Clean Marine Fuels

Emission Control Using Dimethyl Ether in Marine Applications

AUTHORS: Antonio Anselmo & Jeremiah Sullivan

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Forward Comments to: Antonio Anselmo, President

ChemBioPower Ltd.— 11825-145 St., Edmonton, AB, T5R 0H2

T: 914-729-6306 **DD:** 780-454-7070 **E:** antonio.anselmo@chembiopower.com

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About ChemBioPower Ltd.

Antonio Anselmo, an energy expert, founded the company with Mr. Stanton Hooper, a construction executive in 2013. The company has a strong, long-term view on optimal energy use, producing the best fuel and additives for transportation and heating using a very efficient process. ChemBioPower has developed a "better way" to maximize fuel and power production from North America's abundant natural gas reserves. The ChemBioPower process is also environmentally friendly, with a very low carbon footprint.

Combining "off the shelf" technology and proprietary patent pending system designs, ChemBioPower will deploy a network of modular polygeneration plants that will convert natural gas into both electric power and a clean transportation fuel, dimethyl ether ("DME"). In addition, the company's polygeneration plants will possess the additional capability of producing dimethyl carbonate ("DMC"). DMC is a chemical reagent that serves as the backbone of the growing field of green chemistry and is an excellent octane enhancer.

Introduction

Ocean going vessels generate significant pollution. These emissions not only affect populations living near ports and coastlines, but also those living hundreds of miles inland. Studies by the US Environmental Pollution Administration (EPA) shows the impact of maritime engine emissions reaching deep into the continent from all coastal regions.

Marine diesel engines generate large quantities of NOx, fine particulate matter (PM2.5), ozone (O3) and sulfur oxides (SOx) that fail to meet the EPA Air Quality Standards. Emissions from marine propulsion cause harm to both animal and human populations near these ecologically fragile zones.

Maritime engines also emit hydrocarbons (HC), carbon monoxide (CO) and other hazardous air pollutants that are associated with adverse health effects. Moreover, carbon dioxide (CO2) emissions are higher per power output since older engines are inefficient and use very long chain hydrocarbons (bunker fuel). The International Maritime Organization (IMO) estimates that CO2 emissions from shipping were equal to 3.3% of the global human-made emissions in 2007 and expects them to rise by as much as 72 percent by 2020 if no action is taken.

Large marine diesel engines are significant contributors to our national mobile source emission inventory and their contribution is expected to grow in the future. At the current rate, NOx emissions from ships are projected to more than double to 2.1 million tons a year while annual PM2.5 emissions are expected to almost triple to 170,000 tons a year by 2030.

Maritime Pollution Legislation

On August 1, 2012, the North American Emissions Control Area (NAECA) took effect, mandating the use of 1.0% sulfur Heavy Fuel Oil (HFO) or residual fuel oil for ships within 200 miles of the continent of North America. The Emissions Control Areas (ECA) is mandated under the MARPOL agreement. The MARPOL addresses all forms of marine pollution under 6 annexes. Annex VI entered into force 19 May 2005 with the objective to reduce air pollution from ships.

In general, Annex VI applies to all ships 400 GT and above and to all fixed and floating drilling rigs and other platforms. Annex VI contains a set of requirements for survey and issuance of International Air Pollution Prevention Certificate (IAPP) and regulations regarding:

- Ozone depleting substances from refrigerating plants and fire fighting equipment
- Nitrogen Oxides (NOx) from diesel engines
- Sulfur Oxides (SOx) from diesel engines
- Volatile Organic Compound Emissions from cargo tanks of oil tankers
- Shipboard Incineration
- Fuel oil quality

Annex VI of the MARPOL treaty is the main international treaty addressing air pollution prevention requirements from ships. It was implemented in the United States through the Act to Prevent Pollution from Ships, 33 U.S.C. §§ 1901-1905 (APPS). Annex VI requirements comprise both engine-based and fuel-based standards, and apply to U.S. flagged ships wherever located and to non-U.S. flagged ships operating in U.S. waters. Annex VI establishes:

- Limits on NOx emissions from marine diesel engines with a power output of more than 130 kW (175 H.P.). The standards apply to both main propulsion and auxiliary engines and requires the engines to be operated in conformance with the Annex VI NOx emission limits.
- Limits on the sulfur content of marine fuels.

