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by

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THE RANGE PERFORMANCE OF HYPERSONIC AIRCRAFT

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L. F. Crabtree

SUMMARY

A simple analysis is given of the range performance of hypersonic aircraft. Some relatively crude approximations are used to enable the range covered during acceleration and final glide, which can be a considerable fraction of the total range, to be taken into account.

Typical calculations show that global ranges (i.e. of the order of 10000 nm) are obtainable for reasonable values of lift to drag ratio and of specific fuel consumption, and a fuel weight of less than 50% of the take-off weight, with liquid hydrogen fuel.

Comparative calculations of the volume requirements of such aircraft with kerosene and liquid hydrogen fuel are made. These show that a long-range hypersonic aircraft needs to be of a rather large size to make full use of the advantages of liquid hydrogen fuel, and that the penalty is quite severe for a small aircraft due to the reduction in the ratio of lift to drag with increasing volume.

* Replaces R.A.E. Technical Report No.66178 - A.R.C. 28392

CONTENTS

1 INTRODUCTION

A hypersonic-cruise aircraft may cover appreciable ranges during the acceleration and final glide phases of its trajectory. Thus it is necessary to take these into account in any analysis of the range performance. Simple Bréguet-formula calculations of the range may not necessarily be adequate, and it is not sufficient to optimize such a vehicle on the cruise performance alone.

The range covered in the final glide is fairly easy to calculate if a constant value of lift-to-drag ratio is assumed, and the range during cruise can be obtained from the Bréguet formula. For the acceleration or climb phase, however, some relatively crude assumptions are needed in order to obtain simple analytical results.

The assumptions made in Section 2 are

(a) a shallow climb angle (because the range covered during climb is large relative to the altitude attained),

(b) a constant value of L/D, or in effect a mean L/D value which is representative. In terms of distance covered the value of L/D at high Mach number matters most, so in the calculations of Section 3 the mean L/D during acceleration is put equal to that assumed for the cruise. This is probably a pessimistic assumption.

(c) a constant value of T/D, the ratio of thrust to drag.

In fact, the requirement for passenger comfort puts an upper limit on the T/W ratio and the acceleration used, and there is a lower limit corresponding to a pure acceleration-glide (boost-glide) trajectory for a given range, rather than including a cruise phase.

With these assumptions it is possible to obtain simple expressions for work done, range covered etc. during any phase of the trajectory. This is done in Section 2 and some simple conclusions are reached, for the assumption of a "flat" earth. At speeds which are an appreciable fraction of satellite orbital speed, however, the centrifugal force associated with a spherical earth's surface contributes to the effective lift-drag ratio. The analysis is therefore extended to take this into account.

A similar analysis has been carried out independently by Ashford[1], with emphasis on boost-glide vehicles.

Now, during the acceleration phase, the weight of the aircraft changes appreciably due to the high rate of fuel consumption, so that in calculating the range during climb the rate of change of weight has to be allowed for. This is done by assuming that rate of change of weight is proportional to thrust and specific fuel consumption, $\dot{W} = - \sigma T$. This is equivalent to assuming a constant engine efficiency.

Section 3 then presents some typical calculations of overall range for various values of take-off weight, L/D ratio, fuel/weight ratio, cruise Mach number and specific fuel consumption variation with speed, for both kerosene and liquid hydrogen fuel.

The use of liquid hydrogen fuel implies an aircraft of large volume. Accordingly, a comparison is made in Section 4 of the volume requirements of kerosene and hydrogen fuelled aircraft. An increase in volume implies a reduction in the value of L/D which can be achieved at a given speed, and hence a reduced range capability. This has to be offset against the higher calorific value of liquid hydrogen, and some typical calculations are presented in Section 4 to allow the magnitude of this effect to be assessed.

2 ANALYSIS OF RANGE PERFORMANCE

Let us consider first of all the simple case of constant weight throughout the trajectory which is shown schematically in Fig.1. Neglecting centrifugal forces arising from the earth's curvature, resolution of forces acting on the aircraft during climb gives

$$L = W \cos \gamma \simeq W$$

$$T - D = W \sin \gamma + \frac{W}{g} \frac{dV}{dt} \simeq \frac{W}{g} \frac{dV}{dt}$$

assuming a shallow climb angle, γ.

For constant values of the ratios $L/D = k_1$ and $T/D = k_2$, the acceleration during climb is

$$f_A = \frac{dV}{dt} = g\left(\frac{T - D}{W}\right) = g\left(\frac{k_2 - 1}{k_1}\right)$$

and the range covered during acceleration is

$$X_A = \frac{V_c^2}{2 f_A} = \frac{V_c^2}{2g}\left(\frac{k_1}{k_2 - 1}\right) \quad (1)$$

with subscripts A and C referring to acceleration and cruise phases respectively. The work done during acceleration is

$$Q_A = T X_A = \frac{T}{D} D X_A = k_2 \frac{W}{k_1} X_A$$

or

$$Q_A = \frac{W V_c^2}{2g}\left(\frac{k_2}{k_2 - 1}\right) \quad . \quad (2)$$

Similarly, during the glide

$$D = -\frac{W}{g}\frac{dV}{dt} = -\frac{W}{g} V \frac{dV}{dX}$$

i.e.

$$f_G = -\frac{D}{W} g = -\frac{g}{k_1}$$

and

$$X_G = -\frac{V_c^2}{2 f_G} = \frac{V_c^2}{2g} k_1 \quad . \quad (3)$$

Thus for a pure boost-glide flight with no cruise phase the total range is

$$X_A + X_G = \frac{V_c^2}{2g}\frac{k_1 k_2}{(k_2 - 1)} \quad . \quad (4)$$

The work done by the propulsion unit to give this range is simply that in the climb, Q_A, and therefore

$$\frac{Q_A}{X_A + X_G} = \frac{W}{k_1} \quad . \quad (5)$$

Thus for a constant $L/D = k_1$ throughout the flight, the work done per unit range is independent of the thrust/drag ratio used and of the maximum velocity attained. For a given range, therefore, a wide choice of trajectory is possible, from one using a high acceleration to achieve a high speed (which gives a low X_A but a high X_G) to one with low acceleration up to a relatively low speed (which gives a high X_A but low X_G) - all for the same expenditure of work.

Furthermore, if a cruise phase is interposed, with T = D, then the work done in cruise is

$$Q_c = D X_c = \frac{W}{k_1} X_c$$

or

$$\frac{Q_c}{X_c} = \frac{W}{k_1}$$

and the total work done during the flight is $(Q_A + Q_c)$ where

$$(Q_A + Q_c)/(X_A + X_c + X_G) = \frac{W}{k_1}$$

which is independent of k_2 and V_c as in equation (5). Three typical trajectories are illustrated in Fig.2. These all give the same range for the same total work done by the propulsion unit.

If we now repeat these calculations but include the effect of the centrifugal force due to the earth's curvature, then

$$L = W\left(1 - \frac{V^2}{V_s^2}\right)$$

where V_s = satellite orbital speed.

$$X_A = \frac{V_s^2}{2\,g}\left(\frac{k_1}{k_2 - 1}\right) \log_e \left[\frac{1}{\left(1 - \frac{V_c^2}{V_s^2}\right)}\right] \qquad (6)$$

$$= \frac{V_c^2}{2g}\left(\frac{k_1}{k_2 - 1}\right)\left[1 + \frac{1}{2}\left(\frac{V_c^2}{V_s^2}\right) + \frac{1}{3}\left(\frac{V_c^2}{V_s^2}\right)^2 + \dots\right]$$

and

$$Q_A = \frac{W V_c^2}{2g}\left(\frac{k_2}{k_2 - 1}\right)$$

as before.

