FINAL REPORT ON BATTERY RE-INSTALLATION

CAMPBELL FOSS and CAROLYN DOROTHY

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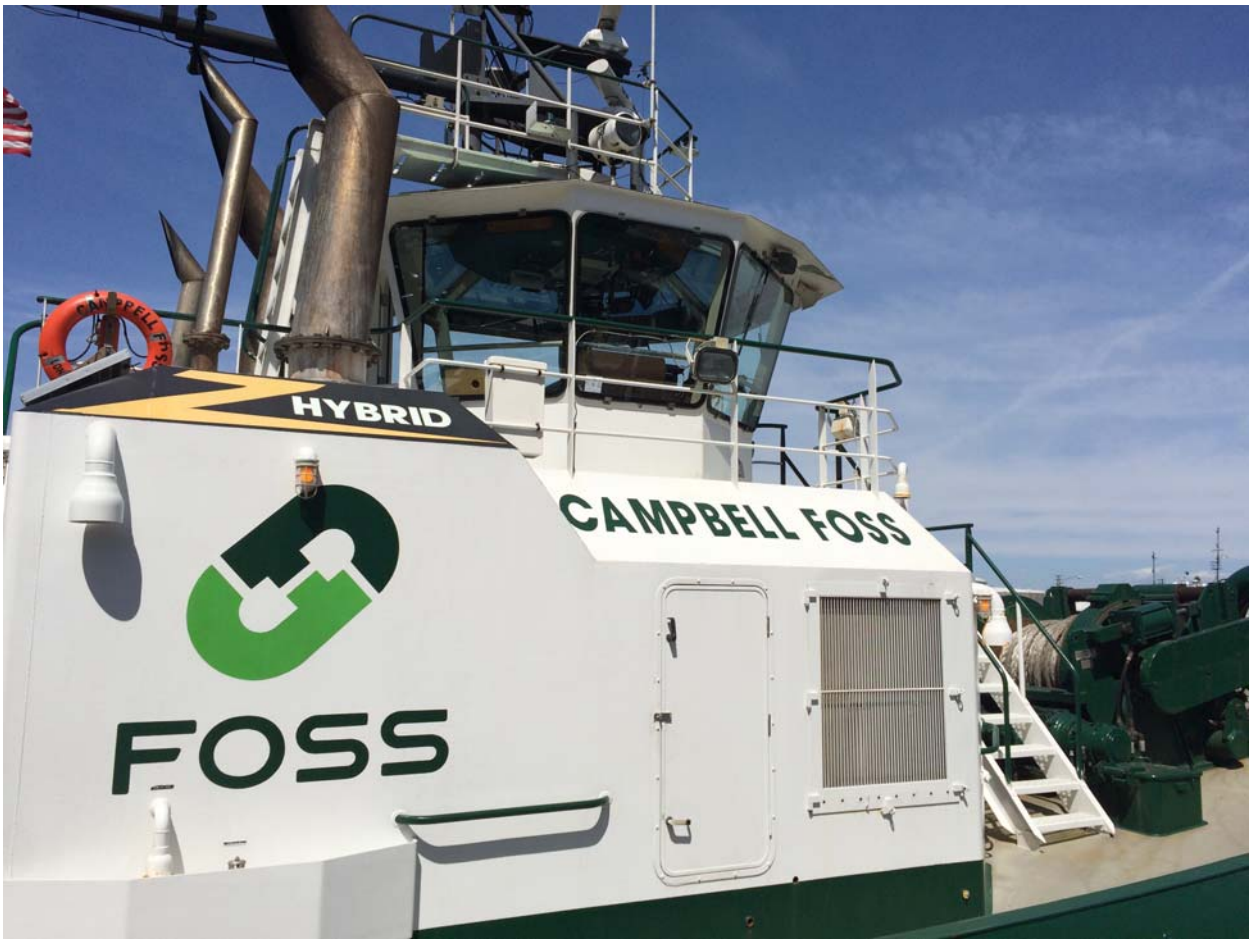


EXECUTIVE SUMMARY

Background

In August of 2012, an explosion and fire occurred in one of the lithium-polymer batteries on the Foss hybrid tug CAMPBELL FOSS. Subsequent to that fire, Foss removed the remaining batteries from the CAMPBELL FOSS and all of the lead-acid batteries on Foss' other hybrid tug, CAROLYN DOROTHY. CAMPBELL FOSS was returned to service in diesel configuration without batteries, and CAROLYN DOROTHY was returned to service in a modified hybrid configuration that did not require the use of batteries.

At the time of the fire on the CAMPBELL FOSS, Foss was applying for MARAD Maritime Environmental and Technical Assistance (META) program funding to help pay for the hybrid conversion of a sister vessel, the ALTA JUNE, from conventional propulsion to a hybrid system similar to the one installed on the CAMPBELL FOSS. Foss was awarded META funding from MARAD for the conversion. After the fire, Foss decided not to pursue the hybrid retrofit until such time as the battery installation could be proven to be safe.

The role of batteries in the hybrid system is not well understood; however, the risk of fire from lithium batteries in various platforms from computers, airplanes to tugs has been well documented. Anecdotal evidence suggests that the use of batteries in a hybrid tug system poses an impediment to more widespread adoption. Therefore, Foss requested to use the funds from MARAD to put batteries back into the two existing hybrid tugs after completing a risk assessment and incorporating lessons learned from the CAMPBELL FOSS fire. The revised project plan also included emissions testing with University of California Riverside (UCR) to quantify the benefits of moving from a Tier 2 to a Tier 3 auxiliary generator in this same hybrid application.

There is no doubt that hybridization is an excellent way for vessels with variable duty cycles, such as harbor tugs, to reduce all emissions as well as fuel and maintenance costs. The hybrid technology used in the CAMPBELL FOSS was verified as a diesel reduction technology by EPA in 2012 but has yet to gain widespread acceptance in the United States. This project further quantifies the benefits from hybrid technology and serves to promote the adoption of this emissions reduction technology for the public benefit. MARAD agreed and awarded Foss $600,000 in funding to help offset the costs for this project.

Risk Assessment

In October of 2014, Foss hired Elliott Bay Design Group (EBDG) to perform a risk assessment study on the hybrid boats with respect to reinstalling batteries. The risk assessment, included as Attachment 1 to this document, showed that with a properly designed and installed battery system, with structural separation from occupied spaces, proper explosion protection and correct and functioning battery control and shutdown protocols, the hybrid boats would be able to realize their full potential in performance, emissions and fuel consumption reductions. Conversely, the cost and risk of <u>not</u>

reinstalling batteries was high, based on increased fuel consumption and emissions, and decreased usability of the CAROLYN DOROTHY due to lower bollard pull. The lower bollard pull is a direct result of the fact this vessel has smaller main engines than her sister tugs; therefore requiring a large array of batteries to supplement the installed diesel power in high load conditions.

In order to proceed with reinstalling the batteries, two key decisions needed to be made as a result of the risk assessment findings. The first was whether or not to move the battery compartment outside of the engine room and the second was to select a battery manufacturer.

Two alternative locations for the battery compartment outside the engine room were examined, the deck locker and the stern void/ballast space. Although the deck locker provided easier access to install the batteries it complicated the engineering of the ventilation system. The stern void space was ultimately chosen because it offered the safest alternative and simplified the engineering of the ventilation system.

Aspin Kemp and Associates (AKA), the company Foss partnered with to develop the existing hybrid control and management systems, Foss and EBDG evaluated two battery manufacturers who met the technical and performance criteria established for the project. The two manufacturers chosen for consideration were Corvus Energy and Energy Storage Technologies (EST). AKA has worked with both manufacturers on different projects and Corvus Energy is the same brand previously used onboard the CAMPBELL FOSS.

Both manufacturers use cells produced by Dow Kokum in Korea, and assemble them into battery modules. Corvus Energy uses parallel connections for the cells while EST does not connect the cells in parallel. Measuring the voltage across parallel cells means measuring the voltage of a group of cells, where the loss of voltage indicated by a failed cell will be masked by the voltage of the remaining cells. This is a risk because the module will suffer from reduced capacity, and a failed cell may eventually explode without a warning from a low/high voltage reading. When cells are connected in series, it is impossible for a failed cell to remain undetected. The EST lithium-polymer batteries along with their attendant control system and hardware were chosen for this project on the basis of their technical and safety merits.

Acting on the EBDG recommendations, Foss developed a team of engineers, naval architects and operators to refit the hybrid tugs with new batteries. This team was led by Foss project engineers and team members included EBDG, AKA and Energy Storage Technologies (EST). EBDG was tasked to design the modifications required to the vessels to accommodate the batteries and AKA worked to integrate the new batteries into the existing control system.

During the design phase of the project, the team determined that CAMPBELL FOSS would require ten of the EST batteries acting in a single string, and the CAROLYN DOROTHY would require (28) of the same batteries, acting in two separate strings of (14) batteries each. With this determined, EBDG designed a separate battery compartment in the stern void tank of each vessel. EBDG also designed the ancillary systems and modifications required to support battery operations, such as ventilation, explosion protection via rupture discs, HVAC systems and installed firefighting systems.

Project Summary

Foss began physical modifications to the CAROLYN DOROTHY in May of 2015. While these modifications were being performed, EST informed the team that the batteries could no longer be shipped via air freight, and required shipping via cargo ship which resulted in a delay of approximately six weeks. With this in mind, Foss continued with the structural modifications on the vessel through July, and then put her back into service in non-battery hybrid mode while awaiting the delivery of the batteries. Foss took the CAMPBELL FOSS out of service in early September to begin the physical modifications. In addition, in September the first set of batteries arrived while the work on the CAMPBELL FOSS was proceeding. Foss finished the modifications to the CAMPBELL FOSS in October, installed the batteries and began testing of the newly reconfigured system.

During this testing, the team found that the batteries could be charged and discharged at high rates with excellent results when the vessel was not moving. Unfortunately, as soon as the vessel's motor generators on the shafts were energized, the resulting electro-magnetic interference (EMI) caused the battery system communications to shut down, causing the breakers to open and the batteries to stop charging as a fail-safe mechanism. Consequently, Foss returned the vessel to normal service in its original diesel configuration and pulled the CAROLYN DOROTHY back out of service to finish installing the batteries and begin commissioning.

After completion of the installation of the batteries and ancillary systems on the CAROLYN DOROTHY, the hybrid system was tested. On the CAROLYN DOROTHY, the EMI was found to be much less than on the CAMPBELL FOSS and allowed the batteries to properly communicate and operate while in hybrid propulsion mode. However, AKA had difficulties getting the hybrid system to integrate both strings of batteries into the system as required. It was determined that 12 batteries supplied by EST for the CAROLYN DOROTHY were defective as well as four of the ten batteries for the CAMPBELL FOSS.

Consequently, EST removed and tested all the batteries from both vessels at the end of January 2016. The defective batteries were rebuilt by EST on site at the Foss location in Long Beach. The rebuilt batteries were re-installed on both vessels during the first week of February 2016. During this same time the DC/DC converters on the CAROLYN DOROTHY were replaced by AKA in order to solve the system integration issues.

After the repairs were accomplished, both vessels underwent Foss acceptance testing and sea trials. The CAROLYN DOROTHY was returned to full hybrid status with all batteries functioning and integrated into the system on February 8, 2016 and the CAMPBELL was accepted and returned to full hybrid status on February 16, 2016.

Design

Design for this project was broken into two portions, "Battery Design" and "Vessel Modification". Descriptions of what each portion entailed are below. In general, AKA was responsible for the Battery Design, with input from EST and review by Foss. The Vessel Modification design was done by EBDG based on physical requirements of the battery components and ancillary equipment.

Battery Design—

This task covered the hardware and software modifications and additional equipment required to modify the existing hybrid system of both vessels to integrate the controls, monitoring and power specifications of the new batteries. This portion of the Hybrid Design was accomplished by AKA.

In addition to supplying the new lithium polymer batteries, EST also provided the hardware and software design for monitoring and controlling the batteries, as well as the physical boxes where the batteries are housed and the interconnecting power and communications cables. They worked with AKA to determine the interfaces between the two systems (hybrid energy management system (EMS) and battery management system (BMS)) and provided direction during the installation.

Vessel Modifications—

This task covered the design of the modifications required to the existing boats' structural, mechanical and electrical systems to accommodate the new battery compartments. EBDG was hired to provide the structural design and perform all necessary structural, stability and heating load calculations.

Foss and EBDG agreed that the stern void directly aft of the engine room provided the best and safest location. The stern void was chosen because, of its size, its separation from normal working areas, and its proximity to the stern of the vessel. New vents were installed at the stern to prevent harm to personnel should a battery catch fire or explode.

The vessel modifications include:

- Installation of bulkheads, inserts, structure and doors to create the new battery compartments
- Installation of rupture discs between the battery compartment and the adjacent void, and the void and the exterior of the boat. In the event of a battery explosion, these discs would blow out at a low pressure to allow the escaping gasses to expand without damaging the structure of the compartment
- Installation of air conditioning and air handling units to keep the compartments cooled to approximately 65F
- Installation of FM200 fire suppression systems to smother any potential battery fires
- Containment boxes in stern bulwarks to direct any potential flame ball or hot escaping gasses out the stern of the vessel and away from personnel.
- Insulation of new battery compartment surfaces.

Design Challenges—

Other than typical challenges associated with designing vessel modifications, the design portion of this project went smoothly with no exceptional challenges or issues. There were a few obstacles however that bear mentioning in this report:

- Quantity of Batteries—
    - The total quantity of batteries required by the CAMPBELL FOSS was not an issue – the team simply replaced the quantity of Corvus batteries (the batteries which were installed on the CAMPBELL FOSS when the fire occurred) with the same number of EST batteries, to achieve essentially the same power and energy. As CAMPBELL FOSS does not use batteries for rapid bursts of energy as the CAROLYN DOROTHY does, there was less risk in simply replacing the old batteries with the new.

Photo: Batteries installed in CAMPBELL FOSS

- On the CAROLYN DOROTHY, batteries are needed for providing top-end power to the propellers, which requires rapid draw down of many batteries to supply the needed power. The vessel is required to have a minimum of 60 tons of bollard pull which meant

batteries were needed to supply supplemental power due to the smaller size of the vessel's main diesel engines. The team then needed to decide on a battery configuration to ensure the required power could be supplied to the hybrid system in the time frame needed without exceeding the current capacity of the cables and power sharing equipment. The other consideration on battery quantity was the physical space available to house them – more batteries require more space, and these Dolphin class tugs are small to begin with.

In the end, the team settled on (28) total batteries, provided in two separate strings of (14) batteries each. This allows the batteries to supply over 400 additional horsepower

to the hybrid system without overloading the equipment and cables.

Photo: CAROLYN DOROTHY battery compartment

- Tonnage Requirements—
    - A vessel "Registered tonnage" (GRT) is a way of measuring the cargo capacity of a vessel. The USCG requires certain crew manning and levels of safety depending on the vessel's registered tonnage. Both the CAMPBELL FOSS and CAROLYN DOROTHY are designed and crewed to have registered tonnage of less than 150 GRT – if the tonnage measurements show the boat could exceed 150 GRT, additional modifications and crew would be required.

      The aft void spaces in which Foss planned to put the battery compartments are exempted from tonnage calculations. Before this modification, both vessels had GRTs in the 144-145 range. However, adding battery compartments to these aft voids reduces the exempted amount, thereby increasing the vessel's tonnage. EBDG had to create battery compartments on both vessels that not only could fit the required number of batteries, but also NOT reduce the volume in the aft void tanks to the point where the calculated tonnage exceeded 150 GRT. In the end, both vessels stayed below 150 GRT.
- Battery Delivery Method—
    - The original schedule for the project anticipated being able to ship the lithium-polymer batteries via air freight, with batteries available overnight if need be (in addition to clearing US Customs). Foss had received a quote from EST's freight forwarder that provided this option. However, in May of 2015, commercial airlines put restrictions on transporting lithium polymer batteries through the air, and the quantity of batteries required for this project exceeded the allowable. As a result, EST had to ship the batteries via commercial shipping, which increased delivery time for the batteries by approximately six weeks. This had a ripple effect through the schedule as the first batteries could not arrive until mid August.

Construction

Foss performed the modification work on both vessels at the Foss berth on Pier D in the Port of Long Beach. Foss hired Biltmore Metal Fabricators (BMF) to perform the structural and system modifications to the vessels, in accordance with the design drawings created by EBDG. Foss hired DeMaria Electrical to pull the required electrical cables for the hybrid and battery systems, in accordance with electrical one-line drawings and cable lists supplied by AKA and EST.

Modifications to the CAROLYN DOROTHY occurred first, starting in mid May and ending in late July. Modifications to the CAMPBELL FOSS took place in September, ending in early October. The scope of work on the CAMPBELL FOSS was significantly less than on the CAROLYN DOROTHY due to the lower number of batteries. This combined with the learning curve realized by BMF and DeMaria allowed for a more efficient construction period and lower project costs.

Construction Challenges

Similar to the Design phase of the project, the construction of the vessel modifications proceeded as planned, without any major issues or challenges. The confined working area in the stern void was a challenge for BMF to gain access to all required areas for welding and painting, and there were some layout and minor structural issues that came up during the course of the modifications, but nothing particularly difficult or challenging.

Photo: Rupture disc on CAMPBELL FOSS

Testing and Commissioning

CAMPBELL FOSS-

After completion of the modifications to the vessel and installation of the batteries, the team began commissioning the battery system. EST technicians arrived onsite and performed the initial system checks and start-up protocols, working with AKA technicians to confirm that all communications and alarms were being properly transmitted to the energy management system. All systems checked out fine; the team confirmed all alarms and shutdowns were functioning properly, and then began using the batteries to supply power to the vessel's non-propulsive electrical needs (e.g., ventilation fans, AC units,

lights and the bow winch). The team also confirmed the batteries could be charged from either a shore power connection or the boat's diesel generator. All operations went according to plan.

The next step consisted of using the batteries to start turning the propulsion shafts. However, as soon as the team tried this the internal battery communications became erratic and unreliable and the batteries shut down. One of the safety features of the EST control system is a requirement that the batteries communicate with the system software on a nearly continuous basis. If the communications are dropped or interrupted for even a short period of time, the physical contactors to the batteries open. While the contactors are open the batteries are effectively shut down and are isolated from the rest of the hybrid system components. This is an important fail-safe for the system and this testing proved that the fail-safe was working correctly.

Investigation into the cause of this communications failure showed very high levels of electromagnetic interference (EMI) when the motor generators on the shafts were energized electrically, which caused the battery communications to become erratic. The team took a two-pronged approach to address this issue – (1) reduce the level of EMI developed by the power converting equipment (the variable frequency drives and the DC/DC converter), and (2) insulate the battery communications to make them less susceptible to the EMI. These solutions were implemented by both AKA and EST which resulted in solving the problem.

After the defective batteries on the CAMPBELL were replaced, the vessel successfully completed sea trials and acceptance testing on February 16, 2016.

CAROLYN DOROTHY—

Like the CAMPBELL FOSS, the EST technicians boarded the boat after the batteries were installed and hooked up and performed the initial system checks and start-up protocols. They worked with AKA to establish proper communications between the systems and tested all alarms and shutdowns. The team has confirmed proper operation of the batteries with the hybrid system, ensuring the batteries would support the vessel's electrical loads and that the batteries could in turn be recharged from the hybrid system.

