Energy Considerations in the Ship Design Process

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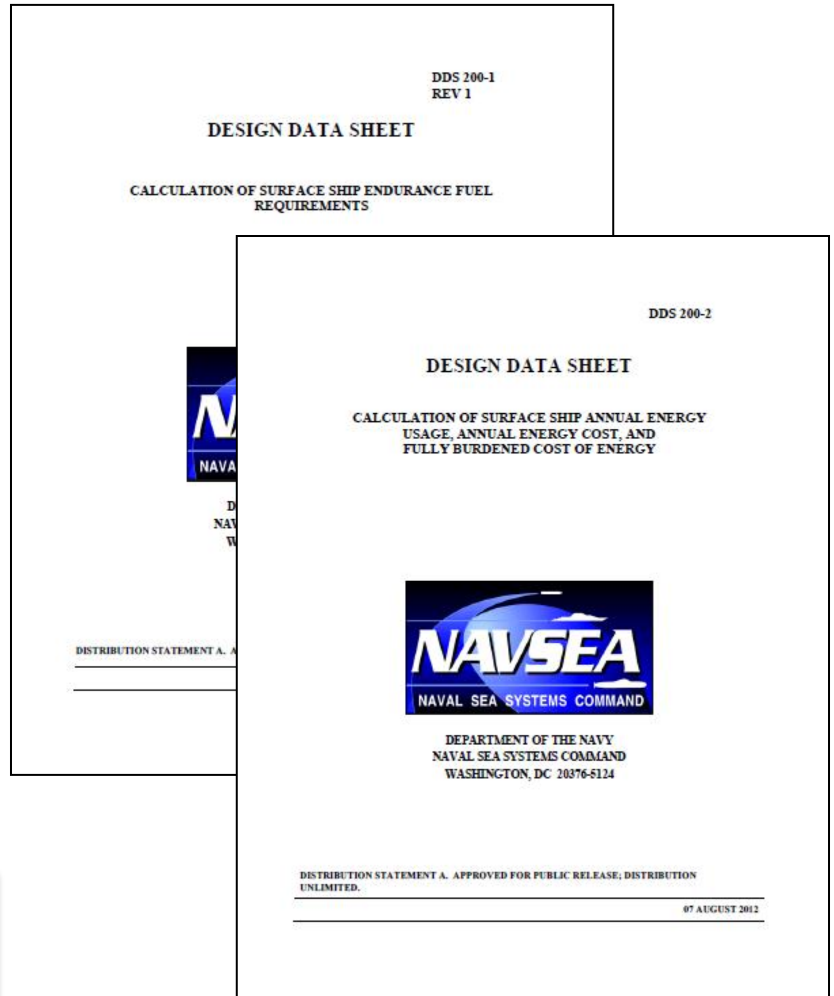
Energy Ship Design Drivers

- Endurance Fuel
  - Determines the required capacity of the fuel tanks
  - Impacts ship size and ship acquisition cost
- Annual Energy Usage and Cost
  - Directly impacts the total ownership cost (TOC) estimates
  - Includes the Fully Burdened Cost of Energy
  - Impacts the selection of equipment and hullform

Design Practices and Criteria (DPC) Manuals (AKA Design Data Sheets (DDS))

- T9070-AW-DPC-010/200-1 Calculation of Surface Ship Endurance Fuel Requirements
  - 04 Oct 2011 (Rev 1)
- T9070-AW-DPC-020/200-2 Calculation of Surface Ship Annual Energy Usage, Annual Energy Cost, and Fully Burdened Cost of Energy
  - 07 Aug 2012

Available from DTIC (http://www.dtic.mil)
(or TDMIS / NLL)



Endurance Fuel: Specified Endurance Conditions

- Economical Transit
  - Range at a moderate speed
  - Traditional way of expressing endurance
- Surge to Theater
  - Range at a high speed
- Operational Presence
  - Time for a given speed-time profile
  - Can be a driver for ships with high power sensors

Ship Requirements should include one or more Endurance Conditions

Requirements Needed

- Economical transit
  - Economical transit distance (nautical miles)
  - Endurance speed (if not specified, use 16 knots)
- Surge to theater
  - Surge to theater distance (nautical miles)
  - Sustained speed (knots)
- Operational presence
  - Operational mission
  - Speed – time profile (knots vs. % time)
  - Operational presence time (hours)
- Optional
  - Ambient condition profile; use the following if not specified:
    - 25% 10 °F with 95% relative humidity
    - 50% 59 °F with 95% relative humidity
    - 25% 100 °F with 40% relative humidity
  - Operating area for calculating sea state and fouling factor
    - Default is North Pacific

