EXTENDED RANGE OPERATIONS OF TWO AND THREE TURBOFAN ENGINED AIRPLANES

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Abstract

Many airlines are replacing middle-aged three engine aircraft by new and more efficiently designed twins. The improvements of safety standards of modern turbofans and the need of commercial operations in quite a large number of overseas routes has pushed the old 1 hour limit for "on one engine flight" up to 3 hours from a suitable airport. The objective of the present work is to analyze comparatively the behaviour of two and three turbofan airplanes after engine failure.

A simple but fairly realistic treatment of the range equation allows to study extended range operations of airplanes after any prescribed decrease in thrust, while keeping the best possible long range attitude. The approach takes into account the increase in parasite drag, and considers variations of thrust and specific fuel consumption with height and Mach number. All peculiarities of the powerplant are translated into a few nondimensional parameters.

The model provides the cruise conditions after engine failure, namely height and Mach number, and the additional fuel needed to reach the final destination. Results for a typical 5000 km route show the relative disadvantages of twins.

Nomenclature

- A aspect ratio of wing
- AF extra fuel needed after engine failure to reach destination
- af normalized extra fuel = AF/W*
- a_o speed of sound at sea level
- C specific fuel consumption
- C_{Do} parasite drag coefficient
- C_L lift coefficient
- C_o 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
- 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
- ϵ exponent in the dependence of T with M
- ϕ induced drag efficiency
- μ exponent in the dependence of T with p
- τ exponent in the dependence of C with p
- θ temperature at flight altitude relative to sea level

Subscripts

- f end of flight
- i beginning of flight

Superscripts

- * conditions prior to engine failure

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Introduction

In the never ended controversy on flight safety, twins have been subject many times of comments, papers and concern. A few accidents, like the one near Britain's M1 motorway, have brought into the arena the adequacy of safety requirements for this type of aircraft /1/. But this controversy becomes paradoxical since at the same time the civil aviation authorities are providing dispensations to fly very long distances with twins, the so called EROPS flights.

EROPS are defined as routes where twin-engined airplanes are allowed to fly more than 60 minutes from a suitable airport /2/. This limit has been slowly increasing along years. The FAA granted exemptions for trans-Caribbean operators, first up to 75 min and then to 85 min. Later on the limit was pushed to 120 min, meanwhile UK CAA allowed 138 min to operate the North Atlantic link. Finally, nowadays, EROPS are allowed (upon application and with many severe requirements) up to 180 min from a suitable airport, which in fact means that almost all no-go areas have disappeared /3/. 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 in 16 hours 27 min from Canada to the Indian Ocean /4/.

The interest for EROPS arises from the need of fleet renovation, affecting mainly to B727 and larger three-engined airplanes, that must be replaced by new and more efficiently designed twins (A310, A320, B757, B767 and the like), and for the mere increase in air transport. It is important to realize that oceans and seas cover about 70% of the earth and, hence, extended range operations are going to take an important fraction of airline activities, particularly in the Pacific ring, Africa, South and Central America, all of them areas of enormous potential, and whose links to developed countries are frequently over seas, deserts and similar areas /3, 5/.

Since the limitation for EROPS comes from the peculiarity of having only two engines, the present paper shows a comparative study on the behaviour of two and three-engined aircraft after engine failure, while keeping the best possible long range attitude.

Problem Formulation

Let's consider an airplane flying in long range cruise, constant altitude conditions when, at the route mid point, an engine fails. Suddenly a sharp decrease in available thrust occurs along with an increase in drag and, therefore, the airplane losses height and speed. At the new situation, the pilot tries to obtain the longest possible range.

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

Let the symbol * to denote the airplane characteristics at the time of engine failure, as indicated in the nomenclature.

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

$$C/C^* = \sqrt{\theta/\theta^*}\; m^{\beta} P^{\tau} \qquad (1)$$

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

$$C_L = \sqrt{\frac{1+\beta}{3-\beta}}\;\sqrt{C_{Do}\pi A\phi} \qquad (2)$$

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

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

$$T/T^* = f m^{\epsilon} P^{\mu} \qquad (3)$$

As it is easy to understand, before the engine failure 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

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

As indicated formerly, when the engine fails a sudden decrease in the available thrust occurs along with an increase in drag. This last is mainly due to the stopped engine drag, although there are additional contributions from fuselage, vertical tail and ailerons. Taking into account typical values of modern airplanes, the parasite drag after engine failure is about 1.3 times higher than the original one for twins and 1.15 for the three engines case /5, 11/.

