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Integrated Electric Plants in Future Great Lakes Self-Unloaders

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Integrated Electric Plants in Future Great Lakes Self-Unloaders

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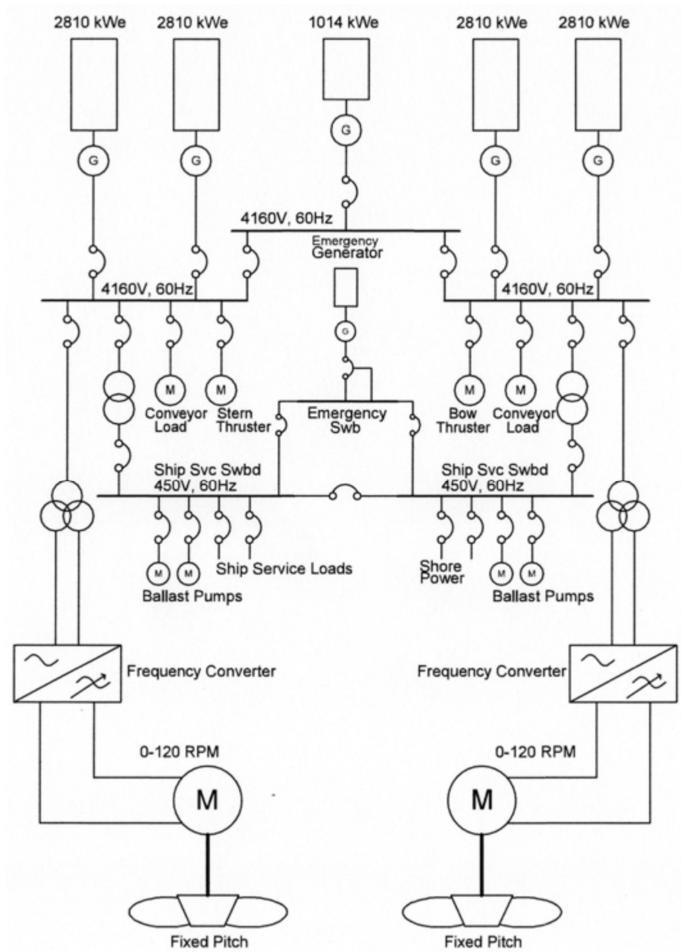

The feasibility and potential benefits of using Integrated Electric Plants in future Great Lakes self-unloaders are evaluated. Integrated Electric Plants, the all-electric ship, utilize electrical propulsion motors and central station power generation that powers all propulsion, thruster, self-unloading equipment and other ship service needs. Integrated Electric Plants have become the plant of choice in many recent naval vessels, cruise ships, high technology cargo vessels and special purpose vessels, such as offshore supply and service vessels and icebreakers. This study considers arrangements, effects on cargo capacity, fuel usage and environmental emissions in all operating modes, maintenance requirements, and manning. The comparison is made for two notional self-unloading bulk carriers: a 1000' Poe Lock maximum self-unloader and a 730' MacArthur Lock, Welland Canal, St. Lawrence Seaway maximum self-unloader.

Keywords: Great Lakes, Self-Unloaders, Integrated Electric Plants, Fuel Efficiency, Emissions

1. Introduction

Integrated Electric Plants have become the plant of choice in many recent naval vessels, cruise ships, high technology cargo vessels and special purpose vessels, such as offshore

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supply and service vessels and icebreakers. While Great Lakes self-unloaders are bulk carriers, their operational profile and high relative auxiliary power requirements have many similarities with these vessels.

George Stewart noted at the recent ASNE/SNAME Electric Ship Design Symposium that "electric drive should be considered for any application where the ship spends much of its time at loitering speeds, when high ship service power requirements exist, or where special mission power requirements dictate its use" and "all modern electric drive installations are of the integrated type with the same generators used to provide both propulsion and ship service power" (Stewart 2009).

Great Lakes self-unloaders do not have a large propulsion power requirement due to their relatively low speed and they are an excellent case of a varying speed profile due to the short distances and many restricted waterways and connecting channels of the Great Lakes system. They also have lateral thruster, self-unloading and ballast pumping loads that are relatively large fractions of the propulsion power required. Joe Fischer noted that Great Lakes self-unloaders spend about 1/3 of their time at reduced speed or in port (Fischer and Shearer 2004).

Stewart describes a typical system one-line diagram of an AC/AC Integrated Electric Plant (IEP) as shown in Fig. 1 (Stewart 2009). For reliability purposes a single screw design can utilize either two separate tandem motors on the main shaft or two higher rpm, thus smaller and lighter, motors geared together through a single-reduction combining gear as shown.

In the Great Lakes self-unloader power range, the IEP power generation is typically at either 4160V or 6600/6900V AC to be compatible with available circuit breakers and reduce the current and resulting cable sizes and weights (Doerry and Fireman 2006). In Europe, 3300V would be more likely to be used. Transformers and frequency converters are used to supply variable frequency AC power for speed control of the main propulsion motors. Transformers also feed the 480/450V and 120V ship service switchboards, which are essentially the same as in other vessels. The larger auxiliary loads, such as tanker cargo pumps and lateral thrusters, are typically supplied at 4160V AC to minimize motor and cable sizes and weights.

The new U.S. Coast Guard Great Lakes ice breaker USCGC *Mackinaw* (WLBB 30), delivered by Marinette Marine Corporation in 2005, has an Integrated Electric Plant with all power generation at 4160V AC and 450/120V ship service power (Sheinberg et al. 2005, McGreer et al. 2006). The two propulsion/steering Azipods and the bow thruster are supplied at 4160V with all other loads served at the lower voltages.

The goal of this study is to evaluate the feasibility and potential impact of using Integrated Electric Plants in future Great Lakes self-unloading bulk carriers.

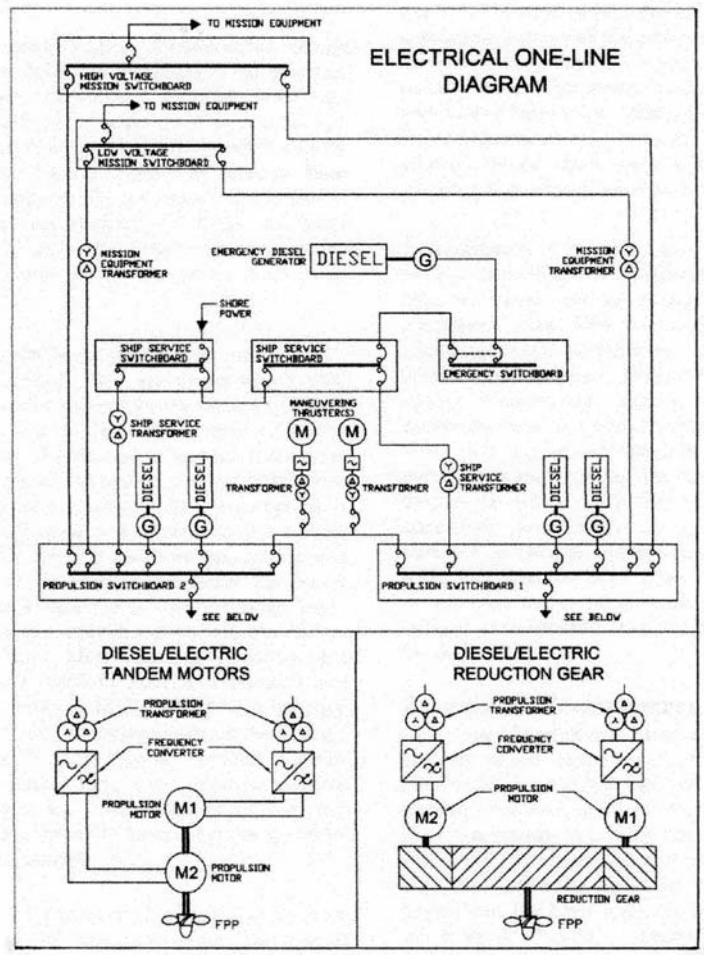


Figure 1 One-line diagram of typical AC/AC Integrated Electric Plant (Stewart 2009)

2. Recent Cargo Vessel Designs

A revealing recent design example is the design of the ORCA class RO/RO vessels (*MV Midnight Sun and MV Northern Lights)* for TOTE's Tacoma to Anchorage service (Boylston and Brooks 2001). Although these commercial cargo vessels have a higher overall power requirement than Great Lakes self-unloaders, an integrated diesel-electric system with direct connected electric motors was selected following an initial Maritech study of 17 propulsion options and a more detailed final study of four diesel options including one with podded propulsors.

The ORCA class ships are characterized by a relatively short sea time versus port time and a varying speed profile due to weather and tides and a fixed schedule. A Great Lakes self-unloader is an even more extreme example of this general type of trade, although a liner schedule is usually not a factor. In the initial study summarized in Boylston and Brooks (2001), an integrated electric plant using five identical diesel generators as shown schematically in Fig. 2 was found to be the best choice.

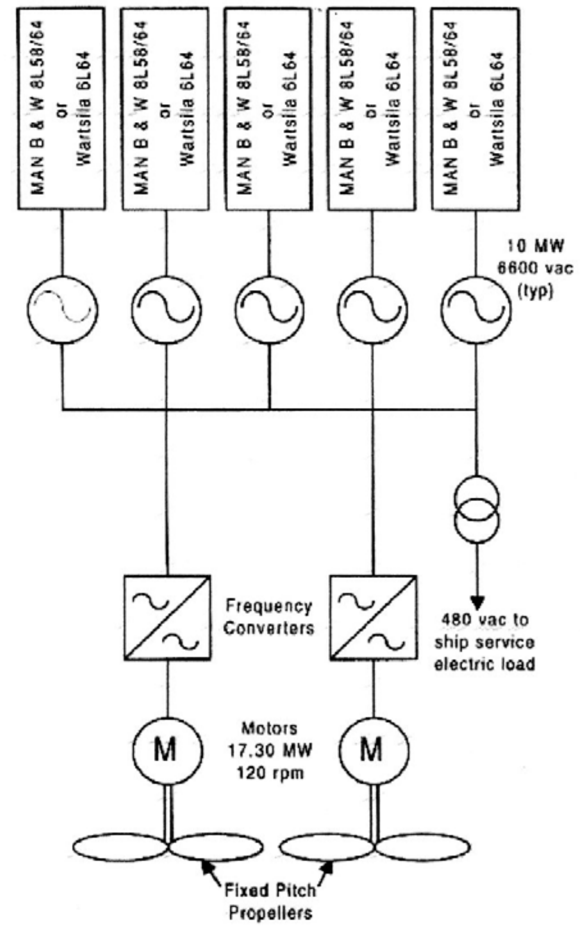


Figure 2 Integrated Electric Plant studied for the ORCA class RO/RO's (Boylston and Brooks 2001)

In the final design of the ORCA class, Boylston went even further and used four larger diesel generators and two smaller diesel generators so that the generators in use at any time could more closely match the speed-power profile of the vessel, as shown in Fig. 3. With this design, each operating generator is at about 90% of its rating, where its specific fuel rate is optimum, regardless of propeller loading.

