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Extended Range Operations of Two and Three Turbofan Engined Airplanes

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The objective of the present work is a comparative analysis of the behavior of two and three turbofan engined airplanes after engine failure. A simple but fairly realistic treatment of the range equation allows study of extended range operations of airplanes after any prescribed decrease in thrust. The approach takes into account the increase in parasite drag, and considers variations of thrust and specific fuel consumption with altitude and Mach number. All peculiarities of the powerplant are translated into a few nondimensional parameters. The model provides the long-range cruise conditions after engine failure, namely altitude and Mach number, and the additional fuel needed to reach the final destination. Results for a typical 5000-km route show the relative disadvantage of twins.

Nomenclature

A = aspect ratio of wing
AF = extra fuel needed to reach destination due to engine failure
a_0 = speed of sound at sea level
af = normalized extra fuel, AF/W^*
C = specific fuel consumption
C_{D0} = parasite drag coefficient
C_L = lift coefficient
C_0 = increment factor in parasite drag due to engine failure
D = drag
d = normalized drag, D/D^*
f = fraction of thrust available after engine failure
H = height of flight
h = normalized height, H/H^*
k = range parameter (see definition of R)
k' = range parameter after engine failure
L = lift
l = normalized lift, L/L^*
M = Mach number
m = normalized Mach number, M/M^*
n = parameter defined in Eq. (10)
P = normalized pressure, p/p^*
p = pressure at flight altitude
R = range, $\int k/w \, dw$
r = parameter defined in Eq. (17)
T = thrust
V = airplane speed
W = airplane weight
w = normalized airplane weight, W/W^*
β = exponent in the dependence of C with M, see Eq. (1)
ε = exponent in the dependence of T with M, see Eq. (3)
θ = temperature at flight altitude relative to sea level
μ = exponent in the dependence of T with p, see Eq. (3)
τ = exponent in the dependence of C with p, see Eq. (1)
ϕ = induced drag efficiency factor

Subscripts
f = end of flight
i = beginning of flight

Superscript
$*$ = conditions prior to engine failure

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Introduction

IN the never-ending controversy on flight safety, twins have many times been subject of comments, papers, and concern. A number of accidents such as the one near Britain's M1 motorway, have brought into the arena the adequacy of safety requirements for this type of aircraft.[1] This controversy, however, becomes paradoxical since at the same time the civil aviation authorities have been providing dispensations to fly very long distances with twins: the so-called EROPS flights.

Extended range operations (EROPS) were defined as routes on which airplanes are allowed to fly more than 60 min from a suitable airport.[2] At the present time, since the limitation applies only to twin-engined aircraft, the acronym has been modified to ETOPS. The aforementioned figure has been slowly increasing over the years. The FAA granted exemptions for trans-Caribbean operators, first up to 75 min and then to 85 min. Later on, this limit was increased still further to 120 min. At the same time, for North Atlantic track operations, UK CAA permitted a limit of 138 min. Finally, ETOPS are allowed (upon application and with many severe requirements) up to 180 min from a suitable airport, which is tantamount to the disappearance of almost all no-go areas[3] as can be observed in Fig. 1. To emphasize the very long range of modern airplanes, it must be recalled that, during delivery, an Air Mauritius B767-200ER set a new twin-engine class record of 16 h 27 min from Canada to the Indian Ocean.[4]

The interest in ETOPS arises from the need for fleet renovation; this mainly affects B727 and larger three-engined airplanes that must be replaced by new and more efficiently designed twins: A310, A320, B757, B767, and the like. It is important to bear in mind, that since oceans and seas cover about 70% of the earth (see Fig. 1), extended range operations will inevitably cover an important fraction of airline activities, particularly in the Pacific rim, Africa, and South and Central America; all of which are areas of enormous potential and whose air links to developed countries are frequently over seas, deserts, and similar areas.[3,5]

Since the limitation for ETOPS comes from the peculiarity of their having only two engines, this article shows a comparative study of the behavior (once one engine has become inoperative) of two- and three-engined aircraft during the second half of the flight, and cruising under the best long-range conditions.

