A Vision for Highly Fuel-Efficient Commercial Aviation

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Abstract

The civil aviation industry has been the *"Prima Donna"* of the transport world over three generations. Growth has been mostly upwards on an economic productivity basis - bigger, farther and faster (often at the expense of fuel usage). With increasing awareness of environmental issues, noise, emissions and energy / fossil fuel concerns, changes will happen to the industry, possibly in an accelerating fashion.

First focus is on Efficiency metrics of Civil Aviation. These lead to a "unified" consistent efficiency theme, relating Payload, Range, Fuel consumed and a measure of Unit Costs. The "value" (cost) and noise effective efficiencies decrease dramatically with increasing Range. A strategy for improving efficiency follows and leads to a vision for Fuel-efficient Commercial Aviation using smaller aircraft, and adopting Air-to-Air Refuelling and Close Formation Flying. For longer ranges, AAR and CFF, in concert, go most of the way toward satisfying ACARE objectives.

1. Introduction

For over three generations, the civil aviation has dominated the transport world. Since the advent of the jet engine and swept wing aircraft, the trends have naturally tended towards greater economic productivity – based on "bigger, farther and faster", **Figs.1-2** (Refs.1-2). The cruise speed of conventional civil aircraft is unlikely to increase beyond current levels and Productivity increases are achieved by increasing Payloads and range. This has led to larger aircraft with increased range capability but at the expense of increased fuel burn.

With increasing awareness of environmental issues (Refs.3-4), noise, emissions and energy / fossil fuel concerns, changes will happen to the industry, in an accelerating fashion. Demand may be for greater fuel efficiency in preference to productivity. The ACARE (& NASA) objectives are to reduce environmental impact due to Aviation by up to 50%. Increasing concern is about noise and emissions from aviation and managing the carbon balances.

The first focus is on Efficiency metrics of Civil Aviation. A series of aircraft operational parameters e.g. Payload, Range, have been analysed (**Fig.3**), Ref.5. Selected data and established trends for current and future aircraft allow a development of a "unified" consistent efficiency theme, relating Payload, Range, Fuel consumed and a measure of Unit Costs. We show that "value" (cost) and noise effective efficiencies decrease dramatically as range increases.

Further, the metrics indicate the directions in which technologies need to be developed to reduce fuel burn. To envisage *plateau jumps*, from an economic and environmental viewpoint, we need to consider more "radical" options e.g. adoption of alternative aircraft designs and operating procedures. These involve intermediate short-range hops (Ref.3-4) or the adoption of Air-to-Air Refuelling (AAR) of smaller aircraft to complete current high capacity long-range services (Ref.6). Another option is Close Formation Flying (CFF), Refs.7-8.

2. Efficiency Issues, Metrics & Derivations

Nangia (Ref.5) has presented results from data analysis on modern commercial (jet) aircraft, accounting for the distinction between maximum payload (Pt. A) and design payload range point (Pt.D), **Fig.4** as well as including fuel reserves, **Fig.5**. The results have been correlated into reliable "first-order" non-dimensional (non-D) forms.

Derivations of Basic Efficiency Metrics

In the well-known Breguet Range Equation (for cruise flight, Refs.11-13), the range R depends on the aircraft weights: at start of cruise (W1), at end of cruise (W2 = W1 – WFB, WFB is fuel burnt) and the Range parameter X. The X parameter relates the flight speed, aerodynamic efficiency and power-plant technology: V, lift-drag ratio (L/D) and Specific Fuel Consumption (SFC). It has unit of length. In turn, it leads to the non-D form for range, Z.

$$X = V\ L/D\ /\ SFC, \qquad R = X \log_e (W1/W2), \qquad Z = R/X = \log_e [W1/(W1-WFB)].$$

For a given V, the Range increases by 10% for a 10% increase in L/D or a 9% decrease in SFC.

A measure representing "useful work done" for unit fuel used is the Payload Range Efficiency (PRE).

PRE = Payload x Range / Fuel burnt, i.e. = WP x R / WFB (in nm or km units).
PRE = WP/WFB . X . $\log_e$[W1/(W1- WFB)] = (PRE/X) . X, where PRE/X = WP/WFB . $\log_e$[W1/(W1-WFB)].

The non-dimensional correlation parameter PRE/X is very useful. Although this may appear to be a function of aircraft weights, it involves WFB - a function of X. For a given technology standard, X improves slightly with range and size, but the Efficiency term PRE/X shows a marked variation with range.

Figs.6-7 (based on Ref.5) summarise the payload range and Efficiency trends. **T**he trends on a non-dimensional basis are encouragingly "smooth". Selected points are for R = 3000, 6000 and 9000nm at X = 15000 and 20000.

From **Figs.6-7**, using practical data at differing values of X, we have derived PRE and WFB/WP variations with range R with respect to a reference Range of 3000nm (PRE/X near 0.24 for X = 15000 & 20000). It is interesting to note the implications in terms of percentages. Note that higher % occur at lower values of X.

		6000nm	**9000nm**
PRE:	**% Decrease**	28-44	51-61
PRE:	**% Improvement Required to 3000 nm level**	39-78	105-159
WFB/WP	**% Increase c.f. 3000nm level**	28-44	51-61

An efficiency improvement of 159% would be required for a 9000 nm range aircraft (at X=15000) to achieve the same PRE/X level as a 3000 nm range aircraft.

The % changes (penalties) for using long-range aircraft are large. This is considered very significant. We can save considerable quantities of fuel by employing 3000 nm range aircraft with hops or with in-flight refuelling.

"Nangia Value Efficiency Parameters" – Cost, Noise & Emissions

The PRE/X graphs do not directly give information about aircraft structure and size (hence noise and cost). To include these we need to look at the Value-Efficiency trends using operating empty weight (OEW) and maximum take-off weight (MTOW). We define "Nangia Value Efficiency" Parameters VEO and VEM and the non-D correlation forms, VEOPX, VEMPX, by relating to Payload:

VEO = PRE/OEW (nm/lb of aircraft) and VEM = PRE/MTOW (nm/lb of aircraft).
VEOPX = (PRE/X) / (OEW/WP) = (PRE/X) x (WP/OEW).
VEMPX = (PRE/X) / (MTOW/WP) = (PRE/X) x (WP/MTOW).

VEOPX denotes the Payload Range and Fuel efficiency per structure weight per unit payload. It can be related to the purchase cost per unit payload. It also serves as a measure of approach and landing noise. Higher values are better for lower structure weight, costs (acquisition and operating) and landing noise. VEMPX denotes the Payload Range and fuel efficiency per total weight per unit payload. It serves as a measure of airport take-off noise, emissions and hence, other fees that may be incurred. Higher values are better for lower noise emissions and operating costs. **Fig.8** shows VEOPX and VEMPX correlations with Z using pt D values. Note that the short-range aircraft are strongly favoured.

Interpretation & Usage of "Nangia Value Efficiency Factors"

For dimensional information, we use value efficiencies VEM and VEO, **Fig.9**. These are functions of payload and range (assuming X = 16000). Smaller aircraft fare better. Such parameters are useful for comparative analyses with given (fixed) staged flight or in-flight-refuelling. For a given Payload, a 6000nm aircraft provides a value-efficiency of only about 25 -30% of that for a 3000nm design. An 8000nm design offers a figure of 20% compared to a 3000nm design. Further work can be done to instil finer detail in such figures, e.g. passenger / cargo proportions and so on.

An interpretation using VEM and VEO follows for flying 200 passengers over 6000 nm with two possible options:

	1 aircraft flying 6000 nm	1 smaller aircraft flying two 3000 nm stages	Ratio
VEM	0.0064	0.0175 or 0.0087 per stage	
Noise	~ 1/0.0064	~ 1/0.0175	2.73 / flight
Emissions	~ 1/0.0064	~ 1/0.0087	1.36
VEO	0.0124	0.0305 each or 0.0152 (2 aircraft)	
cost	~ 1/0.0124	~ 1/0.0152	1.23

Compared with a 2 stage 6000 nm aircraft system, the 6000 nm non-stop flight is 22% more costly, produces 1.36 times more emissions and 2.73 times the noise (assuming that propulsion and noise relate directly to MTOW) .

Next, we take a journey for 200 pax over 9000 nm: Two possible options (systems) are:

	1 aircraft flying 9000 nm	1 smaller aircraft flying three 3000 nm stages	Ratio
VEM	0.0026	0.0175 or 0.0058 per stage	
Noise	~ 1/0.0026	~ 1/0.0175	6.73 / flight
Emissions	~ 1/0.0026	~ 1/0.0058	2.23
VEO	0.0055	0.0305 each or 0.0102 (3 aircraft)	
cost	~ 1/0.0055	~ 1/0.0102	1.854

We infer that compared with 3 stage 9000 nm aircraft system, the 9000 nm non-stop flight could be 85% more costly, produce 2.23 times more emissions and 6.73 times the noise.

We need to continue with efficiency implications and how, in some cases, benefits can be taken, using current aircraft types. However, we do have a good idea of the costs / environmental benefits, with 2500-3000 nm ranges.

3. Hopping

An obvious solution proposed by the "Greener by Design" group (Ref.3-4) is to segment long-range air travel into a series of short hops, refuelling at intermediate airports. Although this appears fuel-efficient, using the 3000 nm range aircraft, it remains unattractive to airlines as it involves additional overall journey time (descent, taxiing, refuelling, take-off and ascent at each stop), extra fuel usage and more wear and tear due to take-offs and landings per journey. Airport congestion is not necessarily improved unless all-new "staging" airfields are built. The Air Traffic Control (ATC) operations at mid-stops would increase as would the costs associated with intermediate airport usage.

4. Exploiting Air to Air Refuelling (AAR) in the Civil Scene

With some lateral thinking, most of the concerns arising from introducing multiple hop flights to increase the efficiency of long-range services can be dealt with in one stroke, availing of a current proven technology. AAR (Ref.6) is a daily routine in military operations, **Fig.10**.

There are many possible AAR alternatives relating the sizing and positioning of the tanker and receiver aircraft e.g. Tanker above or below receiver, Tanker in front of or behind receiver, Tanker larger than, smaller than or same size as receiver, Centre-line to centre-line, centre-line to tip or tip to tip. Some of these locations are more favourable.

The major components of cruise drag, **Fig.11** are: friction (48%) and lift-induced (35%). This is further subject to interference effects in close aircraft formations. Using a simple horse-shoe vortex model on two unswept equal sized wings, Blake and Multhopp (Ref.16) show an interesting graph on lift-induced drag variation as a function of the relative (lateral) positions between a lead and a trail aircraft wing, **Fig.12**. Although subject to chordwise location effects, the "sweet spot" for a drag reduction of 50% occurs at about 20% semi-span overlap with the wings at the same altitude. The ability to fly accurately to maintain lateral position is crucial. Half of the drag benefit is lost if the lateral / vertical position cannot be maintained to better than 10% of wing semi-span. The changes in drag are accompanied by interference effects e.g. in pitch, roll and yaw.

In the symmetric refuelling formation (0% lateral spacing), a drag penalty appears depending strongly upon vertical separation (50% semi-span vertical spacing, penalty near 25%. For 25% semi-span vertical spacing, the penalty rises to near 50%). The 0% penalty line corresponds to about 40% semi-span overlap of wings (at 0% semi-span and more vertical spacing). We confirm that some refuelling locations will be more desirable.