The team also found that the CAROLYN DOROTHY did not have the same problem with EMI that the CAMPBELL FOSS did and that the batteries could be used to turn both shafts with no loss of communications. However, during this testing AKA found some issues with the DC/DC converters. These converters on the CAROLYN DOROTHY were replaced in February 2016 and the vessel successfully completed acceptance testing and sea trials on February 8, 2016.

Emissions Testing

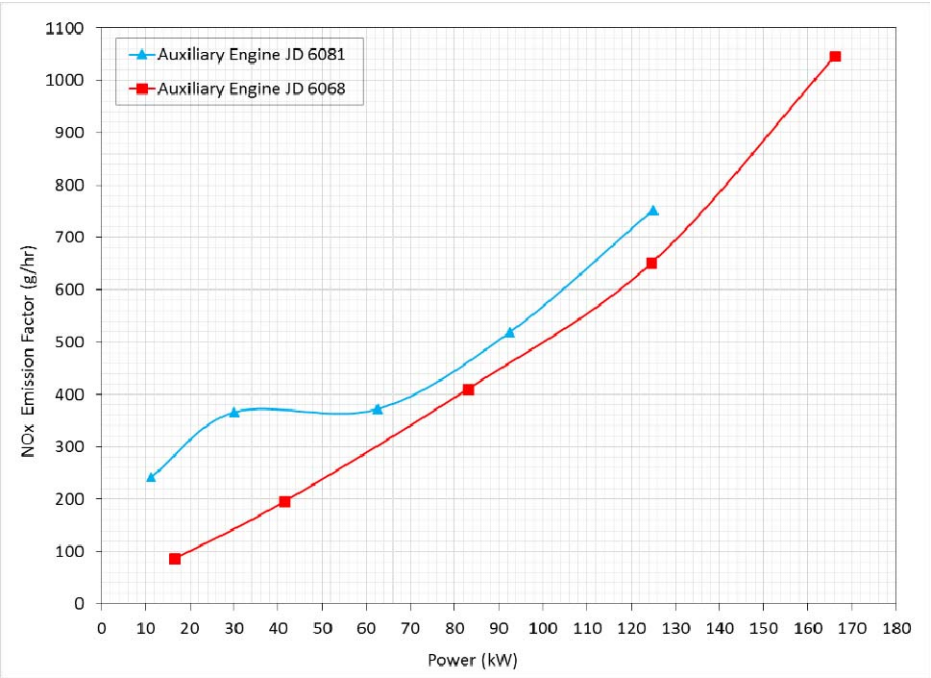
Concurrent with the physical conversion project, the University of California, Riverside (UCR) undertook a project to quantify the emissions benefit of repowering one of the auxiliary engines on the CAMPBELL FOSS from Tier 2 to Tier 3. (Attachment 2) UCR completed the original emissions testing of the CAMPBELL FOSS when it was converted from a conventional to hybrid configuration.

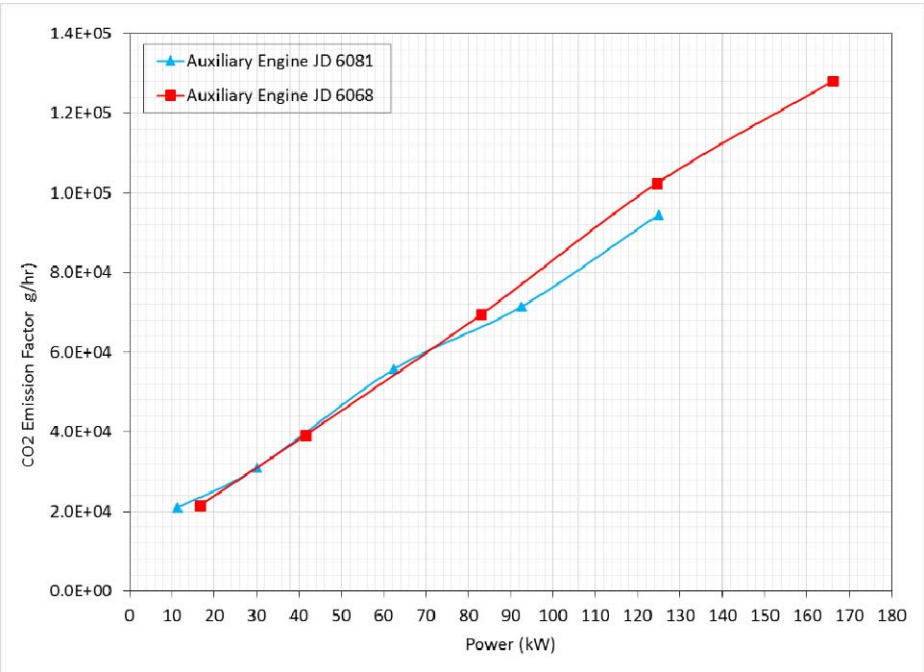
In the intervening years between the original conversion and the current project, Foss replaced the John Deere model 6081 auxiliary engine meeting EPA Tier 2 standards with a John Deere model 6068 auxiliary engine meeting EPA Tier 3 standards. The John Deere 6081 engine was rated at 125kW (168 hp) and was replaced by a John Deere 6068 rated at 166kW (223 hp) so there was more power in the replacement engine than the originally installed engine. The purpose of the UCR study was to quantify the emissions benefit as a result of the repowering.

Photo: John Deere 6068 Tier 3 engine

The emissions rates in grams per hour as a function of the engine load for both NOx and CO2 are shown in the graphs below. As expected, the NOx output for the Tier 3 engine (model 6068) is less than the Tier

2 model 6081 engine while the CO2 rates were essentially the same. Similar charts are not included in this report for $PM_{2.5}$ emissions because of the confidential nature of the data. The $PM_{2.5}$ emissions factors were measured in previous UCR projects for the model 6081 engine and the data for the model 6068 engine was obtained from John Deere. However, this $PM_{2.5}$ emissions data is considered business confidential by John Deere so only the overall factors are included in the UCR report.





UCR followed the same methodology established in the emissions studies done for both the CAROLYN DOROTHY and CAMPBELL FOSS. The activity profiles were calculated from these previous two studies and emission factors were calculated at specific load points. This analysis then combined engine histogram and emission profile data to determine the in-use emissions for the CAMPBELL FOSS with the higher tier engine.

As expected, the study showed that the majority of the emissions benefits are realized when a conventional tug is converted to hybrid operations. The repowering to a higher EPA tier rating showed minimal overall improvement in emission benefit. The chart below shows the percentage reduction of NOx, and $PM_{2.5}$ when compared to a conventional tug configuration, reductions with a Tier 2 engine and reductions with the Tier 3 engine. Because the conversion from Tier 2 to a Tier 3 auxiliary engine did not impact fuel consumption, the CO2 reduction remained the same when comparing the Tier 2 and Tier 3 results.

	Conventional Tug Configuration	Hybrid Tug with Tier 2 Auxiliary Engine	Hybrid Tug with Tier 3 Auxiliary Engine
NOx (g/hr)	3773	2433	2418
% NOx reductions		35.51%	35.91%
$PM_{2.5}$ (g/hr)	36.80	19.47	17.81
% $PM_{2.5}$ reductions		47.10%	51.61%
CO2 (kg/hr)	233.77	140.45	140.44
% CO2 reductions		39.92%	39.92%

Another way to look at this data is in terms of absolute emissions reductions on a tons per year (tpy) basis. Based on the assumption of 8,000 operating hours per year, the NOx reduction from the conversion of a conventional tug configuration to hybrid is 11.8 tpy and for repowering the hybrid tug configuration to a Tier 3 auxiliary engine, the additional reduction is 0.13 tpy.

For $PM_{2.5}$, the reduction through conversion from conventional to hybrid is 0.15 tpy and the additional reduction through the Tier 2 to Tier 3 auxiliary engine replacement resulted in an additional 0.015 tpy reduction.

Financial Results

The EBDG Risk Analysis report provided a rough order of magnitude (ROM) estimate for this project of $870,000 for using EST batteries and creating a battery compartment in the stern void. When Foss looked at the actual expected costs associated with implementing this project as the design progressed, that figure rose substantially based on actual quotes received from AKA, EST and EBDG for their services and materials, and Foss experience with performing this type of work on these vessels at the Foss berth in Long Beach. Foss is estimating the final cost of the project to be just over $1,500,000 with over 95% of these funds spent to date.

Schedule

The original proposed schedule had this project complete in August of 2015, with the final report delivered to MARAD in September of 2015. Due to a variety of circumstances and events both within and outside of Foss' control, Foss requested an extension for submittal of the final report. The following is a summary of the extenuating circumstances and delays that caused the need for this extension:

- Fire to CAROLYN DOROTHY's starboard diesel generator destroyed a large portion of the existing hybrid system and cabling, requiring months of rework. The fire occurred in March, just before Foss was planning to take the CAMPBELL FOSS out of service to begin the modifications on that vessel. With the fire, Foss rearranged the schedule to do the modifications on the CAROLYN DOROTHY first while the vessel was out of service for the fire repairs. The repairs were not completed until the end of July

- The delivery of the batteries was delayed by approximately six weeks due to changes to commercial airline policy regarding shipping lithium polymer batteries via air freight. Foss and EST had established that air freight was allowed at the beginning of the project and based the schedule on that fact; however, in May when the batteries were ready to be shipped, the policy change took effect requiring the batteries to be shipped via ocean freight.

- Repair work on other Foss vessels in the Long Beach harbor during the month of August required both the CAROLYN DOROTHY and the CAMPBELL FOSS to be working to meet the needs of Foss' customer base. This created an unplanned month of no modification work in the middle of doing the modifications.

- Testing and commissioning difficulties due to EMI and hardware and software glitches at the end of the project on both vessels delayed final testing and sea trials until February 2016.

Task Summary

This section provides a description of the work performed on the major individual tasks outlined in the project scope:

Perform Risk Assessment of Reinstallation of Batteries

Description of Actions Performed:

Foss hired Elliott Bay Design Group (EBDG), a well-known naval architecture and marine engineering firm in Seattle, to perform a risk assessment on reinstalling batteries on the two Foss hybrid boats, CAMPBELL FOSS and CAROLYN DOROTHY. The result of this study is the "CAMPBELL FOSS & CAROLYN DOROTHY Hybrid Tug Battery Reinstallation Risk Assessment Report", attached to this report as Attachment (1).

During the study, EBDG reviewed the events that led to the battery fire on the CAMPBELL FOSS in 2012, and analyzed the risks associated with reinstalling batteries on the hybrid boats as well as the commercial, financial and operational risks of NOT reinstalling batteries on the boats.

The result of their analysis is a recommendation to reinstall batteries on the boats, but in separate, environmentally-controlled compartments in the stern voids of the boats with proper explosion prevention and mitigation safeguards in place.

This report formed the basis for design and construction of the new battery compartments and purchase of the new batteries and control systems.

Redesign of Compartments and Systems

Description of Actions Performed:

1. Battery Compartments, Venting Containment, and Fire Protection Systems—
    - Subsequent to the risk analysis, Foss hired EBDG to perform the necessary structural and system design to create a separate compartment for the new batteries. The design includes the following features to enhance the safety and correct operations of the batteries:
        - Ventilation system terminating in confined compartments in stern bulkwark to direct any potential flame or explosive gasses away from personnel to a safe location
        - Rupture discs in battery compartment bulkheads and stern void to immediately release potential explosion gasses into the adjacent void and out the stern bulwark and prevent structural damage
        - Dual air conditioning systems to maintain battery compartment temperature at 68F for optimal battery life and operation
        - Structural insulation to help maintain battery compartment temperature and to protect adjacent deck and spaces from extreme heat in the event of a fire

        - Vibration isolated battery racks to protect batteries from hull-borne vibrations and vessel impacts
        - FM200 fire suppression system to smother any potential fire. Can be energized manually from one of two pull stations or automatically from heat and smoke sensors installed in the compartment
    - In addition to designing the modifications and systems required to be performed on the boats, EBDG also performed stability and tonnage calculations and reviews to make sure that the vessels continued to operate within the original requirements of the vessels prior to modification. These studies confirmed that the vessels would only be minimally impacted by the modifications from a stability and tonnage perspective, and these impacts would not affect vessel operational or regulatory parameters.
2. Battery Control System
    - Based on the recommendations of the Risk Analysis Report, Foss and AKA selected EST headquartered in the Netherlands to provide the batteries and the battery control system. The EST batteries use the same lithium-polymer chemistry and cells provided by Kokum in Korea as the batteries supplied by Corvus Energy, who supplied the batteries that failed on the CAMPBELL FOSS. However, the EST series cell configuration and controls methodology are more straight forward and safer than those that Corvus had in place at the time of the fire, and are in compliance with the recommendations of the Risk Analysis.
    - Having selected EST to supply the batteries, Foss and AKA attended factory testing in the Netherlands to gain assurance that the batteries and control/alarm/communications systems hardware and software designed by EST would be compatible with the AKA-supplied energy management system, and meet the safety requirements of the Risk Analysis Report. After this testing, all parties agreed that the batteries and control systems would perform as desired.
    - The EST batteries are type-approved by Lloyds Register and DNV. As part of the Class approval process, EST hired KEMA, an outside laboratory, to vet the batteries and controls for safety, durability and operation.

Develop and Award Shipyard Contracts for Modifications

Description of Actions Performed:

For this task, Foss contracted with Biltmore Metal Fabricators (BMF) in Long Beach to provide the labor and materials to perform the required vessel modifications. All modifications were performed pier-side at Foss' facility at Berth 49 on Pier D, Long Beach CA. Prior to awarding the work to BMF, Foss reviewed the EBDG drawings with BMF and a competitor, Oceanwide Construction, to obtain pricing quotes. Foss has extensive experience working with both vendors, and was confident that either could perform the work in the time allotted. In the end, BMF provided a lower cost estimate to perform, and Foss selected them as the main contractor on this project.

Foss issued a purchase order on May 15, 2015 BMF to perform the modification work in accordance with the EBDG drawings.

CAMPBELL FOSS Shipyard Period

Description of Actions Performed:

The original schedule called for the CAMPBELL FOSS to be the first boat modified. However, in March of 2015, the CAROLYN DOROTHY suffered a major failure of one of the diesel generators, causing a fire in the engine room that required extensive repair and rework of the hybrid electrical systems. Since this put the CAROLYN DOROTHY out of operation for an extended period, Foss chose to proceed with the modifications to the CAROLYN DOROTHY first.

As a result of switching the order of the modifications, as well as operational constraints that required both boats to be in service for the month of August, modifications to the CAMPBELL FOSS did not begin until September 4, 2015. Modifications were completed one month later, on October 13, 2015

CAROLYN DOROTHY Shipyard Period

Description of Actions Performed:

CAROLYN DOROTHY modifications were started before the CAMPBELL FOSS due to a fire on the starboard diesel generator. Modifications began on the CAROLYN DOROTHY in mid May, 2015, and were completed in the end of July 2015.

The CAROLYN DOROTHY had significantly more work to be done compared to the CAMPBELL FOSS, due to the boat receiving 18 more batteries than the CAMPBELL FOSS. Additionally, the work had to be done in coordination with the ongoing repair work required by the generator fire. These challenges caused the duration of the modifications to be longer than originally anticipated.

Due to an operational requirement that both the CAMPBELL FOSS and the CAROLYN DOROTHY be performing ship assist services in the harbor for the month of August, the CAROLYN DOROTHY was put back in service at the end of July without batteries. CAROLYN DOROTHY was then pulled back out of service for final commissioning and testing after the CAMPBELL FOSS modifications and testing were complete, in early November 2015.

Delivery Acceptance Testing – CAMPBELL FOSS

Description of Actions Performed:

Once the batteries were installed and commissioned, the Foss/AKA/EST team began testing of the hybrid system in concert with the battery system. Initial testing went very well, with the hybrid system able to charge and discharge the batteries as needed depending on the vessel's non-propulsive electrical requirements. However, once the team went to the next step and attempted to turn the propellers using electricity from the hybrid system, the battery control system lost communications with the batteries and caused that system to shut down as a fail-safe mechanism. The subsequent investigation into why this happened revealed significant sources of electromagnetic interference (EMI) on the vessel that distorted the communications signals of the battery management system when the shafts are turned via the hybrid system.

Foss, AKA and EST solved this problem, by both reducing the amount of EMI created by the hybrid system as well as shielding the battery communications systems to make them less susceptible to EMI distortion.

Delivery Acceptance Testing – CAROLYN DOROTHY

Description of Actions Performed:

Once the CAROLYN DOROTHY's batteries were commissioned by EST, Foss, EST and AKA began testing of the hybrid system with support from the battery system. In this case, the team did NOT see the same level of EMI that exists on the CAMPBELL FOSS, and in fact was able to run the vessel's propellers using power from the batteries as intended. However, several other hardware issues occurred during this testing, including problems with the DC/DC converters that caused one of the battery strings to stop working after approximately one hour.

During troubleshooting in December 2015, it was determined that several of the batteries in both vessels were defective. All batteries were removed from both vessels and tested in January 2016. The defective batteries were rebuilt and re-installed on the vessels in early February 2016 and the DC/DC converters were replaced in the CAROLYN DOROTHY. After completion of the battery reinstallation, both vessels successfully completed acceptance testing and sea trials and were returned to full hybrid service in mid-February 2016.

Closing Note

Foss thanks MARAD for helping to offset the cost of this project. The Foss hybrid tugs need to have batteries to allow them to live up to their full potential as industry-leading examples of how environmentally friendly concepts like fuel savings and emissions reductions can exist in full synergy with business-friendly concepts like reduced operating and maintenance costs. Foss fully believes that this technology is on the cusp of becoming widespread, and is proud to have been at the tip of this revolution.

Although this project took somewhat longer than originally anticipated, it resulted in a successful conclusion. Both the CAROLYN DOROTHY and the CAMPBELL FOSS are operating in San Pedro harbor in full hybrid mode with batteries functioning and fully integrated into the system. These hybrid vessels continue to show a significant reduction in emissions compared with the conventional tugs operating in this same harbor.

CAMPBELL FOSS & CAROLYN DOROTHY

Hybrid Battery Reinstallation Risk Assessment Report

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EXECUTIVE SUMMARY

This report summarizes and analyzes the risks associated with reinstalling batteries, or not reinstalling batteries onboard the hybrid tug boats, CAMPBELL FOSS and CAROLYN DOROTHY.

To reinstall lithium-polymer batteries in a safe manner, it is necessary to reexamine the safety features of the battery management system, to increase the safety and capability of the ventilation system, and to improve the structure of the battery compartment. The key decisions that must be made to proceed with reinstalling batteries are whether or not to move the battery compartment outside of the engine room, and to select a battery manufacturer.

Two alternative battery compartment locations are examined, the stern void/ballast space and the deck locker. Moving the battery compartment to the stern compartment significantly increases safety, and simplifies the engineering of the ventilation system. The deck locker offers an easier location to access and install batteries compared to the stern void/ballast space. However, this location complicates the engineering of the ventilation system. The cost of this project is also dependent on the selection of a battery manufacturer. Manufacturer selection requires addressing technical, financial, and schedule concerns.

There is also the alternative of not reinstalling the batteries, and if not, how to move forward with improving the reliability of these vessels. For the CAMPBELL FOSS, restoring hybrid mode without reinstalling batteries, also known as diesel electric drive, may be a viable option. However, the increased operational expenses must be considered.

For the CAROLYN DOROTHY, continuing operations as a non-hybrid tug is much less of an option because of the reduced bollard pull capacity. Restoring this capacity through larger generators is possible but may be prohibitively expensive. It is also important to remember that not reinstalling batteries will have a negative public perception, although the consequence of this is difficult to quantify.

