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

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Disclaimer

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.
Outline

• Vessels under consideration
• Emission Control Area (ECA) emissions
• Reasons to consider conversion to LNG
• Challenges in using LNG fuel
• Predicted future natural gas production and price
• Conceptual design for AAA LNG conversions
  – Engine availability
  – Fuel use and tank sizing
  – Arrangement feasibility
  – Thoughts about conversion
• Conclusions and future plans
U.S. Flag Great Lakes Steam Bulk Carriers

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

* AAA class

Ten remaining U.S. Flag steam bulk carriers

Three, the AAA Class, are to the same design – initial focus
Emission Control Area (ECA)

- Now in place for the Baltic Sea and North Sea
- Requested by U.S., Canada, and France
- Approved by IMO – enforceable beginning August 2012
- ECA will include non-Arctic coastal and inland waters of the U.S. and Canada
- Lower marine fuel sulfur and NOx requirements
MARPOL (EPA) Marine Fuel Sulfur Limits

Alternative: use exhaust gas scrubbers (NaOH, weight, space, labor, cost)
1% S differential for IF now about $30-50/t in Rotterdam
MARPOL (EPA) ECA NOx Emissions Limits

Diesels will require Selective Catalytic Conversion (SCR) for Tier III with aqueous urea, weight, space, labor, cost penalty

Conversions and new construction

80% Reduction
Status of Emission Control Area (ECA) Air Emissions Requirements

Status

• Fuels must be available
• Congressionally mandated steamship exemption
• EPA offer for streamlined conversion to diesel, but S waiver only to 2026

Premise for study:

Not coming up to EPA ECA emissions standards is not socially and politically sustainable in the long run
Reasons to Consider LNG Conversions

• LNG cargo carriers use cargo burn-off for fuel (steam, then diesel) approaching 200 vessels; over 40 years experience (classification by ABS, DNV, others)

• Beginning in 2000 with the ferry Glutra, non-LNG cargo & C.G. vessels in Norway (DNV) – approaching 25

• Recent conversion of a 5 year old 25,000 DWT product tanker Bit Viking from HFO to LNG in a two month conversion (DNV)

• Harvey Gulf International contracted for 4 LNG powered offshore supply vessels (ABS, U.S. Coast Guard)
Advantages: Improved Fuel Efficiency

- Steam plants (7000 normal shp, 450-470 psig/750 deg. F steam, 1 ½” Hg vacuum, 3 stages of feed heating)
  \[ \eta_{th} \times \eta_B = 0.30 \times 0.865 = 0.26 \]
- Current diesel or gas internal combustion engines
  \[ \eta_{th} \times \eta_M = 0.46 - 0.48 \]
- Conversion is almost 85% better on thermal efficiency
### Improved Specific Air Emissions

<table>
<thead>
<tr>
<th>EPA fuel</th>
<th>steam turbine</th>
<th>diesel engine</th>
<th>diesel engine</th>
<th>gas engine</th>
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<tbody>
<tr>
<td>Bunker C</td>
<td>Cat 3, Tier 2</td>
<td>MDO</td>
<td>MDO</td>
<td>LNG</td>
</tr>
<tr>
<td>2% S</td>
<td>1.0% S</td>
<td>0.1% S</td>
<td>0.0% S</td>
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</tr>
<tr>
<td>SOx [g/kWh]</td>
<td>11.90</td>
<td>4.11</td>
<td>0.41</td>
<td>0.00</td>
</tr>
<tr>
<td>PM [g/kWh]</td>
<td>1.16</td>
<td>0.58</td>
<td>0.28</td>
<td>0.00</td>
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<tr>
<td>NOx [g/kWh]</td>
<td>low</td>
<td>9.5-10.5</td>
<td>2.3-2.6</td>
<td>2.00</td>
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<tr>
<td>CO2 [g/kWh]</td>
<td>580-630</td>
<td>580-630</td>
<td>580-630</td>
<td>430-480</td>
</tr>
<tr>
<td>CO [g/kWh]</td>
<td>0.20</td>
<td>1.10</td>
<td>1.10</td>
<td>n.a.</td>
</tr>
</tbody>
</table>

Sources: Harkins 2007, Boylston 2011, EPA 500-900 RPM for NOx

Tier 3 diesel NOx assumes SCR addition
Reduced Fuel Cost

- Recent Washington State ferries tradeoff of LNG or Ultra Low Sulfur Diesel (ULSD = 15 ppm S highway diesel with biofuel % but no state tax)

\[ \begin{align*}
\text{Comparison} & \quad \text{ULSD} & \quad $4.10/\text{gallon} \quad \text{versus} \\
\text{energy equivalent} & \quad \text{LNG} & \quad $2.12/\text{gallon} \quad \text{in 2014} \\
\text{Houston (1/26/12)} & \quad \text{IF380} & \quad $2.41/\text{gal.} \quad \text{-} \quad \text{LNG equiv.} \quad $2.31/\text{gal.} \\
& \quad \text{MDO} & \quad $3.08/\text{gal.} \quad \text{-} \quad \text{LNG equiv.} \quad $2.12/\text{gal.}
\end{align*} \]
Reduced Manning

