
LNG Use for Washington State Ferries

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DOC:	REV: -	FILE: 09909.08	DATE: 19 March 2010

Executive Summary

LNG use as a marine fuel is both practical and cost effective and has been used in Norway for fueling ferries for over a decade. A high level discussion of adapting the WSF 144 vehicle ferry design for use with LNG fuel indicates that the volume exists to add LNG tanks of adequate size while still allowing weekly bunkering. Although the capital cost of the LNG engines and tanks is high compared to conventional diesel equipment, fuel cost savings of \$870,000 per year are estimated at today's prices. For pure gas propulsion engines NO_x emissions reductions will be at least 90% and PM and SO_x emissions will be reduced nearly 100%. CO₂ emissions reductions from pure gas propulsion engines will be approximately 20%.

Introduction

This paper is an introduction to the use of Liquefied Natural Gas (LNG) as a marine transportation fuel, and specifically the advantages, and challenges for its use by Washington State Ferries (WSF). Both new construction and conversion are considered. Issues of storage, safety, fueling, marine regulatory classification and commercial technology are discussed for context and background. Finally a high level look at adding LNG capability to a WSF vessel are discussed including 'rough order of magnitude' (ROM) equipment costs, operating costs, and emissions reductions.

The EPA Clean Diesel program prescribes a path for the stepwise reduction of emissions from diesel engines. Nitrogen Oxides (NO_x), Sulfur Oxides (SO_x), and Particulate Matter (PM) emissions are regulated nationally by the EPA, and regionally by other agencies at the state and local level. For Category 2 marine engines, which encompasses engines sizes used by WSF, Tier 2 emissions levels are now binding. Tier 3 levels will be in effect as early as 2013 and will be addressed with on-engine technology to meet regulations. To comply with Tier 4 regulations, which are effective as soon as 2014, engine manufacturers will likely require off-engine (exhaust after treatment) technology. Reducing NO_x with after-treatment requires the use of Selective Catalytic Reduction (SCR). This technology requires continuous consumption of aqueous urea (typically 5-10% of diesel fuel consumption) and will likely represent a significant operating expenditure for SCR equipped vessels.

Using LNG as a marine fuel could allow WSF to achieve similar NO_x, SO_x, and PM emissions and 20% lower CO₂ emissions when compared to Tier 4 diesels, but without the use of costly

after treatment. If the natural gas is produced from renewable sources, such as biomass, the carbon footprint can be reduced by up to 80%.

Using natural gas as a transportation fuel presents an opportunity to improve US energy security, as compared with petroleum, which dominates the US transportation sector. Natural gas is largely produced domestically, with imports accounting for only 10 percent of gas used. Use of natural gas in transportation has been steadily increasing for the last decade with LNG and CNG (compressed natural gas) being the dominant forms used for this purpose. LNG is created in a process called liquefaction, which in addition to liquefying the fuel it purifies it to at least 95% methane. LNG is the most energy dense form of natural gas.

On an energy basis natural gas is much cheaper than oil. Oil at today's price of \$80 per barrel has a cost per energy of \$13.80 per mmBTU. As a comparison natural gas costs under \$6 per mmBTU. Historically this price gap is tending to widen and favors natural gas. The energy and transportation costs associated with production and delivery of LNG add cost, but LNG is still significantly cheaper than diesel.

Background

LNG is a cryogenic fuel that is maintained at approximately -260°F at atmospheric pressure. The advantage of cooling and liquefying the fuel is that the volume is decreased approximately 600 times as compared to the gas. This improves the energy density significantly for LNG. As a result when compared to diesel fuel LNG has about 2/3 as much energy on a volume basis and almost 90% as much energy on a weight basis. Unfortunately, storing cryogenic (very cold) fuels requires special insulated tanks that significantly erode much of the volume and weight advantages of LNG.

Storage

LNG is typically stored in highly insulated, spherical, or cylindrical tanks at low pressures, (15 - 75 psig). Fitting these tanks on a ship or in a vehicle is quite feasible but does not compare favorably to diesel. In practice it should be expected that the volume required to store LNG will be about 3-4 more than the comparable volume of diesel.

Safety

LNG as a liquid is not flammable or explosive. As with any gas it has a flammability range. This range for LNG gas is between 5 and 15 percent when mixed with air. An explosion can only occur when the gas is in an enclosed space with air, the mixture is between 5 and 15 percent, and an ignition source is present. As with any flammable substance, proper design, regulations, and personnel training are needed to maintain a safe environment.

