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Some Notes on Fuel Boiling Losses and Fuel-Tank Pressurisation in a Long-Range Supersonic Aircraft

by

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SOME NOTES ON FUEL BOILING LOSSES AND FUEL-TANK PRESSURISATION IN A LONG-RANGE SUPERSONIC AIRCRAFT

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SUMMARY

A method of calculating the fuel boiling losses, due to aerodynamic heating, from a supersonic aircraft with integral wing fuel tanks is devised and is applied to the Concord, assuming flight conditions of Mach 2.2 at 64000 ft altitude using low boiling point kerosene fuel. It is shown that if the specified tank pump performance is achieved the quantity of fuel evaporated is no more than 150 lb if the tanks are unpressurised, and is negligible in the present design case where the tanks are pressurised to 2.2 psia. The calculations are based on certain assumptions defined in the text concerning fuel distillation characteristics, heat transfer data and boiling fuel distribution in the tankage. Because much of the evaporated fuel may condense in the vent system and be recovered it is likely that the fuel loss through boiling in unpressurised tanks will be less than the weight of additional equipment required to pressurise the tanks. Since the fuel transfer pump duty is very arduous, the feasibility of operating without tank pressurisation depends on the actual pump performance achieved. Suggestions are made for reducing the severity of the conditions affecting fuel thermal stability by modified fuel handling procedures in the aircraft.

Note (added April 1968)

The Concord performance specifications and fuel system design have been changed since this Report was issued originally and the numerical values quoted for fuel losses, based as they are on the data available in 1967, are no longer applicable to the actual aircraft.

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*Replaces R.A.E. Technical Report 67137 - A.R.C. 29522

CONTENTS

1 INTRODUCTION

In a supersonic transport aircraft such as the Concord* flying at Mach 2.2 at an altitude of 64000 ft, the equilibrium skin temperature is around 115°C. Avtur fuel to Specification D. Eng R.D. 2494, as quoted in the Concord fuel pump specifications, will start boiling in the fuel tanks at 64000 ft altitude at 81°C if the tanks are unpressurised, or at 108°C if they are pressurised to 2.2 psia. In normal flight the Concord fuel tanks are pressurised to 2.2 psia with the object of minimising fuel losses due to evaporation and reducing the time the fuel pumps are operating in a cavitating condition, since cavitation can lead to reduced pump effectiveness and increased impeller wear by erosion. The rate of aerodynamic heating is such that boiling will not occur in a tank, under normal conditions, until it is nearly empty and only the last dregs of fuel in the transfer tanks approach the equilibrium skin temperature.

The purpose of this Report is to calculate the fuel losses due to boiling and to ascertain their dependence on fuel levels for a supersonic aircraft represented typically by the Concord. Consideration is given to the advantages and disadvantages of operating the aircraft without tank pressurisation and emphasis is placed on the essential requirement that the fuel transfer pumps need to have an outstanding suction performance and good cavitation erosion resistance to be capable of pumping to very low levels with boiling fuel.

2 METHOD OF CALCULATING FUEL LOSSES

Three factors affect the quantity of fuel lost by evaporation, namely the rate of heating, the time for which the fuel is boiling and, for a wide boiling range fuel such as kerosene, the extent to which the fuel temperature must be raised to sustain boiling as the light fractions are successively lost. Once boiling starts, the highest fuel loss might be expected in the case of a fixed quantity of residual fuel and this is the case considered in the present Report.

Suppose that at time t_o, after pumping has ceased, a fuel tank contains W_o lb of fuel which has just reached a surface boiling condition at a temperature T_o°C. Suppose that after t min, a weight W_v lb of fuel has been vaporised and the remaining fuel has been raised to a temperature T°C to sustain boiling. Consider a time interval dt min, at the start of which the bulk fuel temperature is T°C and at the end of which it is (T + dT)°C with the fuel still just boiling. Assume that the rate of heat input at time t at temperature T is H CHU/min, and that this is constant over the interval dt. Let the specific heat of the fuel be C_p CHU/lb/°C and the latent heat of vaporisation be λ CHU/lb at $T^{o}C$. Assume that in time dt a quantity of heat, h dt CHUs, is used in raising the fuel temperature through $dT^{o}C$ to sustain boiling. Then of the H dt CHUs which are passed to the fuel, (H - h) dt CHUs are employed in vaporising dW_v lb of fuel.

Hence

$$d\,W_v = \frac{(H - h)}{\lambda}\,dt \tag{1}$$

and approximately

$$h\,dt = C_p\,(W_o - W_v - d\,W_v)\,dT\ . \tag{2}$$

From (1) and (2)

$$H\,dt - \lambda\,d\,W_v = C_p\,(W_o - W_v - d\,W_v)\,dT$$

or

$$d\,W_v = \frac{H\,dt - C_p\,(W_o - W_v)\,dT}{\lambda - C_p\,dT}\ . \tag{3}$$

The distillation curve for a fuel may be given in terms of the percentage weight loss as a function of the fuel temperature. For a small temperature difference, $T - T_o$, the slope of the distillation curve may be taken as constant, but for larger changes, such as might occur in practice over a time interval of several minutes, the percentage weight loss may be better expressed as a function of the difference between the actual fuel temperature and the initial boiling temperature. It is found for Avtur fuel that a reasonable fit to experimental data up to the 10% weight loss point is given by the equation:

$$\frac{100\,W_v}{W_o} = a\,(T - T_o) + b\,(T - T_o)^2 \tag{4}$$

where a and b are both positive.

Differentiating equation (4)

$$\frac{100\,d\,W_v}{W_o} = \{a + 2b\,(T - T_o)\}\;dT \quad . \tag{5}$$

Since dT may be regarded as a very small temperature increment and λ for most fuels is at least an order of magnitude greater than C_p, $\lambda \gg C_p\,dT$. Hence equation (3) may be written

$$\lambda\;d\,W_v = H\,dt - C_p\,(W_o - W_v)\;dT$$

and substituting for dT from equation (5)

$$\lambda\;d\,W_v = H\,dt - \frac{100\;C_p\,(W_o - W_v)\;d\,W_v}{W_o\,\{a + 2b\,(T - T_o)\}}$$

Therefore

$$\frac{d\,W_v}{dt} = \frac{H}{\lambda + 100C_p\left(1 - \frac{W_v}{W_o}\right)\frac{1}{\{a + 2b\,(T - T_o)\}}} \quad . \tag{6}$$

