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ABSTRACT

A strategy for testing naval diesel engines for exhaust emissions was developed. A summary of existing legislative and resulting regulatory initiatives pertaining to marine diesel engine emissions was prepared. Naval ship data covering 11,500 hours of engine operation for four U.S. Navy LSD 41 Class amphibious ships was analyzed to develop a class operating profile. A procedure was detailed combining ship hull form characteristics, ship propulsion parameters, and ship operating profile to derive an 11-Mode Duty Cycle for testing LSD 41 Class propulsion diesel engines. The application of civilian industry standard duty cycles to predict naval ship propulsion engines was found to be inadequate by comparison of the derived 11-Mode Duty Cycle with seven existing cycles.

INTRODUCTION

The U.S. Navy has a long history of using diesel main propulsion engines to power its ships. The first U.S. Navy surface ship to be powered by diesel engines was the 14,500 ton oiler *USS MAUMEE* commissioned on October 23, 1916. Today, diesel engines are used for main propulsion on amphibious ships, mine counter-measure ships, and many large and small auxiliary ships. Most U.S. Navy ships are equipped with medium speed diesel generators for ship service electric load; a smaller number (69) have diesel main propulsion [1]. In the past thirty years diesel engines have also replaced steam plants as the propulsion plants of choice for many commercial ships.

Diesel engines procured for the Navy must successfully pass a 1,000 hour durability test outlined in Military Specification MIL-E-21260D, "Engines, Diesel Marine, Propulsion and Auxiliary, Medium Speed," of March 1976. No procedure is currently specified by the Navy to test diesel engines for exhaust emissions during the procurement process, or when operational with the fleet.

The goals of this paper are to provide a brief overview of legislative and regulatory initiatives currently being considered for marine application; to discuss the naval architecture speed vs. power relationship; to compare the operation of commercial and naval ships; to present a simple methodology for defining a naval ship operating profile; to present a naval ship main propulsion diesel engine duty (test) cycle and compare it with several industry accepted duty cycles; and finally to map out a way ahead for procurement of naval diesel engines for environmental compliance.

For this paper four of the twelve ships of the LSD 41, *WHIDBEY ISLAND*, Class have been selected for study. In developing the naval architecture discussion, the operating profile, and ultimately an 11-Mode Duty Cycle for this ship type were used for illustration. Each ship has four medium speed Colt-Pielstick 16 PC2.5 V400 diesels, each rated at 8,500 brake horsepower for main propulsion. The combined 34,000 brake horsepower (33,000 shaft horsepower) propels the two shafts and powers the 15,745 ton ship to a maximum speed of approximately 22 knots.

The LSD 41 Class includes eight ships of landing-ship-dock configuration and four cargo carrying variants. The mission of this ship class is to provide amphibious assault capability to 450 troops and four air cushion landing craft. This ship is designed and built to operate within visual range of shore and has been recently deployed in support of United Nations initiatives in Iraq, Somalia, and Haiti.

INTEREST IN MARINE EMISSIONS

Since the beginning of human of civilization the benefit of increased industrialization has brought with it the price of pollution. In our modern world the internal combustion engine is the workhorse of commerce. As a source of power, its high energy conversion to weight density has made it the engine of choice for powering our automobiles, trucks, aircraft, and ships. With the shift from wind powered sailing ships, and horse drawn vehicles has come an increase in anthropogenic atmospheric chemicals. These pollutants have degraded the quality of life of our civilization by endangering public health, degrading the public welfare in decreased visibility and by damaging our infrastructure and natural world.

Like all internal combustion engines, diesel engines intake fresh air, burn a fuel/air mixture, produce work and exhaust gases. Currently, the diesel cycle is the most efficient of the heat engine cycles widely used. However, incomplete fuel combustion, engine friction, and heat loses all reduce efficiency from the thermodynamic optimum.

Complete stoichiometric combustion is rarely achieved because of nonuniform mixing of air and fuel. Diesel engines are operated with excess air (lean) to enhance the combustion process. Within the cylinder of a typical diesel engine, combustion takes place in different regimes. In those areas where stoichiometric conditions exist, complete combustion occurs. These areas are typified by high temperature leading to oxidation of atmospheric nitrogen and production of nitric oxide (NO) and nitrogen dioxide (NO_2). Oxides of nitrogen (NO_X) are comprised of NO (80-90%) and NO_2 (10-20%) [2].

Surrounding the stoichiometric regions are fuel lean and fuel rich areas. The fuel lean regions are typified by lower temperatures and complete fuel combustion due to an excess of oxygen and the dilutive effect of excess air. The fuel rich regions have incomplete combustion due to a shortage of oxygen. In these areas carbon monoxide (CO) and pyrolized and unpyrolized fuel hydrocarbons (HC) are produced. Since diesel engines are normally operated fuel lean CO and HC products are not a substantial problem. Carbon dioxide (CO_2) and water (H_2O) are the ultimate products of complete fossil fuel combustion. The rate of CO_2 production increases with combustion efficiency but less fuel is required to produce a given amount of work. Optimization of the combustion process leads to a decrease in CO_2 production, a gas generally accepted as contributing to global warming by the green house effect.

Normal engine operation encompasses both steady state and transient conditions. Transient conditions occur during acceleration and deceleration between steady state conditions. During transients the fuel-to-air ratio changes. Engine responsiveness is limited by the air intake system. The result is often fuel rich combustion. Transient conditions are characterized by decreased NO_X and increased CO, HC and PM levels in the exhaust.

Diesel fuel contains a small (1-5%) amount of sulphur which combines with oxygen in the combustion chamber to form sulphur oxides (SO_X). Sulphur oxides have been shown to contribute to acid rain, degrade visibility and increase human respiratory problems. The problem of sulphur is being addressed by the specification for low sulphur fuels.

The State of California has completed several air quality studies. These studies indicate marine vessels substantially contribute to pollutants in the ambient air inventory. Table 1 provides a comparison of marine vessel emissions versus other sources for the State of California in 1987.

Included in these studies are emissions from all vessels, including diesel, gas turbine, and steam powered vessels. The vast majority of the approximately 22,500 vessels which operated in California waters during 1987 were diesel powered. Economic pressures forced the conversion of most steam and gas turbine commercial ships to more efficient diesel power during the 1970's and 80's. However, this trend has had a negative impact on ambient air quality as diesel engines produce about 10 times more NO_X than steam boilers [3]. The percent contribution of NO_X and SO_X by marine vessels is primarily due to lack of emission regulation compared to other more numerous sources, and the high sulphur content of fuels used for commercial diesel powered ships.

Table 1: Marine Vessels Versus Other Sources (1,000 tons/day) [4]

Source	HC	CO	NO_X	SO_X	PM
Stationary	5.30	6.0	0.97	0.21	11.00
On-Road	1.60	11.00	1.90	0.13	0.27
Off-Road	0.34	4.01	0.79	0.05	0.06
Marine	0.03	0.06	0.41	0.23	0.03
Total	7.27	21.07	4.07	0.62	11.36
% Marine	0.40	0.27	10.1	36.7	0.25

Marine diesel pollutants being considered for future regulation are NO_X , SO_X and particulate soot (PM) which is comprised of carbon and imbedded hydrocarbons. An inverse relationship exists between NO_X and PM. Engine in cylinder design changes to reduce NO_X generally produce an increase in PM. Diesel engine designers trade off reduced NO_X against increased PM.

