Fridge & Freezer Calculations for a Small Cruising Boat

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1 References

Sources of information are:

Reference A:	Boat Owner's Mechanical & Electrical Manual, Third Edition, Nigel Calder
Reference B:	Marine Refrigeration Hints & Advice http://www.penguinfrigo.co.uk/page/marine-refrigeration-12-24-volt-fridge-freezer-tips-on-power-consumption-efficiency-insulation-and-solar/#622
Reference C:	Fitting a Solar Power Fridge, Practical Boat owner, September 2008, http://www.penguinfrigo.co.uk/assets/assets/PBO%20Fridge%20fitting.pdf
Reference D	Boat Refridgeration Seminar, R.L. Kollmann, http://www.kollmann-marine.com/slideshowweb/slide%20show%206b.pdf
Reference E	Heat Influx per 24hrs, per Sq. Ft. of Interior Box Surface Area, http://www.glacierbay.com/Heatcalc.asp
Reference F	Refrigeration Selection Guide, http://xpedio.carrier.com/idc/groups/public/documents/techlit/570-545.pdf
Reference G	This Old Boat, 2nd Edition, Don Casey

2 Introduction

In this article, a "cool box" refers to either a refrigerator or a freezer compartment which is cooled by a DC compressor circulating a refrigerant between an evaporator plate and a condenser. The objective of this article is to predict the battery drain in ampere-hours (Ah) per day caused by the overall heat load of 2 cool boxes, one operating as a fridge and the other as a freezer. The predictions are tested by experiment and by comparison with other authorities. The condenser is assumed to be air cooled and the worst case conditions are cruising in the tropics.

The current consumption of a fridge and a freezer is the main drain on DC batteries in a cruising boat in hot weather. Accurate estimates of the likely current drain, in worst case conditions, are essential for working out what size battery capacity to go for and what re-charging systems are required.

The example given is for a 10m cruising catamaran called an Eclipse, designed by Richard Woods. However, the principles and methodology described in this article are generally applicable to any situation where cool boxes are required and the power to keep them cool is limited.

3 Dimensions of Cool Box installed Between the Sides of a Hull

The shape of a cool box installed between the sides of a hull is shown in Figure 1, together with the calculations required to work out volume and surface area. The sides could slope, giving a larger volume, but having vertical sides and a shelf gives more usable space. In the Eclipse, I chose to have vertical sides so w1t=w1b and w2t=w2b.

The cool box could be exactly the dimensions shown, with the insulation added to the outside, or the insulation could go inside the box shown, in which case the volume of the cool box will obviously be much smaller. In the spreadsheet shown in Figure 4, the external dimensions have been chosen for the fridge to fit between the hull sides underneath the forward bunk in the starboard hull of the Eclipse catamaran and for the freezer to fit between the hull sides under the aft bunk also in the starboard hull.

average width at top of box, wt = (w1t+w2t)/2

average width at bottom of box, wb = (w1b+w2b)/2

average cross-sectional area of box, ax = h*(wt+wb)/2

volume of box = ax*L

average length of side, s = [(wt-wb)/2)^2+h^2]^1/2

panel area of box = 2*s*L+2*ax+wt*L+wb*L

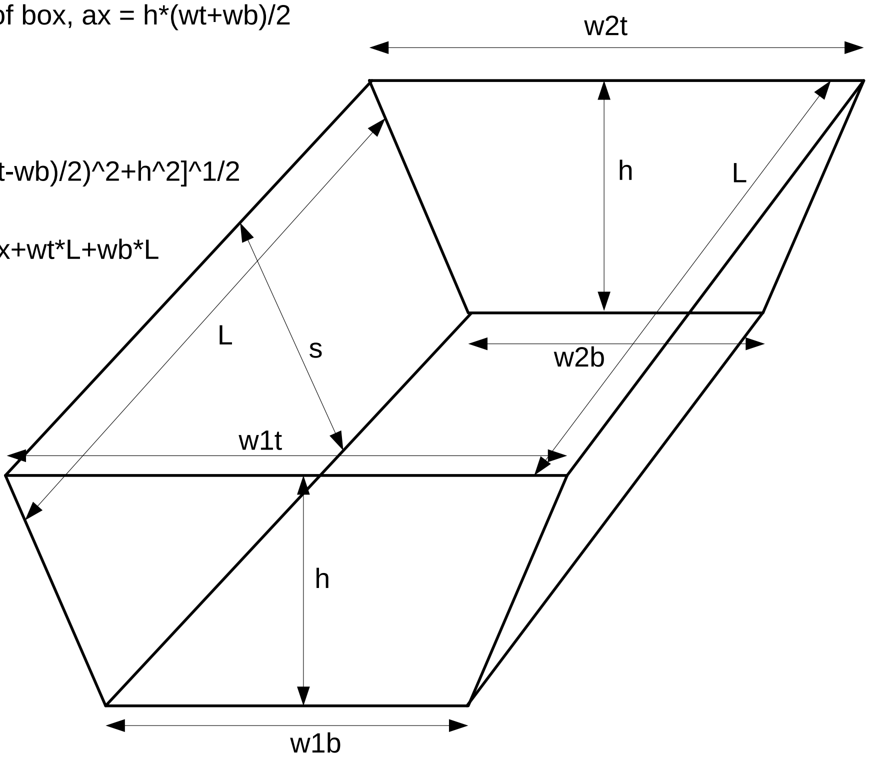


Figure 1: Dimensions of a Cool Box Installed between Hulls

4 Calculation of Heat Load

The main contributions to the heat load of a cool box come from conduction through the sides and its usage – that is to say chilling food and opening the cool box to remove items of food.

4.1 Conduction Heat Load

The key insulation parameter is the conductivity (k) of the insulation material, measured in the rate of heat energy (watts) being transferred through the material per unit thickness (metre) per degree temperature difference (^{0}C or ^{0}K). So, in the SI system the units of k are W/m.K. For example, plywood has a conductivity of 0.13 W/m.K.

