# Powering of Displacement and Semi-Displacement Hulls.

This is a very simple method using formulas that were derived from the **CATERPILLAR** Hull Speed Estimator slide-rule. This was issued in 1961, under copyright, by the CATERPILLAR TRACTOR CO., Engine Division in Peoria, Illinois as Form No. 40-20442.

The Speed~Power relationship for these boats over a wide speed range is complex and the slide-rule contains the following advice; **NOTE: Powering a pure displacement hull with a speed length ratio over 1.34 should not be attempted. Scale beyond 1.34 ratio is proportioned for the semi-displacement hulls which are designed specifically for the higher speed length ratios**. In other words, this spreadsheet should be used for displacement hulls only up to 1.34 speed length ratio and semi-displacement hulls over only 1.34 although a small overlap of about 0.2 may be used for rough guidance.

## Spreadsheet

The method was used as the basis for an Excel spreadsheet, which is given freely for guidance and information only and is used entirely at your own risk.

The intention was to prepare something that can be easily used in the early design stages or for comparisons when doodling. As the design progresses and more information or data is prepared then powering should be checked carefully using recognized methods so details of the hull form can be validated. This spreadsheet required only the length and displacement so it is simple but it will only give “middle of the road” values and cannot account for other variables.

The spreadsheet was “clean” when first posted here and was verified using the Norton AntiVirus module of Norton SystemWorks 2002 with the latest virus definitions.

The spreadsheet was saved as a **Microsoft 97-2002 and 5.0/95 Workbook** so it will run in all versions of Excel since **Office 97.**

## Fuel and engine efficiencies

The choice is made between diesel or gasoline powered engines due to the difference in fuel consumption. No particular engine model has been used and a generalized fuel consumption curve has been adopted that is diesel engine oriented. Each manufacturer has his own twist so that with 2 and 4 strokes it gives four basic types but each of these can have a different usage rating so it is not possible to give one fixed pattern for all. Nevertheless, that is what has been done so the fuel consumption and range results are only approximations.

A few words about fuel in an attempt to clarify the mess of published ill-advised misinformation on the Internet. The thermal energy of petroleum-derived fuels depends on the SG (specific gravity where fresh water is 1.0) at a standard temperature. The accepted US method is to use the **API degrees** system and the relationship between SG and the API scale is;

$$\text{specific gravity} = \frac{141.5}{131.5 + \text{deg. API}} \quad \text{with water and the tested fluid at } 60^{\circ}\,\text{F}\ (15.6^{\circ}\,\text{C})$$

Therefore, a fuel of 10 degrees API has a specific gravity of 1.000 and a US gallon would weigh 8.328 pounds or a litre would weigh 1 kilogram. API is the American Petroleum Institute.

In the US there are several grades of diesel fuel and gasoline but the averages, quoted by the Federal Gov't, are diesel with an SG of 0.84 and gasoline at 0.73. The energy content of fuel is termed the HHV (High Heat Value) and it is the maximum released energy of a fuel free from impurities. The following formula gives the HHV;

$$\text{HHV} = 22{,}320 - 3{,}780 \times SG^2 \ \text{ Btu per lb} \quad \pm 1\% \text{ for normal products}$$

The values typically used on the Net are the HHV times SG and are the Btu per gallon.

The spreadsheet uses a range in SG of 0.70 to 0.75 SG for gasoline and 0.82 to 0.87 for diesel. Intermediate values are assumed to be a blended fuel running in a diesel engine but they should only be used for very rough guidance.

It seems to be impossible to find reliable information on engine efficiencies and dependable data on the differences between diesel and gasoline engines. Almost everyone has a point to make so there is an immediate bias or the description is unclear. Simply declaring that one is x% more efficient than the other is insufficient. The following list is merely a sample of comparisons on the net of diesel compared to gasoline engines;

- Engine efficiency rises from
  - 20% to 30%
  - 25% to 33%
  - 25/28% to 40%
  - 33% to 50%
- Better fuel consumption
  - Up 20%
  - Up 24%
  - Up 27%
  - Up 34%
  - Up to 50%

It is almost certainly a case of confusion of efficiencies due to engine types compounded with differences in fuel. A diesel engine is more efficient than a gasoline engine mainly because of the higher engine compression. Then there is the fuel to take into account. It is clear that the high heat value of fuel ***reduces*** as the specific gravity rises but this is only because it is based on weight, we buy fuel by the gallon or by the litre and the heat value ***rises*** with SG.