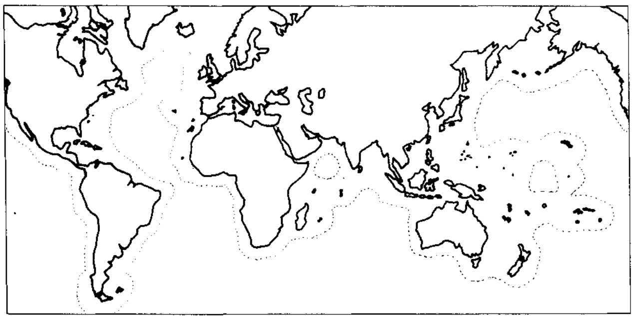

Fig. 1 World map showing approximately the usual limit for twins.

Problem Formulation

Let us consider the effect of engine failure occurring at the halfway mark on a route, to an airplane flying in a long-range, constant altitude cruise. Immediately there is a sharp decrease in available thrust together with an increase in drag which cause the airplane to lose height and speed. Confronted by this situation, the pilot tries to obtain the longest possible range.

The first half of the flight can be analyzed adequately through the range cruise problem which means, in effect, maximizing VL/CD. The classical formulation states that this is equal to maximizing ML/D since C varies in parallel to the speed of sound.[6] Here a more refined treatment is used.

The functional dependence of the specific fuel consumption is considered to be[7,8]

$$C/C^* = \sqrt{\theta/\theta^*}\, m^{\beta} P^{\tau} \tag{1}$$

According to Eq. (1) best range conditions at constant altitude imply

$$C_L = \sqrt{[(1+\beta)/(3-\beta)]}\sqrt{C_{D0}\pi A\phi} \tag{2}$$

instead of the well-known expression of 0.57 times the lift coefficient for optimum efficiency (i.e., for $\beta = 0$).

In a similar way to the above functional dependence, the available thrust can be fitted to

$$T/T^* = f m^{\varepsilon} P^{\mu} \tag{3}$$

It is understood that before engine shutdown, the thrust parameter f is equal to 1.

During the first half of the flight the cruise is assumed to be at constant altitude, which is a reasonable approximation.[9,10] Then

$$(D/L)^* = \frac{C_{D0}}{C_L}\frac{4}{3-\beta} = \frac{C_L}{\pi A\phi}\frac{4}{1+\beta} \tag{4}$$

As previously indicated, when engine failure occurs there is a sudden increase in drag, due mainly to the stopped engine, although there are additional contributions from fuselage, vertical tail, and ailerons. Taking into account the typical values of modern airplanes, the parasite drag rises up to about 1.3 times higher than the original one for twins, and 1.15 times higher in the case of three-engined airplanes.[5,11]

On detecting the trouble, the pilot tries to obtain the best range condition, which implies

$$\frac{\partial}{\partial m}\left(m^{1-\beta}P^{-\tau}\frac{l}{d}\frac{1}{w}\right) = 0 \tag{5}$$

for each given weight (w) subject to the restriction imposed by the cruise drag-thrust equilibrium

$$fP^{\mu}m^{\varepsilon} = \frac{3-\beta}{4}C_0 P m^2 + \frac{1+\beta}{4}\frac{w^2}{Pm^2} \tag{6}$$

On the other hand, according to Eq. (2), the aerodynamic efficiency is

$$l/d = \left(\frac{3-\beta}{4}C_0\frac{Pm^2}{w} + \frac{1+\beta}{4}\frac{w}{Pm^2}\right)^{-1} \tag{7}$$

By means of adequate handling of Eqs. (5–7) the new best range situation is obtained

$$m = \left[f w^{\mu-1}\left(\frac{1+\beta}{1-n}\right)^{(\mu-1)/2}\left(C_0\frac{1+n}{3-\beta}\right)^{-(1+\mu)/2}\right]^{1/(2\mu-\varepsilon)} \tag{8}$$

$$P = \left[f^2 w^{2-\varepsilon}\left(\frac{1+\beta}{1-n}\right)^{1-\varepsilon/2}\left(C_0\frac{1+n}{3-\beta}\right)^{1+\varepsilon/2}\right]^{1/(2\mu-\varepsilon)} \tag{9}$$

where

$$n = (\mu + \tau\varepsilon - \mu\beta)/(1 + 2\tau + 2\mu - \beta - \varepsilon) \tag{10}$$

Thus, the solution depends upon five parameters of the powerplant: namely, the remaining fraction of thrust f, and the influence of height and Mach number in thrust and specific fuel consumption, μ, ε, τ, and β, respectively.