Thus the effect of the earth's curvature is to increase the range covered during acceleration by a factor

$$\left(\frac{V_s^2}{V_c^2}\right) \log_e \left(\frac{1}{1 - \frac{V_c^2}{V_s^2}}\right)$$

for the same work done.

Similarly, during the glide,

$$X_G = \frac{V_s^2}{2g} k_1 \log_e \left(\frac{1}{1 - \frac{V_c^2}{V_s^2}}\right) \tag{7}$$

$$= \frac{V_c^2}{2g} k_1 \left[1 + \tfrac{1}{2}\left(\frac{V_c^2}{V_s^2}\right) + \tfrac{1}{3}\left(\frac{V_c^2}{V_s^2}\right)^2 + \dots\right] .$$

Thus the range during acceleration and glide together is

$$X_A + X_G = \frac{V_s^2}{2g}\left(\frac{k_1 \quad k_2}{k_2 - 1}\right) \log_e \left(\frac{1}{1 - \frac{V_c^2}{V_s^2}}\right) \tag{8}$$

$$= \frac{V_c^2}{2g}\left(\frac{k_1 \quad k_2}{k_2 - 1}\right)\left[1 + \tfrac{1}{2}\left(\frac{V_c^2}{V_s^2}\right) + \tfrac{1}{3}\left(\frac{V_c^2}{V_s^2}\right)^2 + \dots\right]$$

and

$$\frac{Q_A}{X_A + X_G} = \frac{W}{k_1}\left[\frac{1}{1 + \tfrac{1}{2}\left(\frac{V_c^2}{V_s^2}\right) + \tfrac{1}{3}\left(\frac{V_c^2}{V_s^2}\right)^2 + \dots}\right] .$$

Thus the work done per unit range decreases with an increase of cruise speed, but is still independent of the ratio $k_2 = T/D$.

Now, if a cruise phase is included in the trajectory, with a cruise range of X_c, then

$$Q_c = \frac{W X_c}{k_1}\left(1 - \frac{V_c^2}{V_s^2}\right)$$

and

$$\frac{Q_A + Q_c}{X_A + X_c + X_G} = \frac{W\left(1 - \frac{V_c^2}{V_s^2}\right)}{k_1} + \frac{W V_c^2}{4g\, X}\left(\frac{k_2}{k_2 - 1}\right)\left[\left(\frac{V_c^2}{V_s^2}\right)^2 + \frac{1}{3}\left(\frac{V_c^2}{V_s^2}\right)^2 + \frac{1}{6}\left(\frac{V_c^2}{V_s^2}\right)^2 + \ldots\right] . \qquad \ldots (9)$$

This shows that for a given total range $X = X_A + X_c + X_G$, a given k_1, and a given cruising speed V_c, the minimum work done occurs when k_2 is a maximum (i.e. when the acceleration is a maximum) and, therefore, when the cruise phase is as long as possible. However, it must be remembered that there are other factors neglected in this crude analysis, which could affect this conclusion; one such factor is the variation of engine efficiency with speed. Further more detailed studies could well be profitable on this aspect.

So far we have assumed constant values of weight and ratio of thrust to drag. The Bréguet range formula allows for the change in weight during the cruise of course, but for the acceleration phase (where the weight change could be important for a hypersonic cruise vehicle) we must now make due allowance for the weight change in calculating the range.

The simplest way of doing this is to assume that

$$\frac{dW}{dt} = -\sigma T$$

where σ is the specific fuel consumption.

Then from the equations obtained previously by resolution of forces

$$T - D = \frac{W}{g}\frac{dV}{dt} + W \sin\gamma$$

and

$$L = W\left(1 - \frac{V^2}{V_s^2}\right)$$

we have

$$\frac{1}{g}\frac{dV}{dt} = \frac{T}{W} - \frac{D}{W} - \sin\gamma$$

$$= -\frac{1}{\sigma W}\frac{dW}{dt} - \frac{\left(1 - \frac{V^2}{V_s^2}\right)}{k_1}$$

where $k_1 = L/D$ and $\sin\gamma \simeq 0$ has been assumed.

Thus

$$\frac{1}{W}\frac{dW}{dt} = -\frac{\sigma}{g}\frac{dV}{dt} - \frac{\sigma}{k_1} + \frac{\sigma}{k_1}\frac{V^2}{V_s^2} \quad . \tag{10}$$

For a "flat" earth the term $\sigma/k_1 \; V^2/V_s^2$ is absent and if we also assume a constant acceleration

$$\frac{dV}{dt} = ng$$

then equation (10) can be integrated to give

$$\log_e\left(\frac{W_1}{W_2}\right) = -\frac{\sigma t}{g}\, ng - \frac{\sigma t}{k_1}$$

where W_1 is the take-off weight and W_2 the weight at end of climb (see Fig.1).

Thus, since $V = ngt$

$$\log_e\left(\frac{W_1}{W_2}\right) = -\frac{\sigma V}{g}\left(1 + \frac{1}{nk_1}\right) \quad . \tag{11}$$

If centrifugal forces are taken into account and the term $\sigma/k_1 \; V^2/V_s^2$ is not negligible, then equation (10) gives

$$\log_e\left(\frac{W_1}{W_2}\right) = -\frac{\sigma V}{g}\left(1 + \frac{1}{nk_1} - \frac{1}{3nk_1}\frac{V^2}{V_s^2}\right) \tag{12}$$

again for a constant acceleration of ng.

3 RANGE CALCULATIONS

This section presents the results of range calculations using the expressions derived in the previous section. Calculations are made for both kerosene and hydrogen fuel taking various estimates for the variation of specific fuel consumption (s.f.c.) or specific impulse (S.I.), for a constant value $n = 0.2g$ of acceleration during the climb phase, and for values of maximum L/D ratio of 4 and 6.

Fig.3 shows the assumed variation of specific fuel consumption, σ, in lb/hr/lb for kerosene fuel based on estimates made by Lane[2]. Average values, (with respect to Mach number) $\bar{\sigma}$, are also shown; these are used in calculating range covered during the acceleration phase.

Two different assumptions for specific fuel consumption using liquid hydrogen as fuel are shown in Fig.4. The upper set is based on Lane's[2] estimates up to M = 6 and more recent figures due to Avery and Dugger (as quoted by Yaffee[3]). The lower set is based on estimates published by Jamison[4], and represent an envelope of optimum values of s.f.c. throughout the Mach number range. These latter figures are clearly optimistic since the values of σ quoted are those for different types of propulsion unit in different Mach number ranges.

The results of the range calculations to be quoted below all include allowance for centrifugal force, and the calculation procedure is as follows.

The ratio of weights at beginning and end of the climb (acceleration phase) is calculated from equation (12) for cruise Mach numbers from 2 to 14, but the s.f.c. used in equation (12) is the average value $\bar{\sigma}$ as mentioned above. Further, the acceleration is assumed to be $f_A = 0.2g$ in all cases.

Next, the ranges covered during acceleration and glide are calculated from equations (6) and (7) respectively, again for cruise Mach numbers from 2 to 14. A constant value of maximum L/D ratio is assumed for each set of calculations. The two values chosen are 4 and 6. The former is considered to be pessimistic but the value of 6 is reckoned to be attainable for an aircraft to fly in 10 - 20 years time.