The thrust produced by a jet engine reduces as altitude increases. With high by-pass engines, this can be more marked. With 0% lateral spacing, the drag penalty experienced by the trail aircraft requires a significant increase in thrust for the duration of the tanking operation. At certain altitudes, the required increase in thrust may not be available and the tanking procedure has to be carried out at lower altitude. This problem reduces as the 0% drag penalty curve is approached.

Operational Aspects

We look briefly at the practicalities of incorporating AAR equipment and operating procedures into civil operations. A number of issues for the adoption of AAR hardware into civil aircraft need to be considered:

- minimum amount of additional AAR equipment on receiver aircraft to avoid weight penalties
- minimal additional operations to be carried out by the receiver crew

- maximum separation between receiver and tanker during AAR desirable but will depend upon the length and rigidity of the refuelling apparatus
- minimise interference effects between the two aircraft. Certain locations are more advantageous
- tanker ideally positioned out of sight of passengers to avoid concern
- inadvertent contact between refuelling apparatus and tanker or receiver must not result in catastrophic failure
- economic and safety issues between carriage of either AAR back-up equipment (dual system) or additional fuel reserves in case of failure need to be balanced
- AAR to be carried out as near to cruise conditions as possible to minimise the impact of deceleration / descent and acceleration / climb on the overall efficiency of the flight
- Hose and Drogue type AAR equipment would need higher transfer rates and preferably reverse operation (i.e. pump forward)
- Boom type AAR equipment provides more design options: unfolding or extending from tanker upper or lower fuselage and "flown" into rear receptacle
- options for Receiver fuelling points: wing tips, fin tip, under fuselage, etc.
- combi-system with Boom from tanker mating with short drogue from receiver

Comparing 3000, 6000, 9000 & 12000 nm Range Aircraft with & without AAR

Based on work in Ref.6, the approach is to design representative aircraft to carry the same payload of 250 pax. over 6000, 9000 and 12000 nm and estimate the fuel saved by using the base 3000 nm range aircraft with AAR over these longer ranges. The base aircraft requires less than 50,000 lbs of fuel per 3000 nm leg and that is dispensed fairly easily from a tanker. Each tanker may accomplish 3-4 operations in a mission and then land at a suitable airfield.

AAR works with any size of aircraft (payload). If the aim is to move the same number of people from A to B then perhaps it can be argued that a tanker refuelling one 500-seater rather than two 250-seaters may well be more efficient! However, the flexibility and noise reduction arguments would be in favour of the 250-seaters. All this points towards further interesting avenues for investigation.

The prediction methods and models are based on correlated data from current in-service aircraft, likely aerodynamic improvements (L/D up to 20) and currently published costs (fuel, labour, airport fees, etc.), Refs.1, 2, 7, 11 - 14. For consistency, we have used Ref.7 (1995) data as this appeared to be a complete set available for all parameters. The Breguet range equation (Refs.7 & 14) has been used to relate the main parameters. The aerodynamic parameters are: L/D = 20, V = 490 kt (cruise M = 0.85 at 36,000 ft). For the 3000nm and 6000 nm aircraft we have used SFC of 0.65 lb/hr/lb. The range parameter X = V L/D / SFC is then 15,077 nm.

For the 9000 nm aircraft we used a "more efficient" SFC = 0.57 lb/hr/lb. The Range Parameter X is then 16,897 nm.

The base aircraft weight variation over 3000 nm is shown in **Fig.13**. The block fuel used to carry 250 passengers over this range is 46,147 lb (MTOW = 261,932 lb). An aircraft designed to carry the same payload over 6000 nm, **Fig.14**, uses 161,269 lb fuel (doubling the range has more than trebled the fuel required, MTOW = 505,438 lb). The increased fuel, over and above that required for the doubled range, is needed for the additional aircraft weight. This arises mainly from landing gear and wing structure required to carry the additional fuel weight and provide the extra tank volume. **Fig.14** also compares the weight variations with range for the 6000 nm aircraft and the 3000 nm aircraft refuelled at 3000 nm. Fuel used and the savings offered by AAR (41% over 6000 nm) are also shown.

Fig.15 refers to the comparisons for 9000 nm range (250 passengers). An aircraft without a refuelling option would have MTOW of 656,262 lb, and consume 263,073 lb of fuel. With two AAR operations, using the 3000 nm aircraft, the block fuel would be 138,441 lb, a saving of 47%.

The relative sizes of aircraft designed for 250 passengers over 3000, 6000, 9000 and 12000 nm are shown in **Fig.16**. The fuselage size remains almost constant but the wing area increases rapidly to accommodate the fuel requirements and maintain design C_L.

Tankers for AAR

A key point is that Tankers for civil work would operate differently from those employed by the Military. The latter essentially operate a "garage in the sky", with long endurance. Civil tankers will be more "purposeful" with short and more efficient flights envisaged, **Fig.17**.

Fig.18 shows the fuel saving (%) achieved by using a 3000 nm design aircraft, with AAR, over aircraft specifically designed for the 6000, 9000 and 12000 nm ranges, all carrying the same payload. It is interesting to note that we begin to make fuel savings with RT (ratio of fuel given to that used by the tanker) slightly less than 1 and beyond. For RT values about 3, we are close to being within 5 - 7% of the maximum benefit obtainable. We need to explore ranges between 3000 and 6000 nm. This opens up further discussion and work regarding stage length variation.

All this implies that reasonably efficient tanking, giving RT near 4, should be adequate. Although it helps to have more efficient tanking, we do not need to make extensive advances in tanker design. Tankers currently available will allow significant fuel savings to be made on refuelled aircraft over longer ranges.

It is interesting to note from **Fig.19**, the increase in PRE/X achieved by the refuelled 3000 nm design aircraft over the PRE/X achieved by the aircraft designed for that range. This is expressed as a percentage of the PRE/X achieved by the aircraft designed for that range. The improvements are large and higher for the longer range situations. For a "reasonable" RT value of 4, we are touching gains in PRE/X of 60% for 6000nm and 80% for 9000nm ranges, compared with the datum 3000 nm aircraft.

Associated Benefits

Operational issues will need to be solved, no doubt. The AAR operation has been well implemented by the military and a stage of autonomous refuelling is being reached with current research in control systems and differential GPS. The adoption of AAR leads to several other possible benefits using smaller aircraft:

- Smaller propulsion requirement
- Reduced noise at Take-Off and Approach / Landing
- More efficient use of Regional airports by smaller aircraft
- Less congestion (air and land) at Hub airports
- Smaller aircraft = reduced wake problems = increased aircraft flow rate
- Current increasing demands on ATC can be "diluted" away from Hubs to Regionals.
- Enabling Technology: Some technologies, marginal currently e.g. Laminar flow aircraft may be enabled.

5. Close Formation Flying (CFF)

The possibility of using CFF to reduce fuel usage or to extend range is well known. It has become important to assess its implementation in view of environmental aspects. Aircraft formations typified by **Fig.20** occur for several reasons e.g. during displays or in air-to-air refuelling but they are not maintained for any great length of time from the fuel efficiency perspective. Recently NASA has conducted tests on two F/A-18 aircraft formations (Refs.1-4 & **Fig.21**). It was shown that benefits occur at certain geometry relationships in the formation e.g. the trail aircraft overlaps the wake of the lead aircraft by 10-15% semi-span. Some of the NASA work was partly inspired by the sizeable German work programme including flight-tests (Hummel et al, See Nangia paper, Ref.7).

For civil aircraft, Jenkinson, in 1995 (Ref.14), proposed a CFF of several large aircraft as being more efficient, in comparison with flying a *very* large aircraft. He indicated that aircraft could take off from different airports and then fly in formation over large distances before peeling away for landing at the required destinations.

For Cargo aircraft formations (2-5 aircraft), Brachet et al (Ref.15) present an architecture and an evaluation including financial considerations. With fuel costs based on $1/US gallon, they show substantial benefits for long-range aircraft. For medium-range aircraft the benefits are "uncertain" and not much for short-range aircraft. With upward trends in fuel costs, medium-range aircraft may now benefit more.

For CFF, several results are available using idealized approaches e.g. vortex lattice formulations (Ref.16). This also contains a sizeable bibliography. Refs.17-20 refer to NASA and USAF work.

Aircraft formations can comprise large and small aircraft, **Fig.22**. Each aircraft will experience off-design forces and moments. It will be pre-requisite that these are adequately modelled and efficiently controlled. Simply using aileron may trim out induced roll but at the expense of drag. This may compromise any advantages arising due to CFF.

In the modern context, efficient control implies morphing, exploiting variable camber, winglets, span extension or other ideas. We have developed an "inverse" design method (Refs.21-22) applicable to wings with or without winglets. This approach starting with a wake shape and spanwise loading constraints, produces wing camber and twist shapes. Any solver, e.g. panel, Euler or Navier-Stoke types, can be implemented. The technique has been adapted to CFF and we can predict the geometry changes required, not only for safe CFF, but also for minimising drag. Overall the fidelity levels of modelling are raised.

We look, now, at a few selected cases of CFF from Refs.7-8. In each case, the Trail wing is re-designed to cancel out the induced effects due to formation flight in spanwise and chordwise loadings (induced rolling and pitching moments are trimmed out).

Two Equal Sized Aircraft.

We refer to the aircraft as Lead and Trail. We consider the CFF configuration in which streamwise displacement is 1.45b (1.45 x span), spanwise over lap (dy/b) is 10% and vertical displacement (dz/b) is 0%, Case 3. **Fig.23** shows results for the Trail wing in the presence of a Lead wing relaxed wake. Spanwise loadings (Lift and Rolling and

Pitching Moments) are shown in **(a).** The redesigned cambered and twisted surfaces are compared with the original isolated datum wing in **(b)**. Cp distributions are in **(c-d)** at the start and after five redesign iterations. Increased loading on the left wing is evident in both spanwise and chordwise distributions before re-designing.

Fig.24 shows typical trail wing twist changes for several cases. This figure also highlights the effects and importance of relaxing the Lead wing trailing wake, Case 3. In the presence of a rigid Lead wing wake, the Trail wing requires $+/-3.5^o$ additional twist. With Lead wing wake relaxed, these values fall to less than $+/-1^o$. The possibility of using variable camber, in preference to conventional ailerons, to achieve these geometry changes exists. Induced Yawing moment could be controlled by asymmetric throttle settings.

Three Equal Sized Aircraft in V-Formation

A second Trail wing is included, on the LHS, in the mirrored location of the Trail wing described above, to form a three wing CFF, symmetric V - formation. **Figs.25 & 26** show Euler method (Ref.23) results before and after camber control, respectively. In **Fig.25**, the Mach and Cp contours clearly show the differential loading on the Trail wing. In **Fig.26** the loading is evidently more symmetrical. These results compare favourably with those in **Fig.23** in which the Trail wing (echelon formation) was assessed and re-designed in the presence of a Lead wing relaxed wake.

Unequal Sized Aircraft, Lead :Trail = 2.5 :1.0.

The relative sizes can be seen in **Fig.27**. For dx/b=1.45, dy/b=5%, dz/b=-5%, **Figs.27 & 28** show Euler results before and after camber control, respectively. The Mach and Cp contours, in **Fig.27**, show the more significant spanwise extent of the differential loading on the Trail wing. In **Fig.28**, after re-designing, the loading is evidently more symmetrical. **Fig.29** shows the spanwise loadings at the start and after five redesign iterations, on the Trail wing in the presence of relaxed Lead wing wake. The Trail wing is re-designed to cancel out the induced effects in formation flight. The resulting Trail wing twist changes for these cases are shown in **Fig.30**. Re-designing in the presence of a relaxed Lead aircraft wake has resulted in a slightly smoother twist variation across the Trail wing. This gives an indication of the changes needed on the trail aircraft geometry to cancel the induced effects due to formation flight.

