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An Evaluation of the
Energy Efficiency Design Index (EEDI) Baseline
for Tankers, Containerships, and LNG Carriers

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Abstract: The IMO is developing the Energy Efficiency Design Index (EEDI) for new ships, which is a gauge of a ship's CO_2 efficiency. The EEDI is a simple formula that estimates CO_2 output per tonne-mile. The numerator represents CO_2 emissions after accounting for "innovative" machinery and electrical energy efficiency technologies that are incorporated into the design. The denominator is a function of the speed, capacity, and ship specific factors. To determine compliance, the attained EEDI for a newbuilding is compared to a baseline value. Baseline EEDI curves have been proposed at IMO (ex: IMO document GHG-WG 2/2/7 and MEPC 60/4/14) based on analysis of existing ships. As all data required for calculation of the EEDI is not available from the existing ship databases, simplifying assumptions were made to facilitate the baseline calculations. ABS and HEC have jointly conducted a study in which "standard" ship designs were developed for tankers, containerships, and LNG carriers over a range of ship sizes. Highly efficient hull performance and modern power plants are assumed. By evaluating the baselines for tankers, LNG carriers, and containerships utilizing the "standard" ships, this study provides the attained EEDI that can be achieved with well-designed newbuildings prior to application of innovative technologies. As such, they serve as an effective metric for validating the proposed EEDI baselines. This report summarizes the findings from this study, which were submitted to SNAME T&R Ad Hoc Panel 18 tasked with investigating the EEDI. The results were summarized into document MEPC 60/4/33, which has been submitted to IMO for consideration.

1. Overview: IMO Energy Efficiency Design Index (EEDI) and Baseline

Historical Background on the Development of the EEDI

The Energy Efficiency Design Index has been developed by the IMO over the past several years through a series of submissions to MEPCs 57-59 and the 1st and 2nd Working Groups on Greenhouse Gases. The most recent version of the EEDI Guidelines is presented in MEPC.1/ Circ.681 "Interim Guidelines on the Method of Calculation of the Energy Efficiency Design Index for New Ship." This document was released to encourage implementation and testing of the methodology, with the intent that the lessons learned will lead to further refinements.

The EEDI, in close to its present form, was first shown as the "CO_2 Emissions Index" in MEPC 57/4/12 by Japan. The CO_2 Emissions Index value was represented in units of grams of CO_2 per transport work (g CO_2 / tonne-mile). This index was developed to allow for a preliminary assessment of ship performance at the design stage. The philosophy is that the calculation procedure be simple and capable of broad application, and promote efforts by all stakeholders to reduce CO_2 emissions by reflecting a ship's energy efficiency in actual use.

MEPC 57 tasked Japan and Denmark to present mandatory CO_2 emissions indices at the 1st intersessional meeting of the Working Group on Greenhouse Gas Emissions from Ships. The resulting documents GHG-WG 1/2/1/ and 1/2/2 were developed by the respective countries. The basic premise of environmental cost divided by the benefit to society was retained in both instances and an equation was presented in the simplified form of:

$$Attained\ design\ CO_2\ index = \frac{C_F\ SFC\ P}{Capacity\ V_{ref}}$$

*terms are defined below

Denmark expanded upon Japan's ideas and separated the emissions into those produced by the propulsive engines and those produced with auxiliary power diesel generators. Factors for "ship specific design elements" were included in front of each of the contributing engine CO_2 emission components to account for unique design elements (ice strengthening, cargo gear, etc). This equation was presented as:

$$Attained\ design\ CO_2\ index = \frac{\prod_{j=1}^{M}f_j \sum_{i=1}^{NME}C_{FMEi}\ SFC_{MEi}\ P_{MEi}\ +\ \prod_{k=1}^{L}f_k \sum_{i=1}^{NAE}C_{FAEi}\ SFC_{AEi}\ P_{AEi}}{Capacity\ V_{ref}}$$

MEPC 58/4 presents the findings of the 1st intersessional meeting of the Working Group on Greenhouse Gas Emissions from Ships in its Draft Guidelines on the Method of Calculation of the New Ship Design Index found in Annex 5 of the document. The new index is essentially Denmark's proposal with a factor for weather conditions, f_w, as found in Japan's submission:

$$Attained\ new\ ship\ design\ CO_2\ index = \frac{\left(\prod_{j=1}^{M}f_j\right)\left(\sum_{i=1}^{NME}C_{FMEi}\ SFC_{MEi}\ P_{MEi}\right)+\left(\prod_{k=1}^{L}f_k\right)\left(\sum_{i=1}^{NAE}C_{FAEi}\ SFC_{AEi}\ P_{AEi}\right)}{Capacity\times\ V_{ref}\times f_W}$$

Submissions to the 58th Session of MEPC better defined each of the variables and their application across different ship types. An additional factor representing "innovative energy efficiency technologies" was introduced by the United States in MEPC 58/4/35. The resulting equation is as follows:

$$Proposed\ new\ ship\ design\ CO_2\ index = \frac{\left(\sum_{i=1}^{NME}C_{FMEi}\ SFC_{MEi}\ P_{MEi}\right)+\left(\sum_{i=1}^{NAE}C_{FAEi}\ SFC_{AEi}\ P_{AEi}\right)-\left(\sum_{eff=1}^{Neff}f_{eff}C_{Feff}\ SFC_{eff}\ P_{eff}\right)}{Capacity\ \times\ V_{ref}\times f_W}$$

With the conclusion of MEPC 58, the CO_2 emission index became the Energy Efficiency Design Index. Another term was added to account for shaft input motors and reductions in consumption resulting from waste heat recovery technologies. A factor f_i was added to the denominator to account for technical or regulatory limits on capacity. The revised equation became:

$$\frac{\left(\prod_{j=1}^{M} f_j\right)\left(\sum_{i=1}^{nME} C_{FMEi}\ SFC_{MEi}\ P_{MEi}\right) + P_{AE} C_{FAE} SFC^*_{AE} + \left(\sum_{i=1}^{nPTI} P_{PTIi} - \sum_{i=1}^{nWHR} P_{WHRi}\right) C_{FAE} SFC_{AE} - \left(\sum_{i=1}^{neff} f_{eff} P_{eff} C_{FMEi} SFC_{MEi}\right)}{f_i\ \ Capacity\ \ V_{ref}\ \ f_W}$$

After the meeting of 2nd intersessional meeting of the Working Group on Greenhouse Gas Emissions from Ships, the equation was refined to the following form,

$$\frac{\left(\prod_{j=1}^{M} f_j\right)\left(\sum_{i=1}^{nME} P_{ME(i)} C_{FME(i)} \cdot SFC_{ME(i)}\right) + \left(P_{AE} \cdot C_{FAE} \cdot SFC_{AE}*\right) + \left(\left(\prod_{j=1}^{M} f_j \cdot \sum_{i=1}^{nPTI} P_{PTI(i)} - \sum_{i=1}^{neff} f_{eff(i)} \cdot P_{AEeff(i)}\right) C_{FAE} \cdot SFC_{AE}\right) - \left(\sum_{i=1}^{neff} f_{eff(i)} \cdot P_{eff(i)} \cdot C_{FME} \cdot SFC_{ME}\right)}{f_i \cdot Capacity \cdot V_{ref} \cdot f_w}$$

The equation retains this form in the most recent MEPC .1/ Circ. 681, "Interim Guidelines on the Method of Calculation of the Energy Efficiency Design Index for New Ships."