Values of total range from 2000 to 12000 nm are assumed and the cruise range for each obtained simply by subtracting the range calculated for acceleration and glide. The conventional Bréguet range equation is then employed to calculate the ratio of weights at beginning and end of cruise:-

$$\log_e \frac{W_2}{W_3} = 1.685 \, \sigma \, R_c \left(1 - \frac{V_c^2}{V_s^2}\right) V_c \left(\frac{L}{D}\right) \tag{13}$$

where σ is specific fuel consumption in lb/hr/lb, R_c is cruise range in nautical miles, V_c and V_s are cruise speed and satellite speed respectively, in ft/sec.

For simplicity in these calculations it is assumed that $V = 1000 \times M$ ft/sec irrespective of altitude etc.

The procedure outlined above leads to sets of curves of the ratio $(W_1 - W_3)/W_1$, i.e. the ratio of fuel weight to take-off weight against cruise Mach number, for various values of total range. They therefore illustrate what has to be achieved in the way of percentage weights of structure, engines, etc. to get a given range at a given cruise Mach number.

The results are plotted in Figs.5 to 8. Fig.5 shows the variation of fuel fraction with cruise Mach number for a kerosene-fuelled aircraft and different values of total range. Even with the rather conservative specific fuel consumption variation with Mach number that has been assumed it is seen that this aircraft has a range performance corresponding to the supersonic transports currently being developed for transatlantic stage lengths with a similar percentage weight of fuel (approximately 50%). Fig.6 shows similar curves for a hydrogen-fuelled aircraft assuming the same lift-to-drag ratio of 6. Comparison with Fig.5 shows in rather a striking way the advantage of using a fuel with higher calorific value such as hydrogen. Thus it is seen that global ranges (> 10000 nm) are possible for fuel fractions of less than 50% and cruise Mach numbers above about 6. Even with the lower lift-to-drag ratio of 4, very long ranges (of the order of 8000 nm) are possible as shown by Fig.7.

Fig.8 is again for a hydrogen-fuelled aircraft with L/D = 6 and a specific fuel consumption that may be rather optimistic. These curves show that global ranges may be possible for even lower values of fuel fraction than in Fig.6, (i.e. of the order of 40%).

Taken together, these figures show the very great promise of hypersonic cruise speeds for very long range aircraft provided the structure and engine development can be carried out satisfactorily; but with fuel fractions of 50% and less there is a good prospect that this can eventually be done.

The use of liquid hydrogen fuel with its low density raises problems of the volume required to stow the fuel. However, the large excess of engine exit over intake areas which may be required for hypersonic propulsion units implies that the required volume may be provided without too much drag penalty. In any case, the volume requirements of kerosene and hydrogen-fuelled aircraft are compared in the next section in order to assess the adverse effect of larger volume on the lift-to-drag ratio, and hence on achievable range.

4 COMPARISON OF VOLUME REQUIREMENTS OF KEROSINE AND HYDROGEN-FUELLED AIRCRAFT

The densities of kerosene and liquid hydrogen are 50 lb/ft^3 and 4.42 lb/ft^3 respectively, but to allow for the extra tankage weight which will be incurred with hydrogen both because of the larger volume required and because of its cryogenic nature a value of 5.0 lb/ft^3 is assumed for liquid hydrogen.

The increase in volume coefficient τ = volume/(plan area)$^{3/2}$, for a hydrogen-fuelled aircraft over a kerosene-fuelled aircraft is easily calculated for a given take-off weight, given percentage fuel weight and given wing-loading. Curves of $\Delta\tau$ obtained in this way are plotted in Fig.9 for values of wing-loading, ω, ranging from 40 to 80 lb/ft^2, for take-off weights of 100 000, 200 000 and 400 000 lb and for ratios of fuel weight to take-off weight of 0.3, 0.4 and 0.5.

Two spot points are plotted on Fig.9 to show how much greater is the volume increment if no allowance is made for extra tank weight with hydrogen.

Now, because of the higher calorific value of hydrogen, an aircraft using this fuel has a potential factor of about 2.6 on the range possible with kerosene fuel for the same weight of fuel. However, apart from a probable improvement in s.f.c., the larger volume required results in a lower value of lift-to-drag ratio and this therefore detracts from the possible range increase.

As a crude guide, we may use the Bréguet range equation to calculate a parameter η which represents the ralative range efficiency of liquid hydrogen and kerosene fuels.

Thus

$$\eta = 2.6 \left[\frac{L}{D} \log_e \left(\frac{W_1}{W_3}\right)\right]_{\text{Hydrogen}} \div \left[\frac{L}{D} \log_e \left(\frac{W_1}{W_3}\right)\right]_{\text{Kerosene}} \qquad (14)$$

since the ratio of calorific values of hydrogen and kerosene is 2.6.

Fig.10 shows values of η for the same parameters as in Fig.9, values of L/D for given values of the volume parameter being taken from the calculations of Collingbourne and Peckham[5] for caret wings.

Considering Figs.9 and 10 together, it is clear that the increased volume requirement of hydrogen fuel is greater for an aircraft of relatively low take-off weight and also for higher values of wing-loading (Fig.9). This leads to a greater cut-back in the range efficiency factor below that theoretically possible with the higher calorific value of hydrogen.

Thus a hypersonic aircraft using liquid hydrogen for fuel shows the greatest promise if it is relatively large and if it has the lowest possible wing-loading.

5 CONCLUSIONS

A simple analysis of the range performance of hypersonic aircraft including the climb and final glide phases, but with such crude assumptions as for instance a constant lift-to-drag ratio throughout the flight, has demonstrated two main points:-

(1) Ranges of the order of 10000 nm appear possible with reasonable values of lift-to-drag ratio and specific fuel consumption and a fuel weight of less than 50% of the take-off weight, using liquid hydrogen fuel.

(2) To take full advantage of the higher calorific value of hydrogen over kerosene, a long-range hypersonic aircraft needs to be of large size and have the lowest possible wing-loading consistent with other requirements.

It thus appears that the next step is with the structural engineers, to see if it appears possible to build an aircraft within the above limitations, and to put in hand any necessary research and development in connection with materials, structural design, systems, etc., and with the engine designers to continue the development of suitable propulsion units.

SYMBOLS

D	drag
L	lift
Q	work done during phase of flight trajectory
R_c	cruise range in Bréguet equation
T	net thrust
V	velocity
W	instantaneous value of weight
W_1, W_2, W_3	weights at start of acceleration phase, start of cruise phase, and end of cruise phase respectively
X	distance covered during phase of flight trajectory
f	acceleration along flight path
g	acceleration due to gravity
k_1	L/D
k_2	T/D
n	$\frac{1}{g}\frac{dV}{dt}$
t	time
γ	angle of climb in acceleration phase
σ	specific fuel consumption
η	relative range efficiency

Suffixes

A	acceleration phase
C	cruise phase
G	glide phase

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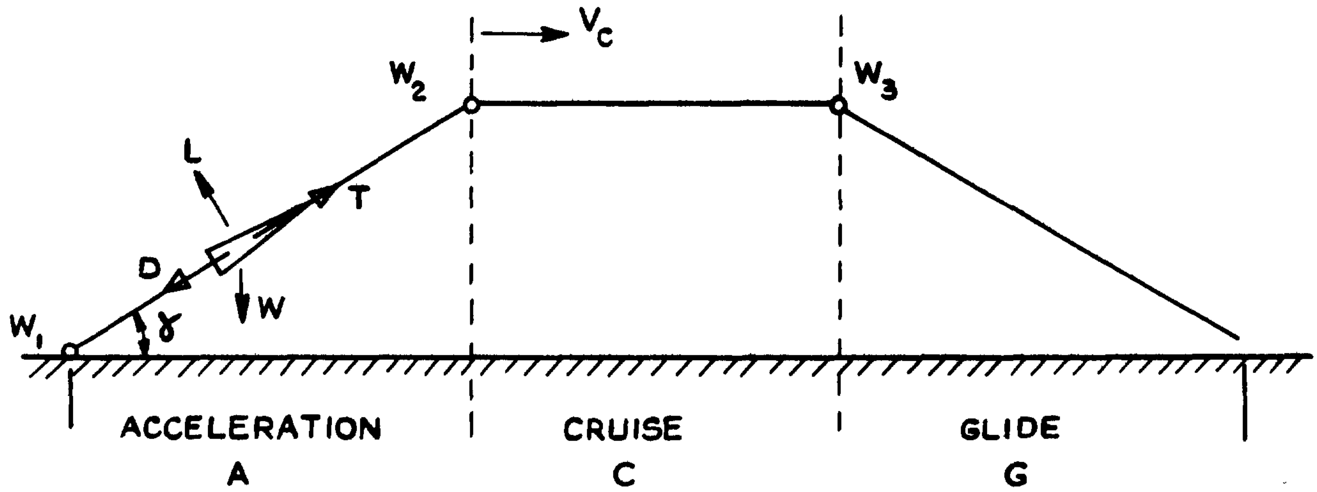