What one is really interested in is the heat conductance through a wall per unit area. This is derived from the k value of the insulation material, simply by multiplying by the thickness of the wall and is given as the U value in Europe with the units W/m^2.K. For example, 9mm plywood has a conductance of 0.13/0.009 = 14.4 W/m^2.K – which is about the same as a 75mm concrete block.

The conductance value can be expressed as a resistance value, R, where R=1/U m^2.K/W. In the US the R value is most commonly quoted, expressed in the imperial units ft^2.F.h/Btu: i.e. (square feet, degrees Fahrenheit, hours) per British thermal unit. Note the appearance of time units in the US R value; they are there in the European R value as well since watts=joules per second. A watt is a unit of power, whereas a Btu and a joule are units of energy; the European R value could be expressed in units of m^2.K.s/J.

The conduction heat load is worked out for a cool box operating as both a fridge and a freezer in Figure 4. However, a section on working out how to calculate heat load is required, and this does involve a differential equation (which forced me to de-rust quite a few brain cells).

4.1.1 Heat Load of a Box

My first attempt at calculating the heat load of the cool boxes assumed the heat radiating into a cool box could be calculated using the internal area of the box; however this underestimates the heat load, as became clear when measuring the heat load of 2 boxes (see Section 0). On the other hand, plugging an average area into the equation [(internal area + external area)/2], as recommended by Nigel Calder in **Reference A**, overestimates the heat gain.

How can we calculate the heat load of a small box with internal temperature θ_1 and external temperature θ_2? The problem is that a small box will have corner effects; the smaller the internal volume and the greater the thickness of insulation, the larger these effects will be. To get a handle on these effects, let's simplify and assume the box is a perfect cube with distance from the centre to the inside of the insulation being X_1 and to the outside of the insulation being X_2 - see Figure 2.

At a distance of x from the centre the heat transfer Φ (in watts) is given by the conductivity k (in W/m.K) multiplied by the surface area (in metres) multiplied by the temperature gradient at that point, dθ/dx (in K/m).

$$\emptyset = k \times A \times \frac{d\theta}{dx} = 24 \times k \times x^2 \times \frac{d\theta}{dx}$$

Rearranging and integrating over the interval X_1 to X_2 and θ_1 to θ_2 …

$$\int_{X_1}^{X_2} \frac{dx}{x^2} = 24 \times k/\emptyset \times \int_{\theta_1}^{\theta_2} d\theta$$

$$-\left(\frac{1}{X_2} - \frac{1}{X_1}\right) = 24 \times k/\emptyset \times (\theta_2 - \theta_1)$$

… gives the result:

$$\emptyset = \frac{24 \times k \times X_1 \times X_2 \times (\theta_2 - \theta_1)}{X_2 - X_1}$$

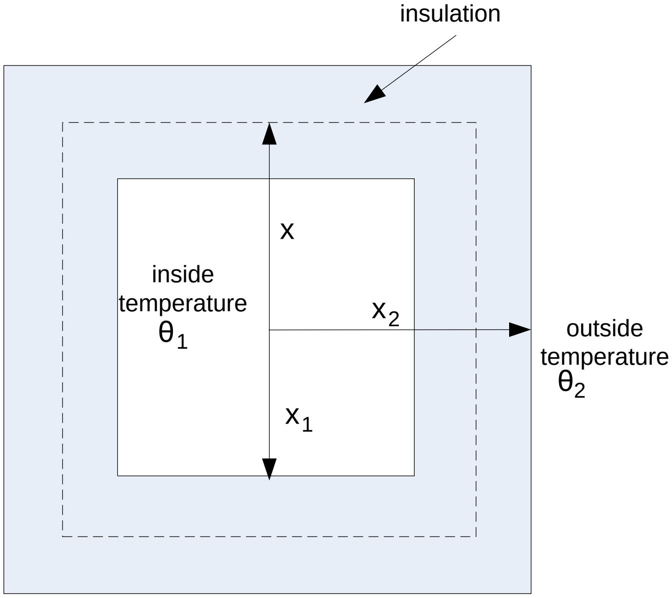


Figure 2: Cross Section Through a Cube-Shaped Box

Note that the term $k/(X_2-X_1)$ is the conductance U (in $W/m^2.K$) and $X_2 = X_1+t$, where t is the thickness of the insulation. This equation can therefore be re-written as:

$$\emptyset = 24 \times U \times X_1 \times (X_1 + t) \times (\theta_2 - \theta_1)$$

If the cube is large, so that t is small in comparison with X1 or X2 this equation approximates to…

$$\emptyset = A \times U \times (\theta_2 - \theta_1)$$

…where A is the surface area of the cube; i.e. the corner effects are negligible.

In cases where the corner effects are not negligible, this equation correctly predicts that the conduction heat load of a small box is worse than calculations solely based upon interior surface area of the box would predict.

The above analysis does suggest a methodology to allow for the corner effects:

- calculated the internal area of the box, say Am^2;
- find the value X_1 assuming the box is a cube;
- find the effective area, say A_em^2, using the factor $X_1*(X_1+t)$ instead of X_1*X_1;

- use A_e to calculate the heat load instead of A (since A_e will be larger than A, the predicted result will more closely correspond with reality).

This is the approach used in the spread sheet shown in Figure 4.

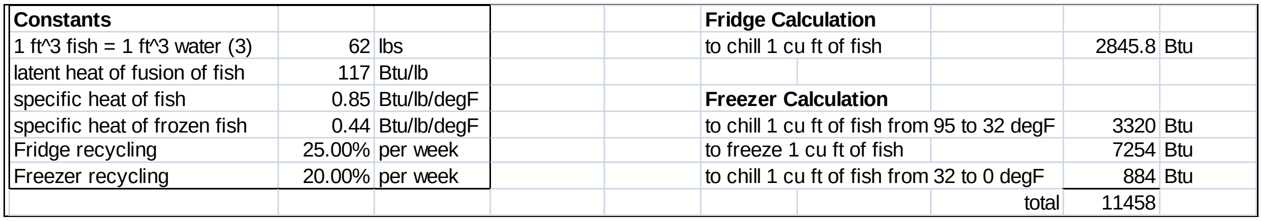
4.2 Usage Heat Load

A lot of energy is used to cool items of food and drink down to the required temperature. If you are also freezing a food or drink item then you have to apply energy just to change the state of the water in that item from liquid to solid, without any temperature change.