Explanation of Terms

Conversion Factors (C_{FME} and C_{FAE})

Conversion factors are given for five categories of fuels used in the marine industry. The conversion factors were selected to be consistent with the Energy Efficiency Operator Indicator (EEOI) and the International Panel on Climate Change (IPCC) emission factors. The factors give the equivalent mass emission of CO_2 from combustion of a given mass of fuel. Specific values for fuel carbon contents and complete combustion are assumed. The type of fuel used in the calculation should be the same as the fuel burned in the determination of the specific fuel consumption on the Engine International Air Pollution Prevention (EIAPP) certificate.

Specific Fuel Consumption (SFC_{ME} and SFC_{AE})

Specific fuel consumption (SFC) is divided into two categories: main engine and auxiliary engine fuel consumption. Main engine fuel consumption is the SFC reported on the EIAPP Certificate for the parent engine in accordance with the NO_x Technical Code at 75% of the Maximum Continuous Rating (MCR). Auxiliary engine fuel consumption is the fuel consumption reported on the parent engine's EIAPP Certificate at 50% of the MCR. If different sized auxiliary engines are used, a single SFC is entered into the equation by taking the weighted average of the different engines.

Power (P_{ME}, P_{AE}, and P_{PTI})

Power from the main engine, P_{ME}, is 75% of the MCR of the engine, in kW, minus the output of any shaft generators. Power from auxiliary engines is determined by an empirical formula representing the hotel load and electrical needs for propulsion systems and machinery. Auxiliary power is taken as a function of the MCR of the main engine(s). This formula is adjusted slightly for vessels that have smaller propulsion engines with an installed power less than 10,000 kW. Additional shaft motor inputs are given at 75% of the rated power consumption divided by the weighted average of the efficiency of the generators.

$$P_{AE(MCRME>10000KW)} = \left(0.025 \times \sum_{i=1}^{nME} MCR_{MEi}\right) + 250$$

$$P_{AE(MCRME<10000KW)} = 0.05 \times \sum_{i=1}^{nME} MCR_{MEi}$$

Speed (V_{ref})

The speed used in the EEDI is the vessel's speed when operating at a draft corresponding to the specified capacity, at a trim as defined by the corresponding condition specified in the approved stability booklet. The speed assumes the vessel is operating at power level P_{ME}, in deep water and in calm weather (no winds or waves).

Capacity (*Capacity*)

Capacity is defined as deadweight for tankers, LNG carriers, and containerships. Capacity for tankers and LNG carriers is taken as the deadweight at the summer load line (SLL) draft. Capacity for containerships is adjusted to be 65% of the SLL deadweight in order to better represent the normal design condition.

Innovative Energy Efficiency Technologies (P_{eff}, P_{AEeff}, and f_{eff})

Innovative technologies that provide mechanical or electrical power reductions are accounted for with the P_{eff} and P_{AEeff} terms respectively. An availability factor, f_{eff}, is given for each technology to estimate what percent of the time the technology is available during normal "at-sea" conditions.

Correction Factors (f_i, f_j, and f_w)

The correction factor f_i accounts for ship specific design elements and the factor, f_j, accounts for any technical or regulatory limit on capacity. Currently, these factors are only used for ships designed with an ice class notation. f_w is a factor representing the decrease in speed in certain sea conditions.

EEDI Baseline Methodology

The methodology used for the development of the baseline equations for the EEDI was first suggested in document MEPC 58/4/8 by Denmark. In GHG-WG 2/2/7, Denmark updated the methodology to reflect the latest version of the EEDI equations while providing the regression equations for six different vessel types. These equations utilized data from the Lloyd's Register Fairplay vessel database to develop a representative EEDI for all ships of a particular type that were built between the years 1998-2007. In order to get baseline EEDI for each data point, simplifying assumptions were required to adjust for missing information in the LRFP database. Some of the simplifying assumptions are:

Conversion Factors (C_{FME} and C_{FAE})

A single fuel type, HFO, was assumed to be used in all engines, both propulsion and auxiliary. At the time of the release of GHG-WG 2/2/7, a value of 3.13 g CO_2 / g fuel was being used as the conversion factor in the EEDI equation.

Specific Fuel Consumption (SFC_{ME} and SFC_{AE})

With SFCs not readily available in the LRFP database, a constant value of 190 g/ kW-hr was applied to all propulsion engines. Auxiliary engine fuel consumptions are assumed to be a constant 210 g/ kW-hr.

Power (P_{ME} and P_{AE})

As in the EEDI formula, P_{ME} is taken as 75% of the listed MCR in the database. P_{AE} is developed with the same empirical formula as used in the EEDI formula.

Speed (V_{ref})

The speed used is the speed listed in the LRFP database. This value may or may not represent speed at the EEDI condition. Further discussion of this is given below.

Capacity (*Capacity*)

The capacity will remain the deadweight at the deepest operational draft. This value is commonly available in the LRFP database.

Innovative Energy Efficiency Technologies (P_{eff}, P_{AEeff}, and f_{eff})

No innovative technologies are assumed to be used, even if the data is available in the database.

Correction Factors (f_i, f_j, and f_w)

All corrections are set to 1.

The baseline index values are then calculated using the speed, capacity, MCR of propulsion engine. The equation, per WG 2/2/7, is:

$$Average\ Index\ Value = 3.13 \cdot \frac{190 \cdot \sum_{i=1}^{NME} P_{MEi} + 210 \cdot P_{AE}}{Capacity \cdot V_{ref}}$$

Data sets with missing values are omitted. A single regression line is then plotted through the values in the form of:

$$Baseline\ value = a \cdot Capacity^{-c}$$

Outliers from the regression lines of more than 2 standard deviations are removed and a new regression line is plotted.

In Denmark and Japan's latest submission to IMO, MEPC 60/4/7, they have recommended slight changes to the above methodology for the generation of updated regression baseline curves. The major differences between GHG-WG 2/2/7 and MEPC 60/4/7 are that C_f is revised from 3.13 to 3.1144 (to be the same as Circ. 681), the constant auxiliary engine SFC is revised from 210 to 215 g/kW-hr, the applicable vessel built years is revised from 1998-2007 to Jan 1, 1999 to Jan 1, 2009, and data from steam powered ships will no longer be used in the development of the curves. Several other minor vessel-specific changes were also recommended.

2. Methodology for Evaluating the EEDI of Standard Designs

For each of the three ship types evaluated in this study (oil tankers, containerships, and LNG carriers), four representative ship designs covering the more typical ship sizes have been developed. These designs are herein referred to as the "standard" designs. The basic steps taken in developing these standard ship designs and calculating their attained EEDI are as follows:

a) Determine principal particulars for each standard design

> The standard designs cover the range of vessel sizes most common for the given vessel type, up to the largest sizes constructed within the last five years. Regression analysis of existing designs was applied when determining the following particulars: LBP, beam, depth, design draft, service speed at the design draft, Cb at the design draft, and the summer load line draft. Some discretion was applied when selecting particulars for each design based on HEC's experience, so that the particulars are representative of the most recent good performing designs.

> With regard to calculating the EEDI, the most influential of these particulars is the service speed.

b) Determine the required propulsion power to attain service speed at the design draft

> The assumed particulars provide the basis for calculating required power at the design draft. The required power to achieve service speed at the design draft is calculated assuming a representative service margin and the main engine operating at 90% MCR. Because design speed is based on regression of existing ship data, the service margins typically used for each type and size of ship is applied when determining the installed power. For tankers, a 15% service margin is applied for all designs. For containerships, a 15% service margin is applied for Panamax size and smaller, and a 20% service margin is applied for the larger designs. For LNG carriers, a 20% service margin is applied for all designs.

