Rubber-Tired Gantry Crane Hybridization Demonstration Project

Final Report

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The Port of Long Beach

The Port of Los Angeles

Prepared by:

Starcrest Consulting Group LLC on behalf of
Long Beach Container Terminal, Inc.
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EXECUTIVE SUMMARY

Long Beach Container Terminal, Inc. (LBCT) is a Port of Long Beach (POLB) terminal operator. Over the past several years, LBCT has partnered with the port in demonstrating several emission reduction technologies, including diesel oxidation catalysts in off-road cargo handling equipment, the use of alternative diesel fuels, alternative fuel and hybrid-electric yard tractors, as well as the demonstration of the Vycon® flywheel energy storage technology in a rubber tired gantry crane (RTG).

This project involved the demonstration of a RTG equipped with an advanced energy capture and battery storage system. The system, called EcoCrane™, was developed by R.J. Corman EcoPower Hybrid Systems, Inc., formerly Railpower Technologies, Inc. The project was sponsored by the Port of Long Beach and Port of Los Angeles (POLA) under the joint Technology Advancement Program (TAP). The cost of the demonstration project was $169,870, with LBCT providing a fifty-percent cost share. The balance of funds, $84,935, was provided by the TAP.

RTG cranes comprise approximately 6% of all cargo handling equipment at the San Pedro Bay Ports (POLA and POLB combined). However, RTG cranes contribute a disproportionally high amount of air pollutant emissions. Approximately 11% of oxides of nitrogen (NOx) emissions and 9% of diesel particulate matter (DPM) emissions from cargo handling equipment at the combined ports is emitted by RTG cranes.1

An RTG crane at LBCT typically operates two eight-hour shifts per day, four to five days per week. Typically, a single eight-hour shift requires the delivery of approximately 60 shipping containers to waiting terminal tractors or drayage trucks – this often requires three to four “picks” within the container stack to retrieve the desired shipping container. This equates to approximately 210 container “lifts” performed by an RTG during an eight-hour work shift.

A conventional diesel-electric RTG uses a diesel-fueled engine to generate electricity that powers electric motors used in container lifting as well as the motive power to move the RTG along the container stack. An RTG diesel genset used in port operations has a diesel engine rated, on average, at greater than 600 horsepower.

In the EcoCrane™ configuration, the diesel genset is equipped with a much smaller diesel engine – less than half of the rated horsepower of a conventional RTG. The reduced engine size and ability to turn the engine off during idling results in significantly lower fuel consumption and exhaust emissions. In addition, the smaller engine used in the EcoCrane™ genset is rated by the EPA at Tier 3, representing the current state-of-the-art for off-road diesel engines. This enables the EcoCrane™ to achieve substantial emission reductions as compared to a conventional RTG crane.

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The project started in July 2009. The EcoCrane™ components were received by LBCT at that time and installed into an existing RTG crane. Installation of the EcoCrane™ components was performed by LBCT employees and required approximately two months. Testing of the EcoCrane™ hybrid RTG began in September 2009.

Multiple engineering issues were initially encountered. These issues required several months to troubleshoot and resolve. This delayed the demonstration phase of the project by approximately one year. It is important to recognize that most, if not all, new technologies experience technical issues when first deployed. The majority of technical issues encountered during initial testing and demonstration of the EcoCrane™ were successfully resolved. The EcoCrane™ was commissioned on November 18, 2010 and placed into container handling operations at LBCT. Overall, the EcoCrane™ is performing satisfactorily in container handling operations.

The EcoCrane has an analytically-derived fuel consumption reduction of approximately 66.6%. It is estimated that NOx plus hydrocarbon emissions will be reduced approximately 77% as compared to a conventional RTG crane. Diesel particulate matter (DPM) reductions on the order of 65% are also expected. If a Level 3 particulate filter is retrofit to the EcoCrane™, a reduction in DPM on the order of 90% or greater is expected.