The recommended solution to most effectively mitigate the risk of another battery compartment fire is the reinstallation of lithium batteries in the stern void/ballast compartments of the subject vessels. While this option is the safest solution, it also represents significant labor hours of work and schedule risks.

1 PURPOSE

The purpose of this report is to summarize and analyze the risks associated with reinstalling batteries as well as leaving the batteries out in order to assist Foss Maritime Company in determining a path forward on improving the reliability of their hybrid tugs. Additionally, rough order of magnitude cost estimates are provided for the options presented.

2 BACKGROUND

Both vessels are Dolphin Class tug boats that operate as part of the San Pedro harbor tug fleet. Their principle characteristics are summarized below in Table 1.

Table 1. Principle Characteristics

	CAMPBELL FOSS	**CAROLYN DOROTHY**
Length (ft)	78	78
Beam (ft)	34	34
Draft (ft)	14	12.4
Gross Tonnage	144	145
Power (BHP)	5080	5000

The CAMPBELL FOSS was constructed as a conventional tug boat in 2005; she was converted to a hybrid vessel in 2011 after the success of the new build hybrid, CAROLYN DOROTHY in 2008. Many lessons from the CAROLYN DOROTHY were applied to the conversion of the CAMPBELL FOSS resulting in slightly different hybrid systems. Both hybrid systems were designed by Aspin Kemp and Associates (AKA).

The CAROLYN DOROTHY was equipped with an array of 126 lead-acid batteries. Smaller engines rated at 1800 HP were installed compared to conventional Dolphin Class tugs because of the multiple power sources available in a hybrid system. Instead of lead-acid batteries, 10 lithium-polymer batteries were used for the CAMPBELL FOSS. Lithium-polymer batteries have many advantages over lead-acid batteries. They have less weight, lower internal resistance, higher energy capacity, and lower heat generation. The CAMPBELL FOSS retained its original engines rated at 2540 HP. Unlike the CAROLYN DOROTHY, the CAMPBELL FOSS can run in hybrid or non-hybrid modes without a loss of bollard pull. A full description of the CAMPBELL FOSS conversion is available in Reference [1].

On August 20th, 2012, lithium battery module #9 exploded onboard the CAMPBELL FOSS causing a battery compartment and subsequent engine room fire as described in Reference [2]. Although no one was injured, the vessel was out of service for three months for extensive forensic investigation and repair.

The lead-acid batteries onboard the CAROLYN DOROTHY were removed around this time because of reliability and safety issues that involved one minor fire in the monitoring circuitry, many battery failures, and battery operating system failures.

Currently, the CAMPBELL FOSS operates as a non-hybrid tug, and the CAROLYN DOROTHY operates as a hybrid tug without a battery array. Currently, they are the two least efficient vessels in the Dolphin Class.

The CAROLYN DOROTHY is the highest consumer of fuel of any Dolphin class tug because the original design required two main engines and two generators to be running for all ship assists, with or without batteries. The CAROLYN DOROTHY's operations are limited because of reliability concerns. Because of the smaller main engines onboard, the official bollard pull was reduced to 53 tons from 63 tons. She also suffers from a lack of electrical stability in the electric drive system.

The CAMPBELL FOSS is currently required to start a standby generator during all ship work because of the lack of batteries. Attempts were made to return the CAMPBELL FOSS to diesel electric drive without batteries; however, incomplete inspections of mechanical hardware post fire lead to many component failures. This includes a major arcing event in the LCL filter, as well as failure of the active front end (AFE) and line contactor. The vessel is ready to return to hybrid operations without batteries with only a system inspection and sea trials but this has yet to be accomplished.

The long term goal of this undertaking is to restore reliability and confidence in the vessels to crews, customers, and upper management.

3 PROCEDURE

The following sections summarize and address project risks and mitigation actions identified at the Risk Identification Meeting that was held on October 30th, 2014. This meeting was attended by stakeholders from Elliott Bay Design Group (EBDG), Foss Maritime Company, and AKA. The minutes from this meeting were made available as Reference [3]. The goals of this meeting were to brain storm and identify risks associated with the reinstallation of lithium batteries, characterize the impacts and probabilities, and develop mitigating actions.

EBDG developed a risk matrix based on comments from this meeting and assigned probability and impacts in accordance with Figure 1. These scores were assigned using the Delphi method. Each stakeholder at EBDG independently assigned probability and impact values. The results were averaged, and a discussion of the scores allowed stakeholders to revise results, converging towards an accurate estimate. The final probability (P), impact (I) and score (S) values are listed following each risk title.

Probability				
5	5	15	25	5 = High
3	3	9	15	3 = Medium
1	1	3	5	1 = Low
	1	3	5	
	Impact			

Figure 1. Risk Probability and Impact Matrix

The completed risk matrix was circulated through the stakeholders at Foss Maritime Company for review and comments. This ensured a clear and common understanding of the risks and mitigation actions.

In this report each risk will be elaborated upon and the identified mitigation actions will be discussed. The final risk matrix is included in Appendix A. The discussion of mitigating actions indicates a few possibilities. A discussion of the decisions that need to be made, and the rough order of magnitude cost estimates for the various solutions are included in Section 7.

The organization of the risks and mitigating actions is as follows. Section 4 summarizes regulatory concerns and limitations that must be considered if the project moves forward. Section 5 addresses risks associated with reinstalling batteries. Section 6 addresses risks associated with not reinstalling batteries.

4 REGULATORY COMPLIANCE

Uninspected towing vessels (UTVs) will soon be regulated by 46 CFR Subchapter M, which has different requirements for existing and new build vessels. Subchapter M was scheduled to be finalized by early 2014 (Reference [4]), but this has yet to be accomplished by the USCG. With the exception of stability, the upcoming regulations for existing vessels pose no conflict with reinstalling batteries. This being said, "major conversions" that can be defined as substantial changes in dimensions, carrying capacity, type of vessel or otherwise prolonged life must be avoided for the vessels to be considered existing vessels. Otherwise, the two regulatory concerns involve change in tonnage and intact stability characteristics.

4.1 Tonnage

(P=1, I=4, S=4)

Tonnage is a measurement of the internal volume of the vessel. It is important to distinguish between gross tonnage (GT) and regulatory tonnage (GRT).

GT was defined by the International Maritime Organization (IMO) through *The International Convention of Tonnage Measurement of Ships, 1969*. Gross tonnage is calculated based on the moulded volume of all enclosed spaces of the ship, and replaced what was known as gross

register tonnage that was a measure of the volume of certain enclosed spaces. This introduced a universal tonnage measurement system.

Gross register tonnage still exists in the United States for domestic purposes as regulatory tonnage. GRT can be used for vessels that do not engage in international voyages, such as most tug boats.

Where GT is a unitless value, GRT is calculated in units of 100 cubic feet per ton. Generally speaking GT values are greater than GRT values, but there is no conversion factor. The regulatory limits associated with tonnage are the following.

- 46 CFR 15.701
  For the vessels to remain uninspected towing vessels operating in near coastal or ocean routes the maximum allowable tonnage is 199.99 GRT.

- 46 CFR Subchapter E
  For the vessels to remain exempt from load-lines, the maximum allowable tonnage is 150 GT.

Currently the CAMPBELL FOSS has a GT of 144, and the CAROLYN DOROTHY has a GT of 145. As long as the principle dimensions of the vessels do not increase, tonnage regulations should not be a concern.

4.2 Stability

(P=1, I=2, S=2)

The applicable stability criteria from 46 CFR Subchapter M section 144.315 are summarized below.

- Each existing towing vessel operating under a previously issued stability document must continue to operate in accordance with the conditions specified therein.

- A weight and moment history of changes to the vessel will need to be maintained. When the aggregate weight change is more than 2 percent of the vessel's approved light ship displacement, or the recalculated light ship LCG is more than 1 percent of its length between perpendiculars a deadweight survey must be performed.

- If the aggregate weight change is more than 10 percent of the approved light ship displacement, or if the deadweight survey results are more than 1 percent off from the recalculated light ship displacement and LCG, a full stability test in accordance with 46 CFR Part 170 Subpart F will be required.

- The cognizant Officer in Charge, Marine Inspection may restrict the route of an existing towing vessel based on concerns for the vessel's stability.

The CAROLYN DOROTHY's stability document (Reference [4]) shows that the vessel was designed to 46 CFR 174.145 Intact Stability Requirements, 170.170 Weather Criteria, and

173.095 Towline Pull Criterion. Because the vessels are UTV's they are technically exempt from 174.145 Intact Stability Requirements. However, it will be necessary to demonstrate continued compliance with 174.145 as stated by the first bullet point above.

Consequently, the vessels stability must be reanalyzed early during the Contract Design Phase to account for each of the following mitigating actions that will affect the vessels weight and centers. The most restrictive requirement will be related to downflooding points where special attention must be paid to the location of the battery compartment venting system (Section 5.7.2).

5 RISKS ASSOCIATED WITH REINSTALLING BATTERIES

The following risks associated with battery reinstallation are organized by risk category in sequential order as shown in Figure 2.

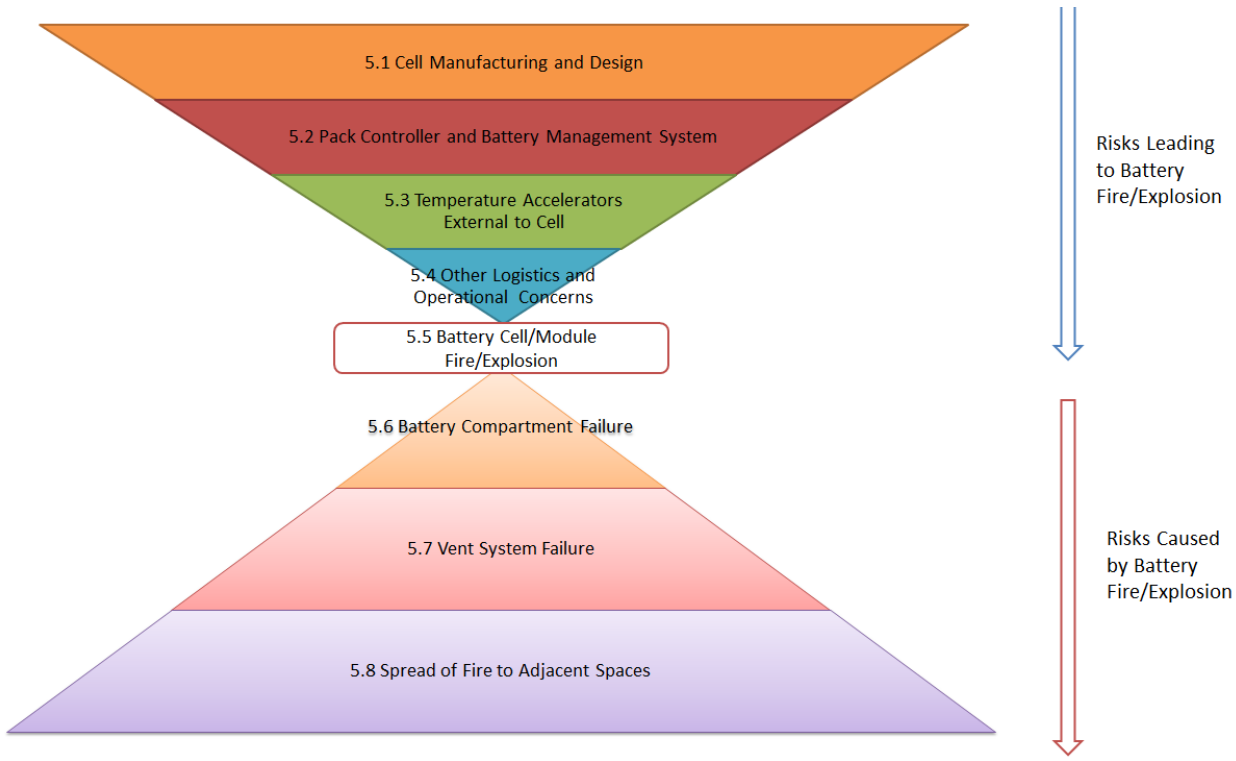

Figure 2. Organization of Battery Reinstallation Risks

A summary of the risks and mitigating actions are available as a risk matrix in Appendix A. The interdependent relationships of the individual risks are shown in a risk schematic that is included in Appendix B.

5.1 Cell Manufacturing and Design

5.1.1 Cell Manufacturing Defect

(P=1, I=5, S=5)

The Boeing 787 Dreamliner uses several types of lithium-ion batteries, and has experienced two battery fires in two separate incidents. The investigation of the failing lithium-ion batteries (Reference [5]) revealed the root cause as an internal short circuit within the cell caused by microscopic contamination. Weeks and months of charge and discharge cycles slowly broke down these impurities to form a metallic dendrite which caused a short circuit in the cell that lead to a thermal run away.

The lithium-ion batteries used by Boeing and lithium-polymer batteries that will be used onboard the subject vessels have some technical differences, but the risks of a cell manufacturing defect and the consequences remain the same.

There is no way to completely mitigate the risk of a manufacturing defect. Cell design and manufacturing processes are beyond the control of battery purchasers. A cell may be well designed, but it is only as reliable as the factory's manufacturing process and practices. While post manufacturing inspections such as a CT scan can further decreases the chances of a defective cell, this is still not a full proof method as the Boeing incident demonstrates (Reference [6]).

To mitigate this risk as much as possible the batteries should be purchased from a well-established and type approved battery manufacture. Shipboard batteries require regulatory approval, if the batteries have ABS approval for example, it can be assumed that the manufacturer is well-established.

5.1.2 Series vs Parallel Cell Arrangement

(P=2, I=2, S=4)

AKA has recommended two battery manufacturers for consideration, Corvus Energy and Energy Storage Technologies (EST). Corvus Energy is the same brand as previously used onboard the CAMPBELL FOSS. EST is a manufacturer that AKA is working with for a different project.

Both manufacturers use cells produced by Dow Kokam in Korea, and assemble them into battery modules. Corvus Energy uses parallel connections for the cells while EST does not connect the cells in parallel. Measuring the voltage across parallel cells means measuring the voltage of a group of cells, where the loss of voltage indicated by a failed cell will be masked by the voltage of the remaining cells. This is a risk because the module will suffer from reduced capacity, and a failed cell may eventually explode without a warning from a low/high voltage reading. When cells are connected in series, it is impossible for a failed cell to remain undetected.

Another issue related to parallel and series connections is cell balancing. Because of production tolerances, there will be uneven temperature distribution and differences in ageing characteristics of particular cells. The weaker cell with decreased capacity will be overcharged until the rest of the chain reaches full charge. Charging and discharging cycles will weaken degraded cells in a series until the battery fails. This is less of an issue for parallel cells that will self-balance, because parallel connections hold all cells at the same voltage.

To address this issue EST batteries are equipped with active cell equalization which balances the cells even if the battery is charging or discharging. The Corvus Energy battery requires a rest

from charging and discharging to allow the cells to balance. AKA considers both systems to have effective cell balancing technology.

From a technical perspective, the EST batteries offer advantages, however, the batteries still must be vetted by AKA. Battery selection has other considerations that need to be addressed as discussed in section 5.4.3 and 5.4.4. If Corvus Energy batteries are selected, the battery management system (BMS) should perform independent calculations of bank voltage that can be compared and verified against the hybrid control system. The contactors should be designed to open if the calculated voltage differential exceeds a predetermined value.

5.2 Pack Controller and Battery Management System

5.2.1 Pack Controller Mismeasuring / Misrepresenting Data

(P=2, I=4, S=8)

Inaccurate data representation can happen in a variety of ways. Post incident investigation of the CAMPBELL FOSS fire revealed that the hybrid control system was using a state of charge value without recognizing that this value was based on an indication of the lowest series element voltage. This meant that the other series elements were at a higher voltage during charging. Other sources of error can include wire breakage leading to a lost connection to the sensor, or inaccurate data reading resulting from miscalibration of the sensing equipment.

The pack controller and BMS are programmed and provided by the battery manufacturer. While the programming logic is beyond the control of the customer, there are qualities to look for. As a risk mitigating action, the BMS should be programmed to perform self-diagnostics based on the battery series elements expected response curve. The pack controller should be configured to recognize any series element that is responding outside the expected curve, and the review of this curve should generate a health status of each element and identify a stressed element well before failure.

The pack controller will broadcast the health status as a heartbeat control to the hybrid system. The battery pack should be disconnected at fault level (in addition to hybrid system) and lock out restart until inspected. If possible, the human machinery interface (HMI) screen provided by the battery manufacturer should display trend data with regards to series element health.

Additionally, an inverse time-current limit for charging and discharging current should be employed by the BMS to avoid overheating the components.

5.2.2 BMS Logic Failure

(P=3, I=3, S=9)

This risk encompasses many possibilities from calculation errors to nuisance alarms. Some of the highest risk items are the charging algorithm, upper and lower state-of-charge limits, voltage limits, and temperature limits.

The BMS control and alarm functionality should be in alignment with the battery parameters and safety requirements according to the manufacturer's knowledge of lithium battery chemistry. As

an additional safeguard, AKA's hybrid control system will check cell voltages and temperatures to provide additional protection. The programming logic of the hybrid control system will be made available to Foss Maritime Company for troubleshooting through collaboration with CASE Inc.

5.2.3 Pack Controller Contactor Failure

(P=1, I=3, S=3)

The contactors in the pack controller did not open onboard the CAMPBELL FOSS for battery fault. Further testing and investigation performed on a similar battery system attributed this to a software error in the pack controller. Had the contactors been found closed after removal of control power, a mechanical failure of the contactor would have been indicated. This being said, AKA has expressed concern that the contactors used by both Corvus and EST may have certain weaknesses, especially when closing and opening under high currents.

To mitigate risk resulting from a potential mechanical failure of a contractor, AKA will provide a second line of defense by installing contactors that will open based on cell voltage and temperature readings provided by the pack controller. The AKA provided contactors have a higher current rating compared to the contactors provided by battery manufacturers. See section 5.2.4.

5.2.4 AKA Redundant Contactor Failure

(P=1, I=3, S=3)

While the second line of defense offered by the redundant contactor is valuable, both contactors are dependent on the same data that is relayed by the pack controller. Consequently, if data is being mismeasured/misrepresented as discussed in section 5.2.1, both contactors will be controlled based on invalid input.

The mitigating action for this risk is to ensure that proper data is being relayed by the pack controller, as described in the same section referenced above.

5.3 Temperature Accelerators External to Cell

Lithium battery fires and explosions are a direct result of heat, and heat sources can be external to the cell. It is important to keep in mind that excess heat will also damage the longevity of the cell, as discussed in Section 5.4.2.

5.3.1 Engine Room / Ship Fire

(P=2, I=5, S=10)

In the event of an engine room fire the FM200 fire suppression system should be deployed. While such safety measures make the following highly unlikely, it is possible that a heat source outside of the battery compartment could increase compartment temperature to the point where one or multiple modules explode.

To minimize the absorption of heat into the battery compartment, the fire rating of the compartment bulkheads should be increased to A-60 or A-30. This will also help prevent the spread of fire into the adjacent space if a battery module were to explode.

Another mitigating action is to move the battery compartment outside of the engine room where the risk of fire is significantly lower. Moving the battery compartment to the void/ballast space aft of the Z-drive room effectively prevents the spread of fire because void spaces have very little, if any, flammable material. Moving the battery compartment to the void/ballast space is also an effective mitigating action for risk 5.7.2. However, occupying the void/ballast space will also increase the vessels regulatory tonnage.