> Adjustment factors have been applied to HEC's powering calculation routines, with the intent that the calculated power be representative of modern designs with very good powering characteristics. A number of recent designs were evaluated and the adjustment factors selected such that the power estimate is less than that achieved by 75% of the existing designs (i.e. only the upper quartile of recent designs would be expected to exhibit equal or better efficiency).

For those designs with slow speed diesel propulsion, a MAN B&W engine of appropriate size was selected. Consistent with current practice, MC series engines are assumed for tankers, and ME-C series engines are assumed for LNG carriers and containerships. The rated RPM of the selected engine is input data into the propulsive coefficient calculations, and the published SFC of the engine at 75% MCR is applied when determining the expected SFC on an EIAPP certificate. For the evaluation of diesel electric propulsion plants on LNG carriers, the rated RPM of the propulsion motors was selected based on current practice.

c) Calculate the lightship and deadweight for each standard design

HEC's algorithms for estimating the lightship of oil tankers, containerships and LNG carriers are applied in this study. The principal particulars and powering requirements obtained in steps a) and b) serve as input into these algorithms. Other key parameters used when calculating lightship (% high tensile steel, generator capacity, accommodation size, etc.) are developed from regression data of existing designs. Although the lightship estimate is based on relatively few parameters, these algorithms develop a lightship weight representative of modern Asian shipyard design and construction practice.

d) Calculate the deadweight and speed at the EEDI specified draft

The LBP, beam, design draft and Cb at the design draft developed in step a) provide the basis for calculating the displacement at the design draft. Regression analysis is used to estimate the waterplane coefficients at the design and SLL drafts, and from these data the displacement at the SLL draft is calculated. The SLL deadweight is determined by subtracting the lightship from the SLL displacement. For tankers and LNG carriers, the SLL deadweight serves as the surrogate for capacity in the EEDI equation. For containerships, the draft at 65% of the summer load line deadweight is determined using a similar approach.

For slow speed diesel propulsion, the EEDI speed (V_{ref}) is calculated with the main engine(s) operating at 75% MCR. For diesel electric plants, propulsion power is taken as 75% of the motor rating. The speed under trial conditions with the vessel at the EEDI specified deadweight is determined for these power levels. The same algorithms applied in step b) are used for this analysis. This approach assumes that the hull lines are optimized for both the design and EEDI deadweight drafts, which is the likely practice once EEDI regulations become effective. For tankers and LNG carriers, the speed at the SLL draft is typically 0.2 to 0.4 knots slower than the speed at the design draft. For containerships, the speed at the EEDI specified condition (65% of SLL deadweight) is roughly equivalent to the design speed.

e) Determine the specific fuel consumption at the EEDI specified power level

Main engine power P_{ME} is taken at 75% of the main engine MCR or 75% of the electric motor rating, as appropriate for the type of propulsion plant. All designs are taken without shaft generators. Auxiliary power P_{AE} is calculated in accordance with the empirical formulas provided in Circ. 681.

The EEDI calculation procedure calls for the specific fuel consumptions for the main engine and auxiliary engines to be taken from the EIAPP Certificates at 75% MCR and 50% MCR respectively. The certificates are usually developed from tests with the engine burning distillate fuels at ISO conditions. The SFC on the EIAPP certificates is typically about 2 to 4% higher than the published values provided by the manufacturer. Throughout this study, specific fuel consumption for both main propulsion and auxiliary engines (SFC_{ME} and SFC_{AE}) are assumed to be MAN B&W's published figures adjusted for partial load (75% or 50%) and Tier II modifications. A 3% increase in the published SFC (out of the listed manufacturer's 5% tolerance) is applied.

f) Selection of the Conversion Factors C_{FME} and C_{FAE}

Conversion factors for "Diesel Gas / Oil", per Circ. 681, were used throughout the study as the majority of manufacturer diesel engine testing for processing the EIAPP certificates are performed using DMX through DMC grade distillates. Fuel consumptions are corrected to ISO conditions and a fuel with Lower Heating Value of 42,700 kJ/kg. For LNG carriers with alternative propulsion plants, i.e. slow speed direct drive and dual fuel diesel electric, the analysis was carried out using the conversion factor for "Liquefied Natural Gas". For comparative purposes, calculations for dual fuel diesel engines were also performed using Diesel Gas / Oil.

g) Calculate the attained EEDI

The methodology and fuel characteristics contained in Circ. 681, "Interim Guidelines on the Method of Calculation of the Energy Efficiency Design Index for New Ships." are applied when calculating the EEDI for each standard ship. No innovative energy efficiency technologies or application of other correction factors (f_i, f_j, and f_w) are assumed for the standard ships.

3. Principal Particulars for the Standard Ship Designs

Oil Tankers

Panamax, Aframax, Suezmax, and VLCC size tankers are evaluated in this study. Principal characteristics of these designs are presented in Table 1. Numbers shown in bold text are derived from regression analysis of existing ships. Other data are calculated from HEC algorithms.

In conformance with common practice, all tanker designs are single screw with slow speed diesel propulsion.

Particulars	Size Type	Panamax Product	Aframax Crude	Suezmax Crude	VLCC Crude
100% Cargo Capacity	m^3	**54,000**	**132,000**	**180,000**	**360,000**
Length Overall	m	**182.000**	**249.000**	**280.000**	**333.000**
LBP	m	**174.000**	**239.000**	**270.000**	**320.000**
Beam	m	**32.200**	**44.000**	**48.000**	**58.000**
Depth	m	**19.000**	**21.200**	**24.000**	**31.200**
Design Draft	m	**11.20**	**13.60**	**15.90**	**21.00**
Summer Loadline Draft	m	**12.62**	**15.06**	**17.41**	**22.05**
Lightship	tonnes	10,052	19,310	25,819	43,258
Design Block Coefficient		**0.800**	**0.825**	**0.825**	**0.820**
Deadweight at Design Draft	tonnes	41,533	101,932	148,869	285,154
Deadweight at Loadline draft	tonnes	49,203	116,135	166,576	303,032
Number of Screws		**1**	**1**	**1**	**1**
Design Speed: 15% SM at 90% MCR	knots	**14.90**	**14.90**	**15.20**	**15.80**
Required Engine Power (MCR)	kW	9,222	13,822	17,185	26,736

Table 1 Principal Characteristics for Standard Oil Tanker Designs

Containerships

The following containership designs are evaluated: 1,000 TEU (Feedership), 4,500 TEU (Panamax), 4,500 (Baby Neo-Panamax), 8,000 (Post-Panamax), and 12,500 TEU (Ultra-large containership). Principal characteristics of these designs are presented in Table 2. Numbers shown in bold text are derived from regression analysis of existing ships.

In conformance with common practice, all containership designs are single screw with slow speed diesel propulsion.

