PHYSICAL PROPERTIES OF SPERMACETI OIL IN THE SPERM WHALE

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(Figs. 1–4)

As a basis for an understanding of the buoyancy function of the spermaceti organ of the sperm whale (*Physeter macrocephalus* L.) this paper deals with the following three physical properties of spermaceti oil: (i) the relationship between its density, temperature and pressure; (ii) heat exchange during freezing and melting; and (iii) the elevation of its temperature during increase in pressure.

INTRODUCTION

This is the second of three papers describing the structure, properties and buoyancy function of the spermaceti organ of the sperm whale (*Physeter macrocephalus* Linnaeus 1758). The first paper (Clarke, 1978*a*) described the detailed structure and proportions of the spermaceti organ and related structures and considered relevant details of the blubber, skin and lungs. Here, three thermal properties of the spermaceti oil are described which are relevant to a study of the function of the oil. Finally, in a third paper (Clarke, 1978*b*) it will be shown that, over its great geographical and depth ranges, the whale varies considerably in buoyancy due to variations in water density and the volume of air in its lungs and it is suggested that, during dives, the whale can control its own density by changing the temperature of the spermaceti oil of the head and may attain neutral buoyancy in dives deeper than 200 m.

METHODS

Spermaceti oil was collected from the head of sperm whales flensed at the Union Whaling Station, Durban, South Africa. Unless stated to the contrary below, samples were immediately deep frozen under nitrogen and stored in this state until the particular experiment was carried out.

RESULTS

Density change of spermaceti oil

As both pressure and temperature affect the density of an oil, it was necessary to examine the three parameters at the same time. At my request, Dr D. Ambrose of the Division of Chemical Standards, National Physical Laboratory, Teddington, measured the fluid compressibility of a spermaceti sample removed from the spermaceti sac of a sperm whale (Beattie, 1934; Douslin *et al.* 1958). Dr Ambrose's report is as follows and includes Table 1 and Fig. 1.

'The sample of spermaceti was received in a refrigerated condition (-78 °C), and was
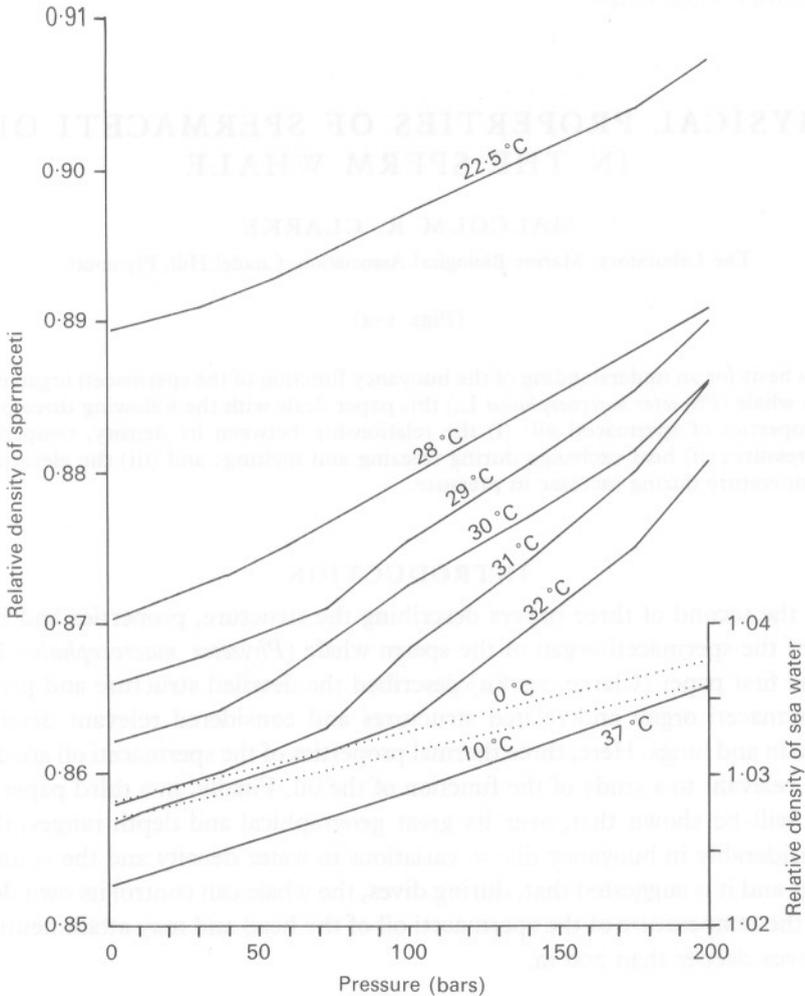
Fig. 1. The relative density of spermaceti oil at various temperatures and pressures. 1 bar ≃1 atmosphere. Measurements made at the National Physical Laboratory, England. The right-hand scale relates to the relative density of sea water at 0 and 10 °C shown as dotted lines.