To calculate the heat load of cooling something, one needs to know the specific heat of that thing expressed in joules per gram per ^{0}C (or ^{0}K) or, in the US imperial system Btu/lb.F. The specific heat of various substances, expressed in the US imperial system, can be found at Reference F. To cool 1lb of water by 1^{0}F requires 1 Btu of energy. Once a substance is frozen its specific heat is about ½ of the value it was above the freezing point.

To calculate the energy required to freeze something one needs to know the latent heat of fusion for that item. These values can also be found in Reference F. To freeze 1lb of water requires 144Btu.

An average sort of food item one is likely to want to cool and to freeze is fish. The energy required to fill a 1cu ft of fridge or freezer is calculated using a spreadsheet called fridge_freezer_calcs.xlsx with the results shown in Figure 3. The internal temperatures of the fridge and freezer are 5^{0}C and -18^{0}C respectively. Since the fish swims in water its density is about the same, therefore a cu ft of fish will weigh about the same as a cu ft of water.



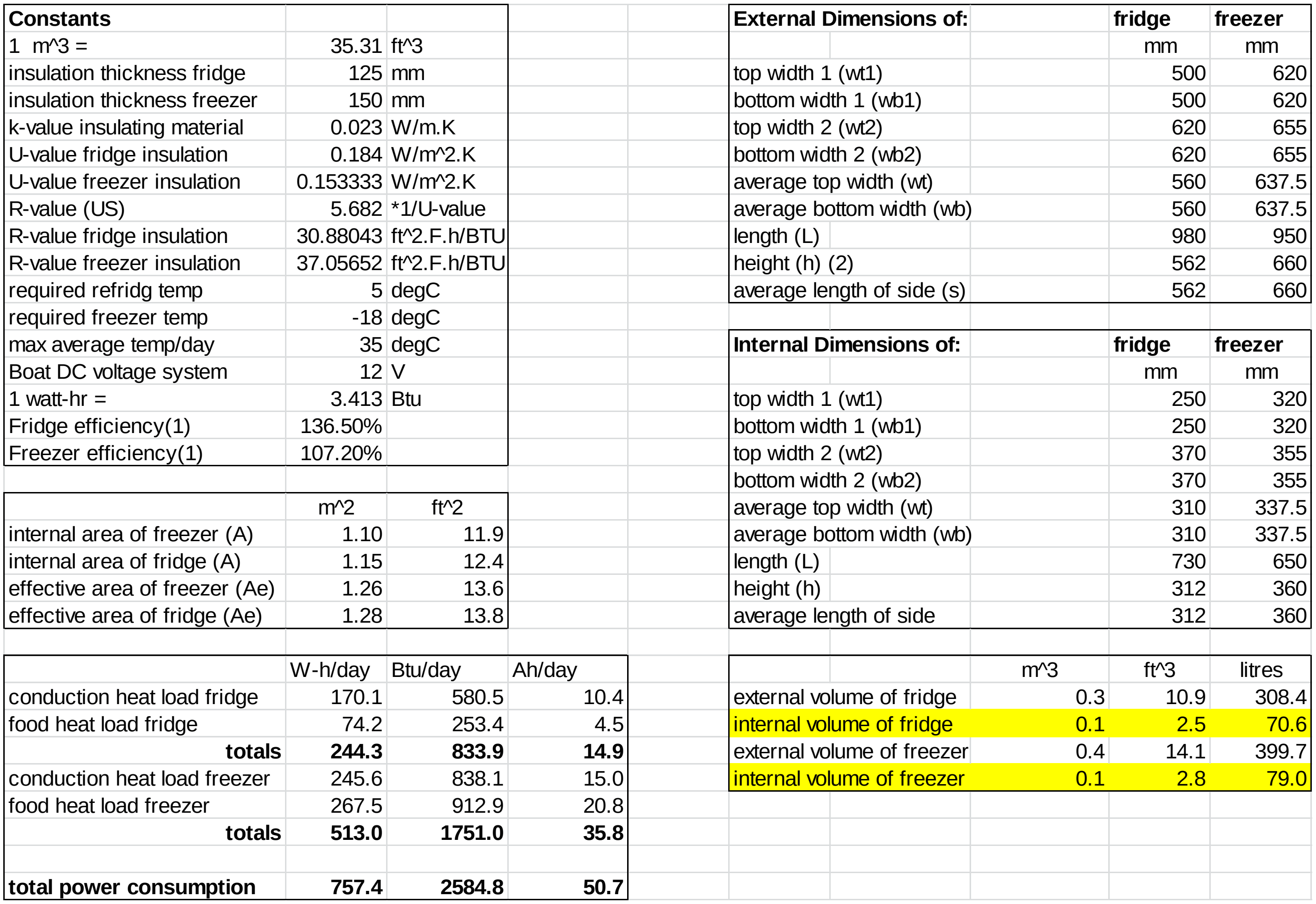
Constants					**Fridge Calculation**				
1 ft^3 fish = 1 ft^3 water (3)	62	lbs			to chill 1 cu ft of fish			2845.8	Btu
latent heat of fusion of fish	117	Btu/lb							
specific heat of fish	0.85	Btu/lb/degF			**Freezer Calculation**				
specific heat of frozen fish	0.44	Btu/lb/degF			to chill 1 cu ft of fish from 95 to 32 degF			3320	Btu
Fridge recycling	25.00%	per week			to freeze 1 cu ft of fish			7254	Btu
Freezer recycling	20.00%	per week			to chill 1 cu ft of fish from 32 to 0 degF			884	Btu
							total	11458	

Figure 3: Heat Loads from Chilling and Freezing

A lot depends upon how the cool box is used. In Figure 3, the assumption is that one will consume and replace 25% of the contents of the fridge and 20% of the contents of the freezer per week. The freezer might be re-loaded with food items that are already frozen, which will significantly reduce the load. However, expect usage to increase the heat load by between ½ to 1 times the conduction heat load.