Particulars		Feedership	Panamax	Baby Neo-Panamax	Post-Panamax	Ultra Large
Slot Capacity	TEU	**1,000**	**4,500**	**4,500**	**8,000**	**12,500**
Length Overall	m	**145.248**	**295.625**	**280.145**	**333.256**	**388.396**
LBP	m	**136.000**	**275.000**	**260.600**	**308.000**	**356.000**
Beam	m	**23.400**	**32.200**	**34.800**	**42.800**	**48.200**
Depth	m	**11.750**	**21.000**	**19.300**	**24.500**	**29.850**
Design Draft	m	**7.60**	**11.80**	**11.80**	**13.00**	**14.20**
Summer Loadline Draft	m	**8.51**	**13.22**	**13.22**	**14.56**	**15.90**
Lightship	tonnes	5,022	19,119	19,071	31,752	47,063
Design Block Coefficient		**0.655**	**0.630**	**0.630**	**0.630**	**0.665**
Deadweight at Design Draft	tonnes	11,257	48,524	50,206	79,187	119,437
Deadweight at Loadline draft	tonnes	13,669	58,817	60,747	96,068	143,865
Number of Screws		**1**	**1**	**1**	**1**	**1**
Sea Margin		15%	15%	15%	15%	20%
Design Speed: with SM at 90% MCR	knots	**18.50**	**24.50**	**24.50**	**25.00**	**25.00**
Required Engine Power (MCR)	kW	9,337	38,532	41,330	57,843	75,920

Table 2 Principal Characteristics for Standard Containership Designs

LNG Carriers

Conventional LNG carriers, typically between 150,000 and 155,000 m^3 capacity, are traditionally single screw and arranged with steam plants. Conventional single screw LNG carriers up to 173,000 m^3 in capacity are under construction, and vessels of 180,000 m^3 capacity have been considered. Most LNG carriers in the 150,000 m^3 to 173,000 m^3 currently on order will be fitted with dual fuel diesel electric (DFDE) propulsion plants. These have the capability of burning either boil-off gas or fuel oil (MDO or HFO).

In recent years, ultra large LNG carriers have been introduced to transport LNG from Qatar to the Gulf of Mexico and Europe. Two basic sizes of the ultra large LNG carriers have been built: QFlex (about 215,000 m^3) and QMax (about 265,000 m^3). All of these vessels are twin screw designs with highly efficient twin skeg sterns, and arranged with DRL propulsion plants. That is, they are propelled by slow speed diesel engines, and fitted with plants for reliquefaction of boil-off gas. HFO is the intended fuel for these vessels.

For the purposes of this study, six "standard" designs have been developed. Three single screw LNG carriers with DFDE propulsion having capacities of 150,000 m^3, 180,000 m^3 and 215,000 m^3, and three twin screw LNG carriers with DRL propulsion having capacities of 180,000 m^3, 215,000 m^3 and 265,000 m^3. A membrane (GTT MK3) containment system is assumed for all standard designs.

Principal characteristics of these designs are presented in Table 3. Numbers shown in bold text are derived from regression analysis of existing ship particulars and comparison to existing designs.

Propulsion Plant Shafting Configuration		DFDE Single	DFDE Single	DFDE Single	DRL Twin	DRL Twin	DRL Twin
100% Cargo Capacity	m3	**150,000**	**180,000**	**215,000**	**180,000**	**215,000**	**265,000**
Length Overall	m	**289.000**	**302.000**	**315.000**	**302.000**	**315.000**	**345.000**
LBP	m	**276.000**	**289.500**	**303.000**	**289.500**	**303.000**	**332.000**
Beam	m	**44.000**	**46.500**	**50.000**	**46.500**	**50.000**	**53.800**
Depth	m	**26.000**	**26.500**	**27.000**	**26.500**	**27.000**	**27.000**
Design Draft	m	**11.50**	**11.75**	**12.00**	**11.75**	**12.00**	**12.00**
Summer Loadline Draft	m	**12.45**	**12.70**	**13.00**	**12.70**	**13.00**	**13.00**
Lightship	tonnes	31,349	35,064	39,858	36,168	41,029	48,159
Design Block Coefficient		**0.746**	**0.757**	**0.770**	**0.757**	**0.770**	**0.788**
Deadweight at Design Draft	tonnes	75,634	87,910	103,903	86,806	102,731	125,407
Deadweight at Load Line draft	tonnes	85,837	99,309	117,537	98,205	116,366	141,710
Design Speed: 20% SM at 90% MCR	knots	**19.80**	**19.80**	**19.80**	**19.80**	**19.80**	**19.80**
Required Brake Power	kW	25,930	28,317	31,696	26,417	29,374	33,665
Required for Main Propulsion (MCR)	kW	31,559	34,464	38,577	29,353	32,637	37,406

Table 3 Principal Characteristics for Standard LNG Carrier Designs

4. Calculation of the EEDI for the Standard Designs

Oil Tankers

Table 4 contains the attained EEDI for each standard design and the baseline EEDI corresponding to the summer load line deadweight. Figure 1 is a graphical presentation of these data. The baseline values for tankers are determined from the following equation:

Baseline EEDI for oil tankers = 1950.7 ($Capacity$) $^{-0.5337}$

where $Capacity$ = the deadweight at the summer load line draft

This is the equation presented in IMO paper GHG-WG 2/2/7 submitted by Denmark.

EEDI Calculation	Size Type	Panamax Product	Aframax Crude	Suezmax Crude	VLCC Crude
100% Cargo Capacity	m^3	54,000	132,000	180,000	360,000
Main Engine Power, 75% MCR (P_{ME})	kW	6,916	10,366	12,888	20,052
Aux. Engine Power (P_{AE})	kW	461	596	680	918
SFC, Main Engine (SFC_{ME})	g-KWhr	177.3	176.3	176.3	175.3
SFC, Diesel Generators (SFC_{AE})	g-KWhr	204.5	204.5	204.5	204.5
Fuel Conv Factors (C_{FME} and C_{FAE})	t CO_2	3.206	3.206	3.206	3.206
Deadweight at SLL ($Capacity$)	tonnes	49,203	116,135	166,576	303,032
Speed at SLL and 75% MCR (V_{ref})	knots	14.47	14.44	14.78	15.49
Attained EEDI ($EEDI_A$)		**5.95**	**3.73**	**3.14**	**2.53**
Baseline EEDI ($EEDI_{BL}$)		6.11	3.86	3.19	2.32
%EEDI = ($EEDI_A$/$EEDI_{BL}$) - 1		-2.7%	-3.5%	-1.5%	9.2%

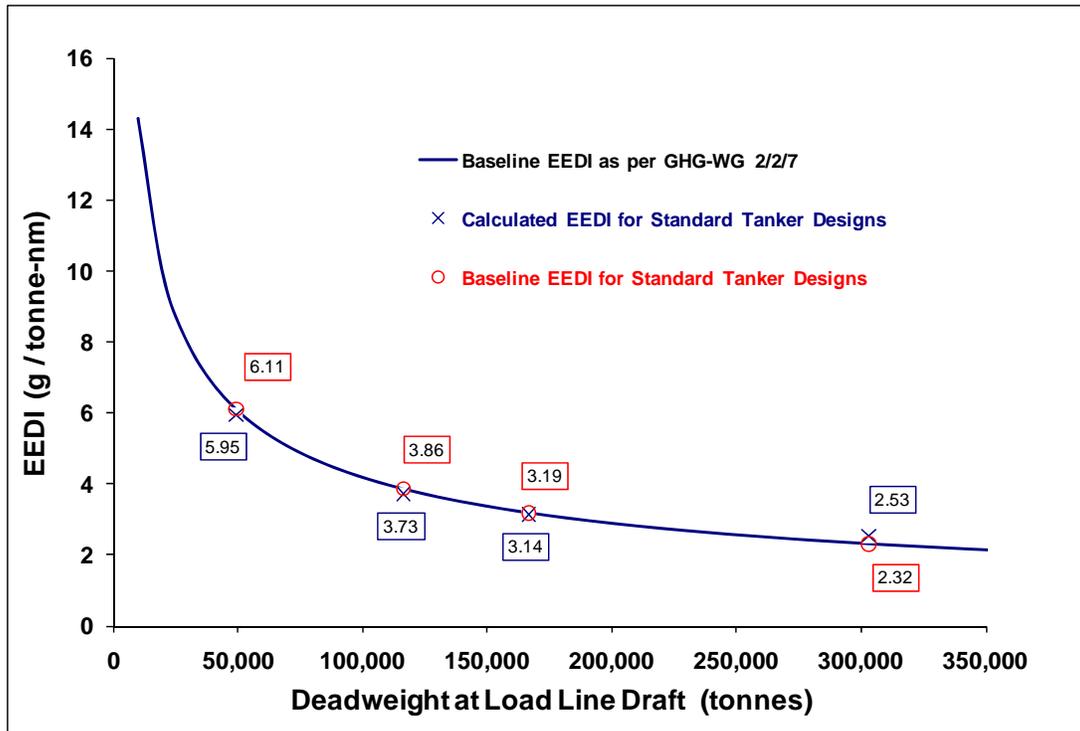**Table 4 EEDI for Oil Tanker Standard Designs**