A second recent design presentation dealing with the use of Integrated Electric Plants in commercial cargo vessels was presented by DELTAMARIN, Ltd at a London *Seatrade* Tanker Industry Convention (Kanerva and Nurmi 1998). This describes their recent European design efforts and designs using IEP propulsion in chemical and product tankers, which are similar in power required to Great Lakes self-unloaders. They note that their "experience has shown that it is not only the owner to be convinced but also and in many cases especially the yard. Having little or no experience in electric propulsion plants yards tend to consider it as a risk and overestimate all additional items and underestimate or do not consider at all the benefits and opportunities."

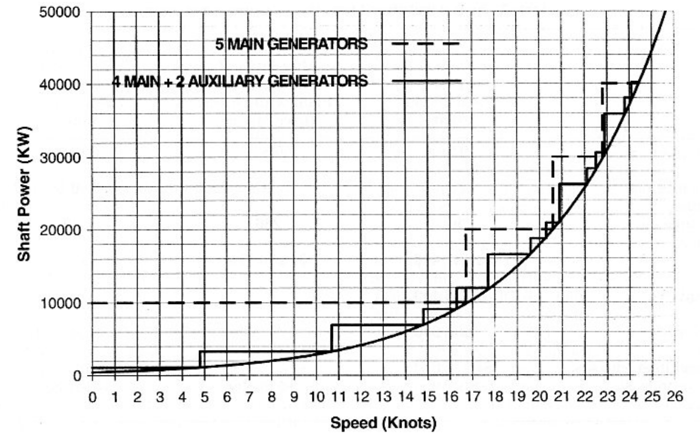


Figure 3 Comparison of power available with five generators or four main plus two smaller generators with ship the propulsion requirement over speed (Boylston and Brooks 2001)

Kanerva and Nurmi (1998) note that "the complete configuration of the vessel must be considered" to reach all available benefits which can include "machinery location, machinery modularization, cargo tank location, cargo volume capacity, loading capabilities, hull form, power requirement, structural principles, machinery and operational availability, operation under special service conditions (restricted waterways, ice, etc.), maintenance, building procedure, installation and timing."

3. Selection of Prototypes

The initial focus of this project was to establish prototype Great Lakes self-unloaders to conceptually redesign with Integrated Electric Plants and then evaluate the arrangements, expected fuel use and emissions in all operating modes. The scope of this effort primarily considered feasible arrangements, fuel use, and air emissions and did not perform a complete vessel design from the ground up as recommended in Kanerva and Nurmi's admonition.

After a review of existing 1000' vessel designs, American Steamship's *MV Walter J. McCarthy, Jr.* (originally the *MV Belle River*, Bay Shipbuilding hull 716), shown in Fig. 4, was selected as the prototype for the 1000' Poe Lock maximum size self-unloading vessel. With EPA Tier 2 requirements coming into effect, this EMD powered, non-heavy fuel plant was judged to give the best comparison basis.

After a review of smaller Great Lakes self-unloaders, American Steamship's *MV American Mariner,* shown in Fig. 5, was selected as the prototype for the 730' MacArthur Lock, Welland Canal, St. Lawrence Seaway maximum size vessel. General Arrangements, Hull Lines, and Electrical Load Analyses (ELA) for these vessels were generously made available by

American Steamship of Buffalo, NY, a subsidiary of GATX, through their Acting President Noel L. Bassett. The principal characteristics of the study vessels are summarized in Table 1.

Don Coles, www.boatnerds.com

Figure 4 *MV Walter J. McCarthy, Jr.* - prototype vessel for 1000' Poe Lock max self-unloader

Capt. George Hughes, www.boatnerds.com

Figure 5 *MV American Mariner* - prototype vessel for 730' MacArthur Lock/Welland Canal/Seaway max self-unloader

Table 1 Principal characteristics of two study vessels

	1000 ft (Poe-max) Self-Unloader	730 ft (MacArthur-max) Self-Unloader
LOA	1000 ft	730 ft
B	105 ft	78 ft
D	56 ft	45 ft
Design T	27.5 ft	27.5 ft
Service speed	14.0 kts	14.0 kts
Cargo capacity	80,900 gross tons	37,300 gross tons
Current propulsion power	14,400 hp = 10,740 kW	7,200 hp = 5,370 kW
Number shafts	twin screw	single screw
Propellers	17.5 ft. dia., 120 rpm FPP	17.5 ft dia., 120 rpm FPP
Bow thruster	1200 kW	800 kW
Stern thruster	1200 kW	800 kW
Hold-loop belt drive	2 @ 750 kW = 1500 kW	conveyor system total
Boom belt drive	2 @ 430 kW = 860 kW	1300 kW
Ballast pumps	4 @ 120 kW = 480kW	2 @ 120 kW = 240 kW
Ship service power	467 kW, max. during docking	510 kW, max. during docking
Design prototype	*MV Walter J. McCarthy*	*MV American Mariner*

4. Systems Design

At first glance an IEP must overcome a significant propulsion efficiency disadvantage relative to the traditional mechanical geared system used on current self-unloaders. The required propulsion brake power P_B is related to the effective power P_E, which reflects the hydrodynamic resistance and speed of the vessel, by the following:

$$P_B = P_E/(\eta_H\ \eta_R\ \eta_O\ \eta_T\ \eta_S\ \eta_B) \tag{1}$$

where η_H is the hull efficiency, η_R is the relative rotative efficiency, η_O is the open water propeller efficiency, η_T is the prime mover to shaft transmission efficiency and $\eta_S\eta_B$ is the shaft bearing and stern tube efficiencies. In a conventional self-unloader, the transmission is through a single-stage reduction gear with efficiency $\eta_T = \eta_G = 0.975$. In an IEP, the transmission is electrical with the prime mover driving a generator ($\eta_{Gen} = 0.96$) with the output passing through a switchboard ($\eta_{Sw} = 1.00$), propulsion transformer ($\eta_{Tr} = 0.99$), AC to AC frequency converter ($\eta_{Fc} = 0.98$) to an electric motor ($\eta_M = 0.96$) that might drive the shaft through a propulsion reduction gear ($\eta_G = 0.975$) giving,

$$P_B = P_E/(\eta_H\ \eta_R\ \eta_O\ \eta_{Gen}\ \eta_{Sw}\ \eta_{Tr}\ \eta_{Fc}\ \eta_M\ \eta_G\ \eta_S\ \eta_B) \tag{2}$$

If the electric motor turns at propeller speed, the reduction gear can be eliminated. The other compensating factor is that with shaft reversal possible electrically, there is no need for a Controllable-Reversible Pitch (CRP) propeller as is commonly used today in self-unloaders. The change in the propeller efficiency $\eta_P = \eta_R\eta_O$ from a CRP to a lighter, simpler, more efficient Fixed-Pitch Propeller (FPP) will be from about 0.65 to about 0.66 or 1.5%. Pulling all these efficiencies that change together gives a total disadvantage for IEP of,

$$(\eta_R\eta_O\eta_G)_{CONV}/(\eta_R\eta_O\eta_{Gen}\eta_{Sw}\eta_{Tr}\eta_{Fc}\eta_M)_{IEP} = 1.074 \tag{3}$$

without gearing, and 1.102 if there is a reduction gear required. This apparent fuel use disadvantage must be compensated for by system design and the operation of all generating sets close to their optimum efficiency in all operating modes.

A typical Great Lakes voyage was assumed to be a round trip carrying Taconite from Duluth, MN to Gary, IN with restricted water travel through the Soo Locks and the St. Marys River. This choice is probably conservative for this comparison since a journey to the lower lakes would involve additional restricted water travel through the St. Clair River, Lake St. Clair, and the Detroit River. The definition of the operating modes, power level, auxiliaries in use and assumed times for one round trip is shown in Table 2. The vessels were assumed to spend 6 hours loading with their ballast pumps in use, 6 hours maneuvering at 30% propulsion power, 8 hours at reduced speed at 50% propulsion power, 103 hours in the open lakes at 85% propulsion power, 2 hours locking and docking with the lateral thrusters in use while at 10% propulsion power, and 10 hours unloading with the ballast pumps and self-unloading conveyor system in use. This voyage was used for both the 1000’ and 730’ vessels in the study.

Table 2 Definition of operating modes for Duluth to Lower Lake Michigan round-trip

mode of operation	percent propulsion power	auxiliaries in use	hours per voyage	percent of voyage
loading	0.00%	ship service, ballast pumps	6	4.40%
maneuvering	30.00%	ship service	6	4.40%
reduced speed	50.00%	ship service	8	5.90%
open lake	85.00%	ship service	103	76.30%
locking/docking	10.00%	ship service, thrusters	2	1.50%
unloading	0.00%	ship service, ballast pumps, conveyors	10	7.40%
total			135	100.00%

To develop the IEP installations for the 1000’ self-unloaders, the required electrical generation capacity in kWe was established for all operating modes as shown in Table 3. The basis for the propulsion power is the 14,400 BHP design power of the prototype. The electrical loads were taken from the prototype ELA. The loads shown are for the cold weather heating condition. The maximum required below the table is the full power propulsion load, when the full service margin is in full use (100%), plus the open lake ship service load.

For the comparison basis, the existing *MV Walter J. McCarthy, Jr.* was updated to utilize the latest EPA Tier 2 qualified versions of the EMD engines used in the existing vessel as shown in Table 4. The Tier 2 qualified Caterpillar C32 Acert V12 engines were used as generators sets using the 634 kW mechanical rating to produce a generator output of 609 kWe. Otherwise, the plant configuration was unchanged.

For the comparisons, two IEP designs were developed. One utilizes yellow Caterpillar generator sets as shown in Table 4 and this might be considered the minimum machinery size and weight design. Three C280-12 generator sets and 2 generator sets using C32 Acert engines at their 634 kW ratings, all Tier 2 qualified, were used. The other utilizes Wärtsilä generator sets as shown in Table 4 and this might be considered the minimum fuel use, but maximum machinery size and weight design. Four 9L26 generator sets and one 6L20DF generator set, all Tier 2 qualified, were used. The Wärtsilä generators also have the ability to burn heavy fuel should suitable fuel and after treatment become available.

Table 4 1000’ self-unloader machinery

twin propeller designs	main engines	main generators	ship service/smaller generators
New *Walter J. McCarthy, Jr.*	4xEMD 16-710G7C-T2 800 rpm, 2629 kW	2xPTO generators 2500 kWe	2xCaterpillar C32 Acert 1800 rpm, 609 kWe
IEP with Caterpillar gen sets		3xCaterpillar C280-12 900 rpm, 3640 kWe	2xCaterpillar C32 Acert 1800 rpm, 609 kWe
IEP with Wärtsilä gen sets		4xWärtsilä 9L26 900 rpm, 2810 kWe	1x6L20DF 720 rpm, 1014 kWe

To minimize the in-harbor air emissions further in the latter design, a smaller 6L20DF dual fuel generator is utilized. These engines can operate either normally as a lean burn Otto cycle engine on natural gas (LNG) with a diesel micro-pilot (less than 1% of the heat input) providing the ignition, or as a normal Diesel cycle engine using Marine Diesel Oil (MDO) as backup.