From equation (4):

$$2b\,(T - T_o) = -\,a + \sqrt{\left(a^2 + \frac{400\,b\,W_v}{W_o}\right)} \tag{7}$$

where, since $T > T_o$, the positive sign is taken for the square root in the solution of the quadratic equation. Thus, substituting from equation (7) in equation (6):

$$\frac{d\,W_v}{dt} = \frac{H}{\lambda + 100\;C_p\left(1 - \frac{W_v}{W_o}\right)\Big/\sqrt{\left(a^2 + \frac{400\,b\,W_v}{W_o}\right)}} \quad . \tag{8}$$

In the case of aerodynamic heating in the flight conditions being considered, the rate of heating may be expressed in the form:

$$H = \alpha - \beta T \qquad (9)$$

as shown in section 3. Hence, from equations (7), (8) and (9):

$$W_o \int_0^{W_v/W_o} \frac{\left[\left\{\lambda + \dfrac{100\, C_p \left(1 - \dfrac{W_v}{W_o}\right)}{\sqrt{\left(a^2 + \dfrac{400\, b\, W_v}{W_o}\right)}}\right\}\right]}{\alpha - \dfrac{\beta}{2b}\left\{2b\, T_o - a + \sqrt{\left(a^2 + \dfrac{400\, b\, W_v}{W_o}\right)}\right\}} \cdot d\left(\frac{W_v}{W_o}\right) = \int_{t_o}^{t} dt \qquad (10)$$

In the temperature range of interest both λ and C_p may be regarded as constant although it is possible, if need be, to take into account their variation with temperature. In consequence, assuming that a, b, α, β, λ, C_p, T_o and W_o are all known constants, equation (10) may be integrated numerically to give the time required to evaporate a quantity W_v lb of fuel.

3 CALCULATION OF THE HEAT INPUT TO A FUEL TANK

In Ref.1, it is shown that the rate of heat input to an integral wing tank of a supersonic aircraft due to kinetic heating at Mach 2.2 and an altitude of 60000 ft is given approximately by the expression:

$$\frac{q}{A} = \frac{115 - T_s}{0.088} \qquad (11)$$

when q is the heat input in CHU/hr, A is the tank base area in sq ft and T_s is the tank base skin temperature in °C. Although equation (11) is only strictly valid at an altitude of 60000 ft, the parameters involved in its derivation change little between 60000 and 64000 ft and it may be regarded as a satisfactory approximation for flight at Mach 2.2 at 64000 ft altitude.

Experimental results[1] show that for kerosene heated in a tank installation representative of that used in the Concord with a base consisting of integral aluminium alloy machined sheet and stringers

$$\frac{q}{A} = (T_s - T)^{4/3} \{13 + 0.0475 (T_s + T)\} \tag{12}$$

where T is the bulk fuel temperature. This equation has been derived from the experimental results presented in Fig.15 of Ref.1. These experimental results show that T is a linear function of T_s and while equations (11) and (12) can not be solved directly for T the following is found to be a reasonably accurate representation of the results:

$$T = 1.23825\, T_s - 28.425 \, . \tag{13}$$

From equations (11) and (13) it follows that

$$\frac{q}{A} = \frac{113.97 - T}{0.109} \, . \tag{14}$$

If H is the total rate of heat input in CHU/min to the total tank base

$$\frac{H}{A} = \frac{1}{60}\left(\frac{q}{A}\right) = 17.43 - 0.153\, T \, . \tag{15}$$

Equation (15) thus gives the values of the parameters α and β in equation (9).

It should be remarked that equation (13) is derived using experimental heat transfer coefficients appropriate to fuel in a non-boiling state. However, these heat transfer coefficients are likely to be approximately correct for fuel just boiling gently at the surface. If the conditions were such that nucleate boiling occurred, then the heat transfer coefficient could increase considerably and the tank skin temperature would decrease, but on the other hand the coefficient is reduced for boiling at altitude. The true heating rate cannot be determined in terms of the bulk fuel temperature without experiment under the appropriate environmental conditions. In the present lack of more accurate data, equation (15) is assumed to give a representative heating rate.

Taking a bulk fuel temperature of 81°C the rate of heat input to the fuel given by equation (15) is 5.043 CHU/min/ft^2 and this is equivalent to a heat input of 0.16 kW/ft^2. It should be noted that the heat input falls by approximately 3% per °C rise in bulk fuel temperature.

4 CALCULATION OF THE COEFFICIENTS a AND b

In Ref.2, the variation of vapour pressure with temperature for an Avtur fuel to Specification D. Eng. RD 2494 is given for fuel samples after losses due to evaporation of 0%, 2.7%, 4.9% and 10% by weight. The fuel samples were chosen because of their low initial boiling point and 10% point as measured by the ASTM distillation method. The vapour pressure data obtained are stated to be representative of the worst conditions likely to be met in service. The results are reproduced in Fig.1 and can be used to construct distillation curves for the fuel for pressures corresponding to a range of flight altitudes.

A reasonable fit to the data above the initial boiling point $T_o = 81^\circ C$ at 64000 ft altitude was found to be given by equation (4) with $a = 0.2667$ and $b = 0.0444$, and these values have been used in the following analysis. Fig.2 shows equation (4) plotted for a range of initial boiling temperatures, together with the points obtained from the experimental data cross-plotted from Fig.1. Fig.2 also shows the experimental points obtained from distillation at sea level pressure in terms of the percentage volume loss, assuming the percentage weight and volume losses are the same. Equation (4), with $a = 0.2667$ and $b = 0.0444$, is also found to give a good approximation to the sea level distillation data given in Ref.2 up to the 30% loss point, after which it deviates rapidly.

5 THE NUMERICAL CALCULATION OF FUEL LOSSES PER UNIT TANK BASE AREA

Equation (10) may be written

$$\frac{t - t_o}{W_o} = \int_0^{W_v/W_o} \varphi\left(\frac{W_v}{W_o}\right) d\left(\frac{W_v}{W_o}\right) \tag{16}$$

where

$$\varphi\left(\frac{W_v}{W_o}\right) = \frac{\left\{\lambda + \dfrac{100\, C_p\left(1 - \dfrac{W_v}{W_o}\right)}{\sqrt{\left(a^2 + 400\, b\, \dfrac{W_v}{W_o}\right)}}\right\}}{\alpha - \dfrac{\beta}{2b}\left\{2b\, T_o - a + \sqrt{\left(a^2 + 400\, b\, \dfrac{W_v}{W_o}\right)}\right\}} \, . \tag{17}$$

Equation (16) can be solved by assigning values to W_v/W_o, calculating $\varphi\ (W_v/W_o)$ and then integrating numerically or graphically by measuring the area under the curve of $\varphi\ (W_v/W_o)$ plotted against W_v/W_o.