Compressed Natural Gas

LNG should not to be confused with CNG (compressed natural gas). CNG is another form of natural gas storage that is used widely in transportation. Typically CNG is stored in cylindrical or spherical tanks at pressures of 3000 to 4000 psig. Even at these high pressures, the energy content is less than half that of LNG. The marine classification rules, discussed more below, do not allow below deck storage of CNG. This limitation, along with a relatively lower energy density makes CNG a less desirable choice for fueling ferries.

LNG as a Transportation Fuel

LNG is used today as a transportation fuel but the market is still small compared to most other alternative transportation fuels. Clean Energy Fuels, a large national supplier of LNG, distributes 3.5 million gallons of LNG per month for vehicle transportation. It is typically transported by truck from liquefaction facilities to the fueling stations. The transportation of LNG is a major contributor to the cost of the fuel, so reducing the transportation distance from the liquefaction facility to the point of use results in a tangible cost reduction.

LNG is in limited use in Washington State today, but if a large enough market existed in the Puget Sound area, the supplier would build a liquefaction plant. Currently two liquefaction facilities exist on the Washington/Oregon border and another on the Canadian side of the Washington/Canada border. One LNG fueled ferry similar in size to the new 144 vehicle ferry would likely consume enough LNG to justify a Puget Sound liquefaction plant.

LNG Buses

A number of large LNG bus fleets are in operation in the US today. The city of Phoenix PTD (Public Transit Department) operates a fleet of 351 LNG buses, representing 71 percent of the city's fleet. Dallas Area Rapid Transit (DART) has been operating a large fleet of heavy duty buses fueled by LNG since 1998 and today the fleet has grown to 181 LNG buses. Tempe, Arizona operates a fleet of over 100 LNG buses.

LNG in Ports

Today in the United States ports, about 500 trucks are operating on LNG as a fuel. Another 500 trucks will be deployed in early 2010. This growth rate will likely continue as the differential costs between LNG and diesel continues to widen, and as pressure on ports from adjacent population centers push for tighter emissions controls.

LNG as a Marine Fuel

LNG has been used as a marine fuel for decades starting with large carriers fueled from the boil off gases in their storage tanks. Modern LNG carriers carry liquefaction plants for boil off gas that allow them to use more efficient slow speed diesel engines. However, a number of newer LNG carriers on order or in operation today carry large dual fuel generators, affording them the flexibility to use either LNG or diesel.

LNG Ferries

Norway, which has the largest fleet of LNG fueled ships in the world, has been operating a number of ferries since 2000. There are at least 6 car ferries fueled by LNG in operation today, three more to be delivered in 2010, and by 2011 the fleet is expected to be 11 ferries. High national emissions taxes on NO_x and others pollutants have been the primary driver in the adoption of LNG fueled ferries.

Other LNG Vessels

In addition to ferries, there are other vessels that are in operation in Norway today that are primarily or solely fueled by LNG.

- Two platform supply vessels (PSV), delivered in 2003
- Small coastal LNG carrier, combination gas and diesel, delivered in 2004

- Three coast guard vessels operating on a combination of gas and diesel, 2008

LNG Bunkering

Fueling ferries with LNG will require a number of considerations for WSF and an understanding of the similarities and the differences from handling diesel. Since LNG is a liquid it can be pumped through hoses and attached to fueling manifolds on the vessel. Fuel transfers must be handled with care by trained personnel. Spills are avoided through proper design and training, but should a spill occur it must be contained. Fuel can be bunkered directly from tank truck or from a dedicated bunkering station at the dock.

Bunkering by Tank Truck

Bunkering by tank truck is commonplace for LNG vessels in Norway. The PSV's are normally bunkered by truck, since the remote quays are far from liquefaction facilities. Tank trucks today carry about 10,000 gallons per truck so this approach is most practical for smaller loads. Dock space, transportation distance from LNG storage facility, available bunkering time and other issues can make this fueling method logistically challenging if more than a few trucks are required. Figure A1 and A2 in the appendix show the bunkering of a Norwegian PSV.

Bunkering from On Shore Storage Tanks

In some cases, it may be most practical to have a large storage capacity on shore, connected by pipe to a dockside bunker station. This approach allows for a larger quantity of fuel to be transferred in a shorter period of time, making a shorter bunkering cycle more practical. It also relieves the crew from much of the logistical issues of switching tank trucks, or directing traffic.