Required Design Details

- Electric Power Load Analysis (EPLA)
  - see DPC 310-1
  - Provides 24 hour average electric load
- Electric power system efficiencies
- Electric and propulsion plant concept of operation
  - Describes which prime movers and the plant line-up for different speeds / operating conditions
- Propulsion speed-power curve
- Drive Efficiency
  - Propulsion Motor Module (electric drive)
  - Reduction Gear (mechanical drive)
- Prime mover specific fuel consumption curves
  - Kg of fuel burned per kWh of useful energy produced
  - Usually provided as a curve with respect to per cent loading
- Plant Deterioration Allowance
- Sea state and fouling factor
- Tailpipe allowance
  - Accounts for not being able to use all of the volume of a tank for recoverable fuel

EPLA Results

Temperature (°F)	Condition III Electric Load (kW)	Mission Electric Load (kW)
10	3000	4800
59	1800	3200
100	2400	4000

GTG Efficiency

Power (kW)	SFC (kg/kWh)
600	0.66
1200	0.42
1800	0.33
2400	0.27
3000	0.26

Electric and Propulsion Plant Concept of Operations Examples

- Mechanical Drive
  - The electric plant consists of three 3000 kW gas turbine generator (GTG) sets. Two GTGs are online at all times. Power is shared evenly among all online GTGs.
  - The propulsion plant consists of two shafts with two 15,000 kW main gas turbines (MGT) on each shaft with a reduction gear. Available configurations are trail shaft with one MGT online, split plant with one MGT on each shaft, and full plant configuration with two MGTs on each shaft. The most economical configuration is used for a given speed. Power is shared evenly among all online MGTs.
- Electric Drive
  - The propulsion plant consists of two shafts each with a propulsion motor module (PMM) on each shaft. Propulsion power is shared equally between the two PMMs. The electric plant consists of two 3,000 kW gas turbine auxiliary turbine generator (ATG) power generation modules (PGM) and three 24,000 kW gas turbine main turbine generators (MTG) PGMs. At least two PGMs are online at all times. Power is shared evenly (proportional to rating) among all online PGMs. The most economical combination of ATGs and MTGs with sufficient power capacity is used for a given power level.

Speed Power Curve & Efficiencies Examples

Mechanical Drive

At interface between shaft and reduction gear

Speed (knots)	Port Shaft (kW)	Starboard Shaft (kW)	Propulsion Configuration
5	217	0	Trail Shaft
10	1733	0	Trail Shaft
15	5850	0	Trail Shaft
16	7100	0	Trail Shaft
20	6933	6933	Split Plant
25	13542	13542	Full plant
30	23400	23400	Full plant
32.3	29250	29250	Full plant

Reduction gear efficiency (assume constant): 0.975

At interface between shaft and motor

Electric Drive

Speed (knots)	Total Propulsion Shaft Power (kW)	Port Shaft (kW)	Starboard Shaft (kW)	PMM Efficiency
5	217	108	108	0.85
10	1733	867	867	0.89
15	5850	2925	2925	0.90
16	7100	3550	3550	0.91
20	13867	6933	6933	0.92
25	27083	13542	13542	0.94
30	46800	23400	23400	0.94
32.6	60000	30000	30000	0.94