For a typical Avtur fuel at temperatures between 70°C and 100°C approximately, the values of the fuel properties are $C_p = 0.48$ CHU/lb/°C, $\lambda = 67$ CHU/lb and the specific gravity is 0.8. a and b have the values 0.2667 and 0.0444 respectively for a sample of fuel near to the upper volatility limit and, from equation (15), $\alpha = 17.43A$ and $\beta = 0.153A$ where A is the wetted tank base area in square feet. At 64000 ft altitude the initial boiling temperature of the fuel is $T_o = 81°C$. Using these values of the parameters in equation (17) $A\ \varphi\ (W_v/W_o)$ can be calculated for a range of values of W_v/W_o. The accuracy tends to be lost above $W_v/W_o = 0.06$ due to the approximation made to the distillation curve.

Table 1 shows the calculated values of $A\ \varphi\ (W_v/W_o)$ and the values of $A\ (t - t_o)/W_o$ obtained from a numerical integration. Fig.3 shows a plot of $A\ \varphi\ (W_v/W_o)$ against W_v/W_o, and Fig.4 a plot of $A\ (t - t_o)/W_o$ against W_v/W_o. Using these data the evaporative loss may be calculated for any period of fuel boiling, or alternatively the time to evaporate a certain percentage of fuel may be determined. The mean evaporative rate in lb/min/ft^2 is given by

$$\frac{W_v}{A\ (t - t_o)} = \left(\frac{W_v}{W_o}\right) \frac{W_o}{A\ (t - t_o)}$$

and the values are given in the fourth column of Table 1. At the beginning of the boiling period W_v/W_o is zero and it may be shown from equation (8) that the initial mean evaporative rate is 0.0204 lb/min/ft^2. Included in the table are values corresponding to weight losses of 15%, 20% and 25%, although the approximation to the distillation curve is not too accurate for these losses. It is evident that the mean evaporative rate increases up to the 10% weight loss point approximately and then decreases, having a maximum value of about 0.032 lb/min/ft^2. Thus, over the full range of initial fuel quantities, the evaporative rate lies between 0.02 and about 0.032 lb/min/ft^2 within the range of validity of the present calculations. The mean evaporative rate is shown plotted against the percentage weight loss in Fig.5, and against $W_o/A\ (t - t_o)$ in Fig.6. For a given boiling period the abscissa in Fig.6 is proportional to W_o/A which in turn is proportional to the fuel depth, so that if the boiling period is known and the fuel specific gravity is given the mean evaporative rate can be plotted as a function of the fuel depth. As an example assuming a boiling period of ten minutes and a specific gravity of 0.8, Fig.7 shows the variation of mean evaporative loss rate with fuel depth.

6 FUEL LOSSES FOR A TYPICAL FUEL TANK INSTALLATION

The British Aircraft Corporation Ltd. have given temperature histories of the fuel in Concord. The calculations are based on the case of a long flight followed by a long flight, i.e. with residual fuel, tanks and system, warm. The take-off temperature for the first flight is assumed to be 35°C and that for the second flight is calculated assuming refuelling with fuel at 35°C with residual fuel in the collector tanks only and no cooling occurring during standing. The probability of this situation occurring in practice is reported to be very low and the temperatures calculated are consequently higher than would be met in the majority of circumstances.

The results show that the fuel in the following tanks will exceed a temperature of 81°C and, if the tanks are unpressurised, will boil for the times shown before reaching the end of cruise or before the tanks are emptied by pumping at the normal rate:-

Tank	Base area		Boiling time min	Mean evaporative rate lb/min/ft^2	Fuel evaporated lb
	Total ft^2	Effective ft^2			
Transfer 4L	180	80	10	0.030	24.0
Transfer 5R	220	80	10	0.030	24.0
Collector 3L	110	110	5	0.024	13.20
Collector 3R	110	110	15	0.025	41.25
Collector 6R	130	130	15	0.025	48.75
				Total	151.20

The collector tanks are not emptied and at least six inches of fuel remain at the pump position at the end of cruise so that despite the floor slope of about 4° from the pump position, the whole of the base area of these tanks might be expected to be covered with fuel. The transfer tanks are emptied and when boiling commences contain approximately 2000 lb of fuel each, which, taking into account the 4° floor slope, covers about 120 sq ft of floor. Assuming that fuel is pumped from the transfer tanks at a rate of 200 lb/min, the wetted area decreases to zero over the ten minutes required to empty the tanks and the mean effective area over the whole period is about 80 sq ft per tank. The adjacent table shows the quantities of fuel evaporated from each of the tanks where boiling could occur. A mean evaporative rate, appropriate to the mean fuel depth during the boiling period, is taken for each tank. These estimates do not purport to be very accurate since the distribution of fuel over the heated aircraft surface is not known accurately, neither has the fact that the liquid fuel leaving the tank abstracts some of the heat input been taken into consideration.

The entire 151 lb of fuel vaporised is not necessarily lost, particularly in the Concord, because it may condense in the venting system. On the Concord the main vent pipe passes through the fuel in the rear trim transfer tank which, at the end of the cruise, is cooler than the other tanks since it has been maintained comparatively full. It is likely that much of the fuel vapour entering the vent system will therefore condense and be drained back into the scavenge tank from which it can be pumped back into the collector tanks and used ultimately in the engines. It is thus possible that the quantity of fuel lost from the aircraft through evaporation is very small.

7 PUMPING PROBLEMS

The Concord fuel transfer pump duty, in relation to achieving low pump-down levels with boiling or near boiling fuel, is very arduous and requires a pump having a suction specific speed maximum in excess of 200 000 in rev/min gal/min, ft units. The low pump down level is specified as desirable rather than essential. A very good conventional centrifugal pump, having a comparable specific speed, will operate at a maximum suction specific speed in the region of 10-15000 but some specially designed fuel pumps have operated with suction specific speeds around 50000 which approximately corresponds with the specified Concord pump performance in pressurised tanks. Because of the severity of the desired suction performance it is likely that, without pressurisation, the fuel transfer pumps would not empty the tanks as completely as when they are pressurised. This would lead to increased aerodynamic heating of the fuel and to the possibility of reduced pump life due to cavitation erosion. It would not necessarily lead to increased boiling losses since the rate of temperature rise would be less than would be attained with smaller residual fuel quantities. The difficulty of completely emptying some transfer tanks towards the end of the cruise may not be too serious since the fuel will be usable during descent when increasing tank pressure and reducing fuel temperature ease pumping problems, and the peak temperatures in the collector tanks are reduced. The feasibility of operating without tank pressurisation is, however, dependent largely on the suction performance of the pumps which can only be determined by test.