### Anticipated Benefits of EcoCrane™ Compared to Conventional RTG Crane

<table>
<thead>
<tr>
<th>Environmental Benefits</th>
<th>NOx + HC</th>
<th>PM</th>
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1.0 INTRODUCTION

Long Beach Container Terminal, Inc. (LBCT) is a Port of Long Beach (POLB) terminal operator. Over the past several years, LBCT has partnered with the port in demonstrating several emission reduction technologies, including diesel oxidation catalysts in off-road cargo handling equipment, the use of alternative diesel fuels, alternative fuel and hybrid-electric yard tractors, as well as the demonstration of the Vycon® flywheel energy storage technology in a rubber tired gantry crane (RTG).

This project involved the demonstration of a RTG equipped with an advanced energy capture and battery storage system. The system, called EcoCrane™, was developed by R.J. Corman EcoPower Hybrid Systems, Inc., formerly Railpower Technologies, Inc. The project was sponsored by the Port of Long Beach and Port of Los Angeles (POLA) under the joint Technology Advancement Program (TAP). The cost of the demonstration project was $169,870, with LBCT providing a fifty-percent cost share. The balance of funds, $84,935, was provided by the TAP.

This report will provide: a) a technical overview of the EcoCrane™ system, including system specifications and operating parameters; b) the demonstrated performance of the EcoCrane in container handling operations at LBCT; c) issues encountered and resolutions implemented during the demonstration period, and d) estimates of reductions in fuel consumption and diesel emissions attributable to the EcoCrane™. These results are discussed in the following sections of this Final Report.
2.0 PROJECT OVERVIEW

A Rubber Tired Gantry crane (RTG crane) is a mobile gantry crane used for stacking intermodal containers within the stacking areas of a container terminal. They are the most common yard handling system at the world's largest container terminals and provide a practical and economical solution when straddling multiple lanes of container storage or when maximum storage density in the container stack is desired.

RTG cranes comprise approximately 6% of all cargo handling equipment at the San Pedro Bay Ports (POLA and POLB combined). However, RTG cranes contribute a disproportionally high amount of air pollutant emissions. Approximately 11% of oxides of nitrogen (NOx) emissions and 9% of diesel particulate matter (DPM) emissions from cargo handling equipment at the combined ports is emitted by RTG cranes.2

An RTG crane at LBCT typically operates two eight-hour shifts per day, four to five days per week. Typically, a single eight-hour shift requires the delivery of approximately 60 shipping containers to waiting terminal tractors or drayage trucks – this often requires three to four “picks” within the container stack to retrieve the desired shipping container. This equates to approximately 210 container “lifts” performed by an RTG during an eight-hour work shift.

This project demonstrated an advanced technology hybrid electric RTG crane in container movement operations at the Long Beach Container Terminal located on Pier F at the Port of Long Beach. The scope of the EcoCrane™ hybrid RTG demonstration project included the following tasks:

- Procurement of the EcoCrane™ system components;
- Assembly and retrofit of the EcoCrane™ components into an existing RTG at LBCT;
- System testing & validation;
- EcoCrane™ commissioning;
- EcoCrane™ demonstration in actual RTG container handling operations at LBCT;
- Documentation & reporting.

2.1 Technical Description & Concept of Operations

There are several variants of RTG, including diesel genset-electric, grid connected electric, and hybrid electric. LBCT has substantial experience in the operation of diesel genset-electric RTGs as well as hybrid electric RTGs that use the Vycon® flywheel energy capture and storage system.

A conventional diesel genset-electric RTG uses a diesel-fueled engine to generate electricity that powers electric motors used in container lifting as well as the motive power to move the RTG along the container stack. An RTG diesel genset used in port operations has a diesel engine rated, on average, at approximately 600 horsepower.

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During operation of a conventional diesel genset RTG, electric motors are used to lift the container and reposition the RTG along the container stack. Once in the proper position, the RTG lowers the container at a controlled rate. In a conventional RTG, the energy available when a container is lowered is wasted. In contrast, a hybrid RTG configuration captures the energy associated with lowering a container and stores it in an energy storage system. The energy is released on a subsequent container lift – the net amount of electricity required by the diesel genset is less due to the availability of the captured, or regenerated, energy. In the Vycon® hybrid RTGs used at LBCT, a mechanical flywheel is used to capture the potential energy associated with lowering a container and store it as kinetic energy in a rotating flywheel.