Moving the battery compartment to the deck locker can also mitigate this risk, although not as effectively as the void/ballast space because the deck locker is located adjacent to accommodation areas.

5.3.2 Module Internal Electrical Fault

(P=1, I=5, S=5)

Another source of heat external to the cell is an internal short circuit or fault in the module that raises the temperature leading to multi-cellular failure and possible module fire. The mitigating action to prevent a module defect is the same as the mitigating action for a cell defect as described in Section 5.1.1.

It is necessary to distinguish a defect in the module and a defect in the cell, because a defect in the module will affect multiple cells at once, accelerating the failure. This being said, an ignition of an adjacent cell can also lead to a multi cellular failure as shown in the risk schematic.

5.3.3 Module Lid Fails to Release

(P=1, I=3, S=3)

One of the causes of cell ignition onboard the CAMPBELL FOSS was that after the initial cell failure and electrolyte vaporization, the module lid did not release until the pressure and temperature inside of the module increased to the point of combustion instead of venting the electrolyte.

The mitigating action for this risk is a redesign of the module lid. Corvus Energy has decreased the module lid release rating from 15 psi to 6 psi. They have replaced the latches on the lid, and modified the module rack design to prevent the lid from opening more than one inch. It will be necessary to verify the lid release rating and mechanism for the EST battery.

5.4 Logistics & Operational Concerns

5.4.1 High Charge / Discharge Demands

(P=3, I=3, S=9)

The nature of tug boat operations will require heavy charging and discharging cycles of the batteries. This can lead to excessive current as observed onboard the CAMPBELL FOSS.

Excessive current leads to increased heat generation, which accelerates aging of the cell as discussed in Section 5.4.2. Beyond proper initial sizing of the battery pack, there is no additional mitigating action required because it is common practice for the BMS programming to limit allowable current based on temperature data of the cells. This feature was not included at the time of the CAMPBELL FOSS fire.

5.4.2 Decreased Battery Longevity

(P=3, I=2, S=6)

Both Corvus and EST batteries have temperature tolerances that must be observed. Surpassing the operating temperature tolerance will dramatically decrease the longevity of the battery.

To control the temperature within the battery compartment it will be necessary to install a cooling system. While the temperature tolerances have a lower limit, it is assumed that heating is unnecessary because the vessels will operate in southern California's warm climate.

It will be easier to cool a battery compartment located outside of the engine room than one inside the engine room. The ambient temperature in the engine room may reach 110 degrees Fahrenheit. The heat from the engine room will cause an additional load on the battery compartment cooling system, which will increase operational expenses.

5.4.3 Status of Regulatory Approval

(P=2, I=2, S=4)

This risk is limited to EST batteries because Corvus Energy's batteries are already ABS approved. EST has obtained DNV and Lloyds approval, and is currently in the process of obtaining ABS approval. Obtaining ABS approval is not only a quality control issue. The potential schedule impact (Section 5.4.4) of any delays can have significant consequences.

To ensure the quality of EST's product, a mitigating action should be an approval from AKA as well as ABS of EST's testing procedure. There is no associated cost for this mitigating action because AKA has already scheduled a visit to EST's facility for a separate project.

5.4.4 Schedule Impact

(P=3, I=5, S=15)

There are significant schedule constraints to accomplish this project, leaving little room for error. The highest schedule risk item is the delivery of the batteries. As a mitigating action, lead times for both battery manufacturers, and a time line for regulatory approval for EST batteries should be obtained. Schedule impacts of all other equipment and resources required to reinstall batteries will also have to be considered.

5.5 Battery Cell/Module Fire/Explosion

This section discusses the various ways the batteries may fail. The resulting action will be the same for all of the following. The venting system will close, the FM200 will be deployed within the battery compartment, and the crew will respond to the fire alarm.

5.5.1 A single cell ruptures and catches fire

(P=3, I=5, S=15)

A single cell failure will most likely be caused by risks 5.1.1 and 5.1.2. This risk can further catalyze in to multi-cellular failure as discussed in Section 5.5.2.

5.5.2 Multiple cells rupture and catch fire

(P=3, I=5, S=15)

Multi-cell failure can be catalyzed from single cell failure; it can also be a result of heat sources external to the cell as described in Section 5.3.

5.5.3 A single module catches fire/explodes

(P=2, I=5, S=10)

A single module failure is a direct consequence of single or multi-cell failure.

5.5.4 Multiple modules catch fire/explode

(P=1, I=5, S=5)

Multiple modules can fail from heat sources external to the battery compartment as described in Section 5.3.1. Multiple modules will fail concurrently. This is to say, it is highly improbable that all of the modules will fail simultaneously. This is the rational for designing the vent system to a one module failure standard.

5.6 Battery Compartment Failure

5.6.1 Structural Failure

(P=2, I=3, S=6)

The current battery compartments are steel enclosures with aluminum hatches. The investigation of the fire revealed that the aft battery compartment door was ajar, indicating a need for a clip to retain the door to the bulkhead. The reason why the aluminum hatches did no fail with the CAMPBELL FOSS fire is because of the early failure of PVC vent piping that released the compartment pressure.

To mitigate the risk of structural failure of the battery compartment, the aluminum hatches will be replaced with steel closures, and the compartment bulkheads will be designed to withstand a one module explosion at minimum.

5.6.2 Battery Compartment FM200 Non-Deployable or Inaccessible

(P=2, I=5, S=10)

During the CAMPBELL FOSS incident the manual release of the FM200 system for the battery compartment was non-deployable because of a disabled pull cable that melted from high temperatures. The FM200 system did eventually deploy from automatic actuation of the heat

sensitive fusible plug. This is one example of the compartment firefighting system being non-deployable or inaccessible.

The FM200 system for the battery compartment will be reinstalled exterior to the compartment with an automatic and a manual discharge. This mitigating action will not have an associated cost because the relocation of the FM200 system to the Z-drive compartment was already planned for all Dolphin Class vessels.

5.7 Venting System Failure

5.7.1 Venting System Material Fails

(P=3, I=5, S=15)

The PVC ducting on the battery compartment ventilation system failed early in the fire onboard the CAMPBELL FOSS because of high temperatures.

To mitigate this risk from reoccurring, the ventilation ducting and fan will be constructed with steel material and the system will be designed to withstand one module explosion at minimum. Previous analysis from Foss Maritime Company has identified a gas expansion rate of 500:1, requiring an eight inch pipe diameter. This analysis must be verified during the future design of the ventilation system.

5.7.2 Venting System Location Harms Crew and/or Ship

(P=3, I=5, S=15)

The arrangement of the ventilation system on the CAMPBELL FOSS was very close in vicinity to crew space. Another concern was that the vent exit would have released hot gas on the stern deck had the PVC ducting remained intact. This has raised awareness that the ventilation system will need to be designed to protect the crew, vessel, and other vessels in the event of a battery failure. This means that the ideal venting system exits are at the stern, where the risks to crew and other vessels are minimal.

Hazardous zones were observed when developing the concept arrangement drawings (References [8] and [9]) to ensure that ignition sources are not present within a three meter radius of vent system exits. Hazardous zones are not a requirement for battery compartment venting, but represent best practice within the maritime industry. The venting system location is highly dependent on the battery compartment location. If the battery compartment were to move to the aft void/ballast space, the vent system could easily be routed through the stern. If the battery compartment locations move to the deck locker or remain the same, it may be necessary to route vent piping through the entire length of the engine room to safely vent through the stern of the vessel. Because the vent inlet and outlet will be below the main deck, it will be necessary to install demisters and reanalyze intact stability to account for the new down flooding points.

5.8 Spread of Fire to Adjacent Spaces

Where Section 5.7 addressed the risks of fire spreading beyond the battery compartment, this section expands to the risks of the fire spreading beyond the engine room or alternate battery compartment locations.

5.8.1 Human Error

(P=3, I=4, S=12)

The largest risk that could lead to the spread of fire to adjacent spaces is human error. There were many examples of human error during the CAMPBELL FOSS incident such as the access door to the Z-drive compartment being left open, and the remote actuation of the FM200 system failing.

The only way to reduce the possibility of human error is through proper training of crew. Understanding of how the hybrid system and BMS work will raise awareness of potential dangers.

5.8.2 Inadequate Insulation from Engine Room

(P=3, I=4, S=12)

The CAMPBELL FOSS incident investigation revealed that the wheel house deck was extremely hot. While all Dolphin classed vessels have engine room overhead insulation, the uninsulated wire chase conducted heat to the pilot house.

To mitigate this risk, spaces adjacent to the engine room should be checked for flammability risks and be insulated as necessary.

6 RISKS ASSOCIATED WITH NOT REINSTALLING BATTERIES

The risks associated with not reinstalling batteries are significantly higher for the CAROLYN DOROTHY compared to the CAMPBELL FOSS as seen in Section 6.2 and 6.3.

6.1 Loss of Redundancy

(P=5, I=4, S=20)

As designed the vessels were to operate with one generator on line and the battery banks providing backup power for the 9-12 seconds required to start and connect the second generator. Without batteries, both generator sets must be operated for redundancy.

The additional generator operation will increase fuel consumption, significantly increasing operational expenses as well as maintenance costs. The maintenance schedule will increase because the generators will have to be maintained twice as frequently as intended.

6.2 Loss of Bollard Pull Capacity

(P=5, I=2, S=10)

The CAROLYN DOROTHY is currently rated for 53 short tons of bollard pull when many services require at least 60 short tons. She was originally rated for 63 short tons, however because of the loss of batteries she is only certified for the conventional operation using main engines. This has consequences extending beyond the loss of revenue for the CAROLYN DOROTHY. The non-uniformity in Dolphin Class vessel performance makes scheduling for the entire fleet a challenge.

To restore bollard pull capacity without reinstalling batteries it will be necessary to install larger generators, which will require substantial upgrades to many equipment such as the variable frequency drive (VFD), active front end (AFE), and transformers. To accomplish this, a feasibility study will have to be performed. The greatest challenge and constraint will be the lack of available space in the machinery room. Installing generators will also exacerbate Risk 6.4.

6.3 Lack of Electrical Stability

(P=4, I=2, S=8)

Since the removal of battery arrays, the CAROLYN DOROTHY has experienced electrical instability which has been addressed to varying levels. For example, the VFD would randomly trip during start up and mode transitions. To resolve this issue encoders were installed. However, this resulted in heavy torsional vibrations that destroyed some components of the driveline. Consequently the encoders are no longer used. Electrical stability has improved since then, however the additional generator still experiences regeneration which can cause instability in the electrical bus.

To improve electrical stability a small array of lead acid batteries could be installed. However, these batteries will not be large enough to be considered a redundant source of power.

6.4 Negative Public Perception

(P=5, I=1, S=5)

The CAROLYN DOROTHY received a combined funding of 1.39 million dollars from the Ports of Long Beach and Los Angeles. The CAMPBELL FOSS conversion was funded by the Port of Long Beach that received a one million dollar grant from the California Air Resources Board to demonstrate the feasibility of modifying an existing harbor tugboat with a hybrid propulsion system.

These financial stakeholders frequently inquire about the status of battery reinstallation for both vessels because these hybrid tugs were supposed to demonstrate the feasibility of a more environmentally friendly port. At their best, these hybrid tugs demonstrated Foss Maritime Companies initiative and leadership in improving California's air quality. Not reinstalling batteries may strain the relationship between Foss Maritime Company and the ports of Long Beach and Los Angeles.

The financial impact of this decision is highly dependent on Foss public relations strategy. At its worst, it can mean the loss of similar future funding of future projects.

7 SOLUTIONS AND COST ESTIMATES

Through the above discussion, it becomes clear that there are decisions that need to be weighed beyond simply reinstalling or not reinstalling batteries. The possible solutions and cost estimates are summarized in Table 2 below, or diagrammatically in a decision making flow chart that is included in Appendix C.

Table 2. Cost Estimate Summary

REINSTALLING BATTERIES

Vessel Name	Battery Compartment Location	Battery Manufacturer	ROM Cost Estimate	
CAMPBELL FOSS	Engine Room	EST	$ 360,000	
		Corvus	$ 560,000	
	Stern Void/Ballast	EST	$ 400,000	
		Corvus	$ 600,000	
	Deck Locker	EST	$ 410,000	
		Corvus	$ 610,000	
CAROLYN DOROTHY	Engine Room	EST	$ 450,000	
		Corvus	$ 740,000	
	Stern Void/Ballast	EST	$ 470,000	
		Corvus	$ 770,000	
	Deck Locker	EST	$ 450,000	
		Corvus	$ 750,000	

NOT REINSTALLING BATTERIES

Vessel Name	Description	ROM Cost Estimate	
CAMPBELL FOSS	Non-Hybrid Mode with 2 Additional Generators	$ -	one time cost
		$ 230,000	per year
	Hybrid Mode with 1 Additional Generator	$ 50,000	one time cost
		$ 120,000	per year
CAROLYN DOROTHY	Cost of Restoring Bollard Pull	$ 2,300,000	one time cost
		$ 300,000	per year
	Loss of Revenue from lack of Bollard Pull, Additional Generator	$ -	one time cost
		$ 220,000	per year

It is important to note that the cost estimates are only provided as an approximate rough order of magnitude (ROM) indication of what the financial impacts may be. It is also important to remember the engineering, operating, and public perception risks associated with the decision making process that cannot be reflected as a cost.

The overall costs of reinstalling batteries include the cost of batteries (Section 7.1), the labor and material costs of battery reinstallation (Section 7.2), and the engineering costs for EBDG and AKA during the contract design phase. The cost of not reinstalling batteries was estimated as discussed in Section 7.3. The calculations performed are provided in Appendix C.

Table 2 shows that the cost of reinstalling batteries is not significantly lower when relocating battery compartments to the deck locker. This is counterintuitive because at first glance the deck locker appears to be a readily available battery compartment location outside of the engine room. The high cost is a result of the long runs of ventilation piping that will be necessary to safely route the exhaust through the stern.

7.1 Cost of Batteries, Integration, and Commissioning

AKA has recommended two battery manufacturers for consideration, EST and Corvus Energy.

The cost of EST batteries was based on a quote provided to AKA for a different project (Reference [9]). The price of the battery hardware was adjusted to account for the number of battery modules that will be necessary for each subject vessel. Shipping and handling costs were estimated as 10% of the battery costs. A conversion factor of 1.25 was assumed between the euro and US dollars.

The cost of Corvus batteries was approximated from a theoretical $/kWh value provided in Reference [10]. This reference was provided to EBDG for a separate project in 2013.

The cost of engineering and commissioning was provided as a quote from AKA (Reference [11]). This quote is specific to the integration of EST batteries. Because Corvus batteries will require more programming as identified in Section 5.1.2, the number of days required for engineering and commissioning was increased by two. The cost of travel that was not included in the quote was approximated.

The results show that the estimated cost for Corvus batteries is significantly higher than that for the EST batteries. It is possible that the cost of Corvus batteries is overstated because the estimate is entirely dependent on the theoretical $/kWh value that was used, the assumptions for which are unknown. While Corvus batteries are likely to cost more than EST batteries, the magnitude difference of the costs cannot be said with certainty until new quotations are solicited from both battery manufacturers.

7.2 Material and Labor Costs of Reinstalling Batteries

Costs for reinstalling the batteries were highly dependent on the subject vessel, and the location of the battery compartment. Approximate measurements of modifications were taken from the conceptual drawings provided in References [8] and [9]. Labor was assumed to cost 78 dollars per hour. Labor and material factors are based on past cost estimates performed at EBDG. The cost of modifying the deck locker to a battery compartment was assumed to be 40% of the cost of manufacturing a battery compartment in the stern void/ballast space. The cost of dry docking the subject vessels is assumed to be 20,000 dollars.

7.3 Costs of Not Reinstalling Batteries

The cost of not reinstalling batteries is separated into a onetime capital expense (CAPEX), and an annual operational expense (OPEX). The OPEX represents the increased cost relative to operating with reinstalled batteries, such as the cost of running additional generators and the loss of revenue from the lack of bollard pull for the CAROLYN DOROTHY. A price of three dollars per gallon of fuel is assumed.

The CAPEX for restoring hybrid mode without batteries on the CAMPBELL FOSS accounts for a systems inspection by AKA and sea trials and was assumed to be 50,000 dollars.

The CAPEX for restoring bollard pull on the CAROLYN DOROTHY is assumed to be similar to the 2.3 million dollars that was spent to convert the CAMPBELL FOSS from a conventional tug to a hybrid vessel.

8 CONCLUSIONS

There are many considerations that must be addressed when deciding on a path forward with improving the reliability and performance of the CAMPBELL FOSS and CAROLYN DOROTHY. The opportunity to reinstall batteries with MARAD funding is attractive yet constrained by schedule difficulty. The success of this project is therefore dependent on the ability to decide upon and efficiently move forward with the following decisions.

The most critical decision for reinstalling batteries is whether or not to move the battery compartments outside of the engine room. Moving the battery compartment to the stern void/ballast space significantly increases safety, and simplifies the engineering of the ventilation system. However, the cost will be greater and it will take longer compared to retaining the current battery compartment locations, and its feasibility is dependent on a stability analysis that has yet to be performed. The deck locker also offers a viable location for batteries. However, this will complicate the engineering of the ventilation system. The long pipe runs that will be required to safely discharge exhaust may offset the cost savings of having a readily available battery compartment.

The second major decision that must be made to reinstall batteries is the selection of a battery manufacturer. To accomplish this, technical, financial, and schedule concerns must be fully addressed.

Lastly, it is important to consider the alternative of not reinstalling the batteries, and if not, how to move forward with improving the reliability of these vessels. For the CAMPBELL FOSS, restoring hybrid mode without reinstalling batteries may be a viable option, although the increased operational expenses must be considered.

For the CAROLYN DOROTHY, continuing operations as is much less of an option because of the reduced bollard pull capacity. Restoring this capacity through larger generators is also prohibitively expensive.

9 REFERENCES

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Appendix A

Risk Matrix

Section Number	Risk Category	Subsection Number	Risk Title	Description/Example of Risk	Probability	Impact	Score	Mitigating Actions	Circular Reference
4	Regulatory Compliance	4.1	Tonnage cannot become greater than 150 GT or 200 GRT	Exceeding 150 GT will require load line, exceeding 200 GRT will make vessel an "inspected tug."	1	4	4	Avoid changing dimensions of hull (vessels are currently 144/145 GT, and GT is calculated solely based on principle dimensions.)	
		4.2	Vessel stability must be compliant with 46 CFR 174.145	CAROLYN DOROTHY was designed to 46CFR 174.145. Stability letter must be checked to see if operation is contingent on 174.145.	1	2	2	Check stability letters. If necessary perform intact stability analysis with estimated weights.	

