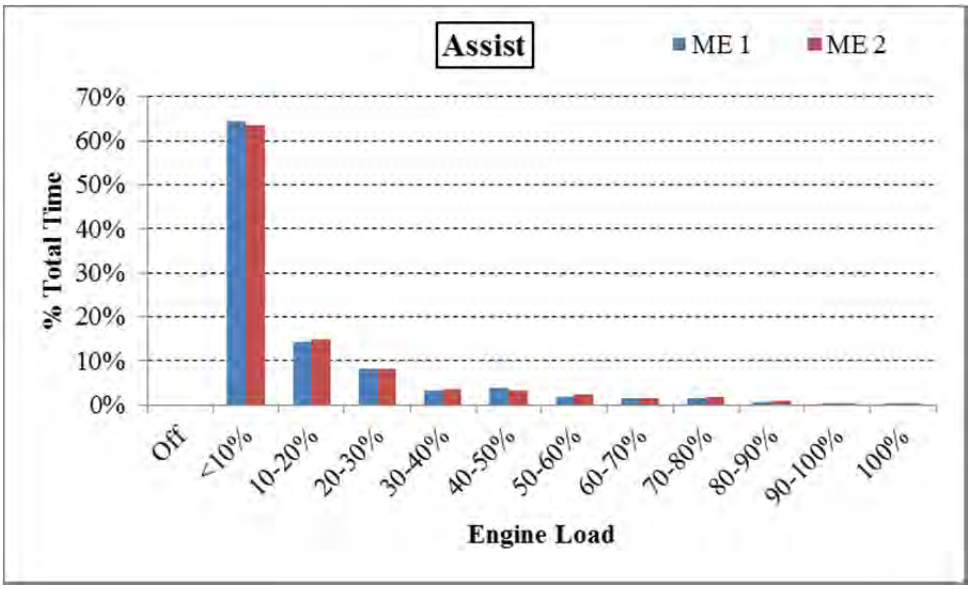


Figure 3-11: MEs histogram during *Assist* mode for Hybrid *Campbell Foss*

3.4 Total In-use Emissions

The total in-use emission form each tug configuration was calculated using the equations stated in Section 2.2. Emissions from each tug at a particular operating mode were

calculated using engine histograms and engine emission profile data. Energy consumed when tug is plugged into shore power is assumed to be same for hybrid and conventional *Campbell Foss*. To determine the emissions for the *Shore Power* mode, the average load during shore power was multiplied by the emission factors of a conventional natural gas fired steam plants with selective catalyst reduction (SCR) for NOx control and with no CO catalyst (Table 3-6).

Table 3-6: Emission Factors for Shore Power[18, 19]

	Emission Factor		
	lbs/10^6scf	lbs/MW-hr[a]	g/kW-hr
$PM_{2.5}$	7.6	0.087	3.948E-05
NO_x	10	0.117	5.195E-05
CO_2	120000	1371	0.623

[a] heating value of natural gas = 1,050 Btu/scf, power generation heat rate = 12,000 Btu/kW-hr

Overall, 31%, 29% and 28% reduction was obtained on using hybrid technology for NOx, CO_2 and $PM_{2.5}$, respectively. Similar to previous study, major benefits of using hybrid technology was obtained during *Transit* mode as the large main propulsion engines are not operating for the hybrid. Table 3-7 and 3-8 shows modal and overall benefits in gaseous and particulate emissions due to the conversion to the hybrid technology. This study expects about 30% of fuel savings, which is similar to 25-28% fuel savings reported by the previous ARB study.

Table 3-7: Modal and Overall Emission Reductions for *Campbell Foss* with Hybrid Technology

Operating Modes	Weighing factors		NOx (g/hr)		% Reduction	CO_2 (g/hr)		% Reduction	$PM_{2.5}$ (g/hr)		% Reduction
	Conv.	Hybrid	Conv.	Hybrid		Conv.	Hybrid		Conv.	Hybrid	
Shore Power	0.13	0.13	0.0002	0.0002	0%	0.002	0.002	0%	0.00013	0.00013	0%
STOP	0.38	0.38	93	42	55%	7998	4831	40%	3.3	1.5	53%
IDLE	0.02	0.02	96	6	94%	3703	658	82%	0.6	0.2	76%
TRANSIT	0.14	0.14	1104	311	72%	69581	31297	55%	9.8	6.0	39%
ASSIST	0.33	0.33	2480	2245	9%	152492	128416	16%	23.1	18.7	19%
Overall	1.00	1.00	3773	2603	**31%**	233774	165201	**29%**	36.8	26.3	**28%**

Table 3-8: Modal and Overall Emission Reductions for *Campbell Foss* with Hybrid Technology

Operating Modes	Weighing factors		CO (g/hr)		% Reduction	THC (g/hr)		% Reduction	EC (g/hr)		% Reduction	OC (g/hr)		% Reduction
	Conv.	Hybrid	Conv.	Hybrid		Conv.	Hybrid		Conv.	Hybrid		Conv.	Hybrid	
Shore Power	0.01	0.18	–	–		–	–		–	–		–	–	
STOP	0.54	0.35	23	5	76%	5.0	2.6	48%	0.3	0.8	-165%	1.8	0.6	63%
IDLE	0.07	0.07	29	4	87%	10.0	2.2	78%	0.1	0.1	13%	0.3	0.1	76%
TRANSIT	0.16	0.18	188	67	64%	30.9	20.7	33%	4.0	3.4	17%	3.7	3.2	15%
ASSIST	0.22	0.22	274	213	22%	40.9	38.8	5%	8.6	7.3	16%	9.1	7.2	20%
Overall	1.00	1.00	514	289	**44%**	86.7	64.3	**26%**	13.1	11.5	**12%**	14.8	11.1	**25%**

3.5 Comparison of Results with Earlier Study

Comparing the overall results of this study with the earlier study shows some similarities and some significant differences. These differences can be explained and are brought about by:

1) The changes in the activity revealed from data logging. For example now with the bridge diversion, the time in the *Assist* mode was increased from 22 %to 33%.

2) The change in emissions due to engines from different manufacturers. In the repower study, the same main propulsion engine was used so there are no differences in emissions from the main engine. However, the first study, *Evaluating Emission Benefits of a Hybrid Tugboat* (2010) was of a conventional tugboat with a Caterpillar 3512 engine and a hybrid with a Cummins QSK50-M engine. While both engines complied with the overall weighted emission factors for US EPA Tier 2, the individual modal emissions differed significantly.

3) Table 3-9 shows the emissions differences in grams per hour at different loads. About 30% of the difference is due to the size of the engine as the CAT was rated at 1902kW and the Cummins was rated at 1342kW. Still as the tugboats showed similar histograms, it is clear that the Cummins on the hybrid was a much cleaner engine at the lower operating modes when the tug mainly operates; thus resulting in the 72% PM benefit in that study and 28% in this study. For this project, the conventional and retrofitted hybrid tugboat had the same main engine so benefits from engine manufacturer cannot be realized.

Table 3-9: Difference in NOx and $PM_{2.5}$ Emission Rates across Load Points

Engine Load	CAT 3512C	Cummins QSK50-M	CAT 3512C	Cummins QSK50-M
	NO_x (g/hr)		$PM_{2.5}$ (g/hr)	
7%	2439	1035	6.3	9.5
25%	4867	2674	94	9.8
50%	7781	5374	195	50
75%	9450	7921	97	58
100%	14124	10215	173	54

Considering specific cases, the NOx emission reduction of the earlier study was 51% and for this study was 31%. This difference can be partially explained by the change in modal activity in the histograms and overall weighting factor for the two cases. Table 3-10 uses the activity factors from the earlier study and the NOx reduction of this study would be boosted from the 31% reported in Section 3.4 to 42%, a value closer to the earlier study.

The remainder of the difference is due to benefits of the cleaner Cummins engine at low loads as described above.

Similarly for the PM some of the differences are due to the higher time in the *Assist* mode. As Table 3-10 indicates, the PM benefits would increase from 28% to 34%. However, it is the near ten-fold differences for PM grams per hour at low loads that the Cummins engine provided in the earlier comparison and boosted the benefit to near 70%. Even operating the Cummins AE provided PM benefits over the JD AE.

Table 3-10: Modal and Overall Emission Reductions based on Operating Weighting Factors are obtained from ARB study

Operating Modes	Weighing factors		NOx (g/hr)		% Reduction	CO_2 (kg/hr)		% Reduction	$PM_{2.5}$ (g/hr)		% Reduction
	Conv.	Hybrid	Conv.	Hybrid		Conv.	Hybrid		Conv.	Hybrid	
SHORE POWER	0.01	0.18	0.0002	0.0002	0%	0.002	0.002	0%	0.00013	0.00013	0%
STOP	0.54	0.35	133	38	71%	11.4	4.4	61%	4.6	1.4	70%
IDLE	0.07	0.07	338	25	93%	13.0	2.8	78%	2.2	0.7	70%
TRANSIT	0.16	0.18	1261	391	69%	79.5	39.3	51%	11.2	7.5	33%
ASSIST	0.22	0.22	1653	1494	10%	101.7	85.4	16%	15.4	12.4	20%
Overall	1.00	1.00	3385	1948	**42%**	206	132	**36%**	33.4	21.9	**34%**

4 Summary

The primary goal of this project was to determine the emission benefits of a hybrid retrofit system on an existing tugboat. For this purpose, a conventional tugboat of "Dolphin" class was chosen and repowered with a new auxiliary engine and the hybrid components.

Emissions measurements were made from the main and auxiliary engines of the conventional *Campbell Foss* tug prior to retrofit. These engines were tested according to ISO 8178 E3/D2 test cycle to ensure that their emissions are within certification limits and US EPA Tier 1 standards. Additional measurements were made at low loads where the tugboat has been reported to spend most of the time during its operation and data are not available. This phase of the study concluded that the engines tested are well maintained and representative of engines in their emission class. Overall weighted emission factors for NO_x, CO, and $PM_{2.5}$ are within standards values. Emissions of CO_2 from both engines are typical of diesel engine of their category and are in agreement with manufacturer expectations.

The second phase of this project was to develop the activity of the hybrid *Campbell Foss* and emissions testing of the new repowered AE engine according to ISO 8178 D2 and in-use test cycle based on activity data. A data-logging system, capable of simultaneously monitoring and reporting the status of the power sources was installed for a period of over one month. Four gigabytes of data were analyzed to determine the weighting factors, i.e., the fraction of time spent by the tug in the six discrete operating modes shore power, stop, idle, transit 1, transit 2 and assist. Further engine histograms for all four engines on the tug at these operating modes were established.

The final analysis combined engine histogram and emission profile data to determine in-use emissions at each tug operating mode for both conventional and the hybrid *Campbell Foss*. These figures were coupled with the weighting factors for the operating modes to get the overall in-use emissions in g/hr for each tug. Significant emission benefits were observed for the hybrid technology.

The major findings of this project include:

- The average weighting factors for the operating modes of the hybrid tugboat were 0.53 for Stop, 0.02 for Idle, 0.14 for Transit and 0.33 for Assist. As previously shown, these values differ significantly from the values ISO 8178 E-3 Cycle.

- A significant difference in the Assist weighting factor was found in comparison to previous study. This was mainly due to the fact that the *Campbell Foss* is

spending more time in moving barges because of the new travel restrictions at the Port of Long Beach.

- Overall in-use emission reductions with the hybrid technology were found to be 28% for $PM_{2.5}$, 31% for NOx and 29% for CO_2.