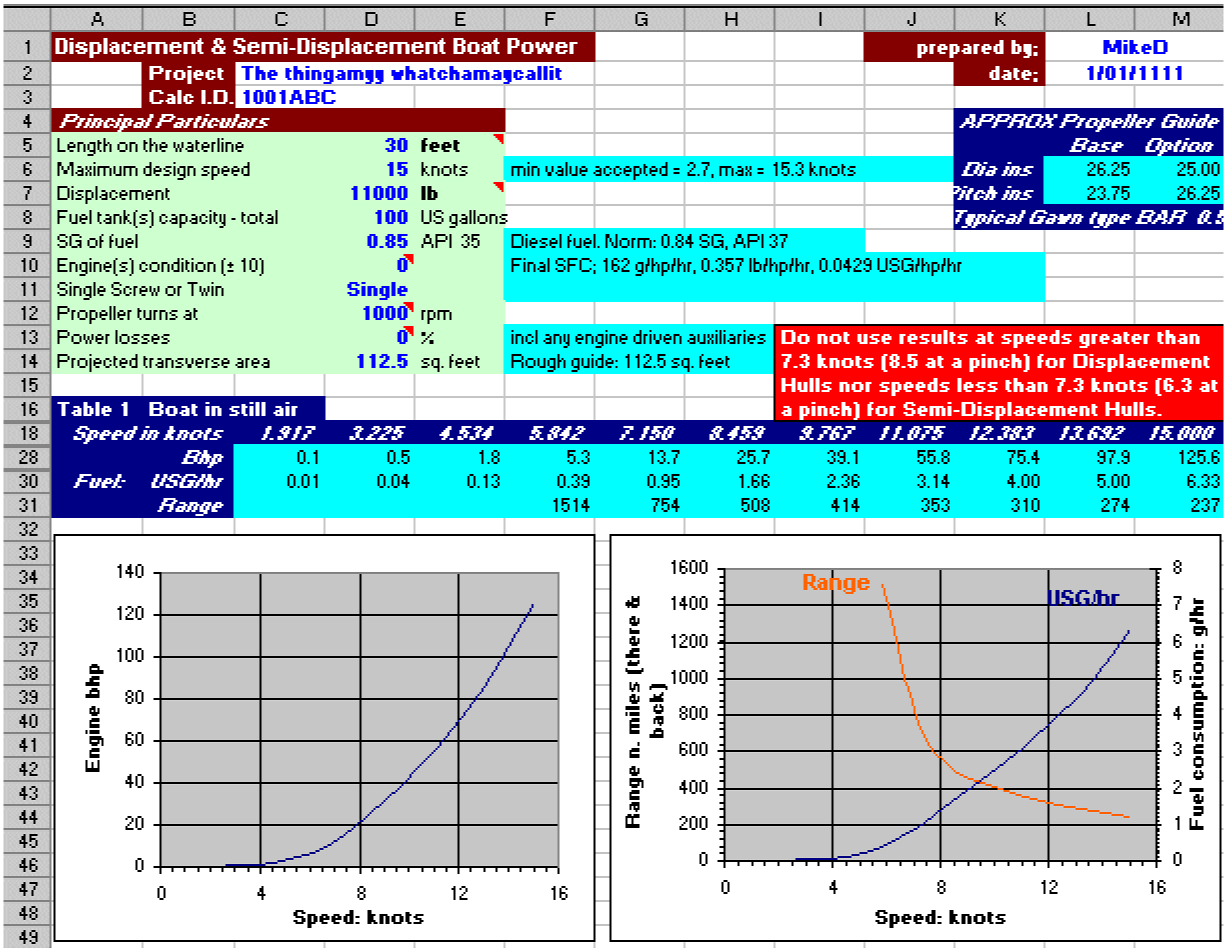
Anyway, for better or for worse, I arranged it so that the diesel powered boat has a range that is 35% greater per gallon of fuel than the gasoline version using the 0.74:0.84 ratio of SG.