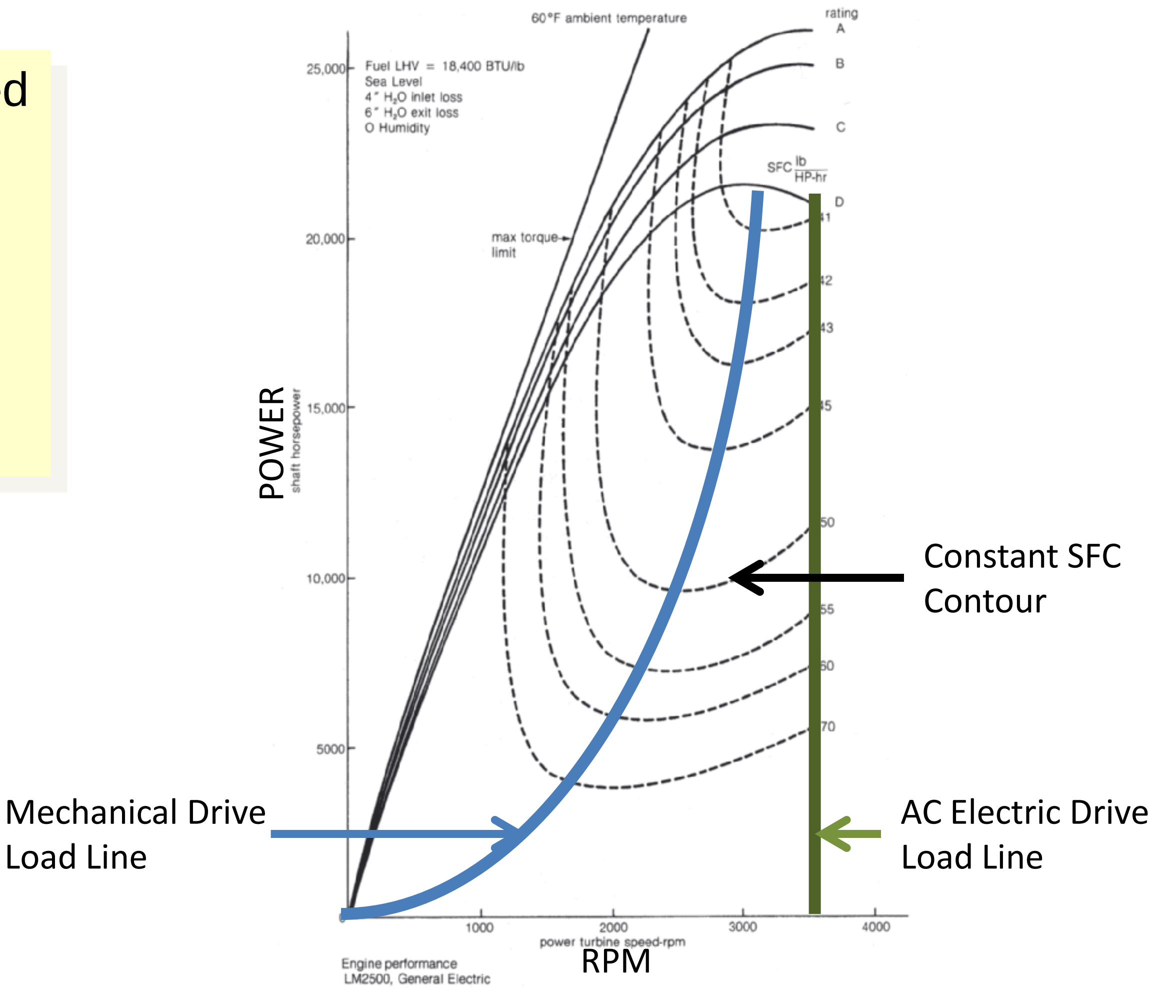
PMM = Propulsion Motor Module

Specific Fuel Consumption Curve derived from Fuel Map

Weight of Fuel Burned
=
SFC
X
Gas Turbine Power
X
Time

SFC Curve

Power (kW)	SFC (kg/kWh)
2400	0.465
4800	0.375
9600	0.263
14400	0.233
19200	0.210
24000	0.200



Additional Details

- Plant Deterioration Allowance
  - Accounts for increased fuel consumption as equipment ages
  - Default value is 1.05
- Sea state and fouling factor
  - Accounts for additional drag due to average fouling and sea state.
  - Determined for a specified operating area, in head seas, at the high end of sea state 4 using the propeller coating, bottom coating, and cleaning methods intended for the ship.
  - Maybe a function of speed.
  - Default value is 1.10
- Tailpipe allowance
  - accounts for the additional fuel required in a tank that cannot be used because it is below the fuel system suction and due to the effects of suction vortexes.
  - If the majority of the tanks are broad and shallow, the factor is 0.95; if narrow and deep, it is 0.98. In later stages of design, the tailpipe allowance can be calculated from the actual geometry of the tanks.

Calculations for Burnable Fuel Load (metric tons)

- Economical Transit

$$\frac{\text{Calculated Economical Transit Fuel Rate (kg/h)} \times \text{Economical Transit Distance (NM)} \times \text{Plant Deterioration Allowance}}{\text{Endurance Speed (knots)} \times 1000}$$

- Surge to Theater

$$\frac{\text{Calculated Surge to Theater Fuel Rate (kg/h)} \times \text{Surge to Theater Distance (NM)} \times \text{Plant Deterioration Allowance}}{\text{Sustained Speed (knots)} \times 1000}$$

- Operational Presence

$$\frac{\text{Calculated Operational Presence Fuel Rate (kg/h)} \times \text{Operational Presence Time (h)} \times \text{Plant Deterioration Allowance}}{1000}$$