MARPOL VI requires a study to be completed by 2018, to determine the availability of fuel oil to meet the global 0.5% sulfur limit specified. The Committee tasked a correspondence group to determine the global availability of 0.5% sulfur fuel oil, which should be submitted to MEPC 68 in 2015 and should address:

- Any new ECA's that may be established;
- Projected global economic activity;
- Use of alternative fuels (such as biofuels, DME and LNG);

- Availability of abatement technologies; and
- Actual and planned refinery capacities

All ships operating up to 200 nautical miles off of U.S. and Canadian shores must meet the most advanced standards for NOx emissions and use fuel with lower sulfur content., This geographic area is designated under Annex VI as the ECA.

For example, regulated diesel engines in U.S. flagged vessels must have an Engine International Air Pollution Prevention (EIAPP) certificate, issued by EPA, to document that the engine meets Annex VI NOx standards. Certain vessels are also required to have an International Air Pollution Prevention Certificate (IAPP), which is issued by the United States Coast Guard (USCG). Ship operators must also maintain records on board regarding their compliance with the emission standards, fuels requirements and other provisions of Annex VI.

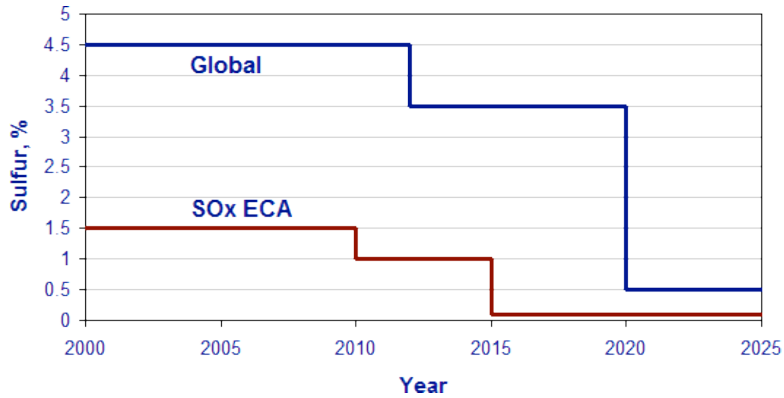

Figure 1: Sulfur Limits for North American Coastal Waters (200 mile)

All U.S. flagged vessels are subject to inspection for compliance with Annex VI. Non-U.S. flagged ships are subject to examination under Port State Control while operating in U.S. waters. The USCG or EPA may bring an enforcement action for a violation.

	Regulation	*Start date*	*Max. NOx*	*Max. PM10*	*Max. Sulfur*
Inland shipping	CCR phase 4	1-1-2016	1.5 g/kWh	0.02 g/kWh	0.001%
Coastal shipping	SECA phase 3	1-1-2015	N/A	N/A	0.10 %
Shipping	IMO phase 3	1-1-2020	N/A	N/A	0.50 %

Table 1: European Emission Regulations

Marine Hybrid Drive

Hybrid marine propulsion system provides fuel savings of up to 25% and corresponding emissions reductions. A hybrid propulsion system consists of:

- A diesel engine
- An electrical generators
- A electrical storage device
- A control system and
- An electric motor that independently or simultaneously drive a propulsion shaft.

Suppliers offer both series and parallel hybrid systems for the commercial and pleasure boat market, making economic electric propulsion available to boatyards around the world.

- A **parallel hybrid** allows the propeller shaft to be driven by both the conventional engine and the electric motor. In a parallel hybrid, when the diesel engine generates shaft power, the electric motor acts as a shaft-driven generator providing power to meet the vessels hotel loads. Auxiliary generators and optional electrical storage provide power for propulsion through the electric motor during electric only modes of operation.

- A **series hybrid** drives the propeller shaft with an electric motor. The conventional engine is mechanically decoupled from the propeller shaft and operates as a generator to provide power electrically to the drive system. All full hybrid vehicles run on the electric motor only, as opposed to parallel hybrids.

Vessels that have a duty cycle profile with extended periods of low to medium power requirements can use hybrid systems. Since diesel engines are least efficient at these load levels, the energy storage system uses electrical power stored to move the ship, keeping the diesel off. Maritime applications include:

- All workboats (tug boats, barge boats, ferries)
- Off-shore and platform supply vessels
- Research and scientific vessels
- Fishing boats and
- Leisure and eco-tourism boats (e.g., whale-watching.)