so maintained until it was required for the measurements. One portion was used for density determination in the apparatus described by Hales (1970) and the following values were obtained:

$$30 \text{ °C } 857·3 \text{ kg/m}^3$$
$$37 \text{ °C } 852·6\text{* kg/m}^3 \Big\} \text{in degassed condition}$$

$$30 \text{ °C } 857·5 \text{ kg/m}^3$$
$$37 \text{ °C } 852·7 \text{ kg/m}^3 \Big\} \text{in air-saturated condition}$$
$$40 \text{ °C } 850·7 \text{ kg/m}^3$$

When the values at 30 °C were obtained, some solid was present in the liquid. Another portion of the sample was charged into the apparatus, similar to that described by Beattie (1934), with which its variation in volume with change in temperature and

pressure could be determined; the volume occupied by the weighed portion of spermaceti at the start of the measurements was calculated from the value of the density given above which is marked with an asterisk.'

The results of these measurements are given in Table 1. From this table the density of the spermaceti oil at any depth or temperature can be determined.

Table 1. *Density (kg m^{-3}) of spermaceti oil (kg/m^3) at selected pressures and temperatures*

1 atmosphere = 1·013 bars.

Pressure bar	Temperature (°C)								
	0·00	15·00	22·50	28·00	29·00	30·00	31·00	32·00	37·00
2·051	925·3	905·3	889·5	870·3	866·0	862·2	858·0	856·9	852·6
3·613	925·3	905·5	889·6	870·4	866·0	862·2	858·0	856·9	852·6
10·51	925·6	905·8	890·0	870·9	866·5	862·6	858·5	857·5	853.2
17·40	925·9	906·2	890·3	871·4	866·9	863·0	—	—	853·7
24·30	926·2	906·6	890·6	871·9	867·4	863·4	859·4	858·4	854·2
31·19	926·6	906·9	891·0	872·4	867·8	863·8	—	—	854·6
38·09	926·9	907·3	891·6	873·0	868·3	864·3	860·2	859·2	855·0
55·32	928·0	908·5	892·8	874·6	869·8	866·3	—	—	856·2
72·56	928·8	909·6	894·5	876·8	871·0	868·4	863·0	861·4	857·3
107·0	930·7	911·8	897·5	880·6	875·6	872·6	868·5	863·6	859·4
141·5	932·7	914·3	900·8	884·4	880·6	877·0	874·3	869·6	861·7
176·0	934·7	917·0	904·1	888·1	885·5	881·5	880·1	875·0	864·0
210·5	936·8	919·7	907·4	891·8	890·2	886·2	886·0	880·8	866·5
Date of run	20/6	19/6	19/6	16/6	16/6	16/6	26/6	27/6	15/6

Heat exchange of the spermaceti oil

It is also necessary to establish the amount of heat which would have to be removed from the spermaceti oil if its temperature were to drop the required amount to balance the lift at each depth.

Spermaceti oil is a complex mixture of wax esters and triglycerides (Morris, 1975), which is a clear straw-coloured liquid above 30 °C but becomes cloudy if lowered below that temperature and progressively crystallizes and sets as the temperature drops. Rough measurements made by dipping a thermometer into the oil which poured from the spermaceti organ of six female whales (33–35 ft long; 10–10·7 m) cut up at Durban showed that after the thermometer was withdrawn the cloudiness hid the bulb of the thermometer at 28·5–29·7 °C. Half a degree lower the wax seemed solid and half a degree higher it was clear. In fact, observation of larger quantities shows that setting or freezing is a progressive process which continues down to below 0 °C. As with freezing of water, latent heat must be exchanged during freezing or melting, but unlike water, this is lost progressively over a large range of temperature.