Table 3 1000’ self-unloader loads by mode

Item	Installed	Open Lake		Reduced Speed		Maneuvering		Locking/ Docking		Loading		Unloading	
	Full Power	LF	kWe	LF	kWe	LF	kWe	LF	kWe	LF	kWe	LF	kWe
propulsion	11070.5	0.85	9409.9	0.50	5535.3	0.30	3321.2	0.10	1107.1	0.00	0.0	0.00	0.0
bow thruster	1200	0.00	0.0	0.00	0.0	0.00	0.0	0.80	960.0	0.00	0.0	0.00	0.0
stern thruster	1200	0.00	0.0	0.00	0.0	0.00	0.0	0.80	960.0	0.00	0.0	0.00	0.0
ballast pumps	240	0.00	0.0	0.00	0.0	0.00	0.0	0.00	0.0	0.80	392.0	0.80	392.0
conveyor system	2360	0.00	0.0	0.00	0.0	0.00	0.0	0.00	0.0	0.00	0.0	1.00	2360.0
ship serviceloads	800	0.69	410.6	0.69	410.6	0.69	410.6	0.85	466.6	0.77	353.3	0.69	408.9
total	16870.5		9820.5		5945.9		3731.8		3493.7		745.3		3160.9
hours per voyage	135.0		103.0		8.0		6.0		2.0		6.0		10.0
percent of voyage	100.0%		76.3%		5.9%		0.0		1.5%		4.4%		7.4%

maximum required 11481.1 kWe

Natural gas is a relatively safe, non-toxic, lighter than air fuel. Ignition temperature is 600^oC, relatively high compared to diesel (250^oC). There is no visible smoke and no sludge deposits. It is flammable only in the concentration range of 5-15% in air. Although all fuel price markets are volatile, LNG in recent years has been relatively steady and has begun to be cheaper than Heavy Fuel Oil (HFO) on a price per energy content (USD/MBtu) basis; significantly less than MDO. In early 2008, the relative price per energy content had a ratio of about 10:13:22 USD/MBtu for LNG:HFO:MDO (Parsons 2009).

Natural gas is primarily methane (CH_4) and its greater hydrogen to carbon ratio gives it a 20 to 25% reduced production of Green House Gases (primarily CO_2) compared to oil. When it is liquefied to -162^oC for transport and storage, the sulfur is removed which means that the SO_X are eliminated. It is clean burning with significantly reduced NO_X naturally meeting the EPA Tier III requirements. Particulates are essentially eliminated compared to oil-based fuels (Parsons 2009).

The one-line diagram for the 1000' self-unloader with Wärtsilä generator sets is shown in Fig. 6. The five Wärtsilä generators feed the 4160V main bus, which is in sections for reliability. Any generator can supply any load. The Caterpillar generator set design would be similar with one of the C280-12 generator sets in the middle and one of the smaller generator sets on the each lower section of the high voltage bus. There are 30^o phase shift propulsion transformers to supply 12 pulse Pulse Width Modulated (PMW) frequency converters (Parsons 2010, Woud and Stapersma 2002) that supply variable voltage, variable frequency power to the two direct connected 0-120 rpm induction propulsion motors that drive fixed-pitch propellers. The large conveyor and lateral thruster loads are supplied from the main 4160V switchboard. Two 4160V/450V transformers supply the two sections of the main ship service switchboard, which supplies the ballast pumps and other ship service loads. The emergency generator and emergency switchboard are typical.

Some companies are now able to eliminate some or all of the high voltage propulsion transformers, such as Wärtsilä's Low Loss Concept (LLC), and this can eliminate those transformer losses and reduce the weight, volume, capital cost, and heat load of the IEP system.

To develop the IEP installations for the 730' self-unloaders, the required electrical generation capacity in kWe was established in all operating modes as shown in Table 5 when tandem 0-120 rpm motors are used and in Table 6 when geared 0-720 rpm motors are used. The basis for the propulsion power is the 7,200 BHP design power of the prototype. The electrical loads were taken from the prototype ELA. The loads shown are for the cold weather heating condition. The maximum required below the table is the full power propulsion load when the full service margin is in use (100%) plus the open lake ship service load.

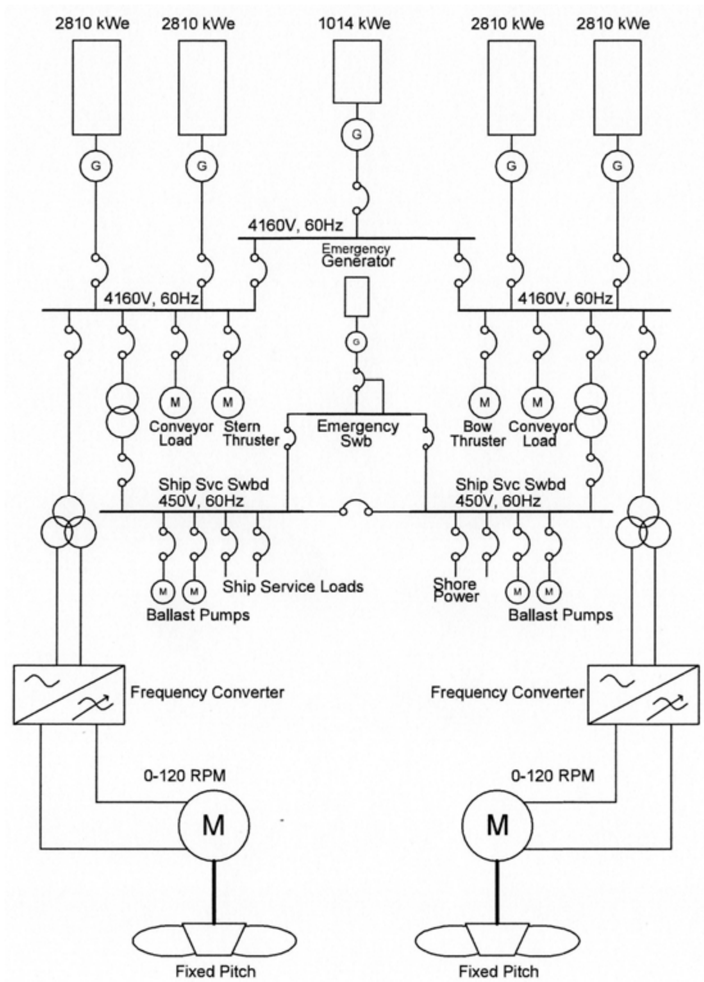


Figure 6 One-line diagram for 1000' self-unloader

For the study basis, the existing *MV American Mariner* was updated to utilize the latest EPA Tier 2 qualified versions of the EMD engines used in the existing vessel as shown in Table 7. The Tier 2 qualified Caterpillar C32 Acert V12 engines at their 634 kW rating were again used as smaller generator sets. Again for the comparisons, two IEP designs were developed. One utilizes yellow Caterpillar generator sets and the other utilizes Wärtsilä generator sets as shown in Table 7. The Caterpillar generator set design uses the C32 Acert V12 engines at a higher 746 kW rating to produce 716 kWe.

The one-line diagram for the 730' self-unloader with Wärtsilä generator sets and tandem 0-120 rpm propulsion motors is shown in Fig. 7. The Caterpillar generator set design would be similar. The three Wärtsilä generators feed the 4160V main bus. The remainder of the system is similar to that for the 1000' self-unloaders. The tandem motors are used to provide smaller diameter motors and higher system reliability.

Geared 0-720 rpm motors would add the gearing inefficiency, but would provide even smaller, lighter motors. With two smaller (2770 kW) motors used in this relatively low power single screw installation for reliability reasons, lower 480V generation might also be used. A 4160V generation design was used here, however, to have symmetry between the 730'er and 1000'er designs.

Table 5 730' self-unloader loads by mode – tandem motors

Item	Installed	Open Lake		Reduced Speed		Maneuvering		Locking/ Docking		Loading		Unloading	
	Full Power	LF	kWe	LF	kWe	LF	kWe	LF	kWe	LF	kWe	LF	kWe
propulsion	5535.3	0.85	4705.0	0.50	2767.6	0.30	1660.6	0.10	553.5	0.00	0.0	0.00	0.0
bow thruster	800	0.00	0.0	0.00	0.0	0.00	0.0	0.80	640.0	0.00	0.0	0.00	0.0
stern thruster	800	0.00	0.0	0.00	0.0	0.00	0.0	0.80	640.0	0.00	0.0	0.00	0.0
ballast pumps	200	0.00	0.0	0.00	0.0	0.00	0.0	0.00	0.0	0.80	160.0	0.00	0.0
conveyor system	1300	0.00	0.0	0.00	0.0	0.00	0.0	0.00	0.0	0.00	0.0	1.00	1300.0
ship service loads	600	0.69	414.0	0.69	414.0	0.69	414.0	0.85	510.0	0.77	462.0	0.69	414.0
total	9235.3		5119.0		3181.6		2074.6		2343.5		622.0		1714.0
hours per voyage	135.0		103.0		8.0		6.0		2.0		6.0		10.0
percent of voyage	100.0%		76.3%		5.9%		4.4%		1.5%		4.4%		7.4%

maximum required 5949.3 kWe

Table 6 730' self-unloader loads by mode – geared motors

Item	Installed	Open Lake		Reduced Speed		Maneuvering		Locking/ Docking		Loading		Unloading	
	Full Power	LF	kWe	LF	kWe	LF	kWe	LF	kWe	LF	kWe	LF	kWe
propulsion	5677.2	0.85	4825.6	0.50	2838.6	0.30	1703.2	0.10	567.7	0.00	0.0	0.00	0.0
bow thruster	800	0.00	0.0	0.00	0.0	0.00	0.0	0.80	640.0	0.00	0.0	0.00	0.0
stern thruster	800	0.00	0.0	0.00	0.0	0.00	0.0	0.80	640.0	0.00	0.0	0.00	0.0
ballast pumps	200	0.00	0.0	0.00	0.0	0.00	0.0	0.00	0.0	0.80	160.0	0.00	0.0
conveyor system	1300	0.00	0.0	0.00	0.0	0.00	0.0	0.00	0.0	0.00	0.0	1.00	1300.0
ship service loads	600	0.69	414.0	0.69	414.0	0.69	414.0	0.85	510.0	0.77	462.0	0.69	414.0
total	9377.2		5239.6		3252.6		2117.2		2357.7		622.0		1714.0
hours per voyage	135.0		103.0		8.0		6.0		2.0		6.0		10.0
percent of voyage	100.0%		76.3%		5.9%		4.4%		1.5%		4.4%		7.4%

maximum required 6091.2 kWe

Table 7 730' self-unloader machinery

single propeller designs	main engines	main generators	ship service/smaller generators
New *American Mariner*	2xEMD 16-710G7C-T2 800 rpm, 2629 kW		4xCaterpillar C32 Acert 1800 rpm, 609 kWe
IEP with Caterpillar gen sets with or without gearing		2xCaterpillar C280-8 900 rpm, 2420 kWe	2xCaterpillar C32 Acert 1800 rpm, 716 kWe
IEP with Wärtsilä gen sets with or without gearing		2xWärtsilä 9L26 900 rpm, 2810 kWe	1x6L20DF 720 rpm, 1014 kWe

5. Machinery Arrangements

The IEP machinery arrangements for the 1000' self-unloader with Wärtsilä generator sets are shown in Fig. 8. They were developed following the conclusion of Kanerva and Nurmi who note that "several studies and new building designs have shown that the optimal arrangement is to locate the machinery vertically" so that the power flows downward giving short, direct high voltage cable runs. This also enables minimum length engine rooms (Kanerva and Nurmi 1998).