At least some ferries in Norway are using dedicated dockside bunkering facilities. Typically the LNG tanks are located several hundred yards inland from the dock, allowing them to be filled independently from the ferries normal bunkering schedule. Underground pipes carry the fuel from the shore side tanks to an elevated hose station on the dock, allowing the ferry a convenient means of getting the fuel. A streamlined operation is critical since the bunkering cycles are as short as three days.

Other issues

Since the LNG needs to be maintained at a very low temperature, it is critical that at least some liquid remain in the tanks at all normal operating times. If an LNG tank is fully emptied, for example for maintenance or repair work, the tank will immediately begin to warm to ambient temperature. When the tank is refilled, or filled for the first time, a cooling down period is required which can take several days. This also affects the tank sizing and fuel system design since emptying the tanks completely would be an emergency or a scheduled event only.

Classification and Regulation

Rules for classifying LNG fueled vessels other than LNG carriers are available from Det Norske Veritas (DNV) and Lloyds Register. Other classification societies may be developing rules as well in recognition of the growing marine market. These rules are largely based on well established safe design practices of the International Maritime Organization (IMO) International Gas Carrier (IGC) Code. There are likely to be differences between society rules until unification effort are made by International Association of Classification Societies (IACS) or IMO. Currently American Bureau of Shipping (ABS) does not have rules applicable to LNG fueled passenger vessels. Since DNV has the greatest amount of experience in classing ferries, it would be a good choice for WSF.

Some of the key features of the DNV rules are presented below. DNV has more experience than any other classification society in classifying ferries since they were the first to create these rules and have applied them to a number of vessels and vessel types.

Gas Fuel Storage

Various requirements for LNG storage tanks and gas piping are described in the rules. Placement of LNG tanks below the main deck is essential for the efficient design of a ferry. Class rules allow placement of LNG below the main deck but various safety requirements are imposed that must be considered at the concept level by the designer.

1. **Distance from side shell:** The lesser of 1/5 of the beam or 11m (36 feet)
2. **Distance from bottom shell:** The lesser of 1/15 the beam or 2m (6.6 ft)
3. **Tank type:** Must be independent IMO ‘Type C’ (pressurized) tanks
4. **Liquid only:** Only gas in a liquid state can be stored below the main deck level
5. **Maximum working pressure:** 10 bar (145 psig) working pressure for tanks
6. **Secondary barrier:** Storage tank and associated valves and piping must be located in a space designed to act as a ‘secondary barrier’. Typically this is addressed by a double walled tank design and a ‘tank room’ connected to the outer wall. The ‘tank room’ is integral to the tank and fulfills the ‘secondary barrier’ requirement.

Safety Design Philosophies

Two safety design philosophies are described in the DNV rules. Both are considered acceptable but they are fundamentally different in their approach.

1. **Inherently Safe:** The arrangements in the machinery spaces are such that the spaces are considered ‘gas safe’ under all conditions, normal as well as abnormal. All gas piping is enclosed in ducts or double-walled pipes in the engine room. The annular space is either filled with an inert gas at a higher pressure than the center pipe, or it is ventilated to 30 air changes per hour with gas detection at the outlet.
2. **Emergency Shutdown (ESD):** Spaces with gas piping are considered non-hazardous under normal conditions, but under certain abnormal conditions may have the potential to become gas hazardous. In the event of abnormal conditions involving gas hazards, emergency shutdown of non-safe equipment (ignition sources) and machinery shall occur automatically. Additionally, equipment in use during these conditions shall be of explosion-proof design. Therefore the ESD philosophy requires a second engine room to maintain operations if one engine room should need to be shut down.

The ferries operating in Norway today are designed with the ESD philosophy. This is a fundamentally less conservative approach and may meet with greater resistance from the USCG. It requires inherently safe and/or explosion proof equipment in the engine room, which adds expense, as well as complicating design and arrangements.

The Inherently Safe method completely isolates the fuel from any ignition sources, and therefore does not require normal engine room equipment to be explosion proof or inherently safe. It does

require double piping of the fuel line right up to the engine, however. Engine manufacturers must therefore provide appropriate on-engine connections.

Both approaches have extensive ventilation and gas monitoring requirements.

Independent Fuel Source

Class rules require an independent fuel supply. If LNG is the only propulsion fuel used on board then the fuel system must be divided between two or more tanks of approximately equal size, and the tanks located in separate compartments. The ferries operating in Norway today all operate on gas only, and have multiple independent cryogenic tanks.