Instead of a mechanical energy capture and storage system, the EcoCrane™ uses a regenerative braking energy capture and storage system, similar to a hybrid-electric automobile. When a container is lowered using the EcoCrane, the motor used to lift the container is “reversed”; the motor becomes a generator, and the electricity produced as the container is lowered is directed to a bank of batteries - the electric energy storage system. The energy stored in the batteries can then be used to augment the EcoCrane’s™ electric motor during the crane’s subsequent lift.

Because batteries provide a portion of the energy used by the EcoCrane™ during container lifting, the amount of energy required from the diesel genset is substantially reduced. In the EcoCrane™ hybrid electric configuration, the reduction in power required from the diesel genset is greater than 50%. This means that the existing diesel genset can operate at a much lower load factor.

In the conventional RTG configuration, the diesel genset often undergoes periods of sustained idling. This is very inefficient for the diesel genset engine, resulting in increased fuel usage. In the EcoCrane™ configuration, the diesel genset engine is shut down during normal RTG idling times, with the RTG operated in an “all-electric” mode. Additionally, the EcoCrane is equipped with a much smaller diesel genset engine – less than half of the rated horsepower of a conventional RTG. The reduced engine size and ability to turn the engine off during idling results in significantly lower fuel consumption and exhaust emissions. In addition, the smaller engine used in the EcoCrane™ genset is rated by the EPA at Tier 3, representing the current state-of-the-art for off-road diesel engines. This also factors in to the potential for the EcoCrane™ to achieve substantial emission reductions as compared to a conventional RTG crane.
2.2 EcoCrane™ Hybrid RTG Specifications

The EcoCrane™ demonstrated during this project and currently used in container movement operations at LBCT has the following specifications:

Table 2.1: EcoCrane™ Technical Specifications

<table>
<thead>
<tr>
<th>GENSET DIESEL ENGINE SPECIFICATIONS</th>
<th></th>
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<tbody>
<tr>
<td>Manufacturer</td>
<td>John Deere</td>
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<tr>
<td>Engine Model</td>
<td>PE4045IO65474</td>
</tr>
<tr>
<td>Power (Prime)</td>
<td>134 kW</td>
</tr>
<tr>
<td>Operating Speed</td>
<td>1,800 PPM</td>
</tr>
<tr>
<td>Warm-up/Cool Down Speed</td>
<td>1,150 RPM</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>GENSET GENERATOR SPECIFICATIONS</th>
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</tr>
</thead>
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<tr>
<td>Manufacturer</td>
<td>Stamford</td>
</tr>
<tr>
<td>Generator Model</td>
<td>UC1274D1H-32D</td>
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<tr>
<td>Electrical Power Rating (Prime)</td>
<td>115 – 117 kW</td>
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<tr>
<td>Electrical Power Rating (Continuous)</td>
<td>80 kW</td>
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<tr>
<td>Voltage Rating</td>
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</tr>
<tr>
<td>Phase</td>
<td>3</td>
</tr>
<tr>
<td>Frequency</td>
<td>60 Hz</td>
</tr>
<tr>
<td>Operating Speed</td>
<td>1,800 PPM</td>
</tr>
<tr>
<td>Power System Stabilizer</td>
<td>Basler-100</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>EOCOCRANE™ BATTERY SPECIFICATIONS</th>
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</thead>
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<tr>
<td>Manufacturer</td>
<td>Exide</td>
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<tr>
<td>Battery Model</td>
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<tr>
<td>Amperage</td>
<td>180 AH</td>
</tr>
<tr>
<td>Voltage</td>
<td>6 V</td>
</tr>
<tr>
<td>Quantity</td>
<td>108</td>
</tr>
</tbody>
</table>
Design attributes of the EcoCrane™ are discussed in further detail in the following sections.