Figure 1 EEDI for Oil Tanker Standard Designs

The attained index variation for each standard design relative to its respective baseline value is expressed as follows;

$$\%\text{EEDI} = \frac{EEDI_A}{EEDI_{BL}} - 1$$

where: $EEDI_A$ = the attained EEDI for the design
 $EEDI_{BL}$ = the baseline EEDI corresponding to the SLL deadweight

We find that the %EEDI for the Panamax, Aframax, and Suezmax designs range from -1.5% to -3.5% (1.5% to 3.5% below the baseline), indicating that these vessels will comply with the proposed baseline criterion. The difference was expected to be somewhat higher as these standard tanker designs represent the more efficient tankers built today. As previously discussed, the hull and propulsion efficiency are based on the upper quartile of top performers and the selected engines.

More surprising is that the attained index for the standard VLCC design exceeds the baseline figure by 9.2%. To achieve compliance, hull efficiency must be improved by 8.4%, which is not achievable without the introduction of innovative technologies. Alternatively, as shown in Table 5, the design speed must be reduced from 15.8 knots (the mean for VLCC newbuildings over the last 10 years) to 15.1 knots.

Particulars	Size Type	Panamax Product	Aframax Crude	Suezmax Crude	VLCC Crude
100% Cargo Capacity	m^3	54,000	132,000	180,000	360,000
Baseline Design Speed	knots	14.90	14.90	15.20	15.80
Adjustment to Speed to meet EEDI	knots	0.13	0.23	0.12	-0.70
Adjusted Design Service Speed	knots	**15.03**	**15.13**	**15.32**	**15.10**
Speed at SLL and 75%MCR	knots	14.60	14.68	14.89	14.79
Attained EEDI ($EEDI_A$)		6.11	3.86	3.19	2.32
Baseline EEDI ($EEDI_{BL}$)		6.11	3.86	3.19	2.32

**Table 5 EEDI for Oil Tankers Standard Designs
(with design speed adjusted to achieve EEDI compliance)**

Some differences in the Attained EEDI and the baseline curve are to be expected, due to simplifying assumptions applied in GHG-WG 2/2/7. This study applies the SFC for MDO under ISO conditions, which is the basis for most EIAPP certificates. SFC figures were determined at the appropriate %MCR from the manufacturer's published data, and then increased by 3% to account for the typical differences between the EIAPP certificates derived from testbed measurements and the published data. GHG-WG 2/2/7 assumes constant values for specific fuel consumption (SFC_{ME} = 190 g/kWh and SFC_{AE} = 210 g/kWh) and C_{FME} and C_{FAE} factors for HFO rather than lighter fuel oils. The quoted speeds in the LRFP database are applied, which are generally speeds at the design draft rather than the summer load line draft. Also, the most common practice is to quote service speeds with 15% service margin and the main engine operating at 90% MCR, which equals 0.90/1.15 = 78.3% MCR rather than 75% MCR.

For illustration purposes, Table 6 shows the Attained EEDI for the standard designs calculated using the same assumptions as in GHG-WG 2/2/7. This analysis fails to explain why the standard VLCC shown in Table 4 as +9.2%, falls so far out of compliance. In fact, we find that for tankers, the overall impact of the simplifying assumptions is slightly conservative (tending to produce a higher attained EEDI value).

EEDI with GHG 2/2/7 Assumptions	Size Type	Panamax Product	Aframax Crude	Suezmax Crude	VLCC Crude
100% Cargo Capacity	m^3	54,000	132,000	180,000	360,000
Main Engine Power, 75% MCR (P_{ME})	kW	6,916	10,366	12,888	20,052
Aux. Engine Power (P_{AE})	kW	461	596	680	918
SFC, Main Engine (SFC_{ME})	g-KWhr	**190.0**	**190.0**	**190.0**	**190.0**
SFC, Diesel Generators (SFC_{AE})	g-KWhr	**210.0**	**210.0**	**210.0**	**210.0**
Fuel Type		**HFO**	**HFO**	**HFO**	**HFO**
Fuel Conv Factors (C_{FME} and C_{FAE})	t CO_2	**3.114**	**3.114**	**3.114**	**3.114**
Deadweight at SLL (*Capacity*)	MT	49,203	116,135	166,576	303,032
Service Speed at Design Draft (V_{ref})	knots	**14.90**	**14.90**	**15.20**	**15.80**
Attained EEDI ($EEDI_A$)		**5.99**	**3.77**	**3.19**	**2.60**
Baseline EEDI ($EEDI_{BL}$)		6.11	3.86	3.19	2.32
Influence of Simplifying Assumptions -- Comparison to Calculated EEDI in Table 2					
GHG 2/2/7 applies constant SFC values		+7.1%	+7.8%	+7.8%	+8.4%
GHG 2/2/7 applies HFO rather than MDO		-2.9%	-2.9%	-2.9%	-2.9%
Impact: Combination of SFC & Fuel Type		+3.6%	+4.2%	+4.2%	+4.8%
GHG 2/2/7 applies speed at design draft		-3.0%	-3.2%	-2.8%	-2.0%
Overall influence of simplifying assumptions		+0.8%	+1.2%	+1.5%	+3.0%