Must calculate fuel rate for each endurance requirement

Calculating Fuel Rates

- The specific method for calculating the calculated economical (surge to theater) transit fuel rate (kg/h) is highly dependent on the details of the power and propulsion architecture and the electric plant and propulsion plant concept of operations. The general process for each ambient condition is to:
  - Determine the amount of power (kW) provided by each online prime mover. The average endurance power (for propulsion) and the 24-hour average endurance (cruise) ship service electric load are apportioned to each prime mover in accordance with the electric plant and propulsion plant concept of operations.
  - For each prime mover, determine its specific fuel consumption (kg/kWh).
  - For each prime mover, calculate its fuel rate (kg/hr) by multiplying the specific fuel consumption (kg/kWh) by the power it provides (kW).
  - Sum the fuel rates for all prime movers to obtain the calculated economical (surge to theater) transit fuel rate (kg/h) for a given ambient condition.

  Apply the ambient condition profile to obtain the final calculated economical (surge to theater) transit fuel rate.
- The operational presence fuel rate is calculated in an analogous manner, except the operational profile is applied to the fuel rates calculated for each speed in the operational profile.

Calculating Tank Capacity

- The Design Burnable Fuel Load is the maximum of the burnable fuel loads for each endurance condition
- Divide the Design Burnable Fuel Load by the Tailpipe Allowance to obtain the Endurance Fuel load
- Tanks must have a greater capacity than the Endurance Fuel load
  - Add 5% for fuel expansion
  - Add factor (~2%) for structure within the tank

Special Cases

- High Speed Ships
  - Can account for decrease in hull resistance as fuel is burned
- Economical Transit special cases
  - Can use a higher speed than the specified endurance speed if it results in less fuel usage
  - Can use a speed profile with an average equal to or greater than the specified endurance speed if it results in less fuel usage
    - May apply to hybrid drives

Observations on Endurance Fuel

- Requirements and power system design choices impact endurance fuel requirements
  - Designers will optimize to how the requirement is specified (e.g. if only economical transit specified, then system will optimize fuel consumption for the endurance speed)
  - Tank capacity can impact ship size and cost
    - Most pronounced on smaller ships
    - Less of an impact on larger ships

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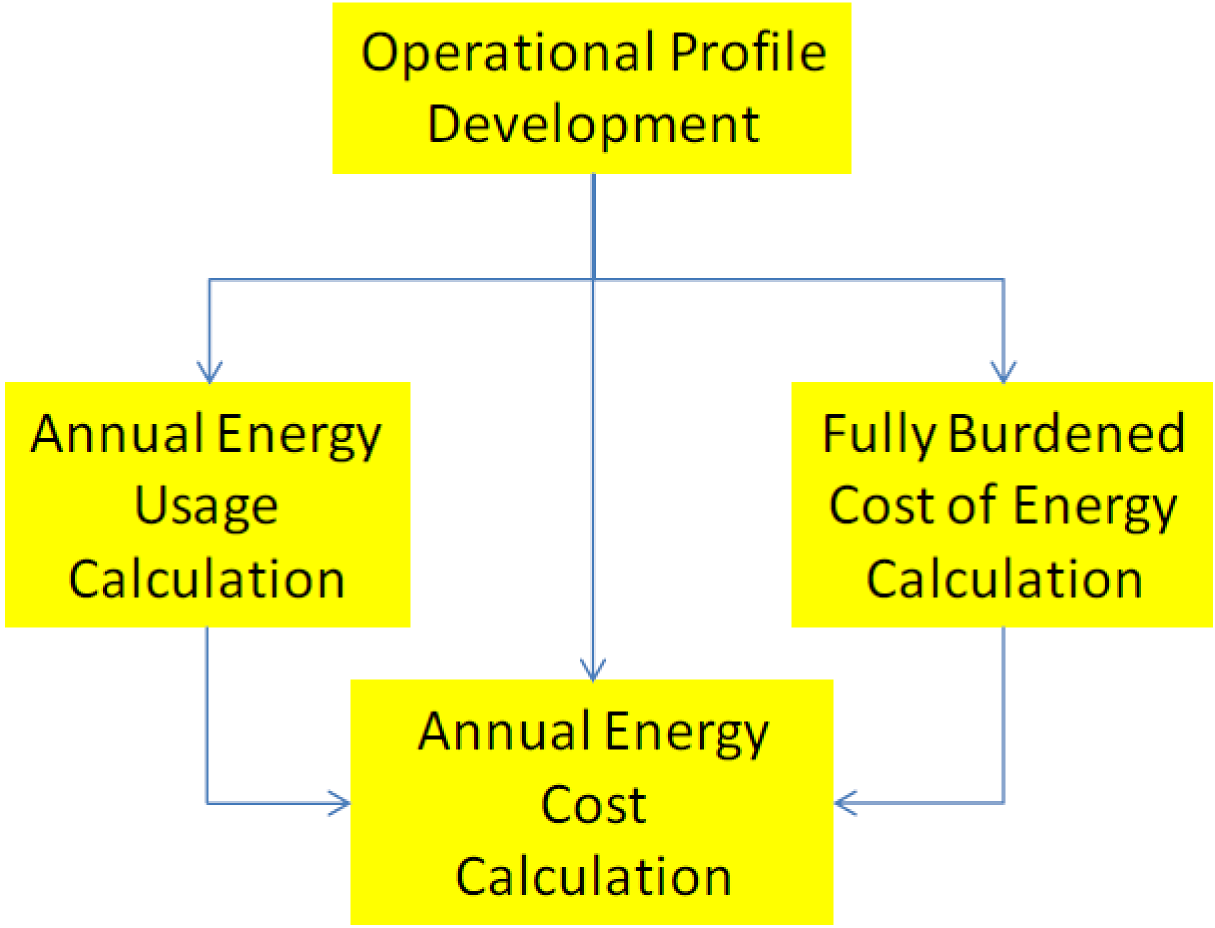
Annual Energy Usage and Cost