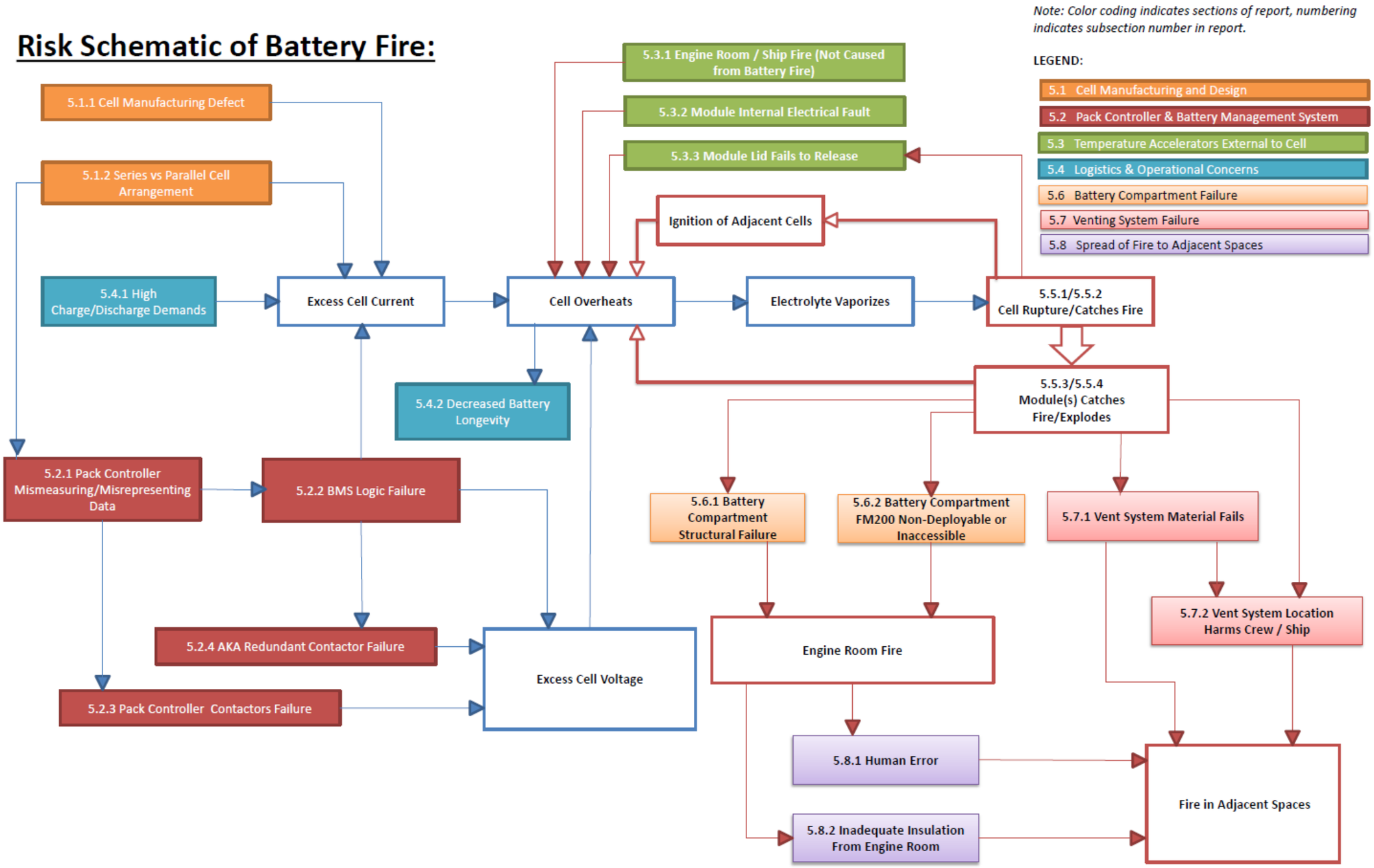
Section Number	Risk Category	Subsection Number	Risk Title	Description/Example of Risk	Probability	Impact	Score	Mitigating Actions	Circular Reference
5.1	Cell Manufacturing and Design	5.1.1	Cell Manufacturing Defect	Example: Contamination of lithium-ion electrolytes leads to an internal short and possible cell fire.	1	5	5	Use an established and type approved battery manufacturer.	5.5.1, 5.5.2
		5.1.2	Series vs. Parallel Cell Arrangements	Corvus connects cells in parallel which can cause imbalanced current and masking of voltage readings, EST connects cells in series which mitigates this problem.	2	2	4	Ideally obtain series (EST) batteries, see circular reference.	5.4.3, 5.4.4
								If Corvus batteries are selected, BMS system should have sanity check to ensure that pack controller voltage readings make sense.	5.2.1
5.2	Pack Controller and Battery Management System (BMS)	5.2.1	Pack Controller Mismeasuring / Misrepresenting Data	This can have multiple sources from wire breakage to miscalibration of sensing systems. Most notable example is the reporting of the state of charge that lead to the CAMPBELL FOSS fire.	2	4	8	Apply lessons learned and program BMS to perform sanity checks of measured data. Pack controller should be configured to perform self diagnostics against expected performance curve.	
		5.2.2	BMS Logic Failure	This criteria encompasses many possibilities.	3	3	9	Thorough review of logic by AKA and training of FOSS personnel of logic.	
		5.2.3	Pack Controller Contactor Failure	Example: The contactors in the pack controller failed to open onboard the CAMPBELL FOSS for battery fault.	1	3	3	AKA will provide second line of defense by installing contactors that are governed by the BMS.	5.2.4
		5.2.4	AKA Redundant Contactor Failure	The BMS operates on the same data measured by the pack controller.	1	3	3	BMS system should have sanity check to ensure that pack controller readings make sense.	5.1.2
5.3	Temperature Accelerators External to Cell	5.3.1	Engine Room / Ship Fire	Heat source outside of the battery compartment increases compartment temperature to the point where one or multiple modules explode.	2	5	10	Increase fire rating of battery compartment bulkheads to A-60 or A-30.	
								Move battery compartment to aft void/ballast space.	4.2
		5.3.2	Module Internal Electrical Fault	An internal short circuit or fault raises temperature internal to module leading to multi-cellular failure and possible module fire.	1	5	5	Use an established and type approved battery manufacturer.	
		5.3.3	Module Lid Fails to Release	Example: After initial cell failure leading to electrolyte vaporization, the module lid failed to release, causing the pressure/temperature to increase to the point of fire.	1	3	3	Corvus has redesigned lid, check rating for EST.	
5.4	Logistics & Operational Concerns	5.4.1	High Charge / Discharge Demands	Example: Charge current was excessive on CAMPBELL FOSS, which led to excessive heat generation within the cell.	3	3	9	BMS limits current based on high cell temperature.	
		5.4.2	Decreased Battery Longevity	Batteries have temperature ratings. When ratings are exceed the life of the battery will decrease.	3	2	6	Install cooling system.	
		5.4.3	Status of Regulatory Approval	Corvus has ABS certification, EST has Lloyds but is currently in the process of obtaining ABS approval.	2	2	4	Obtain timeline of regulatory approval from EST. AKA approval of EST testing procedure.	5.4.4
		5.4.4	Schedule Impact	Project schedule is constrained.	3	5	15	Obtain lead times for both battery manufacturers.	
5.5	Battery Cell/Module Fire/Explosion	5.5.1	A single cell ruptures and catches fire		3	5	15	Close vent, deploy FM200, crew responds to fire alarm	
		5.5.2	Multiple cells rupture and catch fire		3	5	15	Close vent, deploy FM200, crew responds to fire alarm	
		5.5.3	A single module catches fire/explodes		2	5	10	Close vent, deploy FM200, crew responds to fire alarm	
		5.5.4	Multiple modules catch fire/explode		1	5	5	Close vent, deploy FM200, crew responds to fire alarm	
5.6	Battery Compartment Failure	5.6.1	Structural Failure	Current battery compartment is a steel enclosure with aluminum hatches.	2	3	6	Increase fire rating of battery compartment bulkheads to A-60 or A-30. Replace aluminum hatches with steel. Design bulkheads to withstand one module explosion at minimum.	
		5.6.2	Battery Compartment FM200 Non-Deployable or Inaccessible	Example: During the CAMPBELL FOSS incident the manual release was inaccessible due to fire/smoke/battery compartment venting.	2	5	10	Relocate FM200 bottles to Z-drive compartment or outside of battery compartment to allow for local release.	
5.7	Venting System Failure	5.7.1	Vent System Material Fails	Example: CAMPBELL FOSS's PVC vent piping failed.	3	5	15	Design battery compartment venting system with steel piping and explosion proof fan. Design venting system to release one module explosion pressure at minimum.	
		5.7.2	Venting System Location Harms Crew and/or Ship	Example: CAMPBELL FOSS venting system went through crew space.	3	5	15	Reroute battery compartment venting to minimize danger to crew, vessel, and client ship.	
								Move battery compartment to aft void/ballast space.	4.2
5.8	Spread of Fire to Adjacent Spaces	5.8.1	Human Error	Example: CAMPBELL FOSS incident had many preventable errors such as the Z-drive door being open, and remote actuation of FM200 system failing.	3	4	12	Proper training of crew.	
		5.8.2	Inadequate Insulation from Engine Room	Example: CAMPBELL FOSS incident investigation revealed that the wheel house deck was extremely hot because of lack of insulation.	3	4	12	Install engine room overhead insulation.	

Section Number	Risk Category	Subsection Number	Risk Title	Description/Example of Risk	Probability	Impact	Score	Mitigating Actions	Circular Reference
6	Not Reinstalling Batteries	6.1	Loss of Redundancy	It would take 9-12 seconds for second generator to come online in event of a power source failure.	5	4	20	Keep additional generator running.	
		6.2	Loss of Bollard Pull Capacity	CAROLYN DOROTHY can achieve 53t bollard pull when many services require 60t bollard pull.	5	2	10	Limit operations of vessel.	
								Install larger generators.	4.1, 4.2
		6.3	Lack of Electrical Stability	Breaker trips frequently during operations, has been mitigated to an extent on the CAMPBELL FOSS already.	4	2	8	Install resistor bank, encoder, or smaller lead acid battery bank.	6.1, 6.2
		6.4	Negative public perception	Port that funded the Carolyn Dorothy frequently inquires about the status of battery reinstallation.	5	1	5	Dependent upon Foss PR policy and strategy.	

Appendix B

Risk Schematic of Battery Fire

Risk Schematic of Battery Fire:



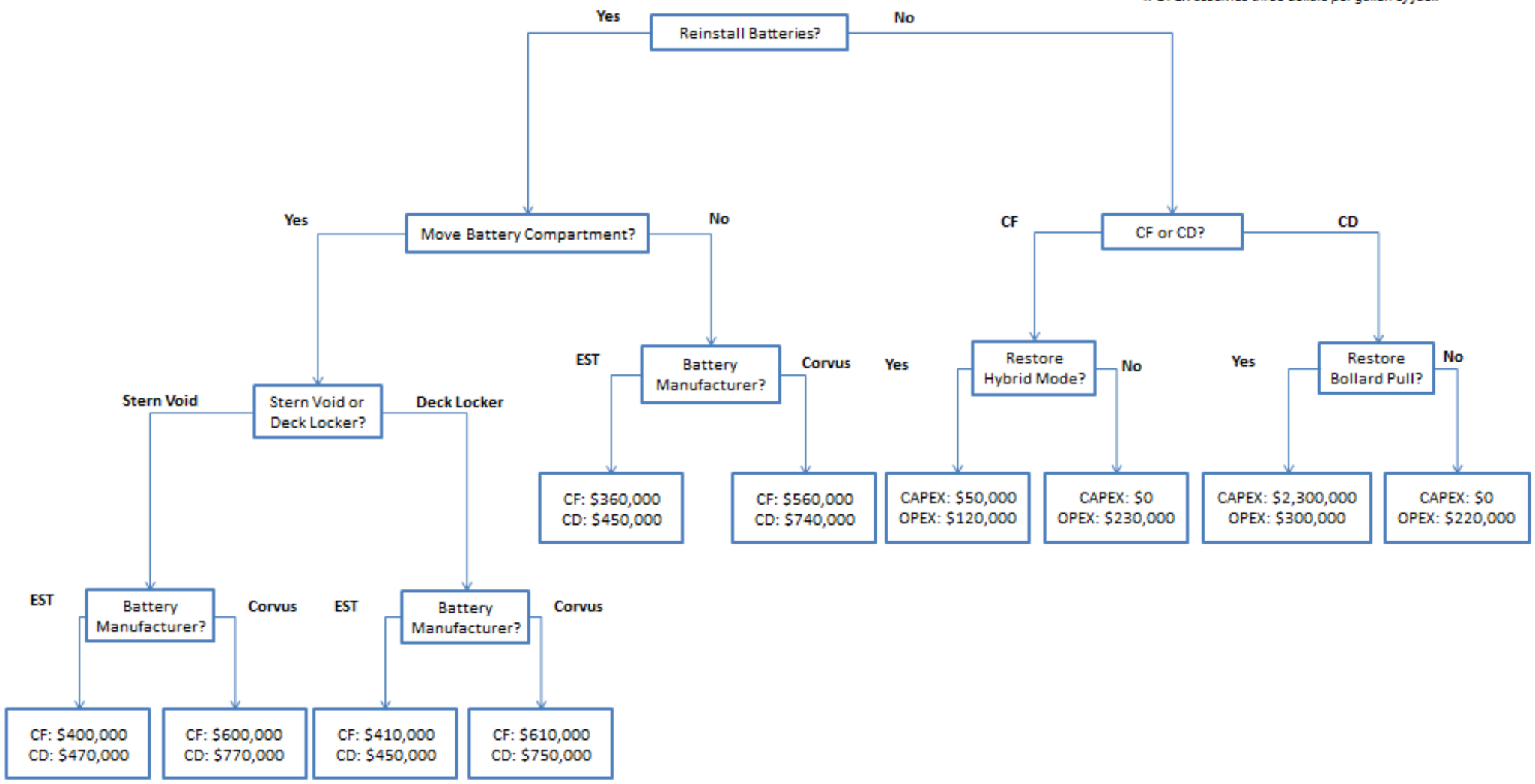
Appendix C

Decision Making Flow Chart and Cost Estimates

Decision Making Flow Chart:

Notes:

1. CF stands for CAMPBELL FOSS.
2. CD stands for CAROLYN DOROTHY.
3. OPEX represents the additional annual operating expenses when compared to hybrid mode.
4. OPEX assumes three dollars per gallon of fuel.



SUMMARY

REINSTALLING BATTERIES

Vessel Name	Battery Compartment Location	Battery Manufacturer	ROM Cost Estimate
CAMPBELL FOSS	Engine Room	EST	$ 360,000
		Corvus	$ 560,000
	Stern Void/Ballast	EST	$ 400,000
		Corvus	$ 600,000
	Deck Locker	EST	$ 410,000
		Corvus	$ 610,000
CAROLYN DOROTHY	Engine Room	EST	$ 450,000
		Corvus	$ 740,000
	Stern Void/Ballast	EST	$ 470,000
		Corvus	$ 770,000
	Deck Locker	EST	$ 450,000
		Corvus	$ 750,000

NOT REINSTALLING BATTERIES

Vessel Name	Description	ROM Cost Estimate	
CAMPBELL FOSS	Non-Hybrid Mode with 2 Additional Generators	$ -	one time cost
		$ 230,000	per year
	Hybrid Mode with 1 Additional Generator	$ 50,000	one time cost
		$ 120,000	per year
CAROLYN DOROTHY	Cost of Restoring Bollard Pull	$ 2,300,000	one time cost
		$ 300,000	per year
	Loss of Revenue from lack of Bollard Pull, Additional Generator	$ -	one time cost
		$ 220,000	per year

DETAILED SUMMARY

CAMPBELL FOSS	Estimated Cost	%Margin	Cost with Margin
Cost of EST Batteries	$ 21,536	10%	$ 23,689
Cost of EST Battery Integration (AKA)	$ 73,207	10%	$ 80,528
Cost of Corvus Batteries	$ 194,916	10%	$ 214,408
Cost of Corvus Battery Integration (AKA)	$ 84,965	10%	$ 93,462
Cost of Labor if BC remains in ER	$ 69,119	30%	$ 89,854
Cost of Material if BC remains in ER	$ 44,518	30%	$ 57,873
Cost of Labor if BC moves to stern	$ 78,637	30%	$ 102,227
Cost of Material if BC moves to stern	$ 64,459	30%	$ 83,797
Cost of Labor if BC moves to Deck Locker	$ 98,469	30%	$ 128,009
Cost of Material if BC moves to Deck Locker	$ 51,298	30%	$ 66,688

CAROLYN DOROTHY			
Cost of EST Batteries	$ 53,182	10%	$ 58,500
Cost of EST Battery Integration (AKA)	$ 73,207	10%	$ 80,528
Cost of Corvus Batteries	$ 311,866	10%	$ 343,053
Cost of Corvus Battery Integration (AKA)	$ 84,965	10%	$ 93,462
Cost of Labor if BC remains in ER	$ 102,558	30%	$ 133,325
Cost of Material if BC remains in ER	$ 49,901	30%	$ 64,872
Cost of Labor if BC moves to stern	$ 107,142	30%	$ 139,285
Cost of Material if BC moves to stern	$ 67,006	30%	$ 87,108
Cost of Labor if BC moves to Deck Locker	$ 103,519	30%	$ 134,575
Cost of Material if BC moves to Deck Locker	$ 51,698	30%	$ 67,207

COST OF EST BATTERIES AND INTEGRATION

EST BATTERIES

..\..\Client\Quotation AKA EST_MR_B_1.pdf

	Capacity	250 Ah	
	Nominal Voltage	52 Vdc	
qty			
9	Module	9580 euro	1064.444 euro/qty
8	Power Cabling	944 euro	118 euro/qty
8	Data Cabling	344 euro	43 euro/qty
1	BCU including cabling	3569 euro	3569 euro/qty
	TOTAL	14437 euro	

CAMPBELL FOSS ESTIMATE 10 modules

qty		
10	Module	10644 euro
9	Power Cabling	1062 euro
9	Data Cabling	387 euro
1	BCU including cabling	3569 euro
	Subtotal Hardware	15662 euro
	Shipping from Netherlands @10%	1566 euro
	TOTAL CF (euro)	17229 euro
	Exchange Rate from Euro to USD	1.25
	TOTAL CF (USD)	$ 21,536 USD

CAROLYN DOROTHY ESTIMATE 16 modules

qty		
16	Module	17031 euro
15	Power Cabling	1770 euro
15	Dta Cabling	645 euro
1	BCU including cabling	3569 euro
	TOTAL	23015 euro
	Shipping from Netherlands @10%	2302 euro
	TOTAL CD (euro)	25317 euro
	TOTAL CD (USD)	$ 31,646 USD

Combined Total of Battery Hardware (USD) $ 53,182 USD

INTEGRATION OF EST BATTERIES (AKA) rmation\AKA Information and Quote\11082 - FC

ENGINEERING (Offsite including drawing modifications and software modifications)

Daily Rate of Automation & Software Development (Travel)	$	1,083	per day
Number of Days	$	14	day(s)
Cost	$	15,162	
Daily Rate of Electrical Drafting (Travel)	$	704	
Number of Days	$	2	day(s)
Cost	$	1,408	
Subtotal Engineering	$	16,570	USD

COMMISSIONING OF SYSTEM (Three individuals will attend site for installation and commissioning)

Daily Rate of Field Technical Resource (Onsite)	$	1,163	per day
Number of Days		10	day(s)
Cost	$	11,630	
Daily Rate of Senior Systems Engineer (Onsite)		1385	per day
Number of Days		7	day(s)
Cost	$	9,695	
Daily Rate of Automation & Software Development (Onsite)	$	1,288	per day
Number of Days	$	14	day(s)
Cost	$	18,032	
Subtotal Commissioning	$	39,357	USD