First-Order Relative Size Ratio Effects

We have considered: Lead : Trail linear ratios of 0.8:1.0, 1.0:1.0 and 2.5:1.0.

For dz/b = -5% (vertical position), the variation of ΔC_{VM} (vector addition of ΔC_L% and ΔC_{Di}%, solid line) is plotted against location across the Lead aircraft span in **Fig.31** for three Lead wing size ratios. The benefits of formation flying, in terms of Trail wing ΔC_{VM}, increases as the Lead aircraft dimensions increase. From the limited amount of results available, it is inferred that a wing overlap of between 5% and 10% of the Lead aircraft span is desired.

It is emphasized that this is very much a first order assessment and further analysis will be required for complete aircraft configurations. Suitable candidates for Trail wing redesign with reference to Lead wing sizing and y-z plane location are selected. After re-designing, to determine Trail wing geometry changes required for corrected flight, ΔC_L levels are less than 1%. The resulting ΔC_{Di} % are plotted as dashed lines in **Fig.31**. These represent the pure ΔC_{Di} % benefits achieved on a trimmed Trail wing in formation (C_L now equal to datum, isolated wing with zero rolling moment). As anticipated, Trail wing benefits increase with increasing Lead wing size.

A number of flight formations with aircraft of varying size have been studied. Predictions show 30% or more benefits in lift-induced drag on the trail aircraft, along lines of **Fig.12**. In turn this should lead to 10-15% improvement in range. There are obviously many operational considerations concerning control, positioning, scheduling etc that need to be brought into focus. The size of likely benefits should provide the impetus. Multi-aircraft formations will multiply the benefits and such aspects are worthy of further detailed consideredation.

6. Short Range Aircraft – Assessing First Order Improvements in OEW or X

Many possible technologies e.g. Composites, Prop-fans, High By-pass engines, Laminar Flow designs are being considered for application to shoter range aircraft. It is interesting to assess the impact of such as exchange rates in a generic manner. Essentially the possible impact falls in terms of either improving SFC or reducing OEW or both.

We take the example of A321-100, **Fig.32(a-e)**. **(a)** shows the weight variation with range R for the reference aircraft. **(b)** refers to two extreme cases, (1) the weight variation either with OEW reduction by 10% and holding range constant, (2) with additional X improvement of 20%, keeping MTOW constant (Note the range improvement). **Fig.32(c-d)** show the PRE relationships for case (1), range constant or case (2) holding MTOW constant **Fig.32(e)** based on **(c)** and **(d)** allows the incremental changes in PRE to be assessed. For example, a 5% reduction in OEW coupled with 10% increase in X (no mean tasks in reality !) will lead to 5% reduction in TOW or 30% increase in Range. It is realized that these are first order effects and there may be well be further “snowballing” (or penalties !).

7. Concluding Remarks

The civil aviation industry has been the "*prima donna*" of the transport world for over three generations. Since the advent of the jet engine and swept wing aircraft, the trends have naturally tended towards greater economic productivity – based on "bigger, farther and faster". We have seen significant efficiency improvements over the first two decades (materials, wing sweep, high by-pass ratio engines, etc.). The trends have levelled off in recent years. Efficiency improvements now, are of the order of a few percent and require high technology levels and great expense (carbon-fibre, laminar flow, winglets, etc.). We have assessed the exchange rates due to advancing technologies with an example of short range aircraft. In the near future, environmental issues will force aviation to cut emissions, either by further technological advances or through reduced operations.

Work towards improving air transport efficiency has led to a set of "robust" efficiency metrics including "Nangia Value Efficiency" parameters. These confirm that smaller aircraft designed to operate over ranges close to 3000nm are most efficient. This leads to the proposal for adoption of AAR for civil aviation for the longer ranges, saving 30-50% fuel depending on the range. Benefits also occur for smaller ranges in terms of taking off with increased payload, but lighter and refuelling soon after take-off. A series of associated benefits may have a major impact on future civil aviation. Some technologies, that are currently impractical e.g. Laminar flow aircraft, may be enabled.

We have examined the effect of size ratio of aircraft in CFF. The benefits vary with size and type of aircraft. The trail aircraft can experience reductions in lift-induced drag of up to 30%. The ideas extend to multi-aircraft formations.

We need to take a new, objective and unbiased viewpoint. The studies and conclusions discussed show possible lines to follow. It is clear that these ideas cut across conventional thinking and the objectives of many different sectors in civil aviation. Such global ideas are not likely to be taken up by just one sector. Integration is the key. Therefore the ideas need a much wider acceptance by a whole host of organisations. This is where the knowledge transfer aspect comes in, to ensure an informed decision process. In parallel, there is need for continued development of analyses.

With CFF and AAR, no amount of predictive work is capable of giving a complete insight into possible implementation. We need to commence with flight simulations in the imminent future to highlight any problem areas. Further research into fuel transfer aspects is required. Similarly the advantages of specific tanker / receiver formation relationships need to be assessed and balanced against possible operational and technical difficulties. For longer ranges, AAR and CFF in concert, go most of the way toward satisying ACARE objectives.

Several avenues for future work have arisen. We need to include, in the analysis, all sorts of aircraft in service now and what may be on offer in the future. The typical airline / aircraft cycle is of the order of 30-40 years. The design cycle of aircraft is 10-15 years. New concepts are effectively under consideration now e.g. prop-fans, that will come into service before 2020. Far into the future lie, possibly, BWB, Oblique Flying Wing (OFW) etc. The question of how these new designs line up on the efficiency metrics basis becomes important. Are the metrics adequate? All this provides the motivation for continued work programme.

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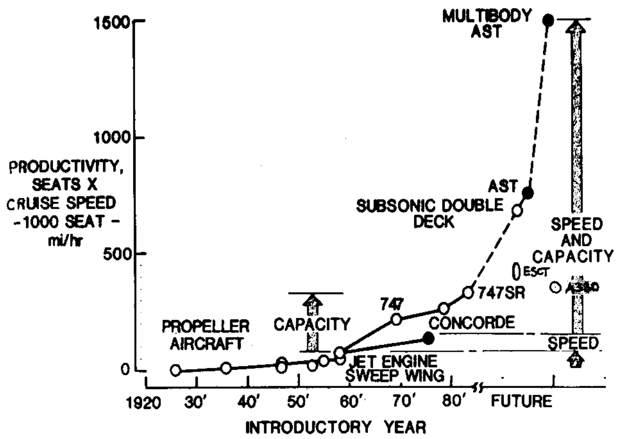


Fig. 1 IMPROVEMENTS IN PRODUCTIVITY OF LONG-RANGE TRANSORT AIRCRAFT (Dollyhigh et al, Ref.1)

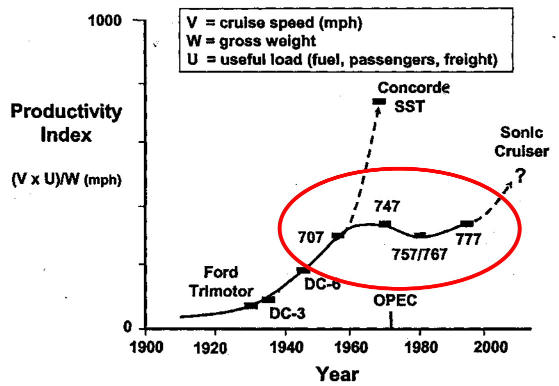
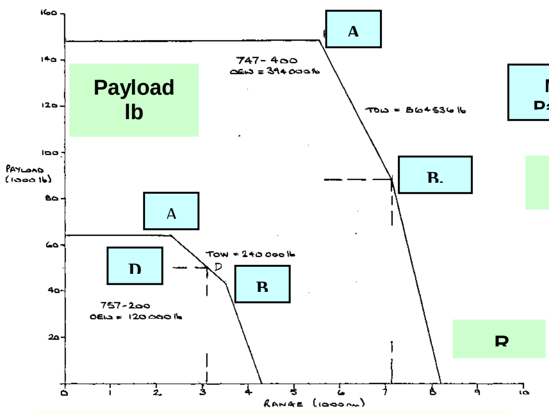
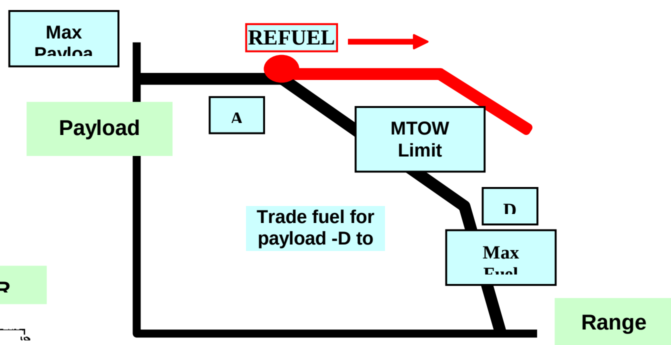


Fig. 2 EVOLUTION IN THE PRODUCTIVITY OF COMMERCIAL AIRCRAFT (McMasters, Ref.2)