This requirement can also be met through the use of Dual Fuel (DF) engines that run on both diesel and natural gas. The DF engine must be capable of switching between fuels reliably without shutting down. If DF engines are used, diesel fuel must be carried, as a minimum to act as a pilot fuel, since DF engines are not spark ignited. The diesel fuel will suffice as a secondary fuel source and therefore a second cryogenic gas storage tank is not required. The PSV's in Norway use DF engines and only carry a single cryogenic tank.

Another way this requirement can be satisfying is by installing both diesel engines and gas engines with the capability to transmit power to the propeller. Obviously a completely independent diesel fuel system must be installed. This approach has been used in several vessels in Norway.

From a design arrangement perspective, fitting the LNG tank(s) is one of the primary challenges and often a starting point of design. Sometimes, it is not possible to fit a sufficient quantity of fuel into a single tank and therefore two or more tanks may ultimately be required anyway.

USCG

Since no LNG fueled passenger or non IGC commercial vessels have yet been built in the United States (other than small retrofit pilot projects), the USCG does not have an established path for review. Therefore early engagement with the USCG to discuss an approach to gaining their approval of an LNG ferry is essential for WSF. Many questions remain not the least of which is finding a reasonable approach to crew training and licensing.

Training and Licensing

No USCG training or licensing requirements are known.

The IMO has interim Guidelines BLG (Bulk Liquids and Gas) 13/6 under development. These guidelines address gas related training in three categories:

- A. Basic training for the basic safety of the crew (8.2.1.1)
- B. Supplementary training for the deck officers (8.2.1.2); and
- C. Supplementary training for the engineering officers (8.2.1.3)

Further information on how this training would be implemented, enforced, or whether USCG would require similar training for domestic passenger vessels is not known.

As with many types of marine equipment, special training can often be provided by the equipment vendor as a condition of sale.

Commercial Marine LNG Prime Movers

Very few options are available for proven marinized LNG prime movers. Additionally, the options will vary depending on the propulsion approach. Rolls Royce and Wartsila both have options for direct drive engines, or propulsion generators either currently on the market or coming to the market soon.

Rolls Royce (Bergen)

Over the last several decades Bergen has invested significant research and development efforts into gas combustion technology with the first commercial gas engine available in 1991. The first marine application was in 2005 and today at least 5 ferries are operating with Bergen gas propulsion generator sets.

Bergen engines are ‘lean burn’ spark ignited (SI) engines. A rich gas-air mixture in a pre-combustion chamber is ignited and forms a strong ignition source for the very lean mixture in the cylinder. In the lean burn engines more air is in the cylinder than is needed for complete combustion. This reduces peak temperatures and therefore lowers NO_x emissions. The electronic control system constantly monitors and optimizes operating parameters to maintain power and emissions across the operating range. The engines produce very low NO_x, even at low load. The Bergen gas offerings are outlined below.

- Gas B Engines:
 - Classed for direct drive and electric drive
 - 720-750 rpm
 - Power range from 6,760 – 9,380 hp
- Gas C Engines:
 - Classed for direct drive and electric drive starting in 2011
 - 900-1000 rpm
 - Power range from 1,960 – 3,260 hp

Wartsila

Wartsila has focused entirely on DF engines for the marine market and has produced and sold hundreds of DF engines for LNG carriers over the last decade. In recent years Wartsila has increasingly focused on the smaller power ranges and also on offering the DF engines for direct drive.

The Wartsila DF engine can operate normally on either diesel fuel or natural gas. When operating on gas the engine uses a small amount of diesel (~1%) as a pilot fuel to initiate combustion. The Wartsila DF engine, like the Bergen gas, operates on the ‘lean burn’ principle for low NO_x operation. Therefore the emissions performance, while not as clean as pure gas, is excellent and offers the added advantage of switching to diesel on the fly if desired. Therefore the ‘range anxiety’ that could be associated with pure gas for certain applications is eliminated. The DF engines are electronically governed, and offer a high efficiency. The Wartsila DF offerings are outlined below:

- 20DF
 - Classed for electric drive.