**Table 6 Attained Index for Standard Tanker Designs
applying WG-GHG 2/2/7 assumptions**

The proposed baseline given in GHG-WG 2/2/7 is derived from statistics for existing tankers built between years 1998-2007. The attained EEDI for these existing vessels and the exponential curve fit to these data are presented in Figure 2. The cluster of points between 300,000 and 350,555 DWT represent the majority of the VLCCs. We find that the exponential curve as proposed in WG 2/2/7 is not a particularly good fit of the VLCC data, partially explaining why the standard tanker VLCC design fails to comply with this baseline criterion.
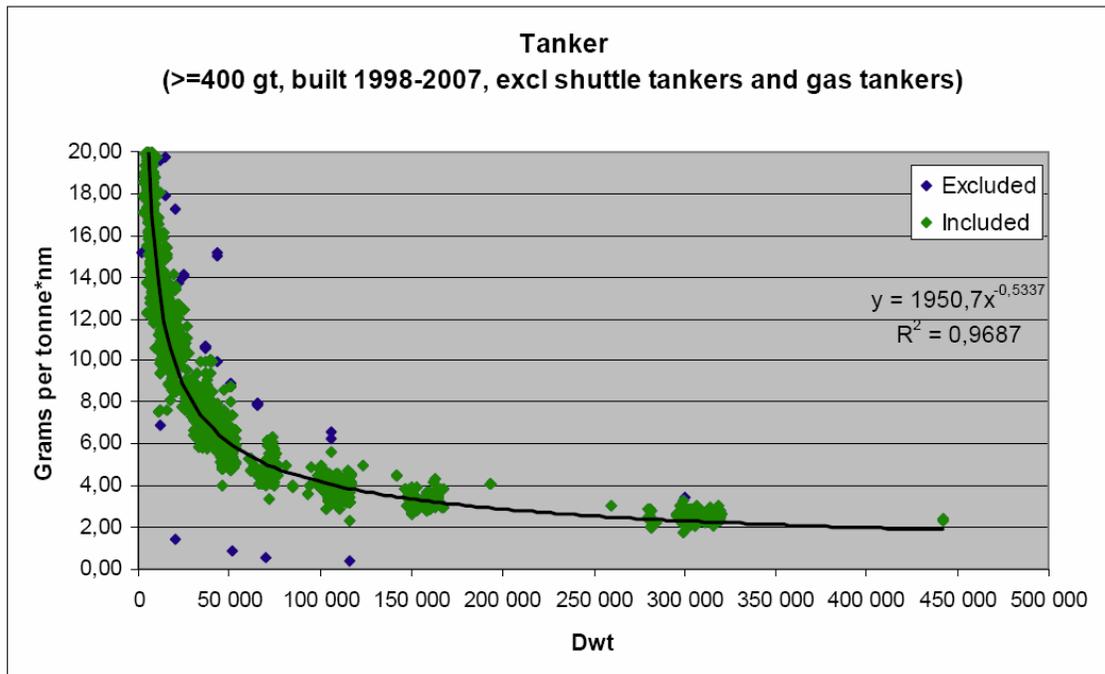
Figure 2 Baseline EEDI for Oil Tankers (per GHG-WG 2/2/7)

Containerships

Table 7 contains the attained EEDI for each standard design and the baseline EEDI. Note that the capacity for containerships is to be taken at 65% of the summer load line deadweight rather than 100% of the deadweight. Figure 3 is a graphical presentation of these data. The baseline values for containerships are determined from the following equation:

Baseline EEDI for Containerships = 214.44 (*SLL DWT*) $^{-0.2166}$

where *SLL DWT* = the deadweight at the summer load line draft

This is the equation presented in IMO paper MEPC 60/4/14 submitted by Denmark et al.

All designs fall 5.6% to 14.4% below the baseline. This is as expected, considering that the standard designs are modern designs with very good performance characteristics.

EEDI Calculation			Feedership	Panamax	Baby Neo-Panamax	Post-Panamax	Ultra Large
Slot Capacity	TEU		**1,000**	**4,500**	**4,500**	**8,000**	**12,500**
Main Engine Power, 75% MCR (P_{ME})	kW		7,003	28,899	30,998	43,382	56,940
Aux. Engine Power (P_{AE})	kW		467	1,213	1,283	1,696	2,148
SFC, Main Engine (SFC_{ME})	g-KWhr		173.3	175.3	175.3	175.3	175.3
SFC, Diesel Generators (SFC_{AE})	g-KWhr		196.9	196.9	196.9	196.9	196.9
Fuel Conv Factors (C_{FME} and C_{FAE})	t CO_2		3.206	3.206	3.206	3.206	3.206
Deadweight at SLL (*Capacity*)	tonnes		13,669	58,817	60,747	96,068	143,865
Speed at SLL and 75% MCR (V_{ref})	knots		18.71	24.73	24.78	25.22	25.46
Attained EEDI ($EEDI_A$)			**25.18**	**17.99**	**18.64**	**16.17**	**14.01**
Baseline EEDI ($EEDI_{BL}$)			27.26	19.87	19.73	17.87	16.37
%EEDI = ($EEDI_A$/$EEDI_{BL}$) - 1			-7.6%	-9.5%	-5.6%	-9.5%	-14.4%

Table 7 EEDI for Containership Standard Designs
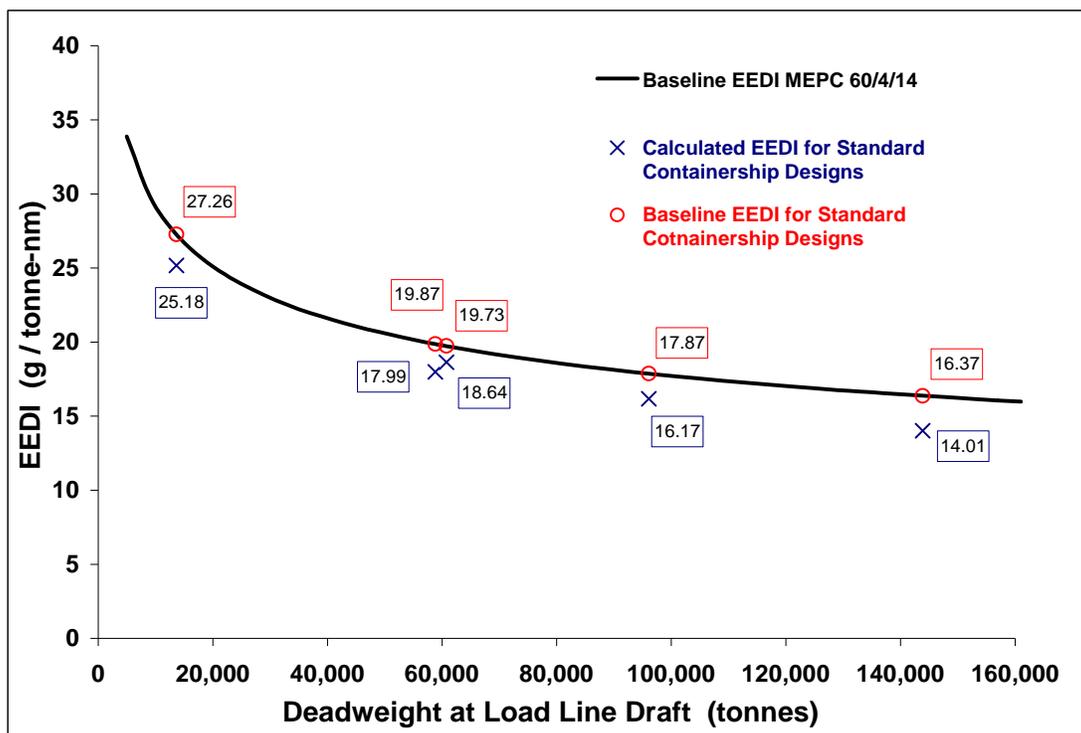

