Conceptual Designs for the Conversion of the U.S. Great Lakes Steam Bulk Carriers to LNG Fueled Propulsion

Annual Report

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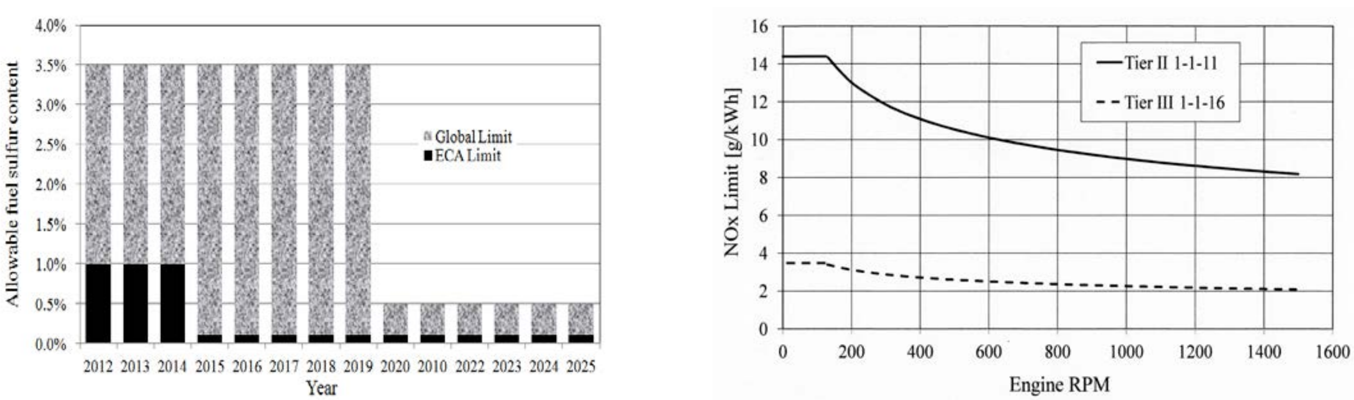
This project is investigating the feasibility of conversion of the approximately 10 remaining steam powered U.S. Great Lakes bulk carriers to Liquefied Natural Gas (LNG) fueled propulsion. These vessels have the worst air emissions within the U.S. bulk carrier fleet and are currently grandfathered relative to EPA requirements. The goal of this research is to develop conceptual designs for the conversion of these vessels to LNG fuel using gas engines to achieve very low emissions and significantly reduced fuel consumption and cost. They would then meet the more stringent Emission Control Area (ECA) air emissions requirements (Fig. 1) that will come into effect on the Great Lakes in 2015/2016 without the need for exhaust gas scrubbers or Selective Catalytic Reduction (SCR) that would be required in a diesel conversion after January 2016. The LNG fueled bulk carrier air emissions would move from worst to first among the U.S. Great Lakes fleet.



(a) ECA Marine Fuel Sulfur Content Limits in 2015 (b) ECA Tier III NOx Emissions Limits in 2016

Figure 1 More Stringent Emissions Control Area Requirements for the Great Lakes in 2015 and 2016

The use of LNG would also result in a significant fuel cost savings that could provide added justification for the vessel conversion and further economic life. Reduced manning may also be feasible with the move away from steam propulsion. The study considers arrangements, effects on cargo capacity at constant draft, fuel usage, air emissions, maintenance requirements, manning, and remaining ship life-cycle economics. The conceptual designs are in accordance with the requirements of the American Bureau of Shipping (ABS) Guide “Propulsion and Auxiliary Systems for Gas Fueled Ships,” May, 2011.

INITIAL REPORT

This project is a result of a meeting held among Great Lakes industry, MARAD, and GLMRI representatives in Cleveland, OH, on August 23, 2011. The project began in November 2011 and an initial report of the effort was presented to the Great Lakes and Great Rivers of the Society of Naval Architects and Marine Engineers (SNAME) in Cleveland, OH, on February 24, 2012. Following the meeting, the paper was revised to incorporate and resolve comments received and the paper Parsons, M. G., O’Hern, P. J. and Denomy, S. J., “The Potential Conversion of the U.S. Great Lakes Steam Bulk Carriers to LNG Propulsion – Initial Report” was published in the August 2012 issue of the *Journal of Ship Production and Design*, Vol. 28, No. 3, pp. 97-111. A WORD version of this paper is included here for completeness.

The Potential Conversion of the U.S. Great Lakes Steam Bulk Carriers to LNG Propulsion – Initial Report

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The feasibility and potential benefits of converting ten remaining U.S. flag Great Lakes steamship bulk carriers to Liquefied Natural Gas (LNG) propulsion using gas engines is investigated. This is the initial report of a study that began in November 2011. The evolving marine air emissions standards and the movement to LNG fuel in international non-LNG carriers are briefly reviewed. The case for the possible conversion of the remaining U.S. flag Great Lakes steamship bulk carriers to LNG fuel is outlined. Initial results of a conceptual design study on the conversion of the three AAA class vessels (*SS Arthur M. Anderson, SS Cason J. Callaway, SS Philip R. Clarke*), focusing primarily on operational and arrangement feasibility, is then presented.

Keywords: Great Lakes; bulk carriers; LNG; fuel efficiency; emissions

1. Introduction

There are 13 remaining U. S. flagged Great Lakes steamship bulk carriers as shown in Table 1. Of these, there appears to be ten that are viable candidates for the possible conversion to the use of LNG as fuel. The *SS Kaye E. Barker* is undergoing conversion to diesel in winter 2012. The smaller, older cement carriers *Alpena* and *St Marys Challenger* have primarily been used for storage in recent years. Thus, the ten vessels above the band in Table 1 are the focus of this study. Of these, the three designated in bold were built to essentially the same plans and are called the AAA class. The AAA designation was an internal accounting designation used by U.S. Steel when the vessels were part of that fleet. (Occasionally one sees the statement that a total of eight AAA vessels were built to similar plans.) As almost one third of the group, it was logical to choose the three AAA vessels as the initial focus of this study.

With the exception of the *Edward L. Ryerson* and the *Herbert C. Jackson*, eight of the vessels use essentially the same 7000 normal shaft horsepower cross-compound steam plants, with the same steam conditions, driving fixed-pitch propellers through a double reduction gear. Most were built to a length of 647′, beam 70′ and depth 36′ and then lengthened to 767′ and converted to self-unloaders in the 1970's. The *Edward L. Ryerson* is the only remaining straight-decker; the *John G. Munson* was the only one initially built as a self-unloader.

From a practical standpoint, the Great Lakes steamship bulk carriers will be unable to meet current air emissions standards unless they are converted to either diesel or LNG propulsion. Their steam plants are also very inefficient by current standards and they require greater manning. These vessels will, therefore, benefit from conversion based upon fuel efficiency, manning, and air emissions. Although most are already 60 years old, by having operated in fresh water the hulls have meaningful economic life remaining if the propulsion can meet evolving EPA requirements.

This paper will review the relevant emissions and LNG fuel issues and the benefits that could be gained by the conversion of these vessels to LNG fuel. The initial results of a conceptual design study on the conversion of the AAA vessels to use LNG propulsion using gas engines, focusing on operational and arrangement feasibility, will then be presented.

2. Emission control area emissions

Upon the request of the United States, Canada and France, MARPOL Annex VI designated the non-Arctic coastal and internal waters of the U.S. and Canada as a special Emission Control Area (ECA) similar to the Baltic Sea and the North Sea. This was adopted in March 2010 and will become enforceable in August 2012.

Table 1 U.S. flag Great Lakes steamship bulk carriers

Name	Length	Year Built	normal SHP	Capacity (net tons)	Typical Cargoes	Fleet	Building Yard	Notes
Edward L. Ryerson	730'	1960	9,000	30,800	Iron ore	Central Marine Logistics	Manitowoc	straight decker
American Victory	730'	1943	7,000	29,120	Iron ore, coal, limestone	American	Bethlehem	AO71 *Neshamic*
American Valor	767'	1953	7,000	28,560	Iron ore, coal, limestone	American	AMSHIP Lorain	
John G. Munson	768'	1952	7,000	28,560	Iron ore, coal, limestone	Keylakes	Manitowoc	boom forward, bunker aft
***Arthur M. Anderson* ***	767'	1952	7,000	28,336	Iron ore, coal, limestone	Keylakes	AMSHIP Lorain	
***Cason J. Callaway* ***	767'	1952	7,000	28,336	Iron ore, coal, limestone	Keylakes	GLEW Detroit	
***Philip R. Clarke* ***	767'	1952	7,000	28,336	Iron ore, coal, limestone	Keylakes	AMSHIP Lorain	
Herbert C. Jackson	690'	1959	6,000	27,776	Iron ore, coal, limestone,	Interlake Steamship	GLEW Detroit	
American Fortitude	690'	1953	7,000	24,976	Iron ore, coal, limestone	American	AMSHIP Lorain	
Wilfred Sykes	671'	1949	7,000	24,080	Iron ore, coal, limestone	Central Marine Logistics	AMSHIP Lorain	parent hull for later ships
Kaye E. Barker	767'	1952	7,000	29,008	Iron ore, coal, limestone	Interlake Steamship	AMSHIP Lorain	to be converted to diesel
Alpena	519'	1942	4,000	15,568	Cement	Inland Lakes Management		layup- storage
St. Marys Challenger	552'	1906	3,000	12,656	Cement	Port City Steamship Services		layup- storage

* AAA class

The MARPOL (and EPA) limit SO_x emissions through the control of the sulfur content in marine fuels. The ECA fuel sulfur content requirements that will be enforceable on the Great Lakes in August 2012 are shown, with the global limit, in Fig. 1. The SO_x emissions requirement can also be met using fresh water/caustic soda exhaust gas scrubbers or similar.

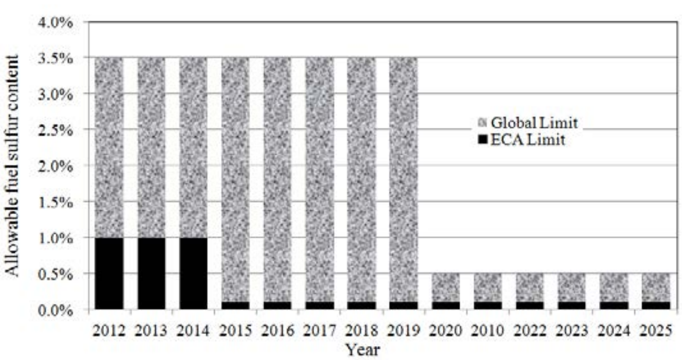

Fig. 1 MARPOL (EPA) sulfur limits in marine fuel

The EPA's final rule for Category 3 marine engines (75 FR 22896, April 30, 2010) exempted the Great Lakes steamships from these sulfur limits for an indefinite period in response to a prohibition by Congress on the "EPA's use of funds to issue a final rule that included fuel sulfur standards applicable to steamships operating in the Great Lakes." Further, EPA announced a final ruling (EPA 2012) that offers the ship owners an automatic, time-limited repower fuel waiver until December 31, 2025, if they repower with a Tier 2 or cleaner diesel engine. This ruling came into effect on March 19, 2012, after no adverse comments were received by February 17, 2012. It is somewhat ironic, coming from the EPA, that this alternative obviously reduces the incentive for any ship owner to consider the greener LNG as an alternative fuel, at least until after December 31, 2025, when the conversion diesels would have to use the ECA 0.1% or lower sulfur fuel or be equipped with exhaust gas scrubbers.

The MARPOL and EPA limits for NOx emissions are shown in Fig. 2. It is generally considered that the existing Tier II requirements can be met with on-engine modifications and that the Tier III requirements, which come into effect in 2016, will require the use of Selective Catalytic Reduction (SCR) systems on diesels. These use \$800/t aqueous urea at 5-10% of the diesel flow rate to reduce the stack gas NOx.

