BNSF ZERO-AND NEAR ZERO-EMISSION FREIGHT FACILITIES PROJECT (ZANZEFF) DATA ACQUISITION SUPPORT

BNSF Contract Number BF 10015561

**TOPICAL REPORT:
RUBBER-TIRED GANTRY (RTG) CRANES**

SwRI Project 03.24318

Prepared for:
BNSF Railway Company
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John Hedrick

July 2021

Benefiting government, industry and the public through innovative science and technology

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This project was supported by the "California Climate Investments" (CCI) program.

Flexible Solutions for Freight Facilities is part of [California Climate Investments](), a statewide initiative that puts billions of Cap-and-Trade dollars to work reducing greenhouse gas emissions, strengthening the economy, and improving public health and the environment — particularly in disadvantaged communities.

DESIGN AND DEVELOPMENT DEPARTMENT
POWERTRAIN ENGINEERING DIVISION

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LIST OF ACRONYMS

CAN	Controller Area Network
CARB	California Air Resources Board
CCS	Combined Charging System
CO	Carbon Monoxide
CO2	Carbon Dioxide
COFC	Container on Flat Car
Ft-lb	Foot Pounds
GCWR	Gross Combined Weight Rating
GPH	Gallons per Hour
GPS	Global Positioning System
GVW	Gross Vehicle Weight
HP	Horsepower
HPQ	Hours per Quarter
H-RTG	Hybrid Rubber-Tired Gantry Crane
KM/Hr	Kilometer per Hour
kW-Hr/Q	kW-Hour per Quarter
Li-Ion	Lithium Ion
LPH	Liters per Hours
MFG	Manufacture
MPD	Mile per Day
MPH	Miles per Hour
MPQ	Milage per Quarter
NO	Nitrogen Oxide
NO_2	Nitrogen Dioxide
NO_x	Oxides of Nitrogen
O2	Oxygen
PIDs	Parameters Identifiers
RPECS™	Rapid Prototyping Electronic Control System
RPM	Revolutions per Minute
RTG	Rubber-Tired Gantry Crane
SJVAPCD	San Joaquin Valley Air Pollution Control District
SOC	State of Charge
SwRI	Southwest Research Institute
THC	Total Hydrocarbons
TOFC	Trailer on Flat Car
US-EPA	United States Environmental Protection Agency
VIN	Vehicle Identification Number
ZANZEFF	Zero and Near Zero Emission Freight Facilities

ACKNOWLEDGEMENTS

The project would like to acknowledge:

- California Air Resources Board (CARB) Mobile Source Control Division for funding this project to investigate Zero and Near Zero Emission Freight Facilities (ZANZEFF) at the BNSF Intermodal Yard.
- This project was supported by the "California Climate Investments" (CCI) program.
    - *Flexible Solutions for Freight Facilities is part of California Climate Investments, a statewide initiative that puts billions of Cap-and-Trade dollars to work reducing greenhouse gas emissions, strengthening the economy, and improving public health and the environment — particularly in disadvantaged communities.*
- San Joaquin Valley Air Pollution Control District (SJVAPCD).
- US-EPA's support on training on the PEMS units and the use of three of their loaner units.
    - Special thanks to Carl Fulper of the US EPA for his assistance.
- Support from SwRI's Ann Arbor, MI office to design, setup, and maintenance of the data loggers.
- Garrett Anderson of SwRI's San Antonio, TX office for data analysis and processing.
- Staff at BNSF's San Bernardino, CA and Stockton, CA Intermodal Yards.

EXECUTIVE SUMMARY

This project is in support of the California Air Resources Board (CARB) Mobile Source Control Division's Zero and Near Zero Emission Freight Facilities (ZANZEFF) solicitation to support transformative emission reduction strategies at freight facilities. The San Joaquin Air Pollution Control District (SJVAPCD), in partnership with BNSF Railways (BNSF), received funding through ZANZEFF for the Flexible Solutions for Freight Facilities Project to demonstrate zero and near zero emissions cargo handling equipment in Stockton and San Bernardino, California, and in rail service between Stockton and Barstow, California.

This topical report focuses on the operational data obtained on a diesel Rubber-Tired Gantry (RTG) Crane and a Hybrid RTG (H-RTG), both operating in BNSF's San Bernardino Intermodal Yard, and an additional H-RTG operating in the BNSF Intermodal Yard in Stockton.

The H-RTGs had a 100 kW-Hr battery pack and demonstrated that they could complete between 33 and 43 lifts between operating the engine to recharge the batteries. This extended time between engine charging events greatly reduced the fuel cost per lift; $0.70 for the diesel RTG and an average of $0.09 for the H-RTGs. This means that the H-RTGs offered an ~87 percent reduction in the fuel cost per lift. Additionally, the NOx emissions per lift for the diesel was 0.82 grams per lift, while the H-RTG's averaged only 0.13 grams per lift; the H-RTG's NOx emissions per lift are ~85 percent lower than the traditional diesel RTG.

The H-RTGs had some early reliability issues, but over time Mi-Jack (the manufacture of the RTGs) worked out these issues and the H-RTGs operated well. However, over the demonstration period, the diesel RTG was used significantly more than the H-RTGs. Because of this disparity, the H-RTGs were not operated up to their full potential and had many days during the demonstration period when they were not used.

Based on this study, the H-RTGs have a significantly lower operating fuel cost and lower emissions. However due to early reliability issues and operators being less familiar with the H-RTG's operations, these units were used less and had longer average times to complete an average container lift (2.67 minutes per lift for the RTG vs. 3.32 minutes per lift for the H-RTG).

1.0 INTRODUCTION

This report supports BNSF's grant from the San Joaquin Valley Air Pollution Control District (SJVAPCD). The SJVAPCD, in partnership with BNSF Railway (BNSF), received funding for the Flexible Solutions for Freight Facilities Project (Project) through the California Air Resources Board (CARB) Mobile Source Control Division's Zero and Near Zero Emission Freight Facilities (ZANZEFF) solicitation. The Project entailed demonstrating zero and near zero emissions cargo handling equipment in Stockton and San Bernardino, California, and in rail service between Stockton and Barstow, California.

SwRI supported BNSF Railway in the Project, by taking on the responsibility for the "purchase, installation, and maintenance of data logging or other data collection equipment" as detailed in Appendix F "Data Collection Requirements" of the CARB ZANZEFF grant solicitation. Appendix A of this report includes the list of items for data collection and associated primary responsibility for the RTG portion of the ZANZEFF project.

2.0 BACKGROUND

SwRI supported the ZANZEFF project by collecting data on locomotives, rubber-tired gantry cranes (RTG), side pick cargo handlers, and drayage trucks, with examples shown in Figure 1.

Figure 1. Types of Equipment Instrumented

The goal of the project was to data log the operation of each piece of equipment performing its intended service for a minimum of three months. The diesel RTG was instrumented with the data logger for a total of 268 days, from 7-July-20 to 1-April-21 and operational data was logged for 221 days of this time. The Hybrid RTG (H-RTG) in San Bernardino was instrumented with the datalogger for a total of 146 days (4-Nov-20 to 30-March-21) and logged operations for a total of 57 days. The H-RTG in Stockton was instrumented for 119 days (30-Nov-20 to 29-March-21) with 46 days of operation logged. The list of parameters that SwRI recorded for this topical report is shown Appendix A.

2.1 BNSF San Bernardino Intermodal Yard

The BNSF San Bernardino Intermodal Yard is located at 1535 W. 4th Street, San Bernardino, CA. 92411. The yard covers more than 150 acres and has ~35,300 feet of track. The yard also has ~1,700 on-site parking spaces for containers in five different lots and additional container parking at Rancho West, Rancho East, and the Pit Property. All locations are shown in Figure 2.

This intermodal facility is a major component in BNSF's Inland Empire system and its primary focus is the loading / unloading of Trailer on Flat Car (TOFC), Container on Flat Car (COFC), and an Auto Facility (located south of Rancho West). This BNSF Intermodal Yard is used to support the transportation needs of consumer goods for many companies, including but not limited to:

- Amazon
- BMW
- Nordstom Rack
- Rite Aid
- Ross
- The Home Depot
- Walmart

Figure 2. Layout of the BNSF San Bernardino Intermodal Facility

Both a diesel RTG and one of the H-RTGs were operated in the San Bernardino Intermodal Yard. Typical RTG activity for this yard includes lifting shipping containers and trailers on and off rail cars along the length of intermodal trains. Figure 3 shows the movement of the diesel RTG "C18" on 08-DEC-2020. During the busy December timeframe, this crane was in operation essentially around the clock.

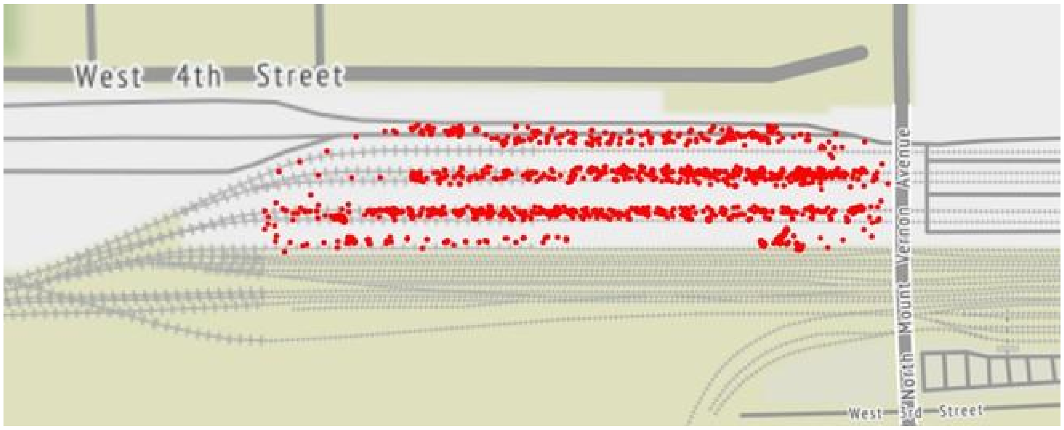
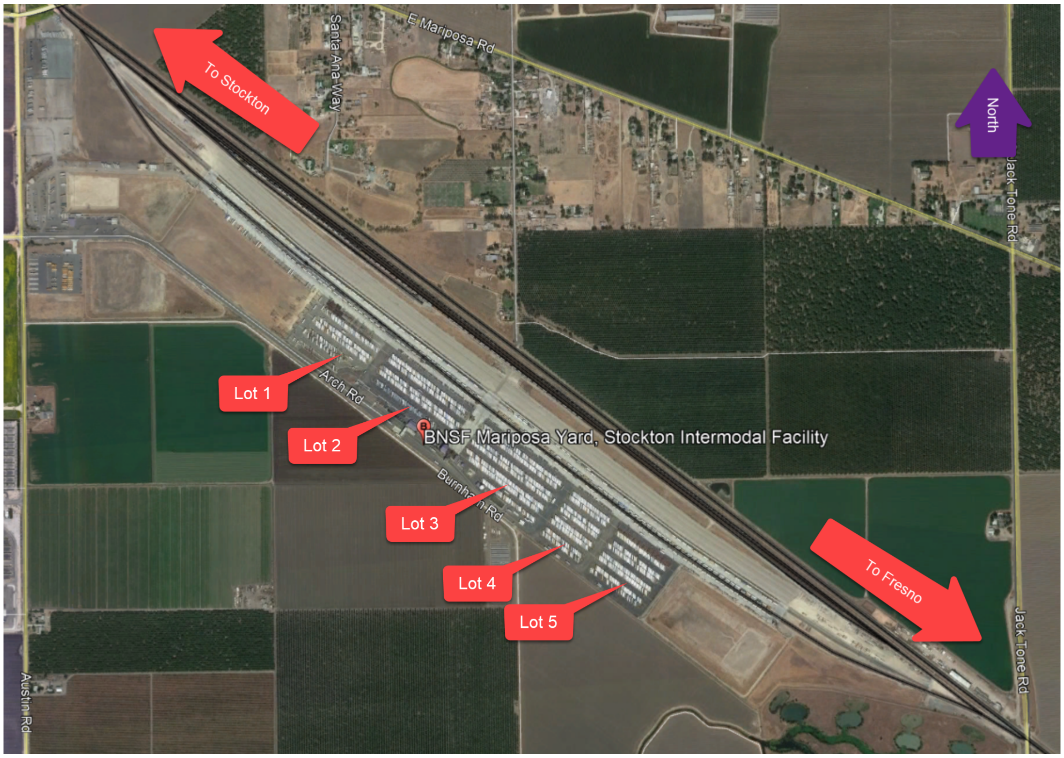


Figure 3. Diesel RTG Activity at BNSF's San Bernardino Intermodal Facility on 08-DEC-2020