- Based on duty cycle obtained from the ARB study, *Evaluating Emission Benefits of a Hybrid Tugboat* (2010) overall in-use emission benefits with the hybrid technology on the *Campbell Foss* would increase to 34% for $PM_{2.5}$, 42% for NOx and 36% for CO_2.

- Emissions factors for the CAT 3512C MEs were within the Tier 1 standards. Similarly, for both AEs; JD 6081 and MTU/Detroit Series 60, emissions were within the Tier 1 and 2 standards, respectively.

- The diesel electric drive train on the hybrid tug that allows the use of auxiliary power for propulsion was the primary cause for the overall in-use emission reductions as opposed to the energy storage device (batteries).

- Like before, the transit operating mode was the most significant contributor to the overall emission reductions. In this mode the hybrid tug was powered by one or two auxiliary engines and batteries while the conventional tug used one auxiliary and two main engines.

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6 Appendix A - Measuring Gaseous & Particulate Emissions

6.1 Scope

ISO 8178-1[2] and ISO 8178-2[3] specify the measurement and evaluation methods for gaseous and particulate exhaust emissions when combined with combinations of engine load and speed provided in IS0 8178- *Part 4: Test cycles for different engine applications*. The emission results represent the mass rate of emissions per unit of work accomplished. Specific emission factors are based on brake power measured at the crankshaft, the engine being equipped only with the standard auxiliaries necessary for its operation. Per ISO, auxiliary losses are <5 % of the maximum observed power.

IMO ship pollution rules and measurement methods are contained in the "International Convention on the Prevention of Pollution from Ships", known as MARPOL 73/78[4], and sets limits on NO_x and SO_x emissions from ship exhausts. The intent of this protocol was to conform as closely as practical to both the ISO and IMO standards.

6.2 Sampling System for Measuring Gaseous and Particulate Emissions

A properly designed sampling system is essential to accurate collection of a representative sample from the exhaust and subsequent analysis. ISO points out that particulate must be collected in either a full flow or partial flow dilution system and UCR chose the partial flow dilution system with single venturi as shown Figure 6-1.

A partial flow dilution system was selected based on cost and the impossibility of a full flow dilution for "medium and large" engine testing on the test bed and at site. The flow in the dilution system eliminates water condensation in the dilution and sampling systems and maintains the temperature of the diluted exhaust gas at <52°C before the filters. ISO cautions the advantages of partial flow dilution systems can be lost to potential problems such as: losing particulates in the transfer tube, failing to take a representative sample from the engine exhaust and inaccurately determining the dilution ratio.

An overview of UCR's partial dilution system shows that raw exhaust gas is transferred from the exhaust pipe (EP) through a sampling probe (SP) and the transfer tube (TT) to a dilution tunnel (DT) due to the negative pressure created by the venturi (VN) in DT. The

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[2] International Standards Organization, IS0 8178-1, *Reciprocating internal combustion engines - Exhaust emission measurement -Part 1: Test-bed measurement of gaseous particulate exhaust emissions*, First edition 1996-08-l5

[3] International Standards Organization, IS0 8178-2*, Reciprocating internal combustion engines - Exhaust emission measurement -Part 2: Measurement of gaseous and particulate exhaust emissions at site,* First edition 1996-08-l5

[4] International Maritime Organization, *Annex VI of MARPOL 73/78 "Regulations for the Prevention of Air Pollution from Ships and NOx Technical Code*".

gas flow rate through TT depends on the momentum exchange at the venturi zone and is therefore affected by the absolute temperature of the gas at the exit of TT. Consequently, the exhaust split for a given tunnel flow rate is not constant, and the dilution ratio at low load is slightly lower than at high load. More detail on the key components is provided in Table 6-2.

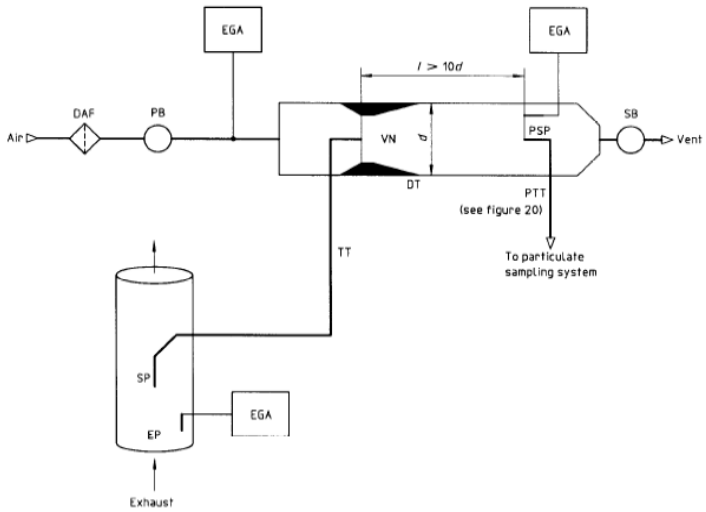

Table 6-1: Partial Flow Dilution System with Single Venturi, Concentration Measurement and Fractional Sampling

6.3 Dilution Air System

A partial flow dilution system requires dilution air and UCR uses compressed air in the field as it is readily available. ISO recommends the dilution air be at 25 ±5°C, filtered and charcoal scrubbed to eliminate background hydrocarbons. The dilution air may be dehumidified. To ensure the compressed air is of a high quality UCR processes any supplied air through a field processing unit that reduces the pressure to about 30psig as that level allows a dilution ratio of about 5/1 in the geometry of our system. The next stages, in sequence, include: a liquid knock-out vessel, desiccant to remove moisture with silica gel containing an indicator, hydrocarbon removal with activated charcoal and a HEPA filter for the fine aerosols that might be present in the supply air. The silica gel and activated carbon are changed for each field campaign. Figure 6-1 shows the field processing unit in its transport case. In the field the case is used as a framework for supporting the unit

Figure 6-1 Field Processing Unit for Purifying Dilution Air in Carrying Case

Table 6-2 Components of a Sampling System: ISO/IMO Criteria & UCR Design

Section	Selected ISO and IMO Criteria	UCR Design
Exhaust Pipe (EP)	In the sampling section, the gas velocity is > 10 m/s, except at idle, and bends are minimized to reduce inertial deposition of PM. Sample position is 6 pipe diameters of straight pipe upstream and 3 pipe diameters downstream of the probe.	UCR follows the ISO recommendation, as closely as practical.
Sampling Probe (SP)	The minimum inside diameter is 4 mm and the probe is an open tube facing upstream on the exhaust pipe centerline. No IMO code.	UCR uses a stainless steel tube with diameter of 8mm placed near the center line.
Transfer Tube (TT)	• As short as possible and < 5 m in length; • Equal to/greater than probe diameter & < 25 mm diameter; • TTs insulated. For TTs > 1m, heat wall temperature to a minimum of 250°C or set for < 5% thermophoretic losses of PM.	UCR no longer uses a transfer tube.
Dilution Tunnel (DT)	• shall be of a sufficient length to cause complete mixing of the exhaust and dilution air under turbulent flow conditions; • shall be at least 75 mm inside diameter (ID) for the fractional sampling type, constructed of stainless steel with a thickness of > 1.5 mm.	UCR uses fractional sampling; stainless steel tunnel has an ID of 50mm and thickness of 1.5mm.
Venturi (VN)	The pressure drop across the venturi in the DT creates suction at the exit of the transfer tube TT and gas flow rate through TT is basically proportional to the flow rate of the dilution air and pressure drop.	Venturi proprietary design provided by MAN B&W; provides turbulent mixing.
Exhaust Gas Analyzers (EGA)	One or several analyzers may be used to determine the concentrations. Calibration and accuracy for the analyzers are like those for measuring the gaseous emissions.	UCR uses a 5-gas analyzer meeting IMO/ISO specs

6.4 Calculating the Dilution Ratio

According to ISO 8178, "it is essential that the dilution ratio be determined very accurately" for a partial flow dilution system such as what UCR uses. The dilution ratio is simply calculated from measured gas concentrations of CO_2 and/or NO_x in the raw exhaust gas, the diluted exhaust gas and the dilution air. UCR has found it useful to independently determine the dilution ration from both CO_2 and NO_x and compare the values to ensure that they are within ±10%. UCR's experience indicates the independently determined dilution ratios are usually within 5%. At systematic deviations within this range, the measured dilution ratio can be corrected, using the calculated dilution ratio. According to ISO, dilution air is set to obtain a maximum filter face temperature of <52°C and the dilution ratio shall be > 4.

6.5 Dilution System Integrity Check

ISO describes the necessity of measuring all flows accurately with traceable methods and provides a path and metric to quantifying the leakage in the analyzer circuits. UCR has adopted the leakage test and its metrics as a check for the dilution system. According to ISO the maximum allowable leakage rate on the vacuum side shall be 0.5 % of the in-use flow rate for the portion of the system being checked. Such a low leakage rate allows confidence in the integrity of the partial flow system and its dilution tunnel. Experience has taught UCR that the flow rate selected should be the lowest rate in the system under test.

6.6 Measuring the Gaseous Emissions: CO, CO_2, HC, NO_x, O_2, SO_2

Measurement of the concentration of the main gaseous constituents is one of the key activities in measuring emission factors. This section covers the ISO/IMO protocols and that used by UCR. For SO_2, ISO recommends and UCR concurs that the concentration of SO_2 is calculated based on the fact that 95+% of the fuel sulfur is converted to SO_2.

6.7 Measuring Gaseous Emissions: ISO & IMO Criteria

ISO specifies that either one or two sampling probes located in close proximity in the raw gas can be used and the sample split for different analyzers. However, in no case can condensation of exhaust components, including water and sulfuric acid, occur at any point of the analytical system. ISO specifies the analytical instruments for determining the gaseous concentration in either raw or diluted exhaust gases.

- Heated flame ionization detector (HFID) for the measurement of hydrocarbons;
- Non-dispersive infrared analyzer (NDIR) for the measurement of carbon monoxide and carbon dioxide;
- Heated chemiluminescent detector (HCLD) or equivalent for measurement of nitrogen oxides;
- Paramagnetic detector (PMD) or equivalent for measurement of oxygen.

ISO states the range of the analyzers shall accurately cover the anticipated concentration of the gases and recorded values between 15% and 100% of full scale. A calibration curve with five points is specified. However, with modern electronic recording devices, like a computer, ISO allows the range to be expanded with additional calibrations. ISO details instructions for establishing a calibration curve below 15%. In general, calibration curves must be < ±2 % of each calibration point and by < ±1 % of full scale zero.

ISO outlines their verification method. Each operating range is checked prior to analysis by using a zero gas and a span gas whose nominal value is more than 80 % of full scale of the measuring range. If, for the two points considered, the value found does not differ by more than ±4 % of full scale from the declared reference value, the adjustment parameters may be modified. If >4%, a new calibration curve is needed.

ISO & IMO specify the operation of the HCLD. The efficiency of the converter used for the conversion of NO_2 into NO is tested prior to each calibration of the NO_x analyzer. The efficiency of the converter shall be > 90 %, and >95 % is strongly recommended.

ISO requires measurement of the effects from exhaust gases on the measured values of CO, CO_2, NO_x, and 0_2. Interference can either be positive or negative. Positive interference occurs in NDIR and PMD instruments where the interfering gas gives rise to the same effect as the gas being measured, but to a lesser degree. Negative interference occurs in NDIR instruments due to the interfering gas broadening the absorption band of the measured gas, and in HCLD instruments due to the interfering gas quenching the radiation. Interference checks are recommended prior to an analyzer's initial use and after major service intervals.