LEGISLATIVE INITIATIVES

The International Maritime Organization (IMO) has acknowledged that national and regional legislation to limit engine exhaust emissions from ships is inevitable. In response, the IMO's Marine Environmental Protection Committee (MEPC) is currently working on standards for the prevention of air pollutants from ships. Specifically targeted is the reduction of NO_X and SO_X without an increase in other air pollutants. IMO has agreed to formulate a new annex to the International Convention for the Prevention of Pollution from Ships (MARPOL) 73/78. The new annex, Annex 6, will apply to new diesel engines over 100 kilowatts, and to non-public vessels over 500 gross tons. Proposed SO_X reduction of 50 percent of 1992 levels by 2000 is to be accomplished by a global cap of 3-4 percent fuel sulphur content and a limit of fuel sulphur of 1.5 percent on a regional basis in special areas. For new engines, 70 percent reduction of 1992 levels by 2000 for NO_X have been proposed. IMO anticipates completing work on Annex 6 by the end of 1994. Although the U.S. Coast Guard has participated in the development of Annex 6 as the official representative of the U.S. government, ratification by the U.S. Congress would be required to make Annex 6 law. Even though Annex 6 will likely exempt public vessels, it is probable that the U.S. Congress will mandate public vessel compliance upon ratification. Congress did just that when it ratified Annex 5 to MARPOL 73/78 in 1987 requiring public vessels to comply with the commercial standards. Regardless of what occurs in the international arena, control of emissions has been a priority of all levels of government within the United States.

The U.S. Congress enacted the Clean Air Act (CAA) in 1970. The central theme of the CAA is a cooperative federal-state scheme to achieve nationwide acceptable air quality. Section 108 and 109 of the CAA require the Administrator of the Environmental Protection Agency (EPA) to establish national ambient air quality standards (NAAQS) for criteria pollutants. Ambient limits have been established for PM, NO_2, Ozone, CO and SO_X.

Section 110 of CAA requires each state to develop State Implementation Plans (SIP's) to achieve the federally mandated primary and secondary NAAQS. In SIP development a state must include enforceable emission limitations and other control measures.

Section 213 of the CAA tasked the administrator to conduct a study of emissions from nonroad engines and nonroad vehicles to determine if such emissions cause, or significantly contribute to, air pollution which may reasonably be anticipated to endanger public health or welfare. Further, this section requires the administrator to issue emission standards for the nonroad source if it is found to endanger public health or welfare. Section 209(e)(2)(A) authorizes the State of California to adopt and enforce standards and other requirements relating to the control of emissions from nonroad engines or vehicles not covered elsewhere in the act. Marine vessels and engines are subject to regulation under this section. The State of California Legislature enacted the California Clean Air Act (CCAA) in 1988 to fulfil its unique status under the federal CAA to pioneer air quality improvement initiatives. Under this act, the California Air Resources Board (CARB) was required to consider controlling emissions from several previously unregulated nonroad mobile sources. Marine vessels and engines were included in the act for CARB regulation. CARB has proposed regulation of vessels operating within a zone defined as "California Coastal Waters". This area parallels the California coast and is within 27 miles off Point Conception, and as far as 100 miles off the San Francisco Bay Area. The distances were developed based on meteorological and modelling data showing how emissions off the coast affect coastal land areas. Information supplied to CARB by the U.S. Coast Guard indicates all commercial shipping calling at California Ports transits within 20 miles of shore. The U.S. Navy conducts extensive amphibious assault training exercises off the coast of the Camp Pendelton Marine Base in San Diego County, an area within the coastal waters zone [5].

On 24 February 1994, the Administrator of the EPA signed the California Federal Implementation Plan (CFIP). The CFIP was developed by EPA since California had not developed SIP's for each of their Air Quality Management Districts as it was required to do under CAA. The CFIP maintains the basic elements of the CARB proposed plan and adds an emission fee system.

The fee system proposed in the CFIP significantly impacts frequent users of California ports and high emitters. The basic fee of $10,000 per U.S. ton NO_X emitted will apply to commercial shipping. Table 1 indicates that commercial ships operating in the California Coastal Waters zone emit 410 tons/day NO_X. At this emission rate, 4.1 million dollars in fees would be collected daily. However, incentives within the fee collection system reward reductions in NO_X: 90 percent fee reduction for 80 percent NO_X reduction; 50 percent fee reduction for 30 to 80 percent NO_X reduction; Full fee if less than 30 percent NO_X reduction; Fee reduction for use of the relocated Santa Barbara shipping channel (located farther out to sea), and use of shore power when in port. [6]

The fee system is expected to encourage the development of shipboard emission control systems and provide incentives for more efficient operation and use of shore power inport (cold-ironing). Each commercial vessel operating in California Coastal Waters must report hours of operation and rated power for each engine on board. The proposed model used for fee collection purposes equates NO_X to RPM based upon engine research conducted in Scandinavia and Japan. Figure 1 gives this model [7].

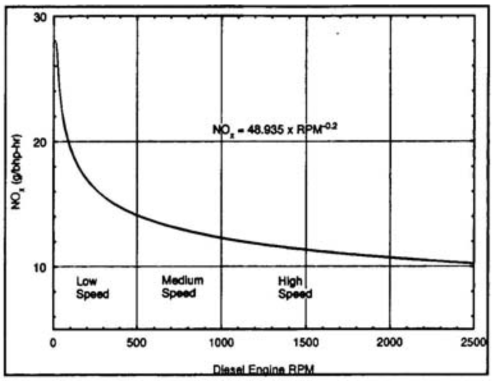

Figure 1: Japanese NO_X Formula

The CFIP presents a clear shift in regulatory strategy. The impact of its full implementation on the work of the IMO and international trade has not been fully assessed. The reliance upon a model equating NO_X to RPM without regard for engine torque or cylinder pressures indicates that the regulatory environment is shifting from analysis to action, but not necessarily the prudent action.

REGULATORY ACTION

The U.S. Congress and EPA have adopted a pareto regulation strategy. To date standards have been established for stationary sources, and light-duty vehicles (automobiles and light-duty trucks). This practice regulates those air pollution sources where the greatest cost/benefit ratio can be had. The emphasis for new regulation in the 1990's will likely be for the more numerous smaller stationary and mobile sources.

The EPA has broad authority to study, propose, enact, and enforce regulations of mobile nonroad emission sources. The Administrator has periodically published emission controls for heavy duty diesel engines under transient conditions, Table 2. Although not binding on marine vessels, these standards offer a preview of probable future marine diesel standards and the trend for reduction.

The EPA completed its CAA Section 213 study of nonroad engine and vehicle emissions in November 1991. Based on this study, on 17 May 1993 EPA proposed nonroad heavy duty diesel emission standards of 6.9 g/bhp-hr NO_X and proposed smoke opacity standard of 20% during acceleration, 15% on lug mode, and 50% peak opacity on either the acceleration or lug mode. EPA did not issue proposed emission standards for SO_X, HC, CO and PM. Available test procedures had not been demonstrated capable of predicting these pollutant emissions from nonroad sources. Specifically excluded from these proposed regulations are engines used for main propulsion and auxiliary power in marine vessels. Marine vessel engines were not included for two reasons. First, marine engines (excluding U.S. Navy applications) are currently subject to safety regulations by the U.S. Coast Guard. EPA must first analyze current Coast Guard safety requirements, then determine the best method for regulating emissions, consistent with Coast Guard regulations. Second, information was unavailable verifying existing test procedures as applicable to marine engines. EPA recognized that existing test procedures are not adequate for predicting marine diesel engine emissions [8].

Table 2: EPA Heavy-Duty Diesel Emission Standards (g/bhp-hr)

Year	NO_x	PM
1986	10.7	0.60
1990	6.0	0.60
1991	5.0	0.25
1994	5.0	0.10
1998	4.0	0.10
2000*	2.5	0.05

Note: * CARB proposal.

Regardless of EPA action, CARB has proposed new marine vessel engine emission standards, in-use marine vessel engine emission standards, new and existing source permit requirements, and a broad market based strategy aimed at reducing vessel exhaust emissions effective in 1995. Table 3 provides these new proposed NO_x standards applicable to marine diesel engines.