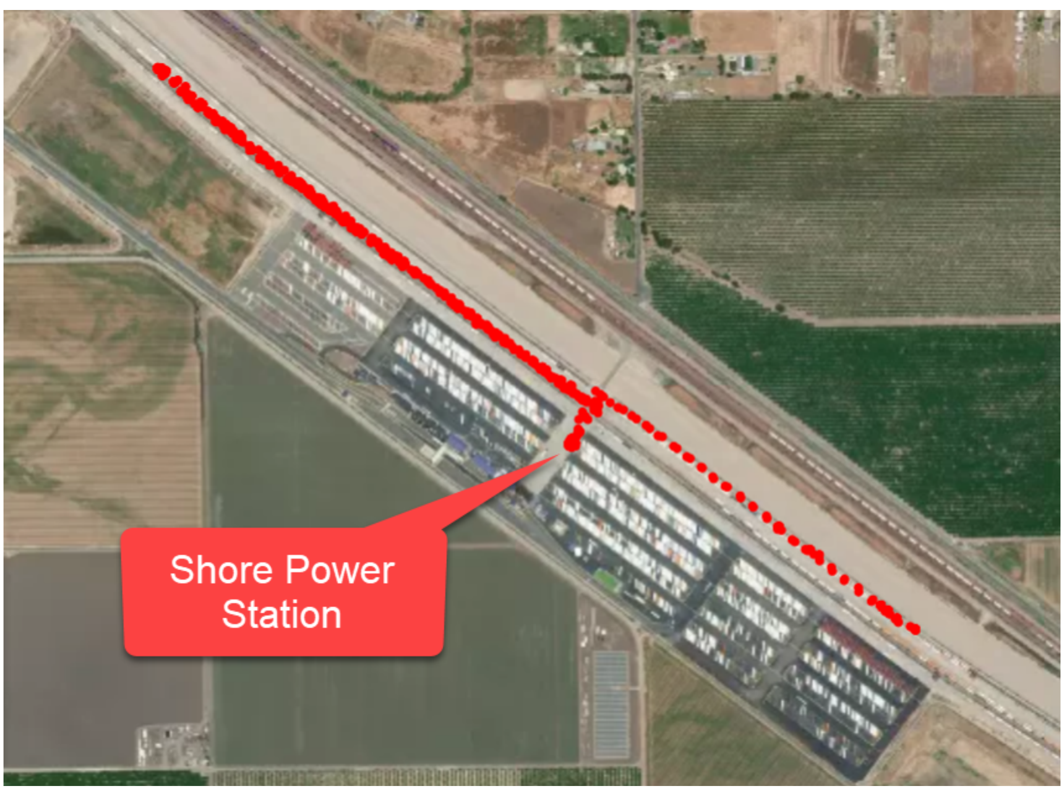
2.2 BNSF Stockton Intermodal Yard

BNSF's Stockton Intermodal Facility is located at 6540 S. Austin Road Stockton, CA 95215. The Yard occupies 425 acres and was designed to improve the efficiency of moving merchandise around Northern California. The facility contains two ~7,000-foot loading and unloading tracks with the ability to hold 150 intermodal railcars on each track. The facility also has three storage tracks that can accommodate an additional 230 intermodal railcars and has approximately 800 container and trailer parking spaces. Figure 4 shows the general layout of BNSF's Stockton Intermodal Yard. The second H-RTG was operated at the Stockton Intermodal Yard. Figure 5 shows the GPS activity of the H-RTG at Stockton over two, roughly 2-hour working periods on 22-Dec-20.



Google Earth image

Figure 4. BNSF's STOCKTON Intermodal Facility Layout



Google Earth image

Figure 5. Hybrid RTG Activity at BNSF's Stockton Intermodal Facility on 22-DEC-2020

2.2 Equipment Specifications - Diesel RTG – San Bernardino

The diesel fueled hydraulic RTG instrumented for this project was designated by BNSF as M1709, also known as "C18". C18 is a Mi-Jack Model 1200R and was assembled and handed over to the BNSF San Bernardino facility in December 2017 and was put into service on January 23, 2018. Additional details about C18 are shown in Table 1 and photos of the diesel RTG and various aspects of the RTG are shown in Figures 6 and 7.

Table 1. Diesel RTG Details

Make	Mi-Jack
Model	1200R
Machine SN	2408PD
Date of Manufacture	Nov. 2017

Figure 6. Diesel RTG C18

Figure 7. Diesel RTG Information Plate

The diesel engine used in C18 is a Cummins QSL8.9 manufactured in October 2016. The engine displacement is 8.9 liters and is rated at 333 HP @ 2,100 RPM. Additional details about the engine are shown in Table 2 and the engine name plate is shown in Figure 8.

Table 2. Diesel RTG Engine Details

Year Model	2016
EPA Engine Family	Cummins GCEXL08.9AAK
Serial number	74056221
Model	QSL9333
Displacement	8.9 Liters
Ratings	333 HP @ 2,100 RPM

Figure 8. C18 Diesel Engine Data Plate

2.3 Equipment Specifications – San Bernardino Hybrid RTG

The H-RTG procured, assembled, and deployed at BNSF's San Bernardino Intermodal Yard was designated by BNSF as M1927, also known as "C20". C20 is a Mi-Jack Model 1200REH hybrid-electric unit, built in 2019-2020. This crane was assembled and delivered to the BNSF San Bernardino facility in May 2020 and put into service in July 2020. Additional details are shown in Table 3 and photos of the H-RTG and various aspects of the H-RTG are shown in Figures 9 and 10.

Table 3. San Bernardino H-RTG Details

Make	Mi-Jack
Model	1200REH
Machine SN	2528
Date of Manufacture	2019

Figure 9. San Bernardino H-RTG

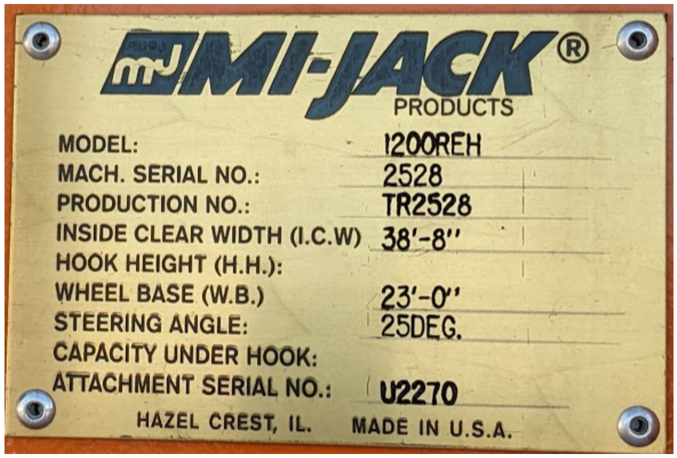


Figure 10. San Bernardino H-RTG Information Plate

The diesel engine used in C20 is a Cummins QSF3.8 manufactured in September 2019. The engine displacement is 3.8 liters and rated at 154 HP @ 2,200 RPM. Additional details about the engine are shown in Table 4, and the engine name plate is shown in Figure 11. Note that the engine displacement and power is roughly half of the engine in the conventional diesel RTG (C-18).

Table 4. San Bernardino H-RTG Engine Details

Year Model	2019
EPA Engine Family	Cummins KCEXL03.8AAF
Serial number	22395676
Model	QSF3.8
Displacement	3.8 Liters
Rating	154 HP @ 2,200 RPM

Figure 11. C20 Diesel Engine Data Plate

2.4 Equipment Specifications – Stockton Hybrid RTG

A second hybrid RTG (H-RTG) procured for the ZANZEFF project was operated in BNSF's Stockton Intermodal Yard. The Stockton H-RTG was designated by BNSF as M1928. M1928 is a Mi-Jack Model 1200REH hybrid-electric unit, built in 2019-2020. This crane was assembled and delivered to BNSF's Stockton facility in August 2020 and put into service in October 2020. Additional details are shown in Table 5, and photos of the H-RTG and various aspects of the H-RTG are shown in Figures 12 thru 14.

Table 5. Stockton H-RTG Details

Make	Mi-Jack
Model	1200REH
Machine SN	2529
Date of MFG	2019

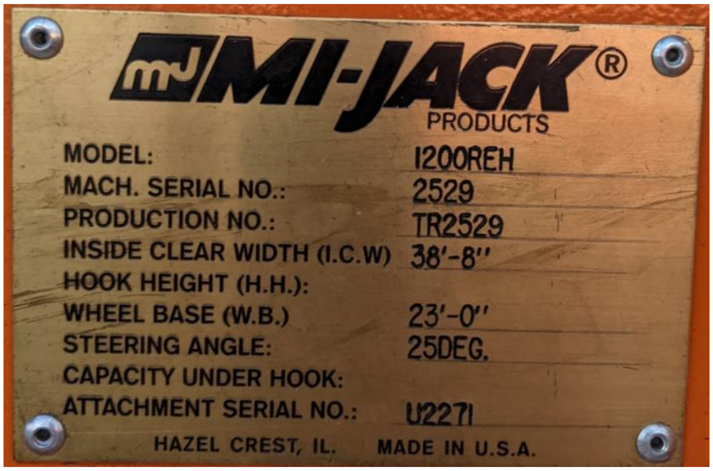


Figure 12. H-RTG Stockton Name Plate

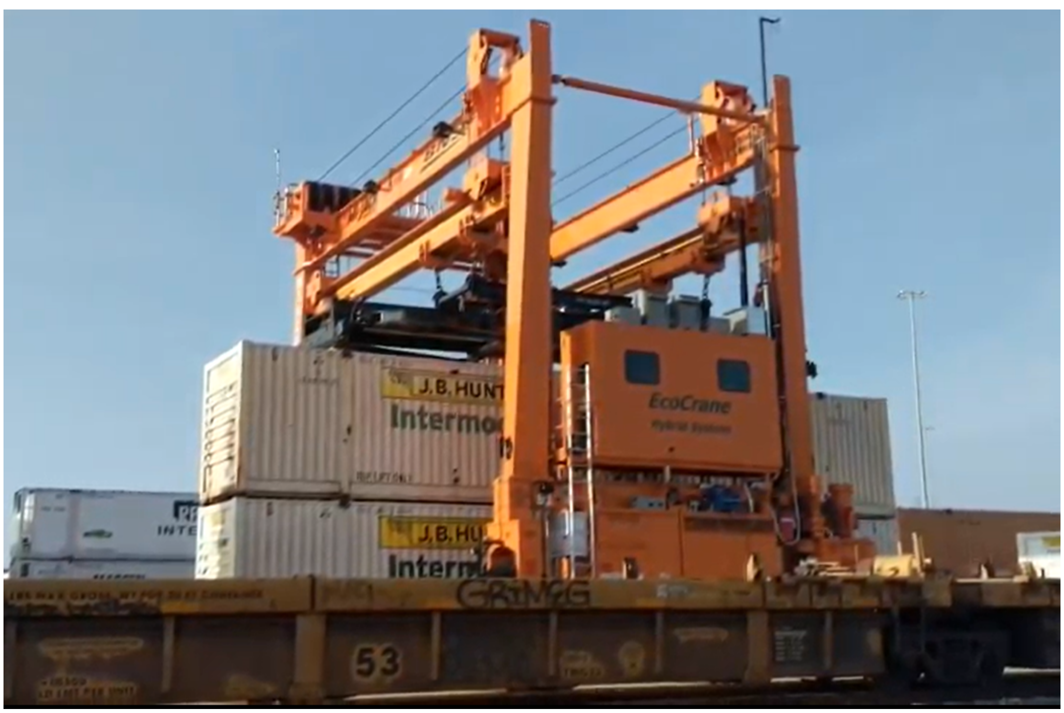


Figure 13. H-RTG Working in BNSF's Stockton Intermodal Yard

Figure 14. BNSF's Stockton Intermodal Yard H-RTG Engine Name Plate

2.5 H-RTG Battery Pack

The battery pack used in the H-RTG is a Li-Ion composition with a 600 - 800 VDC pack voltage range with a storage capacity of 100Kw-Hr. The battery system has an integrated Battery Management System (BMS). Mi-Jack reports that part of the BMS is an automated equalization system to maximize the battery life and charge capacity. The battery of the H-RTG can be charged using "shore power" (a term used by Mi-Jack, the manufacture of the H-RTGs), with the charge controller being built into the H-RTG system. However, only the H-RTG in Stockton utilized shore power charging.

2.6 Stockton H-RTG Shore Power

The H-RTG at Stockton was equipped to accept shore power, a term used by Mi-Jack (the manufacturer of the H-RTG), to charge the batteries during times when the H-RTG was parked close to and connected to the shore power system. The charging receptacle installed for this project uses 480 VAC three-phase power with a 60 Amp service. Figure 15 shows the 480 VAC three-phase H-RTG power connector (right photo) and the power cord receptacle at Stockton (left photo).