B757-200 & B747-400
Note: Data not fully consistent in all



Explaining Various Limits in the Payload-Range Diagram

Fig.3 TYPICAL PAYLOAD RANGE DIAGRAMS & LIMITS

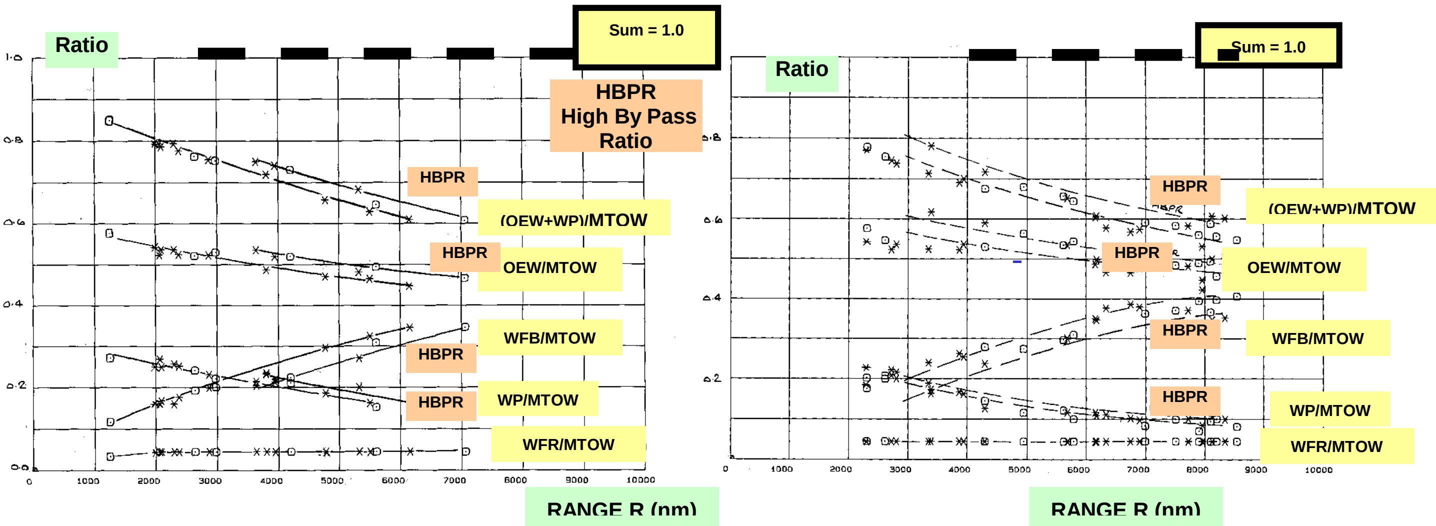
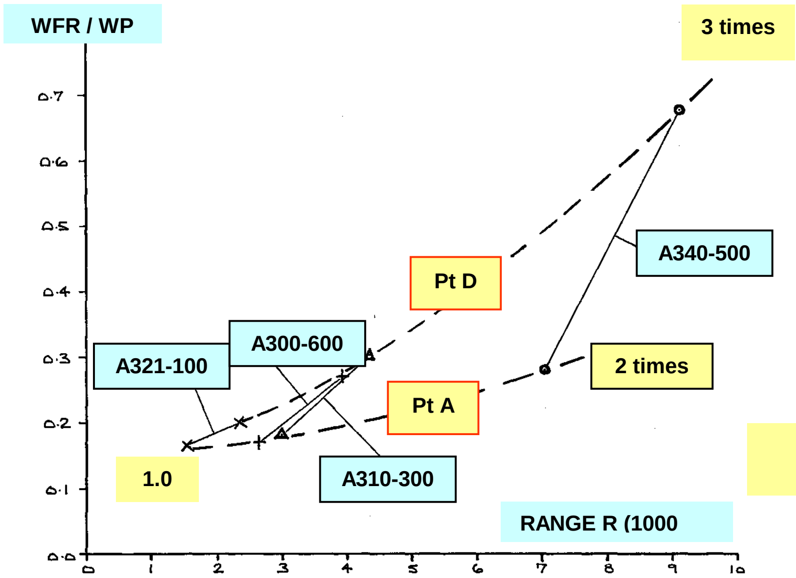
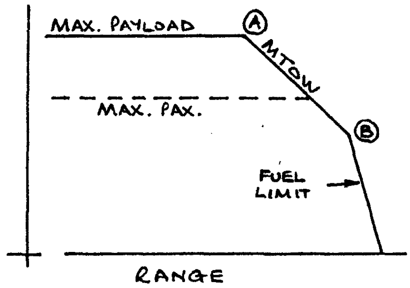


Fig. 4 Pt A, & Pt D, COMMERCIAL AIRCRAFT, DERIVED OEW, FUEL & PAYLOAD RATIO TRENDS

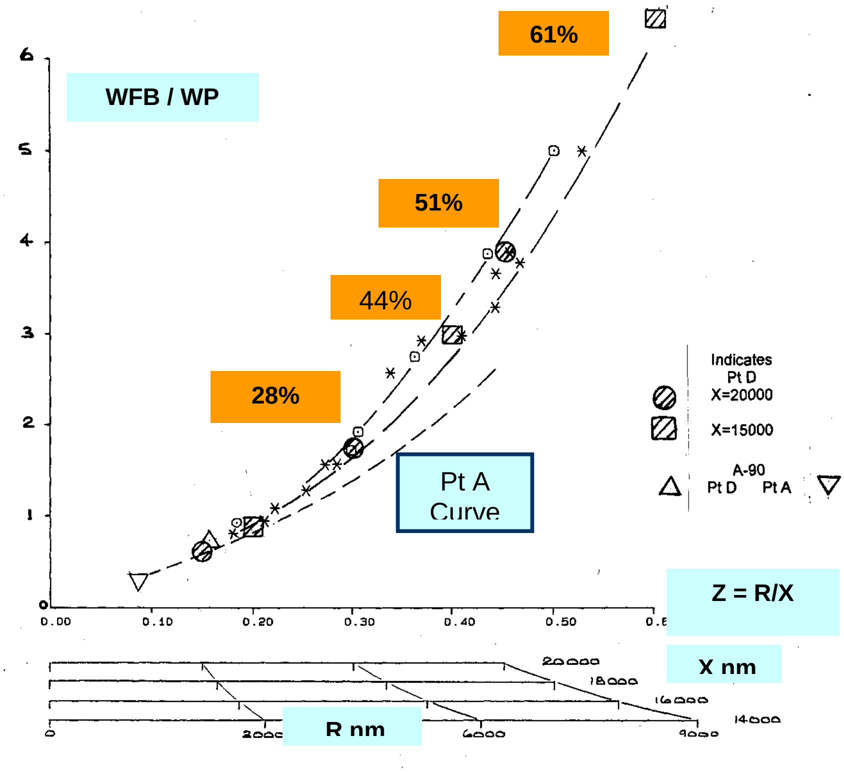




Typical Payload-Range Diagram

Fig. 5 RESERVE FUEL at Pt A, & Pt D, COMMERCIAL AIRCRAFT

Fig. 6 COMMERCIAL AIRCRAFT, WFB / WP & Z = R/X RELATIONSHIPS, Pt A & Pt D
Note: Parallel Scales of R Implied for Different X Values



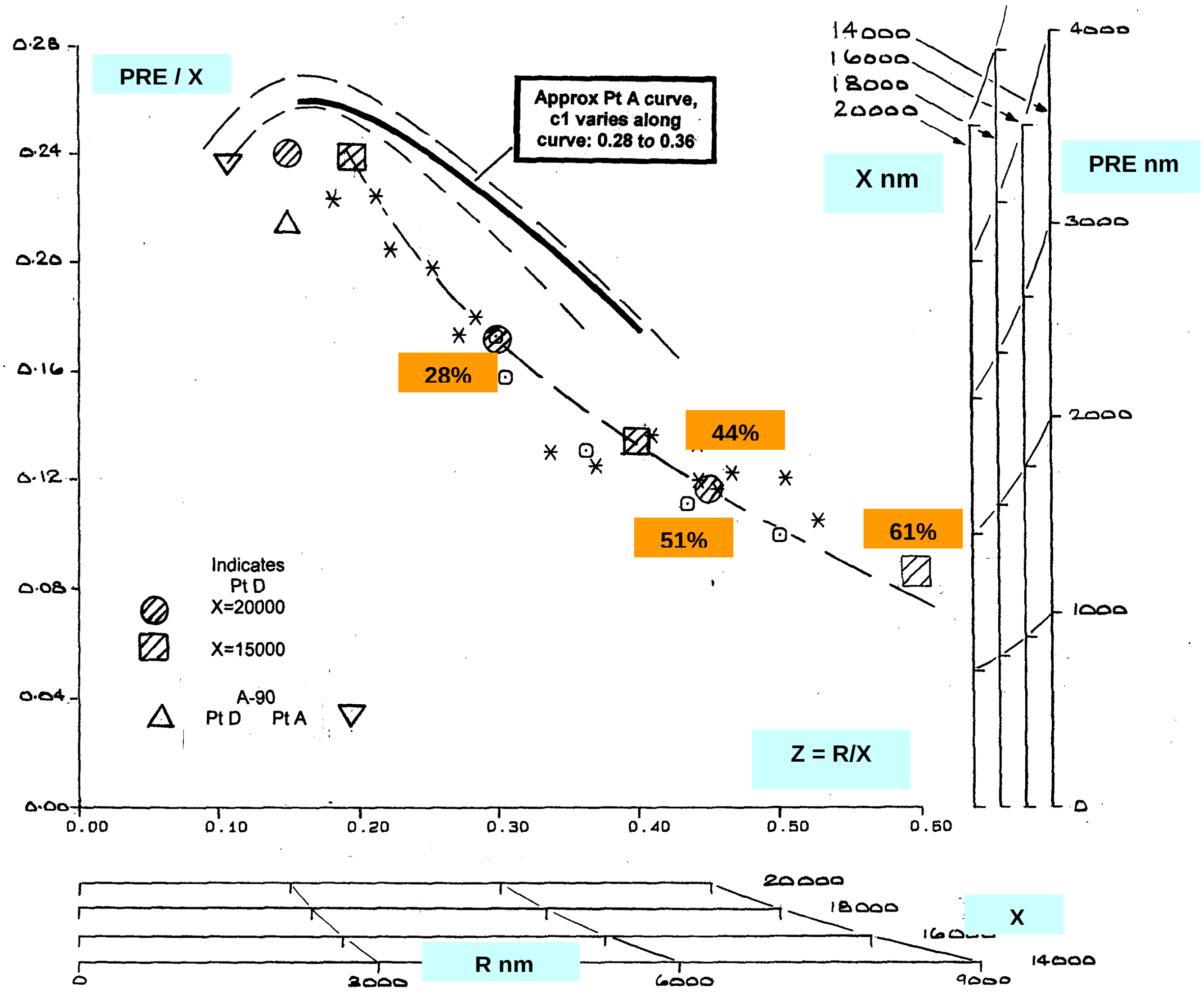


Fig. 7 COMMERCIAL AIRCRAFT, PRE/X & Z = R/X RELATIONSHIPS, Pt A & Pt D
Note: Parallel Scales of PRE Implied for Different X Values

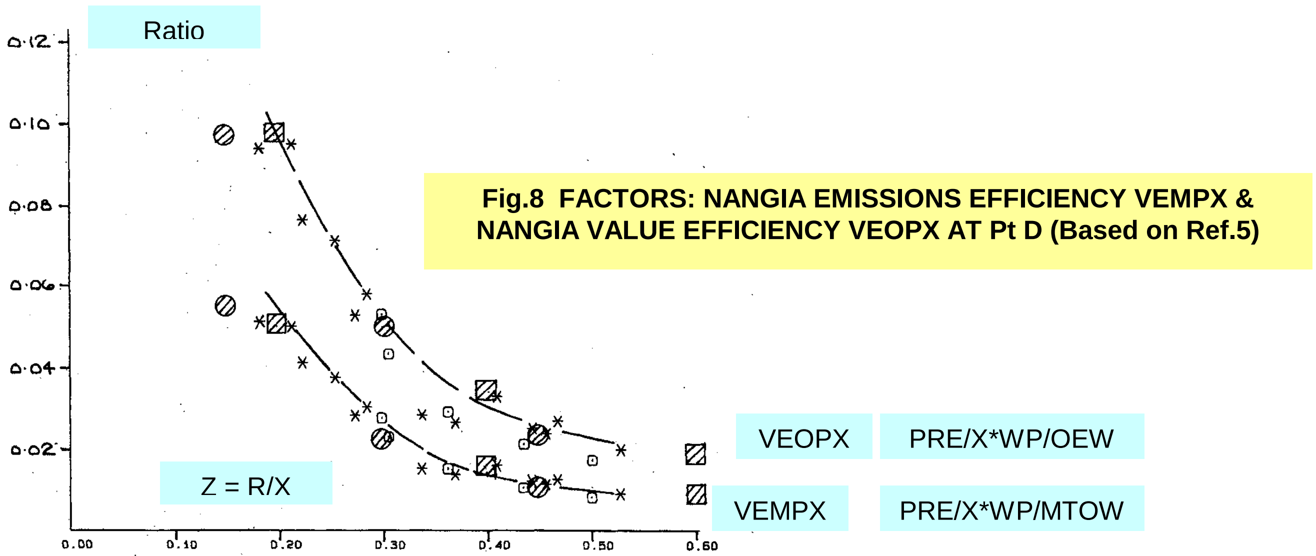


Fig.8 FACTORS: NANGIA EMISSIONS EFFICIENCY VEMPX & NANGIA VALUE EFFICIENCY VEOPX AT Pt D (Based on Ref.5)