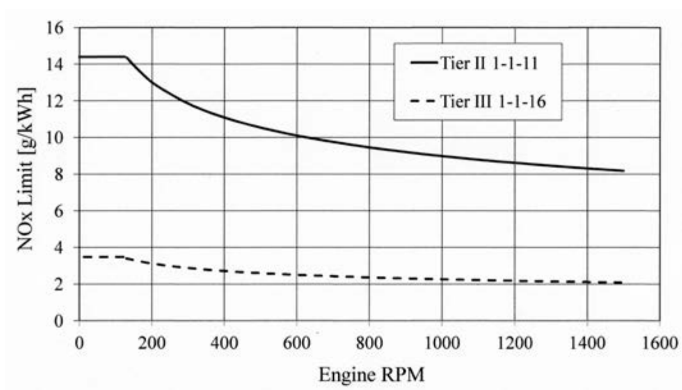

Fig. 2 MARPOL Annex VI (EPA) ECA NO_x limits

3. Reasons to consider conversion to LNG

LNG has been used quite safely as a ship fuel in the form of boil-off from LNG cargo in LNG carriers world-wide for about 40 years. There are now about 200 LNG carriers using LNG as fuel. These were initially steam plants; more recently they have used dual-fuel LNG/diesel engines. In 2000, the Norwegians began a series of new commercial, non-LNG carrier vessels using LNG fuel when the 94.8 m long ferry *Glutra* was delivered (Einang and Haavik 2000, Einang 2007). There are now over 20 such new construction vessels with plants up to 12,370 kW, mostly in Norway (Parsons 2009).

Last year, the *Bit Viking*, a 177 m long, 25,000 DWT oil/chemical product tanker only 5 years old, was converted from HFO to dual-fuel LNG/diesel propulsion. The vessel entered the shipyard in August and returned to service in October. These Norwegian projects have primarily been motivated by improved emissions and aided somewhat by the relief provided from a Norwegian tax on emissions.

In July, 2011, Harvey Gulf International Marine announced plans to construct three (now four) LNG powered offshore supply vessels, the first U.S. flagged, American Bureau of Shipping (ABS) classed vessels using LNG fuel. These vessels will use dual-fuel engines and be some of the first vessels to be built to the LNG fuel Guide issued by ABS last May (ABS 2011). This fuel choice was motivated by the pending ECA emissions requirements, the availability of LNG on the Gulf and anticipated green marketing advantages with offshore platform customers (Varrret 2012).

There is good reason now to consider the conversion of the Great Lakes steamship bulk carriers to LNG fuel to realize improved fuel efficiency, improved air emissions, reduced manning and potential fuel cost savings.

3.1. Improved fuel efficiency

The steam plants installed in the Great Lakes steamships were designed to modest steam conditions judged to be the best choice for plants of 6000-9000 normal shaft horsepower in the early 1950s (Williams et al. 1950). These plants all use 450-470 psig, 750°F steam and 1 1/2″ Hg vacuum and cross-compound turbines driving a fixed-pitch propeller through a double reduction gear. They use three stages of feed heating and water tube boilers with about a boiler efficiency $\eta_B \approx 0.865$.

In commenting on a presentation on the first of these vessels, the *William Sykes*, H. W. Neblett of Inland Steel noted that the overall plant was requiring about 12,000 BTU/hph delivered to the propeller (Williams et al. 1950). Factoring in the auxiliary loads and the boiler, gearing, and shaft line efficiencies, this corresponds to a cycle thermodynamic efficiency of about η_{th} = 0.28 or 345 g/kWh of Bunker C. Checking general data for steam plants with these steam and vacuum conditions and three stages of feed heating as used on these ships, the ideal cycle thermodynamic efficiency could be about η_{th} = 0.312 or 307.5 g/kWh (Salisbury 1944).

Diesel and LNG burning internal combustion engines available today have thermal efficiencies as high as 0.48. For the current steam cycle and boiler plant, the equivalent is about 0.30*0.865 = 0.26 so either of the internal combustion engines will be about 85% better.

3.2. Improved specific air emissions

With the approach of the EPA ECA air emissions requirements and an honest question about whether or not the congressionally mandated exemption for the steamships is politically and socially sustainable, the U.S. Great Lakes steamships are currently the least green vessels on the Lakes, with the probable exception of the *SS. Badger*. The proactive approach would certainly be to improve their emissions.

LNG fuel offers the best approach for meeting and exceeding the ECA air emission standards that may come into effect beginning in August 2012. Table 2 shows a comparison of the specific air emissions from Bunker C burning steam plants, Tier II and Tier III diesel engines burning two levels of low sulfur fuel and LNG gas engines. The LNG essentially eliminates the SO_x and particulate PM that have the highest public health concern for the EPA. The NO_x requirements are met without the need for Selective Catalytic Reduction exhaust gas treatment. The Green House Gas (GHG) CO_2 is reduced by about 25% with LNG due to the lower carbon to hydrogen ratio in natural gas.

Table 2 Typical specific emissions from plants at rated power

	steam turbine	diesel engine	diesel engine	gas engine
EPA		Cat 3, Tier 2	Cat 3, Tier 3	
fuel	Bunker C	MDO	MDO	LNG
% sulfur	2% S	1.0% S	0.1% S	0.0% S
SOx [g/kWh]	11.90	4.11	0.41	0.00
PM [g/kWh]	1.16	0.58	0.28	0.00
NOx [g/kWh]	low	9.5-10.5	2.3-2.6	<1.5
CO2 [g/kWh]	580-630	580-630	580-630	430-480
CO [g/kWh]	0.20	<3.0	<3.0	<2.0

sources: Harkins 2007, Boylston 2011, EPA 500-900 RPM for diesel NOx, typical engine data

3.3. Reduced manning

Steam plants require more manning than either diesel or LNG engine plants. A conversion to either diesel propulsion or LNG gas engine propulsion would permit the reduction of perhaps one licensed officer and three unlicensed oilers. This would be supported by the development of a central engine control room rated as an Unattended Engine Room (ABS notation ACCU). The new modern machinery would be controlled with an equally modern PLC based control system. This would result in the savings in the range of $600,000 to $700,000 in manning cost per year.

Similar crew reductions can be achieved on the steamships by the automation and bridge control of the boilers, accompanied by the creation of a centralized engine control room, as accomplished on the AAA vessel *Cason J. Callaway* in 2002 (Bowler et al. 2002).

3.4. Reduced fuel cost

Conversion to LNG fuel would result in reduced fuel costs compared with using the current low efficiency steam plants burning Bunker C. This would be magnified when the ECA sulfur requirements come into effect. Fuel cost advantages may also be realized when compared with diesel engines, particularly when they are required to use the ECA specified 0.1% sulfur fuel beginning in 2015. This may even be possible when compared to diesel engines burning heavy intermediate, with exhaust gas scrubbers and Selective Catalytic Reduction. This of course depends on the price of the fuels available on the Great Lakes in the future.

Recently there have been studies on whether or not the next Washington State ferries should use LNG or the Ultra Low Sulfur Diesel (ULSD, 15 ppm S) highway fuel that is used in the other Washington State ferries today (Glosten 2010, JTC 2011). In this study, it was estimated that ULSD adjusted for their mandated use of a bio-fuel fraction and a waived state fuel tax would vary from $4.01/gallon in FY2014 to $4.33/gallon in FY2027. The energy equivalent LNG price was estimated to be $2.12/gallon delivered to the ship in FY2014 rising to $2.58/gallon in FY2027. The energy equivalence reflects the fact that a gallon of LNG contains less energy than current fuels so more LNG is actually required. These fuel prices would result in an annual fuel savings of 47% declining to 40% in FY2027 compared to ULSD (JTC 2011). Note that this is a unique case, however, since Washington State ferries have EPA Category 2 engines and are locally mandated to use ULSD (highway) fuel rather than the MARPOL (EPA) diesel (1000 ppm S beginning in 2015).

Current fuel prices are about $675/t for IF380 and $995 for MDO (Houston www.bunkerworld.com 1/26/2012) or about $2.41/gallon for IF380 and $3.08/gallon for MDO. Based on the Washington State ferry study predicted FY2014 LNG price (JTC 2011), the energy equivalent price per gallon for LNG would be $2.31/gallon with respect to IF380 and $2.12/gallon with respect to MDO. At these levels, LNG would provide a fuel cost advantage. This will be magnified when the caustic soda (NaOH) and energy costs for an exhaust gas scrubber and aqueous urea and energy costs for Selective Catalytic Reduction are included to meet ECA requirements after 2015 and 2016, respectively. This equipment will also add to maintenance requirements and crew work load.

Because it will be a critical factor in whether or not it will be economically viable to convert Great Lakes steamships to LNG fuel, the question of future LNG prices will be reviewed in more depth in Section 5 below.

4. Challenges in using LNG fuel

There would be a number of challenges with moving to the use of LNG as a marine fuel on the Great Lakes. These include obtaining adequate access to the fuel, arranging enough volume in the ship for the fuel storage, protecting hull structure from accidental spills and increased capital and maintenance costs. There will also be a need for greater crew training and an increased safety culture. Finally, although somewhat out of the direct control of the user, there is an environmental concern about the release of unburned methane.

4.1. Fuel availability

We are faced with a chicken or the egg issue relative to LNG availability to ships on the Great Lakes. Ship owners say "show us the LNG and we will consider it" while the fuel suppliers say "we could build a liquefaction plant with a large enough, long-term contract for fuel." This situation will require resolution to make LNG available at a price that will justify conversions to LNG rather than conversions to diesel.

As an input to those discussions, Table 3 is offered as a planning target. This shows the approximate aggregate annual LNG demand that could result if all ten Great Lakes steamship bulk carriers were converted to LNG fuel over a period of the four winters entering the 2014, 2015, 2016 and 2017 operating seasons.

The planning assumption is that the conversions would follow a phased program starting with a year-long Phase I to accomplish the initial design, resolve regulatory issues with classification and the U.S. Coast Guard, and purchase long lead equipment. This is particularly important due to the currently undefined nature of requirements for a U.S. flag LNG fueled vessel. All engineering, approvals and planning would be completed in advance of ship arrival.

The lead vessel, selected arbitrarily in Table 3, would enter the lead Great Lakes shipyard in October 2013. The conversion would proceed between October and April. Beginning the second year, the lead yard would complete two phased conversions (October to March and January to June) and a second follow yard would complete one conversion between October and March. This pattern could then continue until all vessels were converted.

Table 3 assumes refueling about once per week and 100% utilization of the vessels during the operating season. This example conversion plan is arbitrary, but emphasizes the AAA vessels first. At steady state after the conversion of all ten vessels, an aggregate annual demand of about 31,000,000 gallons of LNG per year would result as shown in the third column of Table 3.

The location for LNG supply could take two approaches: intermediate points or end points. The Great Lakes steamships mostly operate as tramp vessels going wherever there is a cargo without any fixed trade or schedule. This makes the location of supply particularly challenging. If there were only one source, a location in the DeTour Village, St. Ignace, and Alpena, MI, area would support needs of all traffic leaving Lake Superior or moving between Lakes Michigan and Huron. A location in the Port Huron and Detroit, MI, area would also serve all traffic to the lower lakes. If supply were to be provided only in end point cities, Duluth, MN and the Chicago area with the Detroit area would serve most routes.

4.2. Volume for fuel storage

The critical naval architectural arrangement issue for the use of LNG fuel in ships is being able to store enough fuel within the ship for an acceptable range. Some vessels, like tankers or ferries, can carry external tanks on their weather deck without interfering with the basic function of the ship. Ships such as containerships and dry bulk carriers do not have this option due to their need to access the cargo holds.