Table 3: CARB 1995 Marine Vessel Proposed Diesel NO_x Emission Standards (ppm) [9]

Application	Baseline	Proposed	Reduction
New Engines			
Propulsion (Load ≥ 25%)	650 - 1,200	130	78 - 89
Propulsion (Load <25%)	*	450	*
Auxiliaries	600 - 1,200	600	0 - 50
Existing Engines			
Propulsion	600 - 1,680	600	0 - 64
Auxiliaries	650 - 1,200	750	0 - 38

Legislative and regulatory action has thus far exempted public vessels for compliance to the evolving standards. However, the naval community can not rely upon this to continue indefinitely. Action must be taken now to estimate current emission levels so that when regulation does occur, the magnitude of the problem will be identified. For this reason, the development of a marine test procedure is vital for providing repeatable emission data. Several duty cycles have been proposed to accomplish this. However, the unique operation of U.S. Naval ships and their resulting engine emissions has not yet been properly modeled.

Duty cycle development establishes the normal time history of engine speed and power for a given application. The first step is to apply the fundamental principles of ship powering to relate ship speed to engine parameters. Secondly, ship operating logs were analyzed to determine the time/speed operating profile. Log review provided the three independent variables of time, shaft RPM and propeller pitch. Finally, the operating profile was consolidated into a duty cycle by applying the speed/power equations for representative operating points. The final step was necessitated since logs are not kept detailing engine speed against time. The time history comprising the operating profile is an inference based on recorded ship speed and the speed/power equations. The following sections will detail the procedure followed in developing a duty cycle for the LSD 41 Class ship.

SHIP POWERING

The ship propulsion plant must provide sufficient power to overcome ships resistance to forward motion. This resistance, or drag, is composed of two primary components; frictional resistance and residuary resistance. Frictional resistance usually is the largest single contributor to total ship resistance. Experiments have shown it accounts for 80 to 85 percent of total resistance in slow-speed ships and 50 percent in high-speed ships [10]. Air resistance created by the above water portion of the ship also causes drag. Environmental effects such as wind, waves, currents, biologic fouling, and hull corrosion contribute to frictional resistance, increasing the power required for a given speed.

Residuary resistance consists of both wave making and eddy resistance. Wave making resistance refers to energy expended in producing a surface wave system as the ship moves through water. Eddy resistance refers to energy lost as vortices are produced and shed from appendages such as: propeller shafts, shaft struts, rudders, and ship stern.

At slow ship speeds frictional resistance predominates. At higher speeds the effect of residuary resistance becomes most important. Frictional resistance and residuary resistance are additive. For speed-to-length ratios ($\text{Speed}/\sqrt{\text{Length}}$) of less than about 0.6, frictional resistance is dominant; above 0.6, wave making becomes dominant. In the LSD 41 Class this transition occurs at a ship speed of 12-14 knots. In the frictional regime, viscous forces predominate and resistance is proportional to velocity squared. In the residuary regime, inertial forces predominate and resistance is proportional to velocity cubed.

During ship design, ship powering requirements are determined analytically and by scale model testing. Tests are conducted in both still and rough water to simulate heavy seas. In calculating required installed power, predictions are made for machinery degradation, sea state, wind, currents and other environmental effects. Once the ship has been built sea trials are performed to test each installed system under actual operating conditions. Standardization Trials establish the actual relation between ship speed and propulsion plant parameters.

Underwater hull shape determines ship powering requirements. Principle dimensions of the LSD 41 Class are provided in Table 4. Varying ship loading conditions directly effects displacement and powering requirements.

Design ship power/torque requirements for a given ship speed are uniquely dependent on external ship resistance factors. For this paper ship displacement, speed and power were treated as first order variables. Second order effects of ship heading, wind speed, sea state, and hull fouling were not included in the model.

Table 4: LSD 41 Class Principle Hull Dimensions

Design Displacement	15,745 ltons
Length Overall	609.6 ft
Length Between Perpendiculars	580 ft
Extreme Beam	84 ft
Design Draft	19 ft
Prismatic Coefficient (C_P)	0.612
Maximum Section Coefficient (C_X)	0.945
Block Coefficient (C_B)	0.578
Waterplane Area Coefficient (C_{WP})	0.779
Wetted Surface Area	50,100 ft^2

LSD 41 CLASS PROPULSION PLANT STUDY - Derivation of the naval ship duty cycle required establishing the proper relationships between ship speed, propeller shaft horsepower (SHP) and rotation rate, and diesel engine speed and brake horsepower (BHP). Reduction gear ratio, mechanical efficiency, shaft turns-per-knot and ship speed versus power relationships were determined.

The two shafts of the LSD 41 Class are each powered by two Colt-Pielstick 16PC2.5V four stroke, turbocharged, intercooled, non-reversing diesel engines. Qualification for U.S. Navy shipboard application required derating the engine by 18% to 8,500 BHP at 520 revolutions per minute (RPM). Each diesel is connected to the Philadelphia Gear reduction gear via pneumatic clutch in order to transmit power. The reduction gear is a locked train single reduction gear with two drive pinions, each clutched to a main propulsion diesel engine. The reduction gear reduction ratio (Λ) is given by EQ (1). Power is transmitted into the water via twin 5-bladed, 13.5 foot diameter Bird-Johnson controllable-reversible pitch propellers.

$$\Lambda = \frac{RPM_{Diesel}}{RPM_{Shaft}} = 3.1515 \qquad (1)$$

Power is lost due to component friction where power is transmitted from the prime mover to the propeller. Mechanical efficiency (η_{MECH}) compares SHP measured at the propeller and BHP measured at the prime mover output shaft. EQ (2) provides this relation for the LSD 41 Class.

$$\eta_{MECH} = \frac{SHP}{BHP} = \frac{33,000}{34,000} = 0.971 \qquad (2)$$

LSD 41 Class ships operate over two distinct speed ranges. At speeds below 10 knots ship speed is controlled by varying propeller pitch. At speeds above 10 knots ship speed is controlled by shaft RPM. In the pitch controlled regime the shaft is operated at a constant 64 RPM; speed is varied by changing the pitch of the propeller. Above 10 knots propeller pitch is set at 100 percent and speed is varied by shaft RPM. Within the two regimes a mostly linear relation between pitch/rpm and speed exists. Figure 2 gives the relation in the ahead direction.

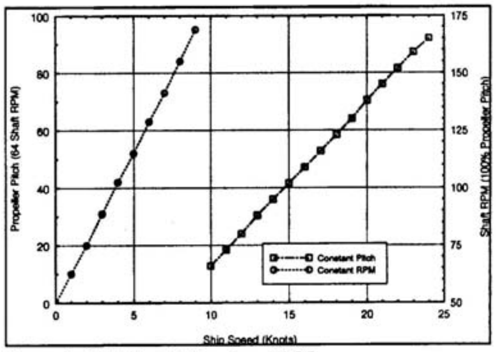

Figure 2: Ship Speed Ahead vs. RPM

The two curves of Figure 2 may be represented by equations for straight lines. Ship speed is modeled as linearly dependent on propeller pitch or shaft RPM. EQ (3) gives the ship speed equation for operation in the constant RPM region where speed is governed by propeller pitch. EQ (4) gives the ship speed equation for operation in the RPM controlled region.

$$Speed_{Ship} = 0.0948 \times Pitch_{Propeller} \qquad (3)$$

$$Speed_{Ship} = 0.143 \times RPM_{Shaft} + 0.571 \qquad (4)$$

Similar equations describe the astern dependence. Greater power is required to move the ship in the astern direction. The shape of the bow presents a streamlined shape which requires less energy to move in the forward direction. The blunt stern section behaves as a bluff body and has a much higher drag coefficient when moving astern.