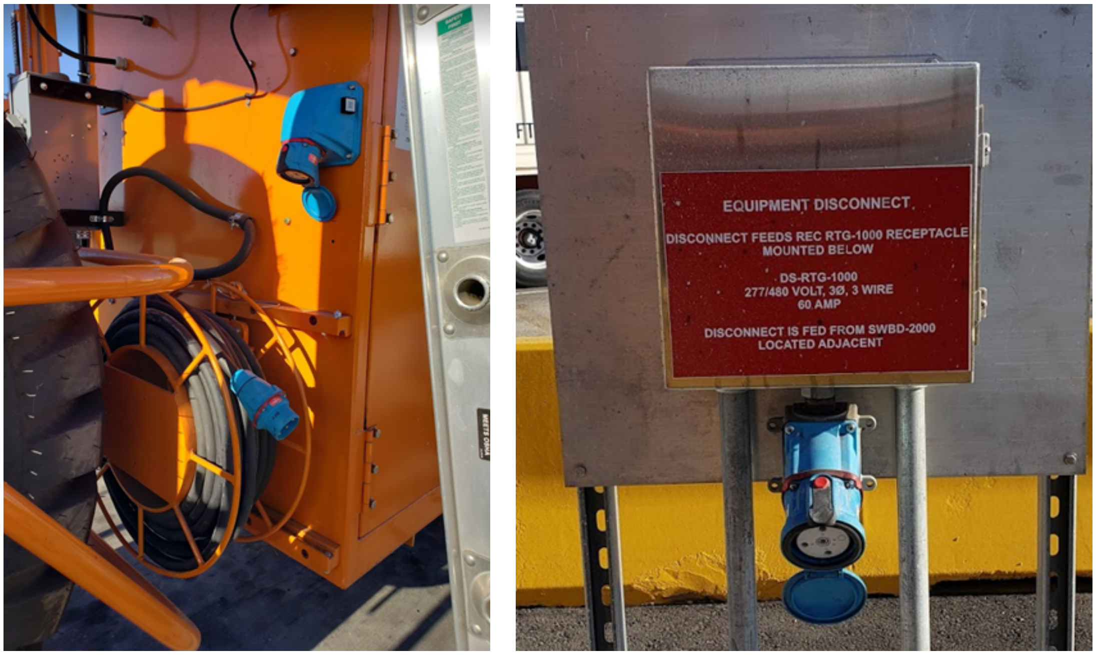


Figure 15. Stockton Shore Power Connector and H-RTG Receptacle

2.7 SwRI RPECS Data Logger

A general overview of the SwRI data logger is shown in Figure 16. At the heart of the system is SwRI's Rapid Prototyping Electronic Control System (RPECS™). RPECS is a powerful, reconfigurable, crank-synchronous platform capable of high-speed data acquisition and real-time engine control. RPECS includes a wide array of modular hardware and software that can be combined to fill complex research and prototyping needs. The RPECS system has evolved over 20 years of test and engine control technology.

The RPECS system monitored the J1939 CAN communication signals from the RTGs. This ability to read the J1939 CAN communication greatly reduced the amount of instrumentation that was needed to meet the project goals and increases the reliability of the system.

The data logger had a 4G LTE system that allowed SwRI staff to access the collected data and make software changes remotely.

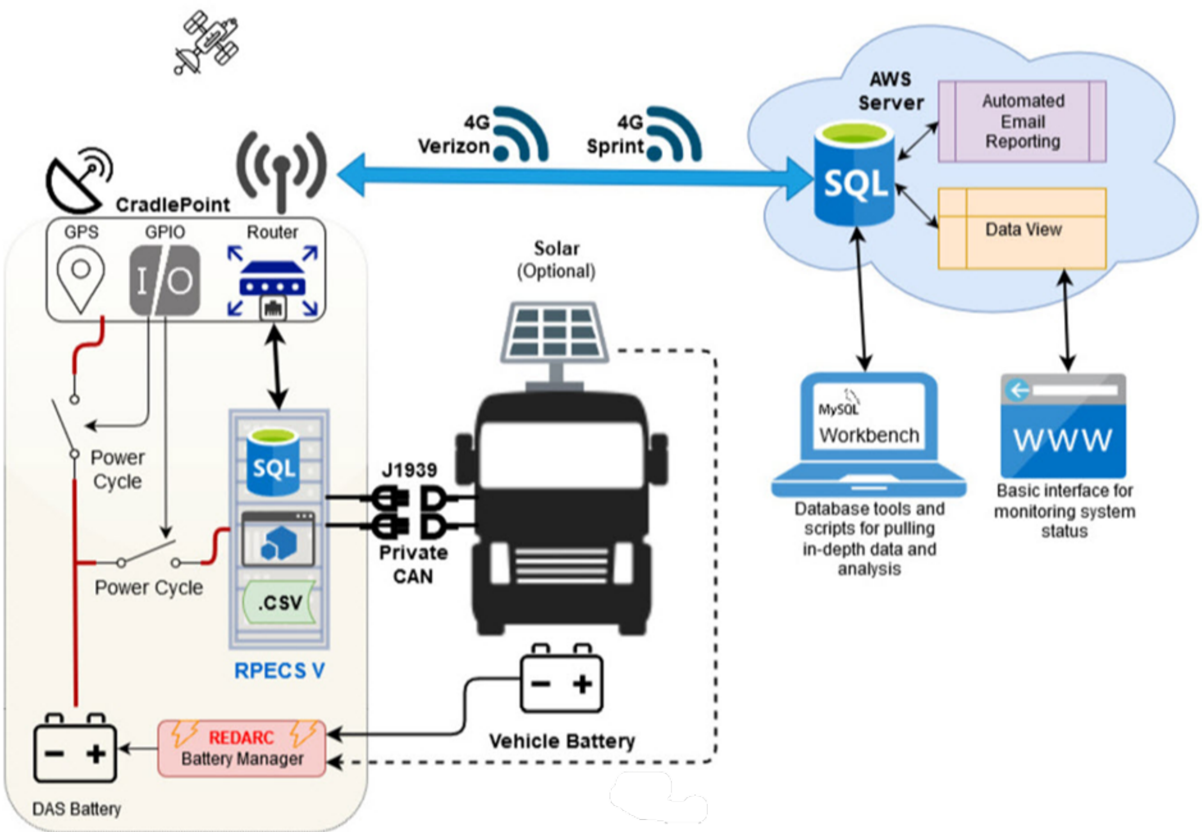


Figure 16. ZANZEFF RPECS Datalogger Overview

Figure 17 shows the RPECS datalogger system on the front of the engine compartment on the diesel RTG and in the electrical cabinet of the H-RTG. The RPECS system was mounted inside of a Pelican case to protect the system from dust, dirt, and other environmental concerns. The GPS antenna was attached to the top of the RTG engine compartment as shown in Figure 18. The RPECS system was connected to the CAN communication system in the engine compartment, at the engine diagnostic power and is shown in Figure 19.

The communication protocol was SAE J1939 signals, combined with some proprietary Parameters Identifiers (PIDs), over the J1939 communication bus. The proprietary PID addresses on the CAN bus were provided by MiJack that allowed the datalogger to monitor channels of interest that are unique to the MiJack RTGs.

Diesel RTG H-RTG

Figure 17. RPECS Datalogger Mounting Locations – Diesel RTG (Left) with RPECS Mounted Outside Engine Compartment and H-RTG (Right) Mounted Inside Electronics Car Body

Figure 18. Mounting Locations of the GPS Antenna

Figure 19. H-RTG CAN Bus Communications Port Location

3.0 VEHICLE OPERATION

The following report sections will describe the observed operating cycles for the diesel RTG and H-RTG located in BNSF's San Bernardino Intermodal Yard and the H-RTG operating in BNSF's Stockton Intermodal Yard.

3.1 Description of Daily Use / Duty Cycle

The daily duty cycles for the three RTGs are shown in Table 6. The diesel RTG in San Bernardino worked more hours and completed more lifts per day on average than the two H-RTGs. Due to differences in some of the controls on the H-RTG versus the diesel RTG, the operators tended to avoid using the H-RTG and use the diesel RTG when possible. These differences of the controls may also account for slower lift time per lift of the H-RTGs when compared to the diesel RTG. However, based on discussions with the various partners on this project, it is believed that the H-RTGs are capable of the duty cycle exhibited by the diesel RTG. Sections 3 and 4 of this report cover the Table 6 metrics in more detail.

Table 6. General RTG Duty Cycle Comparison

Equipment type	Diesel RTG	H-RTG	H-RTG
Location	San Bernardino	San Bernardino	Stockton
Calendar Days instrumented	268	146	119
Days of RPECS operation	257	105	72
Days of RTG operation [A]	221	57	46
RTG utilization (Percent)	86.0	54.3	63.9
Avg. hours per day [A & B]	13.7	4.7	5.5
Max hours per day [A]	20.6	18.1	13.5
Avg. lifts per day [A]	221	52	101
Max lifts per day [A]	353	132	213
Time per lift (Minutes) [C]	2.67	3.32	3.55
Fuel per lift (Gallons)	0.256	0.041 [D]	0.024 [D & E]
Fuel cost per lift (Dollars) [F]	0.70	0.11	0.07

[A] = Operating times less than 2 hours per day was not considered operating day.
[B] = Diesel RTG hours of operation calculated from change in engine hours broadcasted over the CAN network.
[C] = Lifts times were filtered by only using lift times that are greater than 1 minute but less than 15 minutes.
[D] = Fuel per lift is calculated by using the average Gallons per Day / Average Lifts per Day to cover times that the diesel engine operated when no lifts were taking place.
[E] = The H-RTG in Stockton used external power to charge batteries when parked which reduced the diesel fuel consumption when operating.
[F] = Average diesel fuel cost of $2.735 per gallon.

Due to the disparity in number of days, hours, and lifts per day between the diesel RTG and the two H-RTGs, close attention needs to be paid to the following figures when comparing the operation of the RTG's. In many cases the histogram "bins" along the X-axis will be different between the diesel RTG and the H-RTG's. Additionally, the Y-axis will be adjusted for each histogram graph to show the trends.

The differences in the duty cycle can be best shown by the differences in lifts per day. The diesel RTG in San Bernardino averaged 221 lifts per day and the histogram of the diesel RTG

(Figure 20) shows the relatively heavy utilization. For the histogram, average lifts for each day was calculated and each day's average lifts are shown in one of the bins on the X Axis. The Y Axis shows the sum of the days for each of the bins. As an example, Figure 20 has a bin labeled "<100" that has 5 samples; meaning that the diesel RTG only had 5 operating days that had less than 100 lifts.

Figure 21 shows histogram of the lifts per day for the H-RTG in San Bernardino which only averaged 52 lifts per day. The H-RTG in Stockton averaged 101 lifts per day and the histogram of the lifts per day is shown in Figure 22.