Figure 3 EEDI for Containership Standard Designs

The proposed baseline given in MEPC 60/4/14 is derived from statistics for existing containerships built between years 1998-2007. The attained EEDI for these existing vessels and the exponential curve fit to these data are presented in Figure 4. The cluster of points at about 160,000 DWT represent ultra-large containerships. We find that the exponential curve as proposed in MEPC 60/4/14 is not a particularly good fit of the large size vessels. Whereas for the tankers the curve fell below the data points, in this containership plot it lies above the data points. This explains the divergence in the %EEDI values for the ultra-large ships (14.4% below the baseline) as given in Table 7.
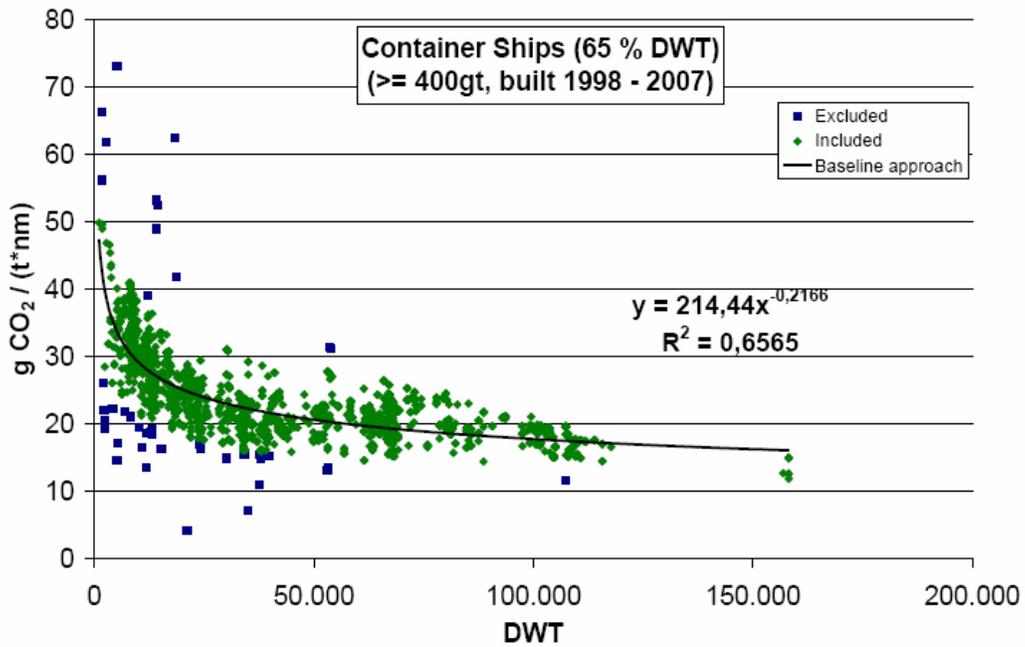
Figure 4 Baseline EEDI for Containerships (per MEPC 60/4/14)

LNG Carriers

Table 8 contains the attained EEDI for each standard design and the baseline EEDI corresponding to the summer load line deadweight. Figure 5 is a graphical presentation of these data. The baseline values for LNG Carriers are determined from the following equation:

Baseline EEDI for LNG Carriers = 1252.6 (*Capacity*) $^{-0.4597}$

where *Capacity* = the deadweight at the summer load line draft

This is the equation presented in IMO paper GHG-WG 2/2/7 submitted by Denmark.

Propulsion Plant Shafting Configuration		DFDE Single	DFDE Single	DFDE Single	DRL Twin	DRL Twin	DRL Twin
100% Cargo Capacity	m^3	150,000	180,000	215,000	180,000	215,000	265,000
Rated Power of Propulsion Motors	KW	25,930	28,317	31,696			
Main Engine Electrical Efficiency		91.3%	91.3%	91.3%			
Installed Main Engine Power (MCR)	kW				29,352	32,638	37,406
Main Engine Power (P_{ME})	kW	21,303	23,264	26,040	22,014	24,478	28,054
Aux. Engine Power (P_{AE})	kW	898	958	1,042	984	1,066	1,185
Deadweight at SLL (Capacity)	tonnes	85,837	99,309	117,537	98,205	116,366	141,710
Speed at SLL and 75% MCR (V_{ref})	knots	19.10	19.11	19.12	19.58	19.59	19.64
Fuel Type (LNG)							
SFC, Main Engine (SFC_{ME})	g-KWhr	159.3	159.3	159.3			
SFC, Diesel Generators (SFC_{AE})	g-KWhr	159.3	159.3	159.3			
Fuel Conv Factors (C_{FME} and C_{FAE})	t CO$_2$	2.750	2.750	2.750	2.750	2.750	2.750
Attained EEDI ($EEDI_A$)		**5.93**	**5.59**	**5.28**			
Baseline EEDI ($EEDI_{BL}$)		6.76	6.32	5.85			
%EEDI = ($EEDI_A$/$EEDI_{BL}$) - 1		-12.2%	-11.5%	-9.7%			
Fuel Type (MDO)							
SFC, Main Engine (SFC_{ME})	g-KWhr	204.2	204.2	204.2	173.3	172.3	173.3
SFC, Diesel Generators (SFC_{AE})	g-KWhr	204.2	204.2	204.2	196.9	196.9	196.9
Fuel Conv Factors (C_{FME} and C_{FAE})	t CO$_2$	3.206	3.206	3.206	3.206	3.206	3.206
Attained EEDI ($EEDI_A$)		**8.87**	**8.36**	**7.89**	**6.68**	**6.23**	**5.87**
Baseline EEDI ($EEDI_{BL}$)		6.76	6.32	5.85	6.35	5.88	5.37
%EEDI = ($EEDI_A$/$EEDI_{BL}$) - 1		31.2%	32.2%	34.9%	5.2%	5.9%	9.4%

Table 8 EEDI for LNG Carrier Standard Designs
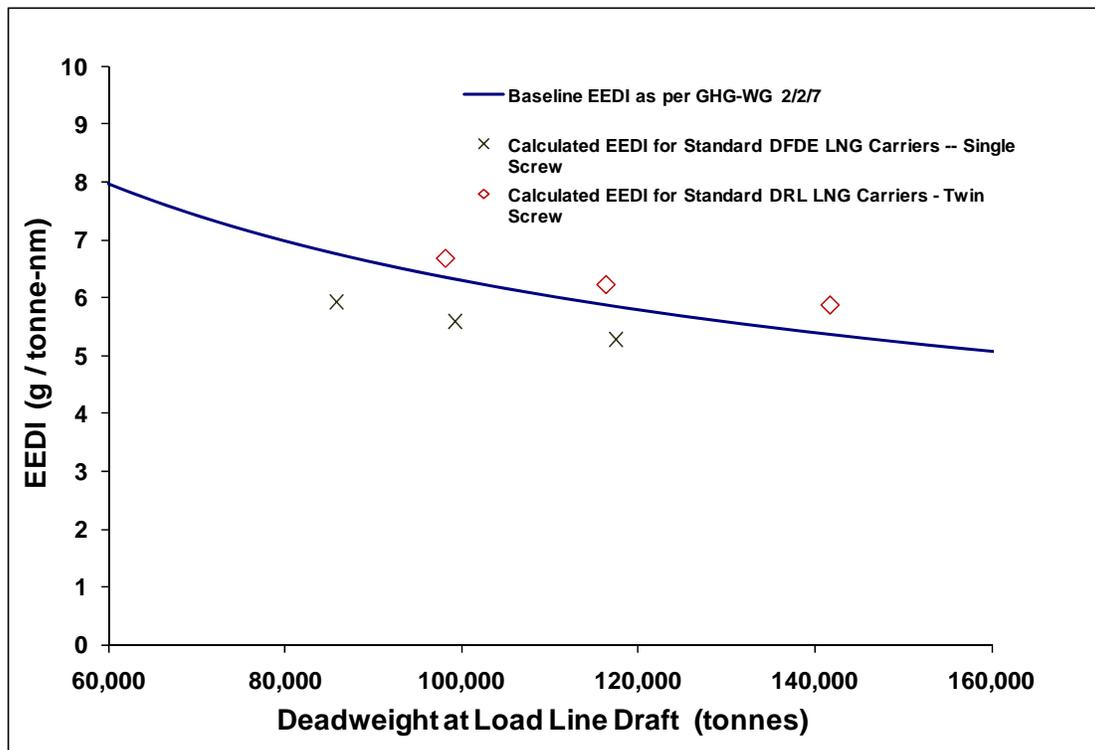
Figure 5 EEDI for LNG Carrier Standard Designs

The baseline index presented in IMO paper GHG-WG 2/2/7 was developed based on existing designs fitted with steam plants. The three single screw DFDE designs which burn boil-off gas are in compliance with the baseline, falling 9.7% to 12.2% below the baseline. The three larger twin screw DRL designs which burn fuel oil are 5.2% and 9.4% above the curve.