- Direct drive coming soon
- Power range from 1,400-2,100 hp
- 34DF
 - Classed for electric drive
 - Power range from 3,500 – 9,300 hp
- 50DF
 - Classed for direct drive and electric drive
 - Power range from 7,640-23,000 hp

Pure Gas vs. DF

Pure gas engines offer superior emissions performance and response time to DF engines. Classification rules require vessels operating with gas fuel alone to carry two independent gas tanks and fuel systems to maintain redundancy. The use of DF engines avoids the use of redundant cryogenic tanks, but DF engines require the use of diesel fuel for normal operation so a secondary fuel system must be installed regardless.

For a WSF ferry, DF is not necessarily an obvious advantage since proximity to LNG supply in Puget Sound is not an issue. Also, fitting a single large LNG tank into a ferry may not be possible, and the designer may therefore be driven to a dual tank arrangement anyway. At present neither Wartsila nor Rolls Royce have direct drive options in the power ranges of WSF vessels although both companies claim they are coming in the next several years.

Other Manufacturers

For the LNG carrier market MAN has been developing DF technology but commercial offerings are not advertised. Many diesel engine manufacturers have gas engine offerings but are not pursuing the marine propulsion market, since it is presently so small. Therefore marinized offerings are very limited at this time.

Application to Washington State Ferries

Adding an LNG vessel to the WSF fleet offers potential emissions as well as operational cost benefits. The two possibilities are to construct a new vessel or to convert an existing vessel within the fleet.

Conversion of an existing ferry to LNG technology is possible, however would likely not be cost effective. Issues for consideration of converting an existing vessel are listed below:

- Identification of the appropriate vessel
 - Vessel needs to be of an appropriate size to allow practical storage of below deck LNG tanks.
 - Operational profile (power level, run time, etc) need to be considered to appropriately size the tanks.
 - Vessel needs to have an appropriate life expectancy to justify an investment in an LNG conversion.

- Getting an existing vessel classed may present significant challenges (current vessels are USCG inspected only but USCG may well require that the vessel be classed by an experienced society such as DNV to mitigate risk).
- Installing large LNG tanks below the main deck is likely to be a technical challenge, and very costly within an existing superstructure.
- Removal of a significant amount of under deck machinery and equipment will be required as well as redesign of under deck engineering spaces.
- Superstructure will require modifications for gas venting and ventilation arrangements.

Adapting the 144 vehicle design for LNG

New construction of an LNG vessel for WSF is more straightforward than converting an existing vessel since locating the tanks, engines, ventilation, and fueling system can be done before construction. However since WSF already has an existing design for a 144 vehicle ferry, the most economical way to bring a new LNG fueled vessel into the fleet would be to adapt the existing design if possible. Classing the design with DNV or Lloyds is an issue that must be considered at the concept level. The following section considers adapting the newly designed 144 vehicle ferry to LNG fuel.

For simplicity the following assumption have been made:

- The propulsion system will operate on pure LNG (not Dual Fuel)
- Engines: 2 – Bergen C9PG Gas propulsion engines, 3200 bhp each
- 2 LNG storage tanks
- All other associated gas auxiliary equipment and piping are assumed to fit within the space available for diesel equipment and do not require special consideration.
- Annual consumption of diesel fuel based on *Issaquah* class vessel.
- Minimum 1 week LNG bunkering cycle.

LNG Tank Sizing

The size of the required LNG tanks is governed by the fuel consumption. For simplicity the fuel consumption is assumed to be roughly equivalent to the *Issaquah* class, or 800,000 gallons per year. This translates to a weekly diesel consumption rate of approximately 15,000 gallons and an LNG volume of 28,000 gallons (on an energy equivalent basis). Therefore with margin, the minimum LNG volume is approximately 30,000 gallons.

Arrangements

The molded beam of the 144 vehicle ferry design at the waterline is approximately 74 feet. This restricts the tank location to approximately 15 feet from the side shell and 5 feet from the bottom shell. With a few iterations it was determined that the LNG volume could be fit into the hull with two tanks, arranged amidships just below the engineering spaces (Figures A3 – A5 in Appendix). The engineering spaces will need to be rearranged but the basic hull form will not have to change. The medium speed engines are assumed to be similar in size to the engines currently specified and therefore engine arrangements were not considered further.

Auxiliary Power

Providing auxiliary power to the ferry requires special consideration. The peak auxiliary power requirements for the 144 vehicle design are approximately 350kW, provided by a primary and standby diesel generator set. Currently there are no gas generator sets available on the market, in this size range that are designed for inherently safe installation (double walled piping to the engine). Therefore, the most straightforward solution to this is to assume diesel generator sets would be installed.