2.2.1 Diesel Genset Engine Description
As shown above, the EcoCrane™ hybrid RTG is equipped with a 134 kW (180 brake horsepower (bhp)) Tier 3 John Deere diesel engine. This engine replaced a Cummins KTA-19 diesel engine rated at approximately 507 bhp at an engine speed of 1,800 RPM. Therefore, the EcoCrane diesel engine is approximately 65% smaller than the conventional RTG diesel engine in terms of rated power. A comparison of the EcoCrane Diesel Engine as compared to the original RTG diesel engine is shown below in Table 2.2.

Table 2.2: EcoCrane™ Diesel Genset Engine as Compared to Conventional RTG Diesel Genset Engine

<table>
<thead>
<tr>
<th></th>
<th>Conventional RTG</th>
<th>EcoCrane™ RTG</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Rated Horsepower (bhp)</strong></td>
<td>507</td>
<td>180</td>
</tr>
<tr>
<td><strong>Fuel Consumption (1,800 RPM)</strong></td>
<td>27.3 gallons per hour</td>
<td>9.1 gallons per hour</td>
</tr>
<tr>
<td><strong>NOx + Hydrocarbon Emissions Standard</strong></td>
<td>4.8 g/bhp-hr³</td>
<td>3.0 g/bhp-hr</td>
</tr>
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</table>

As shown in the above Table, the oxides of nitrogen (NOx) plus hydrocarbon emissions of the Tier 3 John Deere engine are approximately 38% lower than RTG original equipment engine. Fuel consumption of the John Deere engine is also significantly lower than a conventionally-equipped RTG. The overall reduction in fuel consumption and air pollutant emissions for the EcoCrane™ compared to a conventional RTG are analytically derived in Section 4.1 of this Final Report.
2.2.2 *Genset Generator Description*

The EcoCrane™ is equipped with a constant speed/direct current (DC) generator optimized for the *average* container lifting load. This differs from a conventional RTG crane whose generator is sized to accommodate the *peak* or maximum, lifting load condition. The reason the EcoCrane™ generator can be downsized is because electrical energy stored in the battery pack can be used to augment the electrical energy produced by the smaller generator.

The DC current generated by the generator is converted to alternating current (AC) by the EcoCrane™ inverter system. This AC current is then directed to the EcoCrane AC Bus and used to power the electric drive motors that lift and position a shipping container. A schematic of the EcoCrane™ electrical system is shown below in Figure 1.

**Figure 2.1: EcoCrane™ Hybrid Electric RTG Power System**

Also shown schematically in Figure 1 is the Regenerative Braking Energy Capture System (Regen Brake). The regenerative braking system is coupled with the Battery Energy Storage System and allows energy that is otherwise dissipated as heat during container lowering to be captured, stored, and used for a subsequent container lift. As shown in Figure 1, the regenerative braking system is connected to the AC Bus, which transfers the electric power to the electric drive motors used in container lifting, positioning, and movement along the container stack.

2.2.3 *Battery Energy Storage System*

Also shown in Figure 1 is the Battery Energy Storage System (Energy Store). The energy storage system consists of 108 6-volt batteries manufactured by Exide Corporation. DC power from the batteries is directed to the inverter to convert DC current to AC current. This electric power is then coupled to the AC Bus and used along with the genset–produced electricity to power to the EcoCrane’s electric motors.
To maximize the life of the batteries, the EcoCrane™ is equipped with a Battery Management System (BMS). The BMS regulates electricity flow to and from the battery pack. The BMS ensures battery design temperatures are not exceeded and that individual battery cells are recharged to an equal voltage. The EcoCrane™ BMS measures and regulates the voltage of each individual battery, and monitors the temperature of a set of three (3) batteries. The BMS also provides an indication if a battery has failed and requires replacement.