Table 3 Aggregate LNG demand that would result from the conversion Great Lakes steamships to LNG

Name	Normal steam power (shp/kW)	Annual requirement (gallons)	2014 Operating Season	2015 Operating Season	2016 Operating Season	2017 Operating Season
Edward L. Ryerson	9000/6711	3,875,429				3,875,429
American Victory	7000/5220	3,014,000			2,009,000	3,014,000
American Valor	7000/5220	3,014,000		2,009,000	3,014,000	3,014,000
John G. Munson	7000/5220	3,014,000				2,009,000
Arthur M. Anderson	7000/5220	3,014,000		3,014,000	3,014,000	3,014,000
Cason J. Callaway	7000/5220	3,014,000	3,014,000	3,014,000	3,014,000	3,014,000
Philip R. Clarke	7000/5220	3,014,000			3,014,000	3,014,000
Herbert C. Jackson	6000/4474	2,583,286		2,583,286	2,583,286	2,583,286
American Fortitude	7000/5220	3,014,000				3,014,000
Wilfred Sykes	7000/5220	3,014,000			3,014,000	3,014,000
total fleet requirement	gallons/yr	30,570,714	3,014,000	10,620,286	19,662,286	29,565,715
over a 10 mo. season	tonnes/yr	52,764	5,202	18,330	33,936	51,029
	ave. t/day	176	17	61	113	170
	ave. visits/day	1.77	0.18	0.71	1.24	1.77
	ave. t/visit	126	98	98	98	126

LNG fuel is stored on smaller vessels in IMO (ABS) Independent Type C pressurized cryogenic tanks at -162^{o}C. Tanks located within the hull are limited to 10 barg (145 psig) maximum working pressure (ABS 2011). The storage is at 5 to 9 barg (72.5 to 132 psig) with this pressure used to move the re-gasified natural gas into the engines without the need for feed pumps. The tanks are double-walled, insulated, cylindrical tanks with dished ends. The inside shell is made of a cryogenic material such as 304L stainless steel; the outer shell is either of stainless steel or carbon steel. The space between the walls is, for example, insulated with perlite and vacuum (Karlsson and Sonzio 2010, Chart 2011). The tanks do not require cooling equipment since the LNG cools and maintains the tank temperature through boil-off and/or pressure rise in the tank.

ABS (ABS 2011) and Det Norske Veritas (DNV 2012) require in general that LNG fuel tanks installed below decks be located as close to the centerline as possible and inside of B/5 (or 11.5 m if less) from the side at the summer waterline and B/15 (or 2 m if less) above the bottom shell for collision/grounding protection. Although not formally prohibited at this time, U.S. Coast Guard personnel have also expressed unofficial concern about tanks being located below accommodation spaces, service spaces, and control stations, particularly in passenger vessels (Meyers and Woessner 2011). Installations that use dual-fuel diesel/LNG engines can have a single LNG tank; single fuel LNG plants must have two separate LNG tanks each located within its own gas tight tank space.

The lower energy content of LNG requires tankage with about 70% more net volume than on a MDO vessel of equal range. The cylindrical LNG tanks must be supported separate from surrounding structure with a clearance of at least 450 mm laterally and 150 mm below the tank (ABS 2011). There is also a cryogenic material cold box (tank room) that contains equipment to control tank pressure and heat the LNG for its re-gasification and warming to about 15^{o}C as needed for injection to the engine. These will result in the requirement for even more hull volume than would be required for a typical prismatic HFO or MDO tank that is built into the ship's structure above the inner bottom.

A Wärtsilä concept paper (Hannula et al. 2009) states that the weight of fuel storage in pressurized cryogenic tanks is about 1.5 times greater and the parallelepiped volume typically required within a ship is about 3.0 times that of MDO storage above the inner bottom. On an equal energy basis, LNG requires about 1.9 times as much volume as HFO, accounting for the insulation and 95% filling this increases to about 2.3 times, and increases up to about 3 times when the lost space around the cylindrical tanks is considered. Some sources state 4 times the volume is needed.

Because steamships would have available the volume currently occupied by the boilers and the fuel bunkers (if along the centerline), they have reasonable centerline volume available to use for the LNG storage within the hull. Regardless, storing enough LNG to provide an acceptable range would still be a challenge. Note that the bulk carriers built initially as diesel boats would have no equivalent volume available and are, therefore, less likely candidates for later conversion to LNG unless the hull could be lengthened.

4.3. Protecting hull structure from spills

Any spill of LNG onto steel ship structure can result in brittle cracking of the structure since the LNG will rapidly cool the steel well below its nil ductility temperature. This requires the installation of separate cryogenic material drip trays large enough to hold likely spills below all bunkering stations and connections and components that might develop a leak. This issue is addressed in the ABS Guide (ABS 2011)

4.4. Increased capital and maintenance costs

The capital cost of an LNG installation will be greater than an equivalent diesel conversion, largely due to the cryogenic storage tanks and fuel handling systems required. Maintenance may also be higher, although engine overhaul cycles have been longer on LNG. The Norwegian LNG single fuel *Bergensfjord* ferry and her sister ships were reported to have had 15-20% greater capital cost and have about 10% higher maintenance cost than required for equivalent diesel vessels (Bergheim 2010, JTC 2011). The operator Fjord1 has asked their engine manufacturer (Rolls-Royce) to extend the overhaul intervals from 16,000-20,000 to 30,000 operating hours and five years. The initial maintenance cost increase was due to there being relatively more spares purchased for a new type of plant. Maintenance costs have subsequently shown to be lower in normal operations (Horgen 2012). In Norway, the higher costs are offset in part by tax advantages, which include a carbon credit, and access to special funding reserved for projects that reduce emissions (JTC 2011).

The studies of the Washington State ferries conversion of their new 144-car ferries to a LNG design showed the diesel option with a machinery capital cost of $2.5M, the dual-fuel LNG/diesel option at $9.3M and the single fuel LNG option at $10.7M. This was accompanied by first year fuel and maintenance costs of $2.7, $1.8M and $1.4M, respectively, making the single fuel LNG option $29.6M cheaper than the diesel option and $9.3M cheaper than the dual-fuel diesel/LNG option on a 30 year life-cycle cost basis using a 3% discount rate (JTC 2011). Recall that this tradeoff was between an LNG design and a diesel design using ULSD rather than HFO and exhaust gas treatment for SO_x and NO_x.

It has been noted that the Harvey Gulf International Marine dual-fuel LNG/diesel offshore supply vessels will have a 16% greater capital cost than an equivalent diesel design (Verret 2012).

The key issue is that unless some type of external governmental assistance is provided to incentivize the additional reductions in air emissions provided by LNG, the added capital cost must be completely offset by an LNG fuel price that will make an LNG conversion more economic than a diesel conversion. There is certainly a case to be made for incentives since, as is usually the case with air emissions, the benefits are realized broadly within society, while the costs of improvements are paid narrowly by the transportation that is providing a vital service to the economy.

4.5. Training and an increased safety culture

The use of LNG cargo boil-off for ship fuel for over 40 years and the decade of operation of new LNG fueled ships have an outstanding safety record. Concern was expressed, however, at the "LNG Fuel for Ships – Engineering and Regulatory Issues" panel at the 2011 Annual SNAME Meeting that LNG use in a broader range of U.S. shipping would require a more focused safety culture than is common today. Its use does require a higher level of documented safety procedures, crew training, etc. Companies currently exist in the U.S. with experience in specialized training of crews for LNG fuel use.

The Fjord1 LNG ferry crew training "includes a gas course including risk aspects, emergency shutdown (ESD) philosophy, gas plant and demonstrations of gas explosions. The course takes two (2) to five (5) days, and the instructors are from the company. The remainder is familiarization training conducted on board the vessel. An officer needs about one (1) week training before being on duty. There is a detailed program in order to be considered qualified" (Bergheim 2010, JTC 2011).

4.6. Methane slip

There is a small fraction of LNG that is unburned in LNG gas engines and passes up the stack. This is called methane slip. The engine manufacturers are working to minimize this fraction. The EPA regulates the release of non-methane hydrocarbons (HC), but methane is not currently regulated. Methane, however, is a Green House Gas (GHG) that has 21 times greater negative impact on the environment per gram than CO_2, which currently gets most of the EPA attention. This is based upon the Global Warming Potential of CO_2, as the reference 1, and methane at 21. This is presented in the United Nations Framework Convention on Climate Change (UNFCC) based upon each GHG's ability, compared to CO_2 per unit weight, to trap heat within the atmosphere and its decay rate within the atmosphere over a 100 year time horizon (UNFCC 2011). The hydrofluorocarbons (HFC's) that were legislated out of shipboard refrigeration systems some time ago have 100 year Global Warming Potentials of 140 and higher.

Methane slip from gas engines, as well as bunkering operations, must be kept low or the benefit from the 20-25% reduction in CO_2 from the use of LNG can be completely cancelled. The single-fuel Rolls-Royce Bergen LNG engines are reported to have a net CO_2 reduction of 22% which accounts for the methane slip as an equivalent increase in CO_2 (Horgen 2012). Methane slip could become a direct ship owner concern in the future if the U.S. taxes GHG emissions as is now done in some countries in Europe.

5. Future LNG prices

The availability and price of LNG in the Great Lakes region will be critical to assessing the economic viability of conversion of the U.S. flag Great Lakes steamship bulk carriers to LNG fuel. It is, therefore, useful to look a little deeper at the predicted production and cost of U.S. natural gas.

The Henry Hub price is currently the basis for natural gas futures contracts traded on the New York Mercantile Exchange. The Henry Hub is a reference point in Sabine Pipe Line, LLC's pipeline in Erath, LA. It is connected to 13 pipelines that cover the United States. Spot and future prices set at the Henry Hub are currently the basis for quoting and predicting future natural gas prices in the United States. The Department of Energy's Energy Information Agency (EIA) makes an annual review of natural gas production and predicts the future natural gas production and prices within the United States (EIA 2011). Figure 3 shows historical and predicted Henry Hub spot market prices along with those for the average at lower 48 wellheads (EIA 2011).

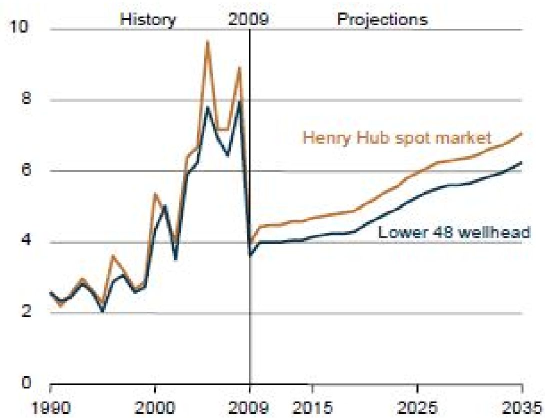

Fig. 3 Future Henry Hub and wellhead natural gas prices (2009 dollars per million Btu) (EIA 2011)

Note that in Fig. 3 there were spikes in natural gas prices during the hurricanes Katrina/Ivan period and then a dramatic decline beginning about 2008. This was partially due to the decline in the overall economy, but primarily because the "recent emergence of substantial new supplies of natural gas in the U.S., primarily as a result of the remarkable speed and scale of shale gas development, has heightened awareness of natural gas as key component of indigenous energy supply and has lowered price well below recent expectations. Instead of the anticipated growth of natural gas imports, the scale of domestic production had led producers to seek new markets for natural gas, such as an expanded role in transportation" (MIT 2011). Shale gas has long been extracted from the Antrim field in Michigan, Ohio and Indiana, but major new fields are under development in Texas and neighboring states, the Mountain West and the Appalachian Basin. The scale of the shale gas development and predictions can be appreciated in Fig. 4 that shows the sources of domestic natural gas and predicts that the shale gas contribution will grow from 14% in 2009 to 45% by 2035.

The net effect of the shale gas development is a predicted healthy growth of domestic production that is predicted to result in a reduction of imports that are currently only about 11% of our domestic demand to only 1% by 2035 as shown in Fig. 5. Figure 5 also shows the change in the predictions between the EIA Overviews in 2010 and 2011. Because of this strong prediction, in May, 2011, the U.S. approved the export of domestic LNG from the Sabine Pass, LA, LNG terminal and is now reviewing two other requests from Gulf terminals.