A particularly important variable is the amount of fuel needed to reach the final destination. It has been considered that during the first half of the trip, altitude is constant, therefore

$$m = \sqrt{w} \tag{11}$$

Consequently, the usual Breguet equation provides[6]

$$R/2 = 2k^*(\sqrt{w_i} - 1) \tag{12}$$

where

$$k^* = (M^* a_0\sqrt{\theta^*}/C^*)(L^*/D^*) \tag{13}$$

In a normal flight with no trouble, the full range condition is equivalent to

$$R/2 = 2k^*(\sqrt{w_i} - \sqrt{w_f}) \tag{14}$$

But, in the present study, during the second half of the trip, the range parameter diminishes according to

$$k'/k^* = m^{1-\beta} l/d P^{-\tau} \tag{15}$$

where l/d, m, and P are determined through Eqs. (7), (8), and (9), respectively.

The specified range for this part is again $R/2$ and, hence

$$R/2 = k^*\int_{w_f}^{1}\frac{k'}{k^*}(1)w^r\frac{dw}{w} \tag{16}$$

the exponent r being

$$r = [\tau(\varepsilon - 2) + (1-\beta)(\mu - 1)]/(2\mu - \varepsilon) \tag{17}$$

From Eqs. (12), (14), and (16) it is possible to compute the extra fuel with the following results:

$$\frac{af}{w_i} = \frac{[1 - (R/4k^*)]^2 - [1 - (rR/2k')]^{1/r}}{[1 + (R/4k^*)]^2} \tag{18}$$

Results for a Typical Route

With a view to making the implications of all this easier to grasp, the former model has been applied to a selected route of 5000 km, i.e., 2700 nm, which is roughly the distance of trans-North Atlantic flights, or between Los Angeles and Hawaii, or the Canary islands and Caribbean coasts, and other interesting links.[3,5]

Immediately before the shutdown, the flying conditions are $M^* = 0.8$ and $h^* = 35{,}000$ ft; in addition, a range parameter of $k^* = 20{,}000$ km is assumed. These values are fairly representative of common practice with modern airplanes.

In the present simplified application, it is assumed that $\varepsilon = 0$ and $\tau = 0$ since, to all intents and purposes, their effects are insignificant.[6,9] There is, on the other hand, a certain variety in turbofan features, and one of the model's main points is the accuracy with which it reproduces them. Consequently, the results include two values for β and also two values for μ. In particular, $\beta = 0$ corresponds to the classical approach in which the specific fuel consumption is not dependent on the Mach number; meanwhile, $\beta = 0.5$, $\mu = 0.6$, and $\mu = 0.9$ correspond to current technology.

As indicated above, there is an indirect relation between the remaining fraction of thrust and the increment of parasite drag. Typical values of f for a twin are in the range 0.55–0.65 after engine failure, since in this case the airplane thrust is determined by takeoff or second-segment climb requirements, and an extra is always available during cruise. For a three-jet aircraft, f will fall consistently between 0.7–0.8. According to this division by number of engines and the different increase in parasite drag, C_0 is set to 1.15 or 1.3 above or below $f = 0.65$, respectively, in Tables 1–4. However, to avoid scrambling of information and to facilitate a better understanding, Figs. 2 and 3 are for $C_0 = 1.15$, uniformly.