AT COST TRAVEL EXPENSES

Number of Travelers		5	
Assumed Cost Round Trip (Ottowa-Portland)	$	1,000	
Accomodation Cost Per Day	$	200	
Total Days		47	day(s)
Travel Expenses	$	14,400	USD
+20% Margin for Miscelaneous Expenses	$	2,880	USD
Subtotal At Cost Travel Expenses	$	17,280	USD
Combined Total of Battery Integration per Vessel	$	73,207	USD

COST OF CORVUS BATTERIES AND INTEGRATION

CORVUS BATTERIES

ndor\Not Used\Corvus\hybrid_ferries_concepts_r

Capacity		240	Ah
Nominal Voltage		25.9	Vdc
Estimated Cost		9320	USD
Energy		6.216	kWh
Cost of Energy	$	1,499	USD/kWh

CAMPBELL FOSS ESTIMATE

Energy		130	kWh
Cost	$	194,916	USD

CAROLYN DOROTHY ESTIMATE

Energy		208	kWh
Cost	$	311,866	USD

INTEGRATION OF CORVUS BATTERIES (

ormation\AKA Information and Quote\11082 - FC

The number of days to install batteries must be increased for CORVUS because of the additional safeguards necessary to mitigate risks cuased from parallel connections

ENGINEERING (Offsite including drawing modifications and software modifications)

Daily Rate of Automation & Software Development (Travel)	$	1,083.00	per day
Number of Days		16	day(s)
Cost	$	17,328	
Daily Rate of Electrical Drafting (Travel)	$	704	
Number of Days		2	day(s)
Cost	$	1,408	
Subtotal Engineering	$	18,736	USD

COMMISSIONING OF SYSTEM (Three individuals will attend site for installation and commissioning)

Daily Rate of Field Technical Resource (Onsite)	$	1,163	per day
Number of Days		12	day(s)
Cost	$	13,956	
Daily Rate of Senior Systems Engineer (Onsite)		1385	per day
Number of Days		9	day(s)
Cost	$	12,465	
Daily Rate of Automation & Software Development (Onsite)	$	1,288	per day
Number of Days	$	16	day(s)
Cost	$	20,608	
Subtotal Commissioning	$	47,029	USD

AT COST TRAVEL EXPENSES

Number of Travelers	$	5	
Assumed Cost Round Trip (Ottowa-Portland)	$	1,000	
Accomodation Cost Per Day	$	200	
Total Days	$	55	day(s)
Travel Expenses	$	16,000	USD
+20% Margin for Miscelaneous Expenses	$	3,200	USD
Subtotal At Cost Travel Expenses	$	19,200	USD
Combined Total of Battery Integration per Vessel	$	84,965	USD

COST OF BATTERY REINSTALLATION

Constants and factors obtained from Jim Cole's construction cost estimate for J14070 ..\..\..\14070\Eng-Des\043.0 Constr. Cost Estim\14070
Rough weight and length measurements obtained from Acad Drawing ..\101.0 GA drawing\14088-001-101-0P0.dwg

Labor Cost	$ 78.00	per hr

CAMPBELL FOSS / LOCATION REMAINS IN ENGINE ROOM

Item Description	Quant.	Unit	Labor Factor	Labor Hours	Labor Cost	Material Factor	Material & Services @ Cost, ($)
Ventilation							
Length of Piping	87.0	Ft.	5	435	$ 33,930.00	$ 25.00	$ 2,175.00
Fittings	5.0	Each	5	25	$ 1,950.00	$ 120.00	$ 600.00
Fan	2.0	Each	33	66	$ 5,148.00	$2,500.00	$ 5,000.00
Lagging	174.0	Sq. Ft.	0.25	43.5	$ 3,393.00	$ 32.00	$ 5,568.00
Fire Dampers	2.0	Each	16	32	$ 2,496.00	$1,500.00	$ 3,000.00
Check Valve	1.0	Each	16	16	$ 1,248.00	$1,475.00	$ 1,475.00
Fire Supression							
FM200	1	Each	100	100	$ 7,800.00	25000	$ 25,000.00
Release Mechanism	3	Each	15	45	$ 3,510.00		$ -
Compartment Structural Modifications							
Replacing aluminum hatches with steel closures	1	Each	10	10	$ 780.00	$ 500.00	$ 500.00
A-60 Insulating Material	181.8	Sq. Ft.	0.35	63.6368	$ 4,963.67	$ 1.10	$ 200.00
Cooling System							
Cooling Module	1	Each	50	50	$ 3,900.00	$1,000.00	$ 1,000.00
SUBTOTAL					**$ 69,119**		**$ 44,518**

CAMPBELL FOSS / LOCATION MOVES TO STERN COMPARTMENT

Item Description	Quant.	Unit	Labor Factor	Labor Hours	Labor Cost	Material Factor	Material & Services @ Cost, ($)
Dry Docking							$ 20,000.00
Ventilation							
Length of Piping	27.6	Ft.	5	137.917	$ 10,757.50	$ 25.00	$ 689.58
Fittings	7.0	Each	5	35	$ 2,730.00	$ 120.00	$ 840.00
Fan	2.0	Each	33	66	$ 5,148.00	$2,500.00	$ 5,000.00
Lagging	55.2	Sq. Ft.	0.25	13.7917	$ 1,075.75	$ 32.00	$ 1,765.33
Fire Dampers	2.0	Each	16	32	$ 2,496.00	$1,500.00	$ 3,000.00
Check Valve	1.0	Each	16	16	$ 1,248.00	$1,475.00	$ 1,475.00
Fire Supression							
FM200	1	Each	100	100	$ 7,800.00	25000	$ 25,000.00
Release Mechanism	3	Each	15	45	$ 3,510.00		$ -
Compartment Structure							
Steel Bulkhead	3198	lbs	0.12	383.757	$ 29,933.01	0.74	$ 2,366.50
Replacing aluminum hatches with steel closures	1	Each	10	10	$ 780.00	$ 500.00	$ 500.00
A-60 Insulating Material	293	Sq. Ft.	0.35	102.696	$ 8,010.28	$ 1.10	$ 322.76
Cooling System							
Cooling Module	1	Each	50	50	$ 3,900.00	$1,000.00	$ 1,000.00
Access Hatch/WT Door	1.00	Each	16	16	$ 1,248.00	$2,500.00	$ 2,500.00
SUBTOTAL					**$ 78,637**		**$ 64,459**

CAMPBELL FOSS / LOCATION MOVES TO DECK LOCKER

Item Description	Quant.	Unit	Labor Factor	Labor Hours	Labor Cost	Material Factor	Material & Services @ Cost, ($)
Ventilation							
Length of Piping	118.2	Ft.	5	590.833	$ 46,085.00	$ 25.00	$ 2,954.17
Fittings	12.0	Each	5	60	$ 4,680.00	$ 120.00	$ 1,440.00
Fan	2.0	Each	33	66	$ 5,148.00	$2,500.00	$ 5,000.00
Lagging	236.3	Sq. Ft.	0.25	59.0833	$ 4,608.50	$ 32.00	$ 7,562.67
Fire Dampers	2.0	Each	16	32	$ 2,496.00	$1,500.00	$ 3,000.00
Check Valve	1.0	Each	16	16	$ 1,248.00	$1,475.00	$ 1,475.00
Fire Supression							
FM200	1	Each	100	100	$ 7,800.00	25000	$ 25,000.00
Release Mechanism	3	Each	15	45	$ 3,510.00		$ -
Compartment Structure							
Assume 40% of Cost of Voidspace					$ 12,285.20		$ 1,146.60
A-60 Insulating Material	200	Sq. Ft.	0.35	70	$ 5,460.00	$ 1.10	$ 220.00
Cooling System							
Cooling Module	1	Each	50	50	$ 3,900.00	$1,000.00	$ 1,000.00
Access Hatch/WT Door	1.00	Each	16	16	$ 1,248.00	$2,500.00	$ 2,500.00
SUBTOTAL					**$ 98,469**		**$ 51,298**

CAROLYN DOROTHY / LOCATION REMAINS IN ENGINE ROOM

Item Description	Quant.	Unit	Labor Factor	Labor Hours	Labor Cost ($68/hr)	Material Factor	Material & Services @ Cost, ($)
Ventilation							
Length of Piping	138.9	Ft.	5	694.583	$ 54,177.50	$ 25.00	$ 3,472.92
Fittings	8	Each	5	40	$ 3,120.00	$ 120.00	$ 960.00
Fan	2	Each	33	66	$ 5,148.00	$2,500.00	$ 5,000.00
Lagging	277.8	Sq. Ft.	0.25	69.4583	$ 5,417.75	$ 32.00	$ 8,890.67
Fire Dampers	2.0	Each	16	32	$ 2,496.00	$1,500.00	$ 3,000.00
Check Valve	1.0	Each	16	16	$ 1,248.00	$1,475.00	$ 1,475.00
Fire Supression							
FM200	1	Each	100	100	$ 7,800.00	25000	$ 25,000.00
Release Mechanism	3	Each	15	45	$ 3,510.00		$ -
Compartment Structural Modifications							
Replacing aluminum hatches with steel closures	1	Each	10	10	$ 780.00	$ 500.00	$ 500.00
A-60 Insulating Material	548	Sq. Ft.	0.35	191.8	$ 14,960	$ 1.10	$ 602.80
Cooling System							
Cooling Module	1	Each	50	50	$ 3,900.00	$1,000.00	$ 1,000.00
SUBTOTAL					**$ 102,558**		**$ 49,901**

CAROLYN DOROTHY / LOCATION MOVES TO STERN COMPARTMENT

Item Description	Quant.	Unit	Labor	Labor	Labor Cost	Material	Material & Services
Dry Docking							$ 20,000.00
	2	Each	15	30	$ 2,340.00		$ -
Rerouting Piping	20	Ft.	5	100	$ 7,800.00	$ 25.00	$ 500.00
Ventilation							
Length of Piping	39.0	Ft.	5	194.917	$ 15,203.50	$ 25.00	$ 974.58
Fittings	7.0	Each	5	35	$ 2,730.00	$ 120.00	$ 840.00
Fan	2.0	Each	33	66	$ 5,148.00	$2,500.00	$ 5,000.00
Lagging	78.0	Sq. Ft.	0.25	19.4917	$ 1,520.35	$ 32.00	$ 2,494.93
Fire Dampers	2.0	Each	16	32	$ 2,496.00	$1,500.00	$ 3,000.00
Check Valve	1.0	Each	16	16	$ 1,248.00	$1,475.00	$ 1,475.00
Fire Supression							
FM200	1	Each	100	100	$ 7,800.00	25000	$ 25,000.00
Release Mechanism	3	Each	15	45	$ 3,510.00		$ -
Compartment Structure							
Steel Bulkhead	4547	lbs	0.12	545.635	$ 42,559.51	0.74	$ 3,364.75
Replacing aluminum hatches with steel closures	1	Each	10	10	$ 780.00	$ 500.00	$ 500.00
A-60 Insulating Material	325	Sq. Ft.	0.35	113.575	$ 8,858.85	$ 1.10	$ 356.95
Cooling System							
Cooling Module	1	Each	50	50	$ 3,900.00	$1,000.00	$ 1,000.00
Access Hatch/WT Door	1.00	Each	16	16	$ 1,248.00	$2,500.00	$ 2,500.00
SUBTOTAL					**$ 107,142**		**$ 67,006**

CAROLYN DOROTHY / LOCATION MOVES TO DECK LOCKER

Item Description	Quant.	Unit	Labor Factor	Labor Hours	Labor Cost	Material Factor	Material & Services @ Cost, ($)
Ventilation							
Length of Piping	118.2	Ft.	5	590.833	$ 46,085.00	$ 25.00	$ 2,954.17
Fittings	12.0	Each	5	60	$ 4,680.00	$ 120.00	$ 1,440.00
Fan	2.0	Each	33	66	$ 5,148.00	$2,500.00	$ 5,000.00
Lagging	236.3	Sq. Ft.	0.25	59.0833	$ 4,608.50	$ 32.00	$ 7,562.67
Fire Dampers	2.0	Each	16	32	$ 2,496.00	$1,500.00	$ 3,000.00
Check Valve	1.0	Each	16	16	$ 1,248.00	$1,475.00	$ 1,475.00
Fire Supression							
FM200	1	Each	100	100	$ 7,800.00	25000	$ 25,000.00
Release Mechanism	3	Each	15	45	$ 3,510.00		$ -
Compartment Structure							
Assume 40% of Cost of Voidspace					$ 17,335.80		$ 1,545.90
A-60 Insulating Material	200	Sq. Ft.	0.35	70	$ 5,460.00	$ 1.10	$ 220.00
Cooling System							
Cooling Module	1	Each	50	50	$ 3,900.00	$1,000.00	$ 1,000.00
Access Hatch/WT Door	1.00	Each	16	16	$ 1,248.00	$2,500.00	$ 2,500.00
SUBTOTAL					**$ 103,519**		**$ 51,698**

COST OF NOT REINSTALLING BATTERIES

ASSUMPTIONS

Cost of Fuel	$	3.00	per gallon
#Days per Year		300	days
#Hours per Day		8	hrs

CAMPBELL FOSS

Cost of Additional Generator			MTU Series 60 Tier II @ 350kW	
Assume		15	gallon/hour	(from CAT @ 340kW)
Cost of Fuel per Y	$	108,000		
Maintenance @5%	$	5,400		
Combined Cost pe	$	113,400.00		

Hybrid Mode	1	additional generators	$	113,400	per year
Non-Hybrid Mode	2	additional generators	$	226,800	per year

CAROLYN DOROTHY

Loss of Revenue from Lack of Bollard Pull	$	100,000	per year
Cost of 1 Additional Generator	$	113,400	per year
Fuel Increase (Compared to Hybrid)		100000	gallons
Cost of Fuel	$	300,000	per year

Benefits from Repowering the Auxiliary Engine on a Hybrid Tugboat

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Executive Summary

Background…The *Campbell Foss* was converted from conventional to hybrid operation and received the first EPA listing as a verified conversion of a conventional to hybrid tug. In this project the *Campbell Foss* was modified further by having one of the auxiliary engines converted from a Tier 2 to a Tier 3 level of emissions control. The project was to figure the emissions benefit as a result of the repowering.

Approach…In an earlier project, the *Campbell Foss* was converted from a conventional to a hybrid tug operation. During that project UCR measured the percentage of time at five discrete activities and determined weighting factors of each activity mode of operation. Furthermore emissions were measured as a function of load and RPM for the main and auxiliary engines. Similar modal emission data were provided by the OEM for the new Tier 3 engine used for repowering. For this project, we used earlier measured values of activity at each mode and engine emission values at those modes to calculate the added benefits of repowering one auxiliary engine.

Results…Two main observations came from the project.

1. Significant benefits in criteria emissions are realized when converting a conventional to hybrid tug operation but the overall benefits are minimal. While there were some modal benefits, those operating modes had low emission rates; therefore a low overall emission benefit.
2. Significant greenhouse gas benefits were realized on converting to a hybrid tug but no further benefits were realized by repowering one of the auxiliary engines.

Quantified results are provided in Table ES-1.

Table ES-1 Benefits of Conversion to Hybrid Tug & to Repowering AE (tons per year)

	Hybrid	Hybrid + Repower AE
NOx	11.8	11.9
$PM_{2.5}$	0.15	0.16
CO_2	822	822

1 Background

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

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

Harbor-craft are typically powered by marine compression ignition engines using diesel fuel and emissions 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. Current EPA emissions for these new marine engines require the use of low sulfur (<500ppm S) diesel or ultra-low sulfur diesel (ULSD) (<15ppm S).

Future regulations 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 climate change. One technology solution is the use of two or more power sources for propulsion, known as hybrid technology. The most common application of hybrid technology today is in passenger cars. Hybrid technology is also used in the marine world; for example, the diesel-electric submarines designs of more than 60 years ago. The propeller on submarines was driven by an electric motor that derives energy from diesel generators or batteries. The diesel generators were also used to charge batteries. Today most cruise ships and some ships and ferries use diesel-electric hybrid systems for their main propulsion so hybrid designs are still popular.

1.1 Foss hybrid tug technology

Foss Maritime Company (Foss) and Aspin Kemp & Associates (AKA) recognized the need for and a path to creating a first-of-a–kind, diesel-electric, hybrid-propulsion system for tugboats. The difference between the convention and hybrid tug can be seen by reviewing Figure 1-1. In the case of the conventional tug, the main engines were mechanically linked to the propellers through a drive shaft. Therefore both main engines were operated for moving and maneuvering the boat. The auxiliary engines were only used for hotelling applications, like, lighting, air conditioning and operating the winch motor. However, in case of the hybrid, there is a motor-generator unit

mounted on the shaft between each engine and ASD. This motor-generator unit allows the electrical power from the batteries and auxiliary engines to drive the shaft for propelling the boat.

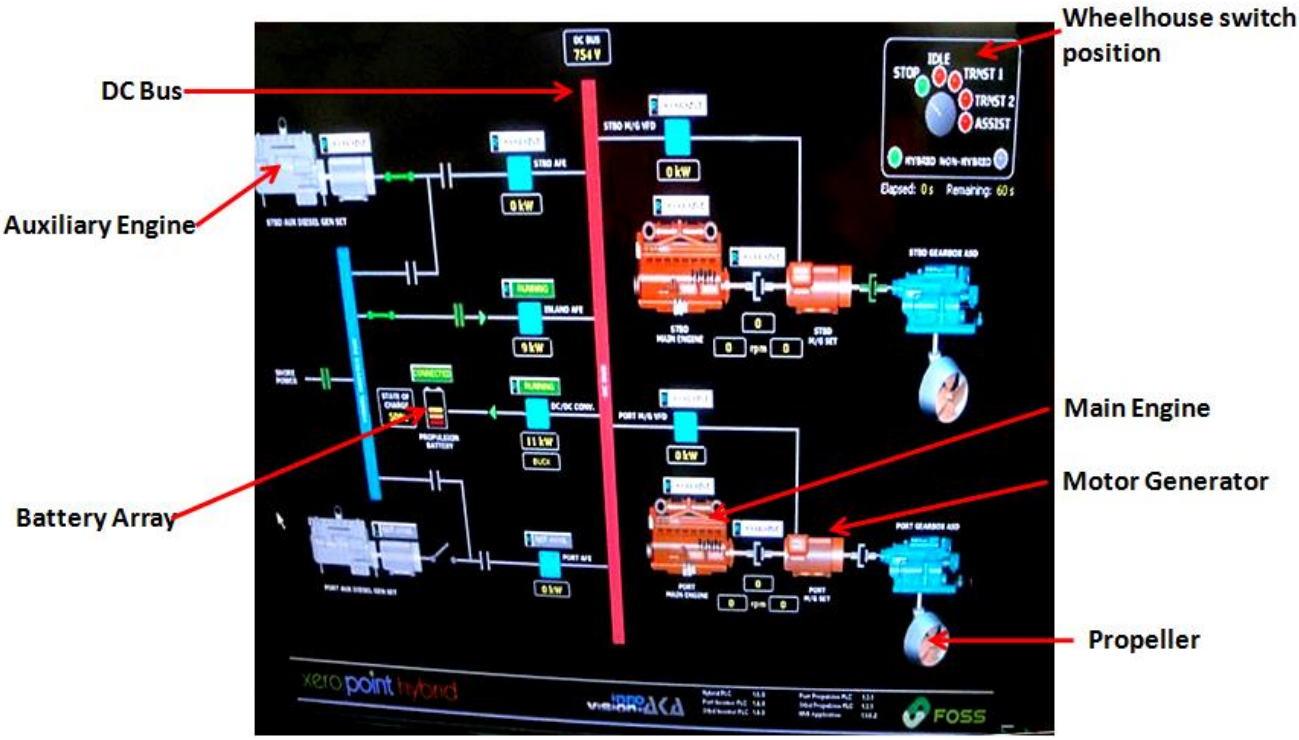

Figure 1-1: Diesel Electric Drive Train on the Hybrid Campbell

The energy management system is a key feature of hybrid tugs in that it manages the power sources and the drive train. The captain on the hybrid tug uses a switch in the wheelhouse to communicate the current operating mode of the tug to the energy management system. The signal from this wheelhouse switch helps the energy management system direct the mix of energies from two large main propulsion engines, two auxiliary engines and 65 kW-hr of battery power that were charged either by the auxiliary engines (AEs) or by shore power when at berth.