The heat exchanged during cooling and heating of spermaceti oil was measured on a Perkin–Elmer differential scanning calorimeter. A first trial was carried out on spermaceti oil which had been collected in August 1969 and stored in air without refrigeration until May 1970. Mr M. R. Cottrell of Perkin–Elmer Ltd very kindly ran this through the model DSC 1 B, and from the heating and cooling thermograms showed that there are

two peaks of heat exchange and found by planimetry that the peak with a maximum near 30 °C showed that the oil needed 12·77 cal/g to raise its temperature from 8 to 38 °C. As this trial with unrefrigerated oil proved hopeful, six more samples of spermaceti oil were kindly collected by Dr R. Gambell from selected positions in the sac and junk of whales
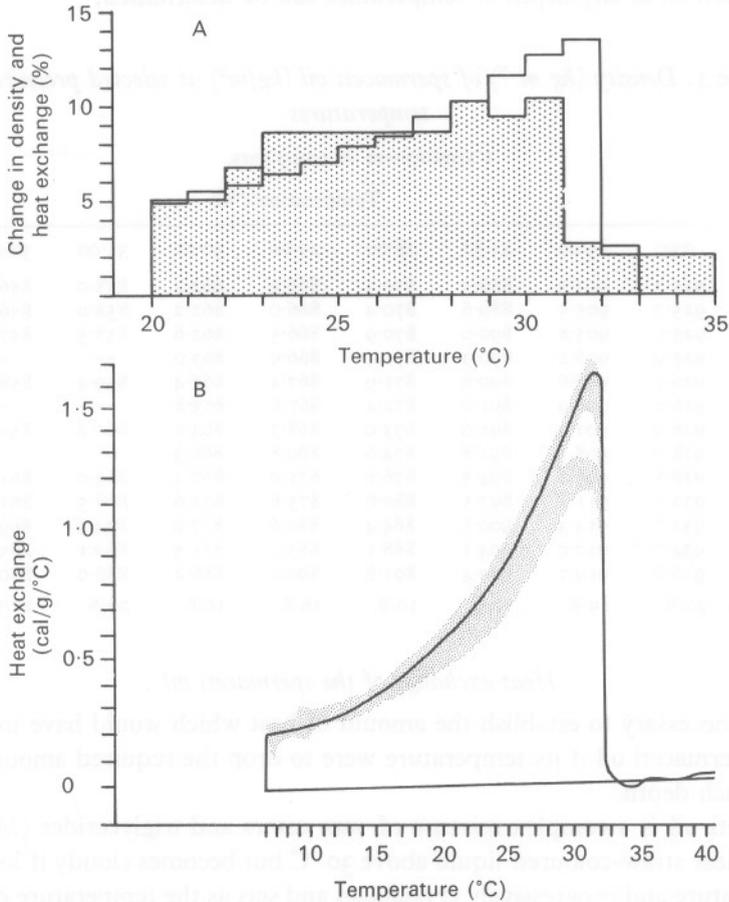
Fig. 2(A) The shaded histogram shows the decrease in density for each degree centigrade, expressed as a percentage of the total decrease in density, if the temperature of naturally occurring spermaceti oil is elevated from 20 to 35 °C. Superimposed on this is a histogram showing the exchange of heat expressed as a percentage per degree centigrade of the total heat exchanged when the oil temperature is elevated from 20 to 35 °C.

(B) The heating traces of naturally occurring spermaceti oil obtained with a differential scanning calorimeter upon which the unshaded histogram in Fig. 2(A) is based. The shaded area includes two traces of all samples given in Table 2. The two samples from the junk had rather lower peaks than the four from the sac. An 'averaged' line for the sac traces is shown and was used to derive the unshaded histogram in Fig. 2(A). The traces were obtained with a scanning rate of 8 °C/min, 3 cm/min with an air reference slope of 400.

examined at Durban and were returned to the United Kingdom in deep freeze under nitrogen. Parts of these were subsequently chemically analysed by Dr R. Morris (Morris, 1975) and he kindly gave me aliquots of the samples. By arrangement with Dr A. J. Collings, Dr Reid of Unilever Research Laboratory, Bedford, then used another

Perkin–Elmer DSC to obtain three heating and one cooling trace for each sample. The conditions used were Range 8 heating rate 8 °C min⁻¹, chart speed 3 cm min⁻¹, and the calibration factor used under these conditions is 1 cm² = 4·164 m cal. The recorder was run at 5 mV full-scale deflexion. The second and third heating traces obtained were measured using a planimeter to give the calorific exchange (Table 2). This shows that there is little difference between the samples, which is borne out by the traces of heating curves when superimposed (Fig. 2B).