The condition of best range after engine failure can easily be interpreted through the height-Mach number planes of Figs. 2 and 3, for $\beta = 0$ and $\beta = 0.5$, respectively. At each specified value of f there is an optimum where the appropriate isoline is tangent to a given range parameter curve. Therefore, in Fig. 2, for $f = 0.8$ the airplane should start the new cruise flying at $m = 0.77$ and $h = 0.87$ (actually $M = 0.62$ and $H = 30{,}100$ ft), thus, reaching a range parameter of 0.79 times the former one (i.e., 15,800 km, instead of 20,000 km).

When Figs. 2 and 3 are compared, it is clear that in spite of an apparent similarity, the indentations of iso-k curves into the low Mach—low height region are more penetrating for the case of $\beta = 0.5$ (Fig. 3). This can be explained in terms of a lower dependence of k with respect to the Mach number, which permits faster flying (albeit at somewhat lower altitudes) and lower fuel consumption, as will be seen later. The fact that the point (1, 1) in both figures does not coincide with $f = 1$ and $k/k^* = 1$ is due to the increase in parasite drag that has already been included (i.e., $C_0 = 1.15$).

The main results of the study are summarized in Tables 1–4, each one for a different $\beta - \mu$ pair. The tables are arranged in the following way: for specified thrust fractions, the normalized Mach number, pressure, and range parameter at the beginning and end of the one-engine inoperative flight (left and right, respectively) are shown; also, the corresponding true speed and height, and the additional fuel needed to reach the final destination are shown.

In all the tables it can be observed that (as might have been expected) when there is an increase in remaining thrust, there is a corresponding increase in both speed and height, together with a drop in additional fuel. The upper value $f = 0.85$ is not far from the initial conditions and the results behave accordingly. There is always a certain gap between twins (upper halves of tables) and three-engined aircraft (lower halves), due to the pronounced increase in parasite drag. It can also be observed that the speed is kept fairly constant after engine failure, but, to counterbalance the evolving weight, flight height must increase from the midpoint to the end of the route; only slightly in the case of three-engined airplanes and considerably more so for twins.

Mach number influence in specific fuel consumption (sfc) can be detected through comparison of Table 1 vs Table 2, or Table 3 vs Table 4. The effect is to produce a somewhat

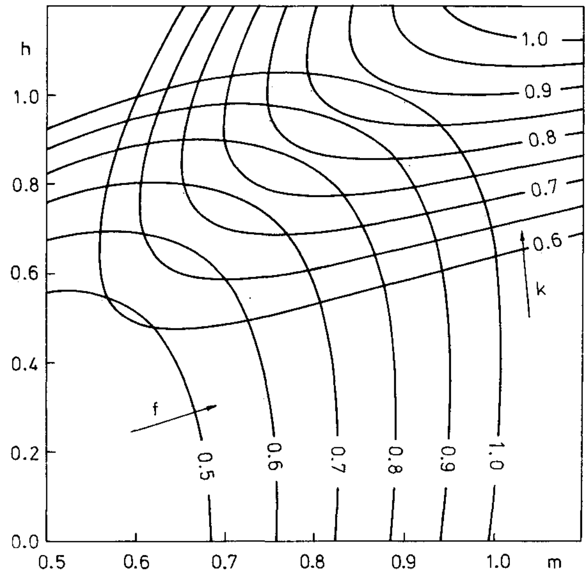

Fig. 2 Locus of constant range parameter and remaining thrust in the (m, h) plane. $C_0 = 1.15$, $\beta = 0$, $\mu = 0.9$.

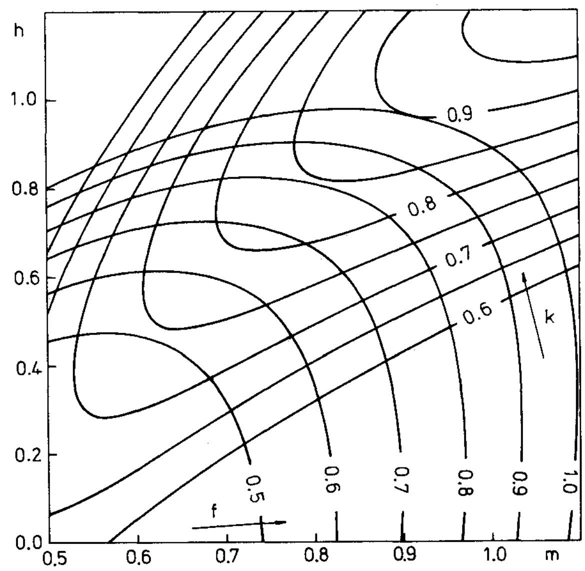

Fig. 3 Locus of constant range parameter and remaining thrust in the (m, h) plane. $C_0 = 1.15$, $\beta = 0.5$, $\mu = 0.9$.