FIG. 1 TYPICAL TRAJECTORY OF A HYPERSONIC CRUISE VEHICLE

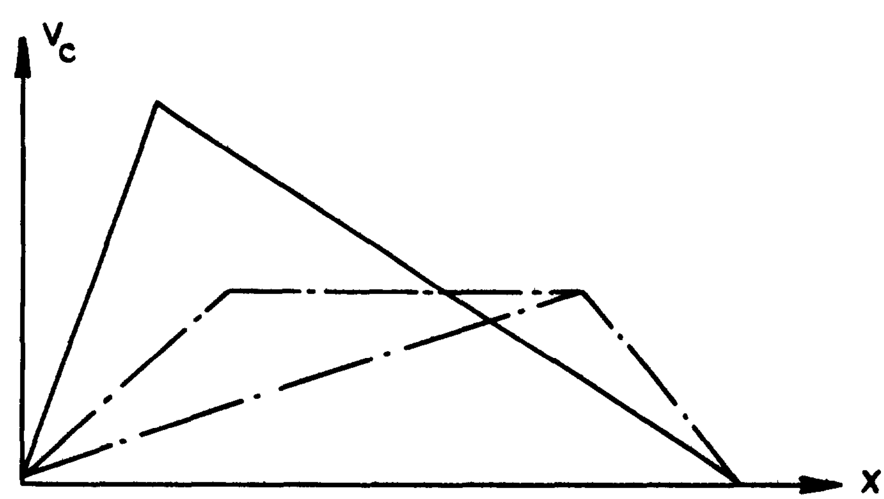

FIG. 2 ILLUSTRATION OF THREE POSSIBLE TRAJECTORIES GIVING SAME TOTAL RANGE FOR SAME AMOUNT OF WORK DONE.
(ASSUMING CONSTANT WEIGHT & NEGLECTING CENTRIFUGAL FORCE EFFECTS)