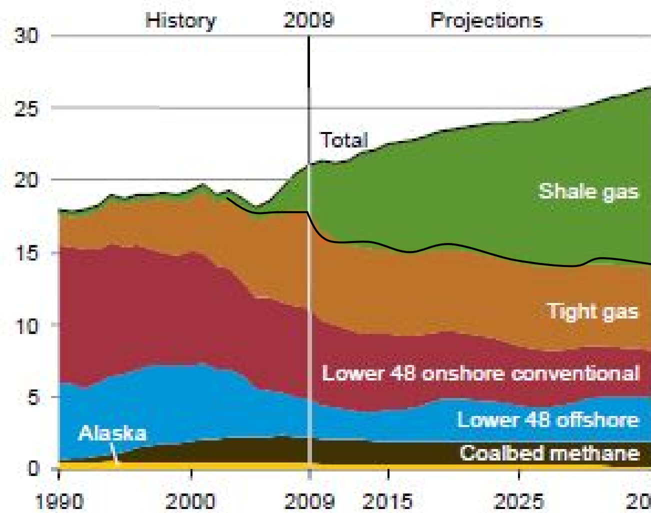

Fig. 4 Projected U. S. sources of natural gas (trillions of cubic ft/yr) (EIA 2011)

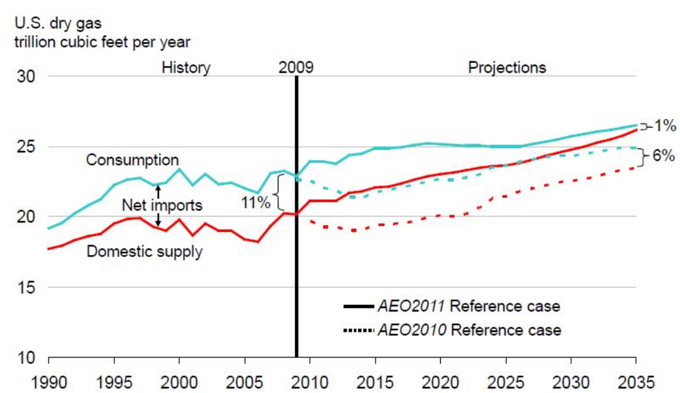

Fig. 5 Projected domestic supply and consumption of natural gas (EIA 2011)

The importance of these developments is that the United States is now predicted to become energy independent with respect to natural gas and it appears that the Henry Hub price has downward pressure and should remain relatively insulated from international events, as opposed to oil prices that are heavily driven by OPEC and external events. Thus, EIA states that "unlike crude oil prices, natural gas prices do not return to the higher levels recorded before the 2007-2009 recession (Fig. 3 *here*). Although some factors continue to relate the two markets loosely, the two do not trace directly (Fig. 6 *here*)" (EIA 2011).

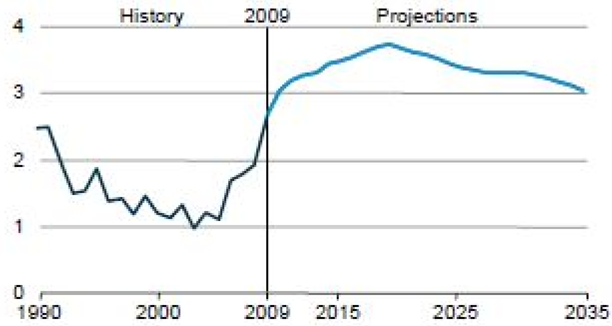

Fig. 6 Ratio of low sulfur crude oil to Henry Hub natural gas prices on an energy equivalent basis (EIA 2011)

Historically, the spot price of natural gas, as reflected in the Henry Hub price, and the spot price of crude oil have not been directly linked in the United States. The U.S. gas prices are set from the Henry Hub price ± discounts. This is in contrast to the regional European price model where gas prices are directly linked with a number of benchmark oil prices as well as some local gas hub spot prices and the regional Asian Pacific market where they are directly linked to the crude oil price (Bourgeois 2011). The Norwegian LNG prices are linked to oil and their recent prices have been about equal to or above those for low sulfur diesel and provide no help in offsetting the greater capital cost of their LNG plants. Because their LNG value chain is estimated to be 50-60% pipeline cost, 25-20% liquefaction and 25-20% distribution to the ships, however, and the "liquefaction and distribution costs are less dependent on oil price, the competitiveness of LNG to Marine Gas Oil (MGO) is expected to improve as the oil price increases" (Einang 2007).

Recent Puget Sound region experience has been that the price of natural gas has even been at a discount to (lower than) the Henry Hub price, mostly due to the influence of local Canadian pipeline imports. Consultants to the Washington State ferry study started with the projected Henry Hub price of $0.50/gallon and inflated this by 1.5% per year. They added a cost for liquefaction of $0.43/gallon based upon a 15% return on investment and a 1.5% inflation rate per year. They added another $ 0.31/gallon for trucking from a California LNG peaking facility and inflated this with their predicted diesel fuel increase. Their energy consultant Poten & Partners warned, however, that they "believe LNG suppliers are likely to try and peg their price to the alternative source available, in this case, ultra low sulfur diesel" (JTC 2011).

In the U.S., Figs 3 through 6 certainly suggest there is little basis for linking the LNG and diesel prices here in the future, unless our regional market becomes dominated by export sales. If it were to be accepted, this linkage could well eliminate an LNG cost advantage that would be critical to justifying an LNG conversion versus a diesel conversion.

6. Conceptual design for AAA LNG conversions

A conceptual design is under development for the conversion of the AAA steamships to LNG fuel. The initial step in a conversion to either LNG or diesel would involve the complete removal of the steam plant, which would be made more costly by the need to deal with asbestos removal and disposal. The inboard profile of the current aft portion of these vessels is shown in Fig. 7 for orientation.

The cargo holds and all self-unloading equipment are forward of FR183. The region between FR183 and FR195 currently contains the boilers and stack and would be the location of the greatest change. This region would be used for two port and starboard (P/S) vertical LNG fuel tanks. The Bunker C fuel bunkers outboard P/S in this region would be eliminated. The ballast pumps and manifolds on the engine room tank top in this region would not have to be changed. The current auxiliary boiler would, however, be removed from the centerline on this level. Cabins eliminated between FR183 and FR195 on the spar deck would not be needed because of the reduction in manning.

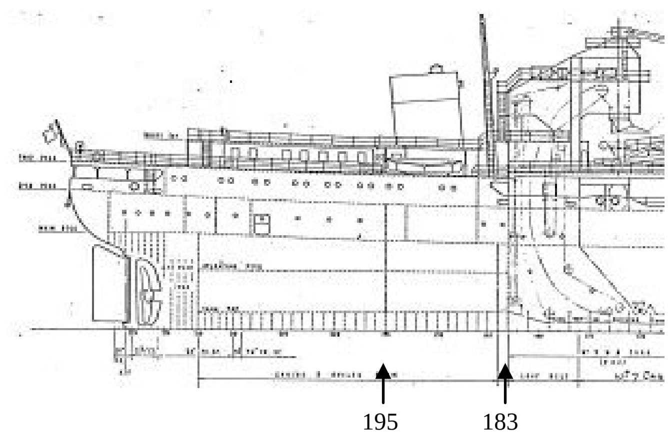

Fig. 7 Aft inboard profile of current AAA vessels

6.1. Engine sizing

Available natural gas (and diesel) engines are highly turbocharged to the extent that they cannot operate along a propeller curve with an adequate maneuvering margin so the stern frame and shaft line would have to be modified to accommodate a Controllable-Reversible-Pitch (CRP) propeller that would also improve the vessel maneuverability.

The current steam plants are rated at 7000 normal *shaft* horsepower (5220 kW). Allowing for the shafting and stern tube efficiencies of 0.99 each, this represents a delivered power to the propeller of 5116 kW. A CRP propeller will typically have a 1.5% lower efficiency than a fixed-pitch propeller (FPP) as currently used so the equivalent delivered power for the same thrust to the ship would be about 5193 kW. Accounting for stern tube and shafting efficiencies and a single-reduction gear efficiency of 0.985, this would ideally require a gas engine *brake* power of 5379 kW for equivalent power to propulsion.

Table 4 shows three engines that could be candidates for use in this application. The Rolls-Royce Bergen B35:40V12PG spark ignited natural gas only engine would provide 5250 kW brake power (Rolls-Royce 2011). This current rating might require a small reduction in the service margin, but should be a suitable replacement engine. The engine will be upgraded to 5720 kW at 750 rpm in March 2013 (Horgen 2012). The B35:40V12PG engine would provide the best emissions performance and the simplest installation, particularly after the Tier III ECA NO_x requirements come into effect in January 2016. These engines have a NO_x specific emission rate of 1.3 g/kWh at MCR, well below the requirement in Fig. 2. It has a heat rate of 7475 kJ/kWh at maximum continuous rating (MCR). This corresponds to a specific fuel consumption of 165 g/kWh, assuming a natural gas with a Lower Heating Value (LHV) of 45,300 kJ/kg.

Table 4 Candidate gas engines for AAA conversions

vendor	Rolls-Royce Bergen	Wärtsilä	MaK
engine	B35:40V12PG	12V34DF	6M46C DF
operating principle	lean burn spark ignition	diesel pilot dual fuel	diesel pilot dual fuel
cylinders	12	12	6
bore (mm)	350	340	460
stroke (mm)	400	400	600
cylinder volume (l)	38.48	36.32	99.71
EPA Category	C3	C3	C3
mean piston speed (m/s)	10.0	10.0	10.3
BMEP (bar)	18.2	19.8	21.1
rpm	750	750	514
MCR (kW)	5250	5400	5400
MCR (hp)	7040	7242	7242
weight (t)	58.0	59.0	93.0
overall length (mm)	6040	6615	8251
width (mm)	2712	3020	2905
height w/o maint. (mm)	4420	4190	5590 incl. maint.
gas heat rate (kJ/kWh)	7475	7700	7200
diesel pilot sfc (g/kWh)	none	1.8	2.0

Sources: Rolls-Royce 2011, Wärtsilä 2011, Westcar 2011

The Wärtsilä 12V34DF dual-fuel (diesel and natural gas) engine would provide 5400 kW, which exceeds the requirement just slightly (Wärtsilä 2011). These engines use a 1% diesel pilot to ignite the natural gas in the gas mode and can also run on diesel only. The engine can be started, loaded and operated up to 100% in the gas mode. Transfer from the gas mode to the diesel mode cannot be made above 80%, however. The engine will also transfer automatically to the diesel mode if operated for more than a set time (3 min) below 10% load. The dual-fuel would provide a valuable alternative fuel backup in case of fuel availability difficulties. This would, however, involve retaining the volume and weight of diesel bunkers and fuel processing. Space would, however, be available on Engine Room Tank Top level. Selective Catalytic Reduction would also be required in the diesel mode to meet the ECA NO_x requirements that begin January 2016. Wärtsilä could also produce a marine version of their gas mode only SG engines that are currently used land-side.

MaK is working on a dual-fuel variation of the M43 frame engines that are to become the M46C diesel-natural gas engines by using a larger bore in the same platform. These engines are targeted to be available by 2014. The 6M46C DF engine from this series is expected to provide 5400 kW and would be a suitable candidate (Westcar, K. 2011). This engine would be expected to provide the general advantages and complications of the Wärtsilä dual-fuel engines.

The Rolls-Royce Bergen B35:40V12G single fuel engine was selected for this initial conceptual design study.

6.2. Assumed operating modes

The AAA vessels operate in a variable tramp trade throughout each year. However for the purposes of this study, the operating modes of the Duluth, MN, to Gary, IN, trade used in our recent study of Integrated Electric Plants in self-unloading bulk carriers was assumed to be representative on average (Parsons et al. 2011). These operating modes are defined in Table 5.

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 bow and stern thrusters in use while at 10% propulsion power, and 10 hours unloading with the ballast pumps and self-unloading conveyor system in use. With the selected engine, the open-lake load represents an 87% load. This trip covers 820 statute miles each way and includes the locks and restricted channels of the St. Mary's River, which should represent the average of a typical tramp trade pattern (NOAA 2009). Lake Michigan to Lake Huron routes would be simpler. Lake Superior to Lake Erie routes could be longer if east of Cleveland, OH, and would add the restricted channels of the St. Clair River, Lake St. Clair, and the Detroit River.