Where possible the arrangement of the prototype was utilized to minimize the change. The IEP equipment sizes were developed from the *Mackinaw* general arrangements, which should be conservative since it has a higher overall power. The propulsion motor sizes were developed using Kanerva and Nurmi (1998).

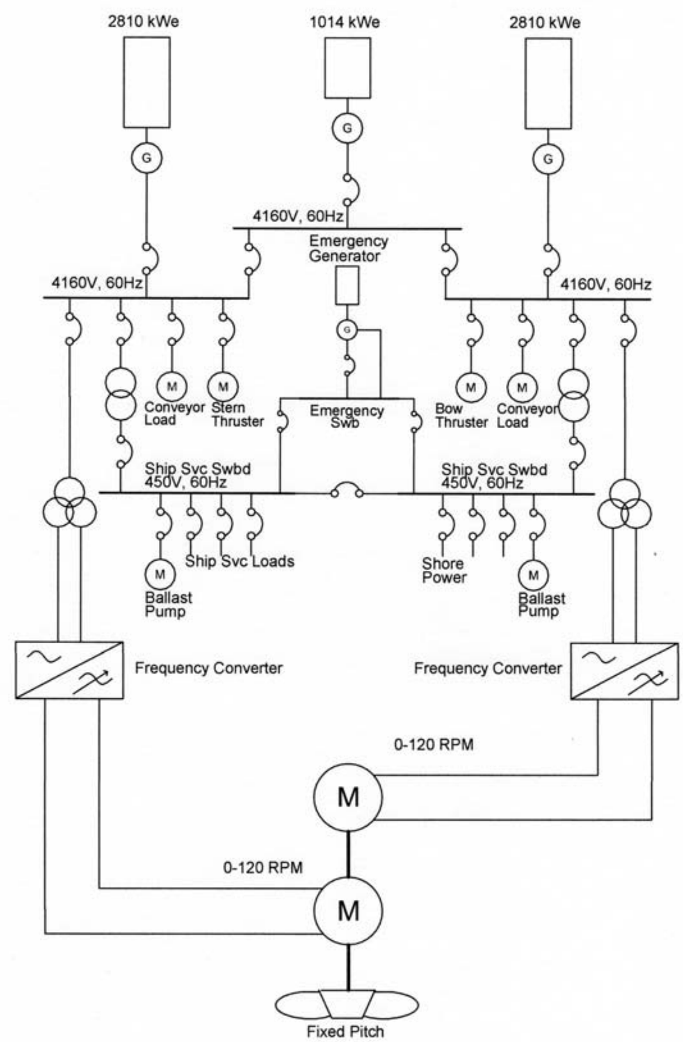


Figure 7 One-line diagram for 730' self-unloader – tandem motors

To best illustrate the IEP machinery arrangement, the inboard profile in Fig. 8 is taken at 20' to port of the centerline with the view to port. The engine room and deck house are located aft between web frames 118 and 126, with the lowest engine room floor level extending forward below the Cargo Hold #7 hopper to web frame 111. The loop belt conveyor is on the centerline. The solid line directly over the main propulsion motor is the sloping hopper bottom at the profile cut 20' off the centerline; this line is inboard of the motors. The solid line above is the hopper at the side. The dashed line indicates the headroom directly over the motor centerline.

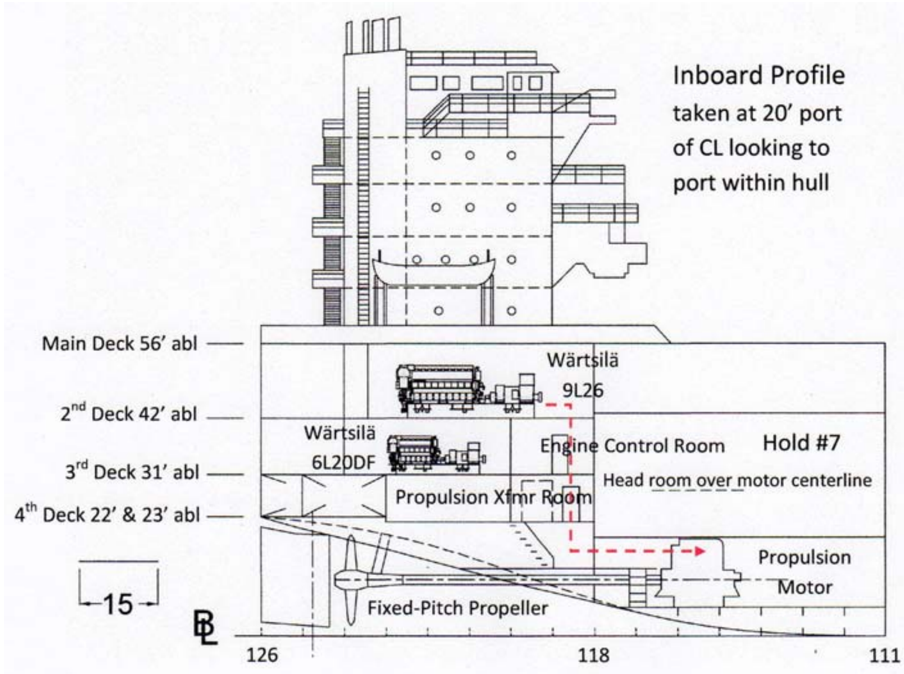
The four larger 9L26 generator sets are located on the 2nd deck with the generators forward to minimize cable runs and facilitate access to the uptakes at the rear corners of the deck house. With their high location, these sets will likely require resilient mounts and their foundations will be challenging. The smaller 6L20DF generator set is located to port below on the 3rd deck and LNG fuel is stored starboard in an insulated 9 bar (132 psi) storage tank. This tank only holds enough LNG for 2 round trip voyages so additional storage would likely be needed elsewhere in the ship. The Engine Control Room, which contains the control console and the combined high voltage and ship service switchboards, is located forward on this level. It is flanked by small rooms containing the 4160V/450V ship service transformers. Two separate propulsion transformer rooms, containing the propulsion transformers and the frequency converters, are located forward on the 4th deck.

Two direct connected main propulsion motors are located on the tank top or engine room floor level that extends between web frames 111 and 121. The ballast pumps are forward on this level. The stern thruster is low aft within the skeg. The main flow of high voltage propulsion power is a short direct route downward from generators, to main switchboard, to propulsion transformers and frequency conversion, down to the motors giving minimized high voltage cable runs.

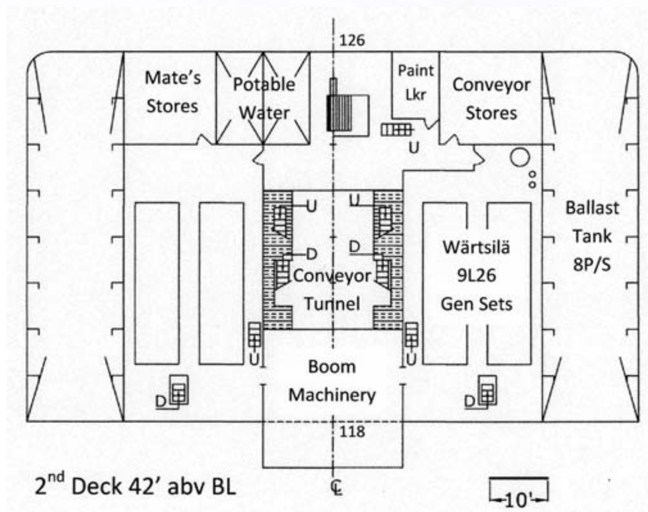
The arrangements for the 1000' IEP self-unloader would have to utilize modified deck heights between web frames 118 and 126. The 2nd and 3rd decks would need to be lowered 3' to 42' and 31' above the baseline, respectively, and the portion of the 4th deck between web frames 118 and 123 would need to be lowered to 22' above baseline to provide adequate equipment headroom. This would result in a modest loss of tank volume on the 4th deck.

A few functions were lost in this arrangement and they would need to be accommodated within the detailed arrangement development. The small crew and officer washrooms and laundries were lost on the 2nd deck. Likewise, the engineer's workshop area was lost forward on the 3rd deck. Significant, but less useful, deck area, is available on the engine room floor level due to the elimination of 2 reduction gears, 4 main propulsion diesels, 2 PTO generators, and 2 ship service generator sets from this level. Air intake filters would also have to be provided for the diesels.

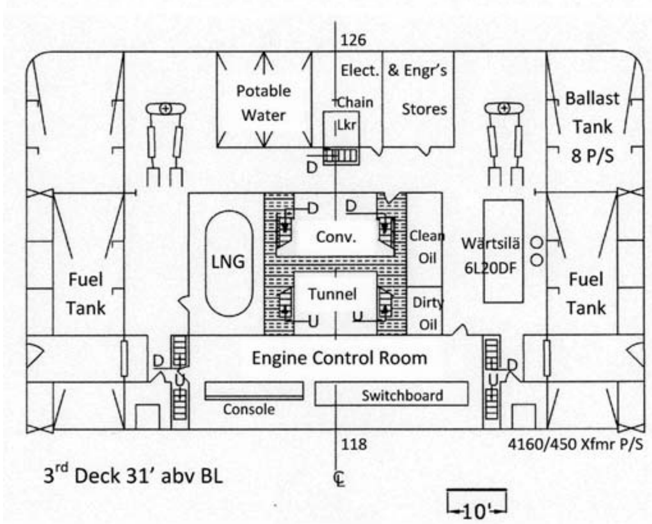
Also with the movement of the main prime movers from the engine room floor to the 2nd deck, with their mufflers previously located between the 3rd deck 34' above baseline and the main deck 56' above baseline, there will probably be a need to expand the uptakes. The uptakes located at the aft, outboard corners of the deck house will likely have to be expanded outward between the main deck and the "B" deck 77' above baseline to accommodate the mufflers.