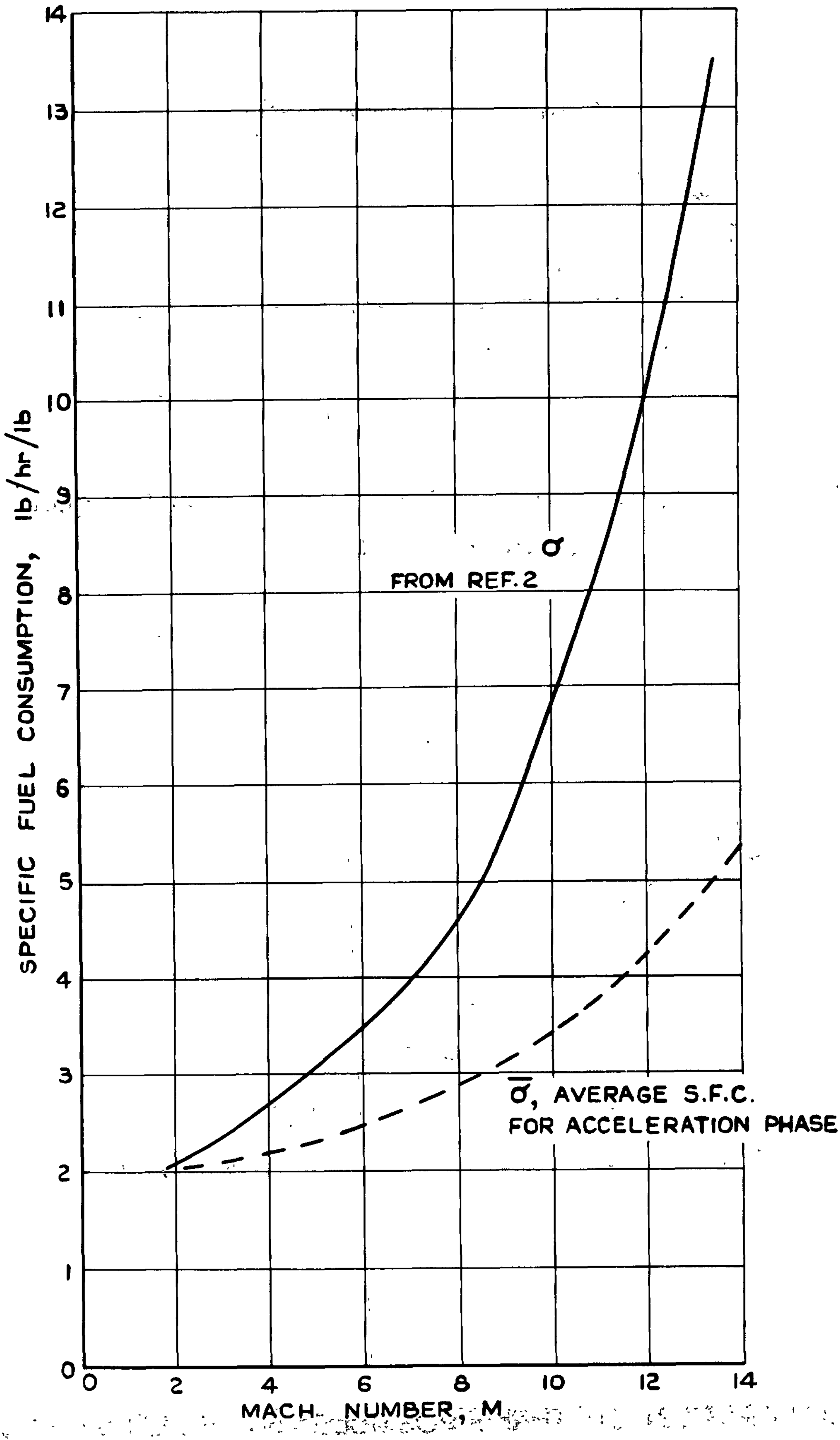

FIG. 3 SPECIFIC FUEL CONSUMPTION — KEROSENE

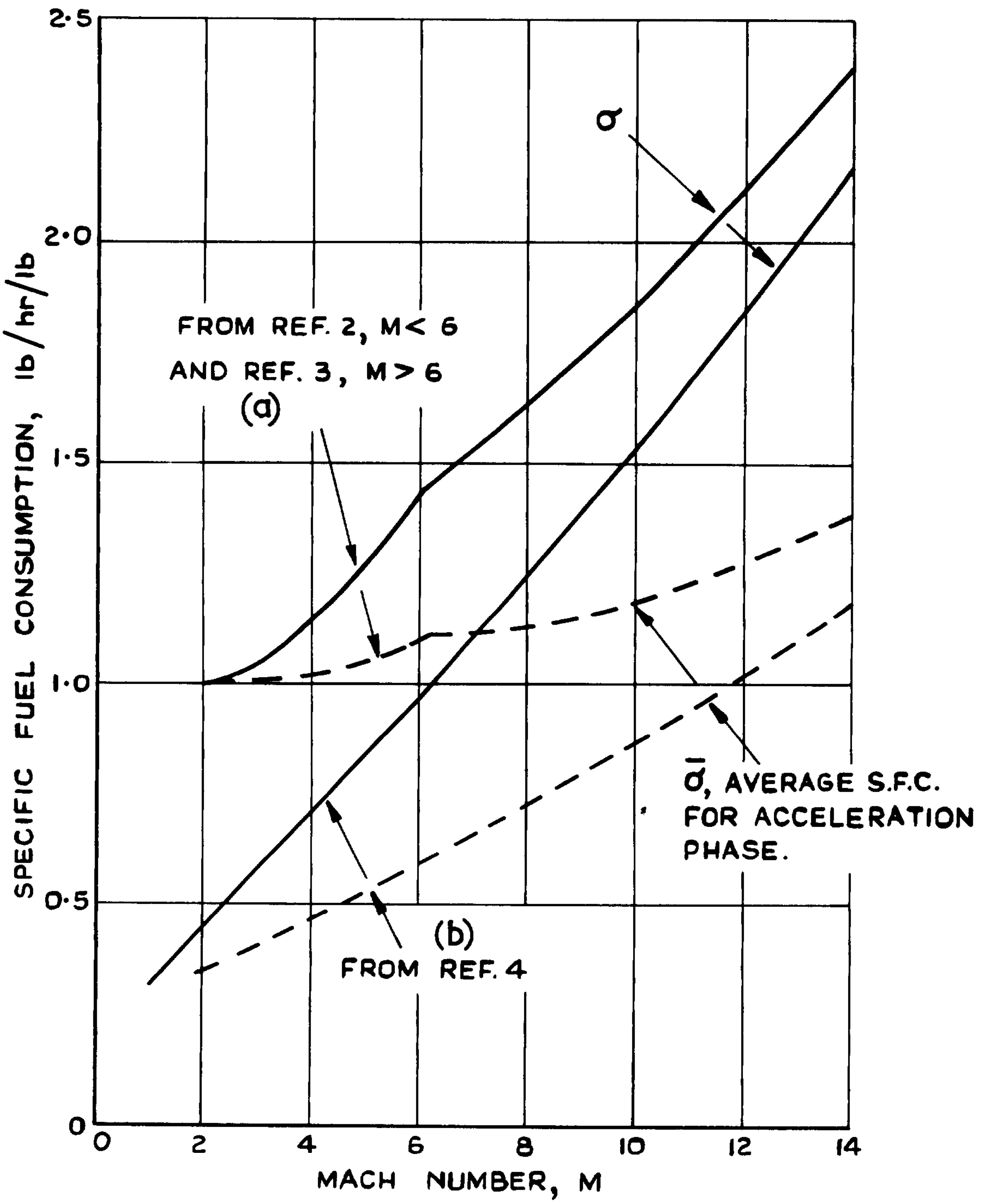

FIG. 4 SPECIFIC FUEL CONSUMPTION — HYDROGEN

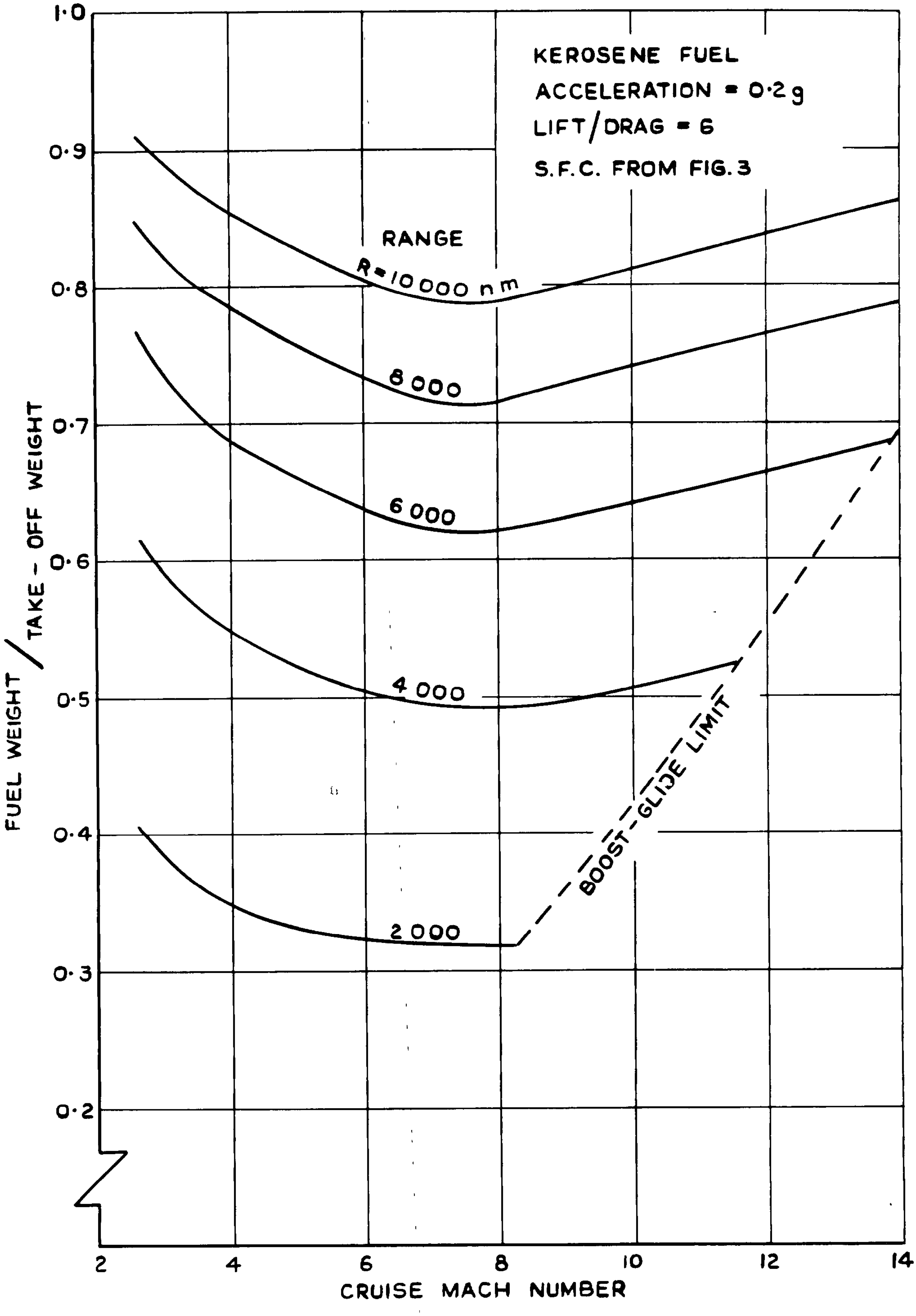

FIG. 5 VARIATION OF FUEL FRACTION WITH RANGE & CRUISE MACH NUMBER (KEROSENE FUEL)