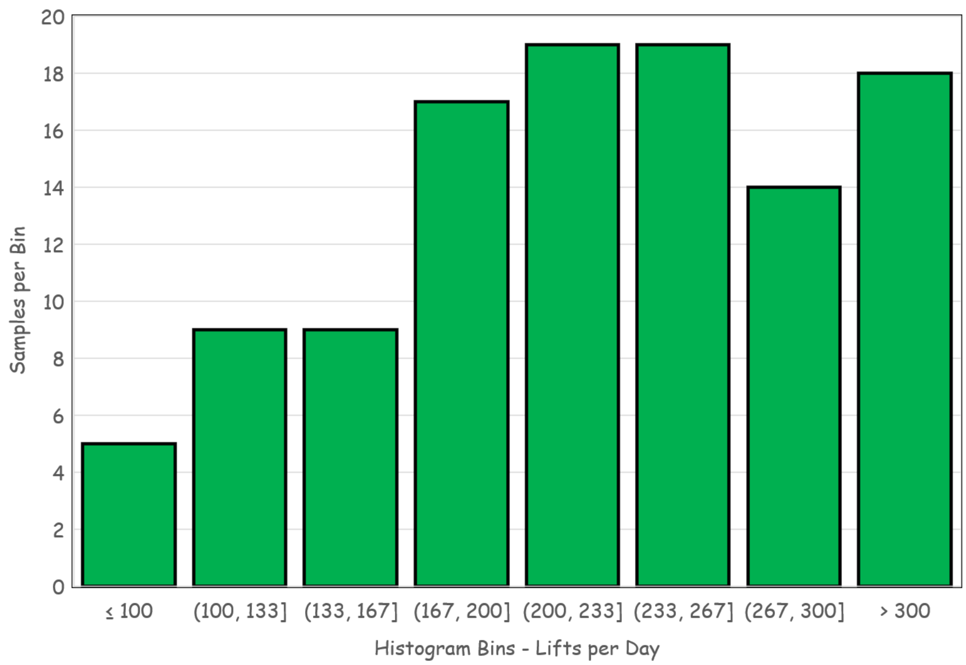


Figure 20. Diesel RTG (San Bernardino) Histogram of Lifts Per Day

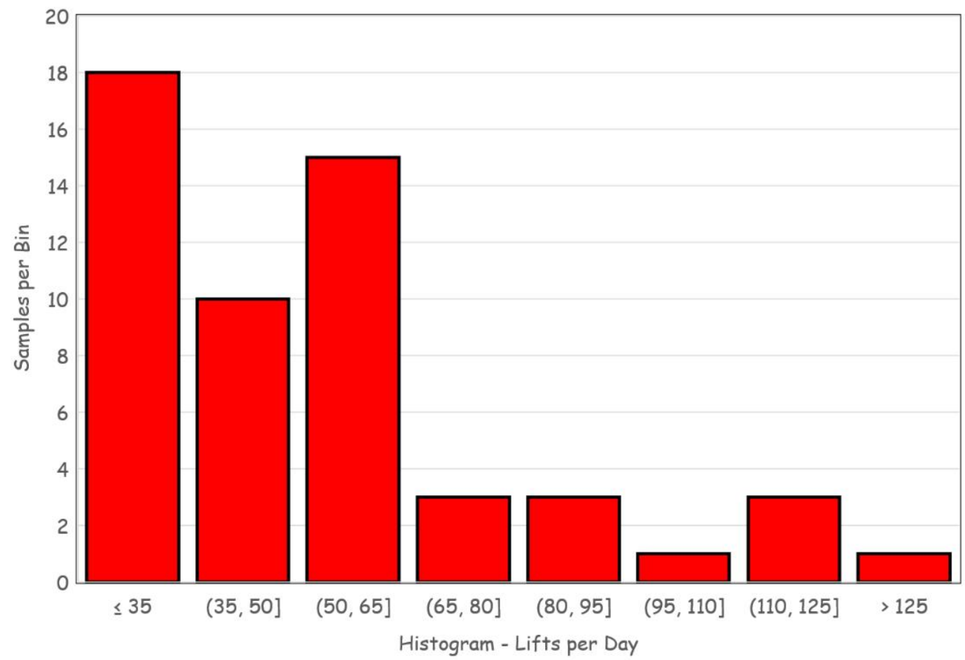


Figure 21. H-RTG (San Bernardino) Histogram of Lifts Per Day

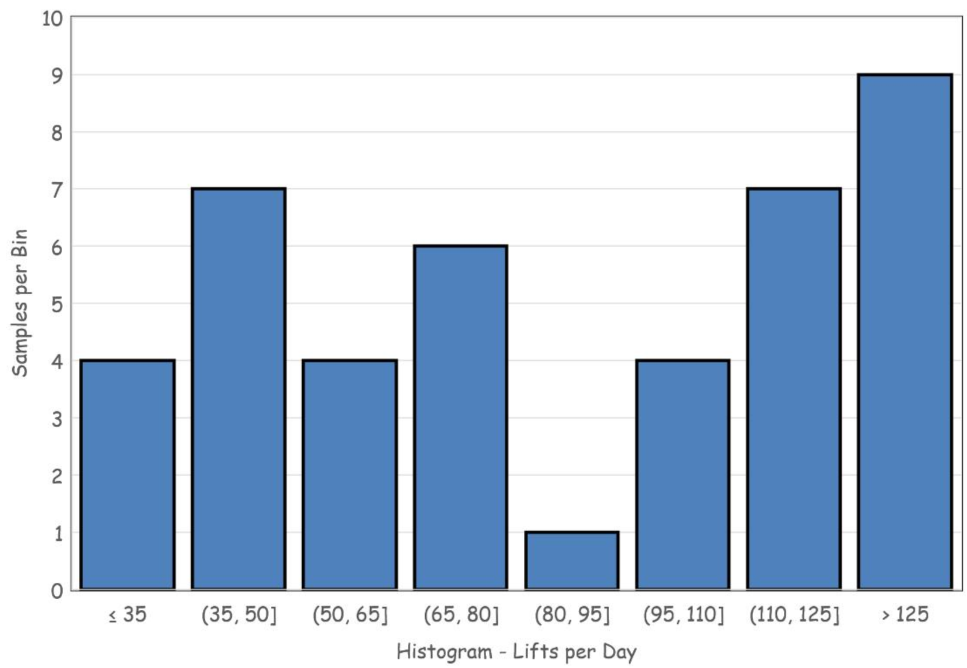


Figure 22. H-RTG (Stockton) Histogram of Lifts Per Day

3.2 Vehicle Usage

As shown in Table 6, the diesel RTG in San Bernardino was instrumented with the RPECS for a total of 268 days, the RPECS was operational for 257 days, and the diesel RTG had more than 2 hours of engine operation for 221 days. The utilization for the diesel RTG was calculated by dividing the days of operation by the number of days that the RPECS was operational. For the diesel RTG, the utilization was 86.0 percent. The H-RTG in San Bernardino was instrumented for 146 days, the RPECS was operational for 105 days, and the H-RTG in San Bernardino had 57 days in this window of time where the H-RTG had the key on for more than 2 hours. This provides a utilization of 54.3 percent for the H-RTG in San Bernardino. The H-RTG in Stockton was instrumented for 119 days, the RPECS was operational for 72 days, and this unit had 46 days with more than 2 hours of operation, providing a utilization of 63.9 percent.

3.2.1 Hours of Operation Per Day

For the diesel RTG in San Bernardino, the hours of operation were calculated from the change in engine hours broadcasted over the CAN network. For the diesel RTG, only days where the RTG engine operated greater than 2 hours was considered as an operation day. The same 2-hour minimum filter was applied to the H-RTG "Key On" data.

The diesel RTG in San Bernardino operated on average of 13.7 hours per day with a maximum of 20.6 hours in one day. A histogram of the diesel RTG's hours per day is shown in Figure 23.

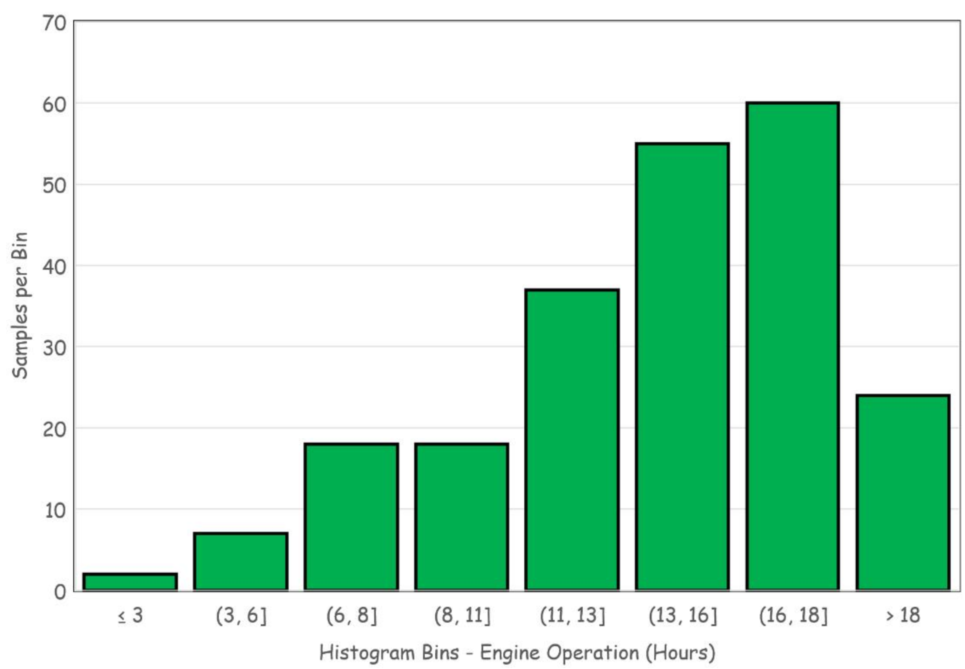


Figure 23. Diesel RTG (San Bernardino) Histogram of Hours Per Day

The H-RTG in San Bernardino only averaged 4.7 hours per day with a maximum of 18.1 hours in one day. The histogram of the hours per day for the H-RTG in San Bernardino is shown in Figure 24.

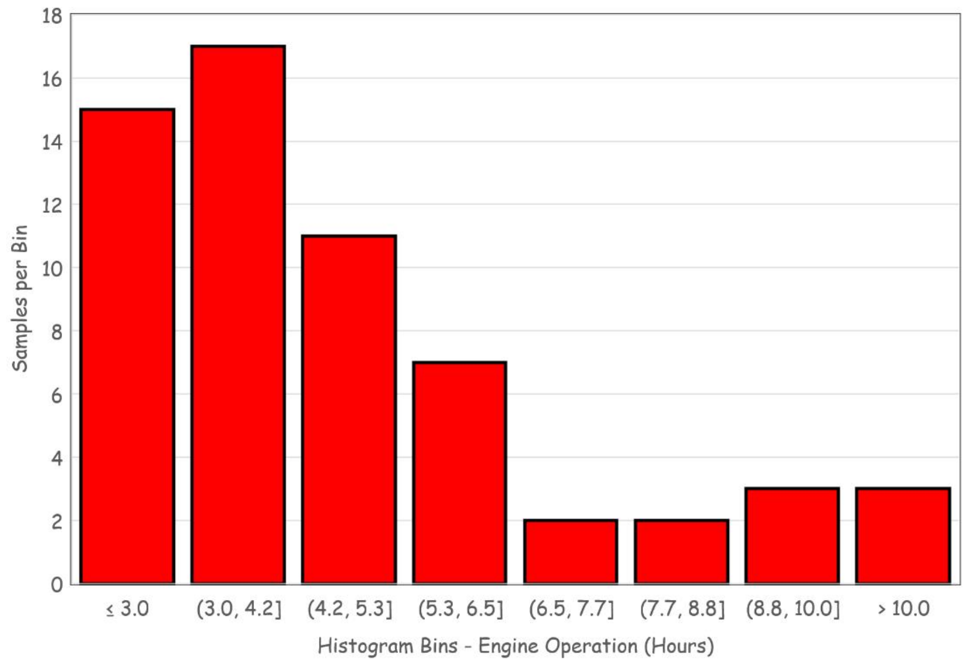


Figure 24. H-RTG (San Bernardino) Histogram of Hours Per Day

The H-RTG in Stockton averaged 5.5 hours per day with a maximum of 13.5 hours in one day. The histogram of the H-RTG Stockton hour per day data is shown in Figure 25.

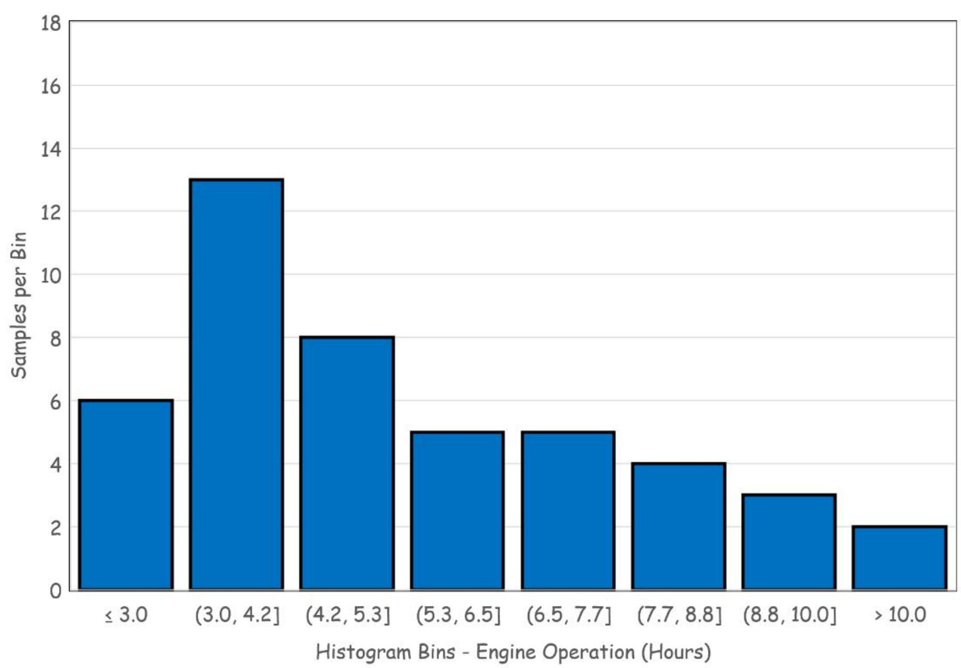


Figure 25. H-RTG (Stockton) Histogram of Hours Per Day

3.2.2 Days of Operation Per Year

Extrapolating the percent utilization discussed in Section 3.2 – "*Vehicle usage*", the estimated days of operation per year would be 314 days per year (365 days per year * 86.0%) for the diesel RTG in San Bernardino, 198 days per year (365 * 54.3%) for the H-RTG in San Bernardino, and 233 days per year (365 * 63.9%) for the H-RTG in Stockton. However, there is no known reason that the H-RTGs could not be utilized as heavily as the diesel RTG once the staff operating the RTGs become accustomed to the controls on the H-RTG.

3.2.3 Odometer/Hour Meter/MWhr Reading (Quarterly)

Extrapolating the average hours per day, the utilization, and the number of days in a quarter provides:

- Diesel RTG - San Bernardino
  - 1,075 hours per quarter
    - 13.7 hours per day * 91.25 days per Quarter * 86.0% utilization
  - 78 days per quarter
    - 91.25 days per Quarter * 86.0% utilization
- H-RTG - San Bernardino
  - 233 hours per quarter
    - 4.7 hours per day * 91.25 days per Quarter * 54.3% utilization
  - 50 days per quarter
    - 91.25 days per Quarter * 54.3% utilization
- H-RTG - Stockton
  - 321 hours per quarter
    - 5.6 hours per day * 91.25 days per Quarter * 63.9% utilization
  - 58 days per quarter
    - 91.25 days per Quarter * 63.9% utilization

There were no known reasons for the reduced utilization of the H-RTG other than the lack of familiarly with the controls of the RTG, so it is expected that the H-RTGs could be utilized at the same level as the diesel RTG.