A marine hybrid control system dispatches the most effective power and propulsion options, at a specific time, meeting the needs of the operator. There are multiple system configurations, providing redundancy, by offering alternate sources of power to the vessel.

A 2010 study by a team from UC Riverside for the California Air Resources Board (ARB) compared the hybrid tug, Carolyn Dorothy (using a Caterpillar hybrid system) to her conventional sister tug, Alta June. The study found a 73% reduction in PM, 51% reduction in NOx and 27% reduction in CO2 with a standard diesel. Significant improvements are also seen in performance, control and noise levels.

Marine hybrid systems optimize the use of currently available components and operate diesel engines at peak efficiency. For customers, this means significant reductions in owning and operating costs, with decreased fuel consumption and maximized reliability. With hybrid system, vessels have the potential to increase operating efficiencies as well as meet or exceed increasingly stringent environmental requirements.

Introducing the Fuel of the Future: Dimethyl Ether (DME)

The search for a viable liquid fuel has yielded one promising candidate that can be used as a direct substitute for diesel. This compound, called dimethyl ether (DME), can be readily synthesized from natural gas using a number of well-established chemical processes. DME is a clean burning, high-density liquid fuel that can be used as a direct replacement for diesel.

Unlike compressed natural gas (CNG) or liquid natural gas (LNG), DME can be used in compression engines. Since DME does not require a particulate filter or a selective catalytic reduction ("SCR") system, DME engines will be slightly less expensive and much simpler than standard diesel engines. They are exempt from the filter cleaning and the "add blue" protocols of modern diesel engines.

DME is a clean, colorless gas that is easy to liquefy and transport. DME holds a major advantage over traditional diesel fuel because it can also be used in turbines, marine applications, fuel cells, refrigeration and heaters. DME has the added environmental advantage of being non-toxic and environmentally low risk. Accidental spills cannot poison water, DME will not sink to the water table and DME is not absorbed by the soil. Moreover, unlike liquid natural gas (LNG), DME can be exported to Europe from East Coast ports in the Mid-Atlantic region.

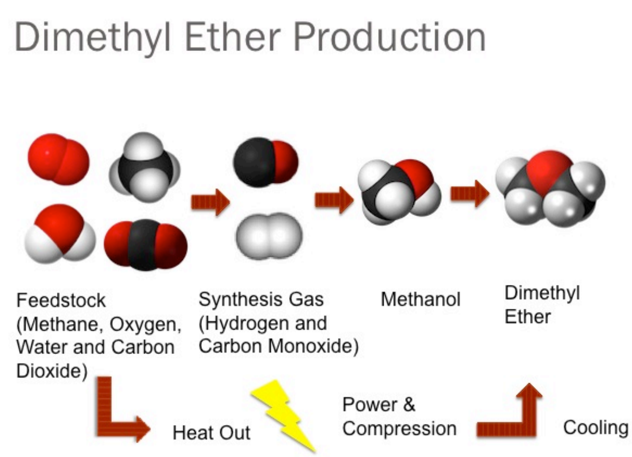

Figure 2: DME Production Sequence

Dimethyl Ether Engines Today

Volvo has invested in DME engine technology for decades and will introduce this technology to North America in selected markets during early 2016. The modified 13 Liter Volvo/Mack (VNL 300 DME) diesel engines run on

DME at higher compression ratios and produce less noise than conventional units. The use of dimethyl ether in trucks eliminates particulate matter, reduces vibration and minimizes nitrous oxides generated by conventional diesel engines. These engines can achieve higher efficiencies, better well-to-wheel costs and emissions reductions over conventional diesels. The cost of DME fuel will also be lower than diesel fuel, since DME is not derived from oil, but from natural gas, coal or biomass via a constantly improving process.

MAN Diesel & Turbine has developed a two-stroke DME engines for marine applications. The ME-LGI concept is an entirely new system that can be applied to all MAN Diesel & Turbo low-speed engines, either ordered as an original unit or through retrofitting. With two new injection concepts, the ME-LGI concept greatly expands the company's multi-fuel portfolio and enables the exploitation of more low-flash-point fuels such as DME and propane.