Once the pilot has governed the airplane he tries to obtain the best range conditions, which implies

$$\frac{\partial}{\partial m}\left(m^{1-\beta}\,\frac{1}{d}\,\frac{1}{w}\right) = 0 \qquad (5)$$

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

$$f P^{\mu} m^{\epsilon} = \frac{3-\beta}{4} C_o P m^2 + \frac{1+\beta}{4}\,\frac{w^2}{Pm^2} \qquad (6)$$

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

$$1/d = \left(\frac{3-\beta}{4}\, C_o\, \frac{Pm^2}{w} + \frac{1+\beta}{4}\,\frac{w}{Pm^2}\right)^{-1} \qquad (7)$$

By means of adequate handling of Eqs. (5), (6) and (7) the new best range situation is obtained:

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

and

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

where

$$n = \frac{\mu+2\epsilon-\mu\beta}{1+2\tau+2\mu-\beta-\epsilon} \qquad (10)$$

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; and τ, β respectively.

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

$$m = \sqrt{w} \qquad (11)$$

Consequently, the usual Breguet equation provides /6/

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

where

$$k^* = \frac{M^* a_o \sqrt{\theta^*}}{C^*}\,\frac{L^*}{D^*} \qquad (13)$$

If the flight proceeds without troubles, the full range condition is equivalent to

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

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

$$k'/k^* = m^{1-\beta}\; 1/d\; P^{-\tau} \qquad (15)$$

where 1/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

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

the exponent r being

$$r = \frac{2(\epsilon-2)+(1-\beta)(\mu-1)}{2\mu-\epsilon} \tag{17}$$

From Eqs. (12), (14) and (16) it is possible to determine the extra fuel, resulting

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

Results for a Typical Route

For a better understanding and as a practical application the former model has been applied to a selected route of 5000 km, i.e. 2700 nm, which is roughly the distance in trans North Atlantic flights, between Los Angeles and Hawaii, the Canary Islands and Caribbean coasts and other interesting links /3, 5/.

Immediately before the engine failure the flying conditions are $M^*=0.8$ and $h^*=35000$ ft; moreover, a range parameter of $k^*=20000$ km is assumed. These values are fairly representative of common practice with modern airplanes.

In the present simplified application it will be assumed that $\epsilon=0$ and $\tau=0$, since their effects are very weak /6, 9/. But, on the other hand, there is a certain variety in turbofan features and one of the model's main points is to accurately reproduce them; consequently, the results will include two values for β and two values for μ. In particular, $\beta=0$ corresponds to the classical situation in which the specific fuel consumption does not depend on the Mach number; meanwhile $\beta=0.5$ as well as $\mu=0.6$ 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 factor of parasite drag. Typical values of f for a twin, after engine failure, are in

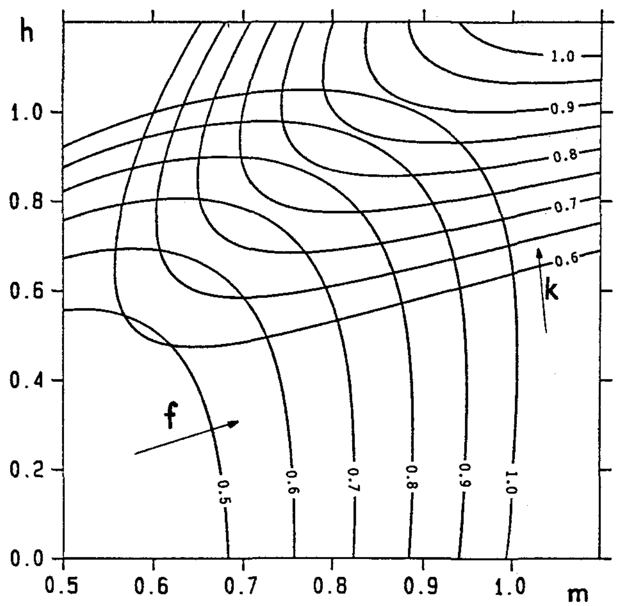

Fig. 1 Locus of constant range parameter and remainig thrust in the (m,h) plane. $C_o=1.15$, $\beta=0.0$, $\mu=0.9$.