## Spreadsheet guidance

It is arranged as two page output sheets that fit on both North American Letter Size (8 ½ x 11 inches) or the International Letter Size (210 x 297 mm), although you may have to reset things slightly depending on your printer etc.

There is only one worksheet and the calculations that are at the side of the main output page are hidden so as not to clutter things up. It is also protected to prevent accidental data entries in the wrong places - don't worry, there isn't a password.

Here is a screen image of the first page



| | | | |
|---|---|---|---|
| Displacement & Semi-Displacement Boat Power | | prepared by: | MikeD |
| Project | The thingamyy whatchamagcallit | date: | 1/01/1111 |
| Calc I.D. | 1001ABC | | |

| Principal Particulars | | | |
|---|---|---|---|
| Length on the waterline | 30 | feet | |
| Maximum design speed | 15 | knots | min value accepted = 2.7, max = 15.3 knots |
| Displacement | 11000 | lb | |
| Fuel tank(s) capacity - total | 100 | US gallons | |
| SG of fuel | 0.85 | API 35 | Diesel fuel. Norm: 0.84 SG, API 37 |
| Engine(s) condition (± 10) | 0 | | Final SFC; 162 g/hp/hr, 0.357 lb/hp/hr, 0.0429 USG/hp/hr |
| Single Screw or Twin | Single | | |
| Propeller turns at | 1000 | rpm | |
| Power losses | 0 | % | incl any engine driven auxiliaries |
| Projected transverse area | 112.5 | sq. feet | Rough guide: 112.5 sq. feet |

| APPROX Propeller Guide | Base | Option |
|---|---|---|
| Dia ins | 26.25 | 25.00 |
| Pitch ins | 23.75 | 26.25 |
| Typical Gawn type BAR 0.5 | | |

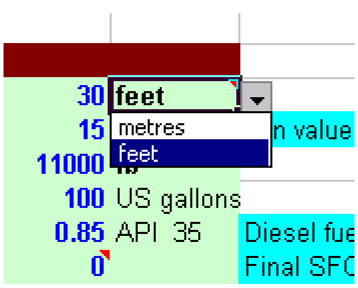
Do not use results at speeds greater than 7.3 knots (8.5 at a pinch) for Displacement Hulls nor speeds less than 7.3 knots (6.3 at a pinch) for Semi-Displacement Hulls.

Table 1 Boat in still air

| Speed in knots | 1.917 | 3.225 | 4.534 | 5.842 | 7.150 | 8.459 | 9.767 | 11.075 | 12.383 | 13.692 | 15.000 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Bhp | 0.1 | 0.5 | 1.8 | 5.3 | 13.7 | 25.7 | 39.1 | 55.8 | 75.4 | 97.9 | 125.6 |
| Fuel: USG/hr | 0.01 | 0.04 | 0.13 | 0.39 | 0.95 | 1.66 | 2.36 | 3.14 | 4.00 | 5.00 | 6.33 |
| Range | | | | 1514 | 754 | 508 | 414 | 353 | 310 | 274 | 237 |



The entries are made in the bold blue font, such as **The thingammy whatchamagcallit** or **1100**. The table of Principal Particulars is all the input that is required.





You may use metric or US measure entries, click on the word feet in Cell E5 for length, for example, and a short list opens, see the picture on the left. Notice that the units are in a bold font to draw your attention to the drop-down list that does not show unless you have selected Cell E5. Make your selection in the standard way.

The calculations are performed in US measurements and the spreadsheet makes any conversions that are required.

The same applies lower in the table for the displacement in pounds or kilos in Cell E7. The example has length in feet and displacement in pounds, use either system you wish or a mix if you prefer it. The answers are in US horsepower but there is so little difference compared to the metric horsepower (1 US = 1.014 metric approximately) that the difference can be ignored in practical terms.