6.8 Measuring Gaseous Emissions: UCR Design

The concentrations of CO, CO_2, NO_x and O_2 in the raw exhaust and in the dilution tunnel are measured with a Horiba PG-250 portable multi-gas analyzer. The PG-250 simultaneously measures five separate gas components with methods recommended by the ISO/IMO and USEPA. The signal output of the instrument is connected to a laptop computer through an RS-232C interface to continuously record measured values. Major features include a built-in sample conditioning system with sample pump, filters, and a thermoelectric cooler. The performance of the PG-250 was tested and verified under the U.S. EPA ETV program.

Figure 6-2: Setup Showing Gas Analyzer with Computer for Continuous Data Logging

Details of the gases and the ranges for the Horiba instrument are shown in Table 6-3. Note that the Horiba instrument measured sulfur oxides (SO_2); however, the UCR follows the protocol in ISO and calculates the SO_2 level from the sulfur content of the fuel as the direct measurement for SO_2 is less precise than calculation.

Table 6-3 Detector Method and Concentration Ranges for Monitor

Component	Detector	Ranges
Nitrogen Oxides (NOx)	Heated Chemiluminescence Detector (HCLD)	0-25, 50, 100, 250, 500, 1000, & 2500 ppmv
Carbon Monoxide (CO)	Non dispersive Infrared Absorption (NDIR)	0-200, 500, 1000, 2000, & 5000 ppmv
Carbon Dioxide (CO_2)	Non dispersive Infrared Absorption (NDIR)	0-5, 10, & 20 vol%
Sulfur Dioxide (SO_2)	Non dispersive Infrared Absorption (NDIR)	0-200, 500, 1000, & 3000 ppmv
Oxygen	Zirconium oxide sensor	0-5, 10, & 25 vol%

For quality control, UCR carries out analyzer checks with calibration gases both before and after each test to check for drift. Because the instrument measures the concentration of five gases, the calibration gases are a blend of several gases (super-blend) made to within 1% specifications. Experience has shown that the drift is within manufacturer specifications of ±1% full scale per day shown in Table 6-4. The PG-250 meets the analyzer specifications in ISO 8178-1 Section 7.4 for repeatability, accuracy, noise, span drift, zero drift and gas drying.

Table 6-4 Quality Specifications for the Horiba PG-250

Repeatability	±0.5% F.S. (NO_x: </= 100ppm range CO: </= 1,000ppm range) ±1.0% F. S.
Linearity	±2.0% F.S.
Drift	±1.0% F. S./day (SO_2: ±2.0% F.S./day)

6.9 Measuring the Particulate Matter (PM) Emissions

ISO 8178-1 defines particulates as any material collected on a specified filter medium after diluting exhaust gases with clean, filtered air at a temperature of </= 52ºC, as measured at a point immediately upstream of the primary filter. The particulate consists of primarily carbon, condensed hydrocarbons and sulfates, and associated water. Measuring particulates requires a dilution system and UCR selected a partial flow dilution system. The dilution system design completely eliminates water condensation in the dilution/sampling systems and maintains the temperature of the diluted exhaust gas at < 52°C immediately upstream of the filter holders. IMO does not offer a protocol for measuring PM. A comparison of the ISO and UCR practices for sampling PM is shown in Table 6-5.

Table 6-5 Measuring Particulate by ISO and UCR Methods

	ISO	**UCR**
Dilution tunnel	Either full or partial flow	Partial flow
Tunnel & sampling	Electrically conductive	Same

system		
Pretreatment	None	Cyclone, removes >2.5µm
Filter material	Fluorocarbon based	Teflon (TFE)
Filter size, mm	47 (37mm stain diameter)	Same
Number of filters in series	Two	One
Number of filters in parallel	Only single filter	Two; 1 TFE & 1 Quartz
Number of filters per mode	Single or multiple	Multiple
Filter face temp. °C	< 52	Same
Filter face velocity, cm/sec	35 to 80.	~33
Pressure drop, kPa	For test <25	Same
Filter loading, µg	>500	500-1,000 + water w/sulfate
Weighing chamber	22±3°C & RH= 45%± 8	Same
Analytical balance, LDL µg	10	0.5
Flow measurement	Traceable method	Same
Flow calibration, months	< 3months	Every campaign

Sulfur content: According to ISO, particulates measured using IS0 8178 are "conclusively proven" to be effective for fuel sulfur levels up to 0.8%. UCR is often faced with measuring PM for fuels with sulfur content exceeding 0.8% and has extended this method to those fuels as no other method is prescribed for fuels with a higher sulfur content.

6.10 Added Comments about UCR's Measurement of PM

In the field UCR uses a raw particulate sampling probe fitted close to and upstream of the raw gaseous sample probe and directs the PM sample to the dilution tunnel. There are two gases stream leaving the dilution tunnel; the major flow vented outside the tunnel and the minor flow directed to a cyclone separator, sized to remove particles >2.5um. The line leaving the cyclone separator is split into two lines; each line has a 47 Gelman filter holder. One holder collects PM on a Teflon filter and the other collects PM on a quartz filter. UCR simultaneously collects PM on Teflon and quartz filters at each operating mode and analyzes them according to standard procedures.

Briefly, total PM was collected on Pall Gelman (Ann Arbor, MI) 47 mm Teflo filters and weighed using a Cahn (Madison, WI) C-35 microbalance. Before and after collection, the filters were conditioned for 24 hours in an environmentally controlled room (RH = 40%, T= 25 °C) and weighed daily until two consecutive weight measurements were within 3 µg or 2%. It is important to note that the simultaneous collection of PM on quartz and Teflon filters provides a comparative check of PM mass measured by two independent methods and serves as an important Quality Check for measuring PM mass.

6.11 Measuring Real-Time Particulate Matter (PM) Emissions-DustTrak

In addition to the filter-based PM mass measurements, UCR takes continuous readings with a Nephelometer (TSI DustTrak 8520) so as to capture both the steady-state and transient data. The DustTrak is a portable, battery-operated laser photometer that gives real-time digital readout with the added benefits of a built-in data logger. The DustTrak/nephelometers is fairly simple to use and has excellent sensitivity to untreated diesel exhaust. It measures light scattered by aerosol introduced into a sample chamber and displays the measured mass density as units of mg/m^3. As scattering per unit mass is a strong function of particle size and refractive index of the particle size distributions and as refractive indices in diesel exhaust strongly depend on the particular engine and operating condition, some scientists question the accuracy of PM mass measurements. However, UCR always references the DustTrak results to filter based measurements and this approach has shown that mass scattering efficiencies for both on-road diesel exhaust and ambient fine particles have values around $3m^2/g$. For these projects, a TSI DustTrak 8520 nephelometer measuring 90 degree light scattering at 780nm (near-infrared) is used.

Figure 6-3 Picture of TSI DustTrak

6.12 Quality Control/Quality Assurance (QC/QA)

Each of the laboratory methods for PM mass and chemical analysis has a standard operating procedure including the frequency of running the standards and the repeatability that is expected with a standard run. Additionally the data for the standards are plotted to ensure that the values fall within the upper and lower control limits for the method and that there is no obvious trends or bias in the results for the reference materials. As an additional quality check, results from independent methods are compared and values from this work are compared with previously published values, like the manufacturer data base.

- For the ISO cycles, run the engine at rated speed and the highest power possible to warm the engine and stabilize emissions for about 30 minutes.
- Determine a plot or map of the peak power at each engine RPM, starting with rated speed. If UCR suspects the 100% load point at rated speed is unattainable, then we select the highest possible load on the engine as Mode 1.
- Emissions are measured while the engine operates according to the requirements of ISO-8178-E3 or ISO-8178-D2 cycles. For a diesel engine the highest power mode is run first and then each mode was run in sequence The minimum time for samples is 5 minutes and if necessary, the time was extended to collect sufficient particulate sample mass or to achieve stabilization with large engines.
- The gaseous exhaust emission concentration values are measured and recorded for the last 3 min of the mode.
- Engine speed, displacement, boost pressure, and intake manifold temperature are measured in order to calculate the gaseous flow rate.
- Emissions factors are calculated in terms of grams per kilowatt hour for each of the operating modes and fuels tested, allowing for emissions comparisons of each blend relative to the baseline fuel.

7 Appendix B - Test Cycles and Fuels for Different Engine Applications

7.1 Introduction

Engines for off-road use are made in a much wider range of power output and used in a more applications than engines for on-road use. The objective of IS0 8178-4[1] is provide the minimum number of test cycles by grouping applications with similar engine operating characteristics. ISO 8178-4 specifies the test cycles while measuring the gaseous and particulate exhaust emissions from reciprocating internal combustion engines coupled to a dynamometer or at the site. The tests are carried out under steady-state operation using test cycles which are representative of given applications.

Table 7-1: Definitions Used Throughout ISO 8178-4

Test cycle	A sequence of engine test modes each with defined speed, torque and weighting factor, where the weighting factors only apply if the test results are expressed in g/kWh.
Preconditioning the engine	1) Warming the engine at the rated power to stabilize the engine parameters and protect the measurement against deposits in the exhaust system. 2) Period between test modes which has been included to minimize point-to-point influences.
Mode	An engine operating point characterized by a speed and a torque.
Mode length	The time between leaving the speed and/or torque of the previous mode or the preconditioning phase and the beginning of the following mode. It includes the time during which speed and/or torque are changed and the stabilization at the beginning of each mode.
Rated speed	Speed declared by engine manufacturer where the rated power is delivered.
Intermediate speed	Speed declared by the manufacturer, taking into account the requirements of ISO 8178-4 clause 6.

7.1.1 Intermediate speed

For engines designed to operate over a speed range on a full-load torque curve, the intermediate speed shall be the maximum torque speed if it occurs between 60% and 75% of rated speed. If the maximum torque speed is less than 60% of rated speed, then the intermediate speed shall be 60% of the rated speed. If the maximum torque speed is greater than 75% of the rated speed then the intermediate speed shall be 75% of rated speed.

The intermediate speed will typically be between 60% and 70% of the maximum rated speed for engines not designed to operate over a speed range on the full-load torque curve at steady state conditions. Intermediate speeds for engines used to propel vessels with a fixed propeller are defined based on that application.

[1]International Standards Organization, IS0 8178-4*, Reciprocating internal combustion engines - Exhaust emission measurement - Part 4: Test cycles for different engine applications,* First edition IS0 8178-4:1996(E)

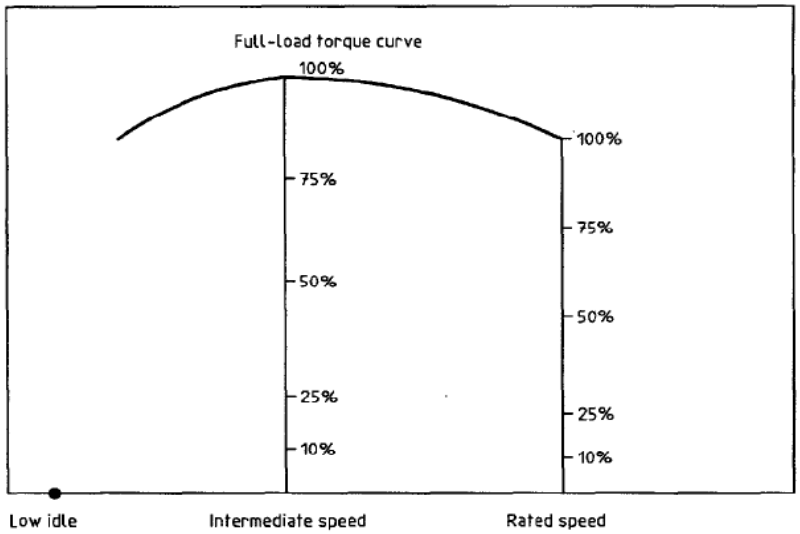

Figure 7-1: Torque as a Function of Engine Speed

7.2 Engine Torque Curves and Test Cycles

The percentage of torque figures given in the test cycles and Figure B-1 represent the ratio of the required torque to the maximum possible torque at the test speed. For marine test cycle E3, the power figures are percentage values of the maximum rated power at the rated speed as this cycle is based on a theoretical propeller characteristic curve for vessels driven by heavy duty engines. For marine test cycle E4 the torque figures are percentage values of the torque at rated power based on the theoretical propeller characteristic curve representing typical pleasure craft spark ignited engine operation. For marine cycle E5 the power figures are percentage values of the maximum rated power at the rated speed based on a theoretical propeller curve for vessels of less than 24 m in length driven by diesel engines. Figure B-2 shows the two representative curves.