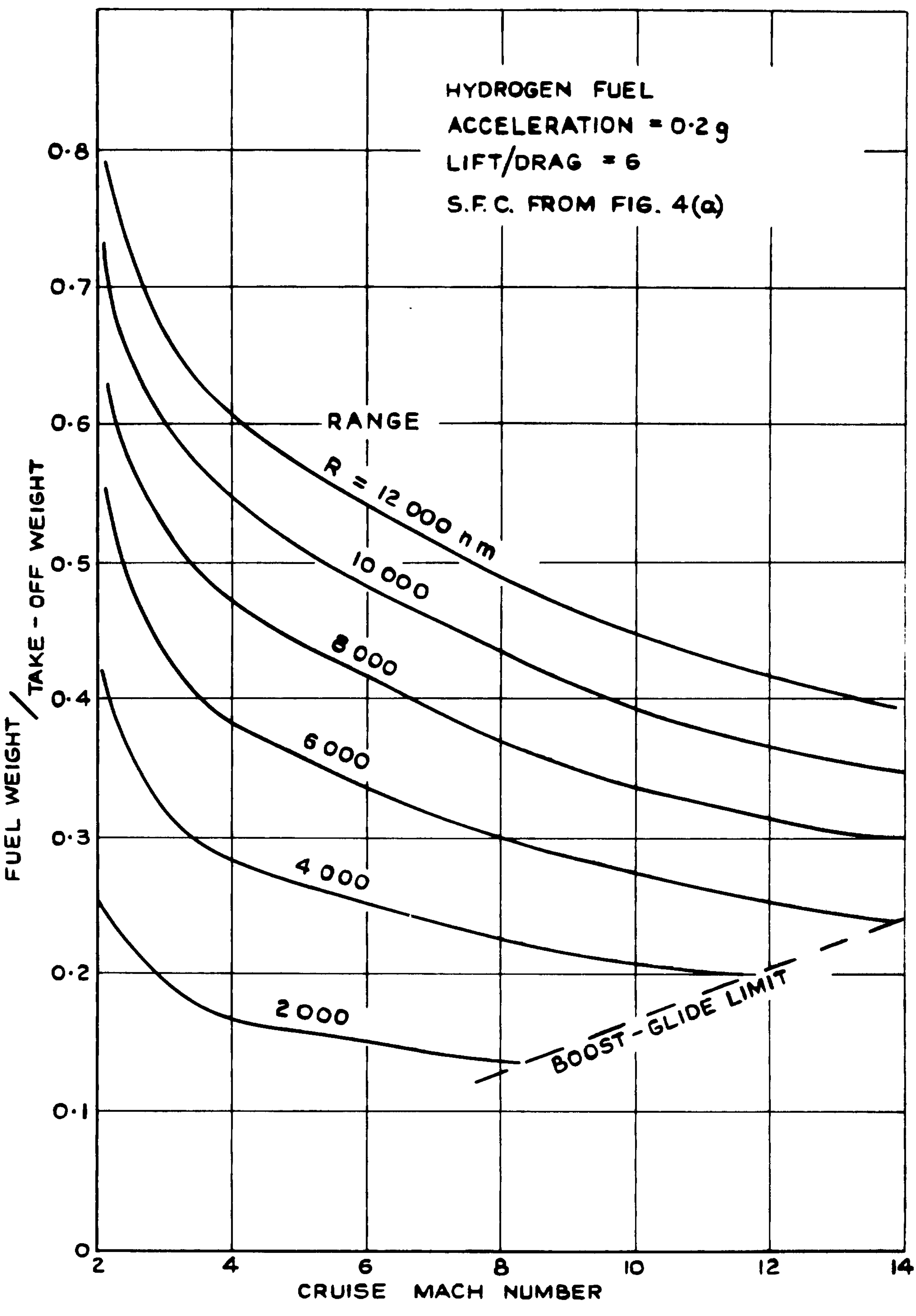

FIG. 6 VARIATION OF FUEL FRACTION WITH RANGE & CRUISE MACH NUMBER (HYDROGEN FUEL)

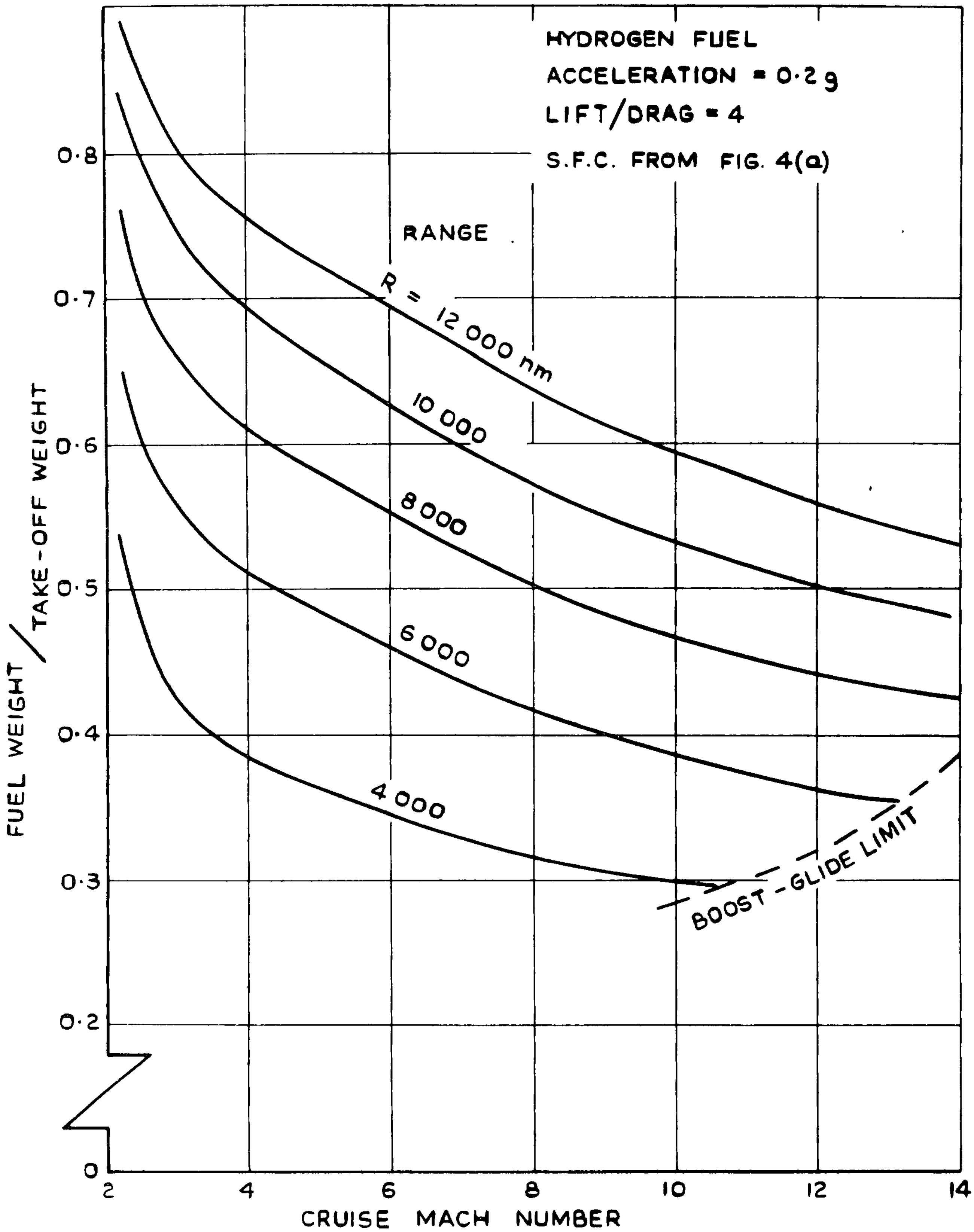

FIG. 7 VARIATION OF FUEL FRACTION WITH RANGE & CRUISE MACH NUMBER (HYDROGEN FUEL)