Data from LSD 41 Standardization Trials provides the relation between speed and power. Curve fitting the Trial speed and shaft power data provides the speed vs. power graph given in Figure 3. The curve of Figure 3 is a combination of two curves covering the two resistance regimes. The frictional regime is represented by EQ (5) and the residuary dominated regime is given by EQ (6). EQ (5) is valid up to 12 knots, and

EQ (6) is valid from 10 to 25 knots. The overlap of 2 knots illustrates the transition from frictional to residuary resistance control.

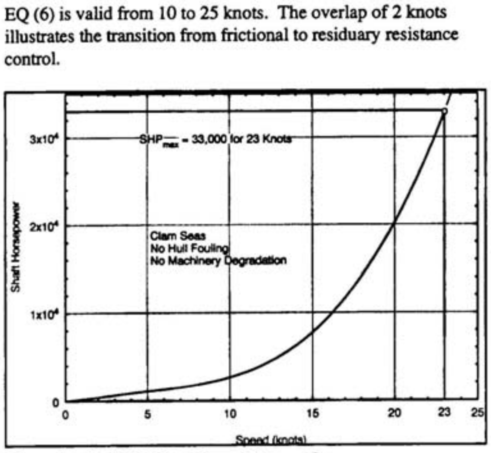

Figure 3: LSD 41 Class Speed Power Curve

$$Power = 9.6\times Speed^{2}+172\times Speed \qquad (5)$$

$$Power = 5.04\times Speed^{3}-79.7\times Speed^{2}+621\times Speed-674 \qquad (6)$$

TYPICAL NAVAL SHIP OPERATION

U.S. Naval ships record a variety of information in official log books. These logs form a record of all significant ship events throughout its service life. Research for this paper reviewed two logs in detail. The information gained from log review was used to develop the class operating profile. Logs analyzed were the ships Deck Log and Engineering Log. Other logs such as engine operating log data sheets and navigation (NAV) logs were examined to correlate the data found in the Deck Log and Engineering Log. The primary log data used in this analysis were time and ordered pitch and shaft RPM.

The Deck Log provides a historical record of all events deemed noteworthy throughout the life of the ship. The time and order given for each change in engine speed and ships course are recorded in this legal record. NAV logs were reviewed to correlate distance from land.

The Engineering Log records information related to the engineering plant such as starting and stopping a major piece of equipment, clutching an engine into the reduction gear, and maintenance actions. Engine operating logs record hourly engine speed, temperatures and pressures for each operating engine. These logs provide an indication of total time in operation, and abnormal, or out-of-specification conditions.

OPERATOR PREFERENCE - Operator preference is the single most important factor governing the operating profile of main propulsion engines. Operator preference refers to the skill, training level, and aggressiveness of those navigating the ship and responding to engine speed change orders. The skill and training level of the navigation team becomes apparent through review and comparison of the Deck Log entries for similar ship evolutions, such as, anchoring, getting underway from a pier, and mooring to a pier. More highly skilled teams will have fewer number of speed changes over the course of the evolution.

Aggressiveness is difficult to quantify, but refers to the level of dexterity demonstrated in how a ship is operated. An aggressive navigation team may not use tug boats in getting underway or mooring to a pier. The time required to perform these evolutions may also by minimized, reducing time engines are operated at low load or at idle.

Ship port departure speed is subject to the preference of the navigation team led by the ships commanding officer. The amount of redundant equipment in operation is also largely a matter of preference. Experience shows accident boards are more forgiving of ship captains who prepare for potential problems by having equipment ready to instantly come on line should a casualty occur. This tendency for equipment redundance may be prudent for vessel operation, but results in lightly loaded equipment operating for long periods of time.

UNDERWAY SHIP OPERATIONS - In developing the LSD 41 Class Operating Profile ship operating logs were reviewed to determine time factors for engine speed/loading conditions. To remain consistent with the California Coastal Waters definition, ship operations out to 100 nautical miles from land were recorded in the database.

Unlike commercial ships getting underway for profit, naval vessels most often get underway for training. Commercial vessels are typically operated at speed and power combinations that maximize fuel efficiency. Commercial vessels also tend to follow tracks that minimize the distance from port to port. Although naval vessels are concerned with fuel economy, efficiency is often sacrificed for speed, maneuverability, and other operational requirements.

Underway preparations usually begin several hours before the ship actually leaves port. Shore services are disconnected and the ship becomes self-sufficient in electric power, fresh water and steam. Approximately 45 minutes prior to underway time the main propulsion diesel engines (MPE's) are started. After warming up for 10 minutes they are clutched into the reduction gear, and remain at idle for the next 35 minutes on average.

Naval ships are operated most conservatively during the transit to and from sea. As a ship maneuvers from the pier through the harbor and out to sea it is most vulnerable to collision with other vessels or to grounding. Probability of an adverse action is greatly increased by failure within the propulsion or electrical plant. To decrease failure probability, redundant systems and equipment are in operation during the time that a ship transits to or from sea. A special operating condition, Sea and Anchor Detail, governed by the Restricted Maneuvering Doctrine (RMD) is manned to maximize equipment and personnel readiness. A normal Sea and Anchor Detail typically lasts for about two hours as a ship transits in and out of port.

The traditional underway usually begins with the shafts turning in opposite directions to twist the stern of the ship away from the pier. Next the shaft directions are reversed and the bow of the ship moves away from the pier. This series of engine orders may number ten bell (speed) changes over a span of five minutes. During this phase of maneuvering the engines are essentially steady-state only briefly, or mostly transient, before the next bell. Away from the pier, the ship slowly makes headway of three to five knots. Clear of close obstacles, ship speed is often increased to ten knots for the remainder of the transit to open water. When in open water, ship speed then becomes more discretionary for the navigation team.

Once at sea, the ship secures from the Sea and Anchor Detail and the RMD. After securing from RMD most ships typically shift engineering plant operation to maximize fuel efficiency and minimize machinery wear. The normal post RMD lineup consists of one MPE per shaft and two SSDG's in parallel. The maximum speed that can be attained by LSD 41 Class in this lineup is roughly 18 knots. Evolutions requiring more speed and power necessitate additional MPE's on the line.

U.S. Navy ships operate off the Southern California Coast in the SOCAL Operation Area, and off the Norfolk, Virginia area in the VACAPES Operation Area. These operating areas are generally within 100 nautical miles of land. While operating in these areas ships will conduct: man overboard drills, shiphandling training, shipwide warfighting and casualty control drills, underway replenishment to resupply with fuel, ammunition and stores, flight operations, and trend analysis/ maintenance on equipment.

LSD 41 CLASS MPE OPERATING PROFILE

The wide range of operator preferences coupled with the variety of ship evolutions complicates the development of a standard naval ship operating profile. The application of commercial or civilian standards to describe naval ship operation is inappropriate. Four LSD 41 Class ships logs, covering several months of operation within 100 nautical miles of land, were analyzed. Logs of ships from the east and west coasts were reviewed to distinguish geographically related differences. Two ships were homeported in Little Creek, Virginia, and two were homeported in San Diego, California. Table 5 presents a summary of the operational time evaluated.

Developing the ship operating profile involved determining time of operation at specific speed and power combinations. Figure 4 provides a flowchart of the logic used to perform the profile analysis using EQ's (1) through (6) presented in the previous section. The method illustrated by Figure 4 links ship speed to MPE speed and power. Figure 5 gives the four ship composite operating profile of the LSD 41 Class operating within 100 nautical miles of land.

The operating profile developed in this paper considered steady state operation only. The method of data collection used was not conducive to capturing transient information. However, this was deemed acceptable since several orders of magnitude separate the time spent in transient and time spent in steady state operations. The typical main propulsion diesel transient event is a relatively short order event.