- Norwegian experience: manning same for diesel and LNG
- Requires central engine control room rated for unmanned engine room, ACCU
- Conversion could save one licensed and three unlicensed
- Save about $600,000 to $700,000 per year
Challenges in Using LNG Fuel

- Fuel availability
- Volume for fuel storage
- Protecting hull structure from spills
- Increased capital and maintenance cost
- Training and increased safety culture
- Methane slip
The Availability Question

- Ship owners: “show me the gas station”
- Suppliers: “show me a long-term fuel contract and we can build a liquefaction plant”

Or could this actually become a “Field of Dreams” question?
### Aggregate Demand with Conversions

<table>
<thead>
<tr>
<th>Name</th>
<th>Normal steam power (shp/kW)</th>
<th>Annual requirement (gallons)</th>
<th>2014 Operating Season</th>
<th>2015 Operating Season</th>
<th>2016 Operating Season</th>
<th>2017 Operating Season</th>
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<tbody>
<tr>
<td>Edward L. Ryerson</td>
<td>9000/6711</td>
<td>3,941,000</td>
<td></td>
<td></td>
<td></td>
<td>3,941,000</td>
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<tr>
<td>American Victory</td>
<td>7000/5220</td>
<td>3,065,000</td>
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<td></td>
<td></td>
<td>3,065,000</td>
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<tr>
<td>American Valor</td>
<td>7000/5220</td>
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<td></td>
<td></td>
<td>2,043,000</td>
<td>3,065,000</td>
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<td>John G. Munson</td>
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<td></td>
<td></td>
<td></td>
<td>2,043,000</td>
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<tr>
<td>Arthur M. Anderson</td>
<td>7000/5220</td>
<td>3,065,000</td>
<td></td>
<td></td>
<td></td>
<td>3,065,000</td>
</tr>
<tr>
<td>Cason J. Callaway</td>
<td>7000/5220</td>
<td>3,065,000</td>
<td>3,065,000</td>
<td>3,065,000</td>
<td>3,065,000</td>
<td>3,065,000</td>
</tr>
<tr>
<td>Philip R. Clarke</td>
<td>7000/5220</td>
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<td></td>
<td></td>
<td></td>
<td>3,065,000</td>
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<tr>
<td>Herbert C. Jackson</td>
<td>6000/4474</td>
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<td>2,627,000</td>
<td>2,627,000</td>
<td>2,627,000</td>
<td>2,627,000</td>
</tr>
<tr>
<td>American Fortitude</td>
<td>7000/5220</td>
<td>3,065,000</td>
<td></td>
<td></td>
<td></td>
<td>3,065,000</td>
</tr>
<tr>
<td>Wilfred Sykes</td>
<td>7000/5220</td>
<td>3,065,000</td>
<td></td>
<td></td>
<td></td>
<td>3,065,000</td>
</tr>
<tr>
<td>total fleet requirement</td>
<td>gallons/yr</td>
<td>31,088,000</td>
<td>3,065,000</td>
<td>10,800,000</td>
<td>19,995,000</td>
<td>30,066,000</td>
</tr>
<tr>
<td></td>
<td>tonnes/yr</td>
<td>53,657</td>
<td>5,290</td>
<td>18,640</td>
<td>34,511</td>
<td>51,893</td>
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<tr>
<td></td>
<td>ave. t/day</td>
<td>179</td>
<td>18</td>
<td>62</td>
<td>115</td>
<td>173</td>
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<tr>
<td></td>
<td>ave. visits/day</td>
<td>1.77</td>
<td>0.18</td>
<td>0.71</td>
<td>1.24</td>
<td>1.77</td>
</tr>
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<td></td>
<td>ave. t/visit</td>
<td>128</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>128</td>
</tr>
</tbody>
</table>

**Assumptions:**

- **PHASE I** – design, regulatory, planning, long lead equipment
- One lead ship in lead yard first winter
- Then two phased in lead yard, one in follow yard
Volume for Fuel Storage

- Energy equivalence requires:
  ~2.0 x as much LNG as IF    ~1.7 x compared to MDO

- Storage is a -162 deg. C at up to 10 barg (145 psig)
- Storage is in cylindrical double-walled insulated tanks
- Cold requires tanks to be independent of ship structure

- Net effect:

  LNG storage requires 3-4 x the ship volume as
  IF/MDO tanks integrated into the ship structure above the IB
Protecting the Hull Structure