The ME-LGI came about due to interest from the shipping world in operating on alternatives to heavy fuel oil (HFO) and diesel. Propane carriers have already operated at sea for many years and many more propane tankers are currently being built as the global propane infrastructure grows. The same ship can carry both propane and DME. With a viable, convenient and comparatively cheap fuel already onboard, it makes sense to use a fraction of the cargo to power the vessel with an important, side-benefit being it's better for the environment. MAN Diesel & Turbo states that it is already working towards a Tier-III-compatible ME-LGI version, which can easily run on DME.

DME Hybrid Drive: The Worlds Cleanest Ship Propulsion System

The United States and Canada have agreed to make the marine environment a priority. This includes the ecosystems above and below the waterline along all coastal regions. Unlike diesel or marine fuels, DME cannot poison aquatic life. DME as a marine fuel would have eliminated the disastrous 2014 Galveston Bay spill. Current DME engines include the Volvo 13L (450 H.P. or 335 kW) and the MAN 2 Stroke low speed engine. Companies that currently produce hybrid packages include BAE Hybrid Systems, Steyr Motors, Caterpillar, Komatsu and Rolls Royce.

Figure 3: The Stena Germanica has Been Converted to Methanol

Hybrid propulsion in various configurations can combine mechanical and electric drives optimally to get the lowest fuel burn in different operating modes. The use of permanent magnet motors also increases operating efficiency. Power can also be recouped with propeller wind milling. Harbor tugs, due to their operating profile are ideal candidates for advanced engines plus battery hybrid propulsion, as are many coastal and short sea vessels.

Using DME as the engine fuel eliminates all particulate and sulfur emissions reduces NOx and CO2 emissions well below guidelines. As with trucks, DME would be held in a propane tank and all selective catalytic reduction technology, exhaust gas recirculation systems, sulfur catalyst scrubbers and particulate filters can be eliminated.

For example, an inland waterway vessel that switching to LNG will cost to €500,000 to €1,000,000 more than a traditional ship. Using a DME hybrid system should cost only slightly more than a regular propulsion system. European prices for bunkered LNG are quoted at between €650 and €750/tonne (bunkered in the ship at 48.63 MJ/kg). This price depends on the LNG market price and bunker location. On a dollar basis, LNG ($/€ at 1.3569) costs are 882 $/t to 1018 $/t. With the DME energy density of 28.88 MJ/kg, DME would be equally competitive at 523 $/t to 604 $/t. Although DME will be slightly more expensive than LNG on an energy basis, DME engines are superior to LNG engines and are much less costly. Moreover, DME does not need to be vented while in port for more than 4 days.

Bunkering Dimethyl Ether

The United States and Canada have well-developed propane infrastructures, with tremendous capacity to carry an abundant supply of DME with high portability via truck and rail. The propane infrastructure in North America moves 25% of the world's propane supply. Unlike LNG or CNG, dimethyl ether has a complete transportation and loading infrastructure already available.

The two most common means for transporting propane across North America from storage facilities or producers to end-users are pipeline and rail. Transporting long distances via truck is often uneconomical. Dimethyl ether can use the exact same rail tanks cars, highway tankers and pipelines as propane.

Dimethyl ether, like propane can be moved west to east across North American. In order for propane and dimethyl ether to be moved by rail, rail car filling and unloading infrastructure (commonly called "racks" or "terminals") are constructed at both the origin and the destination. Upstream firms generally own facilities located at an originating production plant, while a downstream firm generally owns facilities at the destination.

Dimethyl ether "racks" can be located near all port areas worldwide. Ideally, they will be serviced by rail or pipeline. Current propane marine terminals are a fraction of the cost of LNG terminals, since they do not involve cryogenic technology. For example, propane-shipping terminals exist in Providence, RI. and Newington, NH, while no LNG ports exist on the Eastern seaboard. Moreover, Texas Eastern Pipeline currently supplies propane export ships loading from the Eastern seaboard. Sunoco has developed the Marcus Hook Industrial Complex, on the banks of the Delaware River, as the preeminent eastern marine hub for propane.

Any DME spill would evaporate before entering the ecosystem, and unlike LNG, there are no greenhouse gas problems with fugitive emissions. Although some current industry groups support LNG, once study groups take into account the use of the existing and growing seaboard propane infrastructure, DME bunkering is an extremely low cost alternative to LNG bunkering.