Table 5: LSD 41 Class Main Propulsion Engine Ship Data Summary

	LSD 43	LSD 44	LSD 46	LSD 47
Name (USS)	Fort McHenry	Gunston Hall	Tortuga	Rushmore
Coast	West	East	East	West
Dates (1993)	12 Jul 16 Dec	14 Sep 30 Nov	3 Mar 20 Sept	1 Jun 16 Dec
Data Points	5,011	2,816	4,267	3,013
Engine Time in Minutes				
Total	252,324	133,052	159,845	145,517
Secured	74,589	54,499	76,872	51,025
Running	177,735	78,553	82,973	94,492
Warmup	1,458	1,306	1,892	1,571
@ Idle	2,886	1,725	2,357	1,155
@ Power	173,391	75,522	78,724	91,766

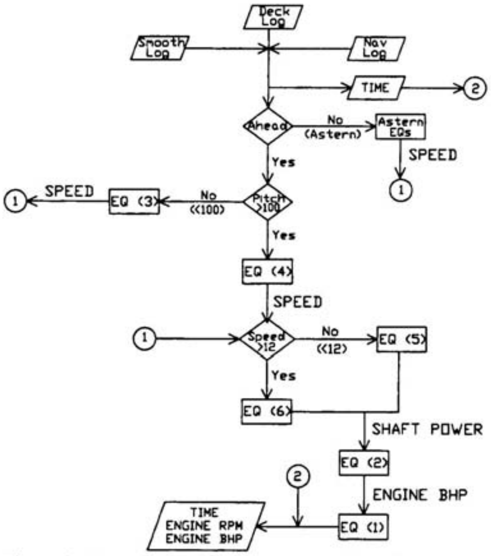

Figure 4: Operating Profile Development Flow Chart

The ship speeds and composite time factors given in Figure 5 should be representative of most naval diesel powered amphibious assault ships while they operate in areas close to shore. The speed profile given in Figure 5 shows that the LSD 41 Class operates primarily in the higher speed ranges centered around 17 knots. This is not coincidence since 17 knots is near the design endurance speed for most U.S. Naval ships. Time factor spikes exist at 0, 5 and 10 knots. The value for 0 knots is comprised of cold and warm idle. Cold idle has a time factor of 0.014 and warm idle 0.067, making warm idle greater than cold idle by a factor of five.

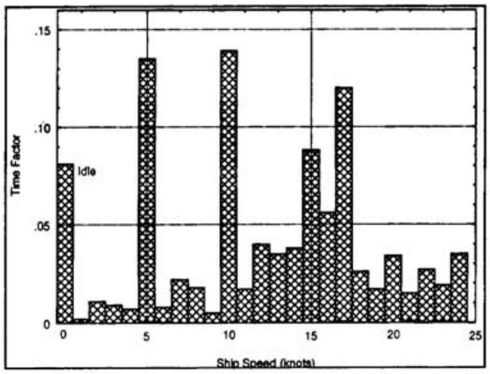

Figure 5: LSD 41 Class Composite Speed Operating Profile

OPERATING PROFILE COASTAL VARIATION - The ship operating profile provided in Figure 5 is a composite of the four ships profiles. Figure 6 illustrates the variation between the four ships. Figure 7 delineates the variation between ships operating on the east and west coasts and compares them to the composite operating profile.

The comparison between ships in Figure 6 shows that each ship is operated in generally the same manner. Trends given by the four curves are of the same shape; they track within a band of 18 percent variation. The greatest variation occurs at speeds above 10 knots. The indicated variation is largely dependent upon the evolutions each ship was engaged in as well as the preference of the individual operator.

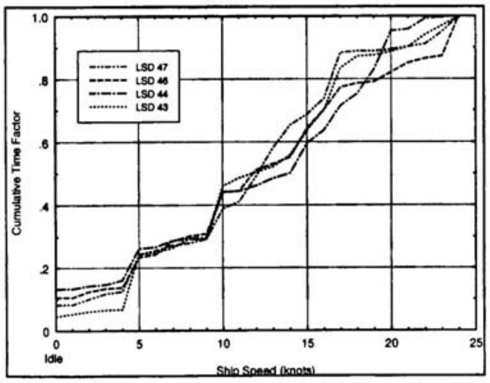

Figure 6: Ship Operating Profile Cumulative Time Factor Comparison

In Figure 7, the widest variation occurred at 17 knots within a span of 15 percent. Except for the region between 16 and 19 knots the three curves tracked very close to one another. The variation below 4 knots was due to differences in time spent at idle. West coast ships spent approximately 7 percent more time at idle than did east coast ships. The greater amount of time spent by west coast ships at idle is primarily due to the layout of the harbor and geometry of the piers. The profile followed by west coast ships takes more time than east coast ships to reach open water. The use of tugs by west coast ships is also greater due to the greater difficulty in maneuvering close to the nested piers.

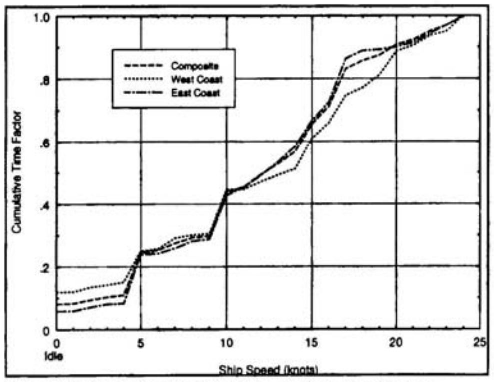

Figure 7: Operating Profile Cumulative Time Factor Comparison by Coast

NAVAL MAIN PROPULSION DIESEL DUTY CYCLE

A duty cycle must provide an accurate model of the range of speed and power points at which an engine is operated, and also be concise and easy to use. A duty cycle consisting of five to ten modes is preferable to one using ten to fifteen, provided it accurately reflects engine operation. However, accuracy should not be sacrificed for brevity. The duty cycle must simulate the actual operating profile such that engine emissions are equivalent.

To date, most duty cycles have been developed for generic application to a wide variety of land based power systems. These systems are on-road vehicles, non-road vehicles and heavy equipment, railroads, power generating facilities and portable industrial equipment. For land based propulsion systems a direct relation between output required and vehicle weight and friction usually exists.

As discussed, underwater hull form shape and wetted surface area determine the ship powering requirement for a given speed. Commercial ship engines are designed to provide optimum fuel economy at some cruising speed. Engines are sized according to ships full load weight. For an established cruising speed, the fraction of rated engine RPM and engine power are relatively constant. The theory behind ISO 8178-4 duty cycles E1, E2 and E3 reflects operation at a few engine speed/power combinations. For most of their operational life commercial ships cruise at between 15 and 20 knots.

Naval ship engines are sized for performance rather than efficiency. The ship hull is established and propulsion plant sized to provide some design sustained speed in excess of the endurance (cruise) speed. For example, the operating profile of Figure 5 shows that the LSD Class has a top speed of 24 knots. However, it operates most frequently at 17 knots. This apparent overcapacity in propulsion plant power results in an extremely wide range of engine operating combinations. The majority of naval ship hulls are displacement type but of many different shapes. Each has a distinct speed power relation. The diversity of diesel engine sizes and types, coupled with the wide variety of hull form designs, complicates the use of generic speed power simplifications.

Each hull design has a unique resistance relationship resulting in a myriad of diesel engine options. For these reasons, a simple four or five mode duty cycle is not appropriate to describe naval ship engine operation. Rather, the operating (speed) profile must be determined then engine speed and power calculated based on appropriate relationships. Figure 8 provides a flow chart for determining the individual ship type propulsion plant duty cycle.

The entering arguments of Figure 8 are the standard composite operating profile and ship specific propulsion train and powering information. The composite operating profile of Figure 5 has been reduced from 25 to seven speed points. Speed points and associated time factors are given in Table 6. Ranges covered by each speed point were grouped by engine speed and power around each major speed spike indicated in Figure 5.