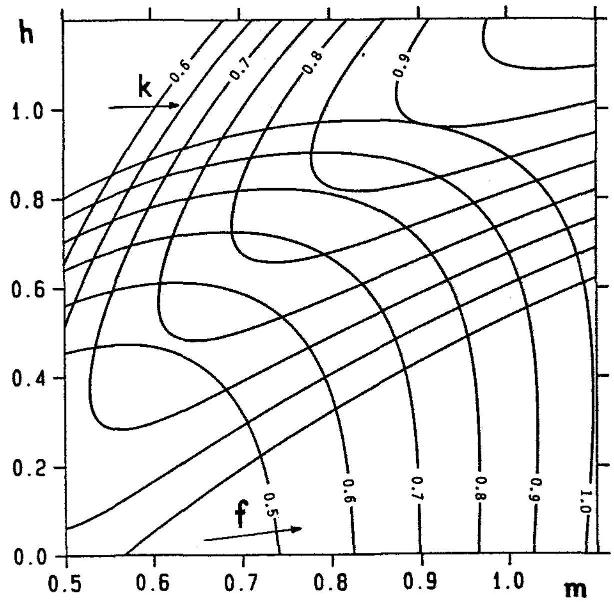

Fig. 2 Locus of constant range parameter and remainig thrust in the (m,h) plane. $C_o=1.15$, $\beta=0.5$, $\mu=0.9$.

the range 0.55 to 0.65, since in this case the airplane thrust is determined by take off or second segment climb requirements and an extra is always available during cruise. Analogously, for a three-jet aircraft, f will fall between 0.7 and 0.8; in this case the extra thrust is not so high. In consistency with this splitting, C_o is set to 1.3 in Tables 1 to 4, for f values lower or equal than 0.65, while is 1.15 above this threshold. However, to avoid scrambling of information and to allow a better view, Figs. 1 and 2 are for $C_o=1.15$, uniformly.

The condition of best range after engine failure can be easily interpreted through the height-Mach number planes of Fig. 1 and 2, 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. So, in Fig. 1, 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=30100 ft), thus reaching a range parameter 0.79 times the former one of 20000 km (i.e. 15800 km).

When comparing Figs. 1 and 2, in spite of a similar appearance, it is clear that the indentations of iso-k curves into the low mach-low height region are more penetrating for the case of $\beta=0.5$ (Fig. 2). This can be explained in terms of a lower dependence of k with respect to the Mach number, which permits to fly faster (although at somewhat lesser altitudes) and consuming less fuel, 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 increment in parasite drag that has already been included (i.e. $C_o=1.15$).

The main results of the study are summarized in Tables 1 to 4, each one for a different β-μ 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; along with the corresponding true speed and height, and the additional fuel needed to reach the final destination.

Table 1. Flight with one engine inoperative at

$\mu=0.60$ $\tau=0.00$ $\beta=0.00$ $\epsilon=0.00$ R/K=0.2500 M*=0.80 h*=35000ft

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	6712	18202	0.104	1.30
0.55	0.49	0.53	2.83	1.86	0.47	0.52	459	480	10842	21206	0.091	1.30
0.60	0.52	0.57	2.45	1.65	0.51	0.55	487	507	14505	23934	0.079	1.30
0.65	0.56	0.60	2.14	1.48	0.55	0.59	514	534	17787	26427	0.068	1.30
0.70	0.65	0.69	1.71	1.26	0.67	0.71	580	599	23152	29984	0.040	1.15
0.75	0.68	0.72	1.52	1.14	0.71	0.75	608	626	25798	32129	0.032	1.15
0.80	0.72	0.76	1.37	1.04	0.75	0.79	635	653	28222	34117	0.026	1.15
0.85	0.76	0.80	1.24	0.95	0.79	0.83	661	680	30454	35966	0.020	1.15

Table 2. Flight with one engine inoperative at

$\mu=0.60$ $\tau=0.00$ $\beta=0.50$ $\epsilon=0.00$ R/K=0.2500 M*=0.80 h*=35000ft

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	2752	11661	0.056	1.30
0.55	0.50	0.53	3.28	2.37	0.63	0.65	476	492	7000	15323	0.050	1.30
0.60	0.54	0.57	2.84	2.07	0.65	0.67	505	521	10768	18589	0.045	1.30
0.65	0.57	0.61	2.48	1.83	0.67	0.70	533	550	14143	21529	0.041	1.30
0.70	0.66	0.70	1.98	1.52	0.77	0.79	602	619	19662	25889	0.024	1.15
0.75	0.70	0.74	1.77	1.36	0.79	0.81	630	648	22384	28310	0.020	1.15
0.80	0.74	0.78	1.59	1.23	0.81	0.84	658	676	24876	30534	0.017	1.15
0.85	0.78	0.82	1.43	1.12	0.84	0.86	686	704	27172	32589	0.014	1.15