There are some cells with comments that are indicated by a red triangle in the upper right corner, one is shown in the image above. The blue highlighted cells to the right of the green table give some intermediate answers that help you make decisions:

1. The speed is calculated from V/ L 0.35 to a maximum of 2.8 and these are shown in knots.
2. The specific gravity of the fuel determines the API ranking and HHV which is used to find the SFC (specific fuel consumption) which is declared in various units after the Engine Condition entry.
3. The Engine Condition allows you a 10% margin up or down in the consumption.

The propeller revs are quite important and they should be given at about 80% of the max revs. This is typical for diesel engines with ratings for recreational purpose. The diesel engine has a torque curve that rises quickly and then levels off at about 70 or 75% rated rpm and falls usually just before the 100% point. The gasoline engine curve is quite different as it continually rises. The fuel consumption and range values are based on a diesel as described so the curve is something like a gasoline engine up to that point. Ideally, the system should be diesel-electric where the motor gives virtually constant torque at all speeds and is hence almost impossible to overload. So the values of consumption are rather iffy but better a SWAG answer than nothing.

The all blue tables are the output, the power and fuel figures on the bottom and two propellers top right.

The two charts don't need any explanation.

The power needed to propel the boat is measured at the propeller and is the SHP (shaft horsepower) but the term can have several meaning and nowadays $P_D$ meaning delivered power is the standard although neither is directly quoted on the spreadsheet. There are several losses of power working from the propeller back to the engine – engine bearing, gearing, universal joint, engine drivel auxiliaries etc. so care must be taken to ensure that the engine has all these included in its rating for BHP which is the brake horsepower measured at the output and the power that drinks the fuel, not the SHP. Manufacturers use various rating systems so be sure you understand which one they use.

The range drops as speed increases and in the spreadsheet it is the range only at the declared speed using 100% of the fuel capacity declared in the input. The true range is obviously a mix of the declared values and depends on how the boat is operated. So say it is half an hour at slow speed, one hour at 7 knots, two hours at 10 knots, two at 12.5 and two at 15 then we can make a table like this;

| Duration hours | Speed knots | Distance n.m. | Gallons/hr | ÓGallons |
|---|---|---|---|---|
| 0.5 | ~4 | 2 | 0.08 | .04 |
| 1.0 | 7 | 7 | 0.85 | 0.85 |
| 2.0 | 10 | 20 | 2.49 | 4.98 |
| 2.0 | 12.5 | 25 | 4.08 | 8.16 |
| 2.0 | 15 | 30 | 6.33 | 12.66 |
| 7.5 | | 84 | | 26.69 |

So the total distance is 84 nautical miles in 7 ½ hours, an average speed of 11.2 knots. A total consumption of 26.69 gallons, an average of 3.56 gallons per hour or say 0.318 gallons per nautical mile (3.15 n. miles per gallon).

Going there at full speed all the time would take 5.6 hours and burn about 35.4 gallons. On the other hand, we could dawdle along at 7 knots, take 12 hours, and use only 10.2 gallons. Such simple exercises clearly show the penalty of speed and all that without accounting for the engine cost, higher maintenance etc.

The propeller guide top right is probably the least accurate of all the output. It is based on some old typical rules of thumb that are stretched to the limit and then some! There was little point in trying to design a proper propeller as the CATERPILLAR method in the spreadsheet deduces SHP i.e. the propeller inefficiency is already built in. In addition, more details would be needed so it would defeat the whole purpose.

I had considered a spreadsheet using the Holtrop-Mennen method, which is the method of choice for larger boats and ships in the early design stages. Unfortunately, small boats are outside the limits due to their wide beam and very low fullness of form.

## Effect of Wind

The basic power in the spreadsheet is the power used (not installed) and it has only a small margin included so allowance should be made for inclement weather. Many Net sites simply recommended doubling or tripling the power but there was no diagram showing Speed~Power so it was not clear if the stated power on those sites was too low with a high correction factor, good for fair weather with increases, worst case, total installed or what.