5 Energy Calculations

Volume, area and energy requirements are shown in Figure 4. The spreadsheet shown is called fridge_freezer_calcs.xlsx; using it one can play with the key parameters such as insulation thickness, conductivity values and the external dimensions of the cool box.



Constants		
1 m^3 =	35.31	ft^3
insulation thickness fridge	125	mm
insulation thickness freezer	150	mm
k-value insulating material	0.023	W/m.K
U-value fridge insulation	0.184	W/m^2.K
U-value freezer insulation	0.153333	W/m^2.K
R-value (US)	5.682	*1/U-value
R-value fridge insulation	30.88043	ft^2.F.h/BTU
R-value freezer insulation	37.05652	ft^2.F.h/BTU
required refridg temp	5	degC
required freezer temp	-18	degC
max average temp/day	35	degC
Boat DC voltage system	12	V
1 watt-hr =	3.413	Btu
Fridge efficiency(1)	136.50%	
Freezer efficiency(1)	107.20%	

	m^2	ft^2
internal area of freezer (A)	1.10	11.9
internal area of fridge (A)	1.15	12.4
effective area of freezer (Ae)	1.26	13.6
effective area of fridge (Ae)	1.28	13.8

	W-h/day	Btu/day	Ah/day
conduction heat load fridge	170.1	580.5	10.4
food heat load fridge	74.2	253.4	4.5
totals	**244.3**	**833.9**	**14.9**
conduction heat load freezer	245.6	838.1	15.0
food heat load freezer	267.5	912.9	20.8
totals	**513.0**	**1751.0**	**35.8**
total power consumption	**757.4**	**2584.8**	**50.7**

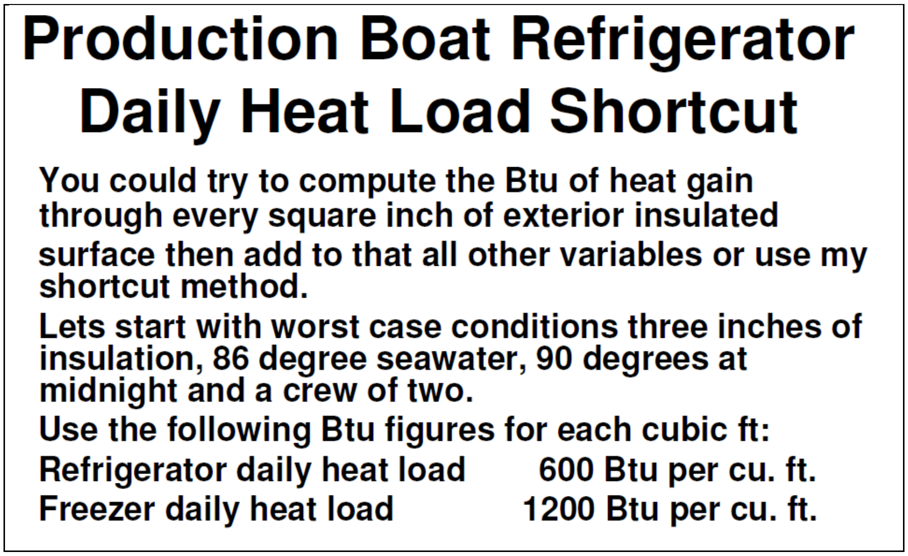
External Dimensions of:	**fridge**	**freezer**
	mm	mm
top width 1 (wt1)	500	620
bottom width 1 (wb1)	500	620
top width 2 (wt2)	620	655
bottom width 2 (wb2)	620	655
average top width (wt)	560	637.5
average bottom width (wb)	560	637.5
length (L)	980	950
height (h) (2)	562	660
average length of side (s)	562	660

Internal Dimensions of:	**fridge**	**freezer**
	mm	mm
top width 1 (wt1)	250	320
bottom width 1 (wb1)	250	320
top width 2 (wt2)	370	355
bottom width 2 (wb2)	370	355
average top width (wt)	310	337.5
average bottom width (wb)	310	337.5
length (L)	730	650
height (h)	312	360
average length of side	312	360

	m^3	ft^3	litres
external volume of fridge	0.3	10.9	308.4
internal volume of fridge	0.1	2.5	70.6
external volume of freezer	0.4	14.1	399.7
internal volume of freezer	0.1	2.8	79.0

Figure 4: Power Consumption of a Fridge & Freezer Cool Boxes

The energy consumption figures are given in watt-hours/day, British-thermal-units/day and amp-hours/day; the former two represent the heat energy which has to be removed every day and the latter figure represents the amount of electrical energy which is needed to do this. Because of the Coefficient of Performance (COP) of heat pumps, one unit of electrical energy can remove more than one unit of heat energy. The COP is higher the smaller the temperature difference between the condenser and evaporator environments; therefore the fridge is more efficient than the freezer. To estimate the COP, Nigel Calder's rule of thumb was used: 1 W-h of applied energy extracts 5Btu of heat energy for a fridge and 4 Btu for a freezer. Further inefficiencies of 10% were also added.



Production Boat Refrigerator Daily Heat Load Shortcut

You could try to compute the Btu of heat gain through every square inch of exterior insulated surface then add to that all other variables or use my shortcut method.

Lets start with worst case conditions three inches of insulation, 86 degree seawater, 90 degrees at midnight and a crew of two.

Use the following Btu figures for each cubic ft:

Refrigerator daily heat load	600 Btu per cu. ft.
Freezer daily heat load	1200 Btu per cu. ft.

Figure 5: Heat Load Calculation from R.L. Kollmann Presentation

6 Comparison of Calculations with Other Sources

How accurate are the figures given in Figure 4? They assume that the load is due purely to conduction through the cool box sides and the heat load due to chilling things down. In addition there is the opening and closing of the cool box to remove items; in a top-loading cool box this is assumed to be negligible.

As far as predicting conduction heat load is concerned, the spreadsheet has been shown to correlate closely with actual measurements – see Section 8.