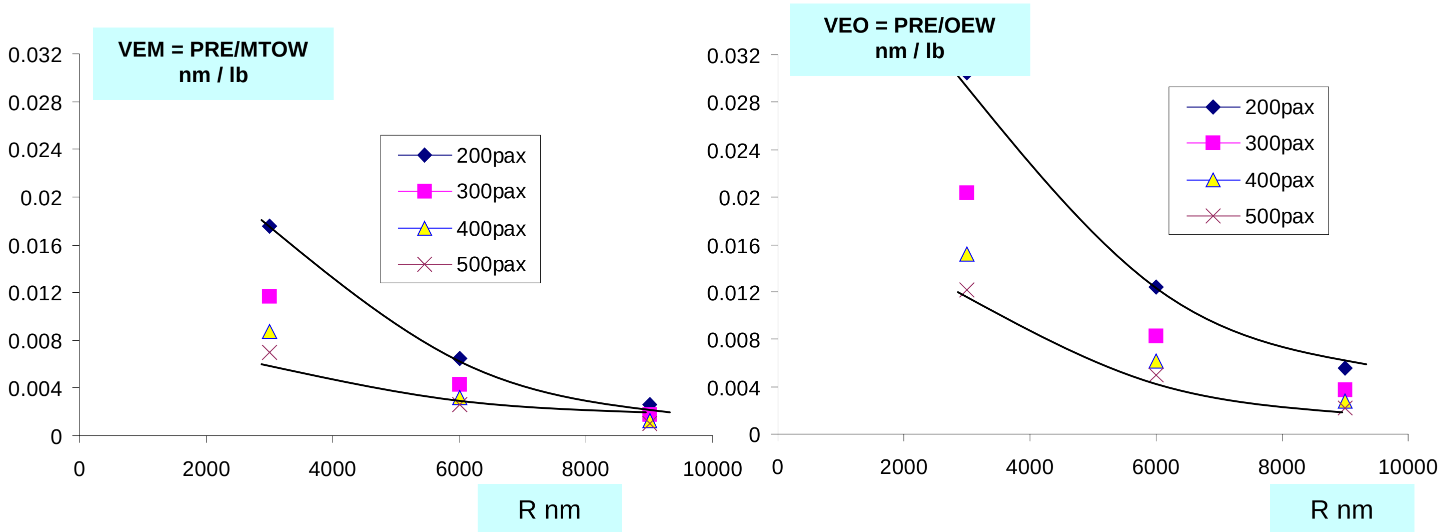
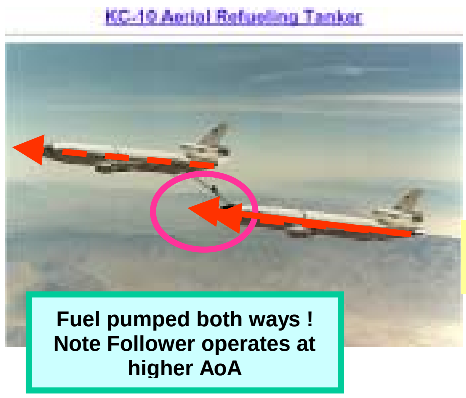
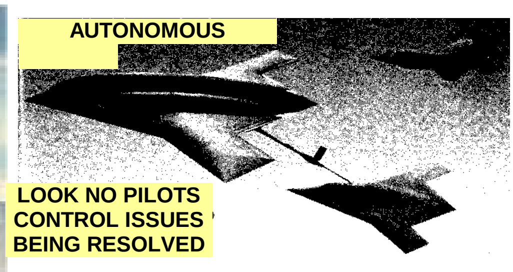


Fig. 9 DERIVED VALUE EFFICIENCY VEM & VEO FOR 200 – 500 seat AIRCRAFT, ASSUMING X = 16000

Biplane Formations





Night Vision & RARO

Fig. 10 Typical AAR Operations

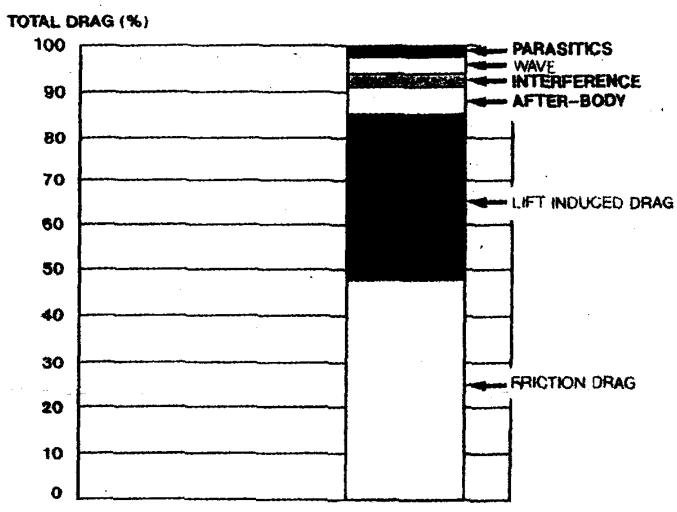


Fig. 11 Drag Breakdown of a Typical Transport Aircraft

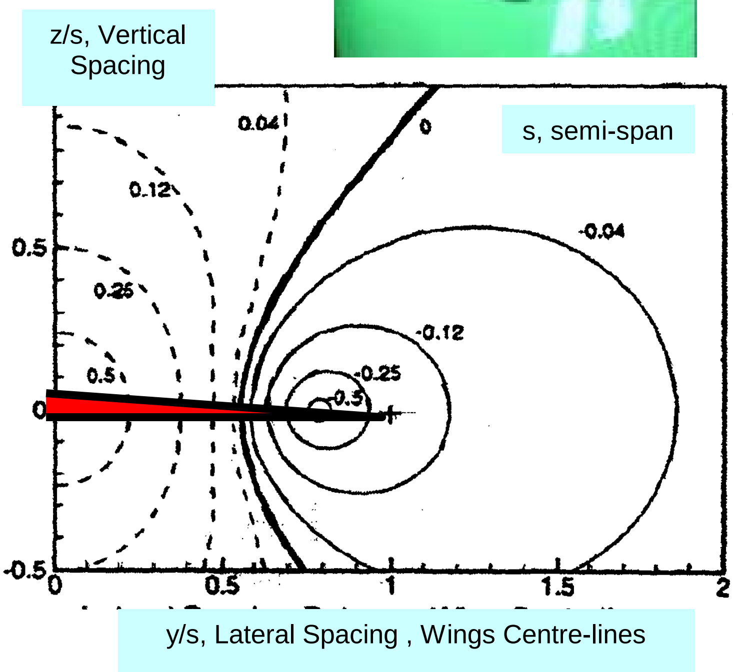


Fig. 12 Induced Drag as Function of Relative Position, 2 Equal Sized Unswept Wings

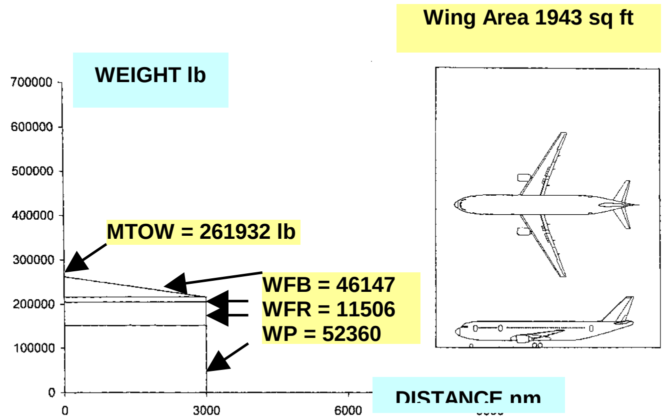


Fig. 13 AIRCRAFT WEIGHT VARIATION WITH DISTANCE FOR 3000 nm RANGE NO REFUELLING, 250 PAX., OEWR = 0.58, X = 15077 nm

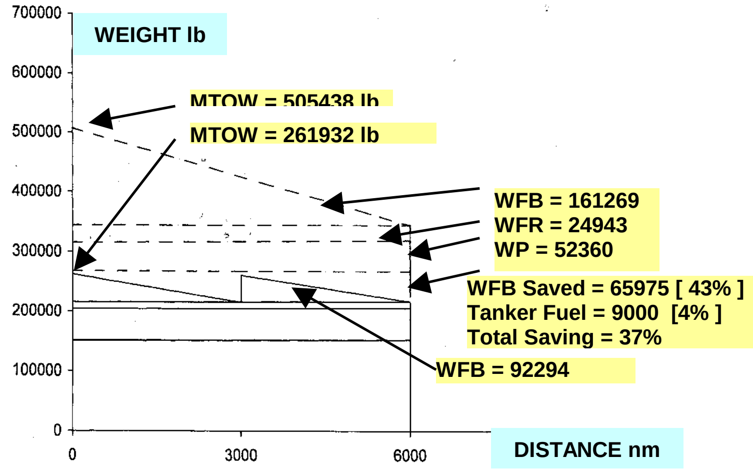


Fig. 14 AIRCRAFT WEIGHT VARIATION WITH DISTANCE FOR 6000 nm RANGE AIRCRAFT, REFUELLED ONCE cf AIRCRAFT WITHOUT REFUELLING, OEWR = 0.528, 250 PAX. 3750 ft^2, X =

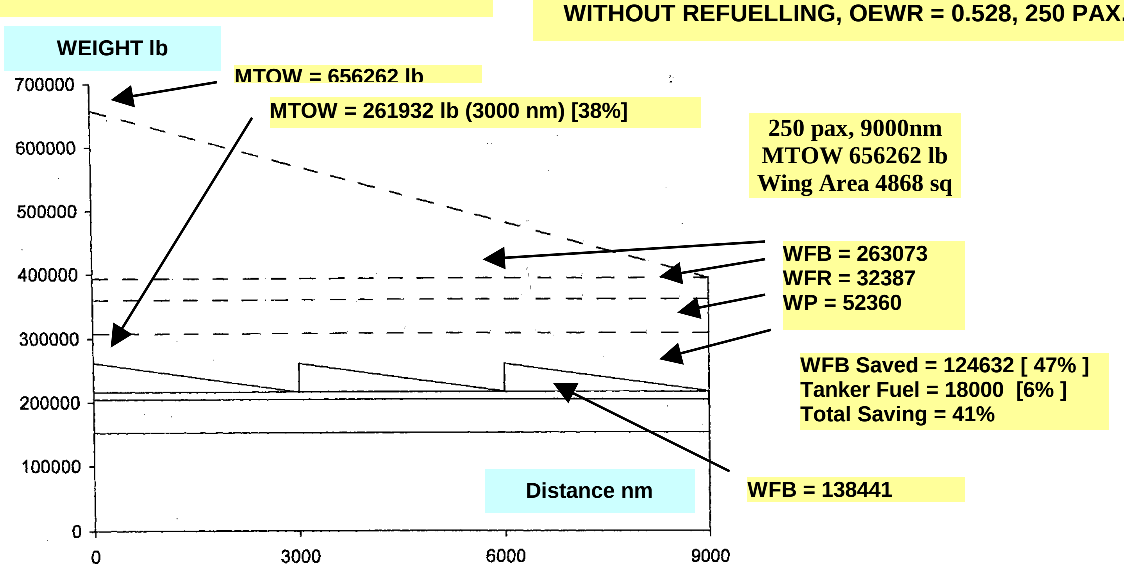


Fig. 15 AIRCRAFT WEIGHT VARIATION WITH DISTANCE FOR 9000 nm RANGE AIRCRAFT (X = 15077nm) REFUELLED TWICE cf AIRCRAFT WITHOUT REFUELLING, OEWR = 0.47, 250 PAX., S = 4968 ft^2, X = 16897