6.3. Plant configuration

The single-screw plant would utilize one Rolls-Royce Bergen B35:40V12G main propulsion engine driving a CRP propeller through a single reduction gear. The two 400 kWe steam turbo-generator sets, small start-up diesel generator set and two 800 kWe unloading system diesel generator sets would be replaced by three gas generator sets. The stern thruster is driven by a 746 kWe electric motor. The independent diesel used to drive the bow thruster would be replaced by a similar 746 kWe electric motor. The single oil-fired auxiliary boiler would be replaced by two gas-fired auxiliary boilers.

Table 5 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%

Work is underway by Caterpillar and their contractor Westport Innovations to develop gas-fueled generator sets for marine use based upon the 3500 family diesel and gas engines. It is understood that plans are for a G3512 set producing 60Hz 550 kWe at 1200 rpm and a G3516 set producing 770 kWe at 1200 rpm, to be available by 2014 (Westcar, K. 2011).

The Electric Load Analysis for the AAA vessels was modified to reflect the elimination of the steam plant and its replacement with an LNG-fueled engine system. The summer case with cabin air conditioning loads was the controlling case. The LNG system requires about 0.05 kW/kW engine power to re-gasify (vaporize) LNG and heat the gas to about 15^{o}C as needed by the engines (RINA 2003). It was assumed that this will be provided by engine jacket cooling waste heat above about 30% power and provided by an auxiliary boiler when maneuvering, locking/docking loading, unloading and during start-up. Based upon this analysis, three Caterpillar 770 kWe G3516 gas generator sets were included in the design. The generator specific fuel consumption was assumed based upon constant rpm operation data presented for smaller Rolls-Royce Bergen engines (Einang 2007).

6.4. Fuel use

The LNG required by one of the AAA vessels during one round trip voyage from Duluth, MN, to lower Lake Michigan operating in the modes shown in Table 5 is summarized in Table 6. The round trip requires 5.63 days so the vessel could complete 53 trips during a 300 day Great Lakes operating season assuming 100% utilization.

One 770 kWe generator would be used in the open lake, reduced speed, maneuvering, and loading modes; all three generators would be used during locking/docking and unloading. As seen in Table 6, the LNG required by the propulsion engine, ship service generators, and auxiliary boilers totals 215.3 m^3 or 56,870 gallons per round trip. During winter operations, the total is the same at 215.2 m^3. The annual use totals 3,014,000 gallons as included in Table 2.

6.5. LNG tank sizing

LNG tanks operate with ullage (head space) over the LNG of about 10% of the volume at filling and the maximum level is limited to 98% full at the relief valve setting when the liquid warns and expands (ABS 2011). With careful design this head space can be as low as 5% (Emmers 2012). Since the tanks will warm to ambient with no LNG in the tank, requiring a lengthy cool down period, there is also an operational incentive to never let the tank become completely empty unless entering dry dock or maintenance. The net useable volume is, therefore, only about 85% of the gross tank volume. Allowance must also be made for the 4″ to 6″ insulated wall spacing of the double-walled tank. Taking account of these issues, the tanks must be sized to provide a useable volume that will provide an acceptable operational fuel margin.

Table 6 Summary of AAA vessel LNG use during one summer round trip Duluth, MN, to lower Lake Michigan

mode	hours	prop. kW	% load	kJ/kWh	LNG cubic m	ship service	ballast pumps	bow/stern thrusters	unload. conv.	total kWe	% e load	kJ/kWeh	LNGe cubic m	total kW
open lake	103	4572.2	87%	7550	168.8	476.4	0.0	0.0	0.0	476.4	61.9%	8800	20.5	5068.5
reduced speed	8	2700.0	50%	7600	7.8	476.4	0.0	0.0	0.0	476.4	61.9%	8800	1.6	3196.3
maneuvering	6	1620.0	30%	7750	3.6	476.4	0.0	0.0	0.0	476.4	61.9%	8800	1.2	2116.3
locking/docking	2	540.0	10%	8280	0.4	519.8	0.0	1491.4	0.0	2011.2	87.1%	8500	1.6	2635.0
loading	6	0.0	0%	0	0.0	392.5	226.0	0.0	0.0	618.5	80.3%	8600	1.5	644.3
unloading	10	0.0	0%	0	0.0	488.9	226.0	0.0	1107.2	1822.1	78.9%	8650	7.5	1898.0
total	135	hours		propulsion	180.6	cubic m						ship service	33.9	cubic m
	5.625	days		assumptions:								propulsion engine	180.6	cubic m
				LHV	45,300	kJ/kg						auxiliary boiler	0.8	cubic m
				density	0.465	t/cubic m						Total	215.3	cubic m

ABS and DNV allow dual fuel plants to use a single LNG fuel tank (ABS 2011, MT 2011, DNV 2012). They require that single LNG fuel plants have two LNG storage tanks located in separate gas tight tank spaces so that with a loss of one fuel supply path, the ship will still have available at least 40% power (Parsons 2011, DNV 2012). The space available for the LNG tanks on the AAA vessels is limited fore and aft such that two vertical tanks P/S of the centerline would be needed to maximize capacity. Thus, the requirement for separate tanks is no particular difficulty in this case.

As will be seen in the arrangement feasibility study below, there is adequate space for two tanks that are about 17.5′ in external diameter and 54′ tall. Assuming a 5″ spacing between the inner and outer walls, these tanks would have a gross tank internal volume of about 294 m^3 giving a net useable volume of about 250 m^3 each. Comparing this to the results of Table 6, two tanks would provide a *next* round trip operational fuel margin of 32.2%, if refueling were every *second* round trip. The operational fuel margin would be about 86.6%, if the refueling basis were about once per week. This is less range than the current AAA design, but could provide an acceptable design solution.

If the voyage length were from Duluth, MN, to Buffalo, NY, these tanks would provide a *next* round trip operational fuel margin of 17.6%, if refueling were every *second* round trip. Acceptance of a smaller operational fuel margin or planned refueling once per trip could result in smaller, cheaper tanks that would be easier to integrate into the design.

6.6. Arrangement feasibility

An initial arrangements feasibility study was undertaken to ensure that the required equipment and adequate LNG tank volume could be integrated into the AAA vessels. Arrangements sketches for the conceptual LNG conversion design for the AAA vessels are shown in Fig. 8. The Inboard Profile is conventional - taken on the centerline looking to port with the bulkhead between the LNG tank rooms removed. The two separate LNG tanks are P/S on the Operating Deck where the boilers were previously located. The LNG tank rooms extend upward through the Poop Deck roof between FR186 and FR193. On the Operating Deck level, the LNG tank rooms have an extension forward to FR183 that contains the cold boxes that contain the re-gasification/heating and tank pressure control equipment. The LNG tank room ventilation discharge and tank pressure relief are in the new vertical mast just forward of FR186. The ballast pumps and manifolds are located below the LNG tank rooms and would not have to be disturbed. The main engine, reduction gear and CRP propeller are aft. The new uptake between FR203 and FR206 satisfies the required separation distance between the tank ventilation/pressure relief discharge and sources of ignition (ABS 2011, DNV 2012).

The poop deck contains the LNG tank rooms that extend about 20′ further up. The CO_2 room, previously to starboard of the uptake on this level, is relocated to athwartships just aft of the LNG tank rooms. The emergency generator room containing the 100 kWe Caterpillar diesel generator set, previously to port of the uptake on this level, is relocated into an extended region in the port aft corner of the after deck house. This relocation and the new uptake result in the loss of one licensed cabin, but this is acceptable with the reduction in manning.

The spar deck is modified to accommodate the greater width of the two LNG tank rooms. Outboard P/S between FR186 and FR190 are two separate bunkering stations that have openings to the outside for LNG refueling access. The messroom, galley, pantry, and dining room are rearranged to accommodate the LNG tank rooms and port bunkering station. Three unlicensed cabins accommodating a total of six are lost to starboard of the LNG tank rooms and aft of the messroom, but this should be acceptable with the reduction in manning.

The main deck is modified to accommodate the LNG tank rooms with the relocated Chief Engineer’s office and Paint Locker and Workshop located outboard. Two of the Caterpillar G3516 generator sets are located P/S next aft outboard of the main engine. A new enclosed Engine Control Room is located to port aft of the gangway door.

The operating deck contains the LNG tank rooms with their extension forward to house the cold boxes. These rooms are equipped with access locks. The two new gas-fired auxiliary boilers are located on the Engine Room Tank Top level and extend up through this level on the port side between FR183 and FR195. Engine stores are relocated outboard to starboard. The third Caterpillar G3516 gas generator set is located outboard of the main engine on the port side.

The engine room tank top level contains the new gas-fired auxiliary boilers on a raised flat to port between FR183 and FR196. The gas main engine, reduction gear and shaft line is located on the centerline. A void remains to starboard where the Bunker C bunker was located. The ballast pumps and manifolds remain between without modification.

Overall, the arrangement of the LNG conversion of the three AAA vessels with the new gas main engine, three gas generator sets, two new gas auxiliary boilers, two bunkering stations and two separate LNG tanks with a net operationally useable LNG volume of 500 m^3 to ABS/DNV requirements (ABS 2011, DNV 2012) appears feasible.

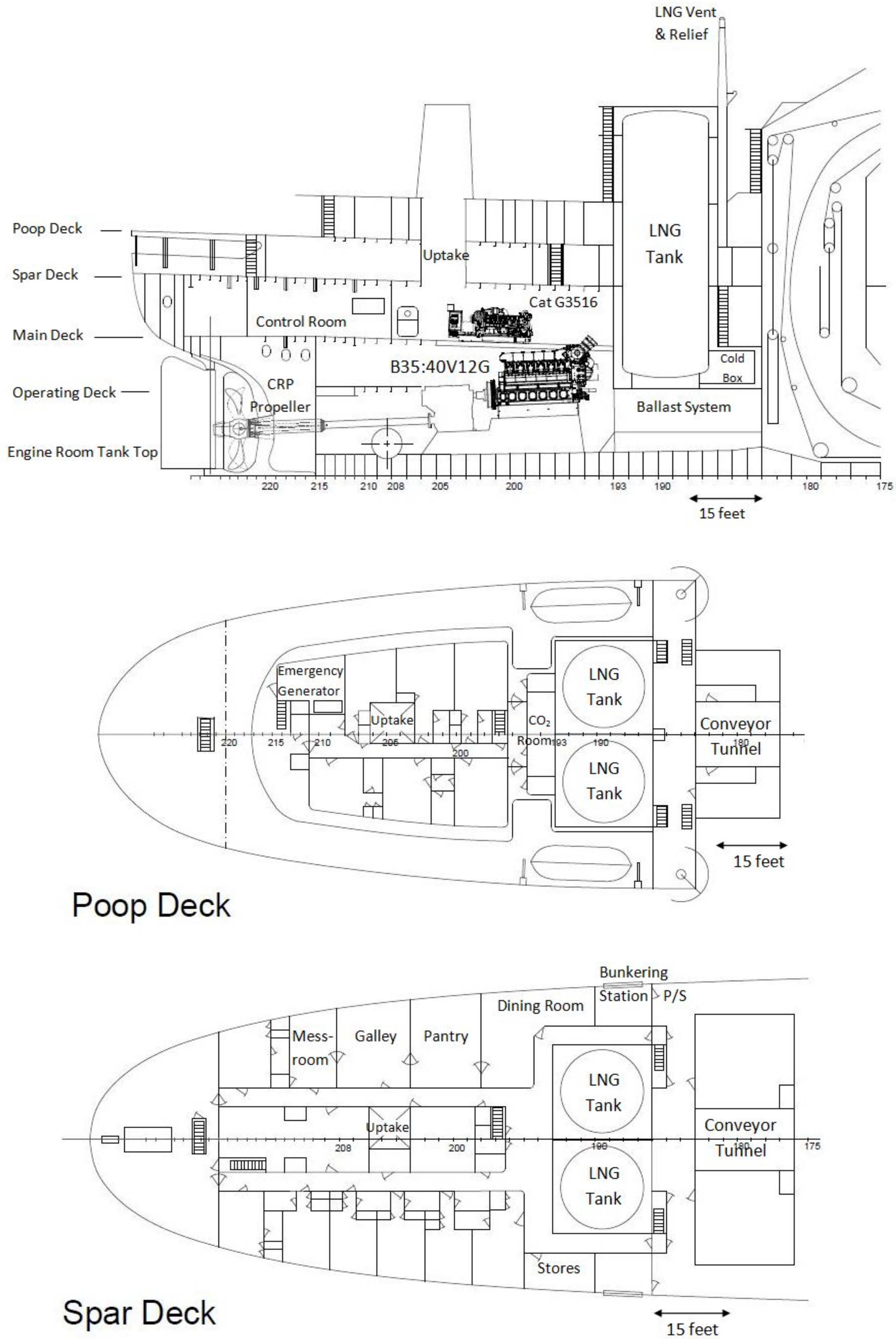

Fig. 8 Conceptual arrangements sketches of the aft portion of the converted AAA Class vessels (continued)