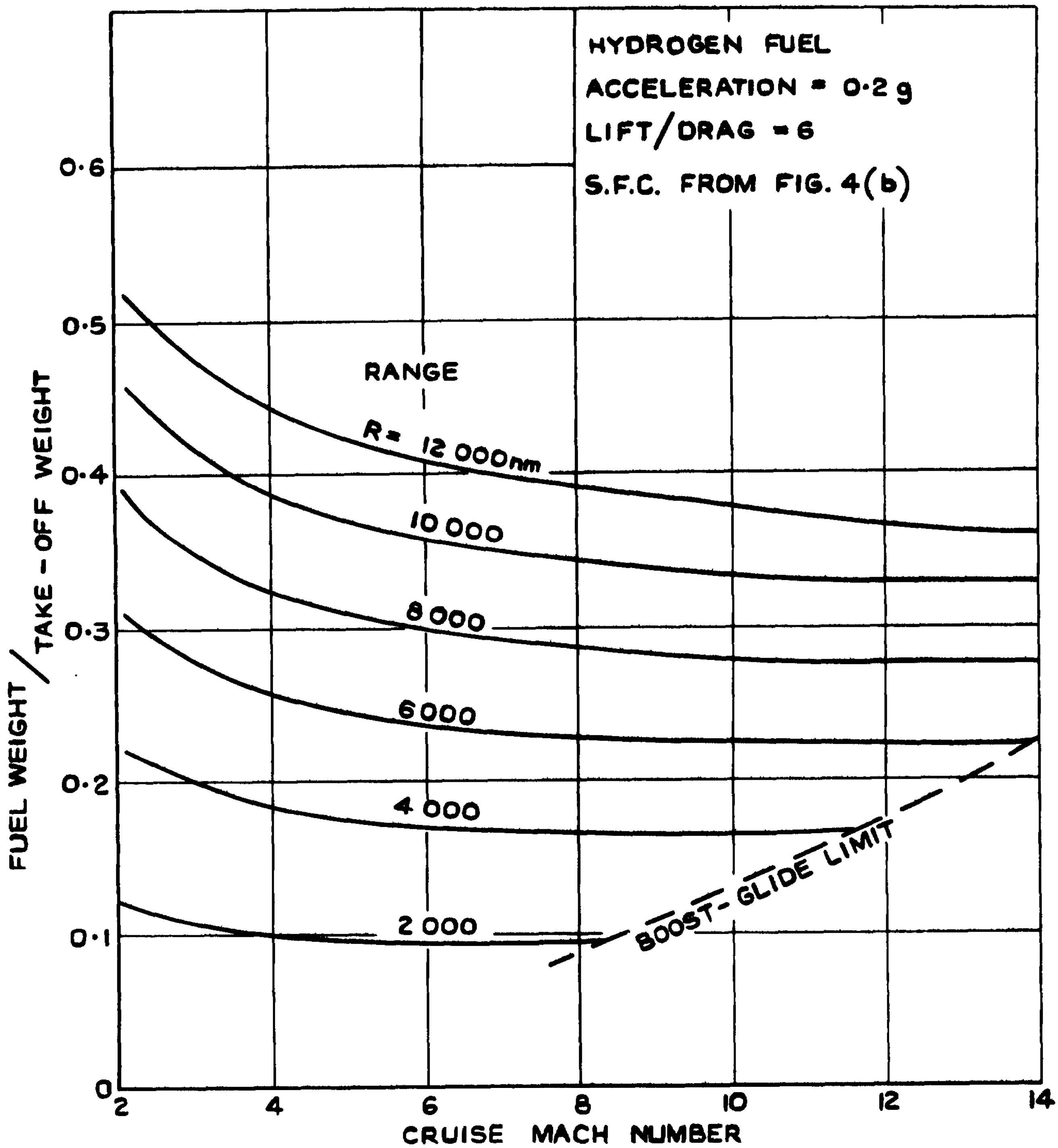

FIG. 8 VARIATION OF FUEL FRACTION WITH RANGE & CRUISE MACH NUMBER (HYDROGEN FUEL)