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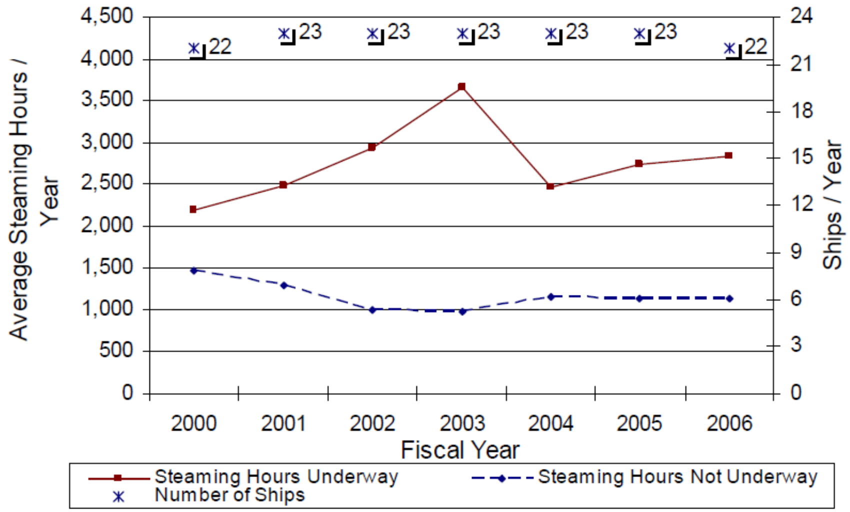
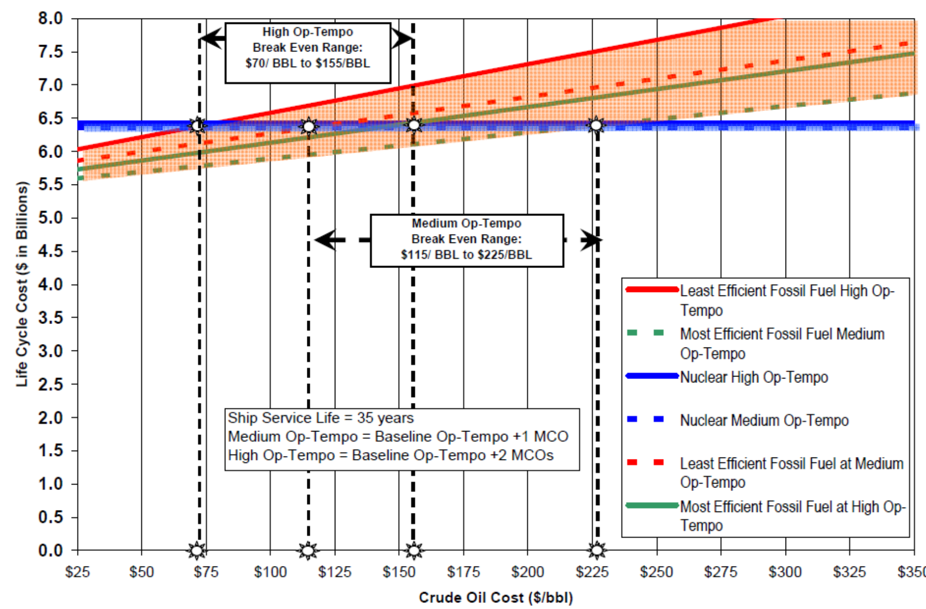
Motivation
2007 Alternate Propulsion Study