Inboard Profile
taken at 20' port
of CL looking to
port within hull
Main Deck 56' abl
2nd Deck 42' abl
3rd Deck 31' abl
4th Deck 22' & 23' abl
Wärtsilä
9L26
Wärtsilä
6L20DF
Engine Control Room
Hold #7
Head room over motor centerline
Propulsion Xfmr Room
Propulsion
Motor
Fixed-Pitch Propeller
15
BL
126
118
111



126
Mate's
Stores
Potable
Water
Paint
Lkr
Conveyor
Stores
Ballast
Tank
8P/S
Conveyor
Tunnel
Wärtsilä
9L26
Gen Sets
Boom
Machinery
118
2nd Deck 42' abv BL
CL
10'



126
Elect. & Engr's
Stores
Potable
Water
Chain
Lkr
Ballast
Tank
8 P/S
Conv.
Clean
Oil
LNG
Wärtsilä
6L20DF
Fuel
Tank
Tunnel
Dirty
Oil
Fuel
Tank
Engine Control Room
Console
Switchboard
118
4160/450 Xfmr P/S
3rd Deck 31' abv BL
CL
10'

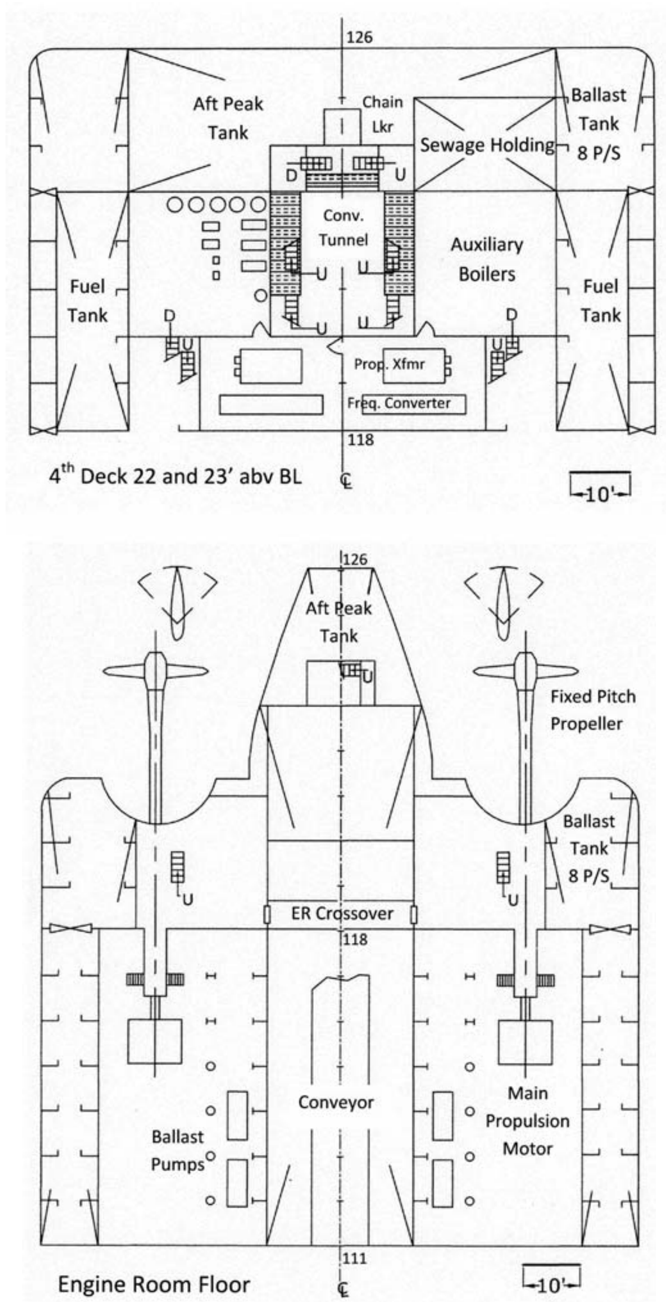
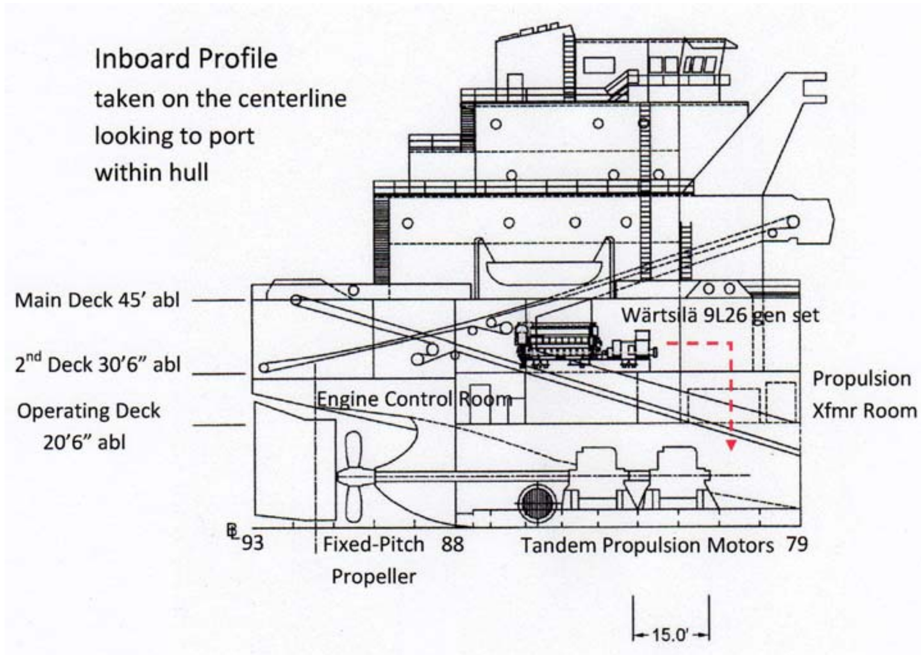
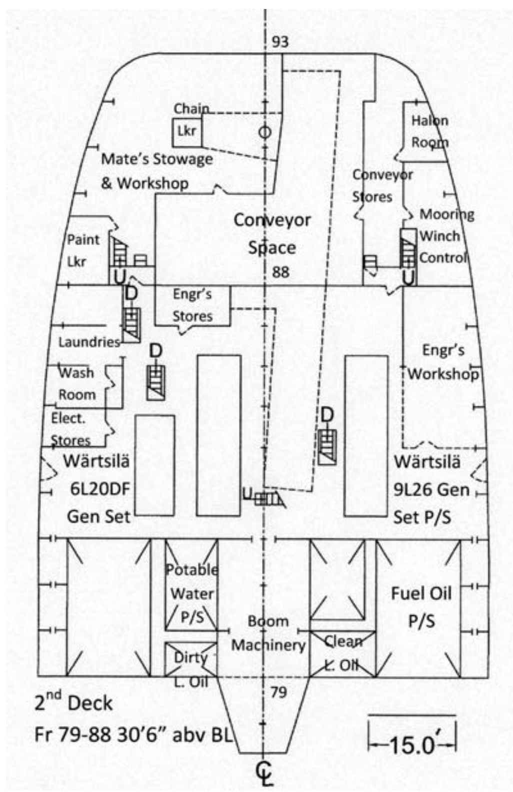


Figure 8 1000' self-unloader propulsion machinery arrangements

Kanerva and Nurmi (1998) note that in product and chemical tankers the use of an IEP with the equipment stacked vertically allowed the engine room to be shortened, which added 3-6.5% additional cargo tank volume. The longitudinal center of buoyancy could then be moved aft to match the aft shift in cargo center of gravity. This allowed the hulls to be made finer forward to reduce the wave resistance and with the use of a pram and gondola stern design (barge stern with wide skeg), the required propulsion power was reduced by as much as 15-18% since the new hull form aft also allowed the use of a larger diameter propeller. These benefits do not, however, appear to be as realizable in Great Lakes self-unloaders, particularly the 1000'ers, since they already have minimum engine room length. They also have very full hulls and already use a barge stern with wide skeg.

The IEP machinery arrangements for the 730' self-unloader with Wärtsilä generator sets and tandem 0-120 rpm motors are shown in Fig. 9. The arrangements with Caterpillar generator sets would be similar.


Inboard Profile
taken on the centerline
looking to port
within hull
Main Deck 45' abl
2nd Deck 30'6" abl
Operating Deck
20'6" abl
Wärtsilä 9L26 gen set
Propulsion
Xfmr Room
Engine Control Room
93
Fixed-Pitch 88
Propeller
Tandem Propulsion Motors 79
15.0'


93
Chain
Lkr
Halon
Room
Mate's Stowage
& Workshop
Conveyor
Stores
Conveyor
Space
88
Mooring
Winch
Control
Paint
Lkr
Engr's
Stores
Laundries
Wash
Room
Elect.
Stores
Engr's
Workshop
Wärtsilä
6L20DF
Gen Set
Wärtsilä
9L26 Gen
Set P/S
Potable
Water
P/S
Boom
Machinery
Fuel Oil
P/S
Dirty
L. Oil
Clean
L. Oil
79
2nd Deck
Fr 79-88 30'6" abv BL
15.0'

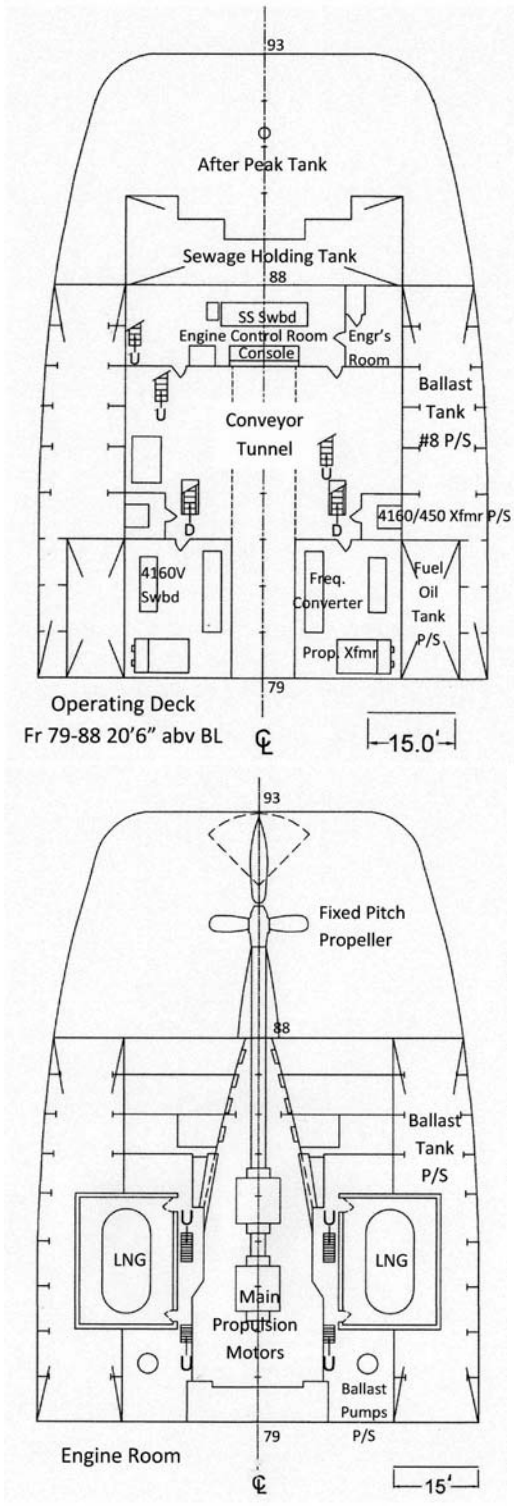


Figure 9 730' self-unloader propulsion machinery arrangements

The 730' self-unloader machinery arrangements are similar to those on the 1000' self-unloader, but differ in that with a lower depth, there is one less deck within the hull. The arrangement approach is similar, however, with the generator sets on the upper level; the switchboards, propulsion transformers, and frequency converters on the mid-level with the engine control room; and the tandem main propulsion motors on the lower level. Where possible the arrangement of the prototype was utilized to minimize the change.