8 FUEL THERMAL STABILITY

There might be some advantage in respect of thermal stability considerations in using unpressurised tanks and having a larger residual fuel quantity in the tanks, particularly if evaporated fuel condenses in the vent lines. This possible advantage arises because a much larger part of the residual fuel will boil off if the tank is unpressurised than if it is pressurised, thus keeping the temperature of the remaining residual fuel down. Barnett and Hibbard[3] show that the rate of gum formation in jet fuels increases tenfold between 90°C and 115°C, hence measures to delay the attainment of fuel temperatures above 90°C in the fuel tanks could be beneficial even though residence times are shorter than those discussed in Ref.3. In unpressurised tanks some 6% by weight has to be evaporated for the residual fuel to reach 90°C and if, say, 1600 lb of fuel at 81°C were left in a transfer tank with pumping stopped intentionally this would take 25 minutes to reach 90°C. If the tanks were pressurised to 2.2 psia and pumping stopped at 81°C it would take about 8 minutes for the same quantity of residual fuel to reach 90°C. For smaller quantities of residual fuel than 1600 lb the times to reach 90°C would be proportionally shorter. This illustrates the possible advantage that might be achieved from the thermal stability aspect by allowing the fuel to evaporate in the later stages of tank emptying, or of intentionally not emptying the tank completely, particularly without pressurisation. In these calculations the tank floor has been assumed horizontal.

9 CONCLUSIONS

Temperature histories of the fuel in a Concord show that, even in an unpressurised tank, the fuel is unlikely to boil for more than fifteen minutes whilst pumping proceeds at normal rates. It is evident from Fig.1 that, with tank pressurisation to 2.2 psia, the total quantity of fuel evaporated is negligible provided the fuel temperature does not exceed 108°C. Without pressurisation it is likely to amount to rather less than 150 lb. Since much of the evaporated fuel may condense in the vent system it is probable that the weight of fuel lost from the aircraft in the unpressurised case will be less than that of the additional equipment required in the tank venting system to pressurise the fuel tanks.

The performance demanded of the Concord tank pumps, even in the pressurised case is very arduous. The elimination of a pressurisation system makes the pump duty even more severe because it necessitates operation at higher suction specific speeds. The feasibility of operating without tank pressurisation is thus dependent on the actual test performance achieved by the Concord pumps.

Fuel thermal stability problems might be alleviated by intentionally stopping pumping with a moderate residual fuel content in the tanks thus retaining a greater heat sink. For the same quantity of residual fuel the advantage gained is greater in unpressurised tanks, where the fuel is allowed to boil and possibly be recovered in the vent system, than in pressurised tanks where boiling does not occur and heat is not used in vaporising the fuel.

It should be emphasised that the calculations in the present Report are based on the use of an Avtur fuel and its distillation characteristics as given in Ref.2 and used in writing the Concord pump specifications. There have been reports that within several years the demand for Avtur fuel will exceed the supply and there will be a trend towards the use of a somewhat more volatile fuel with higher vapour pressure. This trend is already evident and some fuel samples have been found to have significantly higher vapour pressure and lower initial boiling point than the samples considered in Ref.2. Because of this situation fuel boiling losses could present a severe problem since it would not be possible to pressurise further the existing tanks on an aircraft such as the Concord, to suppress boiling, without introducing considerable structural weight penalties, and the required pump performance would become even more severe. Provided the distillation and vapour pressure characteristics of the fuel are known it should be possible to adapt the basic method of calculating fuel losses given in this Report to any fuel.

Table 1

$\frac{W_v}{W_o}$	$A\,\varphi\left(\frac{W_v}{W_o}\right)$	$\frac{A\,(t - t_o)}{W_o}$	$\frac{W_v}{A\,(t - t_o)}$
0	47.74	0	0.0204
0.001	45.67	0.0467	0.0214
0.002	43.42	0.0912	0.0219
0.003	41.92	0.1339	0.0224
0.004	39.95	0.1748	0.0229
0.005	38.76	0.2142	0.0233
0.010	34.97	0.3985	0.0251
0.020	31.77	0.7322	0.0273
0.030	30.48	1.0434	0.0287
0.040	29.93	1.3454	0.0297
0.050	29.75	1.6438	0.0304
0.060	29.81	1.9416	0.0309
0.070	30.01	2.2407	0.0312
0.080	30.33	2.5424	0.0315
0.090	30.72	2.8476	0.0316
0.10	31.21	3.1573	0.0317
0.15	34.52	4.8005	0.0313
0.20	39.05	6.6398	0.0301
0.25	45.28	8.7480	0.0286

SYMBOLS

A	tank base area	ft^2
a b	coefficients defined by equation (4)	
C_p	specific heat at constant pressure	$CHU/lb/^{o}C$
H	rate of total heat input	CHU/min
q	rate of total heat input	CHU/hr
T_o	initial boiling temperature	^{o}C
T	fuel bulk temperatue	^{o}C
T_s	tank base skin temperature	^{o}C
t_o	initial time at temperature T_o	min
t	time at temperature T	min
W_o	initial fuel quantity at time t_o	lb
W	fuel quantity at time t	lb
W_v	total evaporated fuel quantity at time t	lb
α β	coefficients defined by equation (9)	
$\varphi\left(\frac{W_v}{W_o}\right)$	functional relation defined by equation (17)	
λ	latent heat of vaporisation	CHU/lb