Amphibious Ships Average Historical Operational Tempo (2000-2006)

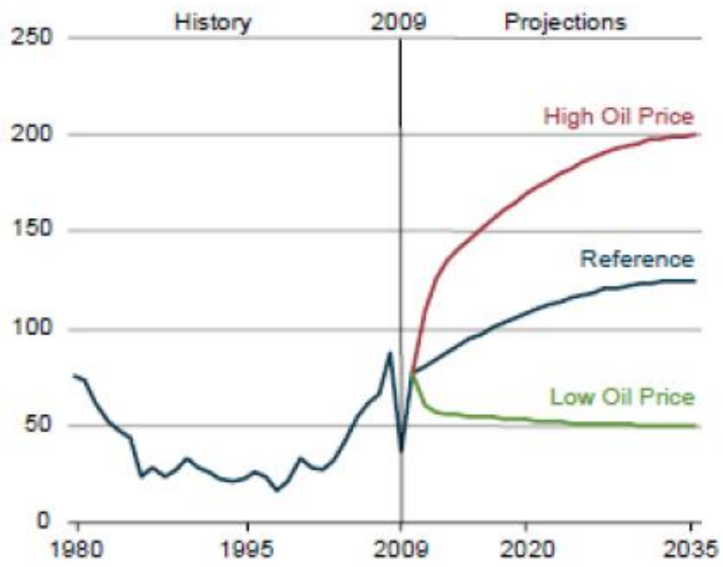


Surface Combatant (21,000 to 26,000 mton) Nuclear vs Conventional LCC comparison

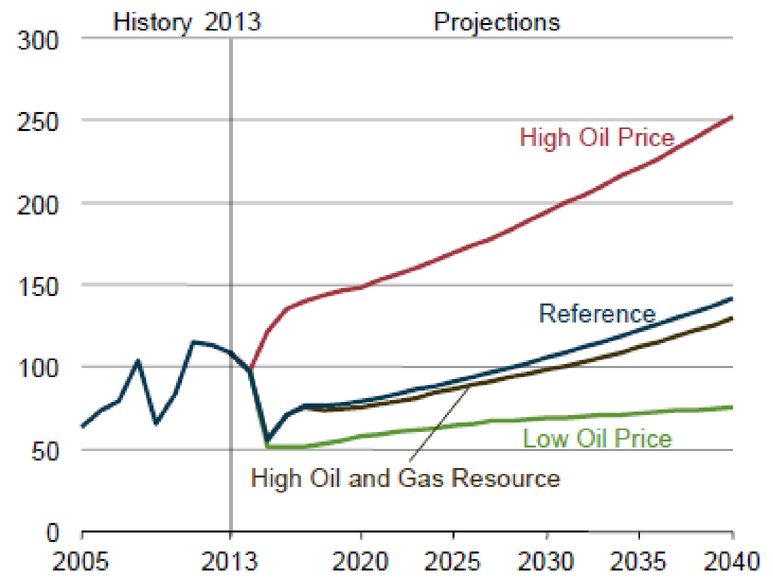
Operational Profile impacts optimal machinery choices
The cost of fuel impacts optimal machinery choices
Operational Profile is not a constant

LCC = Life Cycle Cost

Projected Oil Prices



AEO 2011 Projected Average Annual World Oil Prices
2009 Dollars per Barrel



AEO 2015 North Sea Brent crude oil spot price
2013 Dollars per Barrel

AEO = Annual Energy Outlook

eia.gov: January 2016 price = $30.70 per barrel

The Price of Crude Oil is hard to predict

Fully Burdened Cost of Fuel

	FY11 Fuel Prices - COMPOSITE		Distillate/F76
	Oct-10 - May-11	Jun-11 - Sep-11	OSD and ASN (FM&C) Guidance as of 7/25/2011 Represents Weighted Average for all FY11
Crude Oil	$85.02	$105.00	
Refined Product	$25.51	$31.50	
Adjustments	$2.01	$14.80	
Storage, Transport & Management	$14.72	$14.60	
Standard Price	**$127.26**	**$165.90**	**$139.72**

FY 2011 DLA Energy Standard Price Buildup

F76 fuel is priced per barrel (42 gallons)
Engineering calculations use kg
Density of F76 can vary
- Representative specific gravity = 0.84 Kg/L
- Maximum specific gravity = 0.876 Kg/L