The inboard profile within the hull in Fig. 9 is taken in the traditional manner on the centerline with the view to port. The engine room and deck house are located aft between web frames 79 and 93. The hopper conveyor is on the centerline, with the boom supply conveyor off to port at the stern.

The two 9L26 generator sets are located on either side of the conveyor on the 2nd deck with their generators forward to minimize cable runs. The uptake through the deck house is just to starboard of the centerline between web frames 84 and 86. The smaller 6L20DF generator set is located to starboard on the 2nd deck. With their high location, these sets will likely require resilient mounts and their foundations will be challenging.

The Engine Control Room, which contains the control console and ship service switchboard, is located aft on the operating deck level. Two separate propulsion transformer rooms, containing the 4160V switchboards, the propulsion transformers and the frequency converters, are located forward on this deck. Just aft are two small rooms containing the 4160V/450V ship service transformers.

The tandem direct connected main propulsion motors are located below on the engine room floor level. The ballast pumps are located low forward on this level. The stern thruster tunnel is just aft of the motors within the skeg. The LNG fuel is stored port and starboard in insulated 9 bar (132 psi) storage tanks. These tanks hold enough LNG for multiple round trip voyages, so smaller tanks located within the B/5 lines for greater collision protection would probably be preferred. The flow of high voltage propulsion power is a short direct route downward from the generators to the 4160V switchboard, propulsion transformers and frequency conversion, and then down to the motors minimizing the high voltage cable runs.

The arrangements for the 730' IEP self-unloader would have to utilize modified deck heights between web frames 79 and 88. The 2nd deck would need to be lowered 3' to 30'6" above baseline and the operating deck would need to be lowered to 20'6" above baseline to provide adequate equipment headroom.

Air intake filters would have to be provided for the diesels. Also with the movement of the prime movers from the engine room floor to the 2nd deck, their mufflers would need to be accommodated on that level or more volume would be needed in the uptake through the interior of the deck house.

6. Fuel Consumption

Prime movers are generally optimized to provide the best specific fuel rate (g/kWh) near their design point (typically about 90% power and rpm). When they are operated at partial load either along a propeller load curve (power varying roughly with the cube of the rpm or vessel speed in a self-unloader) or at constant rpm, when needed to generate constant frequency (60 Hz) electric power, the specific fuel rate increases at lower loads as shown in Fig. 10 for the latter case. It is, therefore, important to design power plants so that all operating prime movers are loaded close to the specific fuel rate "sweet spot" in order to minimize fuel consumption. The significant fraction of time that Great Lakes vessels spend in rivers, locks, restricted channels, and harbor approaches, and maneuvering within harbors leads to significant periods of time where the typical plants today are unable to operate at their best fuel rate. By automatically using only those generators needed to meet existing total power requirements, all operating generators in an IEP can be kept close to 90% load (see Fig. 3 for example).

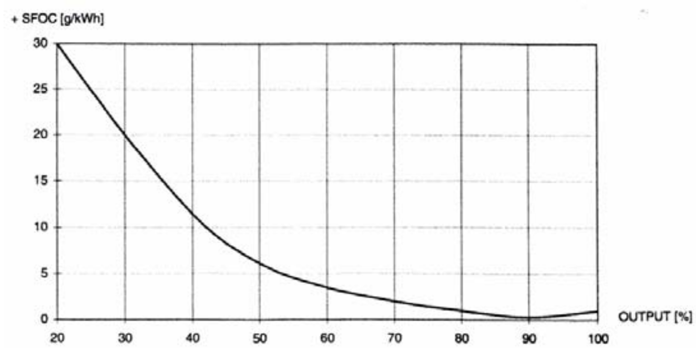


Figure 10 Typical increase in diesel generator specific fuel rate with load at constant rpm

For the 1000' self-unloader comparison as summarized in Table 8, the fuel cost per round trip voyage was found to be 0.4% less, essentially the same, with the IEP design with Caterpillar generator sets compared with that required by the updated prototype vessel. But the Caterpillar C280-12 engines have a 3.5% better specific fuel rate at their design point than the EPA Tier 2 versions of the EMD engines used on the updated prototype vessel. Thus, the 1000' self-unloader with Caterpillar generator sets IEP design alone could not overcome all of the 7.4% fundamental propulsion efficiency disadvantage shown in Eq. (3).

Table 8 Fuel cost for 1000' self-unloaders for round trip

design	effective t/h	fuel $/ voyage	savings
New *Walter J. McCarthy, Jr.*	1.707	$126,713	base
IEP with Caterpillar Gen Sets	1.699	$126,182	$531 (0.41%) (3.5% due to sfr)
IEP with Wärtsilä Gen Sets	1.544/0.026 MDO/LNG	$115,402	$11,311 (8.74%) (7.9% due to sfr)

based on $550/tonne low sulfur MDO, $220/tonne LNG

The fuel cost per round trip voyage was found to be 8.7% less with the IEP design with Wärtsilä generator sets than required by the updated prototype vessel. The majority of this is due to the Wärtsilä engines having a 7.9% better specific fuel rate at their design point than the EPA Tier 2 versions of the EMD engines used on the updated prototype vessel. Thus with proper design, the 1000' self-unloader with Wärtsilä generator sets IEP design can overcome the apparent 7.4% propulsion efficiency disadvantage and a significant fuel cost advantage of as much as 8.7% can be created by the proper selection and design of the IEP generator configuration.

For the 730' self-unloader comparison summarized in Table 9, the fuel cost per round trip voyage with tandem, low rpm motors was found to be almost 0.5% less with the IEP design with Caterpillar generator sets compared with that required by the updated prototype vessel. This reflects that the Caterpillar C280-8 engines have a 5.1% better specific fuel rate at their design point than the EPA Tier 2 versions of the EMD engines used on the updated prototype vessel. The fuel cost per round trip voyage with geared, higher rpm motors was found to be 1.9% more with the IEP design with Caterpillar generator sets compared to that required by the updated prototype vessels. Thus, the Caterpillar generator set IEP design using geared motors cannot fully make up for the 10.2% fundamental propulsion efficiency disadvantage.

Table 9 Fuel cost for 730' self-unloaders for round trip

design	effective t/h	fuel $/ voyage	savings
New *American Mariner*	0.879	$65,296	base
IEP with Caterpillar Gen Sets Tandem 0-120 rpm Motors	0.875	$65,003	$293 (0.45%) (5.1% due to sfr)
IEP with Wärtsilä Gen Sets Tandem 0-120 rpm Motors	0.826/0.005 MDO/LNG	$61,492	$3,804 (5.83%) (7.9% due to sfr)
IEP with Caterpillar Gen Sets Geared 0-720 rpm Motors	0.896	$66,515	- $1,219 (-1.86%) (5.1% due to sfr)
IEP with Wärtsilä Gen Sets Geared 0-720 rpm Motors	0.839/0.005 MDO/LNG	$62,466	$2,830 (4.31%) (7.9% due to sfr)

based on $550/tonne low sulfur MDO, $220/tonne LNG

The fuel cost per round trip voyage with tandem, low rpm motors was found to be 5.8% less with the IEP design with Wärtsilä generator sets than required by the updated 730' prototype vessel. The fuel cost per round trip voyage with geared, higher rpm motors was found to be 4.3% less with the IEP design with Wärtsilä generator sets than required by the updated prototype vessel. Both of these are less than the 7.9% better specific fuel rate the Wärtsilä engines have at their design point compared with the updated EPA Tier 2 versions of the EMD engines used on the updated prototype vessel. Thus, the 730' self-unloader with Wärtsilä generator sets IEP design alone cannot overcome all of the 7.4% fundamental propulsion efficiency disadvantage shown in Eq. (3).

Similar effects might be expected to be found in the air emissions from these plants since fuel use is a major determinate of the air emissions.

7. Air Emissions

The overall ship environmental footprint is receiving increased attention from the EPA and the public and this will only increase in the future as the fraction of total emissions attributable to the marine segment becomes more prominent. By operating central station generators closer to their design point and only having the necessary number of prime movers on the line, it should be possible to reduce the total emissions from Great Lakes ships with an Integrated Electric Plant. Most emissions have as their primary determinant the amount of fuel consumed.

The air emissions from the new prototype and IEP designs was compared using the approach used recently by the Lake Carriers' Association to investigate the total marine air emissions released in a typical year (2004) in Cleveland and Duluth/Superior (Harkins 2007). This approach involves the use of specific emission factors [g pollutant/kWh] multiplied by the time and power used in each mode summed over the operating modes. The prime movers used in this study, involve different EPA categories and subclasses in terms of their EPA Tier 2 and Tier 3 emission requirements for oxides of nitrogen and total hydrocarbons NO_x + THC, particulates PM, and carbon monoxide CO as shown in Table 10. All of the larger generators are EPA Category 2 engines, but they have slightly different requirement based upon their cylinder displacement [$dm^3 = \ell$]. The smaller generators are Category 1 engines with slightly tighter requirements.

Emission factors [EF] are not generally available for specific engines, particularly as a function of engine operating point. Data is available for the Caterpillar C280-8 and C280-12 generator sets and the C32 engines for hydrocarbons HC, NOx, CO and PM; the "not to exceed data" was used here. For NO_x + THC for the other engines and for PM for the Category 1 engines, the EPA limit values shown in Table 10 were used without change. For the remaining, the emission factors given in Table 10 of Harkins (2007), as provided in consultation with the EPA, were used. Some of these emission factors are directly related to the specific fuel consumption (sfc [g fuel/kWh]) and the fuel sulfur weight fraction (%S) expressed as a decimal. Thus, the following was used in this study,

$$EF_{HC} = \text{Cat data or Table 10 of Harkins (2007)} \quad (4)$$

$$EF_{CO} = \text{Cat data or Table 10 of Harkins (2007)} \quad (5)$$

$$EF_{PM} = 0.25+sfc*7*0.02247*(\%S-0.001) \quad (6)$$

Table 10 EPA categories and requirements

40 CFR Part 94								EPA Tier 2 2011			EPA Tier 3 2013-14		
engine	speed	kW/cyl	bore	stroke	cylinder displ.	power density	EPA Cat.	NOx+ THC	EPA PM	EPA CO	NOx+ THC	EPA PM	EPA CO
units	rpm	kW	mm	mm	dm3 = liters	kW/dm3		g/kWh	g/kWh	g/kWh	g/kWh	g/kWh	g/kWh
Wärtsilä 9L26	900	325.0	260	320	16.99	19.13	2	8.70	0.50	5.00	7.00	0.34	5.00
Wärtsilä 6L20DF	720	176.0	200	280	8.80	20.01	2	7.80	0.27	5.00	6.20	0.14	5.00
Caterpillar C280-8	900	287.5	280	300	18.47	15.56	2	8.70	0.50	5.00	7.00	0.34	5.00
Caterpillar C32	1800	62.2	145	162	2.68	n.a.	1	7.20	0.20	5.00	5.60	0.11	5.00
EMD 16 710G7C-T2	800	186.4	n.a.	n.a.	11.63	16.03	2	7.80	0.27	5.00	6.20	0.14	5.00

$EF_{PM2.5} = 0.97EF_{PM}$ (fine particulates) (7)

$EF_{SO2} = sfc * 2 * 0.97753 * \%S$ (8)

$EF_{CO2} = sfc * 0.87 * (44/12)$ (9)

The emissions for the 1000' self-unloader designs expressed as total emissions per round trip voyage and harbor emissions per round trip voyage [tonnes/voyage] are summarized in Table 11. For the purposes of evaluating the air emissions in more populated areas, the harbor operations were assumed here to be the loading, maneuvering, locking/docking, and unloading modes. The assumed fuel was low sulfur MDO with 0.050% = 500 ppm sulfur. The comparison is a little skewed since there is more specific data available for the Caterpillar C280-12 generator set. In particular, the pre-Tier 2 HC and CO emissions factors from Table 10 of Harkins (2007) appear to be high for current Tier 2 engines.