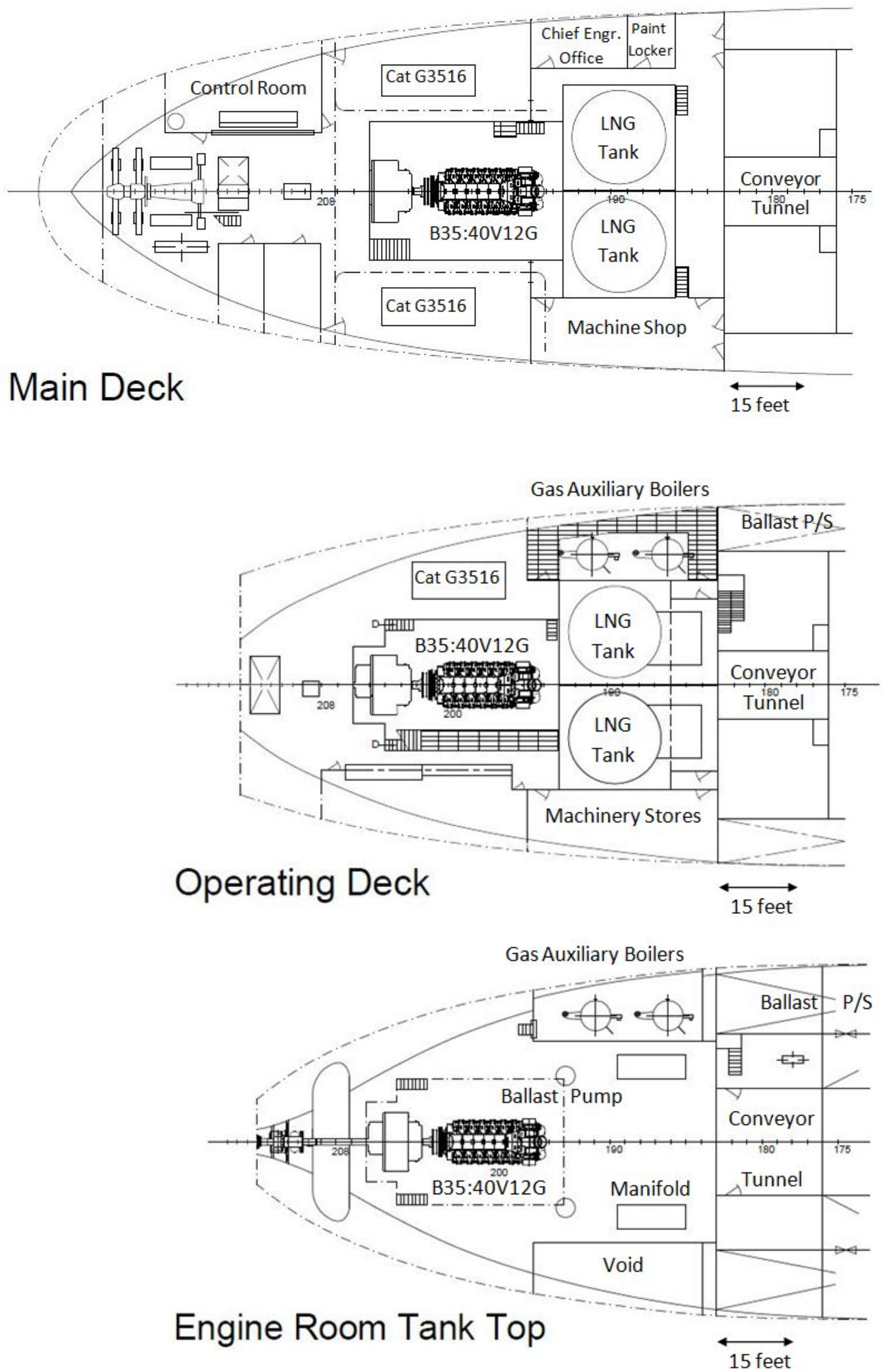

Fig. 8 Conceptual arrangements sketches of the aft portion of the converted AAA Class vessels (concluded)

6.7. Conversion concept

The conversion of a Great Lakes bulk carrier to LNG fuel would be expected to entail more regulatory overhead and input than a diesel conversion due to its newness and the lack of defined U.S. Coast Guard requirements at this time. There would probably be less local Marine Inspection Office on-site decision making and more central control.

Meyers and Woessner (2011) note that "the existing U.S. regulations do not address natural gas fuel for vessels other than LNG cargo ships; such proposals are being reviewed on a case-by-case basis as equivalency requests to existing requirements under Title 46 of the Code of Federal Regulations (CFR)." They note that the Coast Guard has recently reviewed and accepted several concept proposals for vessel LNG fuel designs that use the IMO Guidelines (IMO 2009) as the baseline standard. The ABS Guide (ABS 2011) and DNV requirements (DNV 2012) reflect these IMO Guidelines.

Meyers and Woessner (2011) also state that "the Coast Guard's response to these proposals has taken the form of a Design Basis Agreement which lays the framework of requirements that need to be met for plan approval and vessel certification." They note that the LNG tank rooms are a "considered a Zone 1 hazardous space prohibiting the installation of non-certified electrical equipment." This electrical equipment must comply with 46 CFR 111.105. If the gas supply lines to the main engine, gas generator sets, and auxiliary boilers are double-walled so that these spaces are developed under the "inherently gas safe" (IMO 2009, DNV 2012) or ABS "double-walled" philosophy (ABS 2011), the rest of the engine room can be developed as usual.

The mechanical areas of the conversion would not differ significantly from a normal diesel conversion. The main differences would lie in the LNG tanks rooms and the gas supply system. The LNG storage tanks and associated cold boxes, bunkering stations, and connecting piping can be supplied as an integrated system provided by single contractor.

The conversions considered here would not alter the function, cargo capacity, or propulsion power of the vessels so they should not fall under the strict U.S. Coast Guard definition of a "Major Conversion." The conversion to LNG fuel may still be declared in this category, however, due to its scope, newness, lack of established regulations, and greater inherent risk. It would then be critical to negotiate practical physical and system boundaries to modifications in order to make the conversion economically feasible. With the exception of the removal of the conveyor generators from just forward of FR183, electrification of the bow thruster and the integration of the self-unloading equipment into a centralized electrical distribution system, all of the conversion would be aft of FR183, which would provide a natural physical boundary.

The conversion would begin with the removal of asbestos and the steam plant machinery. Some professional asbestos remediation contractors can also be responsible for the "wreck out" of the boilers. The stack and areas that will be occupied by the LNG tank rooms would be removed to provide vertical access to the boilers. A large plug would also be cut in the Spar Deck, Poop Deck, and Poop Deck roof to allow direct vertical access to the engine room machinery. This superstructure block could then be modified off-hull to incorporate the new stack and uptake, etc. in preparation for a later return to the ship.

The most difficult lifts would be the tall LNG tanks that would have to be inserted down into the LNG tank rooms. The empty tanks would weigh about 100 tonnes each. With this concept, their construction would be complicated by the need to land the cold boxes first and make their final connection in the ship. Perhaps a preferred alternative would be to open the ship forward to FR183 so that each tank and its integral cold box could be landed as one lift. The forward bulkheads of the LNG tanks rooms and associated deck structure could then be landed after the tank installation. This would enable all tank connections to be completed and tested at the factory. An alternative would be a tank design with the cold box equipment incorporated under the tank, but this option would add additional tank height and vertical center of gravity.

The control, monitoring, and alarms would be integrated into a new control room that would be fabricated and pre-outfitted off-hull and landed as a single module. With the development of a new centralized control room, it would be typical to modernize the ballast control as part of the conversion by replacing the manifolds with remotely operated valves controlled from a ballast control console in this control room. Such a ballast system modernization has already occurred on the *Cason J. Calloway* (Bowler et al. 2002).

The extent of the conversion, newness of the technology, and the lack of established regulations for U.S. flagged vessels justifies a phased approach as mentioned in Section 4.1. A year-long Phase I would be recommended to accomplish the initial design, resolve regulatory issues with classification and the U.S. Coast Guard, and purchase long lead equipment. All engineering, approvals and planning should be completed in advance of lead ship arrival.

7. Conclusions and future plans

This has been the initial report of an investigation of the feasibility and potential benefits of converting ten remaining U.S. flag Great Lakes steamship bulk carriers to Liquefied Natural Gas (LNG) propulsion using gas engines. This is an early three-month initial report since the project was just started in November, 2011, but was offered since it was a logical fit for the February, 2012, Great Lakes and Great Rivers Section of SNAME meeting focusing on LNG fuel.

The conversion of the U.S. steam bulk carriers to LNG would offer greatly improved fuel efficiency, the possibility of reduced manning, improved air emissions meeting ECA requirements, and the potential for a significant fuel cost savings. The fuel cost savings would be critical to offsetting the added conversion cost that would result compared to a diesel conversion with exhaust gas scrubber and/or Selective Catalytic Conversion to meet the ECA air emissions standards that will become enforceable after January 1, 2016. The tacit assumption has been made that the congressionally mandated exemption for the steamships from the ECA requirements is not politically and socially sustainable. A conversion to LNG would move these vessels from being worst to first in terms of green operations on the Great Lakes.

A conversion to LNG would entail a number of challenges, primary of which is the development of a reliable source(s) for LNG. An estimate of aggregate LNG demand that would result from a possible conversion plan was presented.

The price of LNG in the Great Lakes region will be critical to the economic viability of conversion of the U.S. flag Great Lakes steamship bulk carriers to LNG fuel rather than the more conservative and cheaper in capital cost conversion to diesel. The other challenges appear to be workable.

Overall, the arrangement of the LNG conversion of the AAA vessels with a new gas main engine, three gas generator sets, two new gas-fired auxiliary boilers, two bunkering stations and two separate LNG tanks with a net operationally useable LNG volume of 500 m^3 to ABS/DNV requirements appears feasible.

The remainder of this project will undertake the following for the AAA class vessels:

- weight study to confirm that there is no lost cargo capacity at constant draft;
- stability study to ensure there will be adequate metacentric height;
- concept development for added ventilation required for LNG tank rooms and systems;
- refinement of arrangements;
- detailed air emissions comparison of steam, diesel, and LNG versions of these vessels;
- notional shipyard planning for the conversion and related conversion cost estimates for work in Great Lakes shipyards;
- life-cycle economic analysis and determination of payback period.

The feasibility study will then consider the remaining seven vessels to confirm that the basic AAA class conceptual design can be adapted and extended to the other seven vessels in group.

Disclaimers

This is the initial report on a conceptual and feasibility study and is, therefore, subject to revision and change as the study moves forward. The opinions expressed here are those of the authors only and do not represent the opinions, conclusions, or plans of any of the companies that have provided assistance to this study.

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WORK SINCE THE INITIAL REPORT

Since February, the effort has continued with a more detail assessment of the fuel costs associated with use of LNG fuel for AAA Class vessels considering four options: the existing steam plants burning Bunker C; single fuel LNG gas engines burning LNG with Marine Diesel Oil (MDO) electric generator sets; dual fuel LNG gas engines burning LNG and a small amount of MDO pilot fuel with MDO electric generator sets; a diesel conversion burning either MDO or Intermediate Fuel Oil (IFO) with MDO electric generator sets. The conversions are based upon using one Rolls-Royce Bergen B35:40V12PG spark ignited single fuel LNG engine, a Wärtsilä 12V34DF dual fuel MDO pilot ignited LNG engine, or a MaK 6M43C diesel engine for propulsion, respectively. The annual fuel cost comparison for these options was completely reanalyzed and the results are shown in Table 1. The LNG conversions offer about a 2 million USD, 30% annual fuel cost savings compared to the current steam plants, which is comparable to that provided by a diesel conversion that is equipped with an exhaust gas scrubber so it could continue to burn IFO after 2015.