Per Barrel of F76	FY 2011
Acquisition	**$139.72**
DLA Energy Price	$139.72
Storage & Handling	**$0.05**
Direct Fuel Infrastructure - Facilities Cost	$0.00
Indirect Fuel Infrastructure - Barge Overhauls	$0.05
Delivery	**$42.01**
Fuel Delivery Ship Acquisition/Depreciation	$11.67
T-AO	*$8.80*
T-AOE	*$2.80*
T-AKE	*$0.07*
T-AE	*$0.00*
T-AFS	*$0.00*
Fuel Delivery Ship Operating & Support	$30.34
T-AO	*$22.80*
T-AOE	*$7.25*
T-AKE	*$0.30*
T-AE	*$0.00*
T-AFS	*$0.00*
Other	**$4.20**
Environmental	$4.20
Service/Platform Specific	$0.00
Burdened Cost	**$46.26**
Fully Burdened Cost	**$185.98**

Breakdown of Fully Burdened Cost of F76 in FY 2011

Fully Burdened Cost of Shore Power

- The major element of the fully burdened cost of shore power is the commodity price for electricity.
  - Naval Facilities Engineering Command (NAVFAC) tracks the usage and cost of electricity by naval facilities.
  - Rate information is provided in the Defense Utility Energy Reporting System (DUERS) Energy Audit Reports (EAR16) available from https://navyenergy.navfac.navy.mil/.
- The AEO includes projections for the commodity price for electricity.
  - The 2011 edition predicts average electricity prices to be essentially constant through 2035 with a price of roughly $0.09 (±$0.003) per kW-h in FY09 dollars. The price for electrical power in west coast ports is typically higher than this average while the price in east coast ports is typically lower.
- While not explicitly known, the additional burden to cover Navy owned electrical system infrastructure is expected to be low.
- Using the AEO average price of $0.09 (±$0.003) per kW-h in FY09 dollars is likely conservative in cases where the homeport is not known or will vary greatly. If the homeport is known, then DUERS data for the ship's homeport may be used.

This guidance may need to be updated with the "Pacific pivot"

Initial Observations

- Annual Energy Usage (barrels) depends on
  - Design of the ship
  - Operational Profile
  - Density of fuel used
- Annual Energy cost depends on
  - Annual Energy Usage
  - Price of Crude Oil
  - DLA adjustments
  - Burdens

Stochastic Modeling and Simulation may be needed to understand anticipated variances

Operational Profile

- Operational profiles consists of the number of hours spent in each year of the ship's service life in each of the ship deployment and employment profiles. The following operational profiles are generally sufficient:
  - Low : Peacetime operations with no Major Combat Operations and a limited number of lesser contingencies over the ship's service life
  - Medium: Add a single MCO to the Low profile
  - High: Add two MCOs to the Low profile
- Ship deployment and employment profiles consist of the percentage of hours in each of several operational modes:
  - Presence and training at home
  - Presence overseas
  - Lesser contingencies
  - Major Combat Operations
  - Maintenance and Modernization
- Operational modes describes the per cent time spent in each of the operational categories used in the EPLA. These are called ship states:
  - Inport
  - Underway peacetime cruising
  - Underway wartime cruising
  - Underway mission (e.g. ASW operations)
- Ship States described by:
  - Electric load for each condition of the ambient profile (cold, temperate, hot) as detailed in the EPLA
  - Speed-time profile

Example

Operational Profiles

Year	Low OPTEMPO (fraction of time)				High OPTEMPO (fraction of time)			
	Maintenance and Modernization	Predeployment Training	Deployment	MCO	Maintenance and Modernization	Predeployment Training	Deployment	MCO
1	0.25	0.25	0.5	0.0	0.25	0.25	0.5	0.0
2	0.25	0.25	0.5	0.0	0.25	0.25	0.5	0.0
3	0.25	0.25	0.5	0.0	0.25	0.25	0.5	0.0
4	0.25	0.25	0.5	0.0	0.25	0.25	0.5	0.0
5	0.25	0.25	0.5	0.0	0.25	0.25	0.5	0.0
6	0.25	0.25	0.5	0.0	0.25	0.25	0.5	0.0
7	0.25	0.25	0.5	0.0	0.25	0.25	0.5	0.0
8	1.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0
9	0.25	0.25	0.5	0.0	0.25	0.25	0.5	0.0
10	0.25	0.25	0.5	0.0	0.25	0.25	0.5	0.0
11	0.25	0.25	0.5	0.0	0.16	0.17	0.0	0.67
12	0.25	0.25	0.5	0.0	0.16	0.17	0.0	0.67
13	0.25	0.25	0.5	0.0	0.16	0.17	0.0	0.67
14	0.25	0.25	0.5	0.0	0.25	0.25	0.5	0.0
15	0.25	0.25	0.5	0.0	0.25	0.25	0.5	0.0