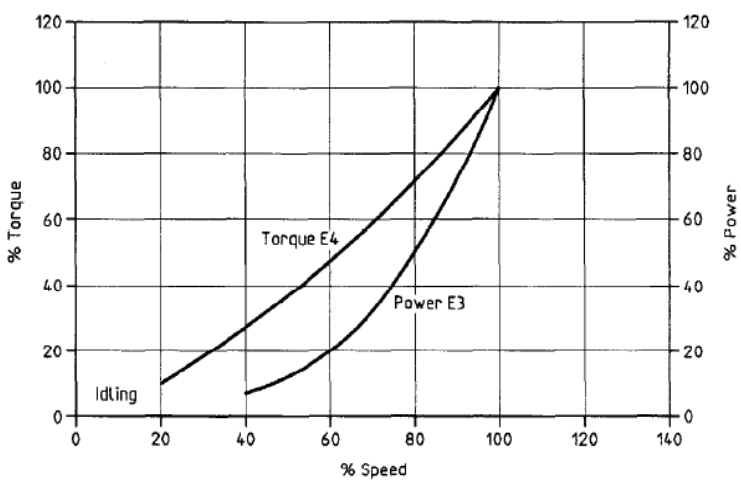

Figure 7-2: Examples of Power Scales

7.3 Modes and Weighting Factors for Test Cycles

Most test cycles were derived from the 13-mode steady state test cycle (UN-ECE R49). Apart from the test modes of cycles E3, E4 and E5, which are calculated from propeller curves, the test modes of the other cycles can be combined into a universal cycle (B) with emissions values calculated using the appropriate weighting factors. Each test shall be performed in the given sequence with a minimum test mode length of 5 minutes or enough to collect sufficient particulate sample mass. The mode length shall be recorded and reported and the gaseous exhaust emission concentration values shall be measured and recorded for the last 3 min of the mode. The completion of particulate sampling ends with the completion of the gaseous emission measurement and shall not commence before engine stabilization, as defined by the manufacturer.

Table 7-2: Combined Table of Modes and Weighting Factors

B-Type mode number	1	2	3	4	5	6	7	8	9	10	11
Torque	100	75	50	25	10	100	75	50	25	10	0
Speed	Rated speed					Intermediate speed					Low idle
Off-road vehicles											
Cycle C1	0,15	0,15	0,15		0,1	0,1	0,1	0,1			0,15
Cycle C2				0,06		0,02	0,05	0,32	0,3	0,1	0,15
Constant speed											
Cycle D1	0,3	0,5	0,2								
Cycle D2	0,05	0,25	0,3	0,3	0,1						
Locomotives											
Cycle F	0,25							0,15			0,6
Utility, lawn and garden											
Cycle G1						0,09	0,2	0,29	0,3	0,07	0,05
Cycle G2	0,09	0,2	0,29	0,3	0,07						0,05
Cycle G3	0,9										0,1
Marine application											
Cycle E1	0,08	0,11					0,19	0,32			0,3
Cycle E2	0,2	0,5	0,15	0,15							
Marine application propeller law											
Mode number E3	**1**					**2**		**3**		**4**	
Power (%)	100					75		50		25	
Speed (%)	100					91		80		63	
Weighting factor	0,2					0,5		0,15		0,15	
Mode number E4	**1**					**2**		**3**		**4**	**5**
Speed (%)	100					80		60		40	Idle
Torque (%)	100					71,6		46,5		25,3	0
Weighting factor	0,06					0,14		0,15		0,25	0,4
Mode number E5	**1**					**2**		**3**		**4**	**5**
Power (%)	100					75		50		25	0
Speed (%)	100					91		80		63	Idle
Weighting factor	0,08					0,13		0,17		0,32	0,3

8 Appendix C - Tug Boat Specifications

FOSS MARITIME

VESSEL INFORMATION SHEET

VESSEL NAME:	CAMPBELL FOSS		
OFFICIAL #:	1177724		
LR / IMO #:	9369198		
ABS #:	05172525	ACTNUM:	0436

REGULATORY

ABS LL:	N	COASTWISE:	Y
ABS CL:	N	TITLE XI:	N
USCG INSP:	N	CCF:	N
REGISTRY:	Y	SOLAS:	N

VESSEL DESCRIPTION

VSL TYPE:	Dolphin-class Tug
SERVICE:	Los Angeles/Long Beach Ship Assist
CALLSIGN:	WDC 7754
HAIL. PORT:	Long Beach, CA
OLD NAMES:	
DATE BUILT:	2005
REBUILT:	
BUILDER:	Foss Shipyard, Rainier, OR

DIMENSIONS

REGISTER. GT:	144	REG. LENGTH:	73.4'
REGISTER. NT:	98	REG. BREADTH:	34.0'
ITC GR TONS:		REG. DEPTH:	12.4'
ITC NT TONS:		LOA:	78.0'
REGULAT. GT:	144	MAX BRDTH:	
REGULAT. NT:	98	MIN HEIGHT:	
DRAFT MIN:		MAX HEIGHT:	
DRAFT MAX:	15.0'	DISPLACEMNT:	278.8 LT

TANKS [# / TOTAL CAPACITY]

FUEL:	10,000 gal	LUBE:	
HYDRAULIC:		WATER:	500 gal
FOAM:			
BALLAST:			

MACHINERY

CONFIG:	Twin Engine, Twin ASD Propulsion
ME [#, TYPE]:	2 Caterpillar 3512C HD Series II
RED. GEAR:	
PROPELLER:	2 US 205 FP Rolls Royce ASD
TAILSHAFT(S):	
ME COOLING:	

MAX ME RPM:	1,800	SHAFT RPM:	
RATED HP:	5,080	ESCORT HP:	
CBHP:		CSHP:	
IBHP:		ISHP:	
BOLLPULL:	124,780	REVERSE:	122,290

AUX #1:	John Deere 6081 Marathon 125 Kw
AUX #2:	John Deere 6081 Marathon 125 Kw
AUX #3:	

CREWING REQUIREMENTS

FULL CREW: OCEAN CREW: SHORT CREW:

ENGINE ROOM EQUIPMENT

MSD:	
FIRE PUMP:	
HOSE CONN:	
MONITOR:	
FIXED SYS:	
FUEL TRAN:	
STEERING:	

DECK GEAR

ANCH GEAR:	N/A
BOW WINCH:	Markey DEPGF-42
BOW WIRE:	500' x 8-1/2" Plasma 12x12
TOW WINCH:	Markey DEPC-32 (stern barge-handling winch)
TOW WIRE:	300' x 6-1/2" AmSteel Blue
TOW WIRE #2:	
DECK CRANE:	N/A
DK CRANE #2:	
UNDERRIDER:	
STERN LINE:	
WORK BOAT:	

ELECTRONICS

AUTO PILOT:	Simrad AP-50
GYRO COMP:	
RADAR #1:	Furuno - FR-7112
RADAR #2:	Furuno - Nav-Net
RADAR #3:	
LORAN #1:	
LORAN #2:	
SAT NAV #1:	
SAT NAV #2:	
WEATHER FAX:	
FATHOMETER:	Y
FATHOM #2:	
VHF #1:	Standard
VHF #2:	Standard
VHF #3:	Standard
PORTABLE VHF:	
UHF/PRIVACY:	
CITIZEN BAND:	
SSB #1:	
SSB #2:	
CELLULAR:	Y
MARINE RADIO:	
ALARM PANEL:	Y
LOUD HAILER:	Y
FACSIMILE:	
SOUND PHONE:	Y
INTERCOM:	Y
MAG COMPASS:	Y
GPS:	Simrad HS50
DIRECT FIND:	
EPIRB:	ADCD0238D142801

REMARKS: Sister vessels: Mikiol, Campbell Foss, Revolution. Bollard pull results per 12/27/05 ABS report.

#Name?

CAMPBELL FOSS - Hybrid Dolphin

VSL Type	Green Assist™ Hybrid Dolphin	**Fuel**	10,000 gal
Service	Harbor – ship assist and vessel escort	**Water**	450 gal
Classification	None	**Propeller**	2 x Rolls-Royce Model US 205 Z-Drives
Registry	United States	**Rated HP**	5100 HP
SOLAS	No	**ME [#,Type]**	2 x Caterpillar 3512D
Year Built	2005 Converted 2011	**Bollard Pull**	65 tons ahead
			69 tons astern
Builder	Foss Shipyard, Rainier, OR	**Aux 1**	John Deere 6081
Length	78 ft	**Aux 2**	MTU Series 60 Tier II 350 kW
Breadth	34.0 ft	**Au 3**	2 x 500 kW Teco-Westinghouse Motor/Generator
Depth	12.4 ft	**Batteries**	10 x Corvus Lithium Polymer
		Bow Winch	Markey DEPGF-42

Foss Maritime Company
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Seattle, WA 98109

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info@foss.com

FOSS

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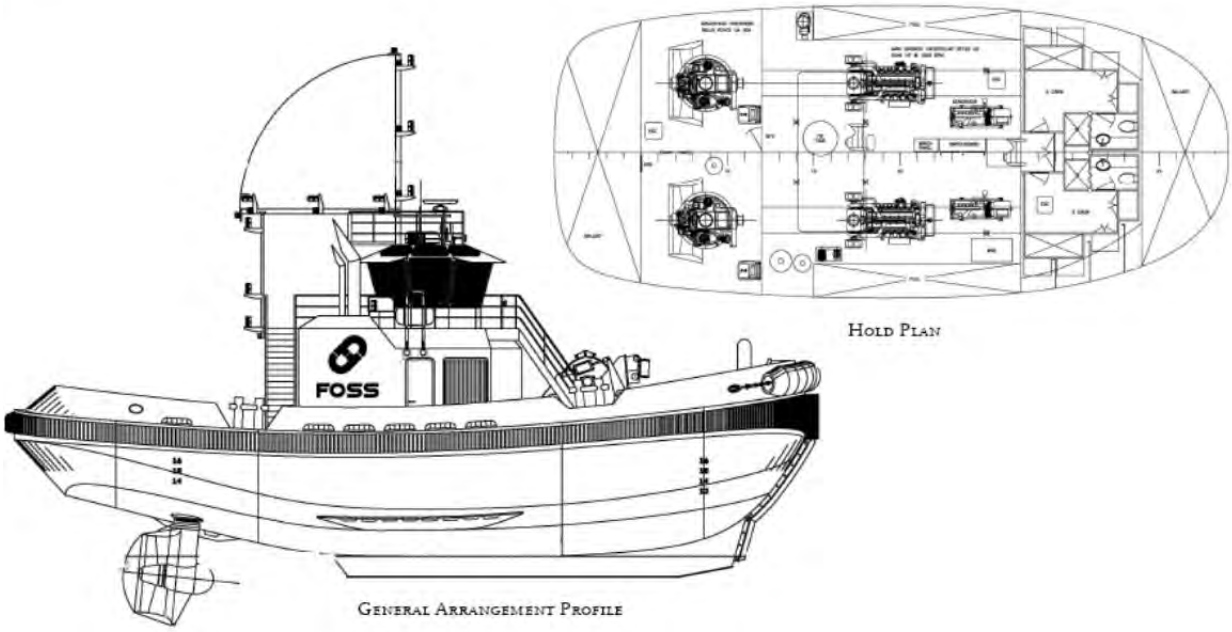
ALWAYS SAFE.