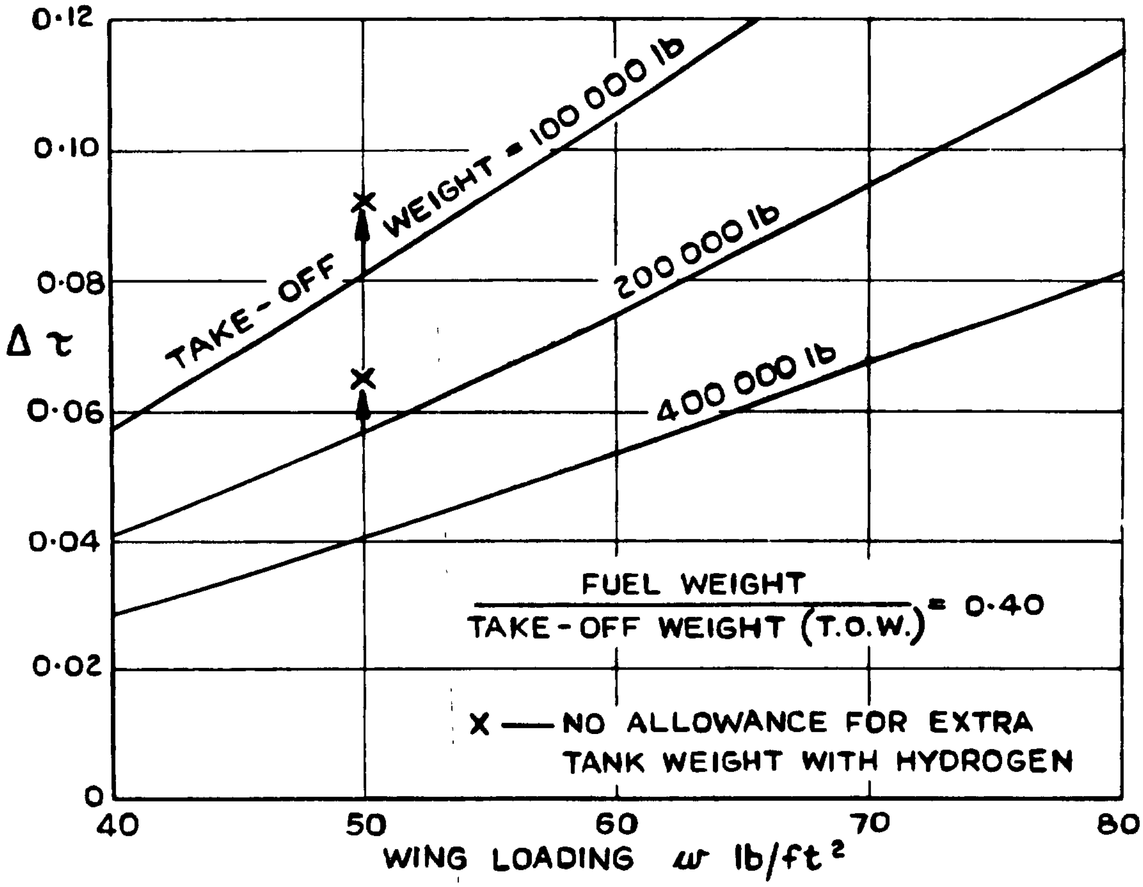

FIG. 9 (a) CONSTANT FUEL-WEIGHT FRACTION

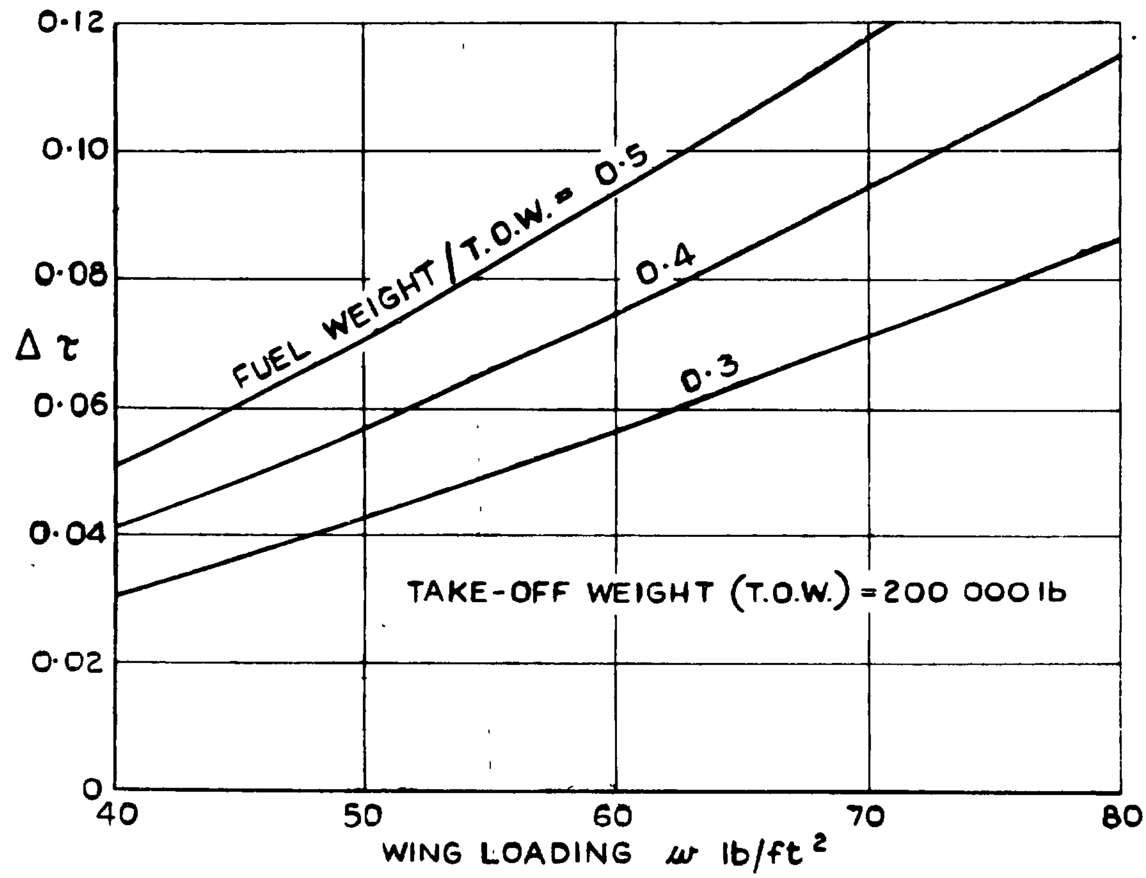

FIG. 9 (b) CONSTANT TAKE-OFF WEIGHT

FIG.9 INCREASE OF VOLUME COEFFICIENT, $\Delta \tau$, WITH USE OF LIQUID HYDROGEN FUEL INSTEAD OF KEROSENE FUEL

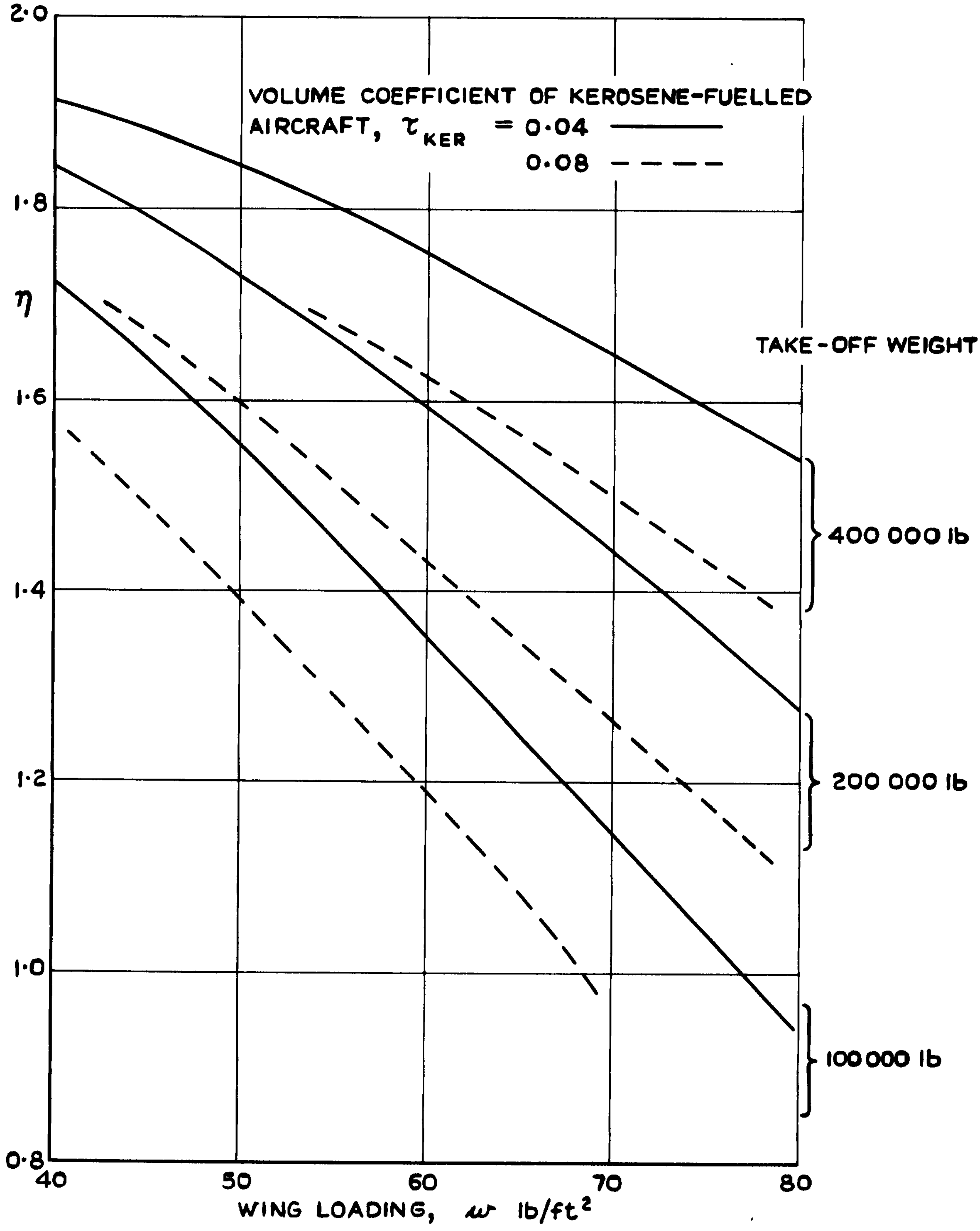

FIG.10 RELATIVE RANGE EFFICIENCIES OF HYDROGEN AND KEROSENE-FUELLED AIRCRAFT

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Typical calculations show that global ranges (i.e. of the order of 10000 nm) are obtainable for reasonable values of lift to drag ratio and of specific fuel consumption, and a fuel weight of less than 50% of the take-off weight, with liquid hydrogen fuel.

(Over)

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June 1966

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DETACHABLE ABSTRACT CARDS

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