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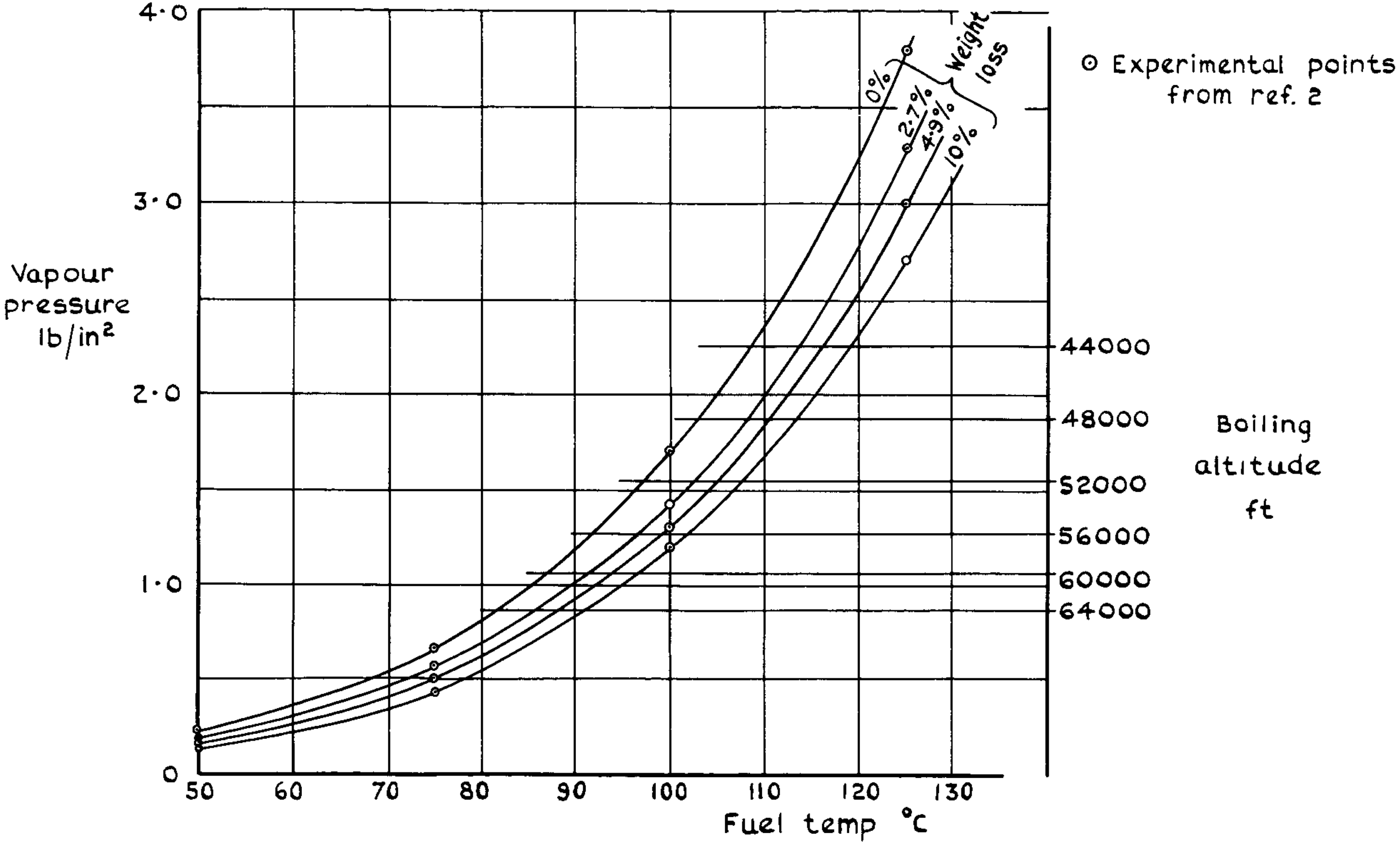