4.0 GPS DATA

4.1 Key off / Key on

For the diesel RTG in San Bernardino, the hours of operation were calculated from change in engine hours broadcasted over the CAN network. For all RTGs, only days where the RTG was operated for more than 2 hours (engine on time for diesel RTG and Key On time for the H-RTGs) was considered as an operation day. Days with less than 2 hours of operation were removed from the analysis.

The diesel RTG in San Bernardino operated an average of 13.7 hours per day with a maximum of 20.6 hours in one day. The H-RTG in San Bernardino only operated an average of 4.7 hours per day with a maximum of 18.1 hours in one day, while the H-RTG in Stockton averaged 5.5 hours of operation per day with a maximum of 13.5 hours in one day.

4.2 Idling/Queuing Time

"Idle" on a diesel-powered machine is often defined as a mode where the diesel engine operates at a relatively low engine speed with light or no load. On the H-RTG engine, there was essentially no conventional "idle" other than brief periods when the engine was started, and the control system was waiting on the engine to build oil pressure before the engine speed was increased and the engine loaded.

There was no throttle position sensor (TPS) on diesel RTG, so there was no way to interrogate the idle command. "Idle" on the diesel RTG was determined by using a filter to look at the time that the engine speed was between 100 RPM and 950 RPM and the vehicle speed was less than 1.2 MPH. Using this criterion, the diesel RTG averaged 1.3 minutes per day or 0.15 percent of the operating day.

The H-RTGs also do not have a direct method for engine control by the operator. The engine is started, loaded, and stopped by the H-RTG controller to maintain the appropriate battery state of charge (SOC). Given the duty cycle of the H-RTGs, there are a limited number of engine starts and stops needed to maintain the battery SOC at the appropriate level. For the H-RTG in San Bernardino, the engine only idled 0.3 minutes per day or 0.09 percent of the operating time. The H-RTG in Stockton only idled 0.2 minutes or 0.06 percent of the operating time. This low idle time is due to the way that the H-RTG operates. As shown in Figure 26, the only time that the diesel engine in the H-RTG idles is:

1. Directly after an engine start command.
    a. To allow the engine to build oil pressure before the engine is loaded.
2. When the engine has a shutdown command.
    a. Idle to provide some minimal amount of time to cool down before the engine is shutdown.

Figure 26. H-RTG (San Bernardino) Examples of Idle Identified by CAN Broadcasted Engine Fuel Rate

5.0 BATTERY CHARGE CAPACITY/POWER OUTPUT (DUTY CYCLE)

The following section focus on the battery system of the H-RTGs.

5.1 State of Charge (SOC) Increase

The SOC data was not broadcasted over the CAN network when the H-RTG's key was off, so the RPECS system continues to log the last valve broadcasted until the H-RTG's key was turned back on. As shown in Figure 27, there was an extended period in the middle of the day that the key was off and there were no updates to the SOC, but the Stockton H-RTG was plugged into shore power to recharge the batteries. The change in SOC caused by the unit being plugged into shore power was shown as a "step change" when the key was turned back on and the CAN system started to broadcast.

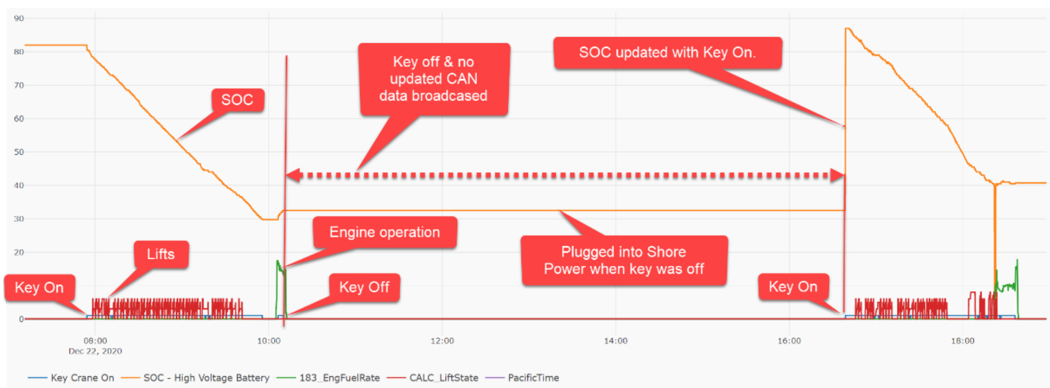


Figure 27. H-RTG (Stockton) Example of Change in SOC Over an Operating Day

The H-RTG's have a 100 kW-Hr battery that can operate the H-RTG for extended periods of time without running the diesel engine. An example of this extended operation is shown in Figure 28, where the H-RTG in Stockton was used for two different sets of lifts on 22-Dec-20. For this case, the engine started when the SOC reaches roughly 35 percent. The minimum allowable SOC before the engine is started is likely dependent on the current SOC, rate of discharge, parasitic loads (i.e.: lights, battery thermal management, HVAC for the operators cab and electronic cabinet, …), ambient conditions, and other inputs to the system.

Figure 28 looks more closely at the operation between 07:45 and 10:15 AM on 22-Dec-20, where the H-RTG completed ~43 lifts over ~1.8 hours without the engine starting. After the lift activity was completed, and with the key off, the engine automatically started at ~10:07 AM and the engine continued to operate as the RTG was moved to the shore power parking location. The engine stopped at ~10:12 AM when the H-RTG was connected to shore power charging station and the batteries finished charging using the shore power.

Figure 28. H-RTG (Stockton) Zoom into the Morning Operation on 22-Dec-20

Figure 29 looks at the late afternoon operation between 16:45 to 18:45 hours, after the batteries had been charged by the shore power. This figure shows that ~33 lifts were completed over ~1.6 hours without the engine starting until the last lift was initiated.

Figure 29. H-RTG (Stockton) Zoom into the Late Afternoon Operation on 22-Dec-20

It must be noted that there are parasitic loads on the H-RTG that will continue to reduce the battery's SOC while the key was in the "off" position. The primary parasitic loads are likely the HVAC in the electrical control cab of the H-RTG. When the parasitic loads drop the SOC below the recharge threshold of approximately 40 percent, the engine starts and runs a recharge cycle, even with the key in the "off" position. Because this recharge event can take place with the key "off", the SOC and other non-engine CAN traffic was not broadcasted during this recharge event and the Mi-Jack PID specific data on the CAN continues to broadcast the last recorded value before key switch was turned off. When the key is turn on, the information on the CAN is updated allowing calculation of the change in SOC and the fuel consumed during the key off and charging period.

Figure 30 shows the change in total fuel used vs. kW-Hrs between when the key was turned off and when the key was turned back on. Because this data was acquired on the H-RTG in Stockton, there are several charge events that required no diesel fuel consumption due to shore power that was available to charge the batteries when the H-RTG was parked at the shore power system. This figure also shows that the diesel fuel consumption is ~0.0833 gallon per kW-Hr of charge.

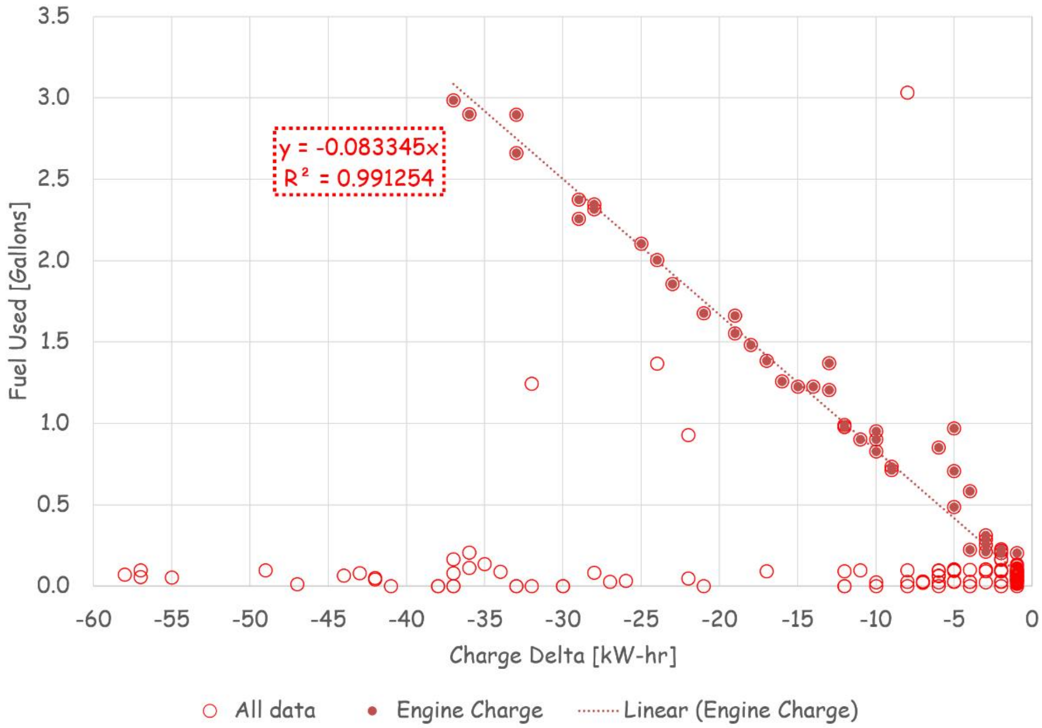


Figure 30. H-RTG (Stockton) Change in Battery Charge Between Key Off and Key On Events

Looking at the differences in the cost of completing the charge event shown in Figure 31, it is highly dependent on the cost of the energy and diesel fuel. During the monitoring period, the average cost of electricity for the meter feeding the Stockton shore power charger was $0.38 per kW-Hr. The average cost of diesel fuel for the first quarter of 2021 was $2.735 per gallon. This was determined by averaging the ULSD highway price per gallon in California for the first 3 months of the year obtained from U.S. Energy Information Administration (EIA) and removing the road taxes from the posted price (used in off road equipment). The diesel fuel recharge is ~40 percent (-0.2279 / -0.38 -1 *100%) less expensive compared to the shore power recharge of the battery at this location.

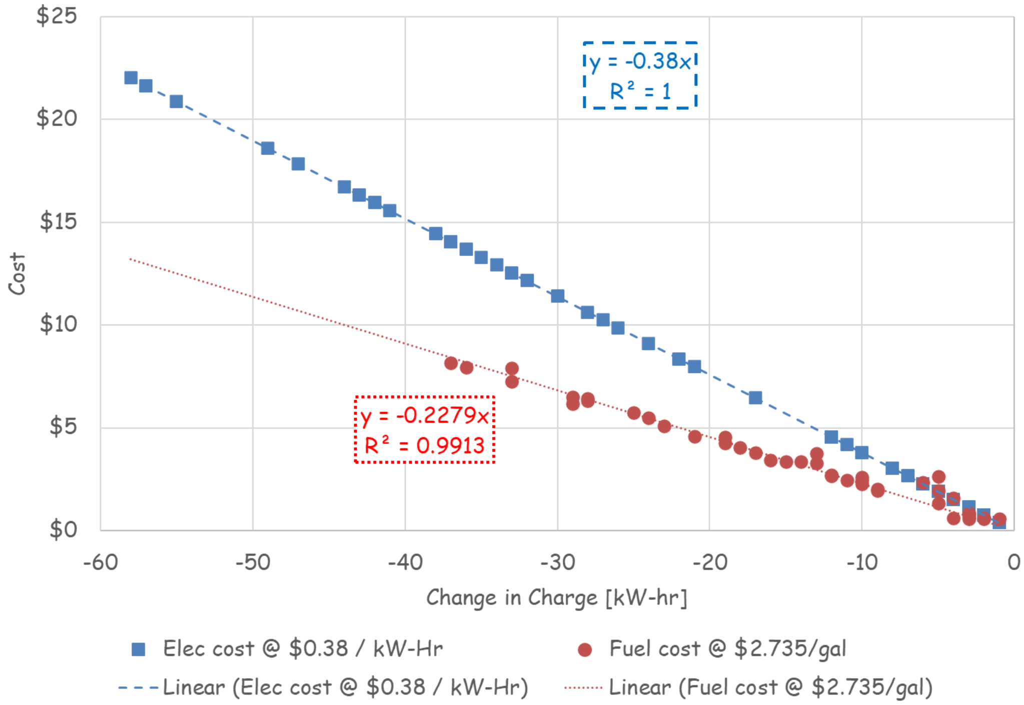


Figure 31. H-RTG (Stockton) Cost of Battery Charge

5.2 Refueling Time/Charging Time

The diesel fuel logs provided by BNSF allowed the project to determine the average amount of fuel used to fill the diesel RTG and the H-RTG in San Bernardino (no data was provided for the H-RTG in Stockton). The average fuel dispensed for the diesel RTG was 142.1 gallons and the histogram of the gallons per fueling event are shown in Figure 32. Velocity Rail, BNSF's direct from truck fueling supplier for this application, was queried about their fuel delivery truck's maximum pumping rates. Cory Clapp of Velocity Rail stated that the typical maximum rate is 50 to 60 GPM because they only idle the truck so that the power-take-off (PTO) driven pump will not provide full flow which reduces the risk of a fuel spill during the fueling event. For this report, it is assumed that the flow rate would average 70 percent of the maximum to make sure that the tank is filled without overfilling the tank. This suggests that the typical refueling time for the diesel RTG is ~3.4 minutes.