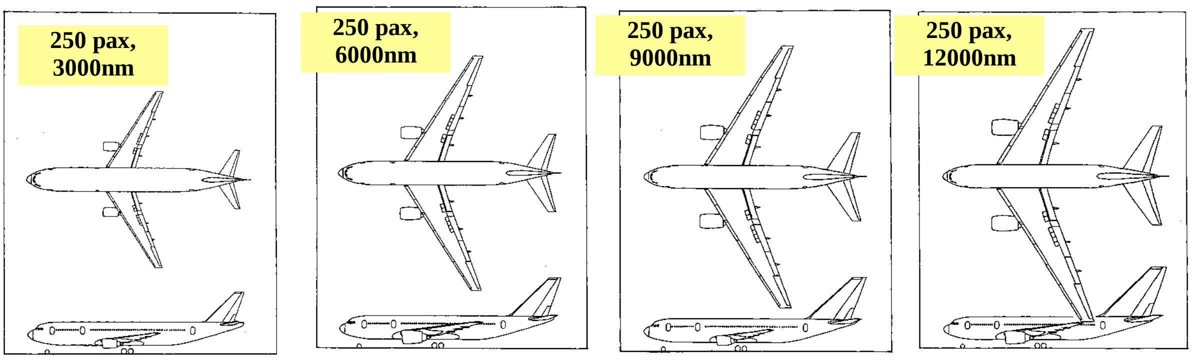


Fig. 16 COMPARING AIRCRAFT DESIGNED FOR DIFFERENT RANGES, 250 Pax.

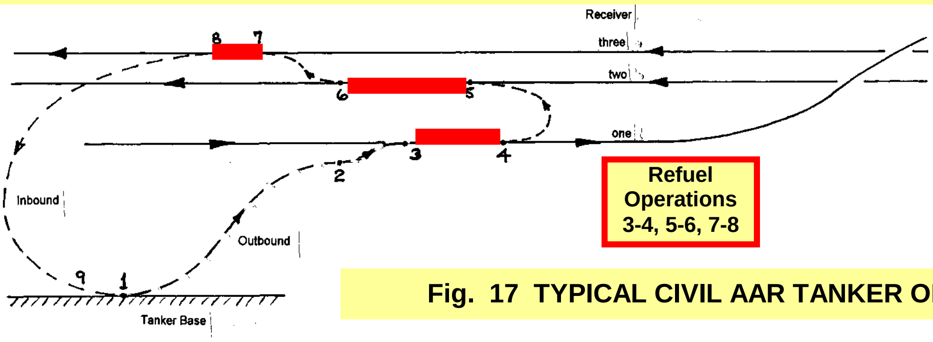


Fig. 17 TYPICAL CIVIL AAR TANKER OPERATING

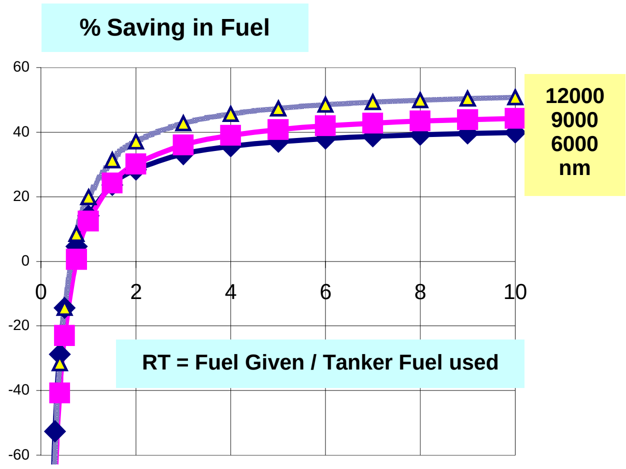


FIG. 18 SAVING IN TOTAL FUEL CONSUMED

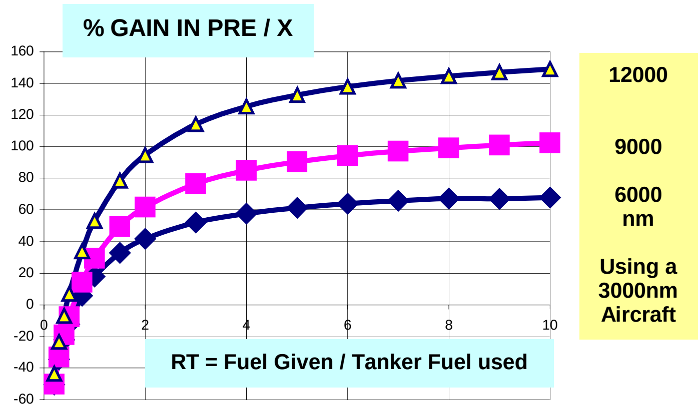


FIG. 19 % IMPROVEMENT IN PRE / X USING a 3000 nm AIRCRAFT WITH AAR, VARIATION WITH TANKER FUEL OFF-LOAD

Fig. 20 DISPLAY FORMATION

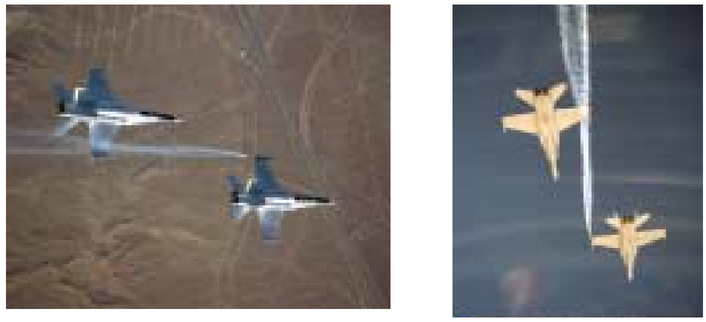
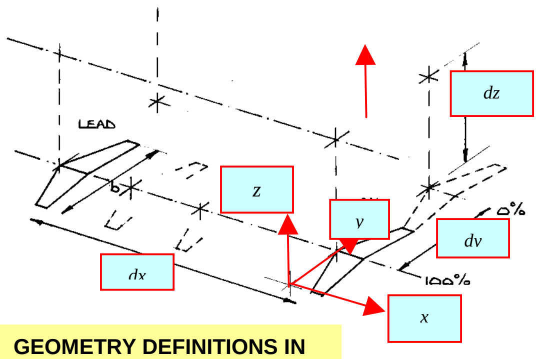