Table 3. Flight with one engine inoperative at

$\mu=0.90$ $\tau=0.00$ $\beta=0.00$ $\epsilon=0.00$ R/K=0.2500 M*=0.80 h*=35000ft

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	16434	22602	0.076	1.30
0.55	0.59	0.60	2.04	1.59	0.57	0.57	538	532	19007	24750	0.068	1.30
0.60	0.62	0.63	1.85	1.46	0.59	0.60	560	554	21312	26691	0.060	1.30
0.65	0.65	0.65	1.69	1.35	0.62	0.63	580	575	23394	28460	0.054	1.30
0.70	0.72	0.73	1.45	1.20	0.73	0.74	636	631	26839	31020	0.031	1.15
0.75	0.75	0.75	1.35	1.12	0.76	0.77	656	651	28556	32525	0.026	1.15
0.80	0.77	0.78	1.25	1.05	0.79	0.80	675	670	30140	33920	0.022	1.15
0.85	0.80	0.81	1.17	0.99	0.82	0.82	694	689	31608	35219	0.018	1.15

Table 4. Flight with one engine inoperative at

$\mu=0.90$ $\tau=0.00$ $\beta=0.50$ $\epsilon=0.00$ R/K=0.2500 M*=0.80 h*=35000ft

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	14329	19340	0.042	1.30
0.55	0.61	0.62	2.22	1.82	0.69	0.70	563	558	16944	21730	0.038	1.30
0.60	0.64	0.65	2.01	1.66	0.71	0.72	586	581	19286	23875	0.035	1.30
0.65	0.67	0.68	1.84	1.52	0.73	0.73	607	602	21403	25817	0.032	1.30
0.70	0.75	0.75	1.58	1.34	0.82	0.82	665	660	24903	28738	0.018	1.15
0.75	0.77	0.78	1.47	1.24	0.83	0.83	686	681	26649	30358	0.016	1.15
0.80	0.80	0.81	1.37	1.16	0.85	0.85	706	701	28259	31853	0.014	1.15
0.85	0.83	0.84	1.28	1.09	0.86	0.86	726	721	29751	33242	0.012	1.15

In all Tables, as it should be expected, when the remaining thrust increases both the speed and the height so do, and the additional fuel drops. 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 distinct increment in parasite drag. Also, it can be observed that the speed is kept fairly constant after the engine failure but, to match the evolving weight, flight height must increase from the mid point to the end of the route; only slightly for the three engines case and remarkably in twins.

Mach number influence in specific fuel consumption can be detected through the comparison of Table 1 versus Table 2, or Table 3 versus Table 4. The effect is to produce a somewhat better cruise point and, thence, a reduction in fuel. 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 μ values, a truly better cruise point is achieved, although the gain in fuel is smaller than the one provided by β variations. Among all figures appearing in the four Tables, the very low altitude corresponding to $f\approx0.5$, $\beta=0.5$ and $\mu=0.6$, namely 2752 ft, is truly noticeable; in fact this means almost to ditch the airplane.

The best behaviour, 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 specific fuel consumption only slightly dependent on the Mach number.

Final Comments

It seems now adequate to devote a few comments to the impact of the former results on the design requirements of airplanes for EROPS. Of course, the engine type is required to possess a very low shutdown rate /3/ and, 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 common transport aircraft. In parallel with this, the minimum equipment list is also, obviously, longer. Although it is not a pure design problem, in EROPS flights and mainly if something has gone wrong, a high degree of man-airplane synergy is essential; this includes an appropriate cockpit, trustworthy and easy to interpret information, special training, etc.

A clear implication of EROPS is the need of additional reserve fuel that can be estimated around at least 3 to 5% of take off weight, according to Tables 2 and 4; this figure does not include any extras due to non-optimal flight profiles that could be obliged /12/ neither the influence of winds /13/. Evidently, this important issues must be taken into account when studying a new EROPS route.

On the other hand, the speeds indicated at Tables 1 to 4 suggest that in best range conditions the airplane would last more than 3 hours to reach the final destination. First, it could fly a bit faster, but with higher fuel demands; or more reasonable, there will be a limitation of about 3500 to 4000 km *(equivalent to six hours on one engine)* between suitable airports, unless a new design requirement for one engine inoperative is imposed yielding, for example, to T/W at take off equal to 0.4, instead of usual values
around 0.3.