- Ship structure nil ductility temperatures well above -162°C
- LNG spills on ship structure can cause brittle cracking
- Tanks and piping must use cryogenic materials; e.g. 304L stainless steel
- Tanks and piping must be thermally isolated
- Potential spill locations must have stainless steel drip trays
Training and Increased Safety Culture

- LNG cargo carrier safety requires greater training and formalization of safety procedures
- Some concern expressed that broader use in marine industry will require a more focused safety culture
- Norwegian Fjord1 has 2-5 days extra training and about 1 week extra training onboard ferries
- Experienced training companies available in the U.S.
Increased Capital and Maintenance Cost

- Norwegian *Bergensfjord* ferry experience:
  - Capital cost 15-20% greater than diesel
  - Maintenance cost 10% greater than diesel
  - Engine rebuild intervals expected to be longer

- Washington State 144 car ferry study
  - Diesel option: $2.5M for machinery
  - Duel-fuel LNG option: $9.3M for machinery
  - Single-fuel LNG option: $10.7M for machinery
  - But single-fuel LNG option 30 year life-cycle (3% discount)
    - $29.9M cheaper than diesel option (on ULSD)
    - $9.3M cheaper than duel-fuel LNG option
Methane Slip

• Methane is currently an unregulated Green House Gas

• Methane is 21x more damaging to the atmosphere than CO₂

• A small fraction is not burned in gas engines – slip

• It can easily cancel the 20-25% reduced CO₂ of LNG

• Losses in bunkering, etc. would also contribute

• U.S. may eventually have a carbon tax like in Europe
Projections of LNG Production and Price

- North America has a regional LNG market
- Henry Hub is a location in the Sabine Pipeline near Erath, LA
- Henry Hub spot price is basis for trading and pricing LNG in N.A.
- Prices have been relatively less affected by international issues

from: DOE EIA
“Annual Energy Outlook 2011 with Projections to 2035”
Effect of Shale Gas Development

from: DOE EIA “Annual Energy Outlook 2011 with Projections to 2035”
LNG Fuel Price Projections

- Norwegian value chain
  - pipeline cost 50-60%
  - liquefaction 25-20%
  - distribution 25-20%

- Washington State ferries study
  - Henry Hub ± $0.50/gal.
  - liquefaction $0.43/gal.
  - trucking $0.31/gal.

- Appears to be little basis for linking LNG price to diesel or oil in North America

Ratio of Low Sulfur Crude Oil to price to Henry Hub natural gas price

from: DOE EIA
“Annual Energy Outlook 2011 with Projections to 2035”
AAA Conceptual Design

- Same delivered power
- Same range, if feasible
- All LNG, if feasible
- ABS/DNV require LNG tanks near centerline
  - min(B/5 or 11.5 m) from side
  - min(B/15 or 2 m) from bottom
- Room for two 17.5 ft OD x 54 ft tall tanks P/S
Requirements Exist but Not Official Yet in U.S.


from January 2009
## Candidate Gas Engines

<table>
<thead>
<tr>
<th>Vendor</th>
<th>Rolls-Royce Bergen</th>
<th>Wärtsilä</th>
<th>MaK (in 2014)</th>
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<tbody>
<tr>
<td>Engine</td>
<td>B35:40V12PG lean burn</td>
<td>12V34DF diesel pilot</td>
<td>6M46C DF diesel pilot</td>
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<tr>
<td>Operating principle</td>
<td>spark ignition</td>
<td>dual fuel</td>
<td>dual fuel</td>
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<tr>
<td>Cylinders</td>
<td>12</td>
<td>12</td>
<td>6</td>
</tr>
<tr>
<td>Bore (mm)</td>
<td>350</td>
<td>340</td>
<td>460</td>
</tr>
<tr>
<td>Stroke (mm)</td>
<td>400</td>
<td>400</td>
<td>600</td>
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<td>EPA Category</td>
<td>C3</td>
<td>C3</td>
<td>C3</td>
</tr>
<tr>
<td>RPM</td>
<td>750</td>
<td>750</td>
<td>514</td>
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<tr>
<td>MCR (kW)</td>
<td>5250</td>
<td>5400</td>
<td>5400</td>
</tr>
<tr>
<td>MCR (hp)</td>
<td>7040</td>
<td>7242</td>
<td>7242</td>
</tr>
<tr>
<td>Gas heat rate (kJ/kWh)</td>
<td>7475</td>
<td>7700</td>
<td>7200</td>
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<tr>
<td>Diesel pilot sfc (g/kWh)</td>
<td>none</td>
<td>1.8</td>
<td>2.0</td>
</tr>
</tbody>
</table>