1.2 EPA verifies Foss hybrid technology

In another project, a traditional tug, the *Campbell Foss*, was converted to a hybrid. On completion of the conversion of the *Campbell* from traditional to hybrid, Foss applied for and received the first technology to be EPA verified for maritime hybrid conversion[1]. The EPA list[2] of verified technologies provides the benefits when someone uses that technology. Those values are shown in Table 1-1**Error! Reference source not found.** and state PM, NOx and CO_2 are reduced by 25%, 30% and 30%, respectively.

[1] EPA Verification http://www3.epa.gov/otaq/diesel/documents/verif-letter-foss.pdf June 28, 2013
[2] http://www3.epa.gov/otaq/diesel/verification/verif-list.htm

Table 1-1 Foss Maritime/AKA on EPA's List of Verified Technologies

			Reductions (%)				
			PM	NOx	HC	CO	CO2
Foss Maritime /AKA	XeroPoint Hybrid Tugboat Retrofit System	Harbor tugboat vessels with auxiliary generator engines with rated horsepower range between 100 and 750 hp and main propulsion engines up to 5,000 hp each	25	30	15	35	30

The EPA verification letter described the technology as follows: "This technology is approved for Foss Maritime Company and Aspin Kemp & Associates (Foss Maritime / AKA) XeroPoint Hybrid Tugboat Retrofit System. The XeroPoint system replaces one of the boat's auxiliary engines and generator sets with a suitably sized new larger generator set and new larger horsepower engine that must comply with current model year EPA emission standards. The XeroPoint system includes the main hybrid switchboard, DCDC converter cabinet, junction boxes, wheelhouse hybrid control, hybrid E-stop panels, clutches, energy management system, 24V DC uninterruptible power supply and optional batteries. The XeroPoint system uses Programmable Logic Controllers (PLCs) that are custom programmed to manage and control engine and motor speeds based on throttle demand and the selected mode of operation. The PLC will also control ancillary systems such as environmental (fans, heaters, water cooling), battery monitoring, clutch operation, system monitoring and data logging. The optional batteries are expected to yield minimal emission reduction benefits except in cases where the vessel has access to on-shore power."

2 Project Plan

2.1 Objective

The primary objective of this project was to figure the benefits of repowering the *Campbell Foss* hybrid tugboat when one of its auxiliary engines meeting Tier 2 standards was replaced with a auxiliary engine meeting Tier 3 standards. All other engines, batteries and energy management system were as originally installed. The tugboat operates in the Los Angeles air basin, the area labeled by EPA as having the highest emissions in the nation.

2.2 Approach

The approach to calculate the criteria and greenhouse emission benefits of the repowered hybrid tug was based on previous measurements of:

1) Activity profile while this tug was operating,
2) Emissions at specified load points for the original engines, and
3) Emissions at the same specified load points when one auxiliary engine was upgraded.

Measurement data for the activity and emissions of the original engines came from earlier UCR reports to Foss, the California Air Resources Board and the US Environmental Protective Agency. Data for the new Tier 3 auxiliary engine came from the manufacturer. As explained later, the activity data and emission values were substituted into equations and that allowed the project to calculate the benefits of repowering without making additional emission measurements.

2.3 Tugboat power systems

Details of the original power sources on the *Campbell* tugboat are described in Table 2-1. The Campbell Foss also had 65 kW-hr of battery power from 10 lithium polymer batteries.

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

	Main Engine (ME)	Auxiliary Engine (AE 1)	Auxiliary Engine (AE 2)
Manufacturer /Model	CAT 3512	John Deere 6081	MTU/DDC 60
Manufacture Year	2005	2004	2011
Certification Standard	Tier 1	Tier 2	Tier 2
Technology	4-Stroke Diesel	4-Stroke Diesel	4-Stroke Diesel
Max. Power Rating /Kw	1902	195	350
Max. GenSet Rating /Kw		125	
Rated Speed /rpm	1800	1800	1800
# of Cylinders	12	8	6
Displacement /liters	58.6	8.1	14

In this project, the John Deere auxiliary engine (AE1) meeting EPA Tier 2 standards was replaced with a John Deere engine meeting EPA Tier 3 standards as shown in Table 2-2. All other engines and batteries were unchanged.

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

	Main Engine (ME)	Auxiliary Engine (AE 1)	Auxiliary Engine (AE 2)
Manufacturer /Model	CAT 3512	John Deere 6068	MTU/DDC 60
Manufacture Year	2005	2014	2011
Certification Standard	Tier 1	Tier 3	Tier 2
Technology	4-Stroke Diesel	4-Stroke Diesel	4-Stroke Diesel
Max. Power Rating /Kw	1902	183	350
Max. GenSet Rating /Kw		166	
Rated Speed /rpm	1800	1800	1800
# of Cylinders	12	6	6
Displacement /liters	58.6	6.8	14

2.4 Tugboat activity

An average emission factor from any power unit depends on two factors: 1) activity and 2) emissions at given loads or during prescribed driving cycles. The activity is determined from the percentage of time a unit spends at a given load for steady-state cycles, like the tug follows. For this project we used the activity of the hybrid tug determined in previous two projects. Due to a major construction project of a bridge in the harbor, the activity determined in second project differed significantly from the first project in that the tug had a longer travel time for some projects when going around the construction. For this project, calculations were carried out with both measured routes in the harbor.

The following sections describe the typical operating modes of the tug boat 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.

2.4.1 Tug operating modes

Earlier it was determined that the hybrid tug, *Campbell*, follows five operating modes: *Stop*, *Idle*, *Transit 1*, *Transit 2* and *Assist*. In addition to these modes, *Shore Power* was determined from in-use activity data.

***Shore Power**:* When the tug is dockside, it is now plugged into shore power for all of its utilities and to recharge the batteries. Today both the hybrid and convention tugs operate on shore power when dockside.

***Stop**:* During this operation the tug boat is at the dock with one auxiliary engine operating for powering the lights, controls and air-conditioning. 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 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 while waiting for a vessel to arrive or for a call from the dispatch office to start or transit to a job. 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 hybrid boat operates its 350kW auxiliary engine for transit at slow speed <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 project, both jobs are considered under *Assist* as both main engines are operating irrespective of job nature. The hybrid boat operates both main engines. The 350kW auxiliary engine rarely operates during *Assist*.

Table 2-3 summarizes the power sources operating during each mode of operation.

Table 2-3: Power Sources Operating for each Activity Mode

Operational Modes	Main Engine #1 CAT 3512C	Main Engine #2 CAT 3512C	Auxiliary Engine #1 JD6081	Auxiliary Engine #2 DDC 60	Battery
Shore Power	Off	Off	Off	Off	Off
Stop (Dock)	Off	Off	On (as needed)	Off	On
Idle (Standby)	Off	Off	On (as needed)	Off	On
Transit	Off	Off	Off	On	Off (as needed)
FastTransit	Off	Off	On	On	Off (as needed)
Assist (Barge Move)	On	On	Off	Off	On (as needed)

2.4.2 Establishing Weighting Factors for Tugboat Operating Modes

The weighing 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. The data logger have five columns which represent five (*Stop*, *Idle*, *Transit 1*, *Transit 2*, *Assist*) operating modes of the tugboat. The 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. The weighting factors for a conventional and hybrid tugboats were shown in earlier projects were shown to be the same.

2.4.3 Developing Engine Histograms

Engine histograms are graphs with the percentage of time that a power source operates at different loads. In this project engine histograms were developed for all four engines for each operating mode. During the data logging segment of data collection, 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. Since auxiliary engines

are constant speed diesel generators, the percent load from the ECM was multiplied by the maximum rated load of the engine in kW to get the load on the engine. The main propulsion engines were 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.

Using these data, the fraction of time spent by an engine for a particular operating mode was calculated. The percentage was plotted as engine histograms. The engine histograms developed from the CSV files are used to calculate the total emissions from a tug. It was important for the state of charge of the battery was unchanged at the start and end of each sample period. This approach eliminates 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 CARB[16] testing protocols for hybrid electric vehicles.

2.5 Emissions data

Emissions data were needed for the three original engines and for the replacement John Deere auxiliary engine.

2.5.1 Original auxiliary and main propulsion engines

Emission values as a function of RPM and load for the two main propulsion engines, CAT 3512C, and for the original auxiliary engines, MTU/DDC 60 and John Deere 6081, were assumed to be the same as measured in earlier programs. Studies have shown that the deterioration rate for emissions from modern engines is a slow process so this assumption is based on good engineering judgment.

2.5.2 Repowered John Deere auxiliary engine

The John Deere 6081 engine rated at 125kW was replaced by a John Deere 6068 rated at 166kW so there was more power in the replacement engine than originally installed. originally present. Modal emission values for the gaseous emissions for the John Deere 6068 were available in the certification data for the John Deere 6068 engine family. The emissions rates in grams per hour as a function of engine load for NOx and CO_2 are shown in Figure 2-1 and Figure 2-2 for both the JD 6081 and JD 6068. Note the NOx data for the Tier 3 engine is less than the Tier 2 engine, as expected; however, there is about the same CO_2 rates for both engines, suggesting there will be the same greenhouse gas emissions.

Modal PM data for the JD 6081 were measured in earlier projects and data for the JD 6068 were considered confidential so only the overall emission rate and factor is provided in this report. Those values are 8.19 grams per hours and 0.10 grams per kW-hour.

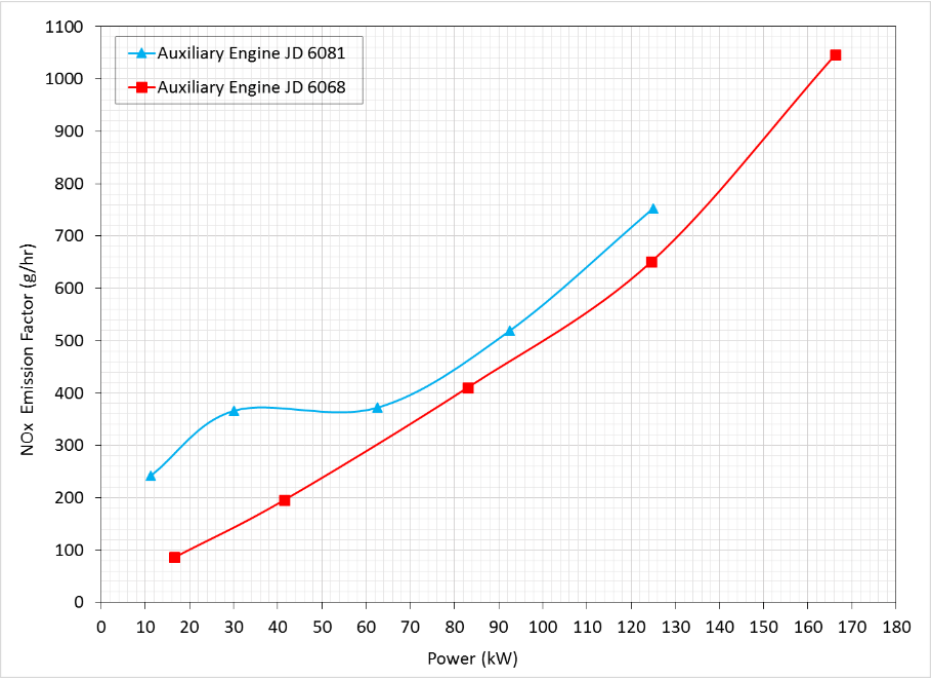

Figure 2-1 NOx Emission Factor

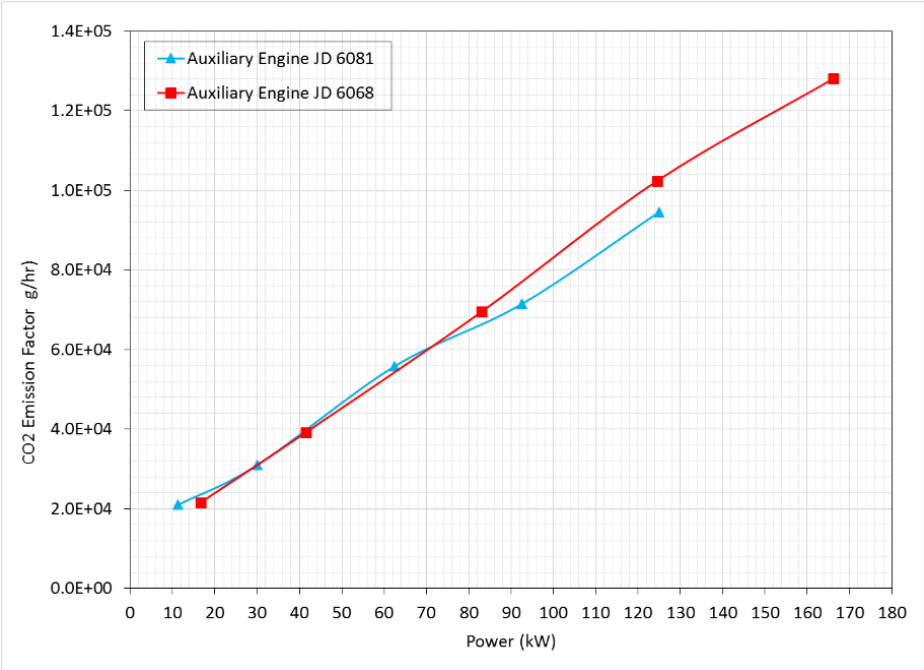

Figure 2-2 CO_2 Emission Factor

2.6 Analytical calculations

Listed below is the approach used to calculate the emission benefits of the repowered *Campbell Foss* hybrid tugboat.

a) The activity for this hybrid tugboat was assumed to be the same as previously measured
b) The emissions were figured at specified load points based on curves of emission rates versus power. The curves were generated in an earlier project for the Caterpillar, MTU/DDC and John Deere 6081 engines. The emission rate curves for the JD 6068 engine were provided by John Deere.
c) Activity and engine histogram data coupled with the emissions data were used to determine the total in-use emission rates in grams/hour for the tugboat in the original configuration and after one of the auxiliary engines was repowered.
d) The total emissions were then used to calculate the reduction of the gaseous and particulate matter species with the repowered hybrid tugboat.

A detailed description of analyses techniques used to determine the emission reduction potential of the hybrid system is provided below. The emission benefits of a hybrid tug were calculated as follows

$$\boldsymbol{Emission\ Reduction}\ \% = \frac{TE_c - TE_h}{TE_c} \times 100$$ ---------- **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:

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

where,

TE total in-use emissions in g/hr
n total number of operating modes
m the total number of power sources on the tug
W_i weighting factor for i^{th} operating mode
E_{ij} total in-use emissions in g/hr from the jth power source for the ith operating mode

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

$$\boldsymbol{W_i} = \frac{t_i}{t_{total}}$$ ---------- **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:

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

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 was obtained from the engine histograms

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

2.6.1 Calculation of emission rate in g/hr

Mass emissions of CO_2, NO_x and CO in g/hr were calculated 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.

2.6.2 Calculation of over emission factor 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:

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

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 Discussion

3.1 Emission rates for the original *Campbell Foss* hybrid tugboat

The primary gaseous emissions measured during the earlier test program included a greenhouse gas carbon dioxide (CO_2), and the criteria pollutants: nitrogen oxides (NO_x), carbon monoxide (CO). Each of these gaseous species was based on the previous measurements. In addition to gaseous emissions, the $PM_{2.5}$ mass emissions were calculated. 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 Table 3-1 and Table 3-2, respectively.

Table 3-1 Emission factors for hybrid tugboat in g/hr

Load (%)	NOx	CO2	PM	NOx	CO2	PM	NOx	CO2	PM
	Main Engine CAT 3512C (g/hr)			Auxiliary Engine JD 6081 (g/hr)			Auxiliary Engine DDC 60 (g/hr)		
100	14,078	1,257,418	207	753	94,530	45.0	2,507	259,240	24.5
75	11,728	922,501	190	519	71,380	37.0	1,879	194,126	12.6
50	8,638	615,489	101	372	55,781	23.0	1,075	129,138	15.4
25	4,860	300,463	32	366	30,950	17.0	506	77,094	10.9
10	2,299	121,606	10	242	20,920	8.6	174	29,843	6.0
Idle							144	26,111	6.2

Table 3-2 Emission factors for hybrid tugboat in g/kW-hr

Load (%)	NOx	CO2	PM	Load (%)	NOx	CO2	PM	NOx	CO2	PM
	Main Engine CAT 3512C (g/kWh)				Auxiliary Engine JD 6081 (g/kWh)			Auxiliary Engine DDC 60 (g/kWh)		
100	7.4	663	0.11	**100**	6.0	756	0.36	7.7	793	0.07
75	8.1	639	0.13	**75**	5.6	772	0.40	7.4	762	0.05
50	9.1	647	0.11	**50**	5.9	892	0.73	6.1	729	0.09
25	10.9	671	0.07	**25**	12.2	1032	0.55	5.8	886	0.13
10	14.3	755	0.06	**10**	21.5	1860	0.76	5.0	861	0.17
Wt. Avg.	8.2	649	0.12	**Wt. Avg.**	7.1	870	0.42	6.7	776	0.08
EPA Tier 1	9.2		0.54	**EPA Tier 2**	*7.2**		0.20	*7.2**		0.20

***** Standard if for the sum of nitrogen oxides and total hydrocarbon emissions

3.2 Emission rates for the repowered *Campbell Foss* hybrid tugboat

In this project, emissions from the Caterpillar and the MTU/DDC engines were assumed to be the same as measured in an earlier project. Then using the John Deere data for the JD 6068, the benefits for the greenhouse gas and criteria pollutants of the repowered *Campbell Foss* could be calculated. Table 3-3 and Table 3-2 show gaseous and particulate emissions in g/hr and g/kW-hr, respectively.