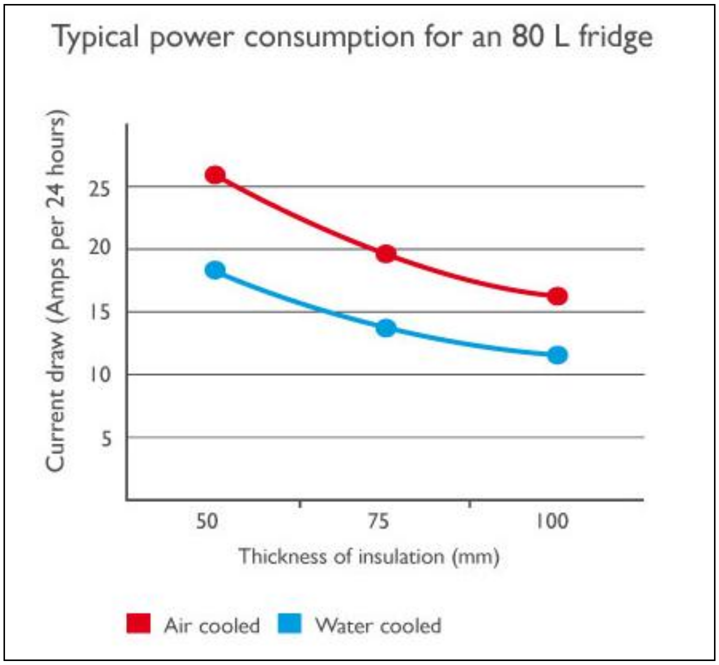
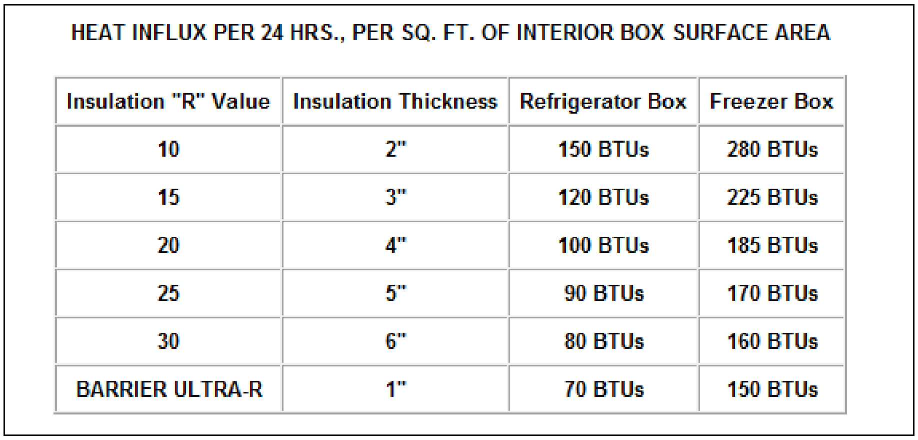


Figure 6: Typical Power Consumption for an 80 Litre Fridge in the UK

In Reference D, there is a slide, reproduced in Figure 5, which gives figures for 1 cu ft of internal volume. In Reference B, there is a graph, shown in Figure 6, which gives the power consumption of an 80 litre fridge with 75mm of insulation. Finally, **Reference A** gives a table (Table 11-2) taken from Glacier Bay documentation linked to at Reference E; this table is reproduced in Figure 7 and gives the heat load per square foot for cool boxes with various insulation thicknesses.

These figures can be compared with a fridge & freezer calculation, using the spreadsheet fridge_freezer_calcs.xlsx, for 3in (75mm) of insulation with R=15 ft^2.F.h/Btu, for 1 cu ft of internal volume; the results of this calculation can be seen in Figure 9. The comparison is shown in Table 1.



HEAT INFLUX PER 24 HRS., PER SQ. FT. OF INTERIOR BOX SURFACE AREA

Insulation "R" Value	Insulation Thickness	Refrigerator Box	Freezer Box
10	2"	150 BTUs	280 BTUs
15	3"	120 BTUs	225 BTUs
20	4"	100 BTUs	185 BTUs
25	5"	90 BTUs	170 BTUs
30	6"	80 BTUs	160 BTUs
BARRIER ULTRA-R	1"	70 BTUs	150 BTUs

Figure 7: Heat Load of Cool Box for Different R-Values (Glacier Bay)

The fridge calculations of Figure 9 are in between the figures given by Kollmann and Glacier Bay. However, the calculation results are very sensitive to the usage figures shown in Figure 3. If the percentage figures given for consumption and replenishment per week are increased from 25% to 50% for the fridge and from 20% to 28% for the freezer then we get very similar figures to those quoted by Glacier Bay. The usage figures will also depend upon the size of the cool boxes; for example, a 1 cu ft fridge will probably have a greater percentage of its contents recycled every week than a 4 cu ft fridge.

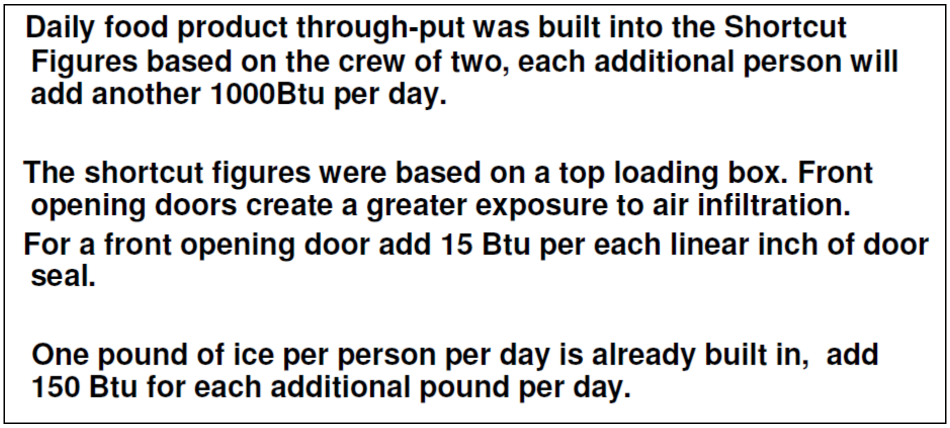
	Spreadsheet (Btw/day/ft^3)	**GlacierBay/Calder (Btw/day/ft^3)**	**Kollmann (Btw/day/ft^3)**	**Penguinfrigo (Btw/day/ft^3)**
Fridge	673	720	600	397
Freezer	1338	1350	1200	

Table 1: Different Calculations of Heat Loads in the Tropics

Changing the temperatures also produces big changes; for example we don’t know what the fridge and freezer thermostat settings are for the Glacier Bay and Kollmann figures nor what the average diurnal ambient temperatures are around the cool boxes.