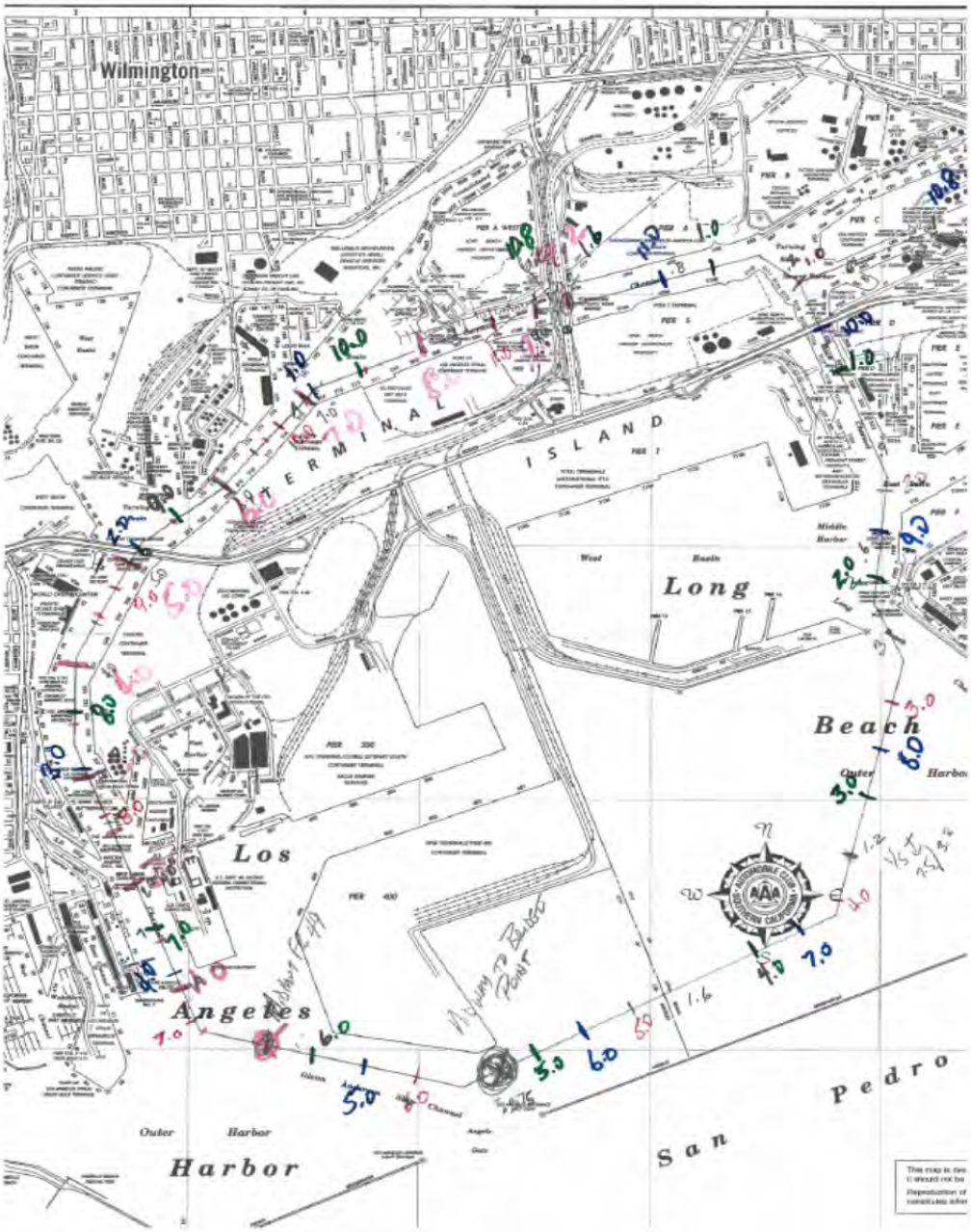


HOLD PLAN

GENERAL ARRANGEMENT PROFILE

Dolphin Class

9 Appendix D- Heim Bridge Diversion


Wilmington
TERMINAL
ISLAND
West
Basin
Long
Beach
Los
Angeles
Harbor
Outer
Harbor
San
Pedro

APPENDIX E

CAMPBELL FOSS FIRE INCIDENT INVESTIGATION REPORT

Foss Maritime Incident Investigation Report
CAMPBELL FOSS FIRE

Date of Incident: 8/20/2012

Date of Report: 10/1/2012

Title: Campbell Foss Engine Room Fire
Date of Incident: 8/20/2012

Responsible Managers: Ed McCain, Jerry Allen

Investigation Team: Tim Stewart (Foss), Paul Jamer (AKA), John Eldridge (AKA), Capt. Ron Burchett (Corvus Energy), Geoff Crocker, P. Eng (Corvus Energy), Chi-Kiu Tsang (Corvus Energy), LCDR James Surber (USCG)

Vessel involved: CAMPBELL FOSS

Employees Involved: Capt. Joe Rock, Eng. Josh Selga, A/B Vince Pereira, A/B Nathan Ikerd

SUMMARY OF INCIDENT:

On August 20th, 2012, the Campbell Foss was conducting a ship assist of the Cosco Malaysia from LB Gate to LB Berth 245 with a crew of four: one captain, one engineer and two able bodied seamen (ABs). The Campbell was in the assist mode with both main diesel engines (MDEs) providing propulsion and motor generators (MGs) supporting the A/C Buss via the Hotel Active Front End (AFD). The Campbell was directed to run with the ship on the port quarter, and was later shifted to starboard quarter with a line, as the Cosco vessel was turning at the entrance to southeast basin. The approach to the berth was uneventful with the pilot working the tug in push/pull maneuvers, with orders up to working the tug both pulling and pushing up to half power. The Campbell was pushing one third on starboard quarter of ship as the Cosco vessel was alongside berth. At that time, the crew heard a loud bang along with a shudder through the hull, engine RPM appeared normal and heavy black smoke was immediately sighted coming from engine room vents on the aft side to pilothouse. Alarms were heard coming from panel. The engineer had just departed the wheelhouse prior to

the loud bang and observed black smoke coming from vents. The engineer then sounded the alarm. The captain notified the pilot on VHF of a fire and received response to do what was needed. The Tug Alta June was working the starboard bow of the Cosco vessel and communicated that they would make emergency notifications. Heavy black smoke continued to come out of the Campbell's aft vents. The engineer was directed to pull emergency stops for ventilation to the battery compartment. The crew had mustered on the tug's starboard side aft. The ABs broke out the fire hose from aft station to cool the deck. The captain started the fire pump from the pilothouse and secured e-stops for both mains and generators. The captain returned to overlook the aft deck from pilothouse deck. The captain directed the engineer to crack the ASD compartment hatch and investigate. Smoke was observed from compartment and the hatch was re-dogged. The Captain directed the engineer to pull the release cables to the fixed fire suppression systems to battery compartment and engine room. Smoke was around the main entrance to the vessel where releases were located. The FM-200 Fixed Fire Fighting System was deployed and the smoke began to clear. The Alta June came along the Campbell's starboard side and put up a line on the starboard aft bitt and held her off the counter of the Cosco ship until the Campbell could retrieve the headline. The fireboat Challenger and two rescue boats responded at around this time. The crew continued to cool the Campbell's decks using the Alta June's fire main and two sections of hose. Fire personnel from Challenger came aboard the Campbell. The Campbell's captain directed them not to enter the engine room compartment or to un-dog the engine room doors. The Alta June made up with two lines and the shifted the Campbell to LB Pier 35.

During the event, the Campbell's alarm and monitoring system identified numerous faults and alarms associated with the battery system and other electrical systems as shown in the timeline (Attachment 1).

Upon arrival at LB 35, the vessel was met by Tim Stewart (Foss Maritime) and Eric Ryan (AKA). The fire department continued to prepare the engine space for entry by opening the Z-Drive compartment hatch and fogging the space. Four (4) fire department personnel entered the space and continued fogging the Z-Drive compartment. The Fire Department exited the space with the decision to enter the Engine Room from the main deck access. When it was determined that it was safe to enter the main engine room, fire department personnel obtained information on equipment lay-out from Foss personnel and opened the door to the space. They water fogged as they advanced and though the space was warm (approximately 140 deg F) there was no evidence of flames. The fire was confirmed extinguished.

Upon entry, it was found that there was significant residual heat in the space; and it became apparent that the damage was largely localized to the battery compartment and surrounding area. The battery compartment was still intact, but there was evidence of high heat in the aft port engine room space. The PVC ventilation piping from the battery compartment was melted and appeared to be the exit path of the hot gases from the battery compartment.

Once the temperature had dropped in the space and sufficient ventilation had been provided, the air was tested and confirmed as safe to enter without breathing apparatus. At this point, Tim Stewart and Eric Ryan accompanied the firemen into the space and proceeded directly to the battery compartment area. It was noticed that the left hand battery compartment door, though intact, was slightly ajar. It was also noted that the battery compartment structure had not been breached or damaged. The temperature of the door was tested and deemed safe to touch.

The doors to the battery compartment were removed, and a preliminary inspection was conducted. There was a layer of soot over all surfaces inside the compartment, and there was an obvious breach of Battery Module #9 which was located at the bottom center of the pack. All other modules appeared to be intact and the cabling associated with the battery modules, although charred, was substantially intact.

At this point, the heat in the battery compartment was intense enough to require withdrawal of Foss and AKA personnel until further ventilation and cooling permitted safe entry.

Once the Engine Room was safe for entry an initial survey was conducted. The initial survey revealed the following damage concentrated in the Port Aft Engine Room:

- Battery Compartment
- Battery Modules.
- Battery Cables, (charred but substantially intact)
- Battery Pack Controller and Communication Cabling.
- Melted Lighting Fixtures.
- Battery Compartment Ventilation System.
- Key pads and fan louvers on the exterior of AKA hybrid switchboard (facing the source of the fire).
- External cable runs (through engine room space) associated with hybrid system as well as other vessel systems. (The extent of damage will not be known until the vessel's systems have been completely tested.)
- The outboard Air Cleaner Housing and Turbo of the Port Main Diesel Engine.
- The Port and Aft sides of the AKA Hybrid Switchboard were exposed to significant heat, damaging the external surfaces and components.

Inspection of the remaining areas of the engine room and ASD space indicated it had sustained light to moderate smoke and heat damage. Equipment, components and wiring in direct line of sight of the battery compartment received more damage than areas protected by obstructions. Upon completion of the inspection, the vessel was secured and access to the vessel was restricted to approved personnel participating in the investigation.

At 1200 on August 21st, the vessel was towed to Pier 49 and secured for further investigation.