However, there are several disadvantages to installing diesel generator sets on a vessel designed for pure LNG. First is that it requires that the vessel have a complete diesel system installed on board (storage tanks, bunker lines, fuel delivery lines, pumps, filters, etc). Installing and maintaining the diesel fuel system is a tangible cost to WSF. Second, the diesel generator sets will negatively offset the emissions reductions that are a primary goal of installing LNG in the first place. If the generator sets were Tier 4, the emissions would be very low, but meeting Tier 4 will require after treatment technology. This means additional expenses incurred for urea, and systems for urea storage and delivery.

One possible solution is to equip the propulsion engines with power take off (PTO) capability so that the main engines also provide auxiliary power. Standard PTO solutions require the main engines to operate at synchronous speeds to provide power to the alternator but the 144 vehicle ferry is intended for variable speed operation. However it is technically feasible to install PTO alternators that can take variable speed input and produce 60 Hz power output through the use of solid state frequency converters. Although the technical issues of this approach are outside the scope of this discussion, it would allow the vessel to operate with lower emissions and fewer subsystems to install and maintain.

Emissions

Actual emissions reductions will depend on the operational load profile. Combustion engines typically produce fewer emissions when operating closest to their best efficiency. However, in general the emissions reductions from a Tier 2 diesel *propulsion* engine to a pure LNG *propulsion* engine are predicted below:

- NO_x – At least 90% reduction
- PM – Approximately 100% reduction
- SO_x – Approximately 100% reduction
- CO₂ – Approximately 20% reduction

Hydrocarbon (HC) emissions from diesel engines are caused primarily by unburned fuel that passes into the exhaust. *Non-methane* HC emissions are regulated by the EPA as an air pollutant but *methane* emissions are not. Since LNG is nearly pure methane, a small percentage of unburned methane passes up the exhaust which is known as ‘methane slip’. Methane is a greenhouse gas and its release into the atmosphere should be minimized since it has the potential to offset the lower CO₂ benefits of LNG propulsion. Engine manufacturers are aware of the methane slip and are continually working to decrease this since it directly impacts fuel efficiency.

Capital Costs

Adapting the 144 vehicle ferry design for LNG would require a number of additional expenses above the base design:

- Acquisition of Gas Equipment (2 gas engines, 2 LNG tanks, gas piping, gas monitoring equipment, ventilation, etc)
- Design effort to adapt 144 vehicle ferry to LNG propulsion
- Classification of adapted 144 vehicle design by DNV, Lloyds or other
- Regulatory interface effort with USCG
- Installation of gas equipment at shipyard

However, since the diesel engines and fuel system would not be required the cost for these would need to be subtracted from the total. A brief cost summary is below.

Item	Cost (USD)	Source
2 Bergen C9PG, 2 x 15,000 gal LNG tanks, Gas Control System	\$8.3M	Rolls Royce Estimate
Installation (gas engine, tanks, piping ventilation etc)	\$3M	Estimated
Adapt 144 Vehicle Design to LNG	\$1M	Estimated
Regulatory (USCG, DNV)	\$1M	Estimated
2 Diesel Engines	-\$2M	WSF Provided Estimate
Diesel propulsion fuel system	-\$3M	WSF Provided Estimate
Estimated LNG Installation Premium	8.3M	

Table 1. Differential costs for adapting the 144 vehicle ferry for LNG propulsion

Operational costs

Fueling with LNG can significantly offset operational costs due to the much lower cost of LNG fuel compared with diesel. WSF currently fuels ferries with Ultra Low Sulfur Diesel and on some vessels biodiesel. The fuel consumption estimates are 800,000 gallons of diesel per year based on the *Issaquah*. To supply an equivalent quantity of energy, a volume of 1,360,000 gallons of LNG is required. However, LNG is much less expensive than diesel even after transportation and liquefaction costs are included. The estimated yearly fuel cost savings are summarized in **Table 2**.

	Gal/yr	Cost/gal	USD/yr	Source
Issaquah Fuel Consumption	800,000	\$2.50	\$2,000,000	WSF provided cost per gallon
LNG Fuel Consumption	1,360,000	\$0.83	\$1,128,800	Vendor estimated cost per gallon
Savings per year			\$871,200	

Table 2. Fuel cost savings for adapting the 144 vehicle ferry for LNG propulsion

While the estimated savings in **Table 2** are significant, the savings could be even greater if the vessel is built to Tier 4 requirements. If the vessel were Tier 4, which it will be if built after 2014, there may well be a cost incurred by the purchase of urea for use in an SCR system. Urea consumption is typically about 5-10% of the diesel volume. Even at 5% this would add a cost of \$120,000 per year at today's urea price of \$800/ton.