By using the method of Figure 8 a naval ship specific duty cycle may be readily developed. As some ships may have multiple engines clutched to each shaft, care must be taken to ensure each engine speed/power combination is adequately represented for all machinery lineups normally used.

Table 6: Consolidated Naval Amphibious Ship Operating Profile

Ship Speed (knots)	Time Factor	Speed Range (knots)
0	0.083	Idle - 1
5	0.192	2 - 7
10	0.218	8 - 12
15	0.160	13 - 15
17	0.200	16 - 18
20	0.093	19 - 22
24	0.054	23 - 24

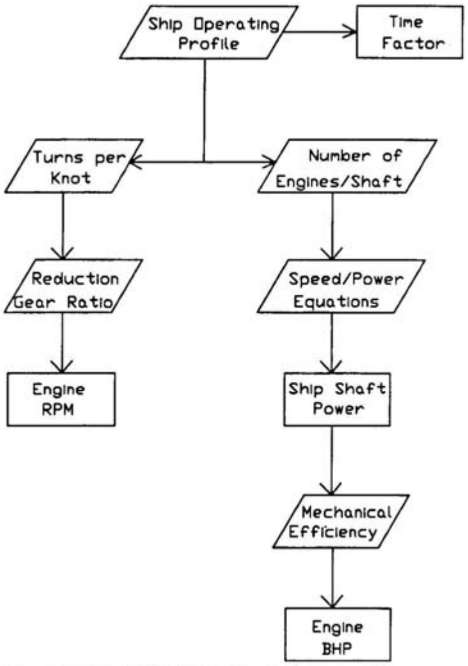

Figure 8: Naval Ship Duty Cycle Determination

LSD 41 CLASS MPE DUTY CYCLE - The LSD 41 Class may be operated with either one or two engines per shaft. Both conditions must be included in the resulting duty cycle. The LSD 41 MPE Duty Cycle, as developed from the method given in Figure 8, is given in Table 7.

Table 7: LSD 41 Class MPE Duty Cycle

Mode	Ship Speed	Engine Speed (% Rated)	Engine Power (% Rated)	Time Factor
1	0	Idle	0.000	0.083
2	5	0.387	0.065	0.064
3	5	0.387	0.032	0.128
4	10	0.398	0.158	0.077
5	10	0.398	0.078	0.141
6	15	0.615	0.468	0.051
7	15	0.615	0.234	0.109
8	17	0.700	0.704	0.040
9	17	0.700	0.352	0.160
10	20	0.833	0.612	0.093
11	24	1.000	1.000	0.054

DUTY CYCLE COMPARISON

Diesel engine duty cycle comparisons were performed to validate methodology used in preparing the naval ship duty cycle, and compare it to industry accepted standards. The MPE comparisons were performed using emission contour maps provided in *The Motor Ship* article "Designers Anticipate Engine Emission Controls", of August 1992 for the Colt-Pielstick PC4-2B. Three dimensional information is displayed as a contour map in two dimensions. Graphs were normalized to rated power and RPM to give maximum speed and power values of unity. Engine power was normalized to Power Fraction using EQ (7) and engine RPM was reduced to RPM Factor by EQ (8).

$$Power_{Fraction} = \frac{Power_{Point}}{Power_{Rated}} \qquad (7)$$

$$RPM_{Factor} = \frac{RPM_{Point} - RPM_{Idle}}{RPM_{Rated} - RPM_{Idle}} \qquad (8)$$

Propeller curve plots of single and twin engines per shaft were superimposed on the emission contour maps. Figures 9 to 12 provide these superimposed graphs. Brake specific emission levels were then read from the curves by linear interpolation. Values given describe engine emissions as a function of ship speed.

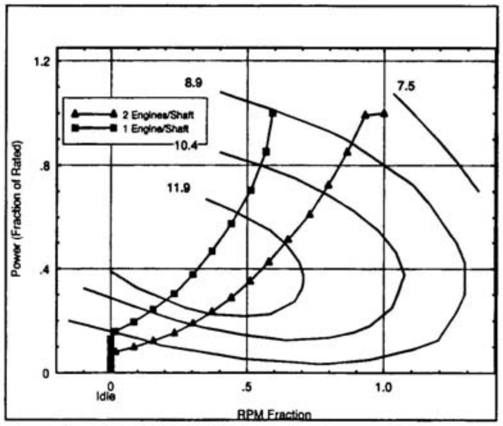

Figure 9: LSD 41 MPE NO_X Emission Contour Map (g/bhp-hr)

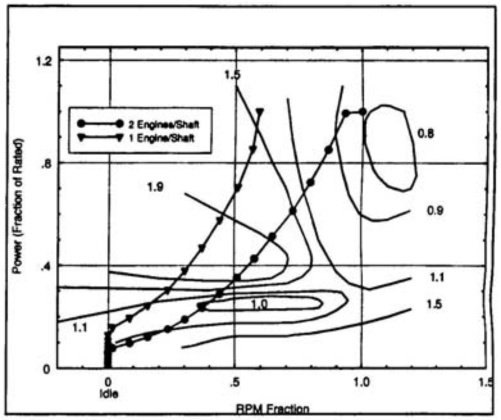

Figure 10: LSD 41 MPE CO Emission Contour Map (g/bhp-hr)

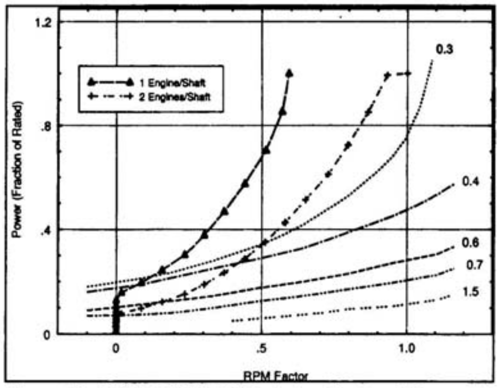

Figure 11: LSD 41 MPE HC Emission Contour Map (g/bhp-hr)

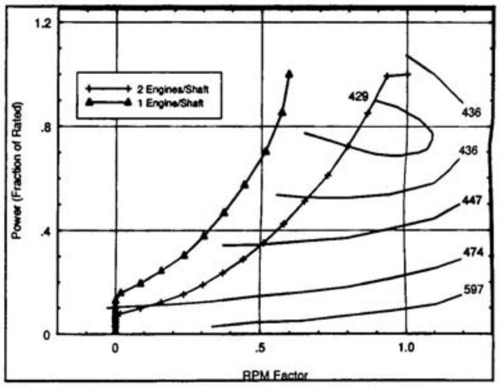

Figure 12: LSD 41 MPE CO_2 Emission Contour Map (g/bhp-hr)

LSD 41 Class MPE Duty Cycle modes listed in Table 7 were next superimposed on the emission contour maps and engine specific brake emissions calculated. Table 8 provides the resulting LSD 41 Class propeller curve and LSD 41 Class Duty Cycle emission predictions.

Table 8: LSD 41 Class Emission Predictions (g/bhp-hr)

Prediction Method	NO_x	CO	HC	CO_2
Propeller Curve	8.5	1.5	0.6	475
Duty Cycle	8.3	1.5	0.7	483

Data presented in Table 8 shows strong correlation between the propeller curve and duty cycle predictions. Differences between emission values are of the order two percent and deemed negligible. Since the propeller curve is assumed to reflect actual operation, this provides a high degree of assurance that the 11-Mode duty cycle is accurate. The next section provides a comparison with industry standards.

COMPARISON WITH INDUSTRY DUTY CYCLES- The comparison was conducted by plotting each of the duty cycles of interest on the emission contour maps. Figure 13 provides a graphical description of the LSD 41 Class 11-Mode and seven industry duty cycles studied in this section. The speed/power points plotted represent each duty cycle described using EQ's 8 and 9. The actual test points for each duty cycle are given in the appendix.