Table 1 Flight with one engine inoperative

$\mu = 0.60$	$\tau = 0.00$		$\beta = 0.00$		$\varepsilon = 0.00$		$R/K = 0.2500$		$M^* = 0.80$		$h^* = 35{,}000$ ft	
f	m		P		k'/k^*		v, km/h		h, ft		af/wi	Co
0.50	0.45	0.49	3.32	2.10	0.44	0.48	430	451	6,712	18,202	0.104	1.30
0.55	0.49	0.53	2.83	1.86	0.47	0.52	459	480	10,842	21,206	0.091	1.30
0.60	0.52	0.57	2.45	1.65	0.51	0.55	487	507	14,505	23,934	0.079	1.30
0.65	0.56	0.60	2.14	1.48	0.55	0.59	514	534	17,787	26,427	0.068	1.30
0.70	0.65	0.69	1.71	1.26	0.67	0.71	580	599	23,152	29,984	0.040	1.15
0.75	0.68	0.72	1.52	1.14	0.71	0.75	608	626	25,798	32,129	0.032	1.15
0.80	0.72	0.76	1.37	1.04	0.75	0.79	635	653	28,222	34,117	0.026	1.15
0.85	0.76	0.80	1.24	0.95	0.79	0.83	661	680	30,454	35,966	0.020	1.15

better cruise point and, as a result, a reduction in fuel needs. On the other hand, height influence on thrust is known from simultaneous observation of Table 1 vs Table 3, or Table 2 vs Table 4. For higher values of μ, a considerably better cruise condition is achieved, although the gain in fuel is smaller than that provided by β variations. Of all the figures appearing in the four tables, the very low altitude corresponding to $f = 0.5$, $\beta = 0.5$ and $\mu = 0.6$, namely 2725 ft, is indeed noteworthy; in fact, this is almost equivalent to ditching the airplane.

The better behavior, irrespective of the number of engines, is found with $\beta = 0.5$ and $\mu = 0.9$; or, in other words, thrust almost linear with pressure at the flying level, and sfc only slightly dependent on Mach number.

Final Comments

At this stage it seems appropriate to devote a few comments to the impact of the former results on the design requirements of airplanes for ETOPS. It goes without saying that the engine type is required to have a very low shutdown rate[3] and that, preferably, its performances be close to $\beta = 0.5$ and $\mu = 0.9$. Taking into account the engine failure problem, the electrical and hydraulic systems must include additional independent sources, beyond the equipment of ordinary transport aircraft. Although it is not a pure design problem, a high degree of man-airplane synergy is essential in ETOPS flights and mainly if something has gone wrong; this includes an appropriate cockpit, information which is both reliable and easy to interpret, special training, etc.

A clear implication of ETOPS is the need for additional reserve fuel that can be estimated to be around at least 3–5% of takeoff weight (according to Tables 2 and 4); this figure does not include any extras due to nonoptimal flight profiles that could be imposed,[12] nor to the influence of winds.[13] Obviously these important issues must be analyzed in depth when studying a new ETOPS route.

On the other hand, the speeds indicated in Tables 1–4 suggest that in best-range conditions the airplane would need more than 3 h to reach the final destination, i.e., above the limit of 180 min. To overcome the situation the airplane could fly a little faster, but in this case fuel demands would consequently be higher. A more reasonable supposition would be that there is a limitation of about 3500–4000 km (equivalent to 6 h on one engine, assuming that the trouble occurs at route midpoint) between suitable airports, unless a new one-engine inoperative design requirement is introduced yielding, e.g., T/W at takeoff equal to 0.35, instead of usual values around 0.3.