Table 3-3: Emission factors for repowered hybrid tugboat in g/hr

Load (%)	NOx	CO2	PM	NOx	CO2	PM	NOx	CO2	PM
	Main Engine CAT 3512C (g/hr)			Auxiliary Engine JD 6068 (g/hr)			Auxiliary Engine DDC 60 (g/hr)		
100	14,078	1,257,418	207	1047	128,090	-	2,507	259,240	24.5
75	11,728	922,501	190	650	102,340	-	1,879	194,126	12.6
50	8,638	615,489	101	410	69,410	-	1,075	129,138	15.4
25	4,860	300,463	32	196	39,140	-	506	77,094	10.9
10	2,299	121,606	10	86	21,510	-	174	29,843	6.0
Idle						-	144	26,111	6.2

Table 3-4: Emission Factors for repowered hybrid tugboat in g/kW-hr

Load (%)	NOx	CO2	PM	Load (%)	NOx	CO2	PM	Load (%)	NOx	CO2	PM
	Main Engine CAT 3512C (g/kWh)				Auxiliary Engine JD 6068 (g/kWh)				Auxiliary Engine DDC 60 (g/kWh)		
100	7.4	663	0.11	**100**	5.7	693	-	**100**	7.7	793	0.07
75	8.1	639	0.13	**75**	4.7	745	-	**75**	7.4	762	0.05
50	9.1	647	0.11	**50**	4.5	754	-	**50**	6.1	729	0.09
25	10.9	671	0.07	**25**	4.2	849	-	**25**	5.8	886	0.13
10	14.3	755	0.06	**10**	4.7	1169	-	**10**	5.0	861	0.17
Wt. Avg.	8.2	649	0.12	**Wt. Avg.**	4.7	819	0.10	**Wt. Avg.**	6.7	776	0.08
EPA Tier 1	9.2		0.54	**EPA Tier 3**	*4.0**		0.20	**EPA Tier 2**	*7.2**		0.20

***** Standard for the sum of nitrogen oxides and total hydrocarbon emissions

3.3 Weighting Factors for tug operating modes

Figure 3-1 shows the overall weighting factors for the hybrid tugboat. The figure shows that the dolphin class tug spends about ~51% of its total operating time at Stop plus shore power; ~2% in Idle; ~14% in Transit (Transit 1 and Transit 2); and ~33% in Assist, including barge moves.

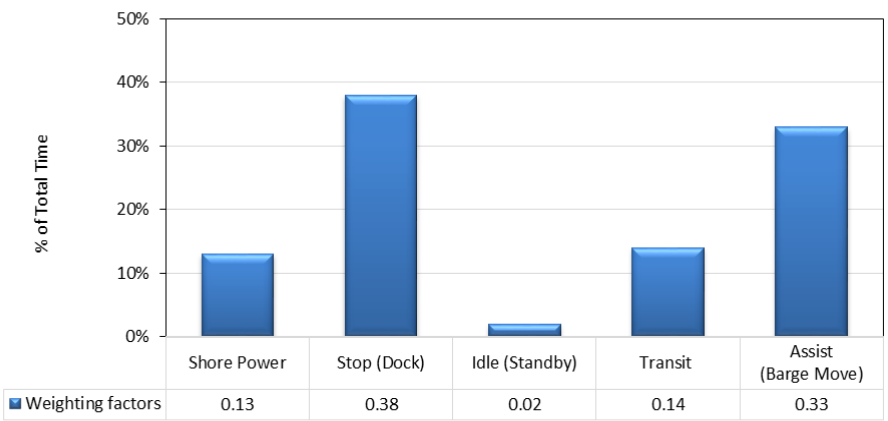

Figure 3-1: Overall Weighing Factors for Hybrid Tugboat Operating Modes

Tugboat operations in the port of Los Angeles and Long Beach harbor consist primarily of docking and undocking ocean going vessels such as containerships and bulk carriers, providing tanker escorts and moving barges used for bunkering in the harbor.

As mentioned earlier, weighting factors are determined by data logging and measuring the percentage of time that the tug spends in each of its operating modes. Sometimes

the weighting factors change so data logging is necessary to confirm earlier factors. For example, in the last study of the *Campbell Foss*, the percentage of time for barge movements increased. A deeper investigation revealed that the increase in time for barge movements was attributed to a bridge construction project in the harbor. The Campbell is normally berthed on Berth 49 at Pier D and the bunker barges are loaded at the Vopak fueling facility at Berth 187 in Los Angeles. In between Berth 49 and Berth 187 is the Schuyler Heim drawbridge over the Cerritos Channel. Until January 2012, the horizontal clearance under this bridge was 142 feet and allowed tugs moving barges to move freely under this drawbridge. However in January 2012, a Caltrans project began to replace the aging Schuyler Heim drawbridge and the width of a tug-barge combination could no longer physically navigate through the newly restricted channel. This construction project was expected to continue for five years at which point the trestles will be removed and the time for barge movements and weighting factors will change again. For this project, we used the same weighting factors as in the project converting the *Campbell Foss* to a hybrid tug.

3.4 Engine histograms for hybrid *Campbell Foss*

Stop Mode: In this mode both main engines are off similar to conventional *Campbell*. Energy required for hoteling purposes are either extracted from JD auxiliary engine (AE) or batteries. The MTU AE is rarely operated during Stop mode as shown in Figure 3-2.

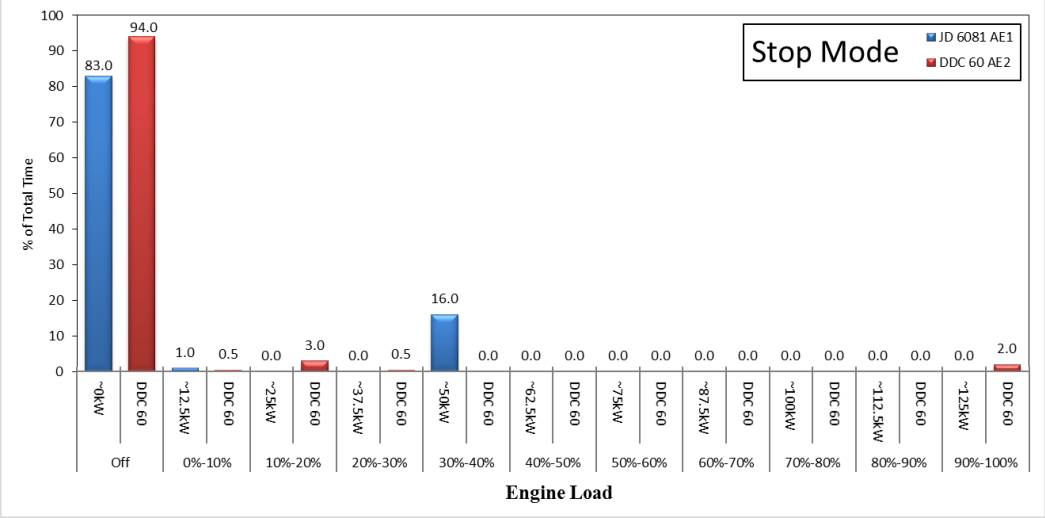

Figure 3-2: AEs histogram during Stop mode for Hybrid *Campbell*

Idle Mode: In this mode, both main engines are off in the hybrid. Both AEs and batteries switched between each other during Idle mode. AEs histogram for hybrid *Campbell* is shown in Figure 3-3.

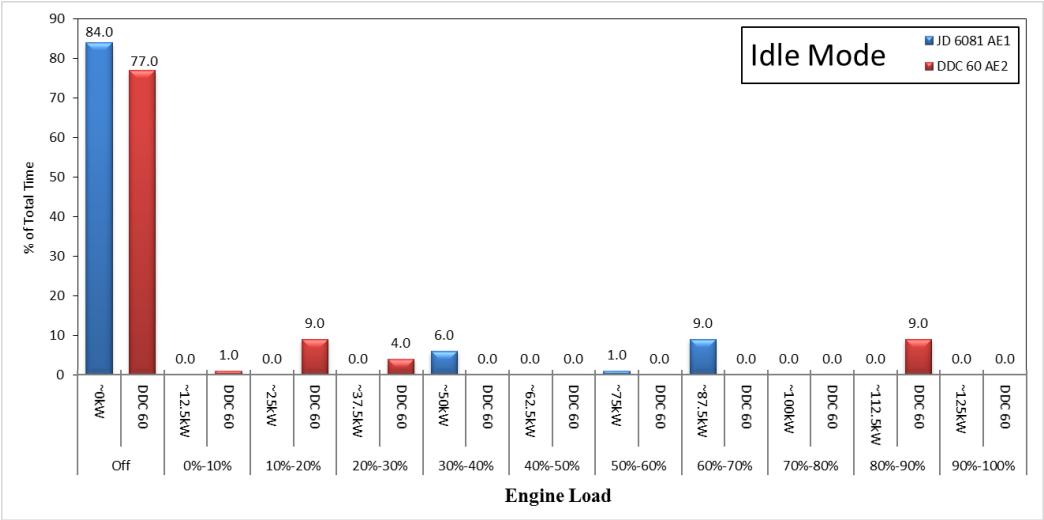

Figure 3-3: AEs Histogram during Idle Mode for Hybrid *Campbell*

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 as power can be supplied from the AEs and shaft coupler installed on the tugs. Either one AE or both AEs are operated in Transit mode depending upon the speed requirement. As the hybrid *Campbell* was propelled by AEs at mid-power range instead of MEs at very low power settings, significant emission benefits were expected and found in earlier studies during Transit mode on operating hybrid tug.

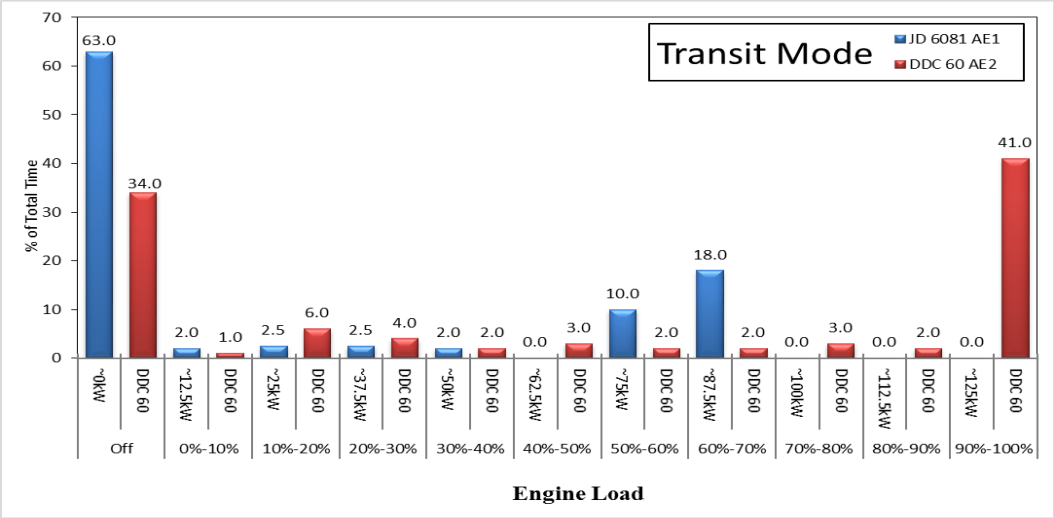

Figure 3-4: AEs Histogram during Transit Mode for Hybrid Campbell

Assist Mode: Both MEs are in operation for hybrid *Campbell* during Assist mode. MEs histogram during Assist mode is shown in Figure 3-5. AEs in the hybrid *Campbell* are rarely operated during Assist mode.

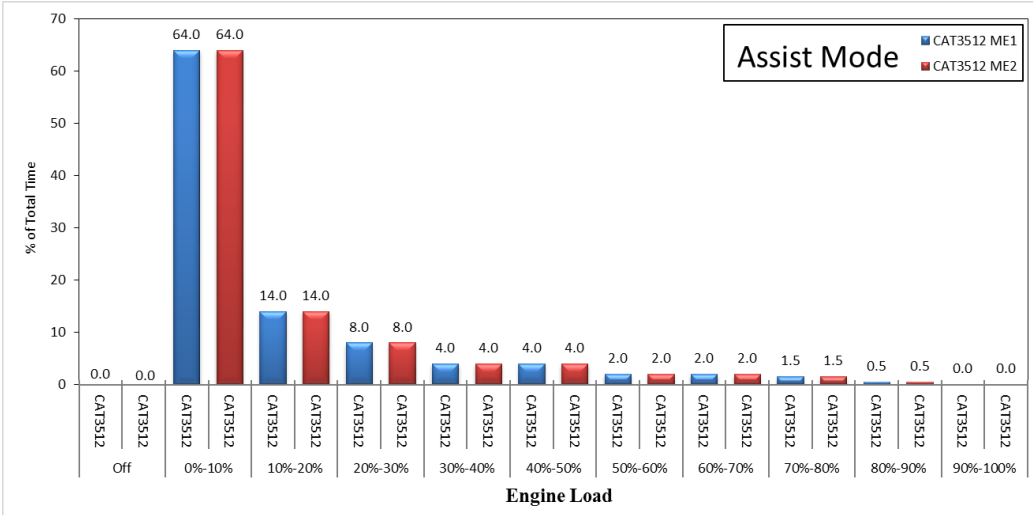

Figure 3-5: MEs Histogram during Assist Mode for Hybrid Campbell

3.5 Emission rates for shore power

The total emissions from each tug were calculated using the equations stated in Section 2.6. Emissions from each tug at a particular operating mode were calculated using engine histograms and engine emission profile data. 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 3-5: 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

3.6 Calculated total emission benefits

Table 3-6 shows modal and overall reductions in gaseous and particulate emissions comparing a conventional tug to: 1) emissions after conversion to a hybrid tug and 2) emissions after replacing a Tier 2 engine on the hybrid tug with a lower-emitting Tier 3 engine.

3.6.1 Modal benefits

Modal benefits vary with operation and comparison base. For example with NOx, there are no benefits for shore power between conventional and 1) hybrid tug or 2) repowered hybrid tug. However, in the stop mode when the AEs are operating, the emissions are reduced from 93 g/hr to 47 g/hr when converted to a hybrid tug and further reduced to 36 or ~25% when repowering the AE. Reductions in the transient and assist modes are basically non-existent.

3.6.2 Overall benefits

Overall benefits represent the total emissions of a working *Campbell Foss* in the harbor and are heavily weighted by the emissions for the Transient and Assist modes where emission rates are the highest values. The NOx data in Table 3-6 show a reduction of 35.5% is captured when converting to a hybrid tug and 35.9% in realized when repowering one of the AEs. For $PM_{2.5}$ the gains are 47.1% and 51.6% respectively.

Another perspective is the emissions reduction in the local inventory. For a tug operating 8,000 hours per year, the NOx reduction in converting to hybrid tug is 11.8 tons per year and for repowering one AE on the hybrid tug, the additional reduction is 0.13 tons per year. For PM, the respective numbers are: 0.15 tons per year and 0.015 tons per year. The greenhouse gas or CO_2 benefits of converting to a hybrid tug are 822 tons per year and no further benefits are realized by repowering am AE. Clearly the benefits of conversion to a hybrid tug are the most important investment.

Table 3-6 Modal & Overall Emission Rates with Hybrid & Repowered Tugboat

Operating Modes	Weighting factors			NOx (g/hr)			PM2.5 (g/hr)			CO2 (kg/hr)		
	Hyb_Yusuf	Hyb_Yusuf	Hyb_Model	Conv_Yusuf	Hyb_Yusuf	Hyb_Model	Conv_Yusuf	Hyb_Yusuf	Hyb_Model	Conv_Yusuf	Hyb_Yusuf	Hyb_Model
Shore Power	0.13	0.13	0.13	0.0002	0.0002	0.0002	0.00013	0.00013	-	0.002	0.002	0.002
Stop (Dock)	0.38	0.38	0.38	93	47	36	3.30	1.50	-	8.00	5.37	5.34
Idle (Standby)	0.02	0.02	0.02	96	6	6	0.60	0.15	-	3.70	0.76	0.76
Transit	0.14	0.14	0.14	1104	198	194	9.80	3.15	-	69.58	21.72	21.74
Assist (Barge Mov	0.33	0.33	0.33	2480	2182	2182	23.10	14.67	-	152.49	112.60	112.60
Overall	1.00	1.00	1.00	3773	2433	2418	36.80	19.47	17.81	233.77	140.45	140.44
%Reduction					**35.51%**	**35.91%**		**47.10%**	**51.61%**		**39.92%**	**39.92%**

4 Summary

The primary goal of this project was to calculate the emission benefits of a repowering a Tier 2 auxiliary engine with a Tier 3 auxiliary engine on the *Campbell Foss* hybrid tugboat. Towards that end, the activity profiles were calculated from the previous two hybrid evaluation projects and emission factors were calculated at specified load points.

The final analysis combined engine histogram and emission profile data to determine in-use emissions for the repowered hybrid. These figures were coupled with the weighing factors for the operating modes to get the overall in-use emissions in g/hr. significant emission benefits were observed for the hybrid technology and repowered auxiliary engine.

The major findings of this project include:

3. Emissions factors for the CAT 3512C MEs were within the Tier 1 standards. Similarly, for both AEs; JD 6068 and MTU/Detroit Series 60, emissions were within the Tier 3 and 2 standards, respectively.
4. 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 emission reductions as opposed to the energy storage device (batteries).
5. The hybrid design eliminated use of the main engines during the transit operating mode and this engineering change led to the significant 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.
6. Overall benefits for repowering an auxiliary engine were minimal for criteria pollutants as compared with converting a conventional to a hybrid tug. While there were some modal benefits, those operating modes had low emission rates; therefore a low overall emission benefit.
7. Significant greenhouse gas benefits were realized on converting to a hybrid tug but no further benefits were realized by repowering one of the auxiliary engines.

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Appendix A - 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.

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#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
1151 Fairview Avenue
Seattle, WA 98109

206.281.3800
www.foss.com
info@foss.com

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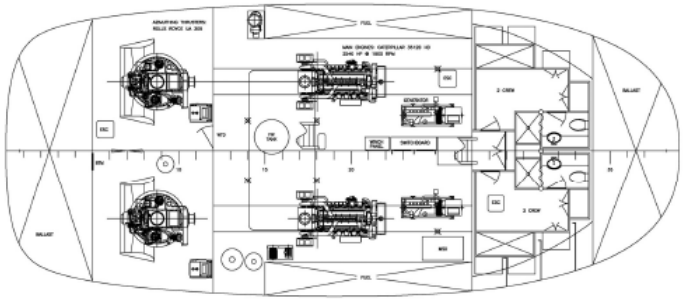
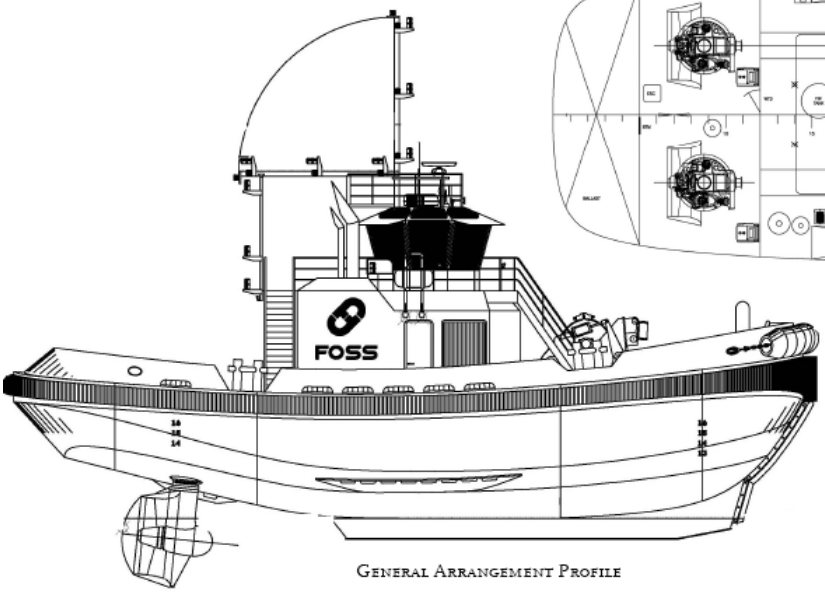


Hold Plan



General Arrangement Profile

Dolphin Class

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