Fig. 21 F/A-18 FORMATIONS, NASA



GEOMETRY DEFINITIONS IN FORMATION FLYING

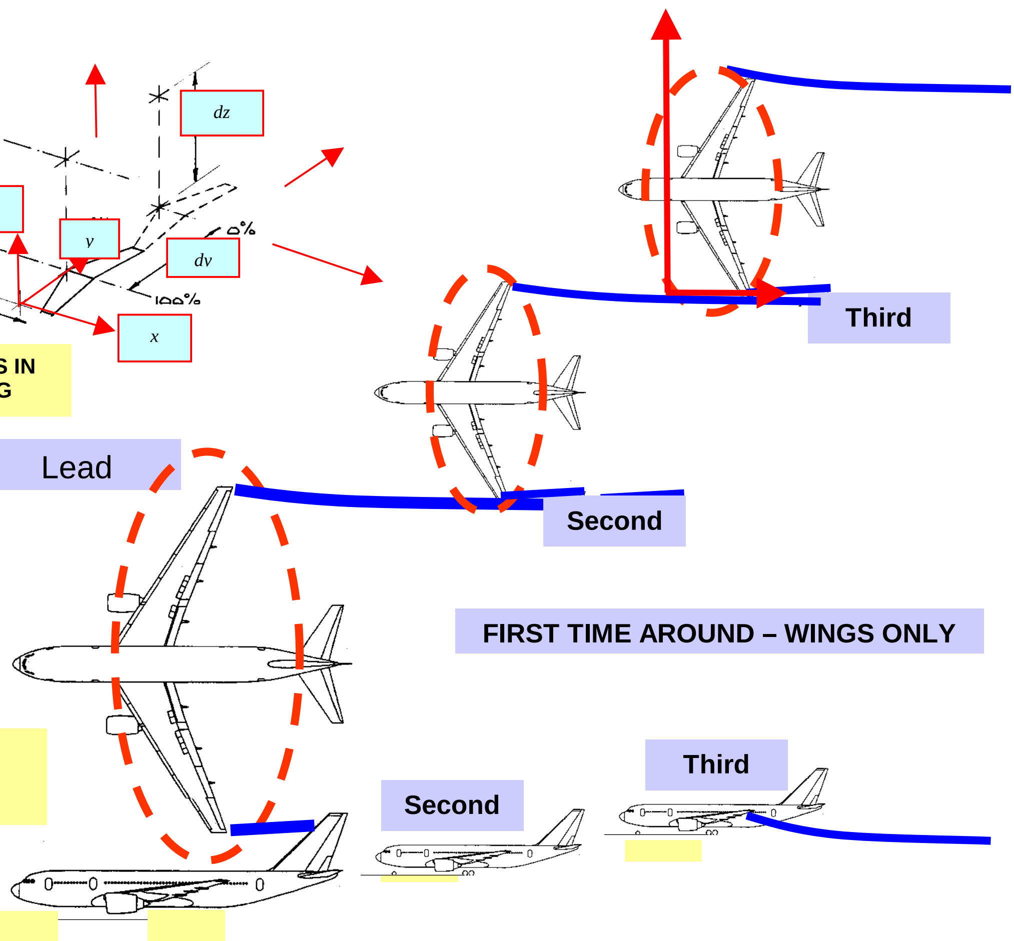


Fig. 22 FORMATION, 3 UNEQUAL SIZE AIRCRAFT

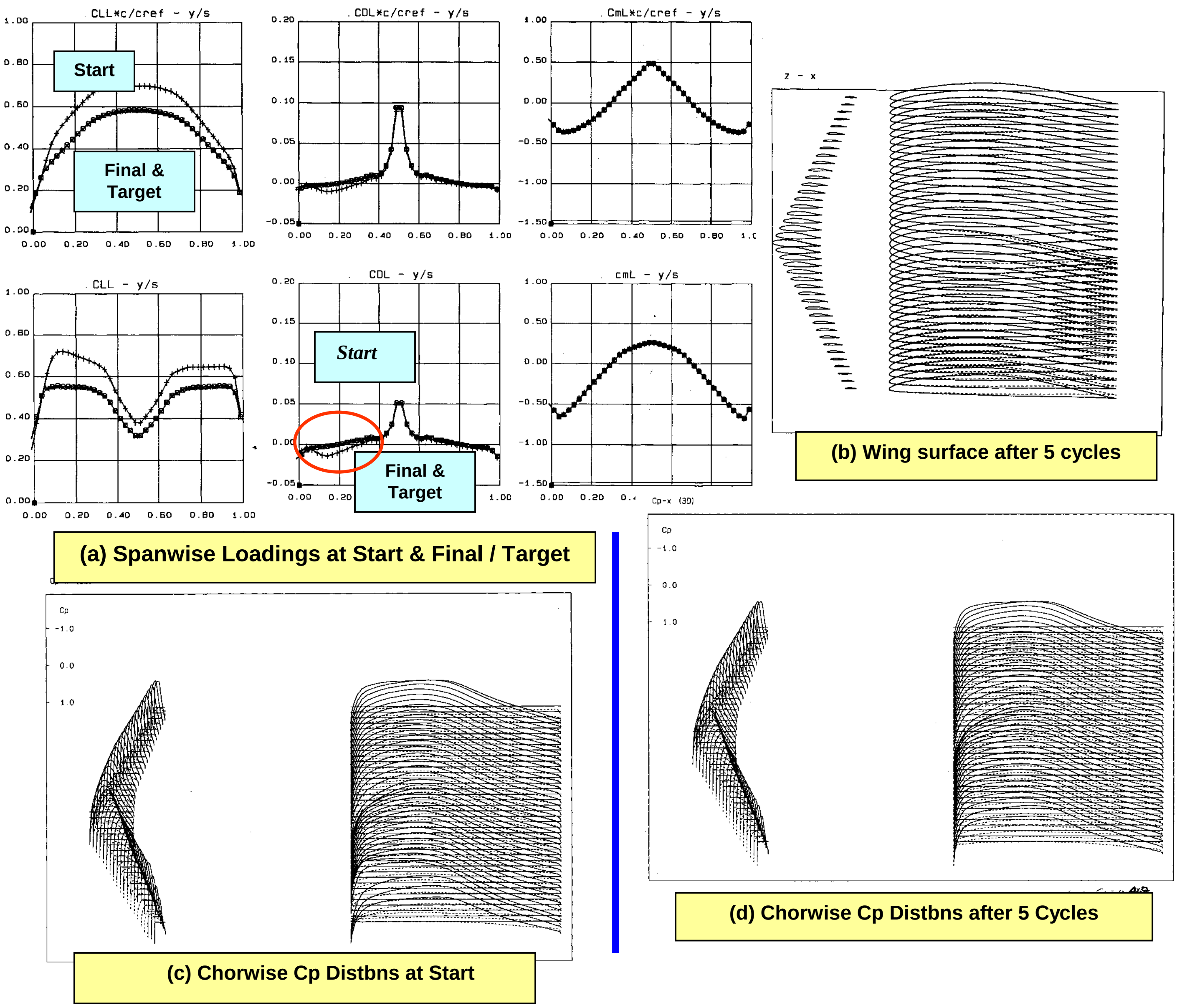


Fig. 23 2- Aircraft Formation, Typical CASE, RELAXED WAKE of LEAD AIRCRAFT

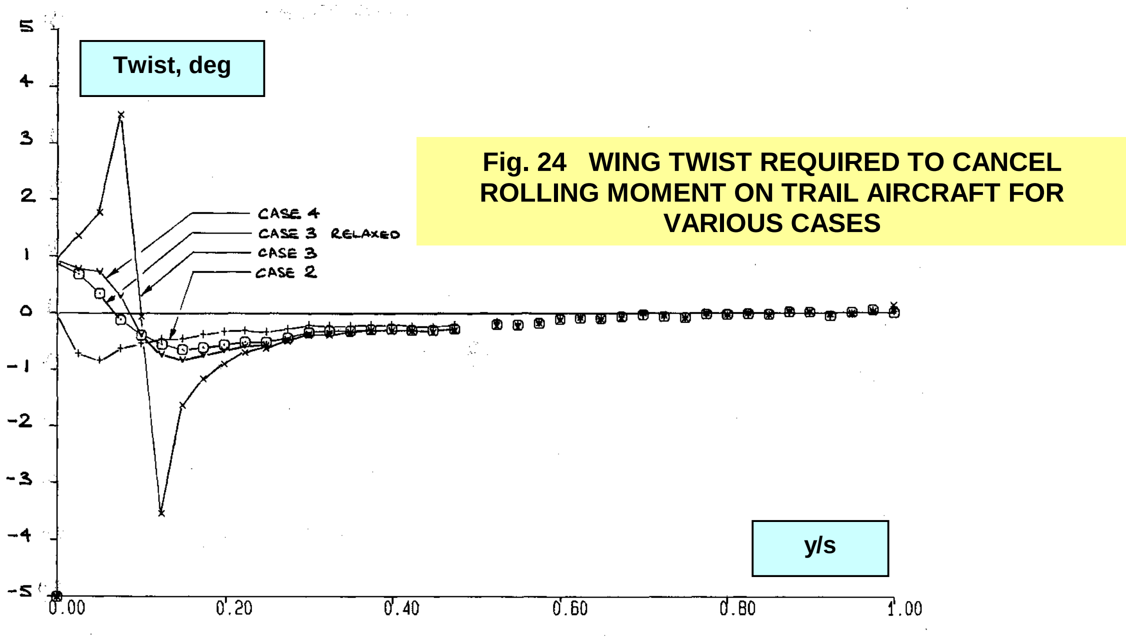


Fig. 24 WING TWIST REQUIRED TO CANCEL ROLLING MOMENT ON TRAIL AIRCRAFT FOR VARIOUS CASES

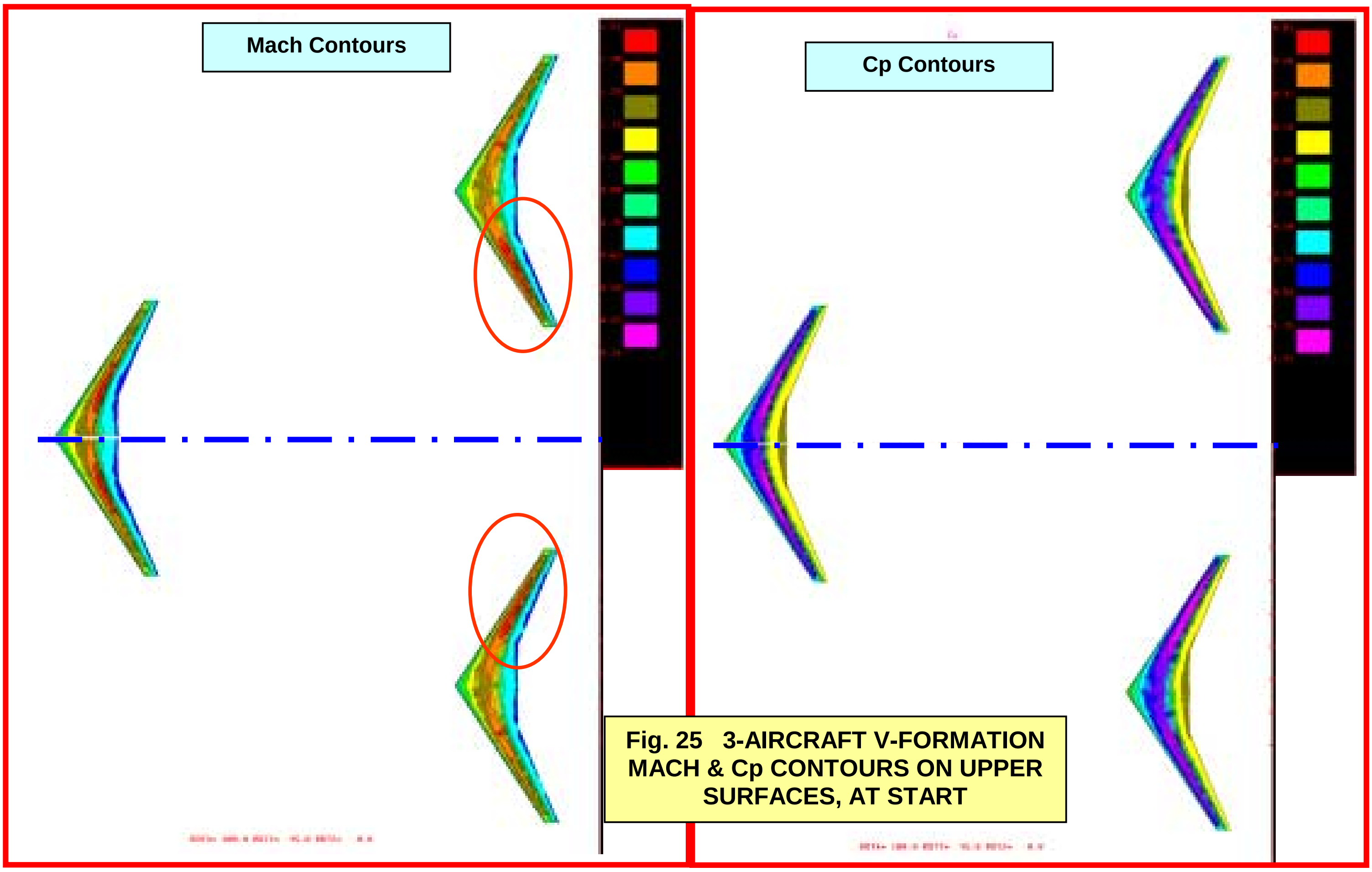


Fig. 25 3-AIRCRAFT V-FORMATION MACH & Cp CONTOURS ON UPPER SURFACES, AT START