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

- Two P/S 250 cubic m useable volume LNG tanks
- Single fuel gas main engine
  Rolls-Royce Bergen B35:4012VG engine (5250 kW)
- CRP propeller driven through single reduction gear
- Three gas generator sets – under development
  Cat G3516 60 Hz 770 kWe @ 1200 rpm (available in 2014?)
- Two new gas auxiliary boilers
- Stern thruster electric; bow thruster local diesel or electric
## Assumed Round Trip Voyage Duluth to Gary

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

### LNG Use in One Summer Round Trip

<table>
<thead>
<tr>
<th>mode</th>
<th>hours</th>
<th>prop. kW</th>
<th>% load</th>
<th>kJ/kWh</th>
<th>LNG cubic m</th>
<th>ship service</th>
<th>ballast pumps</th>
<th>stern thruster</th>
<th>unload. conv.</th>
<th>total kW</th>
<th>% e load</th>
<th>kJ/kWh</th>
<th>LNGe cubic m</th>
<th>total kW</th>
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<tbody>
<tr>
<td>open lake</td>
<td>103</td>
<td>4572.2</td>
<td>87%</td>
<td>7550</td>
<td>172.1</td>
<td>476.4</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>476.4</td>
<td>61.9%</td>
<td>8800</td>
<td>20.9</td>
<td>5068.5</td>
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<tr>
<td>reduced speed</td>
<td>8</td>
<td>2700.0</td>
<td>50%</td>
<td>7600</td>
<td>7.9</td>
<td>476.4</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>476.4</td>
<td>61.9%</td>
<td>8800</td>
<td>1.6</td>
<td>3196.3</td>
</tr>
<tr>
<td>maneuvering</td>
<td>6</td>
<td>1620.0</td>
<td>30%</td>
<td>7750</td>
<td>3.6</td>
<td>476.4</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>476.4</td>
<td>61.9%</td>
<td>8800</td>
<td>1.2</td>
<td>2116.3</td>
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<td>locking/docking</td>
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<td>540.0</td>
<td>10%</td>
<td>8280</td>
<td>0.4</td>
<td>519.8</td>
<td>0.0</td>
<td>745.7</td>
<td>0.0</td>
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<td>82.2%</td>
<td>8550</td>
<td>1.0</td>
<td>1858.2</td>
</tr>
<tr>
<td>loading</td>
<td>6</td>
<td>0.0</td>
<td>0%</td>
<td>0</td>
<td>0.0</td>
<td>392.5</td>
<td>226.0</td>
<td>0.0</td>
<td>0.0</td>
<td>618.5</td>
<td>80.3%</td>
<td>8600</td>
<td>1.5</td>
<td>644.3</td>
</tr>
<tr>
<td>unloading</td>
<td>10</td>
<td>0.0</td>
<td>0%</td>
<td>0</td>
<td>0.0</td>
<td>488.9</td>
<td>226.0</td>
<td>0.0</td>
<td>1107.2</td>
<td>1822.1</td>
<td>78.9%</td>
<td>8650</td>
<td>7.6</td>
<td>1928.0</td>
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<tr>
<td>total</td>
<td>135</td>
<td>hours</td>
<td>184.1</td>
<td>cubic m</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
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<td></td>
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</tr>
<tr>
<td></td>
<td>5.625</td>
<td>days</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

**Tank margins:**
- head space: 10%
- cooling margin: 5%

Operational fuel margin with two 250 cubic m useable volume tanks:
- 12.4% when refueling every second round trip
- 45.5% when refueling once per week
AAA Conversion Inboard Profile
AAA Conversion Spar Deck

Spar Deck

15 feet
AAA Conversion Operating Deck
AAA Conversion Tank Top

Engine Room Tank Top

Gas Auxiliary Boilers

Ballast Pump

Ballast P/S

Conveyor

Tunnel

Manifold

Void

B35:40V12G

15 feet
Conversion Thoughts

• No regulations at this time – case-by-case equivalency
• More regulatory overhead – recommend a Phase I
• Two vertical accesses – 100 tonne lifts for tanks
• Mechanical conversion ~ same as a diesel conversion
• Pre-outfitted control room – ballast control panel?
• Important to load tanks with cold boxes – FR183-FR193
• Gas generator set availability problematic for first few
Conclusions and Plans

Conclusions

• The availability of LNG at an appropriate price will be critical to the economic viability of conversion to LNG fuel rather than conversion to diesel.

• The other challenges appear to be workable.

• The arrangement of the AAA LNG conversions to ABS/DNV requirements appears feasible.

Next tasks for AAA class

• Weight study
• Stability study
• Ventilation
• Refine arrangements
• Air emissions comparison: steam, diesel, LNG
• Notional shipyard planning/cost
• Life-cycle cost/payback

Feasibility for other vessels
Acknowledgements

GLMRI study funded through a grant funded by the U. S. Department of Transportation Office of the Secretary and the Maritime Administration (Grant #DTMA1H11002).
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Thank you.

Questions?