Fig. 1 Vapour pressure of avtur fuel after 0%, 2·7%, 4·9% and 10% weightloss

$\%$ Weight loss $= 0{\cdot}2667\,(T-T_o) + 0{\cdot}0444\,(T-T_o)^2$ full lines

Points cross-plotted from Fig. 1 shown ○

Experimental points from sea level distillation shown ϕ

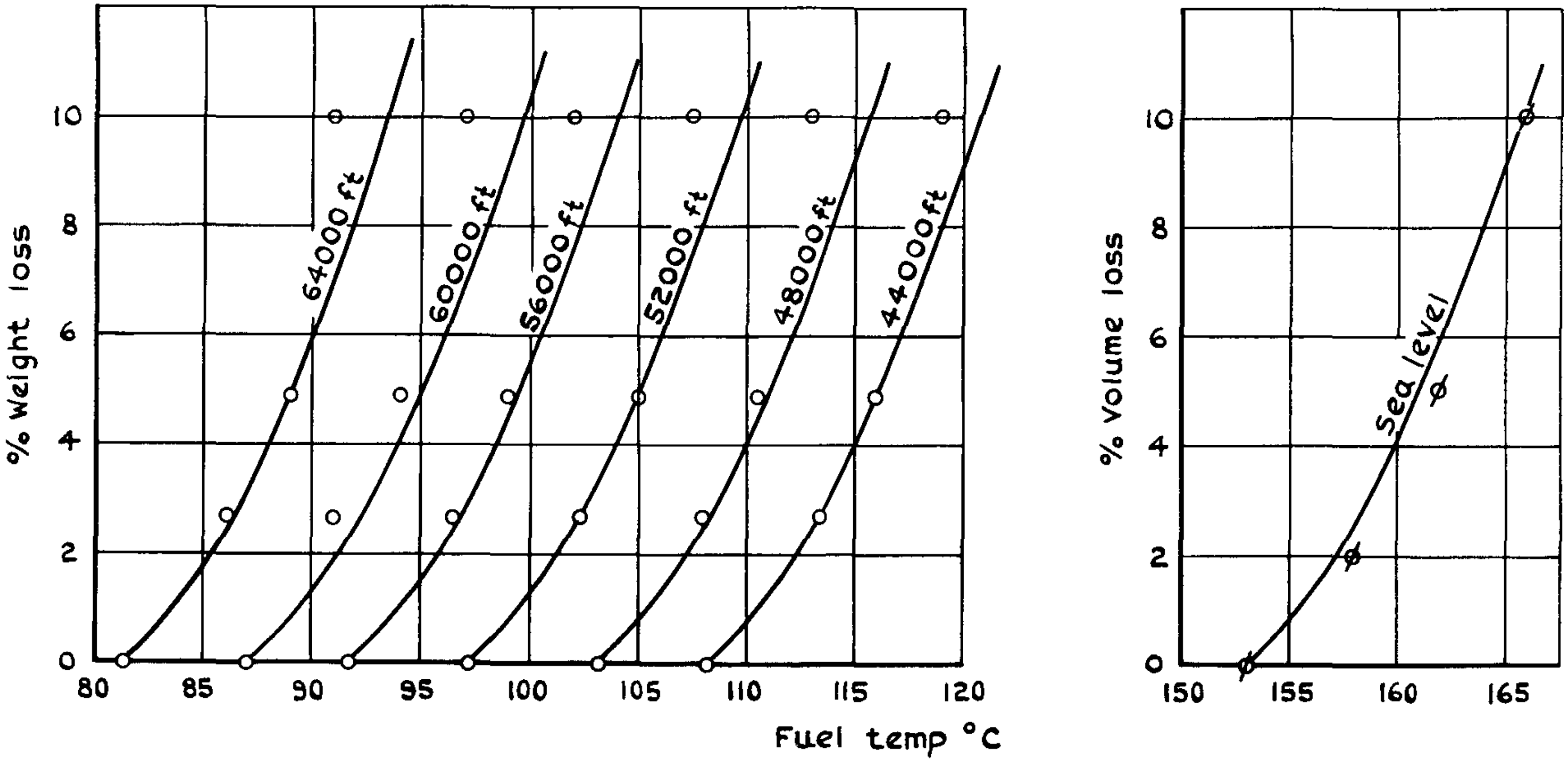

Fig 2 Distillation curves for avtur fuel