Similar to tankers, compliance with the baseline diverges at larger sizes, suggesting the proposed baseline needs adjustment for larger ships.

It should be noted that MEPC 60/4/7 proposes the elimination of steam powered vessels from the database when developing the LNG carrier baseline regression line. This decision would have a significant impact on the regression equations.

Propulsion Plant Shafting Configuration		DFDE Single	DFDE Single	DFDE Single	DRL Twin	DRL Twin	DRL Twin
100% Cargo Capacity	m3	150,000	180,000	215,000	180,000	215,000	265,000
Baseline Design Speed	knots	19.80	19.80	19.80	19.80	19.80	19.80
Adjustment to Speed to meet EEDI	knots	**0.75**	**1.00**	**0.46**	**-0.36**	**-0.40**	**-0.64**
Adjusted Design Service Speed	knots	20.55	20.80	20.26	19.44	19.40	19.16
Speed at SLL and 75%MCR	knots	19.83	19.74	19.58	19.22	19.20	19.00
Attained EEDI (EEDIA)		6.78	6.32	5.86	6.35	5.87	5.36
Baseline EEDI (EEDIBL)		6.77	6.33	5.85	6.35	5.87	5.36

Table 9 EEDI for LNG Carrier Standard Designs
(with design speed adjusted to achieve EEDI compliance)

5. Findings and Conclusions

Many of the findings and conclusions listed below are incorporated into IMO MEPC 60/4/33. This document was peer reviewed by SNAME Ad Hoc Panel No. 18 tasked with evaluating the EEDI, and submitted to IMO by the professional society IMarEST on behalf of SNAME. IMarEST has NGO status at IMO. MEPC 60/4/33 is attached as Appendix 1 to this paper.

Findings related to the EEDI baseline development

1. For the Panamax, Aframax, and Suezmax standard tanker designs, the Attained EEDI lies 1.5% to 3.5% below the baseline curves presented in GHG-WG 2/2/7 EEDI. However, the Attained EEDI for the VLCC lies 9.2% above the curve. The design speed of the standard VLCC is 15.8 knots, which is an average value for modern VLCCs. To achieve compliance, the design speed must be reduced to 15.1 knots, well below the typical service speed of VLCCs.

2. Some differences in the Attained EEDI and the baseline curve are to be expected, due to simplifying assumptions applied in GHG-WG 2/2/7. GHG-WG 2/2/7 assumes constant values for specific fuel consumption (SFC_{ME} = 190 g/kWh and SFC_{AE} = 210 g/kWh) and C_{FME} and C_{FAE} factors for HFO rather than lighter fuel oils. The quoted speeds in the LRFP database are applied, which are generally speeds at the design draft rather than the summer load line draft. The most common practice is to quote service speeds with 15%

service margin and the main engine operating at 90% MCR, which equals 0.90/1.15 = 78.3% MCR rather than 75% MCR. However, we find that for tankers, the overall impact of the simplifying assumptions is slightly conservative (tending to produce a higher attained EEDI value).

3. The likely source for the discrepancy in the VLCC EEDI calculation is the application in GHG-WG 2/2/7 of a single, exponential regression curve to represent all ships ranging from GT>400 to the largest vessels. At the tail of the curve representing the larger vessels, a majority of the data points lie above the curve. It is important that the baseline be a proper representation over the entire range of sizes, so that one particular size of vessel is not unduly impacted.

4. The attained EEDI for all containerships fall well below the proposed baseline presented in MEPC 60/4/14. The *%EEDI* (the attained/baseline EEDI ratio) for the ultra-large containerships fall 14.4% below curve, which is more favorable than the smaller sizes which lie 5.6% to 9.5% below the curve. As with tankers, much of the discrepancy can be traced to the exponential curve fit utilized in MEPC 60/4/14 to produce the baseline equation. In this case, the curve lies above the data points.

5. For LNG carriers arranged with DRL propulsion, the attained EEDI values when burning MDO as typically applied for the EIAPP certificate lie 5.2% to 9.4% above the baseline. The agreement between the attained EEDI and the baseline diverge for the larger vessels. For the LNG carriers with DFDE propulsion plants, the attained EEDI falls significantly below the baseline curve when burning boil-off gas, and significantly above the curve when burning fuel oil.

Conclusions related to the EEDI baseline development

1. The simplifying assumptions applied in GHG-WG 2/2/7 deviate significantly from actual performance data, but appear to largely offset one another. This was verified for tankers, but should be confirmed for other ship types.

2. The baselines are onerous for the VLCC per the regression curve from GHG-WG 2/2/7, while it appears lenient for the Ultra-Large containership using the updated curve from MEPC 60/4/14. Fitting of the regression curves should be reconsidered, so that all sizes of ships are properly represented.

3. Use of historical data does not necessarily reflect modern practice. This is particularly true for LNG carriers, which in recent years have increased in size by more than 60% and transitioned from steam propulsion to DFDE and DRL propulsion.

6. References

1. Larkin, J., Ozaki, Y., Tikka, K., Michel, K., "Influence of Design Parameters on the Energy Efficiency Design Index (EEDI)", SNAME Symposium, Climate Change and Ships: Increasing Energy Efficiency, Feb. 16-17, 2010.

2. MEPC .1/Circ 681 - "Interim Guidelines on the Method of Calculation of the Energy Efficiency Design Index for New Ships," 17 Aug 2009.

3. MEPC 58/4/8 - "Methodology for Design CO_2 Index Baselines and Recalculation thereof," 21 Jul 2008, submitted by Denmark.

4. GHG-WG 2/2/7 - "Recalculation of the Energy Efficiency Design Index Baselines for Cargo Ships," 4 Feb 2009, submitted by Denmark.

5. MEPC 60/4/7 - "Guidelines for Calculation of Baselines for Use with the Energy Efficiency Design Index," 18 Dec 2009, submitted by Denmark and Japan.

6. MEPC 60/4/14 - "Consideration of the Energy Efficiency Design Index for New Ships – Recalculated Baseline for Containerships," 12 Jan 2010, submitted by Denmark, Marshall Island, and World Shipping Council.

7. MEPC 60/4/33 – "Energy Efficiency Design Index Baseline Evaluation for Tankers, Containerships, and LNG Carriers," 15 Jan 2010, submitted by IMarEST.

8. MEPC 60/4/34 – "Influence of Design Parameters on the Energy Efficiency Design Index for Tankers, Containerships, and LNG Carriers," 15 Jan 2010, submitted by IMarEST.

Appendix   Document to MEPC 60 – MEPC 60/4/33