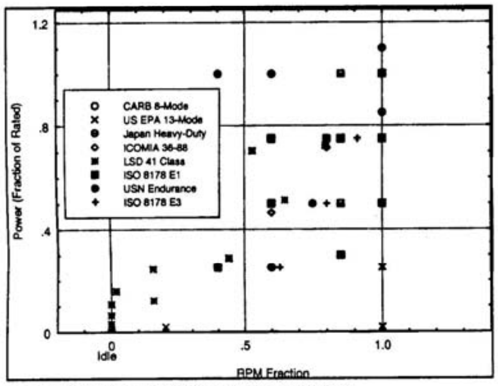

Figure 13: Duty Cycle Speed/Power Points

Table 9 provides the MPE duty cycle comparison. Figures 14 to 18 illustrate the comparison graphically. Included in Table 10 is the Japanese NO_x prediction given by the curve of Figure 1. Values for NO_x predicted by the Japanese method are much greater than those predicted by the emission contour map method. However, excellent correlation exists between the two LSD 41 Class methods demonstrating the validity of operating profile time factors.

Comparison charts of Figure 14 to 18 show duty cycle variation between emission predictions. In all five figures, the LSD 41 Class 11-Mode Duty Cycle provided the closest comparison to the LSD 41 Class Propeller Curve. The CARB 8-Mode Duty Cycle gives the next best NO_x comparison at 0.6 g/bhp-hr (7%) greater than propeller curve prediction (Figure 14). The ICOMIA 36-88 Duty Cycle calculates the second best Japanese NO_x Prediction at 0.3 g/bhp-hr (2%) over the propeller curve (Figure 15). CO predictions provided by the LSD 41 Class Propeller Curve, LSD 41 Class 11-Mode Duty Cycle, ICOMIA 36-88 Duty Cycle, and U.S. EPA 13-Mode Duty Cycle are the same (Figure 16). The CARB 8-Mode is second best in predicting HC emissions at 0.1 g/bhp-hr (17%) below the propeller curve (Figure 17). For CO_2, the U.S. EPA 13-Mode Duty Cycle follows the LSD 41 Class 11-Mode Duty Cycle at 22 g/bhp-hr (5%) over the value of the propeller curve (Figure 18). In short, no single duty cycle offers the consistency of the LSD 41 Class 11-Mode Duty Cycle in predicting LSD 41 Class engine exhaust emissions.

Table 9: MPE Duty Cycle Emission Prediction Summary (g/bhp-hr)

Method	NO_x	J NO_x	CO	HC	CO_2
LSD 41 Class Propeller Curve	8.5	15.9	1.5	0.6	475
LSD 41 Class 11-Mode Duty Cycle	8.3	15.9	1.5	0.7	483
ISO 8178-4 E3 Duty Cycle	9.9	14.4	1.0	0.3	433
ISO 8178-4 E1 Duty Cycle	6.9	16.3	1.6	1.0	499
ICOMIA 36-88 Duty Cycle	6.8	16.2	1.5	1.0	499
Japanese Heavy-Duty Diesel Cycle	9.8	15.5	1.2	0.4	444
U.S. EPA 13-Mode Duty Cycle	7.3	15.4	1.5	1.0	497
CARB 8-Mode Duty Cycle	9.1	14.6	1.1	0.5	452
U.S.N. Endurance Test	7.7	14.3	1.0	0.4	444

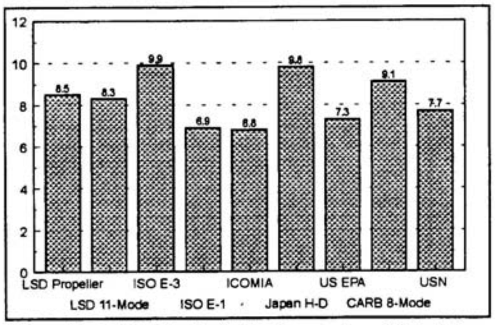

Figure 14: MPE NO_x Prediction Comparison (g/bhp-hr)

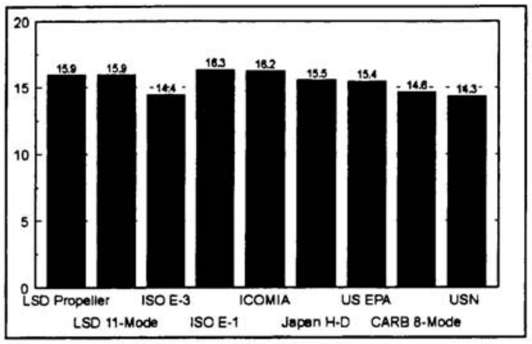

Figure 15: MPE Japanese NO_X Prediction Comparison (g/bhp-hr)

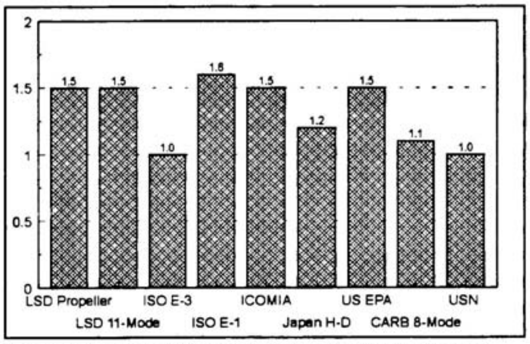

Figure 16: MPE CO Prediction Comparison (g/bhp-hr)

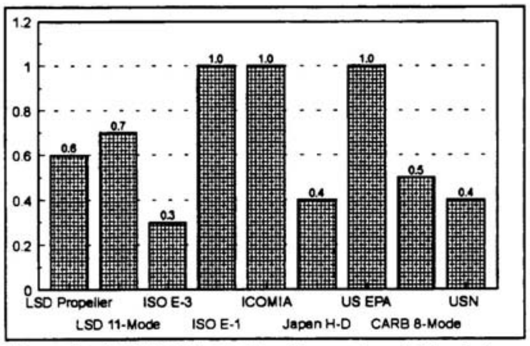

Figure 17: MPE HC Prediction Comparison (g/bhp-hr)

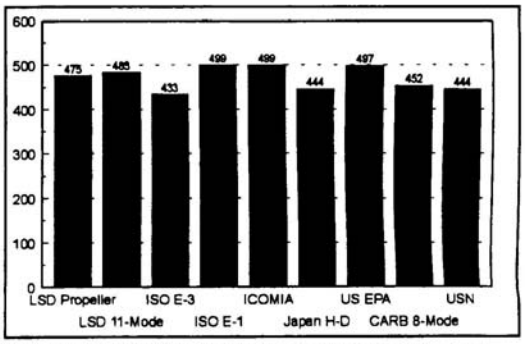

Figure 18: MPE CO_2 Prediction Comparison (g/bhp-hr)

NAVAL DUTY CYCLE APPLICATION

A duty cycle must provide an accurate correlation and prediction of actual emissions performance over some range of operation. The range of operation will include different applications that must be modeled individually. To facilitate the U.S. Navy ship design process, a two step procedure for engine emission certification is proposed. First, prequalify the engine at the same time the Endurance Test is performed by measuring emissions at Endurance Test speed/power points. Second, certify the engine after matching engine to hull form.

Naval ship designers choose main propulsion engines from a list of those that have passed the endurance test and receive certification. Table 9 indicates that the U.S.N. Endurance Test points provide a reasonable approximation of engine emission performance for LSD 41. However, the best duty cycle for emissions is not the same one for wear and endurance testing. To facilitate naval ship design candidate diesel engines should continue to be tested via Military Specification MIL-E-23457B for endurance and wear. Engine emission measurements should be taken concurrently. The U.S.N. Endurance Test continues for 1,000 hours offering ample time to measure engine emissions under steady state conditions. The emissions test procedure should follow the guidelines of ISO 8178-2. Concurrent emission measurement done in this manner should not present a burden to the engine manufacturer.