Table 2. *Spermaceti oil: calorific exchange during heating*
(see text for explanation)

Sample	Weight (mg)	Area (cm²), trace 1	Area (cm²), trace 2	Area (cal/g), trace 1	Area (cal/g), trace 2
Sac waxes B upper	10·339	45·6	46·3	18·365	18·647
Sac waxes F upper	10·313	46·5	47·4	18·775	19·138
Sac waxes A lower	10·388	41·2	41·3	16·515	16·555
Sac waxes E lower	7·748	41·6	39·4	22·357	21·175
Junk waxes D upper	11·041	44·6	45·5	16·820	17·160
Junk waxes C lower	8·280	34·1	34·0	17·149	17·099

Trace 2 of the sample sac waxes B upper was measured up in certain sections:

	0–40 °C	38–33 °C	33–31 °C	31–29° C	29–27 °C	25–8 °C
cal/g	18·647	0·040	1·571	3·021	3·021	7·692

Table 3. *Exchange of calories required to cool or heat the spermaceti oil between degrees Centigrade in the range 20–33 °C.*

Derived from a mean curve of 6 samples.

Temperature (°C)	cal/g	cal/g cumulative
> 32	0·3	0·3
31	1·612	1·912
30	1·513	3·425
29	1·384	4·809
28	1·225	6·034
27	1·131	7·165
26	1·023	8·188
25	0·933	9·121
24	0·843	9·964
23	0·770	10·734
22	0·701	11·435
21	0·658	12·093
20	0·589	12·682

Trace 2 of the sample taken from the upper sac B was measured up in sections and the calorific exchange for each section is shown in Table 2.

By dividing the energy exchange curve into 1 °C sections the calories per gram exchanged for each degree at atmospheric pressure can be determined (Table 3, column 2). The total calories per gram which must be lost if the temperature is dropped from 33 °C (the oil's temperature in the whale – see Clarke, 1978b) to any temperature is shown in Table 3, column 3.

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Because of the lag in the instrument, the shape of the peak is likely to be slightly distorted since the temperature scale is only accurate to a degree or so.

The maximum for the exchange of heat would be expected to be at the same temperature as the maximum change in density. From the measurements, however, the peaks do not exactly coincide, the greatest change in energy exchange appears to take place at 32 °C while the greatest change in density takes place at 31 °C (Fig. 2A). As the energy
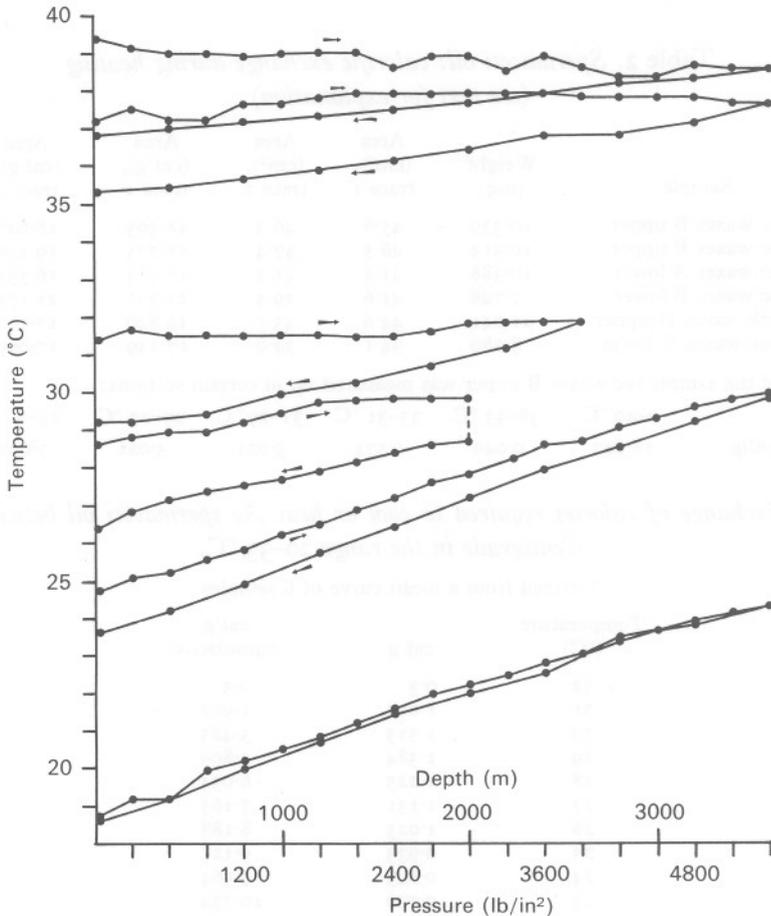
Fig. 3. Measurements of the temperature of spermaceti oil subjected to pressure in a pressure chamber. Arrows indicate whether the pressure was rising or falling.

exchange is based upon heating curves, this is probably due to the lag in the instrument and 31 °C is likely to be the temperature at which both the greatest change in density and the greatest change in energy exchange occurs.