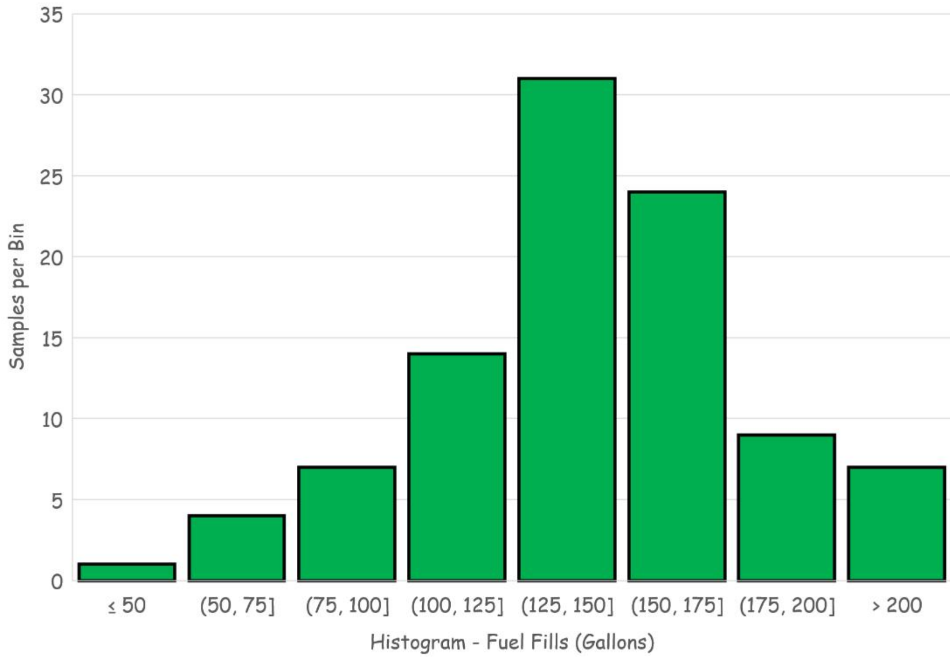


Figure 32. Diesel RTG (San Bernardino) Gallons per Refill Histogram

For the H-RTG in San Bernardino, the average amount of fuel used to fill the fuel tank was 71.0 gallons and the histogram of the gallons per refill is shown in Figure 33. Using the same assumptions for the fuel pumping rate suggests that the H-RTG could be refueled in ~1.7 minutes.

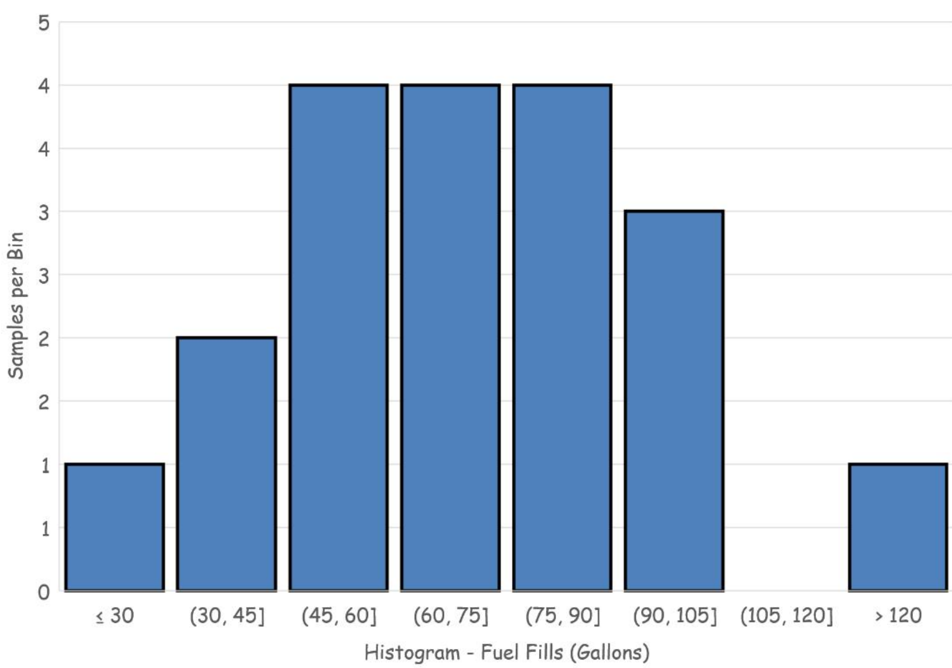


Figure 33. H-RTG (San Bernardino) Gallons per Refill Histogram

5.3 Refueling/Charge Frequency

Because of the high utilization of the diesel RTG, the crane was refilled on average every 2.4 days and the histogram of the days between refills is shown in Figure 34. The H-RTG in San Bernardino had a refill every 11.8 days on average and the histogram of the refill data is shown in Figure 35. Again, no fuel logs were provided for the H-RTG in Stockton.

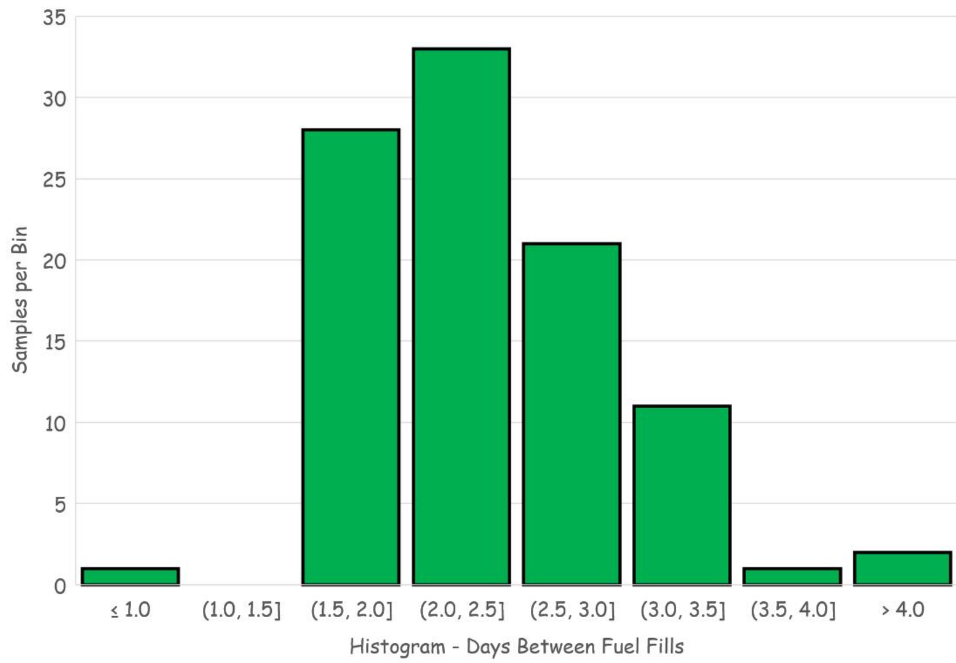


Figure 34. Diesel RTG (San Bernardino) Days per Refill Histogram

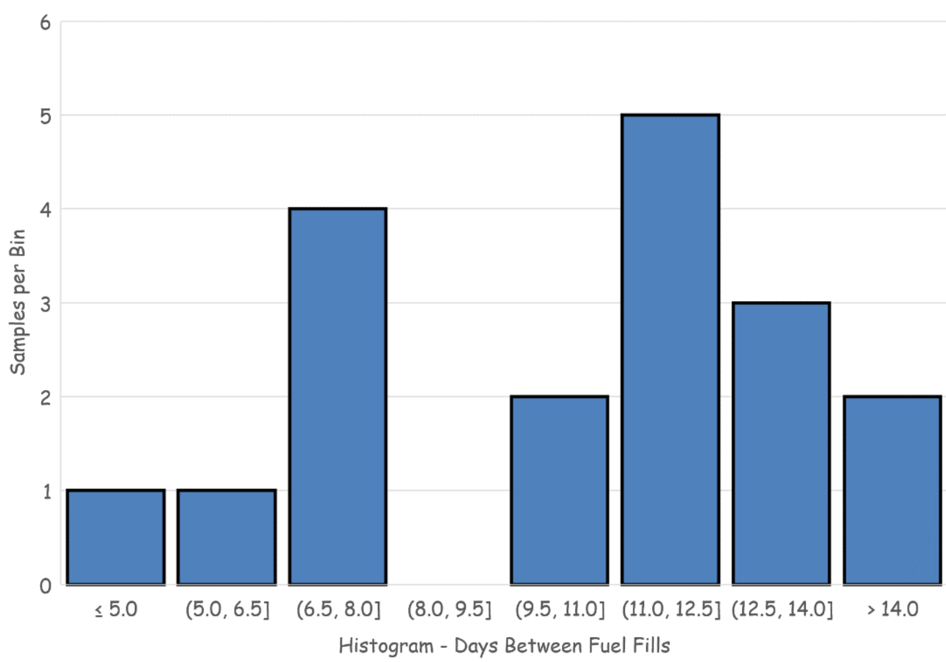


Figure 35. H-RTG (San Bernardino) Days per Refill Histogram

5.4 Vehicle Efficiency: Energy/Fuel Consumed Per Unit of Production

The diesel RTG allowed for an integrated fuel rate to be calculated for each lift and the average fuel consumed for the diesel RTG was 0.22 gallons per lift. The histogram for the diesel RTG gallons per lift is shown in Figure 36.

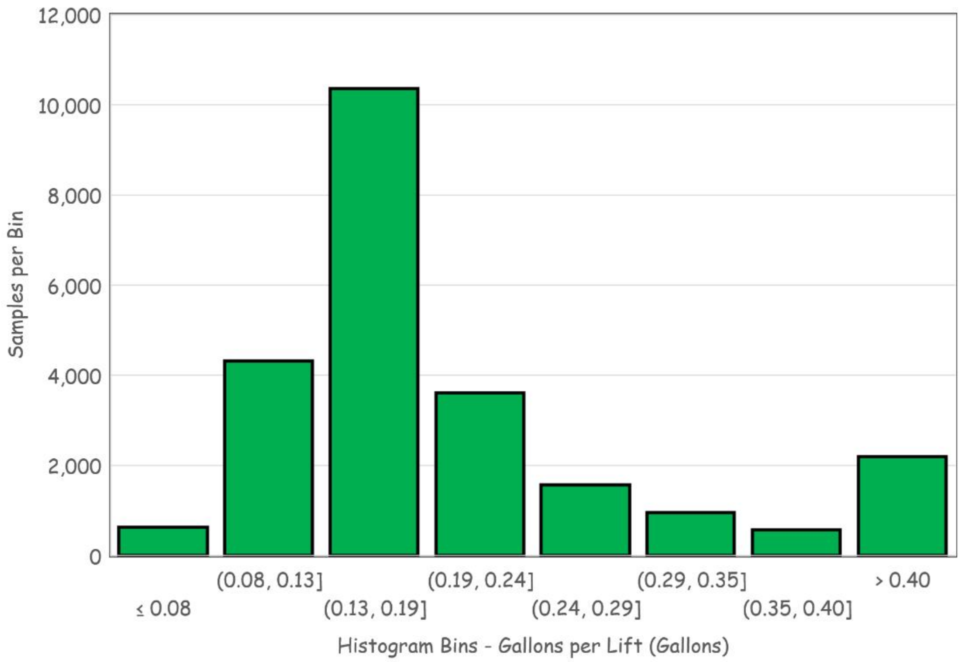


Figure 36. Diesel RTG (San Bernardino) Histogram Gallons per Lift

As shown in Figures 28 and 29, the H-RTGs were able to make several lifts without the engine operating / consuming fuel during the lifts and discussed in Section 5.1 – "*State of charge (SOC) increase*". The calculation for the fuel consumed per lift on the H-RTGs used the average lifts per day divided by the average fuel consumed per day. The results showed that the H-RTG in San Bernardino averaged 0.041 gallons per lift and the H-RTG in Stockton averaged 0.024 gallons per lift. The H-RTG in Stockton had a shore power charging system that reduced the amount of diesel used to maintain the battery charge and covered the parasitic loads while the H-RTG was plugged into the shore power, and this shore power charge allowed a lower gallons per lift for the H-RTG in Stockton.

5.5 Fuel/Energy Consumption While Idling

As discussed in Section 4.2 – "*Idling/queuing time*", the RTG's have an average daily idle time of:

- Diesel RTG in San Bernardino – 1.3 minutes
- H-RTG in San Bernardino – 0.3 minutes
- H-RTG in Stockton – 0.2 minutes

Because of these low amounts of idle time, the fuel consumed at idle, and the fuel cost of $2.735 per gallon, the cost of the fuel for engine idle is only a few cents per day.