All former handicaps can be observed from the air transport productivity viewpoint, through the payload-range diagram. The need for additional equipment[14] along with more powerful engines can account for up to 2% of the maximum takeoff weight, producing a parallel decrease in payload if maximum takeoff weight (MTOW) is maintained. Furthermore, common fuel reserves of about 4–5% of MTOW do not provide sufficient safety margin (according to Tables 1–4), and should be increased to 8–9%. Figure 4 summarizes these effects on the general weight range diagram[6] of a typical modern wide-body aircraft for the particular case in which both MTOW and maximum zero fuel weight (MZFW) are maintained at the original values. It is easy to see how the segment of commercial interest has been reduced.

Table 2 Flight with one engine inoperative

$\mu = 0.60$	$\tau = 0.00$		$\beta = 0.50$		$\varepsilon = 0.00$		$R/K = 0.2500$		$M^* = 0.80$		$h^* = 35{,}000$ ft	
f	m		P		k'/k^*		v, km/h		h, ft		af/wi	Co
0.50	0.46	0.49	3.84	2.74	0.60	0.63	446	462	2,752	11,661	0.056	1.30
0.55	0.50	0.53	3.28	2.37	0.63	0.65	476	492	7,000	15,323	0.050	1.30
0.60	0.54	0.57	2.84	2.07	0.65	0.67	505	521	10,768	18,589	0.045	1.30
0.65	0.57	0.61	2.48	1.83	0.67	0.70	533	550	14,143	21,529	0.041	1.30
0.70	0.66	0.70	1.98	1.52	0.77	0.79	602	619	19,662	25,889	0.024	1.15
0.75	0.70	0.74	1.77	1.36	0.79	0.81	630	648	22,384	28,310	0.020	1.15
0.80	0.74	0.78	1.59	1.23	0.81	0.84	658	676	24,876	30,534	0.017	1.15
0.85	0.78	0.82	1.43	1.12	0.84	0.86	686	704	27,172	32,589	0.014	1.15

Table 3 Flight with one engine inoperative

$\mu = 0.90$	$\tau = 0.00$		$\beta = 0.00$		$\varepsilon = 0.00$		$R/K = 0.2500$		$M^* = 0.80$		$h^* = 35{,}000$ ft	
f	m		P		k'/k^*		v, km/h		h, ft		af/wi	Co
0.50	0.56	0.57	2.26	1.75	0.54	0.54	516	510	16,434	22,602	0.076	1.30
0.55	0.59	0.60	2.04	1.59	0.57	0.57	538	532	19,007	24,750	0.068	1.30
0.60	0.62	0.63	1.85	1.46	0.59	0.60	560	554	21,312	26,691	0.060	1.30
0.65	0.65	0.65	1.69	1.35	0.62	0.63	580	575	23,394	28,460	0.054	1.30
0.70	0.72	0.73	1.45	1.20	0.73	0.74	636	631	26,839	31,020	0.031	1.15
0.75	0.75	0.75	1.35	1.12	0.76	0.77	656	651	28,556	32,525	0.026	1.15
0.80	0.77	0.78	1.25	1.05	0.79	0.80	675	670	30,140	33,920	0.022	1.15
0.85	0.80	0.81	1.17	0.99	0.82	0.82	694	689	31,608	35,219	0.018	1.15

Table 4 Flight with one engine inoperative

$\mu = 0.90$	$\tau = 0.00$		$\beta = 0.50$		$\varepsilon = 0.00$		$R/K = 0.2500$		$M^* = 0.80$		$h^* = 35{,}000$ ft	
f	m		P		k'/k^*		v, km/h		h, ft		af/wi	Co
0.50	0.58	0.59	2.46	2.01	0.68	0.68	540	535	14,329	19,340	0.042	1.30
0.55	0.61	0.62	2.22	1.82	0.69	0.70	563	558	16,944	21,730	0.038	1.30
0.60	0.64	0.65	2.01	1.66	0.71	0.72	586	581	19,286	23,875	0.035	1.30
0.65	0.67	0.68	1.84	1.52	0.73	0.73	607	602	21,403	25,817	0.032	1.30
0.70	0.75	0.75	1.58	1.34	0.82	0.82	665	660	24,903	28,738	0.018	1.15
0.75	0.77	0.78	1.47	1.24	0.83	0.83	686	681	26,649	30,358	0.016	1.15
0.80	0.80	0.81	1.37	1.16	0.85	0.85	706	701	28,259	31,853	0.014	1.15
0.85	0.83	0.84	1.28	1.09	0.86	0.86	726	721	29,751	33,242	0.012	1.15