Table 11 Emissions of 1000' self-unloaders for round trip

total per voyage

design	HC	NOx	CO	PM	PM 2.5	SO_2	CO_2
New *Walter J. McCarthy, Jr.*	0.150	8.356	2.689	0.260	0.252	0.225	735.1
IEP with Caterpillar Gen Sets	0.848	10.605	0.982	0.341	0.331	0.224	732.5
IEP with Wärtsilä Gen Sets	0.148	9.491	2.780	0.260	0.252	0.204	676.3

harbor only per voyage

design	HC	NOx	CO	PM	PM 2.5	SO_2	CO_2
New *Walter J. McCarthy, Jr.*	0.010	0.491	0.155	0.016	0.016	0.014	45.8
IEP with Caterpillar Gen Sets	0.057	0.612	0.063	0.025	0.025	0.013	43.3
IEP with Wärtsilä Gen Sets	0.007	0.474	0.157	0.013	0.012	0.011	40.9

The emissions for the 1000' self-unloader IEP design with Wärtsilä generator sets were lower than the new prototype for hydrocarbons, SO_2 and the Green House Gas CO_2 for either total or harbor operations. They are also lower for NOx and particulates in harbor operations. The impact of the smaller dual fuel generator set is seen in the harbor operations. It was higher for total voyage NOx and PM because the EPA Tier 2 limits were used and the main generators have a higher acceptable limit based on their power density. They were higher for CO even though the main engine emission factors are the same because the total power is higher and all of this is generated by the large main generators which have over twice the emission factor of the small ship service generators in use in all modes in the conventional design.

The emissions for the 1000' self-unloader IEP design with Caterpillar generator sets were lower than the new prototype for CO, SO_2 and CO_2 for both total and harbor operations. For the CO emissions, at least, this was because current specific data were available for the Caterpillar generators.

The emissions for the 730' self-unloader designs expressed as total emissions per round trip voyage and harbor emissions per round trip voyage [tonnes/voyage] are summarized in Table 12. The emissions for the IEP designs with Wärtsilä generator sets were lower for SO_2 and CO_2 for both total and harbor operations. They were also lower for particulates for harbor operations. They were higher for the other emissions for the reasons cited above for the 1000' self-unloader designs.

The emissions for the 730' self-unloader IEP designs with Caterpillar generator sets were lower for CO for all cases. With tandem, 0-120 rpm main propulsion motors, they were also lower for SO_2 and CO_2 for total operations and just CO_2 for harbor operations. Again for the Caterpillar generator set designs, the CO emissions, at least, are lower because current specific data were available for the Caterpillar generators.

Table 12 Emissions of 730' self-unloaders for round trip

total per voyage

design	HC	NOx	CO	PM	PM 2.5	SO_2	CO_2
New *American Mariner*	0.079	4.343	1.388	0.137	0.133	0.118	384.2
IEP with Caterpillar Gen Sets and Tandem 0-120 rpm Motors	0.362	4.627	0.364	0.144	0.139	0.116	377.2
IEP with Wärtsilä Gen Sets and Tandem 0-120 rpm Motors	0.079	5.031	1.463	0.138	0.134	0.108	355.4
IEP with Caterpillar Gen Sets and Geared 0-720 rpm Motors	0.363	4.713	0.366	0.143	0.138	0.118	385.9
IEP with Wärtsilä Gen Sets and Geared 0-720 rpm Motors	0.080	5.145	1.496	0.141	0.137	0.111	363.4

harbor only per voyage

design	HC	NOx	CO	PM	PM 2.5	SO_2	CO_2
New *American Mariner*	0.005	0.248	0.073	0.009	0.008	0.008	24.9
IEP with Caterpillar Gen Sets and Tandem 0-120 rpm Motors	0.026	0.307	0.024	0.010	0.009	0.008	24.9
IEP with Wärtsilä Gen Sets and Tandem 0-120 rpm Motors	0.005	0.297	0.092	0.008	0.008	0.006	23.0
IEP with Caterpillar Gen Sets and Geared 0-720 rpm Motors	0.026	0.308	0.024	0.010	0.009	0.008	25.0
IEP with Wärtsilä Gen Sets and Geared 0-720 rpm Motors	0.005	0.299	0.093	0.008	0.008	0.007	23.1

8. Maintenance

The IEP has a potential advantage in terms of maintenance costs since there can be fewer prime movers to maintain and the total number of cylinders can be reduced. Kanerva and Nurmi state using an IEP the "maintenance costs are 20-30% lower due to less installed power and smaller number of parts and items to be maintained, especially cylinders". They also note that the maintenance costs are about 15% of the fuel costs and 80% of those are due to the diesels (Kanerva and Nurmi 1998).

Engine maintenance dominates the total maintenance costs and cylinder number is major factor, although it is less so in MDO operations. Cylinder wear is critical to the engine time between overhauls and this is related to the diesel wear index defined as,

$$\text{diesel wear index} = i * B * P_B * V_m \tag{11}$$

where i is the number of cylinders, B is the bore diameter, P_B is the Brake Mean Effective Pressure, and V_m is the mean piston speed, the engine rpm times the stroke (Woud and Stapersma 2002).

Comparisons of the number of prime movers, total rated kW, and total number of cylinders for the 1000' self-unloader designs are shown in Table 13. The reduction of one prime mover for both designs and the more than factor of 2 reduction in total number of cylinders to maintain with the IEP design using Wärtsilä generator sets are particularly noteworthy.

Table 13 1000' self-unloader cylinder comparison

design	no. prime movers	total rated kW	total no. cylinders	gen set total weight
New *Walter J. McCarthy, Jr.*	6	11,734	88	95.2*
IEP with Caterpillar gen sets	5	12,138	60	137.9
IEP with Wärtsilä gen sets	5	12,254	42	217 t

* includes just prime mover for main units and no PTO generators

Comparisons of the number of prime movers, total rated kW, and total number of cylinders for the 730' self-unloader designs are shown in Table 14. The dramatic reduction in all three of these factors affecting the maintenance cost is much more significant in these single screw designs. The number of prime movers is cut in half and the number of cylinders to maintain is reduced from 80 to 24 in the design with Wärtsilä generator sets. The design with Caterpillar generator sets does almost as well. These dramatic reductions are primarily due to the prototype's use of four smaller ship service generators to meet the large self-unloading power requirement.

Table 14 730' self-unloader cylinder comparison

design	no. prime movers	total rated kW	total no. cylinders	gen set total weight
New *American Mariner*	6	7,694	80	70.2*
IEP with Caterpillar gen sets	4	6,272	40	75.7
IEP with Wärtsilä gen sets	3	6,634	24	117 t

* includes just prime mover for main units

9. Additional Considerations

A number of additional considerations with respect the use of IEP designs in future Great Lakes self-unloaders are worth comment here.

Personnel Training. Some concern has been expressed over the lack of high voltage experience within the Great Lakes fleet personnel. Stewart notes that "special training is required for personnel who perform maintenance on high voltage equipment because of safety considerations" (Stewart 2009). Some of the current group of 1000' self-unloaders, including the *MV Walter J. McCarthy, Jr.* and sister ships, already use shaft driven PTO generators that produce 4160V output to power the self-unloading machinery or lateral thrusters (Miller 1979).

Graduates from the Great Lakes Maritime Academy have experience in the Integrated Electric Plant of their training ship *TS State of Michigan* and receive related training. The cadets are trained to deal with its AC rectified to DC integrated electrical system where four Caterpillar D398 generators supply the two 800 hp DC propulsion motors, a 550 hp bow thruster, and ship service needs.

With the increase in the number of higher voltage applications within the U.S. Navy, U. S. Coast Guard, and the cruise and offshore industries, the pool of engineers with higher voltage experience should continue to increase.

Manning. The overall degree of automation required for power management within an Integrated Electric Plant and the introduction of a "new technology" within the Great Lakes self-unloader fleet should provide the basis for the discussion of reduced engineering manning on these vessels. It is worth noting that from the 1970's, Chevron Shipping Company operated their all electric Gas Turbine product tankers for up to 34 years with unmanned engine rooms and a crew of 16 with only four licensed engineers and no unlicensed engineering personnel onboard (Kemp and Arcy 2010 and commenters).

Operations in Ice. The use of an IEP offers some advantage when operating in Great Lakes ice, particularly when compared with some of the current highly turbocharged four-stroke diesel engines. Many current marine propulsion diesels have very restrictive operating envelopes due to their high level of turbocharging and related concerns, primarily over compressor stall.

With a normal propeller load, a system is usually designed to operate with a power service margin, such as the 15% shown *schematically* as point C in Fig. 11. When ship resistance increases due to weather and/or ice, the design intent is for the power service margin to cover this increase. When it does not, such as in heavier ice operations (shown as line 0-A in Fig. 11 for a 40% load increase) and the required load exceeds the engine's full throttle or torque limit, the engine slows and becomes severely restricted in its power (shown schematically as point B in Fig. 11).

In the IEP designs such as described here, the ability of the frequency conversion to produce variable voltage and variable frequency output means that the electric propulsion motors can produce essentially constant power over their speed range. Thus if the motors and the shafting system are properly designed for the resulting motor heating and the higher torque at the slower rpm, the system can maintain full propulsion power when it is needed in ice operations (point A in Fig. 11).