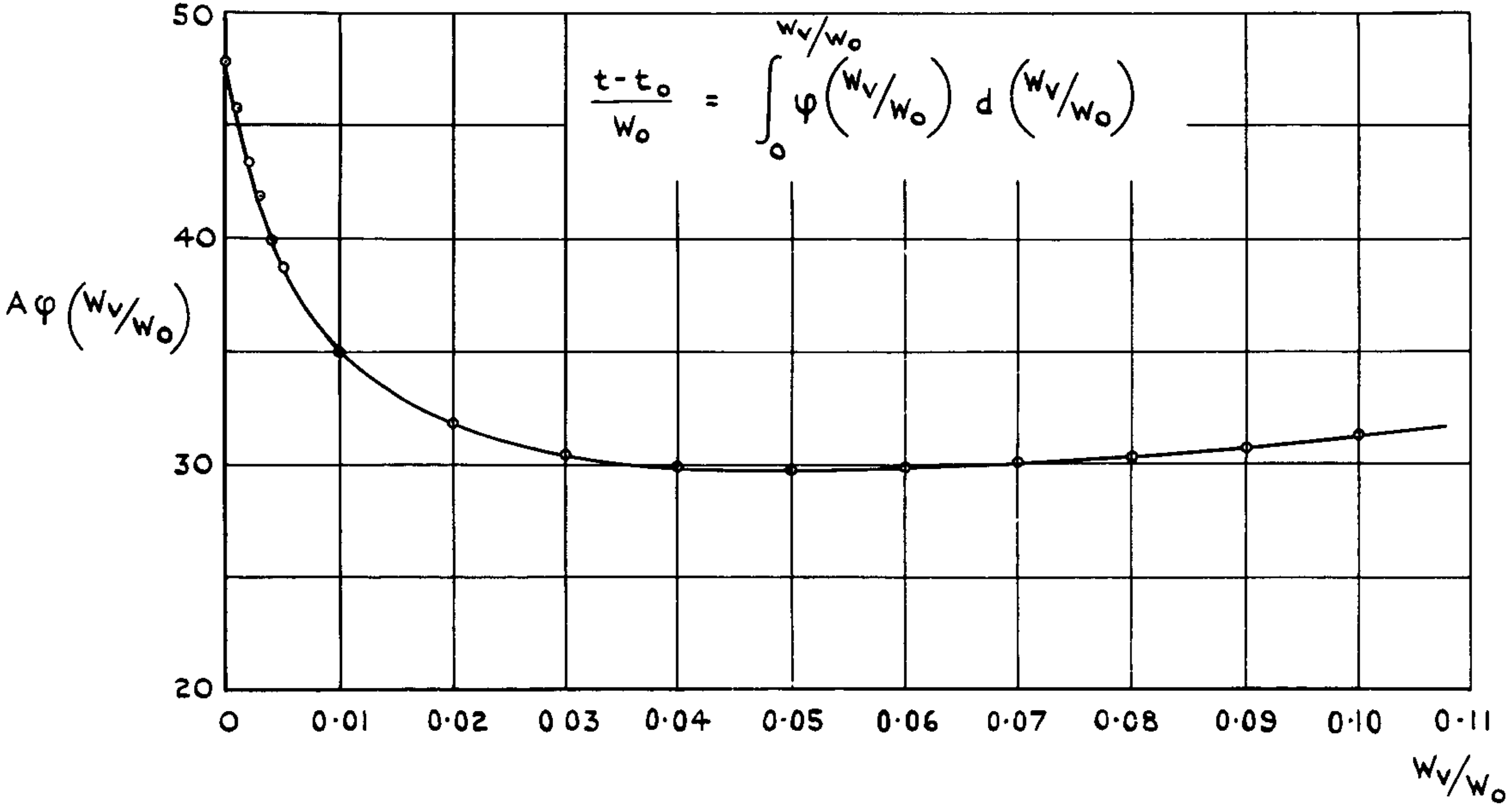

Fig. 3 Plot of $A\varphi\left(W_V/W_o\right)$ against W_V/W_o

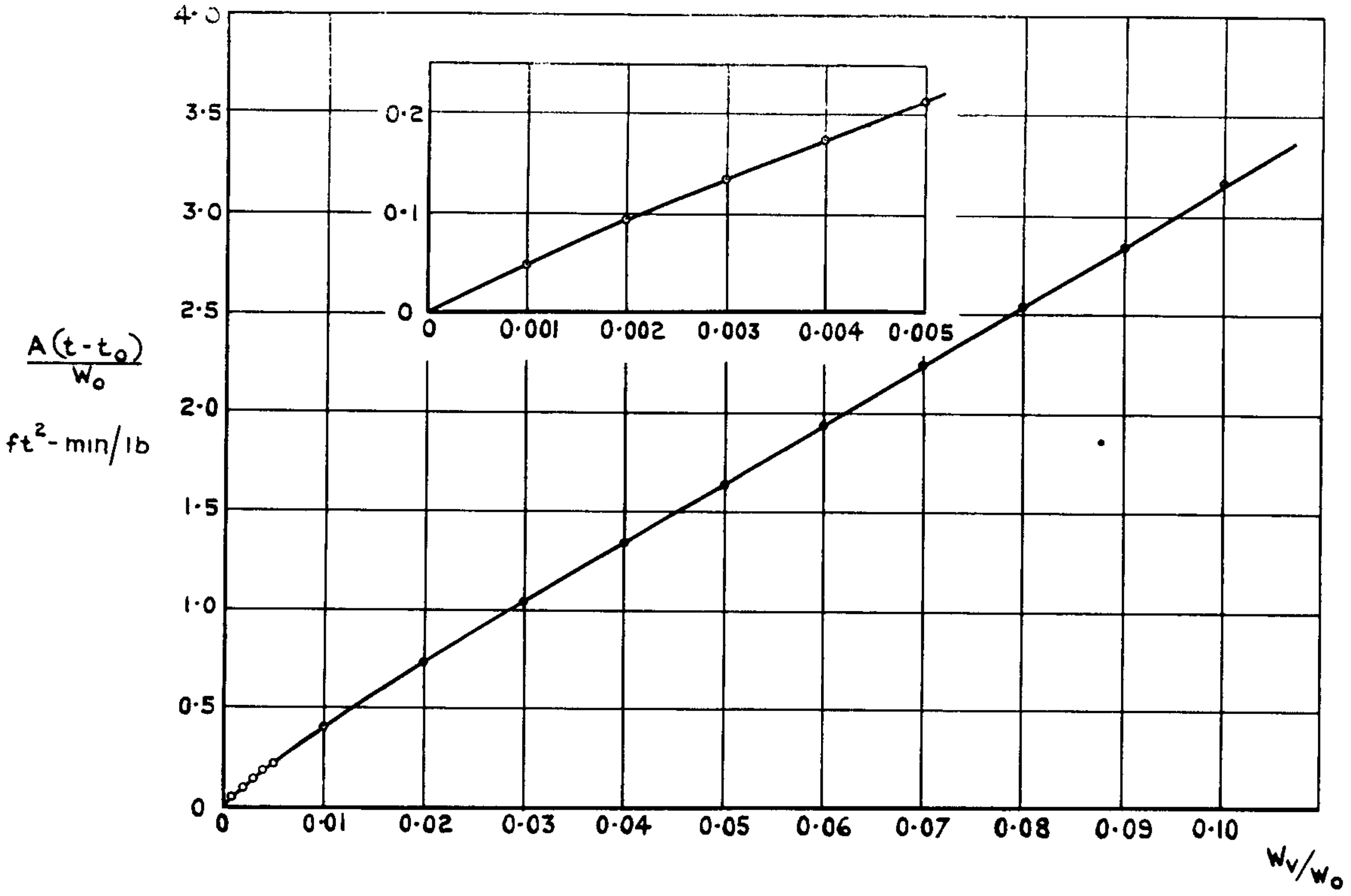

Fig. 4 Plot of $A(t-t_o)/W_o$ against W_v/W_o

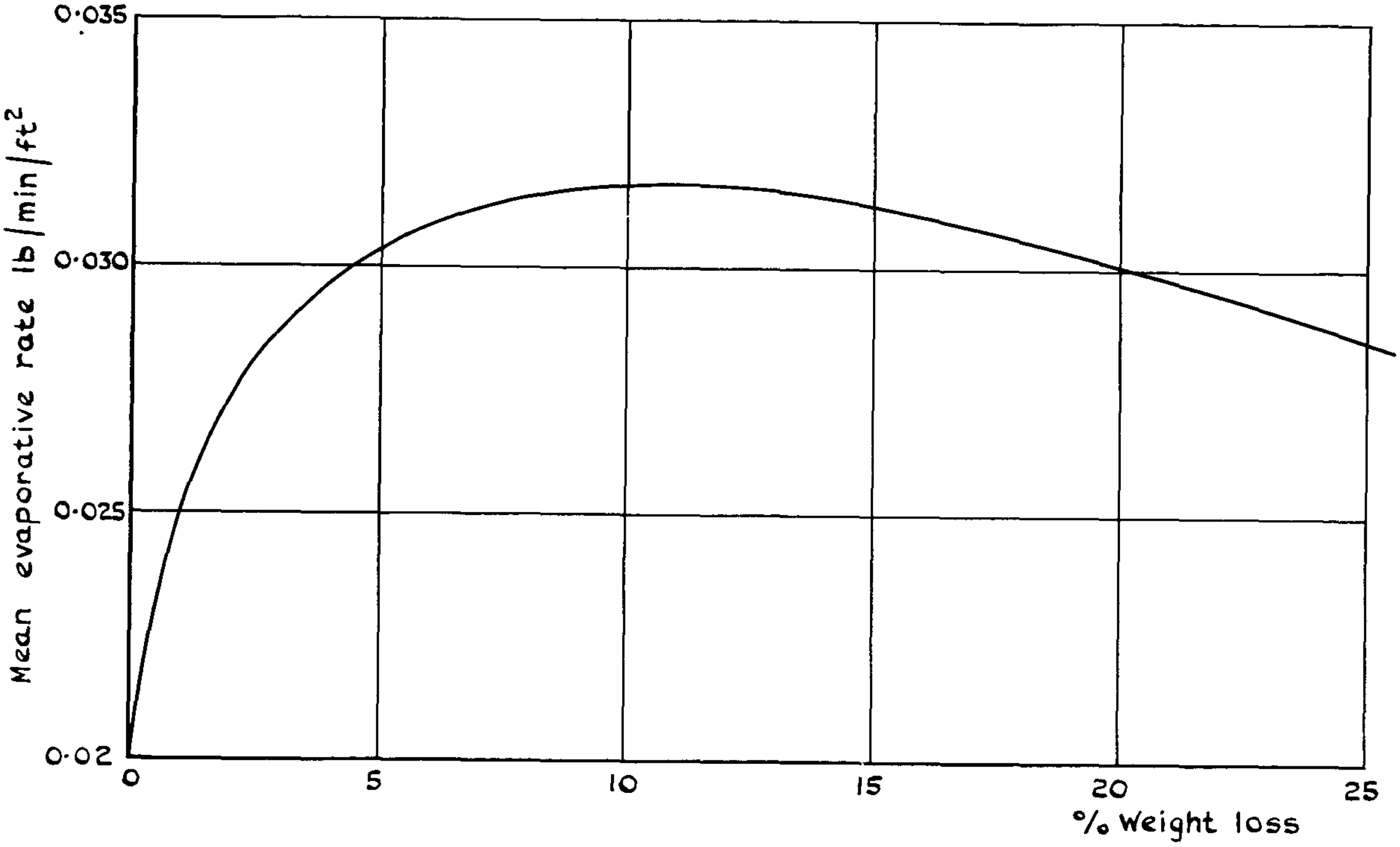

Fig. 5 Mean evaporative rate as a function of percentage weight loss