The expected life of an EcoCrane™ battery is two (2) years. Due to the available space and battery packaging constraints, the preferred battery maintenance procedure is to change out the entire 108 battery pack as a single unit as opposed to replacing individual failed batteries. The EcoCrane™ is capable of operating as a hybrid RTG with multiple individual battery failures; however, overall system performance will be degraded based upon how many individual batteries have failed or are operating at reduced capacity. The entire 108 battery pack is replaced at two years or whenever the number of individual battery failures degrades overall EcoCrane™ performance to an unacceptable level.
3.0 EcoCrane™ Demonstration in Cargo Handling Operations

3.1 Project Timeline

The project started in July 2009. The EcoCrane™ components were received by LBCT at that time and installed into an existing RTG crane. Installation of the EcoCrane™ components was performed by LBCT employees and required approximately two months. Testing of the EcoCrane™ hybrid RTG began in September 2009.

As discussed in Section 3.2, below, several engineering issues were initially encountered. These issues required several months to troubleshoot and resolve. This delayed the demonstration phase of the project by approximately one (1) year. The EcoCrane™ was commissioned on November 18, 2010 and placed into container handling operations at LBCT.

3.2 Issues Encountered & Resolved

Initial testing of the EcoCrane™ uncovered engineering issues that required design changes as well as replacement of system components. Issues encountered and resolved include the following:

- Inverter Failure – the EcoCrane™ uses a DC generator to supply current. This current must be converted to AC current to be used by the electric motors that support crane movement and lifting functions. This inverter failed during initial EcoCrane™ testing. The inverter was removed by LBCT and returned to the manufacturer (ABB, Inc.) to determine the cause of the failure; it was determined that the inverter had a manufacturing defect and a new inverter was provided by the manufacturer. This resulted in a delay of approximately two (2) months;

- Battery/Inverter Compatibility Issues – The EcoCrane™ designer (RailPower Technologies, Inc.) specified the battery depth of discharge limits for normal system operation. “Depth of discharge” refers to the percentage of electrical energy removed from the battery; e.g., at an 8-% depth of discharge the battery retains 20% of its stored energy. However, the limits established for normal operating battery depth of discharge resulted in the inverter shutting down, or “tripping”. This required LBCT personnel to manually reset the tripped inverter, resulting in disruptions in container movement operations. This issue was resolved by raising the battery depth of discharge threshold as well as modifying the operational parameters of the inverter unit;

- Generator Failure – the DC generator failed under warranty and was replaced by the manufacturer (Stamford). This resulted in a project delay of approximately two (2) months.

It is important to recognize that most, if not all, new technologies experience technical issues when first deployed. The majority of technical issues encountered during initial testing and demonstration of the EcoCrane™ were successfully resolved. Voltage faults do occasionally occur; LBCT mechanics continue to make adjustments to the EcoCrane™ voltage parameters. Overall, the EcoCrane™ is performing satisfactorily in daily container handling operations.
4.0 QUANTIFICATION OF EMISSION REDUCTION & FUEL CONSUMPTION BENEFITS

The following sections discuss estimated reductions in diesel fuel consumption and air pollutant emissions attributable to the EcoCrane™ as compared to a conventional diesel generator RTG crane.

4.1 Estimated Reduction in Fuel Consumption

The fuel consumption estimates included in the original proposal were analytically derived and projected reductions on the order of 65%. This initial estimate was based upon the performance characteristics of the John Deere 4045H Tier 3 replacement engine compared to the original equipment Cummins KTA-19 engine.

The EcoCrane™ utilizes a regenerative braking energy capture system coupled with battery energy storage that allows energy that is otherwise dissipated as heat during container lowering, to be captured, stored, and used for a subsequent container lift. The availability of this additional, stored electrical energy allows the EcoCrane™ to utilize a much smaller diesel genset as compared to a conventional RTG crane.

Specifically, the John Deere 4045H engine used as the diesel genset engine in the EcoCrane™ has a brake specific fuel consumption of approximately 64.8 lb/bhp-hr at 1,800 rpm, producing approximately 180 bhp (134 kW). This equates to approximately 9.1 gallons per hour of continuous operation. The original equipment Cummins KTA-19 engine produces approximately 507 bhp at 1,800 rpm at a fuel consumption rate of approximately 27.3 gallons per hour. Thus, assuming sufficient energy is available in the battery storage system, the EcoCrane has an analytically-derived fuel consumption reduction of approximately 66.6%.