Emission data derived from the Endurance Test would form the basis for engine certification by the Navy. After marrying a specific hull design with a certified engine, emission prediction refinement, using the procedure of Figure 4, would be required. The environmental impact statement prepared by the ship program manager should reflect the refined emission prediction. Figure 19 illustrates the procedural steps for qualification of a diesel MPE for use on a specific new naval vessel design. Existing naval ship MPE's should be tested at speed/power points and time factors derived from Figure 4, using ISO 8178-2 for procedural guidance.

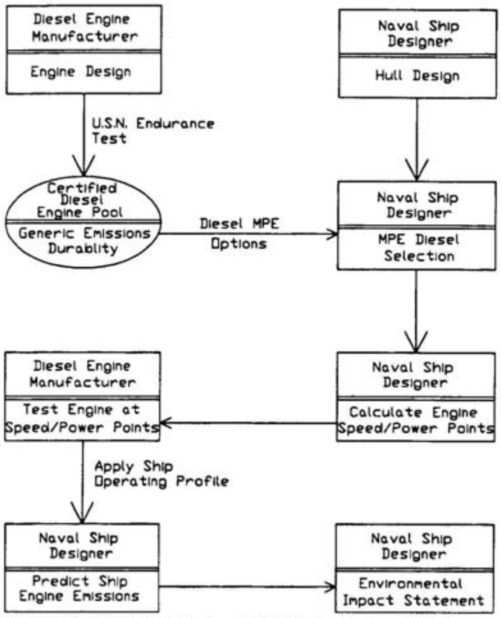

Figure 19: New Ship Design MPE Emission Certification Process

Ship service diesel engines should be exhaust emission pre-qualified and final emission certified using a procedure similar to that illustrated in Figure 19. In the case of constant speed diesel generators, it is probable that a modified ISO 8178-4 duty cycle D2 could be adopted by the Navy for final emission certification. The time factors (weight factors) of D2 can be readily modified to match actual ship operation by cursory review of the ship's Electrical Division logs. Procedural guidance of ISO 8178-1 for bench testing and ISO 8178-2 for shipboard testing should be used.

SUMMARY AND CONCLUSIONS

The U.S. Navy, Naval Sea Systems Command Code 03X3, published *Internal Combustion (Gas Turbine and Diesel) Engine Exhaust Emission Study* in 1991. On page 6-1 of this study, the following observation is made: "Before the Navy can begin an emission test program it must decide the test points for which to collect emission data..." This paper recommends a methodology for determining the test points for diesel powered ships.

Log review, used in preparing this paper, offers a method to develop ship operating profiles which formed the basis for developing engine duty cycles. This approach expended approximately 200 man-hours. Although this method provided reasonable and consistent results it is recommended that NAVSEA instrument two LSD 41 Class ships (one on each coast) to validate the operating profile derived by log review. After validation, operating profiles and emission estimates for other naval diesel ship classes should be derived by log review and prediction methods developed in this paper. Engine exhaust emissions should be calculated for each ship type. Following ship emission determination, comparison with emission limits can be made and strategies for ship engine emission reduction studied for their interdependence and effect on naval ship operations.

CARB proposed NO_x emission limits for existing diesel powered ships is 600 ppm. U.S. Naval vessels are currently exempt from this policy. Future regulations may require naval ship compliance. Development of specific engine emission contour maps requires many hours of costly engine operation on the test stand. NO_x emission concentrations of 565 ppm over a 24 hour period were predicted in this research using the LSD 41 Class Duty Cycle and generic engine emission contour plots. Determination of actual Colt-Pielstick PC2.5 V400 diesel engine emissions at LSD 41 Class Duty Cycle points is recommended to certify LSD 41 Class emissions.

Industry standard duty cycles of ISO 8178-4, EPA and others were shown to be inadequate for estimation of naval ship engine exhaust emissions. The method outlined in this paper should be presented to national and international regulatory organizations and classification societies (such as EPA, CARB, ISO, IMO, etc...) for adoption. In addition, the procedure of Figure 19 should be formalized by adding it to Military Specification MIL-E-21260D, *Engines, Diesel Marine, Propulsion and Auxiliary, Medium Speed*, and its sister document for high speed diesel engines. The certification method advocated in this paper is applicable to both MPE and SSDG engines.

The method advocated in the California Federal Implementation Plan (CFIP) to calculate NO_x based solely on engine speed is oversimplified to the point of presenting grossly inflated estimates of engine exhaust emission performance. Table 9 indicates over estimations of up to 100 percent. The procedure and evaluation presented in this section provide a simple, yet accurate method for predicting engine emissions based upon the actual operating profile of naval diesel powered ships.

ACKNOWLEDGEMENTS

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The views expressed herein are the personal opinions of the authors and are not necessarily the official views of the Department of Defense or any military department thereof.

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APPENDIX

This appendix contains the test points for the seven duty cycles that were used for comparison purposes. They appear in the order given in Table 9. Parent documents may be found in the Reference section. Engine speed and power have been normalized to the rated condition.

Table 10: ISO 8178-4 E3 Duty Cycle [11]

Mode	Engine Speed	Engine Power	Time Factor
1	0.63	0.250	0.15
2	0.80	0.500	0.15
3	0.91	0.750	0.50
4	1.00	1.000	0.20

Table 11: ISO 8178-4 E1 Duty Cycle [12]

Mode	Engine Speed	Engine Power	Time Factor
1	Idle	0.000	0.40
2	0.60	0.250	0.25
3	0.60	0.500	0.15
4	0.60	0.750	0.14
5	1.00	1.000	0.06

Table 12: ICOMIA Marine Engine Duty Cycle (Standard No. 36-88) [13]

Mode	Engine Speed	Engine Power	Time Factor
1	Idle	0.000	0.40
2	0.40	0.253	0.25
3	0.60	0.465	0.15
4	0.80	0.716	0.14
5	1.00	1.000	0.06

Table 13: Japanese Heavy-Duty Diesel Duty Cycle [14]

Mode	Engine Speed	Engine Load	Time Factor
1	Idle	0	0.035
2	0.40	1.00	0.071
3	0.40	0.25	0.059
4	0.60	1.00	0.107
5	0.60	0.25	0.122
6	0.80	0.75	0.286

Table 14: EPA 13-Mode Duty Cycle [15]

Mode	Engine Speed	Engine Torque	Time Factor
1	Idle	0	0.067
2	Intermediate	2	0.08
3	Intermediate	25	0.08
4	Intermediate	50	0.08
5	Intermediate	75	0.08
6	Intermediate	100	0.08
7	Idle	0	0.067
8	Rated	100	0.08
9	Rated	75	0.08
10	Rated	50	0.08
11	Rated	25	0.08
12	Rated	2	0.08
13	Idle	0	0.067

Table 15: CARB 8-Mode Duty Cycle [16]

Mode	Engine Speed	Engine Load	Time Factor
1	Idle	0.00	0.05
2	Rated	0.75	0.15
3	Rated	0.50	0.15
4	Idle	0.00	0.05
5	Max. Torque	1.00	0.15
6	Max. Torque	0.75	0.15
7	Max. Torque	0.50	0.15
8	Max. Torque	0.30	0.15

Table 16: U.S. Navy Medium Speed Diesel Engine Endurance Test [17]

Mode	Time Factor	Engine Load	Engine Speed
1	0.250	100	100
2	0.125	85	100
3	0.021	0	Idle
4	0.229	100	100
5	0.021	0	Idle
6*	0.063	50	75 (Reverse)
7	0.021	0	Idle
8	0.021	85	100
9	0.229	110	100
10	0.021	0	Shutdown

* For main propulsion engines, for constant speed engines (i.e. SSDG) 50 % load at rated speed in the forward direction.