The fridge calculation is more than Penguinfrigo estimate, but the test which gave us the graph shown in Figure 6 was conducted in the UK in summertime with an average temperature in the order of 20 deg C. If we redo the spreadsheet with an outside temperature of 22.5 deg C, then we get a heat load calculation of 393 Btu/day which agrees with the value in the table.

Kollmann also provided details of variables which add to the heat load: his heat load short cut assumes 2 people using a top-loading refrigeration system which supplies them with 1lb of ice every day! For an extra person you need to add 1000 Btu/day – see Figure 8. For a 4 cu ft box the heat load calculations, including these variables, is shown in Figure 14.



Daily food product through-put was built into the Shortcut Figures based on the crew of two, each additional person will add another 1000Btu per day.

The shortcut figures were based on a top loading box. Front opening doors create a greater exposure to air infiltration.
For a front opening door add 15 Btu per each linear inch of door seal.

One pound of ice per person per day is already built in, add 150 Btu for each additional pound per day.

Figure 8: Factors that Increase Daily Heat Load

Constants		
1 m^3 =	35.31	ft^3
insulation thickness fridge	75	mm
insulation thickness freezer	75	mm
k-value insulating material	0.0284	W/m.K
U-value fridge insulation	0.378667	W/m^2.K
U-value freezer insulation	0.378667	W/m^2.K
R-value (US)	5.682	*1/U-value
R-value fridge insulation	15.00528	ft^2.F.h/BTU
R-value freezer insulation	15.00528	ft^2.F.h/BTU
required refridg temp	5	degC
required freezer temp	-18	degC
max average temp/day	35	degC
Boat DC voltage system	12	V
1 watt-hr =	3.413	Btu
Fridge efficiency(1)	136.50%	
Freezer efficiency(1)	107.20%	

	m^2	ft^2
internal area of freezer (A)	0.56	6.0
internal area of fridge (A)	0.56	6.0
effective area of freezer (Ae)	0.61	6.6
effective area of fridge (Ae)	0.61	6.6

	W-h/day	Btu/day	Ah/day
conduction heat load fridge	**167.5**	571.5	10.2
food heat load fridge	29.8	101.8	1.8
totals	**197.3**	**673.3**	**12.0**
conduction heat load freeze	**295.8**	1009.7	18.1
food heat load freezer	96.1	328.0	7.5
totals	**391.9**	**1337.6**	**25.5**
total power consumption	**589.2**	**2011.0**	**37.6**

External Dimensions of:	**fridge**	**freezer**
	mm	mm
top width 1 (wt1)	455	455
bottom width 1 (wb1)	455	455
top width 2 (wt2)	455	455
bottom width 2 (wb2)	455	455
average top width (wt)	455	455
average bottom width (wb)	455	455
length (L)	455	455
height (h) (2)	455	455
average length of side (s)	455	455

Internal Dimensions of:	**fridge**	**freezer**
	mm	mm
top width 1 (wt1)	305	305
bottom width 1 (wb1)	305	305
top width 2 (wt2)	305	305
bottom width 2 (wb2)	305	305
average top width (wt)	305	305
average bottom width (wb)	305	305
length (L)	305	305
height (h)	305	305
average length of side	305	305

	m^3	ft^3	litres
external volume of fridge	0.1	3.3	94.2
internal volume of fridge	0.0	1.0	28.4
external volume of freezer	0.1	3.3	94.2
internal volume of freezer	0.0	1.0	28.4

Figure 9: Heat Load Calculations - 1cu ft Fridge & Freezer with 75mm Insulation

7 Construction of a Cool Box

There are several likely candidates for the insulation material for a cool box – see Table 2.

	E.g. Product Name	k (W/m.^{0}K)
Vacuum Insulation Panels	Vacupor	0.004
Aerogel based products	Spacetherm	0.013
Phenolic insulation	Kingspan Kooltherm	0.021
Polyurethane (PUR) or Polyisocyanurate (PIR)	Celotex TB4000	0.023
Extruded polystyrene	Styrofoam	0.027
Plywood		0.13

Table 2: Conductivity of Various Insulation Materials

The clear best is the VIP but edge effects mean that the performance quoted is not easily met and they need to be protected from puncturing. Clearly, they cannot be cut to size. Finally, they are expensive. Aerogel products are also impressive but there are not many products on the market place and they are also expensive. If space is limited, VIP or Aerogel may be the answer.

Going just by the insulation properties of PUR/PIR and Phenolic insulation, there is little to separate them; Phenolic foam is better, but only just. However, Phenolic foam is more resistant to moisture than PUR/PIR foam and extruded polystyrene is more resistant still. Ingress of water, perhaps through condensation, will dramatically reduce the insulation properties of any foam – even the closed-cell foam, which they all are. Extruded polystyrene is freely available and cheap; Phenolic foam is also readily available, but considerably more expensive.

However, the cool box is encased in plywood coated by epoxy on the outside and a laminate of epoxy & glass cloth on the inside; it is unlikely to get wet. In Reference G, Don Casey describes his cool box, made out of PIR, which has seen no increase in condenser run time in 10 years. Since PUR/PIR is much cheaper than phenolic foam, it is a very attractive option.