It is a major hassle to calculate accurately the additional power to maintain speed in adverse conditions, buy a good CFD program but be prepared to shell out many thousands of dollars. A good designer/manufacturer should have extensive records of performance for many types and sizes in all kinds of weather. These would permit charts and simple empirics to be derived and the extra power would then be a simple exercise. But these are trade secrets (if they even exist) so the DIY builder or potential buyer must resort to simple but crude methods.

A small boat is much more effected by bad weather than a larger one; take the extreme of something only 15 or 20 feet long compared to a CruiseShip about 800 feet long. So while doubling calculated power is acceptable for a certain size it is far too much for a ship but it may be insufficient for a boat.

An easy way out of this is simply to find the wind resistance and hence the power. But even this entails long tedious calculations of projected areas, shape, wind direction and so on. The worst case is when the wind is blowing on the forward quarter and it depends on the side area as well as the transverse area so I simplified it all by using a combination of two methods (Adml. Taylor and records of the small ship *Lucy Ashton*) and adjusting the coefficients so that only the wind on the bow is considered.

Cell D14 is the entry cell for the area of the boat and is approximately the beam times the

| | | | | |
|---|---|---|---|---|
| 14 | Projected transverse area | **112.5** | sq. feet | Rough guide: 112.5 sq. feet |

freeboard amidships plus the house height times its width plus any topside bulwarks or windbreakers. I am unable to find any consistency whatever in the area compared to the boat length so I made a very rough and ready formula and the value is shown on the spreadsheet

$$\text{Projected transverse area} = 0.125 \times LWL^2$$

There is a wide variance in the proportion that depends on the type of boat and also if it is a commercial working boat or a recreational version. Take a trawler as an example where some are fishing boats of styles common in the Canadian Maritimes and the US New England states. These tend to have a smaller house than the recreational varieties with quite extensive living accommodations. While the formula has a coefficient of 0.125 it can fall anywhere in the range of 0.1 to 0.15 so you should calculate the area yourself if you have the arrangement drawing of the boat.

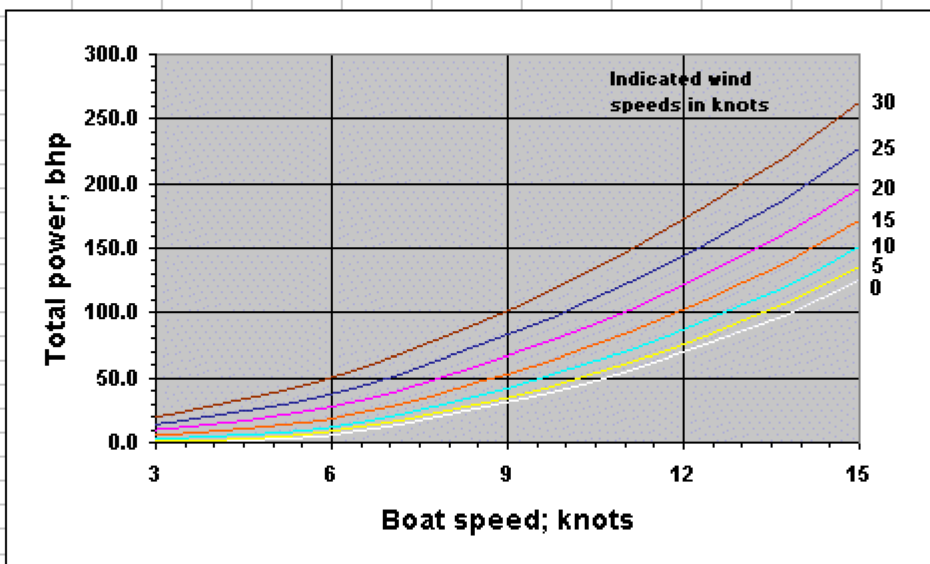
So page 2 of the output looks like this;