INCIDENT TIMELINE: Attachment 1

TECHNICAL BACKGROUND:

Hybrid systems for tugboats provide a significant benefit to the environment, reducing every category of air emissions. The systems also provide for a reduction in the operating cost of the vessel through fuel savings and reduced maintenance expense. Lithium Polymer batteries provide the above benefits with the advantage over lead-acid batteries of having a lower internal resistance. This allows for higher energy capacity and lower heat generation in the batteries during use. The reduced weight and maintenance of the battery system are additional benefits to the operation of the tugboat.

The low internal resistance is due to the conductivity and chemistry of the materials inside the cell. The smallest working unit in a battery is the electrochemical cell, consisting of a cathode and an anode separated and connected by an electrolyte. The electrolyte conducts ions but is an insulator to electrons. In a charged state, the anode contains a high concentration of intercalated lithium while the cathode is depleted of lithium. The lithium inside the cell is not in a metallic form; it is in ionic form, dissolved in a salt. During the discharge, a lithium ion leaves the anode and migrates through the electrolyte to the cathode while its associated electron is collected by the current collector and used to power electric devices.

The electrodes in lithium-ion cells are always solid materials. One can distinguish between cell types according to their electrolytes, which may be liquid, gel, or solid-state components. The electrolytes in gel and solid-

state cells represent a structural component and do not need additional separators for the effective separation of electrodes and avoidance of short circuits.

For low-energy and low-power applications, a cell often represents a full battery. For high-energy and high-power applications (such as transportation or stationary storage) a number of cells are packaged in a module, and a number of modules are packaged in a battery pack.

Corvus Energy utilizes advanced lithium ion polymer cells in multi-cell module configurations. These configurations are monitored by a proprietary Battery Management System (BMS) to control charge, discharge and monitor all aspects of the cells, modules and pack. The BMS starts at the module level monitoring voltage, temperature and actively balancing cells. At the pack level, a pack controller monitors all the cells and modules in addition to current flow and overall voltage. The pack controller contains contactors to allow for controlled disconnection due to faults within the system including over/under voltage and over temperature. There are also fuses to protect the output cables to the DC bus in case of short circuit and overloads. Although the pack self-monitors and can disable itself, it is also necessary for the system integrator to ensure voltage and current limits provided by the BMS are not exceeded. Current flow through the battery pack must be managed by the system integrator to ensure the temperature rise is managed within the predefined limits of the battery manufacturer. In addition, lower and upper voltage limits must never be exceeded at the cell level and pack level. Exceeding these values is supposed to cause the pack controllers' contacts to open as a means of protecting the cells.

INVESTIGATION METHODOLOGY:
The investigative team consisted of Tim Stewart of Foss Maritime Co., Ron Burchette, Geoff Crocker and Chi Tseng of Corvus Energy, Paul Jamer and John Eldridge of Aspin Kemp and Associates. The US Coast Guard Marine Safety Office LA/LB retains regulatory authority but has opted to allow Foss Maritime to conduct the investigation with reports and evidence to be delivered to them upon completion.

The investigation primarily consisted of the following components:

- Vessel viewing.
- Component/equipment inspection.
- Data capture from relevant systems.
- Collation of crew statements and reports.
- Establishment of event timeline.
- Review of data and determination of causal effect(s).
- Development of corrective actions.

FINDINGS / CAUSAL FACTORS:

The following contains the facts that the team has been able to verify since commencement of the inspection. The corrective action for each of these points is detailed in the appropriate section.

1) **Battery Pack** –
    - Series Element Cells in battery Module 9 (M9) failed.
    - M9 is damaged beyond detailed component inspection other than being able to view the remaining material and infer the sequence of failure.
    - 8 of the 9 remaining battery modules show high cell voltages combining to have a pack voltage of up to 540VDC; however, they show no apparent physical signs of the failure as seen in M9.

- The contactors in the pack controller are in an open state. they did not fail closed) Had the contactors been found closed after removal of control power a mechanical failure of the contactor would have been indicated.
- The Pack Controller Current Sensing Board had not been operational since commissioning due to the interference caused by electrical noise on the vessel. The electrical noise prohibited the sensor from providing an accurate measurement. The sensing board was disabled by forcing the output of the current sensor to zero. Pack balancing requires a current measurement of 0 +/- 1.5 amps to enable balancing of the cells which is necessary to optimize pack capacity.
- AKA installed a current sensing circuit connected directly to the hybrid control system to provide information required for integration of the battery pack.
- Testing performed on a similar battery system identified a software error in the pack controller. This error prevented the pack controller from opening contactors on a battery fault. The Campbell Foss pack controller has an equivalent software installation which would exhibit an identical failure. This information is detailed in a Corvus Energy Memo dated September 13, 2012. (**Attachment 2**)

2) **Battery Compartment** – The battery compartment remained intact and the aluminum compartment doors are not damaged to the point of deformation. The internal surfaces are covered in soot, but external paint appears to be undamaged.

3) **Ventilation** - The ducting on the battery compartment ventilation system was destroyed by the event. When exposed to burning gases, the ducting melted; and, as it deformed, the connections to the fan and elbows were compromised. This resulted in hot gases from the battery compartment being vented to the engine room space. There is indication that this occurred in a progressive way. Initially, the joint between the piping and the elbow (which directed it vertically) parted. This allowed the hot gases to be directed forward and starboard. The next joint to fail was at the discharge from the fan, which directed the gases to starboard at the portside of the Hybrid switchboard. Finally, with the loss of the vent piping between the battery compartment and the fan, hot gases were directed athwartships across the aft side of the Hybrid switchboard toward the starboard side of the engine room. At some point during the event, the hot flammable gases ignited in the engine room further igniting combustibles in their path.

4) **Control System –** The hybrid control system and the battery pack controller work together to control the flow of energy to and from the batteries. The hybrid control system relied on a state of charge (SOC) indication from the pack controller as a means of determining whether the batteries were able to be charged or discharged. The designed lower limit is 20% and the designed upper limit is 90%. Above the upper limit, the system reduces to a trickle charge. At 92%, charging is terminated and the energy flow is away from the batteries. (The intent of these set points is to not expose the battery to extremes of voltage.) The present methodology for the pack controller to calculate state of charge is based on an indication of the lowest series element voltage. This means that other series elements <u>will be</u> at a higher voltage during charging. The design intent of the Corvus battery BMS was not to use the SOC in accordance with memo "DOC1000001 Memo Pack Charging" communicated to AKA on June 3, 2011 (**<u>Attachment 3</u>**), this information <u>was not</u> relayed to Foss Maritime. This memo details the use of a "charge parameters message" that defines the maximum voltage and current during charging. The voltage limit was not included as part of the hybrid control system; however, current limits below the values recommended by the battery manufacturer were in place. The use of "SOC" to control the battery charging and discharging remained in place until the fire incident.

5) **Alarm and Monitoring System –**The alarm and monitoring system had been reporting numerous alarms associated with the battery system over a considerable period of time (3 months). As time progressed, many of these alarms were silenced, but not acknowledged. The result is, as additional faults were identified by the system, they did not result in audible or visual indication to the operators. Prior to the fire, there had not been any faults indicated since August 16th, although the battery system was likely sending continual alarm information. Additionally, the alarm and monitoring system level of resolution, with respect to battery system fault reporting, does not provide sufficient detail to allow operators to determine the exact cause of the alarm condition. In essence, a "summary alarm" will be annunciated for many of the battery alarms, masking the specific information being broadcast from the pack controller. This along with information provided by Corvus Energy in emails dated May 31, 2012 and June 11, 2012, lead Foss to conclude the alarms were nuisance in nature and posed no additional risk for continued operation. In this particular case, alarms were being broadcast that appeared to be of the same nature as the previous alarms when in fact the actual information from the battery may have changed.

6) **Engine Room Overhead Insulation –** During the fire, the deck in the wheelhouse was hot to the point of softening the glue under the carpet. During the vessel inspection, it was noted that the overhead of the access trunk was not insulated, permitting the transfer of heat from the engine room overhead to the wheelhouse deck.

7) **Findings As a Result of Response Actions**

   a. The Captain intended to initiate an emergency shut-down of all machinery. However, this is a two stage process where the protective guards are lifted, then a toggle switch must be moved to the upper position. In this case, the second action was not accomplished; and, as a result, the shut-down did not occur.

   b. The Crew attempted to gain access to the Z-Drive compartment for investigation. As a result of the aft door of the engine room being opened, the Z-Drive compartment was full of smoke. The door to the Z-Drive compartment should always be closed at sea for the following reasons:

      i. The FM200 system is not sized for the engine room space and the Z-Drive compartment combined.

      ii. Local activation of the FM200 system can only be done from the Z-Drive compartment.

   c. The battery compartment was fitted with a manually operated FM200 fire suppression system. The Captain gave the order to activate this system following the Chief Engineer's report of fire. The system could not be manually activated due to an internally fused pull cable. Inspection of the FM-200 bottle confirms a discharge of the bottle by automatic actuation of the heat sensitive fusible plug. The electrical contacts are now open confirming proper operation with a resultant damper closure.

ANALYSIS:

One or more Series Elements in Battery Module Nine (9) ruptured due to continuous or numerous overcharging events. The cell pouch burst due to gas generation inside the cell as a result of cell overheating beyond 100°C. The gasses expelled from the cell pouch are flammable. It is unknown if the gasses ignited inside the module or if the pressure build-up inside the sealed module caused the lid latches to fail. Once the lid seal and retention were compromised, the gasses generated would have vented through the open lid and filled the battery compartment. Current can still be drawn from the cells at that point, including the failing

cell. As the cell releases gas, the electrolyte of the cell depletes, exposing the anodes and cathodes inside the cell. This reduces the cell's capacity to deliver energy efficiently and heat is increasingly generated, raising the temperature of the cell and in particular the cell electrodes and tabs. Ignition of the flammable gasses is likely due to extremely high temperatures in the cell electrodes and tabs. Series Elements 4 and 7 show signs of being the first cells to fail based on the amount of damage to the module enclosure adjacent to those cells. Once the heat transferred from the first failed cells, the remaining cells reached a critical point causing these cells to fail in a similar manner, contributing to the overall combustion. Combustion would have continued until the supply of electrolyte in the cells had depleted. Combustion heat transferred to the remaining modules but did not cause them to fail; however, the thermal mass of the modules is such that the battery compartment retained heat for an extended period, as shown by the temperature monitoring results obtained.

There is substantial data to indicate these overcharging cycles were being alarmed over a 3 month period but were considered a nuisance. Emails were received from Corvus Engineering on May 31, 2012 and June 11, 2012 (**Attachements 4 & 5**) in response to specific questions from Foss Maritime Port Engineer Romen Cross concerning new alarms on Module #9 that were brief in duration (seconds). Foss noted that voltages and temperatures were in-line with the other modules from hybrid system data. Corvus Energy had asked for additional information with regards to the alarm period and any definable patterns. Corvus had also stated in the email that unless temperature differentials between modules exceeded 15°F to 20°F there should be no additional risk for continued operation. Foss was not able to establish a pattern and alarm periods were essentially the same as discussed in the May 31, 2012 email, therefore additional information was not conveyed to Corvus Energy.

The over temperature was not monitored directly, and the temperature rise was therefore not observed. As a final line of defense, the pack controller should have opened the contactors. Based on testing performed on a pack controller in a similar installation, a software programming error prevented the contactors from opening during a battery fault. Since the Campbell Foss has an equivalent software installation, the pack controller would not have opened the contactors in the event of an overcharge. Due to the Hybrid Control System using "State of Charge" as provided by the battery pack controller to determine when charging was to terminate, multiple overcharge events were realized on the Campbell Foss. The use of "State of Charge" is not in accordance with Corvus BMS design further requiring the pack controller to open contactors to prevent these overcharging events. Further testing also revealed that the pack controller is not designed to latch the contactors in the open position. As a fault condition clears, the contactors will close and continue charging. This type of cycling is often observed where voltage set points are utilized to initiate a corrective action. If voltages are on the threshold of the set point, the system will cycle as the load or charge current varies.