Reference G also gives excellent detail on how to construct a cool box. A cool box that is to serve as a fridge has a structure similar to that shown in Figure 10. Here five layers of 25mm insulation board are overlapped within a plywood box which is top opening. Note that the lid only has four layers; this is to make the fridge easier to use when the lid is open and to gives more interior volume – since the warmest part of the fridge is at the top thinner insulation will have less effect at the top than at the bottom.

Careful construction and double seals, which go all around the lid, ensures the opening does not leak. During the construction, wooden hardwood cleats are added behind the interior glass-fibre skin for subsequent mounting of the evaporator plate and any shelves required. Any gaps, e.g. where the connections to the evaporator plate enter and leave, are filled up with expanded polyurethane foam. The interior of the box is finished with 2-part polyurethane paint which is “rolled and tipped” to give a hard glassy finish, which is easy to keep clean.

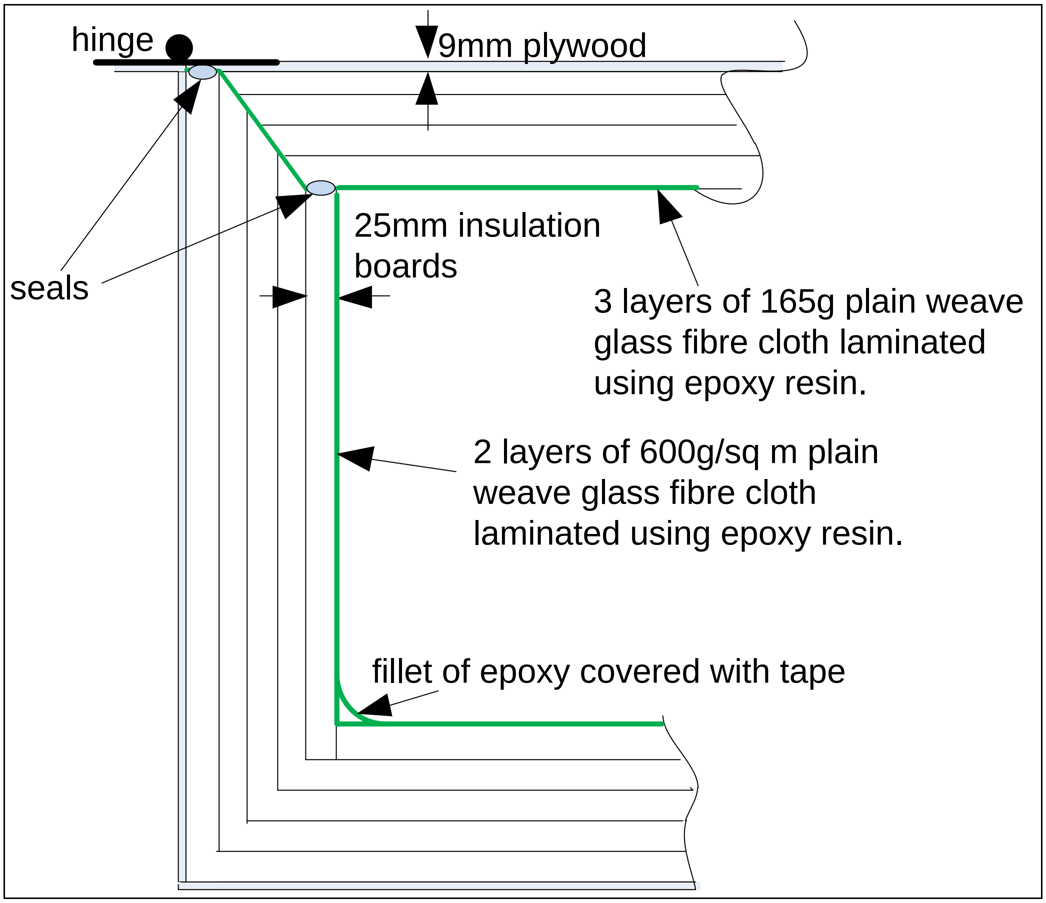


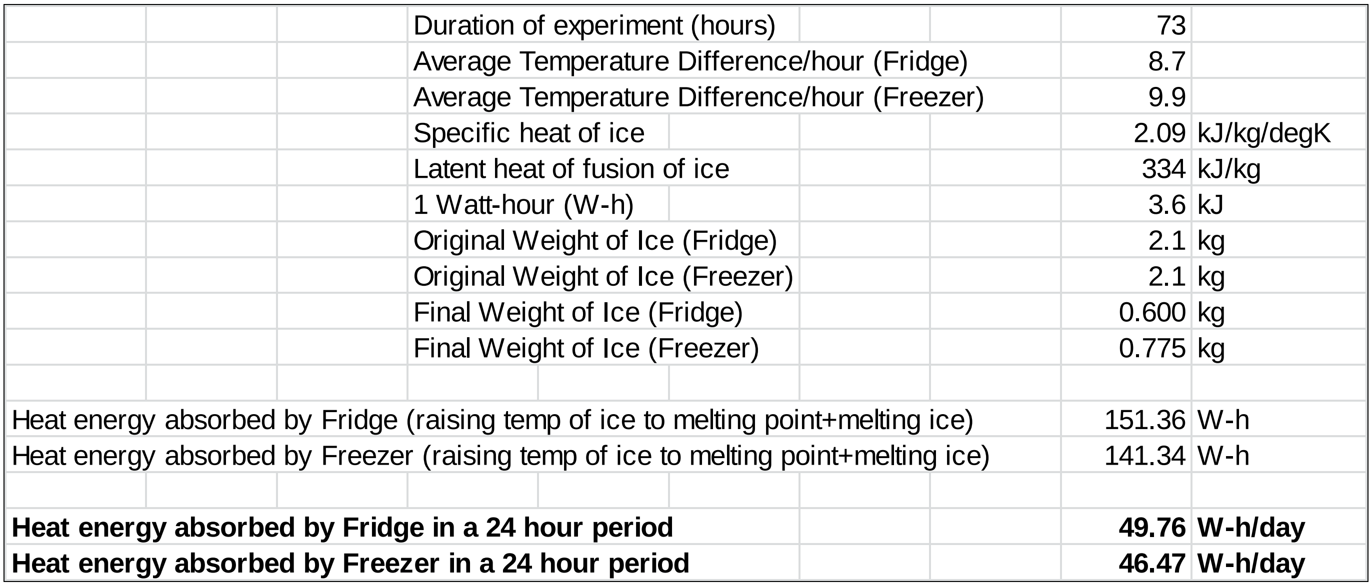
Figure 10: Cool Box Construction Details

8 Experiment to Measure Conduction Heat Load

After the cool boxes were built, an experiment was conducted to see how well they performed. I wanted to answer the question: how does the actual conduction heat load compare with the predicted values given by the spreadsheet?