Table 1 Annual Fuel Cost Comparison for AAA Class Bulk Carriers

	Existing Steam	Single Fuel LNG	Dual Fuel LNG	Diesel	Diesel
main engine fuel	Bunker C	LNG	LNG & MDO	MDO	IFO
generator set fuel	Bunker C,MDO	MDO	MDO	MDO	MDO
main engine fuel price	$675/t	$690/t	$690/t,$1025/t	$1025/t	$682/t
generator fuel price	$675/t,$1025/t	$1025/t	$1025/t	$1025/t	$1025/t
fuel cost per voyage	$123,038	$83,261	$86,535	$110,035	$82,520
voyages in 300 day season	53	53	53	53	53
annual fuel cost	$6,521,014	$4,412,833	$4,586,355	$5,831,855	$4,373,560
annual fuel savings rel. to current steam plant		$2,108,181 32.3%	$1,934,659 29.7%	$689,159 10.6%	$2,147,454 32.9%

The study has also evaluated the air emissions associated with use of LNG fuel for AAA Class vessels considering four options: the existing steam plants burning Bunker C; single fuel LNG gas engines burning LNG with Marine Diesel Oil (MDO) electric generators; dual fuel LNG gas engines burning LNG and a small amount of MDO pilot fuel with MDO electric generators; and a diesel conversion burning MDO. This was based upon operations after January 1, 2015, when the 0.1% sulfur marine fuel requirement would be in effect. The results of this study are summarized in Table 2. The same three engines were considered. The LNG conversions offer major improvements in the NOx emissions compared to a diesel conversion. All of the conversions offer major improvements in particulate matter (PM), SOx and CO_2 emissions. The LNG conversions, particularly the single fuel option, offer significant advantages over the diesel conversion in terms of the particulate and SOx emissions.

Table 2 Annual Air Emissions Comparison [metric tonnes/300 day operating year]

	Existing Steam	Single Fuel LNG	Dual Fuel LNG	Diesel
main engine fuel	2% S Bunker C	LNG	LNG/0.1% S MDO	0.1% S MDO
generator fuel	0.45% S MDO	0.1% S MDO	0.1% S MDO	0.1% S MDO
notes	turbogenerators			no SCR
HC w/o CH4	4.26	64.52	91.05	14.52
CH4	n.a.	93.59	152.15	n.a.
NOx	76.71	70.19	73.44	307.76
CO	8.38	36.67	64.44	15.73
PM	36.28	0.64	2.54	3.97
PM-10	36.28	0.64	2.54	3.97
PM-25	35.19	0.62	2.46	3.85
SOx	371.05	1.60	1.65	11.45
CO2	30722.7	15091.0	15540.1	18156.6
CO2 equivalent GHGs	30722.7	17056.3	18735.2	18156.6

The conceptual design developed for the single fuel conversion using a Rolls-Royce B35:40V12PG engine reported in the Initial Report was updated to reflect the fact that Caterpillar has decided to no longer develop the gas version of the GS3500 engines as anticipated in the Initial Report. Two MDO fueled 550 ekW Caterpillar C18 ACERT generator sets were utilized in place of the steam turbogenerator sets and the current diesel engines and generator sets used to power the self unloading equipment and the bow and stern thrusters on the

AAA vessels were left unchanged. This results in a lower fuel cost advantage and additional air emissions due to the loss of the conversion of the electrical generation to LNG. It does result in no change to the vessel forward of web frame (FR) 183 which might ease the U.S. Coast Guard "major conversion" issue negotiations. The unique aspects of the arrangements for the dual fuel LNG conversion using a 12V34DF engine were also developed.

The most challenging naval architectural issue is to obtain enough volume within the vessel to store the LNG since it requires 3 to 4 time as much gross hull volume as an equivalent amount of petroleum fuel. The AAA vessels are particularly good candidates for an LNG conversion, however, because the portion of the vessel between FR183 and FR195 currently occupied by the boilers, deaerating feed tank, and fuel bunkers can become available for two vertical LNG fuel tanks. An LNG storage tank design for the AAA vessels was developed for the project by Chart Ferrox, a.s. of Decin, The Czech Republic. These 17.5' outer diameter, 43' tall double wall, vacuum and perlite insulated cryogenic tanks have the equipment for tank pressure control and LNG re-gasification installed in a cold box within the tank support skirt below the tanks. These 199 gross cubic meter tanks with an 8 bar design pressure would have enough capacity to allow the AAA vessels to fuel once per typical round trip (Duluth, MN, to Gary, IN) with a fuel margin of about 60%.

The inboard profile of the aft part the conversion using the single fuel Rolls-Royce Bergen B35:40V12PG engine is shown in Fig. 2. Two Chart VST199/8 LNG storage tanks are located port and starboard of the centerline in separated tank rooms between FR186 and FR193. A new uptake is developed between FR203 and FR206. The aft deck plan views of the single fuel LNG conversion of the AAA class vessels are shown in Figs. 3 through 7.