Over time, other modules alarms were raised; and the frequency of alarms increased. Based on the previously discussed emails, these additional alarms were assumed to be a nuisance in nature and therefore this information was not relayed to Corvus Energy. Corvus had communicated their desire to complete battery system upgrades on or about the last week of July, however these upgrades were considered non-critical to the operation of the battery system.

Once the combustion process initiated, pressure inside the module increased to the point of lifting the lid with an approximate force of 3000 lbs. This is most likely the sound heard by the crew at the onset of the event. Inspection of the Battery Compartment indicates that the initial combustion was quick and intense; however, combustion was not sustained due to the discharge of the FM-200 in the compartment, as the result of the activation of the fusible plug. The discharge of the FM 200 system also initiates a damper closure. Hot gases from the initial combustion were propelled thru the PVC Vent Duct to the Port Aft Engine Room until the PVC

Ducting failed due to extreme heat. Once the PVC Ducting failed, the hot gases escaped into the engine room most likely igniting in the presence of oxygen and further igniting combustibles in the area. The Engine Room FM-200 Fixed Fire System was deployed and was effective in extinguishing the fire, preventing a total loss of the Engine Room.

PROBABLE CAUSE:

The Battery Monitoring System (BMS) monitors individual series elements for over voltage. Additionally, temperature sensors are embedded in each module to monitor temperature. In the event of over voltage or over temperature, the pack controller was designed to open its contactors to protect the battery pack from additional charge / discharge. In this case the pack controller software error prevented this last line of protection from activating. Since these designed protective devices were not functional, the method by which State of Charge is used by the Hybrid System will in fact create overcharge cycles in numerous Series Elements. Since the Pack Controller reports State of Charge based on the single lowest Series Element Voltage other Series Elements will continue to charge until the lowest Series Element has achieved a 90% State of Charge. Cell balancing during charging / discharging may have impacted the ability of the BMS to effectively bring the cells into balance. The problem was further exacerbated by critical alarms / faults being reported as module summary alarms / faults within the alarm and monitoring system. This prevented the crew from fully understanding the nature of the alarms and faults. There was also no programmed absolute maximum setting on the control system of 500VDC as specified in the Corvus Energy memo dated March 2011. This combination led to a series of overcharge cycles and the assumption that the alarms being annunciated were of the same type as previously encountered by Corvus Engineering in May/June, as per the noted emails. Once the combustion event started the failure of the PVC vent ducting allowed the hot gases to escape the battery compartment and engulf the Port Aft Engine Room in flame. The failure of the significant safety systems built into the Corvus Energy Pack Controller along with the contributing factors noted, created a chain of events culminating in the fire event of August 20.

HUMAN CAUSAL FACTORS:

- Based on Corvus Energy email response of June 11, 2012 the alarms were viewed as a nuisance. The email stated that unless temperatures between modules were greater than 20F then the system was able to continue safe operation. As previously discussed in the alarm and monitoring section of the findings, the Alarm and Monitoring System masks the detailed information from the Battery Pack Controller. This led the crew to assume the new alarms were of the same nature as the previously investigated alarms creating an atmosphere of complacency with the crew.

- The failure to understand the operation of the Alarm and Monitoring System, with regards to acknowledging alarms, prevented further alarms from being annunciated on the Human Machine Interface Panel. It is not believed that any new alarms would have been treated differently due to the nuisance issue previously discussed, but that cannot be confirmed in light of the event.

- The access door between the engine room and Z-Drive room was left open during operations. In this event, this posed no significant problem; however, had the fixed FM-200 System not deployed from the remote pull stations, then the crew would not have been able to access the FM-200 System for a local actuation.

MANAGEMENT SYSTEM CAUSAL FACTOR:

- This event clearly illustrates that Foss should have been an integral part of the design with regards to battery system control, alarm/monitoring, and troubleshooting. There is evidence to indicate that Corvus delivered a memo to AKA in 2011 stating a change in the charge algorithm was in order. The information was not sent to Foss. Neither Corvus or AKA tracked the information to ensure implementation. As a result, State of Charge continued to be utilized by the Hybrid System as the means to determine when to commence or cease charging.

- The information received from Corvus Energy indicated the battery pack would pose no additional risk since battery temperature differentials were within the stated limits and the alarms were brief in duration. Based on these assurances of continued safe operation, a risk analysis was not performed. The unknown need for a risk benefit analysis led to continued operations where potential risk outweighed the benefit.

MECHANICAL CAUSAL FACTORS:

- Evidence suggests that the initial fire was an intense and rapid event which self-extinguished due to consumption of oxygen within the space and the discharge of the installed FM-200 bottle thru the actuation of the heat sensitive fusible plug. The failure of the PVC ventilation ducting allowed the hot gases to escape the battery compartment and re-ignite in the engine room due to the introduction of oxygen. The use of PVC in the battery system ventilation was based on the perception that the multiple layers of safety devices in the pack controller and battery modules would prevent a catastrophic failure of a battery module. Furthermore, the installation of dampers in the ventilation system would prevent a fire from reaching the PVC ducting. Clearly, the risk analysis was flawed by the failure to obtain or analyze technical data regarding the potential energy release with respect to intensity and speed.

- The remote pull cable for the Battery Compartment FM-200 System fused to its liner just outside the battery compartment rendering it inoperable. Had the system not self-actuated the system would have been entirely dysfunctional.

Recommended Corrective Actions:

#	Corrective Action	Assigned To	Due Date
1	**Battery Pack** A. Perform self-diagnostics based on the battery series elements expected response curve. The pack controller is to be configured to recognize any one cell that is responding outside the expected curve. The review of this curve will generate a “health status” of each element and identify a stressed cell well before failure. The pack controller will broadcast the “Healthy” status as a heartbeat control to the hybrid system; “Healthy” calculation to be performed during operation and heartbeat to be sent at 1 second intervals. Disconnect battery pack at fault level (in addition to hybrid system) and lock out restart until inspected by Corvus. B. Change alarm system to only report critical warnings and no information warnings. Latch contactors open on critical alarms; these must be manually reset.		

	C. Review all module and pack controller algorithms and parameters. D. Commission battery system to ensure control and alarm functionality is in alignment with battery parameters and safety requirements. Specifically, but not limited to: • Charging algorithm • Upper and lower state-of-charge (SOC) limits • Voltage limits • Temperature limits		
2	**Battery Compartment** – Although the Battery Compartment remained intact, the aft door was ajar, indicating a need for a clip to retain the door to the bulkhead. During the fire response it was noted that only 3000 GAL of fuel was aboard the vessel, creating some significant concern as to the vapor in the adjacent fuel tank. The adjacent fuel tank BHD should be insulated to an A-60 fire rating.		
3	**Ventilation** - The PVC ducting on the battery compartment ventilation system failed early in the event. The Battery Compartment Ventilation Ducting and Fan will be constructed of steel material, and all ducting is to be welded fume tight. The ventilation ducting is to be led to a safe location on the exterior of the vessel. The ventilation shutdown will be designed to automatically close on an over temperature event as well as deployment of the fixed fire system.		
4	**Control System** A. Perform independent calculations of bank voltage based on information provided by pack controller allowing a comparison between the Pack Controller and the Hybrid Control System. Use this as a comparative value for verification of the voltage being reported by the Pack Controller. This will insure that the critical parameter of voltage in the hybrid system will continue to operate the battery pack in a safe manner. Contactors shall be opened if the calculated delta exceeds a predetermined value. (Values to be determined by Foss, Corvus, AKA) B. Control System will be programmed to look for a “healthy message” from the Corvus Energy Pack Controller. As indicated in section 1, this message is to be sent at 1 second intervals, contactors will be opened upon message failure. C. Create an HMI Screen for display of Corvus provided trend data with regards to Series Element Health. This will allow a Series Element to be identified as it deviates from the expected performance curve. See Corrective action 1A. D. Program an absolute upper limit of 500VDC to the DC/DC converter E. Implement the 2 second, 10 second, 30 second maximum current limits for charging and discharging transmitted by the Corvus system.		

	Alarm and Monitoring System A. Reprogram the system to cease charging based on a High Voltage Reading from any single Series Element rather than "State of Charge", which in essence reports the single lowest Series Element within the Battery Pack. This will prevent the continual overcharge cycles that the battery pack has been subjected to. B. Open the battery contactors as both the DC-DC Converter and the Battery Pack Controller in the event of any single "critical alarm" related to the battery system. This will require reprogramming of the Alarm and Monitoring System to segregate warning and critical alarms. This will enhance the alarm system's functionality, allowing the crew to determine if an alarm needs immediate attention, and/or affects the immediate operation of the vessel. C. Program the system to re-annunciate all unacknowledged or active alarms at a frequency determined by Foss , forcing the crew's attention.		
6	**Engine Room Overhead Insulation –** The overhead of the engine room access trunk should be insulated to prevent conductance of heat to the wheelhouse deck.		
7	**Findings As a Result of Response Actions** A. Recommend replacing toggle type E-Stops with single action guarded push type or single action guarded toggle type. These 2 Step guarded toggle type E-Stops are common in the industry; however, are not the best option for this installation. B. Recommend this issue be discussed with all crews and Water Tight Doors labeled to remind personnel to keep closed while vessel is in operation. C. Review design and implementation of the FM-200 System for the battery compartment with an installation exterior of the battery compartment if possible. It is desirable that this system become an automatic discharge actuated from a Form C Relay on each battery module in addition to a manual discharge. Manual pull cable installation is to be redesigned.		
8	**Human Causal Factors** A. The alarm and monitoring systems are to be redesigned to indicate critical and non-critical alarms with distinctive alerts. Unaddressed alarms are to be annunciated at frequency determined by Foss until cleared. Foss engineering should aggressively pursue a corrective action to correct alarms by repairing the failed system or a change in the software as needed. B. Provide training to all crews as to the proper operation of all alarm and monitoring systems. Foss should institute an alarm and monitoring standard and require all new systems to meet the defined standard.		

C. The access door to the Z-Drive Room should be labeled to be kept closed during vessel operation. Crews should be trained to keep all watertight doors closed while underway as required for Load Line vessels. These doors have open indicators in the wheelhouse to provide the captain with this status. Captains should make use of these indicators.

9 Management Causal Factors

A. Foss Maritime must be an integral part of all communication regarding design and implementation of equipment and systems aboard our vessels. This will require the commitment of resources and time to engage in these somewhat lengthy and arduous processes. The direct impact to our operations and reputation dictate a change is required in this area.

Hardware and Software design recommendations and changes must be accurately tracked with regards to implementation and testing by Foss Engineering. Approval for all changes should reside with the Director Fleet Engineering or his designee

10 Mechanical Causal Factors

A. The battery compartment ventilation system must be redesigned and installed to prevent a compromise in the event of a future failure. The design should take into account the following items;
   1. All ventilation components should be made of metal and or other fire resistant material.
   2. The vent system shall exhaust to the exterior of the vessel in such a way as to prevent discharge of hot gases on personnel in the area or from impacting vessels alongside.
   3. Ventilation shutdown shall occur upon the discharge of either the engine room or battery compartment fixed fire systems.