Ship deployment and employment profile

Operational Modes

	Inport – shore	Underway – Economic al Transit	Underway – Surge to Theater	Underway – Mission
Maintenance and Modernization	0.9	0.05	0.0	0.05
Predeployment Training	0.6	0.2	0.0	0.2
Deployment	0.1	0.2	0.0	0.7
MCO	0.05	0.15	0.05	0.75

Electric Load (Operational Categories)

Temperature (°F)	Inport - Shore (kW)	Underway - Economical Transit (kW)	Underway - Surge to Theater (kW)	Underway - Mission (kW)
	Shore Power	Generators	Generators	Generators
10	1000	3000	3000	4800
59	500	1800	1800	3200
100	900	2400	2400	4000

Underway – Mission: Speed-time profile

Speed (knots)	Profile % time
5	20%
10	30%
15	25%
20	15%
25	8%
30	2%

Creating an Operational Profile

- Developing a useful and representative operational profile is perhaps the most challenging activity in performing annual fuel calculations.
- In many cases, the simplest manner to construct the operational profile is to modify the operational profile used in a previous study.
  - Must ensure the assumptions of the original study are consistent with the current study.
- In some cases, it will be necessary to develop an operational profile from scratch.

Source data for developing Operational Profiles

- DPC 200-2 Appendix B: Speed vs. Percent-time Profile Reference Data
- DPC 200-2 Supplements
  - S1: DDG 51 Class
  - S2: LSD 41 and LSD 49 Class

Table B-5. DDG 51 Class.

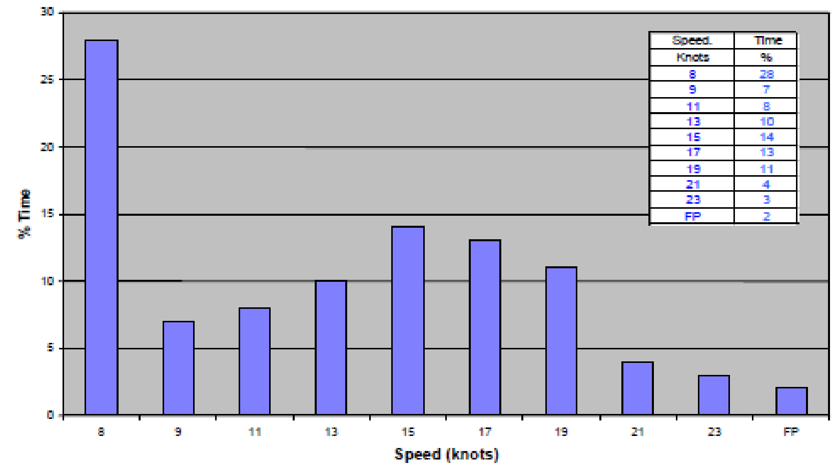


Table C-6. DDG 51 Five Year Class Average 1998-2002.

Year	Underway Hours	Not Underway Hours	Underway Barrels Used	Not Underway Barrels Used
1998	2723	1358	71841	8171
1999	2436	951	65355	5392
2000	2401	1121	66481	6394
2001	2512	914	68070	5314
2002	2745	785	75167	5156
Average	2563	1026	69383	6085

Calculating Annual Energy Usage

- Fuel consumption calculations use same methods as for endurance fuel calculations.
- Produce table of calculated fuel used for each year of the ship's service life.
- Calculate an average over the ship's service life.

Calculating Annual Energy Cost

- Estimate the Fully Burdened Cost of fuel (and inport electricity) for each year of the ship's service life.
- Apply to calculated fuel used (shore power used) for each year of the ship's service life.
- Calculate total cost of fuel (electricity) used over the ship's service life.
- Calculate average annual cost of fuel (electricity)

Stochastic Modeling and Simulation may be needed to understand anticipated variances

Annual energy usage and cost impact on ship design

- Energy efficiency across the operational modes is important if Total Ownership Cost (TOC) is a priority.
- Hard TOC limits are meaningless; More a function of assumptions than ship features.
- Annual energy usage has less variance annual energy cost but still depends highly on Operational Tempo.
- Important to understand sensitivity of results to sources of variance.

Summary

- Established practices exist for considering energy usage in ship design.
- Endurance requirements impact the size of the ship's fuel tanks.
  - DPC 200-1 applies
- Estimates for annual energy usage and cost are developed using DPC 200-2 and associated supplements.
  - Must understand the source and impact of variances in the energy usage calculations and in the burdened cost of fuel calculations