**Displacement & Semi-Displacement Boat Power**

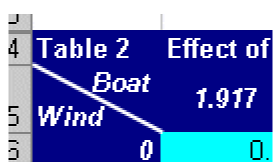
Project: The thingamyy whatchamaycallit
Calc I.D. 1001ABC

**Table 2 Effect of wind on power**

| Wind \ Boat | 1.917 | 3.225 | 4.534 | 5.842 | 7.150 | 8.459 | 9.767 | 11.075 | 12.383 | 13.692 | 15.000 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 0.1 | 0.5 | 1.8 | 5.3 | 13.7 | 25.7 | 39.1 | 55.8 | 75.4 | 97.9 | 125.6 |
| 5 | 0.6 | 1.4 | 3.2 | 7.4 | 16.6 | 29.6 | 43.9 | 61.8 | 82.7 | 106.6 | 135.7 |
| 10 | 1.7 | 3.4 | 6.2 | 11.5 | 21.9 | 36.3 | 52.1 | 71.6 | 94.1 | 119.8 | 150.9 |
| 15 | 3.4 | 6.4 | 10.7 | 17.6 | 29.7 | 45.8 | 63.6 | 85.1 | 109.8 | 137.7 | 171.1 |
| 20 | 5.8 | 10.6 | 16.8 | 25.7 | 39.9 | 58.2 | 78.3 | 102.3 | 129.6 | 160.2 | 196.4 |
| 25 | 8.8 | 15.8 | 24.4 | 35.7 | 52.5 | 73.5 | 96.4 | 123.2 | 153.5 | 187.3 | 226.8 |
| 30 | 12.5 | 22.2 | 33.5 | 47.7 | 67.5 | 91.6 | 117.7 | 147.9 | 181.7 | 219.1 | 262.2 |




Typical Microsoft sloppiness occurs when the image size is changed and cell formats go crazy! The top left of Table 2 is actually what is shown here on the right.




When the boat is travelling in still air there is a resistance due to the resultant speed of the air which is the boat speed. The power plotted for the wind effect allows for this and the formula used is

$$\text{Power to overcome wind} = \frac{A \times V^3}{50{,}000}$$

In which A is the area and V is the (wind speed + boat speed) in knots then the value is reduced using the formula with only the boat speed. When the boat is slow compared to the wind, the effect can be ignored but if they are the same then the reduction is 12.5%. A pain doing calculations manually would put the wind up anyone but in a spreadsheet it's a breeze.

## Installed power

Suppose in this example boat it was decided to drive it at 15 knots then 125 bhp would be the starting point. If the boat were only to operate recreationally then perhaps 200 hp in a 20 knot wind would be satisfactory. If, however, it was to be a commercial venture at sea it would be more prudent to select a 30 knot wind or even more giving about 260 or 270 hp.

Then there is the question of engine rating by the manufacturer. A pure recreation boat for the summer might operate for only a few hundred hours per annum for only 4 or 5 hours maximum in any 24 hours. In such cases the engine settings, fuel lines, valve train etc allow the engine to put out more power than the same engine expected to operate 24/7 over a lengthy period. This has the effect of increasing engine size for commercial craft to ensure compliance with a more onerous long-term power demand. Also too the question of the setting at which the maximum power will be delivered. A reserve of power is often allowed for in commercial vessels so the design output may be at 75% power with another 15% in hand.

This can all add up to a hefty increase in the original estimate so even the recreation boat could be 125 up to 200/0.8 = 250 hp installed and the commercial boat could be 125 to 265/0.75 + 15% = say 410 hp.

Clearly, the proper selection of weather allowance and rating has a major effect on the end power and with it the engine cost. If the commercial operator accepted a speed penalty he could opt for only 10 knots in a 30 knot wind for no increase in power compared to 15 knots in no wind. So carefully check out the weather conditions in which you intend to operate.

## Wrap-up

There is a danger that the method concentrates on old hull forms and is not characteristic of present forms. This could cause wide errors over most of the output so everything should be treated with caution. But anyone having solid and reliable data could easily prepare a few fudge factors.

If anyone has any suggestions and can supply some info I could include it and make any necessary corrections.

Michael D
18 Jan, 2003