When considering energy exchange at different temperatures it is therefore necessary to correct for this lag (Clarke, 1978b).

Rise in temperature of oil with pressure

As pressure is applied to oils their temperature rises slightly prior to loss of heat to the environment. Experiments were carried out to ascertain the increase in temperature when 1 litre of spermaceti oil was compressed in a polythene bag at several different temperatures. The sample was warmed to above the temperature required and placed in water within the pressure chamber. Temperature of the oil was measured with a calibrated thermistor which was not sensitive to pressure changes, placed approximately in the centre of the oil. When the oil had dropped to the desired temperature, pressure was applied by pumping and the temperature of the oil was read at regular intervals of
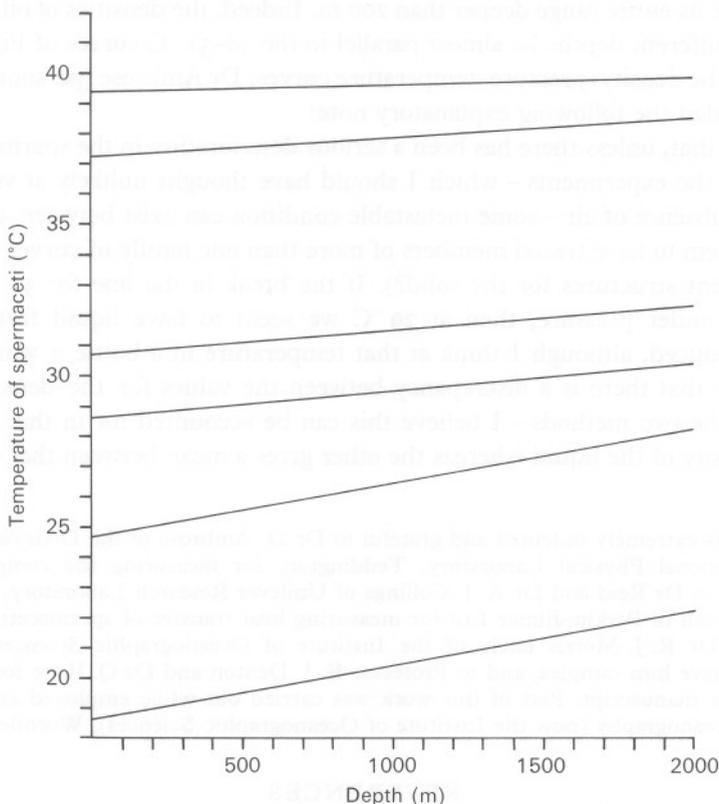
Fig. 4. Lines showing increase in temperature of spermaceti oil with increase in pressure. Derived from the measurements in Fig. 3 by removing the effect of loss of heat from the oil to the water in the pressure chamber.

pressure (as in Fig. 3). Pauses at each pressure were kept as brief as possible. The pressure chamber was full of water at a lower temperature than the oil in all but one experiment. Consequently, heat was lost from the oil during experiments with starting temperatures over 20 °C (Fig. 3). The difference between the starting temperature and the final temperature at atmospheric pressure gave the average rate of cooling and this was used to correct the curve as pressure was increasing so as to give an approximate

measure of the increase in temperature with increase in pressure at several temperatures (Fig. 4). From this it is clear that the spermaceti does not behave in an unusual way when compared with other oils. The rise in temperature is greater, the lower the initial temperature, particularly when the oil is partly frozen (below 31 °C).

DISCUSSION

In the paper dealing with the buoyancy control function of the spermaceti organ (Clarke, 1978b) it is shown that the whale only needs to drop the temperature of the spermaceti oil about 3 °C to achieve the change in density necessary to obtain neutral buoyancy over its entire range deeper than 200 m. Indeed, the densities of oil required by the whale at different depths lie almost parallel to the 30–31 °C curves of Fig. 1.

Regarding the density–pressure–temperature curves, Dr Ambrose (personal communication) appended the following explanatory note:

'It appears that, unless there has been a serious deterioration in the spermaceti during the course of the experiments – which I should have thought unlikely at such temperatures in the absence of air – some metastable condition can exist between 30 and 32 °C because we seem to have traced members of more than one family of curves (could there be two different structures for the solid?). If the break in the line for 32 °C indicates solidification under pressure, then at 29 °C we seem to have liquid forming as the pressure is reduced, although I think at that temperature in a bottle it would be solid. You will note that there is a discrepancy between the values for the density at 30 °C obtained by the two methods – I believe this can be accounted for in that one method gives the density of the liquid whereas the other gives a mean between that of the liquid and the solid.'

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