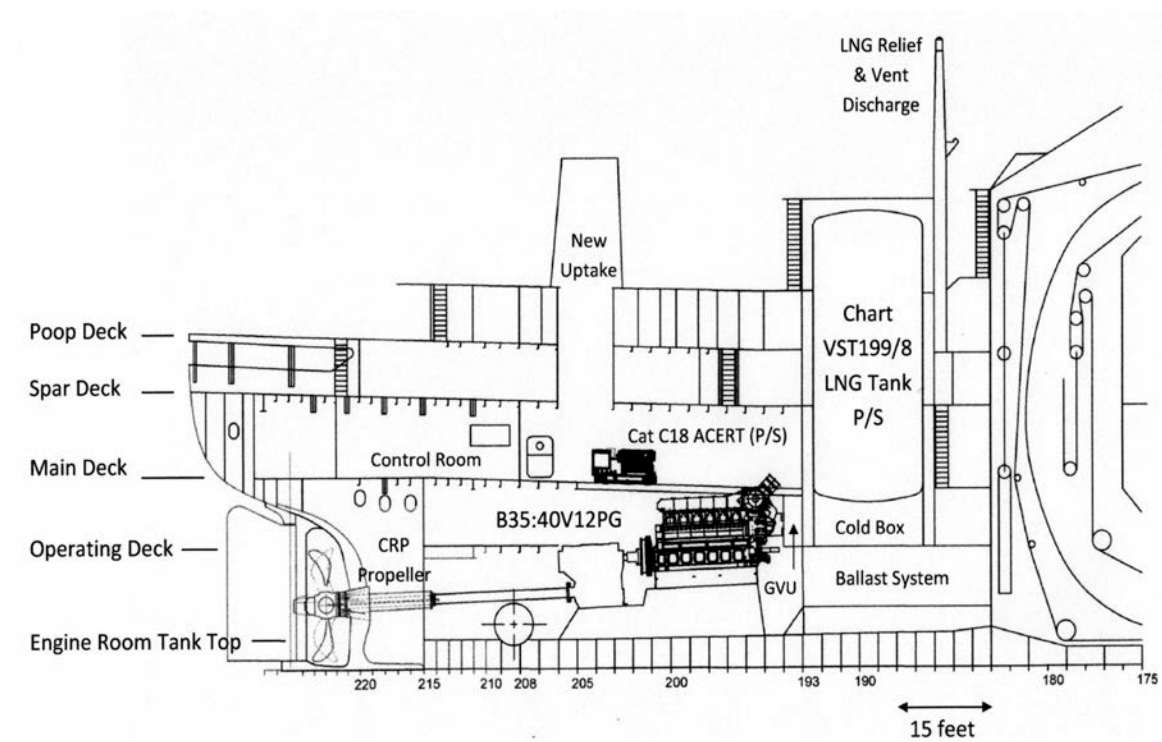

Figure 2 Inboard Profile Aft of AAA Class Vessel Single Fuel LNG Conversion

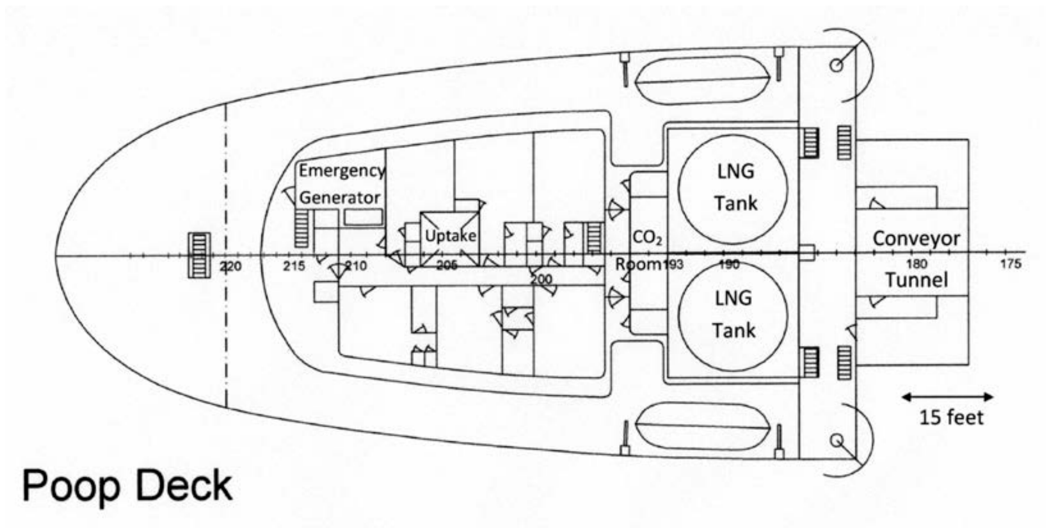

Figure 3 Poop Deck Aft of AAA Class Vessel Single Fuel LNG Conversion

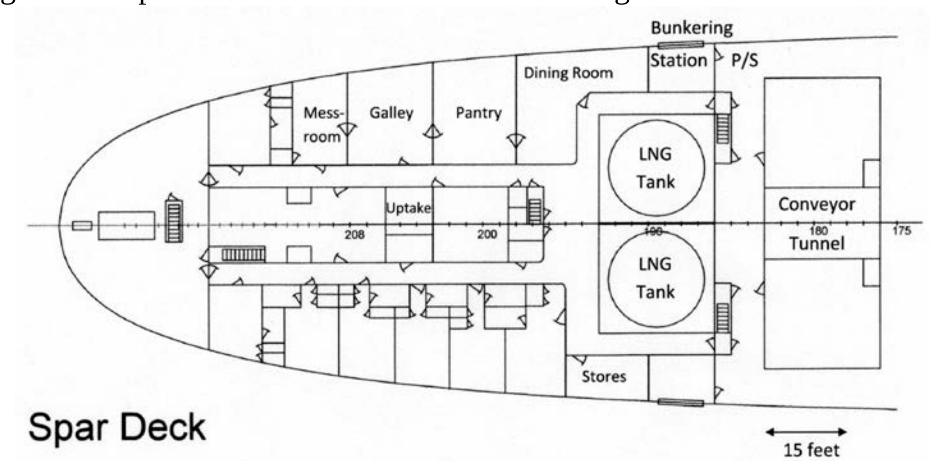

Figure 4 Spar Deck Aft of AAA Class Vessel Single Fuel LNG Conversion

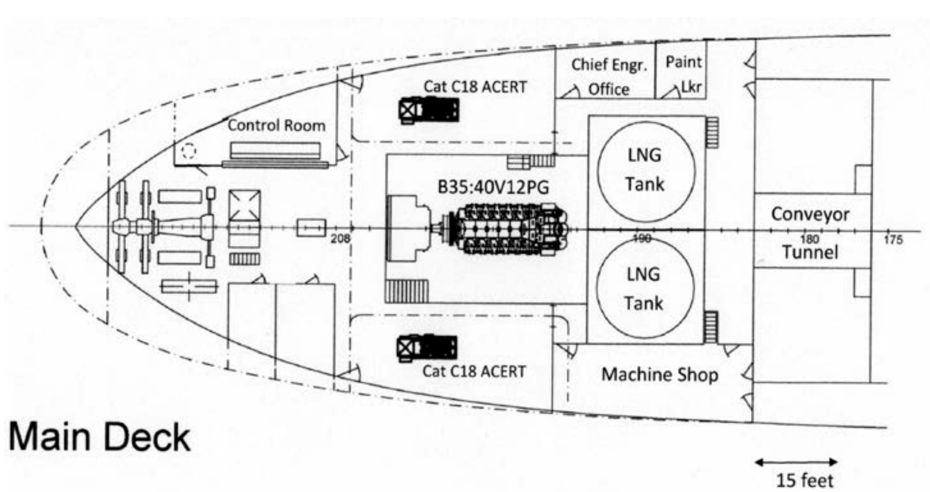

Figure 5 Main Deck Aft of AAA Class Vessel Single Fuel LNG Conversion

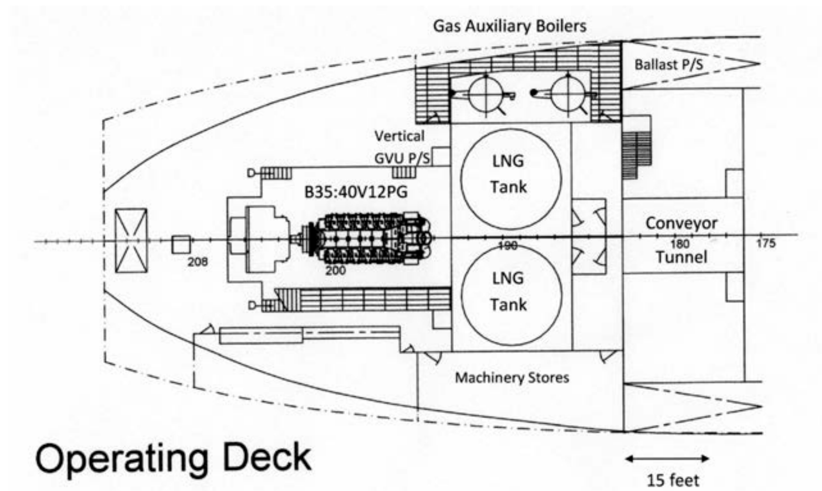

Figure 6 Operating Deck Aft of AAA Class Vessel Single Fuel LNG Conversion

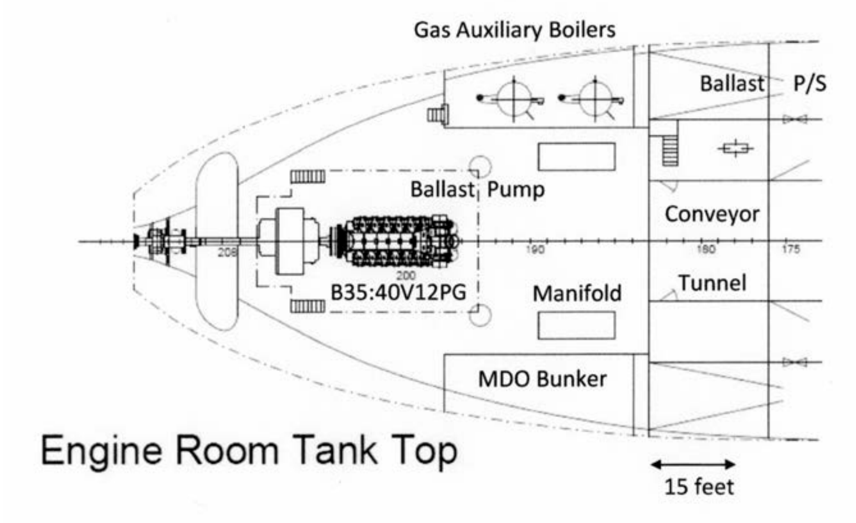

Figure 7 Engine Room Tank Top Aft of AAA Class Vessel Single Fuel LNG Conversion

The dual fuel LNG conversion using a Wärtsilä 12V34DF engine is similar with only minor variations needed to accommodate a slightly (0.6 m) longer engine and the needed MDO fuel bunker as shown in Figs. 8 and 9 for the inboard profile and operating deck plan, respectively. Although slightly inferior in terms of fuel savings and emissions, the dual fuel option would offer a potentially major advantage since it could also operate on MDO only if LNG is not available when and where needed in the initial years of the development of an LNG infrastructure on the Great Lakes.

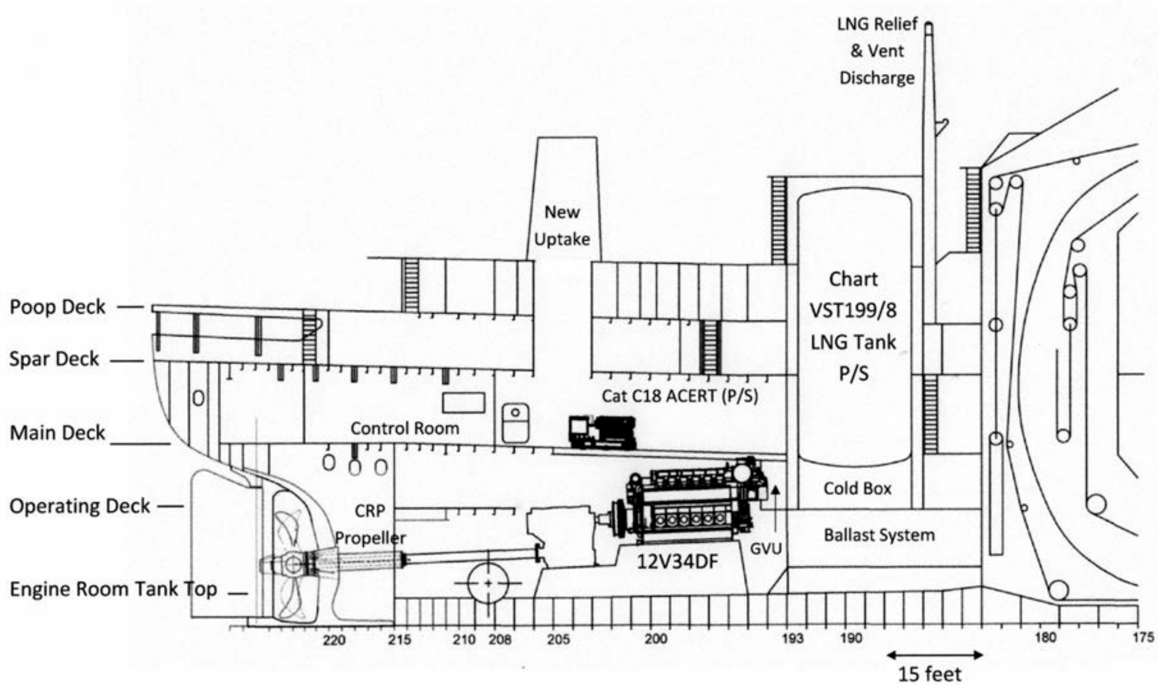

Figure 8 Inboard Profile Aft of AAA Class Vessel Dual Fuel LNG Conversion

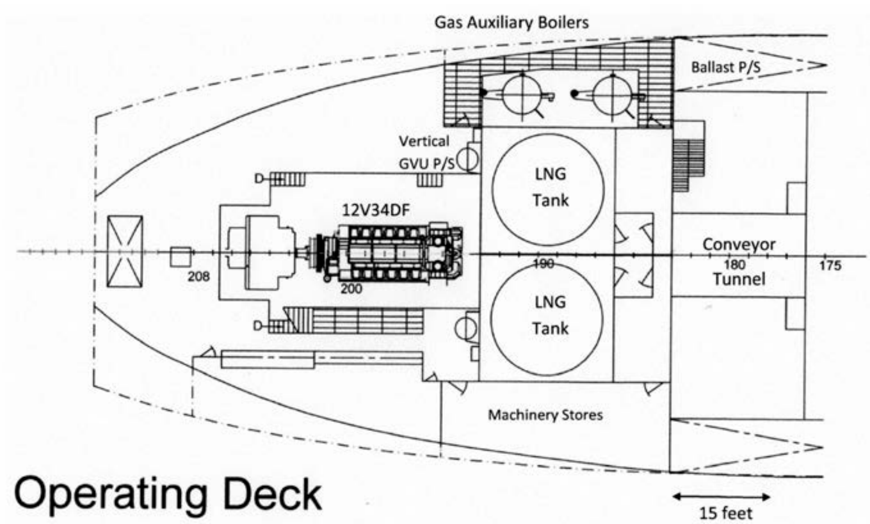

Figure 9 Operating Deck Aft of AAA Class Vessel Dual Fuel LNG Conversion

NORWEGIAN LNG FUEL USE OBSERVATION TRIP

To support the goals of the project, the PI arranged and led an August 12-18, 2012, visit to Norway to observe the propulsion plant designs, construction, and operation of the LNG powered ferries and platform supply vessels that have been developed in Norway over the past 12 years. The PI, project consultants Patrick O'Hern and Richard Harkins, GLMRI consultant Randolph Helland and GLMRI Executive Director Carol Wolosz were able to participate in this visit. The trip was based in Bergen, Norway, and included side visits to Halhjem, Alesund, Ulsteinvik, Haugesund and Oslo. The team was able to tour the Rolls-Royce LNG engine factory in Bergen, tour the propulsion plant on a single fuel LNG engine plant onboard the operating ferry *MV Raunefjord*, observe refueling of the LNG supply tanks at Halhjem from truck, observe the LNG bunkering of the *MV Raunefjord*, tour the propulsion plant of the dual fuel LNG engine plant onboard the nearly completed platform supply vessel *Viking Princess*, meet with Norwegian Maritime Authority personnel who regulate LNG vessels in Norway, visit the Kleven Verft shipyard building the *Viking Princess*, visit the Fiskerstrand shipyard that built the latest Fjord1 single fuel LNG ferry *MV Boknafjord*, and meet with Det Norske Veritas classification personnel involved in LNG vessel development and approval. The *MV Raunefjord* and the *PSV Viking Princess* are shown in Figs. 10 and 11.

The Norwegian hospitality and openness was outstanding and the visit was able to accomplish all goals and exceed expectations. While the use of LNG fuel involves new, higher technology and additional safety considerations, the use of LNG as a marine fuel for non-LNG cargo vessels is now a normal and successful part of marine practice in Norway following the introduction of the ferry *MV Glutra* 12 years ago.

Figure 10 Single Fuel Ferry *MV Raunefjord* at the Ferry Terminal at Halhjem, NO

Figure 11 Dual Fuel Platform Supply Vessel *Viking Princess* within 4 Weeks of Completion at Kleven Verft Shipyard in Ulsteinvik, NO

PLANS FOR THE REMAINDER OF THE PROJECT

The project is scheduled to end at the end of 2012. Work is now underway to complete a detail study of the changes to weights and centers to confirm that the conversions will be suitably stable and to establish if there are any impacts on vessel weight capacity in the draft limited operations of the Great Lakes system. The team is also awaiting price data from the gas engine vendors so that detailed remaining life cycle economics and payback periods can be established for the single fuel LNG conversion, the dual fuel LNG/MDO conversion, and a pure diesel conversion using either MDO with Selective Catalytic Reduction or IFO with both Selective Catalytic Reduction and an exhaust gas scrubber. This data has been very slow in coming following initial requests in May since the project does not have a "potential sale" linked to it and the companies know that their data will be published with comparisons made among options. The Final Report of the project will be presented at the Great Lakes and Great Rivers Section Meeting of the Society of Naval Architects and Marine Engineers on February 13, 2013, in Cleveland, OH. That section meeting will focus on the economics of LNG use as a marine fuel in the U.S.