Operational costs for maintenance of LNG engines are reportedly lower than diesel engines, according to the engine vendor. Since the fuel is cleaner, all equipment runs cleaner. However, a significant amount of control and monitoring equipment is required for an LNG vessel above what would be expected for a conventional diesel which could offset some of the savings.

APPENDIX



Figure A1, Quayside LNG bunkering with tank truck



Figure A2. Close up of quayside LNG bunkering

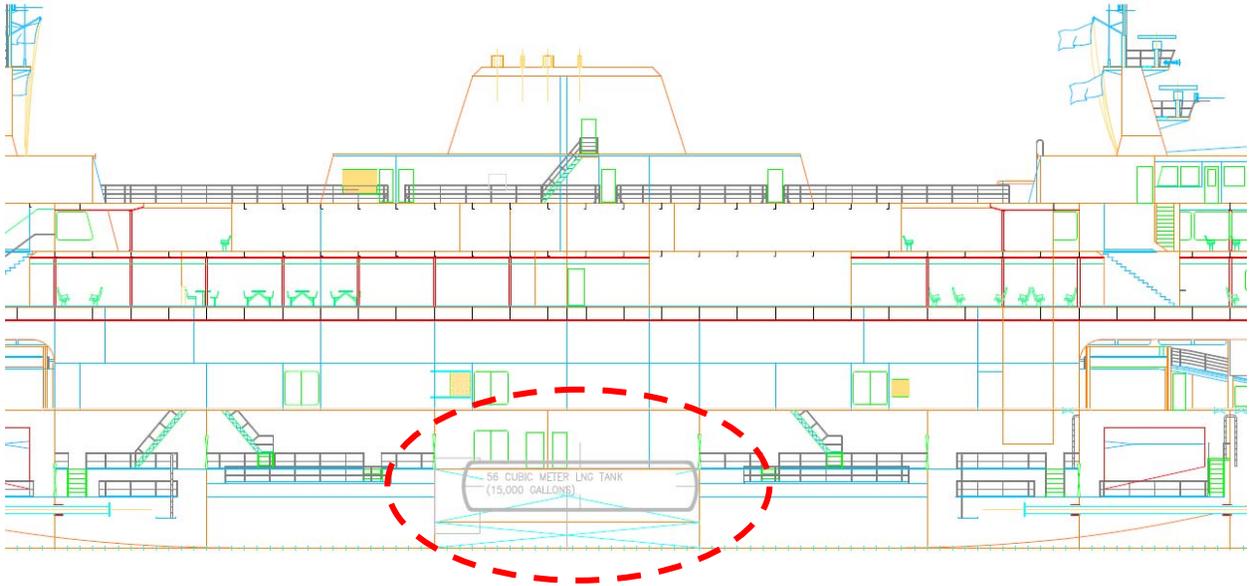


Figure A3. 15,000 gallon LNG tank below EOS

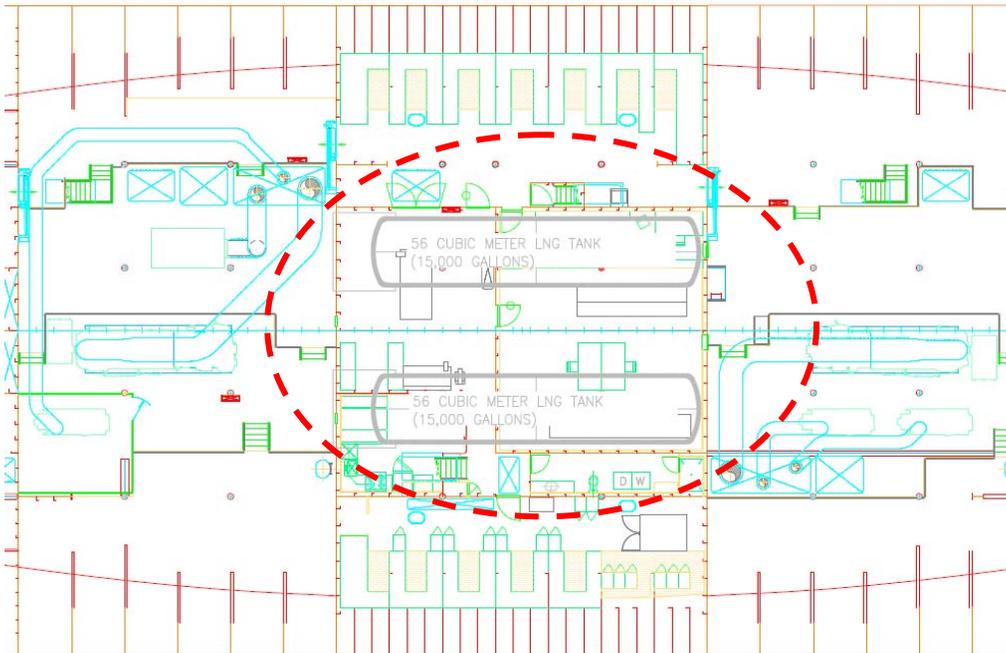


Figure A4. Two 15,000 gallon LNG tank below EOS

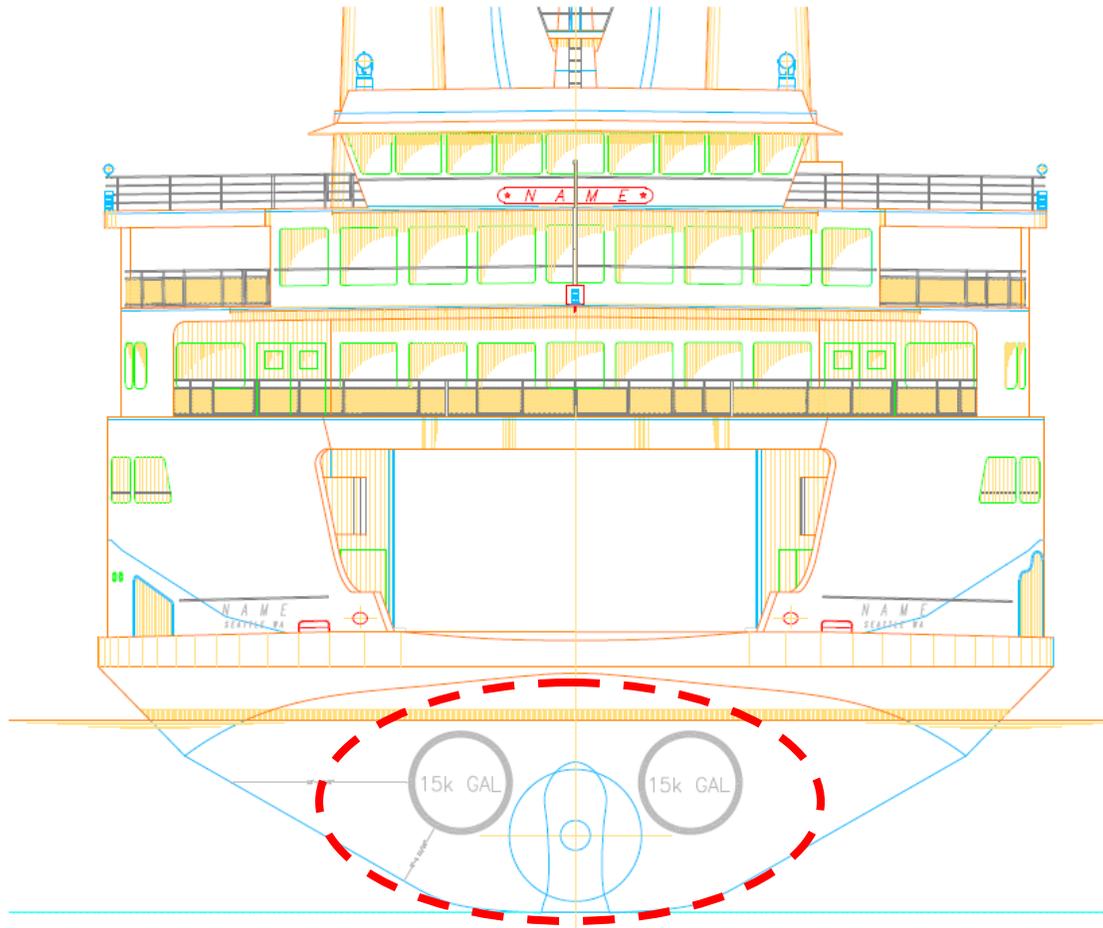


Figure A5. LNG Tanks below EOS with minimum offsets from shell