5.6 All-Electric Range and Average Electric Usage in Hybrids as a Function of Trip Duration and Work Output, if Applicable

The H-RTG's demonstrated the ability to operate for extended periods of time without the engine starting. As discussed in Section 5.1 - "*State of charge (SOC) increase*" and shown in Figures 27, 28, and Figure 29, the H-RTG in Stockton was able to make over 30 lifts over ~1.5 hours without the engine starting because the battery was at a high SOC at the start of the operation. However, as discussed in Section 5.1, the cost of charging the batteries with shore power is ~40 percent higher than the energy cost of charging the batteries with the diesel engine.

If an all-electric RTG would be required as a next step, an initial estimate on battery size can be made based on a combination of the diesel RTG and the H-RTG data.

H-RTG

- Published battery size = 100 kW-Hr
- Number of lifts between engine starts = 30
  - Dependent on:
    - Initial state of charge
    - Ambient conditions
    - RTG moves between lifts
    - Number of missed lifts due to operator error

Diesel RTG:

- Max number of lifts = 353
- Maximum hours per day = 20.6

With these assumptions, the estimated battery size is ~1,200 kW-Hrs (100 kW-Hr /30 lifts * 353 lifts). The concern is that this battery system would potentially need to accept a full charge in 3.4 hours [24 hours in a day - 20.6 hours of operation (max)]. As a point of reference, this ~1,200 kW-Hr battery is ~3 times larger than the battery in the BYD all electric drayage truck.

6.0 EMISSIONS

Tailpipe emissions testing for vehicles/equipment that are not 100% zero emission was completed using PEMS technology. The system used to measure the exhaust emissions from the diesel fueled RTG and the H-RTG while operating around the BNSF's San Bernardino and Stockton Intermodal Yards was a SEMTECH-DS mobile emissions analyzer, like the one shown in Figure 37, which is known as a PEMS unit. The PEMS can monitor the raw exhaust from both spark ignition and compression ignition engines and provides CO, CO2, O2, NO, NO2, and THC emissions concentration.

The PEMS systems used for this project was provided by the US-EPA in Ann Arbor, MI. Training on the PEMS system was held at SwRI's Ann Arbor, Michigan office on 16-October-20 by Carl Fulper of the US-EPA. Mr. Fulper is the PEMS coordinator for the US-EPA.

Figure 37. SEMTECH-DS PEMS System

Two days of PEMS testing was performed on each of the RTGs in this study. The PEMS unit was installed on the engine side of the RTG and the H-RTGs, as shown in Figure 38. The installation required modification to the exhaust system so that the exhaust flow sensor and sampling zone was mounted to meet the PEMS requirements. Figure 39 shows a closeup of the PEMS system installed on the diesel RTG.

The activity log of the PEMS testing is provided in Appendix B of this report. As discussed in Appendix B, the PEMS testing was conducted on:

- H-RTG - Stockton – 12 and 13-Jan-21
- H-RTG - San Bernardino – 15 and 16-Jan-21
- Diesel RTG - San Bernardino – 17 and 18-January-21

Figure 38. PEMS System Installed on H-RTG (Left) and Diesel RTG (Right)

Figure 39. PEMS System Installed on Diesel RTG

When comparing total fuel/emissions between hybrid and diesel cranes, note that there were electric loads on the H-RTGs that can drain state of charge and initiate an engine start recharge event even with the crane turned off and not in use. For example, the electronics cabinet air conditioner was observed to be running all day with crane turned off on the maintenance pad, waiting to be tested using the PEMS unit. This caused the state of charge to drop below the recharge threshold of 40% and the engine started up and ran a recharge cycle. Also note that State of Charge (SOC) and other non-engine CAN traffic is not broadcasted when crane is turned off, so the RPECS data loggers received the engine CAN data but the rest of the CAN data (Mi-Jack PID specific) broadcasted the last recorded value before key switch was turned off.

6.1 Emissions Certification Levels

The engine in the diesel RTG was an 8.9-liter engine rated at 333 HP @ 2,100 RPM and the H-RTGs were fitted with a 3.8-liter diesel engine rated at 154 HP @ 2,200 RPM. The engine family for the diesel RTG was GCEXL08.9AAK, while the H-RTG's engine family was KCEXL03.8AAF. The US-EPA certification emissions levels for these engines are shown in Table 7.

Table 7. RTG Engine Emissions Certification

RTG	HC (g/Hp-Hr)	NOx (g/Hp-Hr)	CO (g/Hp-Hr)	PM (g/Hp-Hr)
Diesel	0.01	0.11	0.1	0.02
Hybrid	0.0	0.12	0.0	0.01

These low emissions levels reflect that both engines were certified to US_EPA's Tier 4 off-highway engine emissions standards. To meet these low emissions levels, the engines were fitted with the following:

- High pressure common rail diesel fuel injection
- Turbocharged and charge air cooler (aftercooler)
- Exhaust Gas Recirculation (EGR)
- Exhaust aftertreatment
    - Diesel Oxidation Catalyst (DOC)
    - Selective Catalytic Reduction (SCR) – Urea
    - Ammonia Oxidation Catalyst

6.2 Summary of Emission Testing

Table 8 shows the PEMS emissions results along with calculated emissions per lift. The emissions generated per lift for the hybrid RTG are exceptionally low due to the energy recovery of the hybrid system and the engine exhaust after treatment working at high efficiency due to the steady and high load factor when the engine is started and operated.

Table 8. PEMS Emissions Results

	Diesel RTG San Bernardino	H-RTG San Bernardino	H-RTG Stockton
Total Fuel Consumed (gal)	9.77	8.65	5.94
CO2 (g)	101076	89438	60960
CO (g)	142.3	119.2	74.9
corrected NOx (g)	31.3	28.9	28.3
THC (g)	2.9	0.2	1.5
CO2 (g/Gallon)	10342	10337	10270
CO (g/Gallon)	14.6	13.8	12.6
corrected NOx (g/Gallon)	3.2	3.3	4.8
THC (g/Gallon)	0.3	0.0	0.3
CO2 (g/Lift)	2648	424	246
CO (g/ Lift)	3.74	0.57	0.30
corrected NOx (g/ Lift)	0.82	0.14	0.12
THC (g/ Lift)	0.08	0.00	0.01

The PEMS emissions data can be converted to the same units that was used for the US-EPA certification (g/Hp-Hr) by using the following assumptions:

- CARB Diesel Fuel Density = 7.0 pounds per gallon
- Certification brake specific fuel consumption of the US-EPA test cycle = 0.40 pounds per horsepower hour

Table 9 shows the calculated PEMS emissions levels in grams per horsepower hour, and the US-EPA certification data. The NOx and the HC emissions were somewhat higher than the certification results and the CO emissions was notably higher than the certified level.

Table 9. Emissions Comparison PEMS and US-EPA Certification

			CO	**NOx**	**HC**
Diesel RTG	**San Bernardino**	PEMS (g/Hp-Hr)	0.83	0.21	0.02
		EPA Cert (g/Hp-Hr)	0.1	0.11	0.01
H-RTG	**San Bernardino**	PEMS (g/Hp-Hr)	0.79	0.22	0.00
		EPA Cert (g/Hp-Hr)	0.0	0.12	0.0
H-RTG	**Stockton**	PEMS (g/Hp-Hr)	0.72	0.29	0.02
		EPA Cert (g/Hp-Hr)	0.0	0.12	0.0

7.0 MAINTENANCE AND REPAIRS

Summaries of RTG maintenance and repairs are provided in Attachment C. These summaries were provided by BNSF and were included in the report for completeness.

Local maintenance and repair (M&R) technicians did not play an active role in the H-RTG because the equipment was still under warranty through the demonstration period and Mi-Jack dispatched specialized repair technicians to diagnose and repair issues. As noted in Appendix C, the H-RTGs experienced overheating of the batteries during high summer ambient temperatures, which led to the H-RTG shutting down. The fix for this issue was increasing the capacity of the battery cooling system. There were also a number of control system software updates performed during the demonstration period to address various issues identified with the H-RTGs.

BNSF reports that with any new technology, there is an acclimation period for M&R technicians. Though the OEMs provided initial training on how to properly and safely conduct routine maintenance sessions, the M&R personnel still needed time to familiarize themselves with the procedures and the differences from a routine Preventative Maintenance (PM) session of a conventional diesel RTG. Initially, there wasn’t much of a time savings on a H-RTG PM session vs the conventional RTG. That is primarily due to the mechanics taking their time with the process to ensure they are following proper protocols. But with any process, with increased frequency comes greater confidence and efficiency.

8.0 SUMMARY

This report documents datalogging results comparing a diesel RTG and two H-RTGs for more than the 90 days. The diesel and one of the hybrids RTGs were used in BNSF's San Bernardino Intermodal Yard. The second H-RTG was used in BNSF's Stockton Intermodal Yard.

This topical report does not address the capital cost for the Hybrid RTG, the shore power system in Stockton, or maintenance and other associated cost difference between the diesel and the H-RTGs. However, this report does allow for an energy and emissions comparison for the operation of the different RTGs.

The H-RTG system required power from shore power or the diesel engine during non-productive times (with the key off), to maintain an appropriate state of charge of the battery because of the parasitic loads on the H-RTG. This suggests that the H-RTGs would be more efficient if they were highly utilized, because of the "energy overhead" when there is no productivity.

Some of the notable observations for the three RTGs are:

1. The diesel RTG on average completed 221 lifts per day, while the H-RTG in San Bernardino averaged 52 and the H-RTG in Stockton averaged 101 lifts per day. The disparity in the lifts per day is also shown in hours of operation per day. The diesel RTG operated 13.7 hours per day, while the H-RTG in San Bernardino had 4.7 hours per day and the H-RTG in Stockton averaged 5.5 hours per day.

2. The H-RTG performed much better than the diesel RTG when comparing energy consumption and emissions per lift. The diesel RTG averaged 0.256 gallons per lift and 0.95 g/lift NOx emissions, where the H-RTG in San Bernardino averaged 0.041 gallons per lift and 0.16 g/lift NOx emissions, and the H-RTG in Stockton averaged 0.024 gallons per lift and 0.12 g/lift NOx emissions. The reason that the Stockton H-RTG had lower fuel consumption per lift was due to the shore power that was used to charge the battery when the unit was parked. However, the cost of the electricity made this option expensive.

3. The data shows that the H-RTGs are "fit for purpose" in the BNSF Intermodal Yards and can offer a reduced fuel consumption and NOx emissions per lift. However, SwRI was informed the operators did have issues with the different layout of the H-RTG operational controls and this caused the productivity (time per lift) to decrease by ~30%, when compared to the diesel RTG. It is possible that this reduced productivity could be reduced or eliminated as the H-RTG operators become more proficient / familiar with the H-RTG controls layout.

Attachment A
SwRI's Reporting Requirements – Rubber-Tired Gantry Crane (RTG)

	Diesel	Hybrid - Stockton	Hybrid - San Bern
Appendix A - Vehicle Specification			
Manufacturer	SwRI	SwRI	SwRI
Model	SwRI	SwRI	SwRI
Model year	SwRI	SwRI	SwRI
Gross vehicle weight	SwRI	SwRI	SwRI
Fuel type	SwRI	SwRI	SwRI
Propulsion system description	SwRI	SwRI	SwRI
Engine label photos	SwRI	SwRI	SwRI
Appendix B - Vehicle Operation			
Description of daily use / duty cycle	SwRI	SwRI	SwRI
Vehicle usage:			
Hours of operation per day	SwRI	SwRI	SwRI
Days of operation per year	SwRI	SwRI	SwRI
Odometer/Hour meter/MWhr reading (quarterly)	SwRI	SwRI	SwRI
GPS data:			
Key off / Key on	SwRI	SwRI	SwRI
Miles traveled per trip	NA	NA	NA
Average speed	NA	NA	NA
Number of stops per mile	NA	NA	NA
Duration per trip	NA	NA	NA
Idling/queuing time	SwRI	SwRI	SwRI
Battery charge capacity/power output (duty cycle)	NA	SwRI	SwRI
Appendix C - Vehicle / Equipment Performance			
Vehicle zero emission range/work performed per charge	NA	Mi-Jack	Mi-Jack
Appendix D - Fuel / Energy Consumption			
Amount of fuel/electricity fueled	ITS	BNSF	BNSF
Fuel price per unit when a vehicle is fueled	BNSF	BNSF	BNSF
Include electricity rates as applicable	BNSF	BNSF	BNSF
State of charge (SOC) increase, if applicable	NA	SwRI	SwRI
Refueling time/charging time	NA	SwRI	SwRI

Refueling/charging source:			
Grid	NA	BNSF	BNSF
On-site fueling	BNSF	NA	NA
Refueling/charge frequency	SwRI	SwRI	SwRI
Vehicle efficiency: energy/fuel consumed per unit of production	SwRI	SwRI	SwRI
Fuel/energy consumption while idling (if applicable)	SwRI	SwRI	SwRI
All-electric range and average electric usage in hybrids as a function of trip duration and work output, if applicable	NA	SwRI	SwRI
Appendix E - Maintenance			
Type of maintenance:			
Scheduled	ITS	ITS	ITS
Unscheduled	ITS	ITS	ITS
Equipment modification	ITS/BNSF	ITS/BNSF	ITS/BNSF
Repairs:			
Date	ITS	Mi-Jack	Mi-Jack
Description of problem	ITS	Mi-Jack	Mi-Jack
Description of repair performed	ITS	Mi-Jack	Mi-Jack
Parts replaced	ITS	Mi-Jack	Mi-Jack
Odometer/hour meter reading	ITS	Mi-Jack	Mi-Jack
Actual repair time	ITS	Mi-Jack	Mi-Jack
Time out of service W/ explanation for extended delay	ITS	Mi-Jack	Mi-Jack
Appendix F - Safety			
Service interruptions or delays: (relevant issues that drove SI or delays)			
Equipment malfunction caused	ITS/BNSF	ITS/BNSF	ITS/BNSF
Other relevant causes	ITS/BNSF	ITS/BNSF	ITS/BNSF
Appendix G - Emissions Testing			
Tailpipe emissions test for vehicles/equipment that are not 100% zero emission, and their respective baseline vehicles/equipment using PEMS technology.	SwRI	SwRI	SwRI

NOTES

Appendix B
RTG PEMS Testing Log

The following sections describe the PEMS testing of the three RTGs.