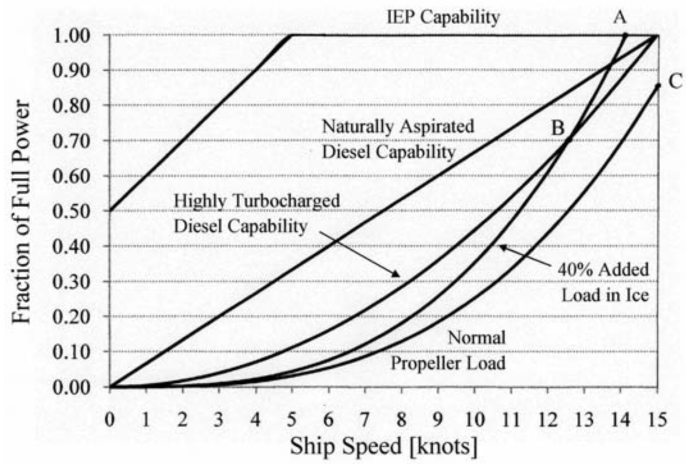


Figure 11 Diesel Mechanical and IEP Operation in Ice

Machinery Weight. As can be seen in Tables 13 and 14, the main generators are heavier than the prime movers on a diesel-mechanical system. The design using Caterpillar generators sets is lighter; the design using Wärtsilä generator sets is notably heavier for the 1000' self-unloader design. The weights of the switchgear, transformers, and propulsion motors only add to this. The comparison in Table 13 and 14 is also incomplete because the updated prototype plant equipment weight does not include the reduction gears and the PTO shaft generators needed to provide a full comparison. Regardless, an IEP design will typically weigh more which has important potential consequences for a weight limited self-unloading bulk carrier. Any weight increase would have to be compensated for elsewhere to ensure an unchanging cargo capacity given the fixed draft operating environment.

Kanerva and Nurmi (1998) note that in a detailed study of the weights of tankers of different sizes and powers "machinery weight including main engines, auxiliary engines, emergency generator, foundations, power transmission, ancillary systems, and propeller plant" compared with low-speed diesel plants as the base at 100, gave the mechanically geared medium speed diesel plants at 67, diesel electric with direct connected propulsion motors at 72-73, and diesel electric with geared, higher rpm propulsion motors at 54-55. Thus, the IEP can be fairly competitive and even lighter compared to conventional plants.

Deck Mounted Modular Generator Sets. When the main prime movers are released from their shaft line location with the introduction of IEP, the generating sets can go anywhere in the ship. Higher locations have the advantage of shortening the engine room, shortening the air intake and exhaust paths and allowing later arrival and installation of the generators resulting in a capital cost savings.

A natural extension of this would be to go to modular generating sets located on the main deck so that they could arrive late and be easily changed out for overhaul and replacement. Today's 1000' self-unloaders, in particular, are highly evolved in terms of short engine rooms and deck house reduction as seen in the *MV Walter J. McCarthy, Jr.* Thus, it would require a major redesign of the deck house to be able to obtain adequate room and access for four or five generators on the main deck. The life boat and aft mooring placement would have to be revised accordingly. This approach is certainly more practical on smaller, simpler vessels that do not have loop belt self-unloading capability located centrally within the deck house.

Possibility of Buying Power by the kW. In the offshore industry, in particular, users of diesel generating sets often do not own the sets, but rent/buy the electrical power output by the kW. This reduces capital outlay and shifts all the power costs to operating costs with fuel and maintenance. Casual discussion with one U.S. supplier of diesel generating sets who is engaged in this approach in the offshore industry indicated that there would be interest in considering this approach for future Great Lakes ships. This approach would be most compatible with the use of deck mounted modular generator sets. The sets could be landed just prior to system testing and they could be swapped out for major overhaul or in case of a casualty.

Depending upon their funding mechanism for new construction, this approach might be attractive for some Great Lakes shipping companies if it is easier to minimize the capital outlay during construction and defer these major acquisition costs entirely to annual operating costs.

Total costs. The authors lack the current data resources to be able to perform a detailed and convincing total cost comparison of IEP designs within the scope of this project. It seems better then to just note some published observations based on actual IEP designs and construction projects.

Kanerva and Nurmi (1998) note that with short and straight routing of piping and cables, extensive prefabrication, modularization, and short installation periods, IEPs can achieve "a savings of at least 50% in machinery and piping installation hours." Stewart (2009) notes that the "initial cost of mechanical drive is usually substantially less than for electric drive, by as much as 20-25%." Any increase in capital cost needs to be offset by operating cost reductions and improved overall performance.

11. Conclusions

The feasibility and potential benefits of using an Integrated Electric Plant (IEP) in future Great Lakes self-unloaders have been evaluated. Systems have been conceptually designed for two notional self-unloading bulk carriers: a 1000' Poe Lock maximum self-unloader and a 730' MacArthur Lock, Welland Canal, St. Lawrence Seaway maximum self-unloader. Comparisons have been made between an EPA Tier 2 updated version of the prototype vessels and IEP designs using Caterpillar and Wärtsilä generator sets. Machinery arrangements, effects on cargo capacity, fuel usage and environmental emissions in all operating modes, maintenance requirements, and manning have been considered.

The following main conclusions can be made based on this work:

- Great Lakes self-unloaders are strong candidates for the use of an IEP because of their relatively low power requirement; their relatively large self-unloading equipment, lateral thruster, and ballast pump auxiliary loads; and their varying speed profiles.

- IEP designs can be integrated into Great Lakes self-unloaders without major disruption to the current design approaches.

- With proper system design and optimization and proper generator set selection, IEP designs can make up for the propulsion transmission disadvantage of about 7% and provide a significant fuel cost savings.

- The IEP designs considered did not appear to provide a significant improvement in air emissions, but it should be possible. The notable exception was the harbor emissions from the plant using a smaller dual fuel generator set.

- Dual fuel and LNG generator sets will become more attractive for at least in-port emissions reductions as the EPA emission requirements continue to tighten.

- IEP designs should provide reduced maintenance costs due to the possible reduction in the number of prime movers and the number of cylinders that require maintenance.

- Reduced manning should be feasible with an IEP.

- With proper design, improved ice operations should be possible due to the availability of constant power at reduced rpm.

Integrated Electric Plants should be considered for use in future Great Lakes self-unloaders.

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Written Comments Receive from Stephen G. Kemp, Ann Arbor, MI

The authors present a very thorough and compelling analysis of diesel-electric drive for Great Lakes Self-Unloaders. As a former Chief Engineer on an ocean-going all-electric ship I would suggest that gas turbines also be considered as a power source.

I worked on the Chevron gas turbine-powered oil tankers (the Chevron GT's referenced in this paper) for almost 30 years, 20 of them as Chief Engineer. These ships (five were built) were powered by a single 12,000 HP gas turbine driving a single 4160V generator. Propulsion was provided by a 10,000 HP AC synchronous electric motor rotating at a constant 100 rpm, driving a controllable pitch propeller. There was a 1,000 HP bow thruster for maneuvering (also with a controllable pitch propeller), eight (8) deep-well cargo pumps and two (2) deep-well ballast pumps, all driven by 4160V motors. The ship's auxiliary and hotel loads (450V and 115V) were provided by redundant step-down transformers.

The five GT's were operated for almost 35 years (the last one will be retired this spring), three by Chevron and two others by Maritrans. The long operating lives of these ships, which were spent entirely in salt water, were due in part, I believe, to the simplicity of the plant, the reliability of the machinery, and the extremely low maintenance requirements of the gas turbine, which was a GE Frame 3 industrial model.

At Chevron we regularly looked at replacing the gas turbine with one or more diesel engines because of the cost of the fuel (the gas turbine burned only #2 diesel) and the inefficiency of the turbine. The gas turbine was fitted with a heat recovery unit (shell and tube), but as I recall, at full power and in the coldest environments the specific fuel consumption (sfc) was never lower than 0.45 – 0.48 lb/HPh. A diesel engine would be much lower than that (perhaps 0.35 – 0.40), and the diesels might burn IBF rather than #2 diesel, but as many times as we looked at changing out the gas turbine for diesel engines the economics were never there. In fact, in the early 90's we actually looked at replacing the GE Frame 3 industrial with more efficient GE LM 500 gas turbines, and the newer gas turbines were actually cheaper over the long run than any diesel engine we considered, primarily due to the extensive structural modifications needed to support the heavier diesel engines.

The on-board maintenance requirements for the gas turbine were also very low. I do not believe we ever spent more than 8-10 man hours/month maintaining the gas turbine, so the four engineers the ship carried could spend many more hours/month maintaining the rest of the ship's machinery. I have heard anecdotal evidence from diesel-run ships that the maintenance on the diesel engines is much higher than anything we did on the GT's. The GT's did have diesel fuel oil purifiers which ran 24/7 (one on line constantly), but we generally took the online purifier offline for cleaning only once every 90 days, which is unheard of on ships burning IBF or heavy fuel.

Yes, the GT's paid a large fuel penalty burning #2 diesel, and the gas turbine was very inefficient during in port operations, whether loading or unloading, but there is also something else to consider with gas turbines, and that is the emissions. Gas turbines have very low SOx and NOx emissions due to the massive air flow through the turbine and the high exhaust temperatures. I would suggest that gas turbines are better suited to meet Tier III emission requirements than diesel engines, and probably with fewer "add-ons" or specialized equipment. It may turn out that the Tier III requirements will simply mean that ships will have to burn only #2 diesel, and that will bring gas turbines into play as a viable power source.

A gas turbine is also smaller and lighter than a diesel engine of comparable horsepower, requires simpler structural supports, auxiliary systems, etc. With heat recovery equipment utilizing the exhaust gas, a gas turbine package can be very appealing as a power source on ships.

As far as operations go, I would suggest that bringing generators on line or taking them off line to suit load changes is a risk best avoided, at least during maneuvering operations in confined waterways. My own experience with high-voltage circuit breakers is that they are simply not that reliable, and a prudent ship operator will have enough generators on line to provide whatever power the ship may need during transit operations, and should not be starting or stopping generator sets to maintain a load profile.

Finally, I would suggest the controllable pitch propellers be considered in lieu of fixed-pitch propellers. For ships that are in confined waterways and maneuvering situations much of the time, the ease of thrust reversal with CPP's as opposed to reversing gear, reversing an electric motor, etc., make the CPP very attractive. The CPP's on the Chevron GT's ran for many years without problems (we did have some failures, but they were very few), and these ships spent much of their time in confined waterways where reliability of the propulsion system was an absolute requirement. Reversing an electric motor with a fixed-pitch propeller requires the closing and opening of large, high-voltage circuit breakers, which are very complex devices with many failure points within them. I believe CPP's would be much more reliable for maneuvering.

Author's Closure

The authors would like to thank Steve Kemp for his valuable addition to this paper and future thinking about Great Lakes self-unloader powering. Gas turbines have a significant fuel rate disadvantage (25-35%), but an emissions advantage (particularly NOx) relative to diesels. The added issues of maintenance, volume, weight, and foundationing high in the ship also favor the gas turbine. They have a disadvantage in the volume of air (2x) that must be handled in the intake and exhaust paths with very low pressure drop. Specific cost can be quite comparable.

It should be restated here that all the designs considered in this paper were already based on the use of No. 2 diesel due to arrival of EPA Tier 2 and Tier 3 requirements. Industrial type gas turbines as used by Chevron operated on No. 2 diesel, but the more available aviation derivative gas turbines require the lighter Marine Gas Oil (price 2% more than MDO in Los Angeles, same in Houston, www.bunkerworld.com, March 15, 2011).

The issue of operating risk in restricted waters and its implications for the number of generators carried on line and the use of a Fixed-Pitch Propeller versus a Controllable-Reversible-Pitch propeller certainly requires careful consideration in future designs. These choices could well preclude the maximum exploitation of the potential advantages offered by the IEP concept.