The demonstrated reduction in fuel consumption, however, was less than the analytically derived value noted above. This was primarily due to an operational control strategy modification for the EcoCrane that was necessitated by voltage limitations associated with an inverter in the EcoCrane™ hybrid power system. This control strategy modification reduced overall system efficiency. Based upon operational data recorded from remote EcoCrane™ monitoring, it is estimated that the EcoCrane™ is capable of reducing diesel fuel consumption on the order of 35% to 40%.

4.2 Estimated Reduction in Air Pollutant Emissions

The original estimates for air pollutant emission reductions anticipated NOx and DPM reductions on the order of 85% and 90%, respectively. These estimates were analytically derived in accordance with the engine performance parameters included in Section 4.1, above, and assumed the EcoCrane™ would be retrofit with a CARB-verified diesel emission control system.

Refined emission reduction estimates have been subsequently derived for the EcoCrane™; however, it is important to state that the reduction estimates included herein are based upon the certified emissions standards of the original Cummins KTA-19 as compared to the John Deere 4045H certified by EPA at Tier 3. Actual emissions testing of the EcoCrane using a portable emissions monitoring system was not conducted by LBCT.
To estimate reductions in NOx, hydrocarbon (HC), and DPM emissions, the emissions standards of the original Cummins KTA-19 engine were compared to those of the Tier 3 John Deere 4045H engine. Also, the relative diesel genset power requirements of the EcoCrane were compared to the conventional RTG genset.

As an example, the NOx + HC emissions standard for the original Cummins KTA-19 engine is 4.8 g/bhp-hr. The NOx + HC emissions standard for the Tier 3 John Deere 4045H EcoCrane™ engine is 3.0 g/bhp-hr. The rated power for the KTA-19 engine is 507 bhp at 1,800 rpm; the John Deere engine is rated at 180 bhp at 1,800 rpm. The reduction in NOx + HC emissions as a percentage can be calculated as $1 - \left(\frac{3.0\ g/bhp-hr \times 180\ bhp-hr}{4.8\ g/bhp-hr \times 180\ bhp-hr}\right) \times 100$, or an estimated 77% reduction in NOx plus hydrocarbon emissions.

Diesel particulate matter reductions on the order of 65% are expected without additional exhaust after-treatment. If a Level 3 particulate filter is retrofitted onto the EcoCrane™, a reduction in DPM on the order of 90% or greater is expected.

Table 4.1: Anticipated Benefits of EcoCrane™ Compared to Conventional RTG Crane

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5.0 SUMMARY

The LBCT EcoCrane™ project demonstrated the application of hybrid-electric technology to cargo handling equipment in a marine terminal environment. Significant reductions in criteria air pollutant emissions, as well as reductions in fuel consumption and greenhouse gases, are being achieved by the EcoCrane™ as compared to a conventional diesel-electric RTG crane.

The experience gained and lessons learned from the LBCT project have resulted in EcoPower Hybrid Systems, Inc. modifying the original EcoCrane design and developing a second-generation EcoCrane™ hybrid RTG system.

The new EcoCrane™ design is equipped with alternating current (AC) motors and eliminates the high power inverter. Only a small inverter is installed to feed auxiliary AC requirements. Control, power electronics and hardware have also been improved. In addition, the new EcoCrane™ configuration is equipped with a dual battery pack of batteries with a total capacity of 440 amp-hours (Ah), as compared to the LBCT EcoCrane™ battery capacity of 180Ah. This new battery configuration was designed to adapt to the voltage and energy requirements of existing RTG crane drive systems.

Ports America will demonstrate this next generation EcoCrane™ at their West Basin Container Terminal. The new design has targeted reductions in diesel particulate matter of 85% and reductions in greenhouse gases on the order of 70%.

The EcoCrane™ will be tested over a twelve month period. Following successful completion of the demonstration phase, it is expected that EcoPower Hybrid Systems, Inc. will seek EPA and CARB verification for the EcoCrane™ system.

Questions or comments regarding this Final Report should be addressed to Rose Siengsubcharti, Environmental Specialist Associate, Port of Long Beach, at sieng@polb.com.