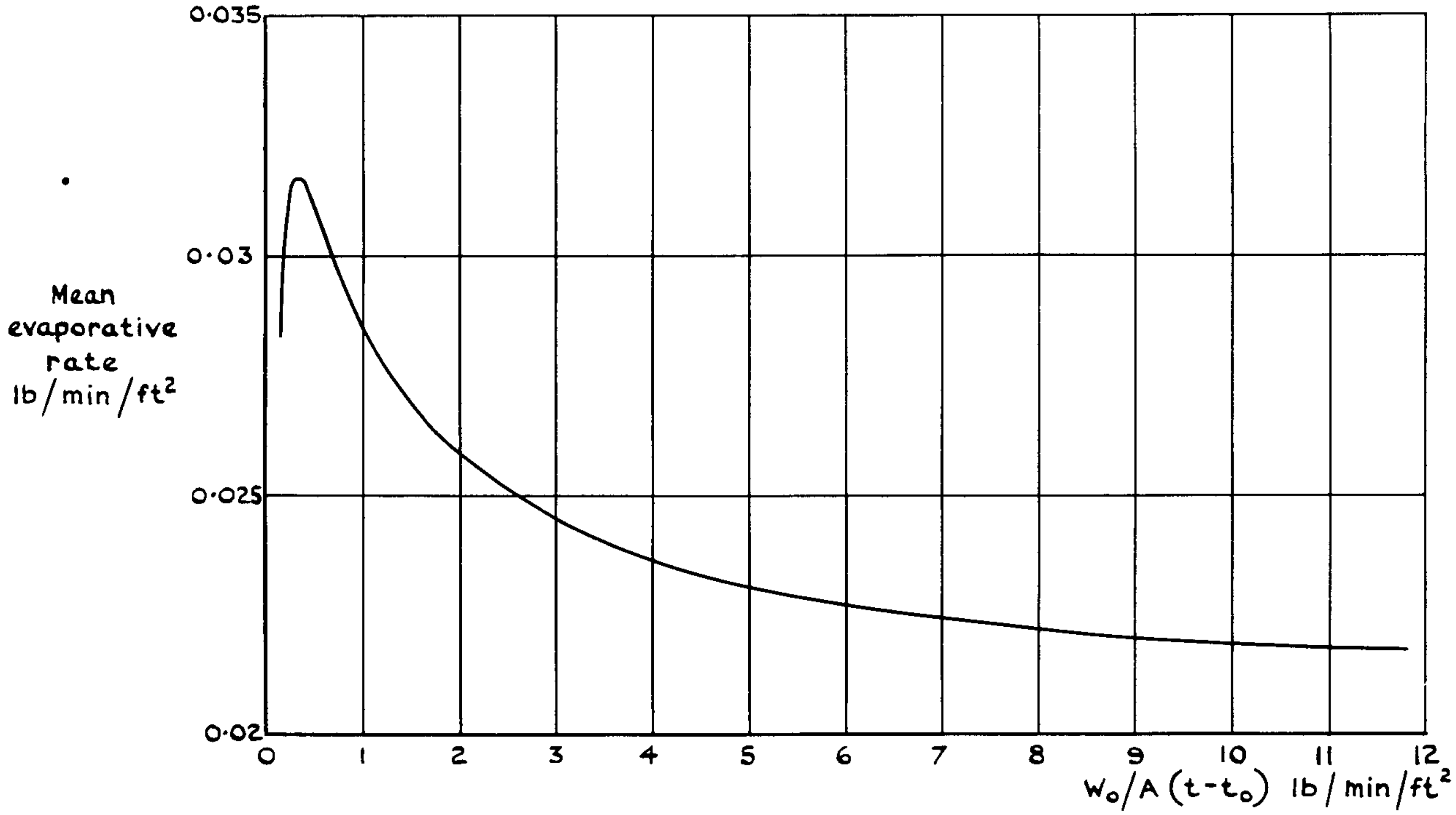

Fig. 6 Mean evaporative rate as a function of $W_o/A\left(t-t_o\right)$

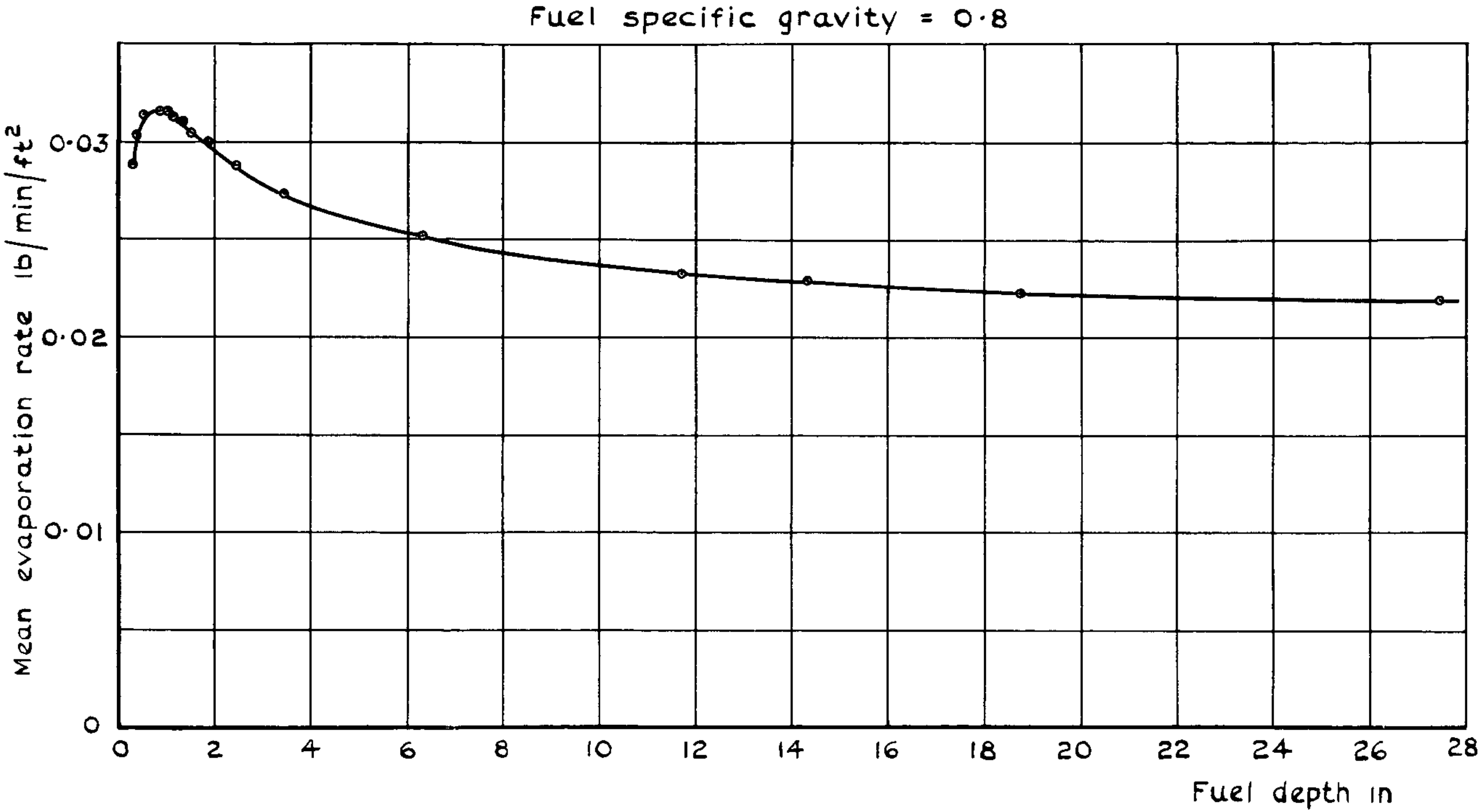

Fig. 7 The variation of mean evaporative loss rate with fuel depth determined for a ten-minute boiling period

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