Recently, a Conoco-Phillips plan for a 23 million gallon propane storage and export terminal was designed and priced at 40 MM$. The storage tanks would have been 138 ft. tall and safely stored propane all year long, without the need for venting. Desfa SA, a Greek natural gas grid operator, invited firms to bid for the design and construction of a third liquefied natural gas storage tank at its Revithoussa LNG terminal facility near Athens. The tank, expected to cost as much as 115 million Euros (150 MM$), will have capacity of 95,000 cubic meters (25.6 million gallons of LNG). On a volume basis, coastal storage of LNG requires 1.56 $/liter of CAPEX versus 0.47 $/liter for DME or propane. This cost does not include the ongoing cryogenic cooling costs required for LNG.

The Best Marine Fuel, Period

Abstract From Report 10: Department of Shipping and Marine Technology, Chalmers University of Technology, Göteborg, Sweden by Selma Brynolf, Shweta Kuvalekar and Karin Andersson:

The combined effort of reducing the emissions of sulfur dioxide, nitrogen oxides and greenhouse gases to comply with future regulations and reduce impact on climate change will require a significant change in ship propulsion. One alternative is to change fuels. In this study the environmental performance of two potential future marine fuels, methanol and dimethyl ether (DME), are evaluated and compared to present and possible future marine fuels.

Methanol and DME produced from natural gas was shown to be associated with a larger energy use and slightly more emissions of greenhouse gases in the life cycle when compared to HFO, MGO and LNG. Use of methanol and **DME results in significantly lower impact when considering the impact categories particulate matter, photochemical ozone formation, acidification and eutrophication compared to HFO and MGO without any exhaust abatement technologies** and of the same order of magnitude as for LNG.

Methanol and DME produced from willow or forest residues have the lowest life cycle global warming potential (GWP) of all fuels compared in this study and could contribute to **reduce the emissions of greenhouse gases from shipping significantly.**

Market Factors Supporting the Rapid Growth of Dimethyl Ether

The following market factors have created a favorable investment environment for the ChemBioPower system:

- North American natural gas prices are lower and supply is higher since the 2008 financial crisis.
- Refined oil products (diesel & petroleum) remain high in price.
- North American natural gas prices will continue to remain low due to horizontal drilling and hydraulic fracturing.
- The North American propane infrastructure is robust and universal. Dimethyl ether can be stored in the same infrastructure and moved anywhere across the continent and into existing marine terminals.
- The price spread between refined oil products and natural gas will provide an ongoing competitive advantage to plants using natural gas as production inputs, and therefore, liquids produced from natural gas will be competitive with oil distillates for decades.
- Governments will continue to penalize carbon dioxide, sulfur and particulate emissions. Green facilities that reduce CO_2 emissions will emerge as an important component of governmental energy policy and will receive preferential treatment (including tax cuts and credits) from national and local authorities.

About the Authors

Antonio Anselmo (Chief Executive Officer)

Dr. Anselmo is a principal at Altametric and a founder of The Allocated Materials Management Company. Dr. Anselmo is a recognized world-class expert in the fields of advanced particle accelerators, plasma physics, system engineering and financial engineering. He is an expert on the design and control of complex systems. Dr. Anselmo worked for 12 years at J.P. Morgan Chase in the Financial Engineering and Electronic Commerce groups in the Investment Bank. Prior to this, he was a Scientist at Varian Associates for 4 years designing accelerator and radar systems. He has written numerous scientific papers on nuclear fuel chain optimization, particle accelerators and complex systems.

He holds a B.Sc., M. Eng. and Ph.D. from Cornell University and an M.B.A. from the Amos Tuck School at Dartmouth College. He was a McMullen Honorary Scholar and a Teagle Graduate Fellow at Cornell and an Edward Tuck Scholar and Adams Entrepreneurial Award Winner at Dartmouth.

Jeremiah Sullivan (Chief Financial Officer)

Jeremiah has served as CFO and COO of three PE/VC owned companies and one private company. He increased shareholder value at all four companies by leading strategic growth and turnaround initiatives. He has extensive international experience and has negotiated transactions in Europe, Asia and Latin America. Most recently, Jeremiah served as the CFO of Cirqit.com, Inc., a technology firm that provides print procurement SaaS software and on-site technical services solutions to its clients. He helped the company's private equity owners engineer a turnaround of the company's operations culminating in two liquidity events involving the sale of Cirqit’s operations in North and South America.

He holds a M.B.A. from the Amos Tuck School at Dartmouth College and B.S. in International Affairs from Georgetown University. He was an Adams Entrepreneurial Award Winner at Dartmouth.