Stockton Hybrid RTG PEMS Testing

On 12-Jan-21 the PEMS system was installed in the early morning and the recorded operation with the PEMS system was from 12:53 PM Pacific Time until 4:35 PM, where the H-RTG lifted approximately 20 to 25 container lifts. Engine operation started at ~3:00 PM when the SOC reached 40%. This engine charging event continued for ~1.5 hours and the crane was stationary for about the last 1 hour of this engine charging event. It was at this time the SwRI Team witnessing the operation noted that once the crane key is turned off, the SOC channel is no longer active on CAN bus.

On the next day (13-Jan-21) at ~9:14 AM, the first work cycle of day was started with PEMS equipment running; however, the engine never came on to charge the battery. Operator parked crane and went to lunch with SOC at 60%.

After the H-RTG operator returned from lunch, testing started at 11:19 AM. Crane operated about 1 hour before engine started at 12:16 pm and ran at 1000 RPM briefly in a warm-up mode, then to 1800 RPM but did not enter recharging mode. Crane then started to move very slowly due to derated operation. The H-RTG operator was told by his supervisor to return to Shore Power station where a hard reset of crane controls was completed by an H-RTG maintenance crew member. Upon reboot of the H-RTG system, the engine started at 1:06 PM, operated for 20 seconds at 1000 RPM then to 1800 RPM and started to recharge the battery system. The engine returned to 1000 RPM at 1:54 PM and engine shutdown at 1:58 pm with SOC at 65%. The SwRI Team attempted to turn on the H-RTG key periodically during charging event to keep CAN bus active so that SOC was logged.

San Bernardino H-RTG PEMS Testing

The test setup on the H-RTG in San Bernardino was completed by ~10 AM on 15-Jan-21. While waiting for an H-RTG operator, the electronics cabinet HVAC was running and drawing down SOC of the hybrid battery. Around 12 PM the engine started and an engine driven recharge event began. However, due to the unexpected start of the engine, the SwRI Team could only capture the last 10 minutes of the recharge event with the PEMS system. Because of the brevity of this emissions sample, this data was not included in the summarized emissions totals.

At ~2:30 PM, the H-RTG operator arrived and the H-RTG was being used to remove containers from a train and place them onto individual trailer chassis. At ~3:45 PM, the H-RTG crane returned to maintenance pad with engine running in a recharge event that lasted for ~50 minutes. At ~4:30 PM the H-RTG was deployed for another PEMS data run but a crane malfunction occurred around 5:15 and the crane froze and was unable to move. Crew eventually were able to reset electronics and get it working again 30 min later. Crane was used to finish moving containers from train to trailer chassis, and then operator just went back and forth, up/down etc. until triggering recharge event, and then returned to maintenance pad around 6:15 PM. Upon return we found that somehow the PEMS was unplugged during operation and we lost PEMS data from ~4:30 pm to ~6:15.

On 16-Jan-21, the H-RTG started first run of day at 8:28 AM. The H-RTG picked up 20-30 containers from trailer chassis and placed them onto bottom row of train. Recharge event started 9:39 AM and engine shutoff occurred at 10:28 AM. Began stacking second row of containers onto train between 10:00 and 10:30 AM. The H-RTG finished loading train ~11:18 AM and stopped crane, operator waiting for clearance to head back to maintenance pad, but the live track between the H-RTG and the maintenance pad prevented the move. The H-RTG finally made it back to pad about 12:45 PM with SOC at 46%.

At 1:40 PM, with the H-RTG stationary at maintenance pad, all known electrical loads (i.e.: all lights, cab AC, fans, seat heater, electrical cab AC) were applied to bring SOC down from 46% to 40% to trigger and capture one more recharge event. Turned on. Recharge event started at 2:11 PM and the diesel engine charging event was completed at 2:47 PM.

San Bernardino Diesel RTG PEMS Testing

On 17-Jan-21 the PEMS system was setup between 5:30 AM – 2:15 PM. The system captured crane operation from 2:25 PM to 3:41 PM. At 3:45 PM the operating crew moved the diesel RTG off pad to fix another crane that was down, so testing for the day was stopped.

The next morning (18-Jan-21), the PEMS system was inspected and calibrated. At ~10:20 AM the diesel RTG was used to offload containers from train to ground. These containers were different than previous because they were already mounted to trailer chassis and the crane moved both chassis and container off the train. Crane returned to maintenance pad around 11:30 AM and test file closed at 11:35 AM.

Later that afternoon (~12:25 PM), Mike Frye helped to force a DPF regeneration so the PEMS system could capture a representative snapshot. According to Mike, they do not ever have to do it in practice because the engine load is high and there is enough exhaust temperature to keep the DPF back pressure below the level needed to force a regeneration. For this test, the engine was started at 12:43 PM as part of the forced DPF regeneration and said the engine was stopped at 12:56 PM.

APPENDIX C
RTG MAINTENANCE & REPAIRS

Start Date	End Date	Elapsed Time	Affected Component	Impact	Root Cause	Repairs Made	Parts Replaced	Cost to Repair	Repair Time (hrs)	Odometer/Hour Meter Reading	Comments
6/2/2020	6/2/2020		Diesel RTG	NONE	LEAKING TUBE LINE	Install tube line	tube line		4		crane in pad for repairs replace leaking tube line.
6/17/2020	6/17/2020		Diesel RTG	NONE	UNCLAMP FUNCTION SLOW	REPLACE FLOW VALVE	FLOW VALVE		1		
7/8/2020	7/8/2020		Diesel RTG	NONE	LEAKING OIL PAN GASKET	REPLACE GASKET	OIL PAN GASKET		8		
8/12/2020	8/12/2020	-	hybrid RTG - SBD	overheating batteries	insufficient cooling of batteries	Replaced HVAC system	HVAC	Warranty			Installed new A/C unit; determined insufficient
8/13/2020			hybrid RTG - SBD	overheating batteries	insufficient cooling of batteries	TBD	TBD		4		Installed new A/C unit
8/15/2020	9/21/2020		hybrid RTG - STO	overheating batteries	insufficient cooling of batteries	upgrade HVAC system		$ 21,909	230		Total time includes diagnosis assessment, troubleshooting, installation of HVAC system, testing, etc.
8/22/2020	8/22/2020		Diesel RTG	NONE	LOCK PROX FLASHING ON/OFF	REPLACE PROX SWITCH	PROX SWITCH		5		
8/27/2020	8/27/2020		Diesel RTG	NONE	FUEL PUMP MAKING NOISE	REPLACE FUEL PUMP	USED FUEL PUMP		8		
9/11/2020	9/11/2020		Diesel RTG	NONE	FAILED LIMIT SWITCH	REPLACE LIMIT SWITCH	LIMIT SWITCH	$ 590	1.5		
9/21/2020	9/29/2020	9	hybrid RTG - SBD	overheating batteries	insufficient cooling of batteries	upgrade HVAC system		$ 21,909	102		Total time includes installation of HVAC system, testing, etc.
9/30/2020	9/30/2020		hybrid RTG - SBD	panel doors coming open	poorly designed latches	installed barrel lock	barrel lock	$ 44.38	1		
10/10/2020			Diesel RTG	none	bad unlock prox	REPLACE PROX SWITCH		$ 4,216	1		
10/12/2020	10/12/2020		Diesel RTG	Routine 165-hr. PM	N/A	N/A		$ 618			
10/9/2020	10/23/2020		hybrid RTG - SBD	BATTERY NOT CHARGING	SOFTWARE	TROUBLESHOOT WITH MI-JACK	NONE		66		
10/14/2020	10/15/2020	2	hybrid RTG - SBD	LOST FRONT TROLLEY	ENCODER	REPLACE		Warranty	16		
11/24/2020	11/24/2020		hybrid RTG - SBD	Routine 165-hr. PM	N/A	N/A		$ 309	7		Two mechanics, 3.5 hours each
12/2/2020	12/2/2020		Diesel RTG	Routine 165-hr. PM	N/A	N/A		$ 618	12		
12/2/2020	12/2/2020		Diesel RTG	Trolley issue		Replaced switch, magnetic limit trly st.B "Go" Switch		$ 985	7.5		
12/6/2020	12/8/2020	2	hybrid RTG - STO	Wheel speed sensor fault		adjustment to the steering parameters and re-sync of the counts on the encoder	N/A	Warranty	7.5		the crane keeps "toeing in" intermittently. When they turn it on, the wheels will turn in slightly and they can't move it. The mechanics have to go and manually adjust in order to get it moving again.
12/9/2020			hybrid RTG - STO	Same as above		Additional troubleshooting, adjustments and testing	N/A	Warranty	2		
12/10/2020			hybrid RTG - SBD	Crane generator not turning on	software upgrade?						
12/10/2020			hybrid RTG - SBD	Power reset required occasionally		N/A					
12/10/2020			hybrid RTG - SBD	Battery charge issue		Adjustment to parameters	N/A	$ -	2		generator not charging and the shore power not charging the generator
12/10/2020			hybrid RTG - STO	Battery charge issue		Adjustment to parameters	N/A	$ -	2		generator not charging and the shore power not charging the generator
12/18/2020	12/18/2020		hybrid RTG - STO	Inability for crane shutdown		Reset antenna to ground through DAQ system		$ -	2		Component in the DAQ system was causing feedback that would not allow the crane to shutdown completely and do a reset. Technician discovered that the SWRI system GPS/modem antenna was grounded to the crane structure. Once they isolated the antenna to ground through the DAQ system, everything was working properly again.
12/30/2020	12/30/2020		hybrid RTG - STO	PM inspection		N/A; inspection only	N/A		4		
1/2/2021			hybrid RTG - SBD	Intermittent faulting that caused loss of function. machine had to be shutdown and repowered to clear fault	Internal setting of the frequency drive was incorrect	Altered setting on frequency drive	N/A	$ -	52 total man hours (includes troubleshooting & diagnosis time, repair time, and post-repair test time		Unable to recreate the fault on-demand, MiJack assigned an engineer to ride-along to take scope traces of the drive when the fault happened. After a review with the manufacturer, a setting was changed to correct issue. Reported by Ed Gonzalez, ITS
1/3/2021			hybrid RTG - STO	Intermittent faulting that caused loss of function. machine had to be shutdown and repowered to clear fault	Internal setting of the frequency drive was incorrect	Altered setting on frequency drive	N/A	Warranty	1 (was able to apply lessons learned at SBD to STO)		Unable to recreate the fault on-demand, MiJack assigned an engineer to ride-along to take scope traces of the drive when the fault happened. After a review with the manufacturer, a setting was changed to correct issue.
1/7/2021	1/9/2021		hybrid RTG - STO	Right wheel steering fault; will not traverse	Parameter out of alignment; needed adjustment	Adjusted steering parameters	N/A	Warranty	1		Per Mike Jones: Hybrid crane in Stockton is showing a steering right wheel fault and will not travel.
1/12/2021			hybrid RTG - STO	Generator not turning on	Program Change	Program Change	N/A	Warranty	8		Generator did not kick on once SOC dropped below 40%; continued operations and when SOC dropped more, a warning was triggered.
1/19/2021			Diesel RTG		Worn spreader blocks	Replaced		$ 427	8		
1/20/2021			Diesel RTG		Worn tire and rear left inside trolly bearing and roller	Replaced tire, bearing and roller		$ 830	4		
1/27/2021			hybrid RTG - STO	Won't travel; not charging	Program Change	Program Change	N/A	Warranty	10		soc dropped to low locking out travel
1/27/2021	1/29/2021		hybrid RTG - STO	Steering faults	Parameters out of adjustment	Readjustments to steering parameters	N/A	Warranty	4		adjustments made and the crane performed correctly
2/24/2021			hybrid RTG - STO			fuse replaced	fuse	Warranty	2		Reported by Michael Jones on 2/24; fuse replacement per Mike Frye
2/28/2021			Diesel RTG	165-hr. PM	N/A	N/A		$ 640	7		
2/28/2021	2/28/2021		hybrid RTG - STO	PM inspection		N/A; inspection only	N/A		4		