A bag of ice was put into both boxes and the temperature difference between the outside and inside measured every hour until over half the ice had melted. The actual heat load over the course of the experiment is the amount of energy it takes to raise the temperature of the ice to its melting point plus the energy involved to change the state of the ice which has melted. It is called the ‘heat load’ because this is the heat energy the condensing units have to remove to keep the boxes cool.

The results are shown in Figure 11. The heat load in Watt-Hours per day can be compared with the output of the spreadsheet given the same inputs – see Figure 12.



Duration of experiment (hours)	73	
Average Temperature Difference/hour (Fridge)	8.7	
Average Temperature Difference/hour (Freezer)	9.9	
Specific heat of ice	2.09	kJ/kg/degK
Latent heat of fusion of ice	334	kJ/kg
1 Watt-hour (W-h)	3.6	kJ
Original Weight of Ice (Fridge)	2.1	kg
Original Weight of Ice (Freezer)	2.1	kg
Final Weight of Ice (Fridge)	0.600	kg
Final Weight of Ice (Freezer)	0.775	kg
Heat energy absorbed by Fridge (raising temp of ice to melting point+melting ice)	151.36	W-h
Heat energy absorbed by Freezer (raising temp of ice to melting point+melting ice)	141.34	W-h
Heat energy absorbed by Fridge in a 24 hour period	**49.76**	**W-h/day**
Heat energy absorbed by Freezer in a 24 hour period	**46.47**	**W-h/day**

Figure 11: Measurements of Heat Load - Fridge & Freezer

The results are remarkably similar, within 1% - see Figure 12. When I first did the results, the measurements were about 10% higher than the calculations. Thinking about sources of error, I realised that the calculations were underestimates because I hadn’t taken into account the corner effects of the box; including those (see Section 4.1.1 for how this was done) resulted in a much closer agreement.

Constants			
1 m^3 =	35.31	ft^3	
insulation thickness fridge	125	mm	
insulation thickness freezer	150	mm	
k-value insulating material	0.023	W/m.K	
U-value fridge insulation	0.184	W/m^2.K	
U-value freezer insulation	0.153333	W/m^2.K	
R-value (US)	5.682	*1/U-value	
R-value fridge insulation	30.88043	ft^2.F.h/BTU	
R-value freezer insulation	37.05652	ft^2.F.h/BTU	
required refridg temp	3.3	degC	
required freezer temp	2.1	degC	
max average temp/day	12	degC	
Boat DC voltage system	12	V	
1 watt-hr =	3.413	Btu	
Fridge efficiency(1)	136.50%		
Freezer efficiency(1)	107.20%		
	m^2	ft^2	
internal area of freezer (A)	1.10	11.9	
internal area of fridge (A)	1.15	12.4	
effective area of freezer (Ae)	1.26	13.6	
effective area of fridge (Ae)	1.28	13.8	
	W-h/day	Btu/day	Ah/day
conduction heat load fridge	**49.3**	168.3	3.0
food heat load fridge	21.5	73.5	1.3
totals	**70.9**	**241.8**	**4.3**
conduction heat load freeze	**45.9**	156.5	2.8
food heat load freezer	193.5	660.4	15.0
totals	**239.4**	**817.0**	**17.8**
total power consumption	**310.2**	**1058.8**	**22.2**

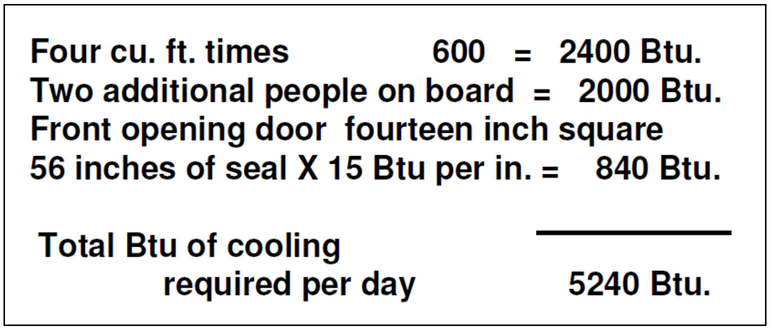
Figure 12: Calculations of Heat Load - Fridge & Freezer

	Calculation	**Measurement**
	W-h/day	W-h/day
Fridge	49.3	49.8
Freezer	45.9	46.5

Figure 13: Calculated and Actual Heat Loads for Fridge & Freezer

9 Conclusions

The spreadsheet gives good enough results with which to plan a refrigeration system. Unlike the various ballpark estimates out there it does give full control of the variables which is useful when choosing the size of the box or insulation materials or if you have definite ideas about how you will be using cool boxes and where you will, or will not be cruising.



Four cu. ft. times	600 =	2400 Btu.
Two additional people on board =		2000 Btu.
Front opening door fourteen inch square		
56 inches of seal X 15 Btu per in. =		840 Btu.
Total Btu of cooling required per day		5240 Btu.

Figure 14: Example of a 4 cu ft Refrigerator in the Tropics

Factors which significantly affect the efficiency and energy drain of a cool box include:

- whether you want a fridge or a freezer, or both;
- the quality and thickness of the insulation;
- whether you load the freezer with food which is already frozen;
- whether you will be cruising the tropics.

Greater efficiency is possible if water cooling is used instead of air cooling, but this brings its own problems: e.g. having to turn off the fridge and/or freezer if you dry out. It also significantly increases the cost of the system.