B. The FM-200 bottle should be placed exterior of the battery compartment to allow for a local release in the event of a remote or automatic release failure. In the case of the Campbell Foss the Z-Drive Room would be the optimal location.

Incident Investigation Report (continued)

Attachments:

1. Time Line
2. Corvus Energy Memo Dated September 13, 2012
3. Corvus Energy Memo "DOC1000001 Pack Charging" Dated March 2011
4. Email From Corvus Energy to Foss Maritime Engineering on May 31, 2012
5. Email From Corvus Energy to Foss Maritime Engineering June 11, 2012

T.S. Stewart, Manager
Fleet Engineering Technical
Foss Maritime Company

Incident Investigation Report (continued)

PICTURES

FAILED BATTERY MODULE #9

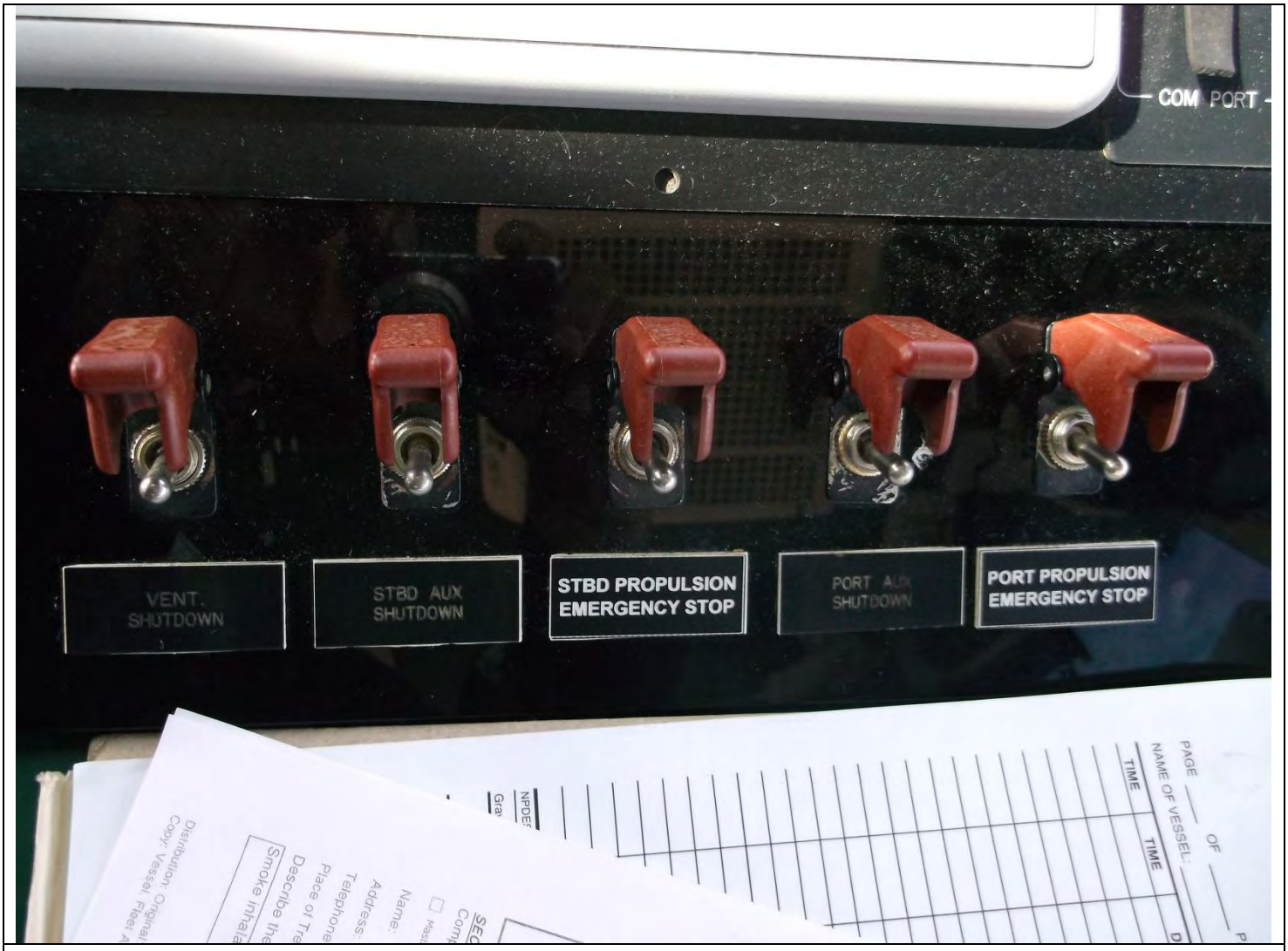
Incident Investigation Report (continued)

BATTERY COMPARTMENT PVC DUCTING

8/20/2012 3:43:17 PM	674	Error	Failure	Port Propulsion	Motor Generator VFD
8/20/2012 3:43:16 PM	786	Error	Failure	Stbd Propulsion	Motor Generator VFD
8/20/2012 3:43:11 PM	11	Error	Alarm	Hybrid Main	Spare DP 010
8/20/2012 3:42:46 PM	1	Error	Alarm	Hybrid Main	SW Cooling Pump 1
8/20/2012 3:42:38 PM	2	Error	Alarm	Hybrid Main	SW Cooling Pump 2
8/20/2012 3:42:37 PM	658	Error	Alarm	Stbd Incomer	Auxiliary Generator AFE FW Coolin
8/20/2012 3:42:36 PM	642	Error	Alarm	Stbd Incomer	Auxiliary Generator AFE FW Coolin
8/20/2012 3:42:34 PM	4	Error	Alarm	Hybrid Main	FW Cooling Pump 2
8/20/2012 3:42:26 PM	355	Error	Alarm	Hybrid Main	DC Bus
8/20/2012 3:42:26 PM	419	Error	Alarm	Hybrid Main	DC Bus
8/20/2012 3:42:19 PM	13	Error	Alarm	Hybrid Main	24Vdc Distribution
8/20/2012 3:42:19 PM	14	Error	Alarm	Hybrid Main	24Vdc Distribution
8/20/2012 3:42:18 PM	24	Error	Alarm	Hybrid Main	230Vac Distribution
8/20/2012 3:42:18 PM	15	Error	Alarm	Hybrid Main	24Vdc Distribution
8/20/2012 3:42:16 PM	49	Error	Failure	Hybrid Main	DC-DC Converter
8/20/2012 3:41:54 PM	44	Error	Alarm	Hybrid Main	C-AMP CAN Bus Network
8/16/2012 3:02:30 PM	74	Error	Alarm	Hybrid Main	Battery Module 2
8/16/2012 3:02:04 PM	73	Error	Alarm	Hybrid Main	Battery Module 1
8/16/2012 3:01:23 PM	76	Error	Alarm	Hybrid Main	Battery Module 4
8/16/2012 3:01:23 PM	64	Error	Failure	Hybrid Main	Battery Module 4
8/16/2012 2:59:47 PM	61	Error	Failure	Hybrid Main	Battery Module 1
8/16/2012 2:58:56 PM	62	Error	Failure	Hybrid Main	Battery Module 2
8/16/2012 2:55:36 PM	68	Error	Failure	Hybrid Main	Battery Module 8
8/16/2012 2:55:36 PM	80	Error	Alarm	Hybrid Main	Battery Module 8

ACTIVE ALARM SCREEN (NOTE UNACKNOWLEDGED ALARMS FROM 8/16)

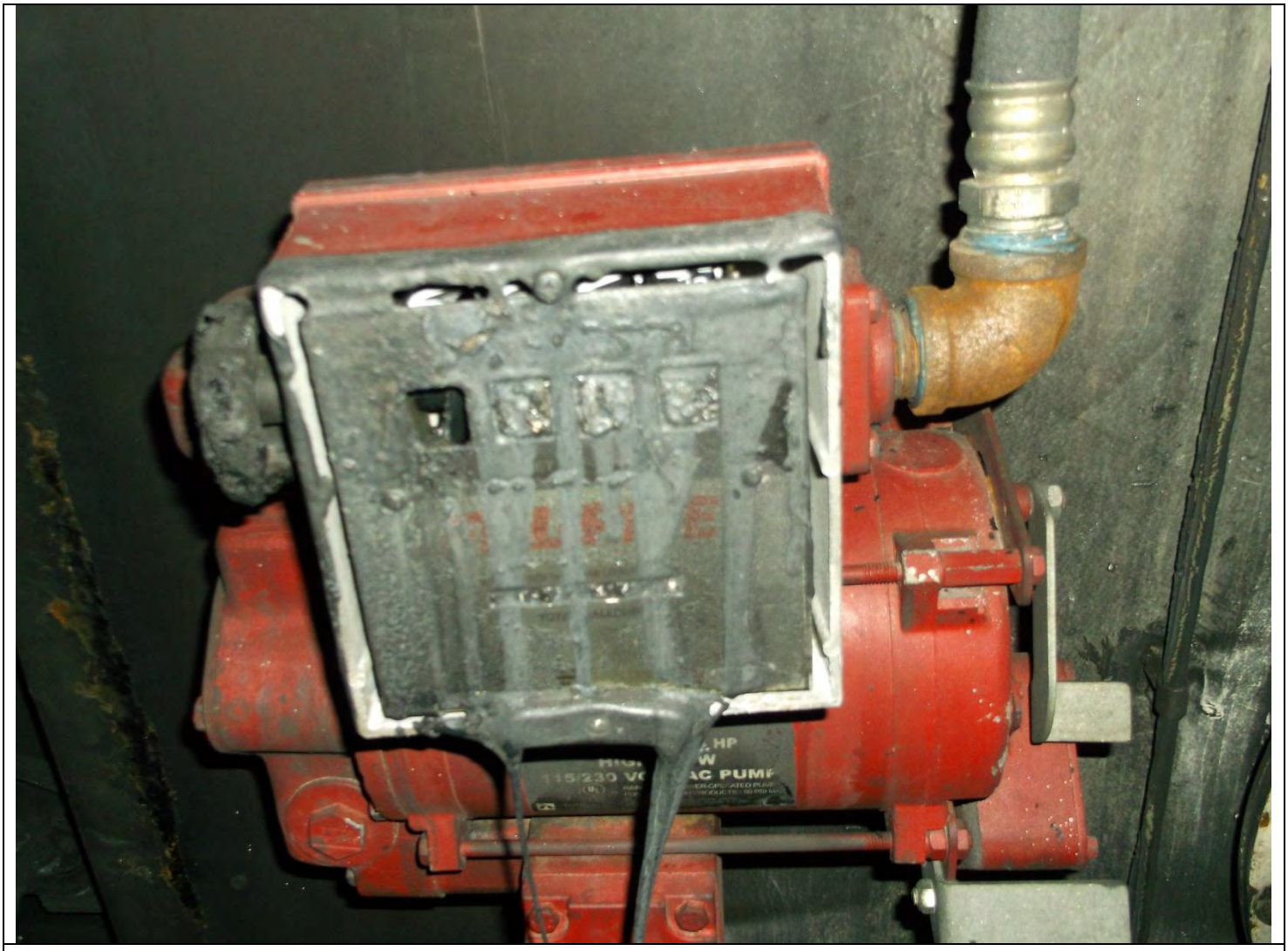
BATTERY COMPARTMENT VENT FAN & FAILED DUCTING



MACHINERY E-STOPS (NOTE POSITION OF SWITCHES)

OVERHEAD CABLING & INSULATION DAMAGE

Incident Investigation Report (continued)



DAMAGED FUEL TRANSFER PUMP & METER