All former handicaps can be observed from the air transport productivity viewpoint, through the range-payload diagram. The needs of additional equipment along with more powerful engines can account for up to 2% of the maximum take off weight, producing a parallel decrease in payload if MTOW is maintained. Furthermore, common fuel reserves of about 4-5% of MTOW do not provide enough safety margin, according to Tables 1 to 4, and should be risen up to 8-9%. Figure 3 summarizes these effects on the general range-weight diagram /6/, of a typical modern widebody biturbofan, for the particular case in which both the maximum take off weight and the maximum zero-fuel weight are maintained at the original values. It is easy to see how the region of commercial interest has been reduced.

For a better understanding of the obliged modifications, the range-payload diagram is shown with more detail in Fig. 4. Apart from the general changes, an anomaly has appeared in the upper border. Since no special permission is needed to operate routes that are closer than one hour from a suitable airport, any distance that can be travelled in less than 120 minutes at the one-engine-out speed, could not be subject to any restriction; this represents about 1300-1500 km. Analogously, from around 4000 km (six hours at the one-engine-out speed) onwards, the above mentioned limitations apply. Between these two points, a linear fitting seems reasonable.

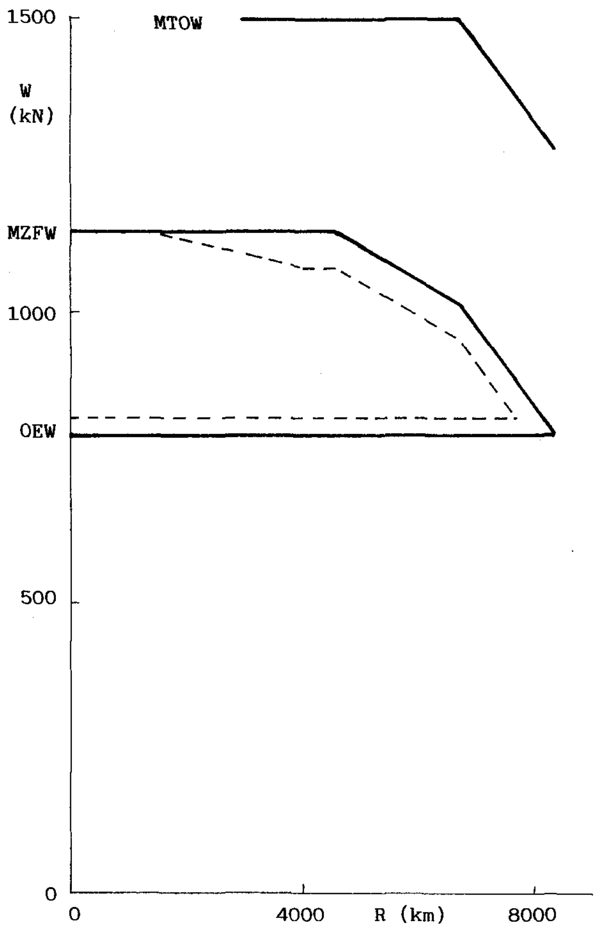

Fig. 3 Modifications (dashed lines) of the range-weight diagram due to EROPS.

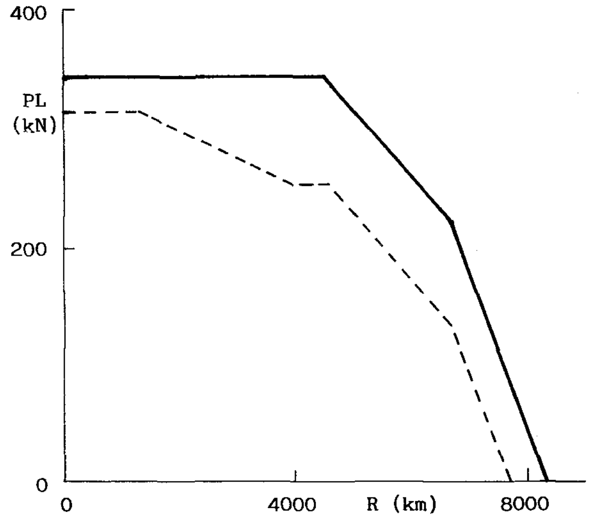

Fig. 4 Modifications (dashed lines) of the range-payload diagram due to EROPS.

The severe safety standards and large losses in productivity of EROPS twins are true disadvantages that aeronautical engineers must overcome; either by designing special airplanes, or by adapting new versions of already existing aircraft (for example, increasing MTOW). Although some important burdens will always remain, the ever growing commercial needs will push the technology and operation to new and challenging aims.

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