A closer view of the payload range diagram is depicted in Fig. 5. Apart from the general changes already discussed, an anomaly has appeared in the upper border. Since no special permission is needed to operate routes that are closer than 1 h from a suitable airport, any distance that can be traveled in less than 120 min at the one-engine-out speed would not be subject to any restriction; this represents about 1300–1500 km. Analogously, from around 4000 km (6 h at the same speed) onwards, the above-mentioned limitations apply. Between these two points, a linear fitting seems reasonable.

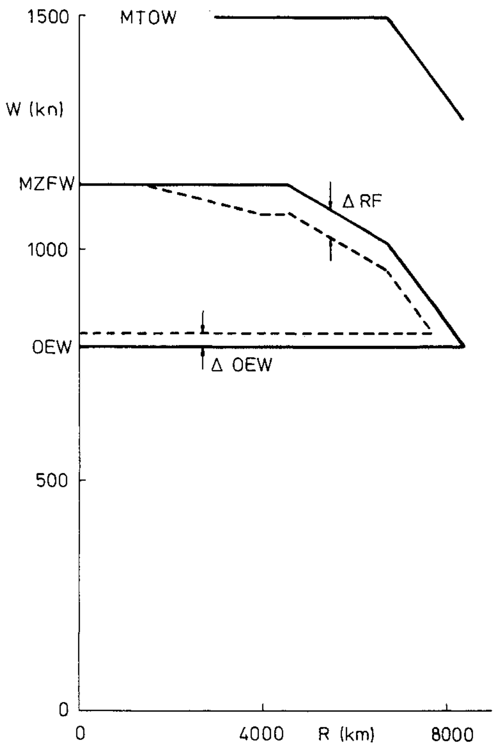

Fig. 4 Modifications (dashed lines) of the weight-range diagram due to ETOPS.

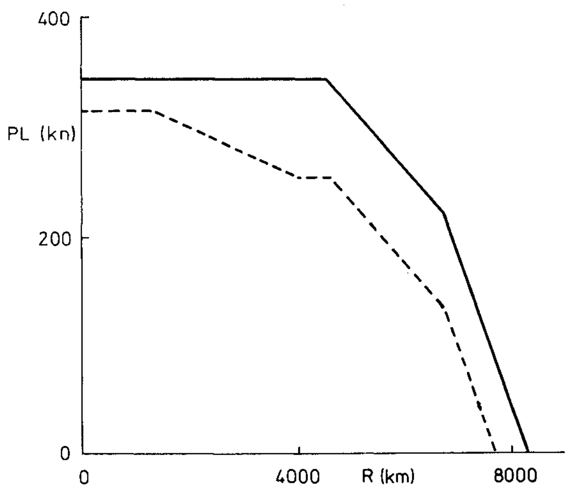

Fig. 5 Modifications (dashed lines) of the payload range diagram due to ETOPS.

The main conclusions of this work are 1) the losses in the payload range diagram due to ETOPS are real disadvantages that must be counterbalanced by appropriate air transport demand and ETOPS-oriented new designs (or, for example, by increasing MTOW); 2) after engine shutdown the airplane should not fly on long range conditions but at maximum cruise; and 3) the actual postfailure performance depends essentially on a few engine parameters (namely, the remaining fraction of thrust, a factor related to the dependence of thrust with altitude and another linking the specific fuel consumption to the Mach number).

Although the model has been developed to study the engine failure problem in long range flights, it could also be used to analyze other reduced thrust or increased drag situations (ice formation, external loads, etc).

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