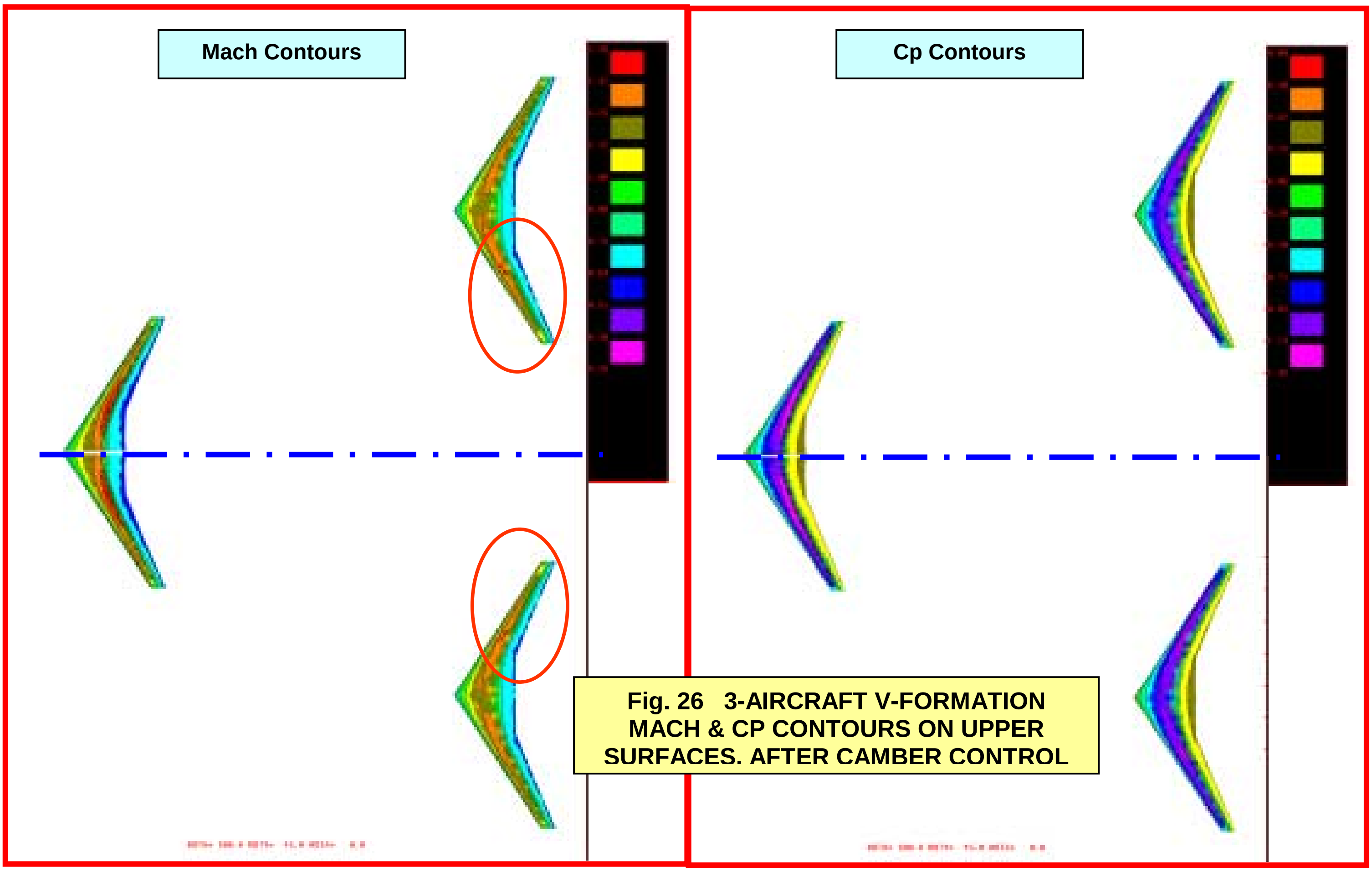


Fig. 26 3-AIRCRAFT V-FORMATION MACH & CP CONTOURS ON UPPER SURFACES. AFTER CAMBER CONTROL

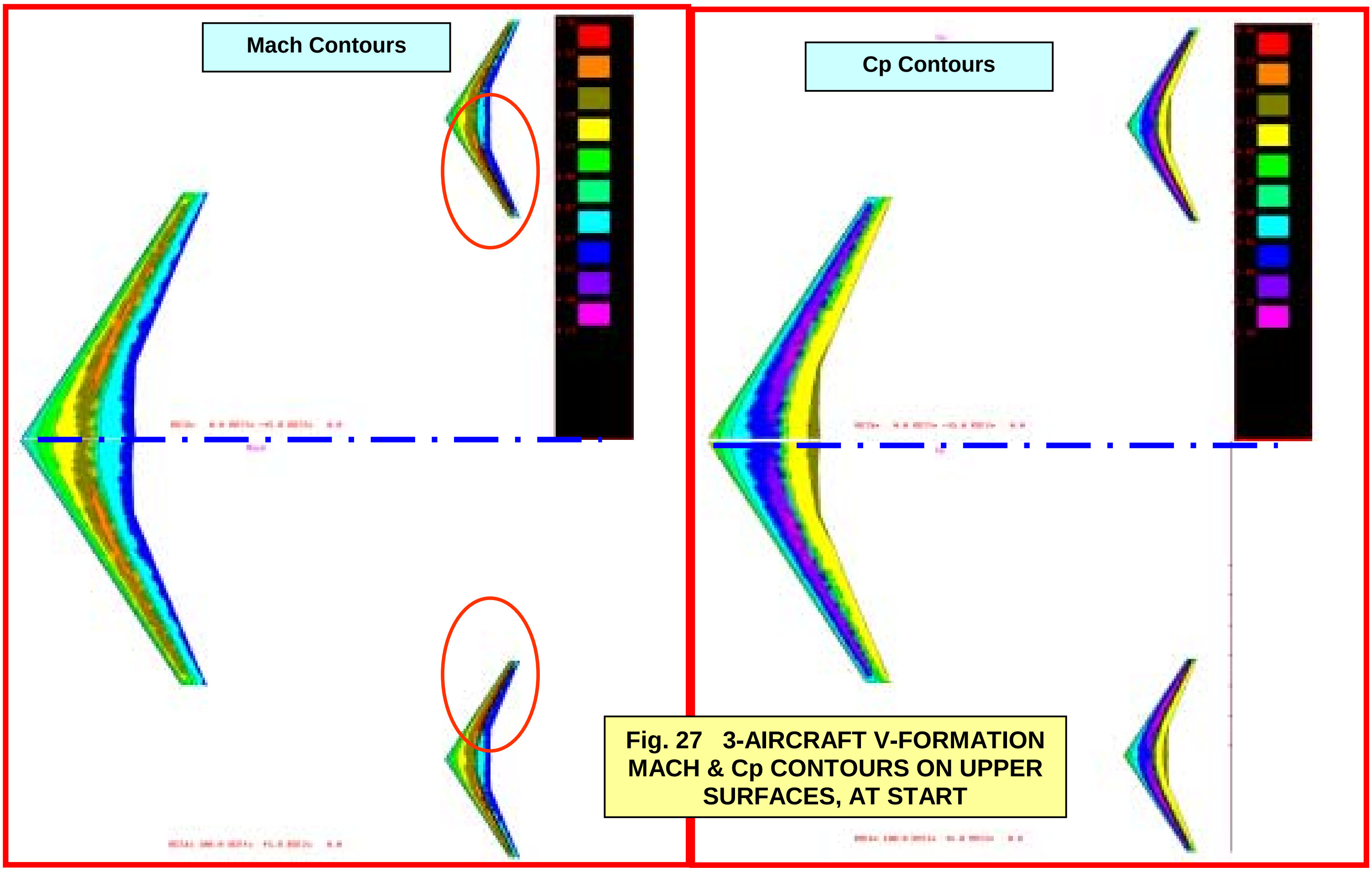


Fig. 27 3-AIRCRAFT V-FORMATION MACH & Cp CONTOURS ON UPPER SURFACES, AT START

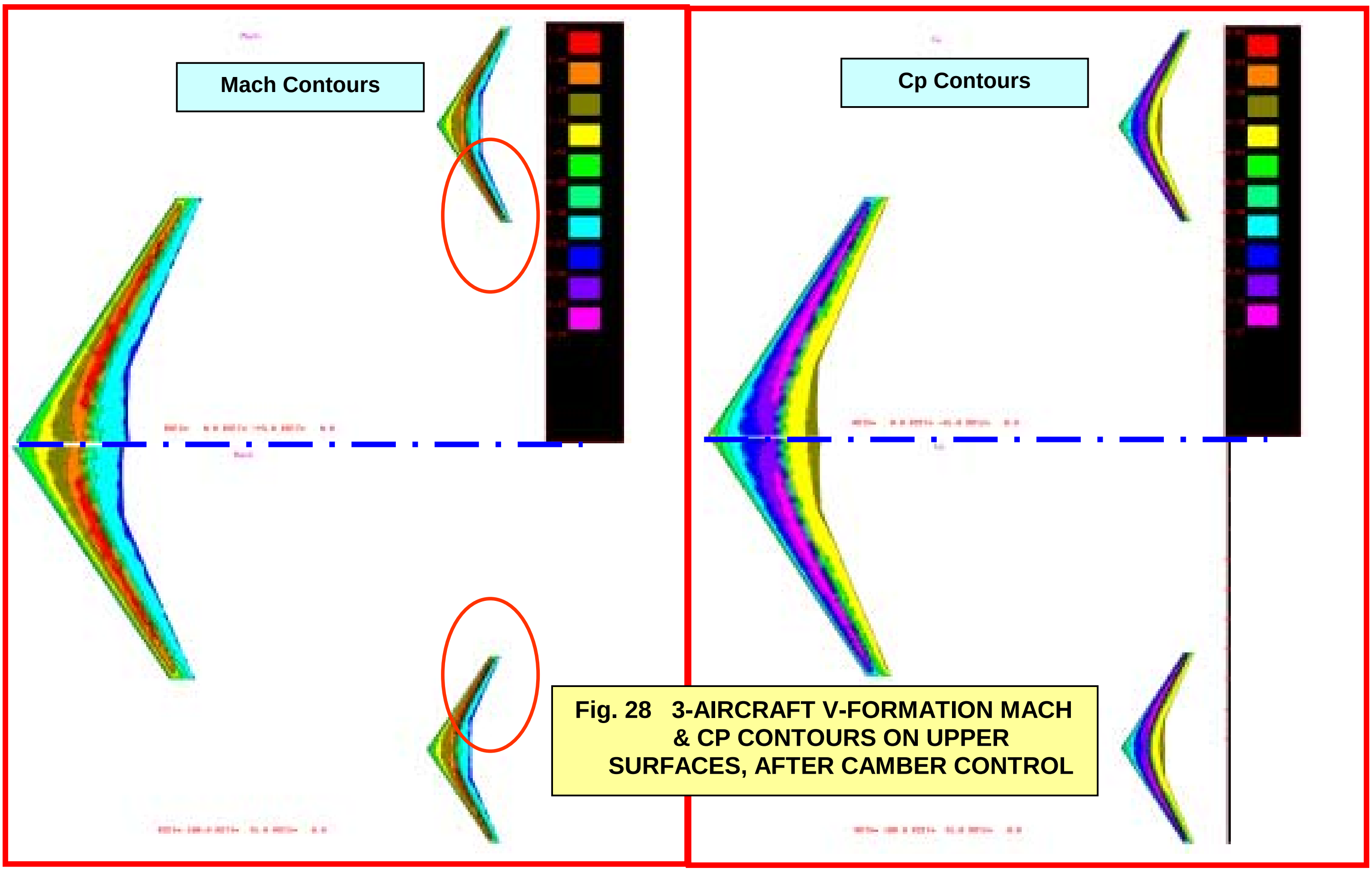


Fig. 28 3-AIRCRAFT V-FORMATION MACH & CP CONTOURS ON UPPER SURFACES, AFTER CAMBER CONTROL

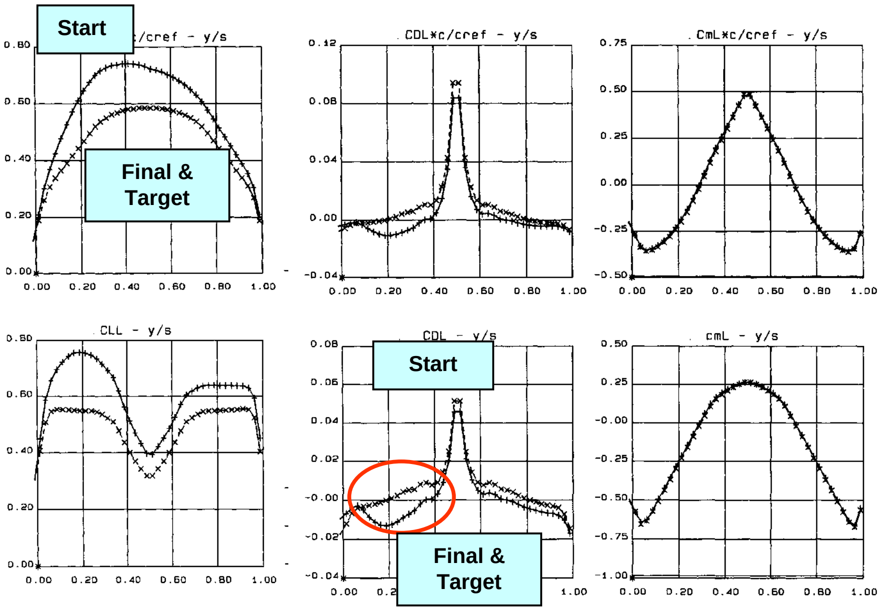


Fig. 29 LARGE LEAD (2.5:1.0), RIGID WAKE, Spanwise Loadings at Start & Final / Target, dx/b = 1.4, dy/b = +5%, dz/b = -5%

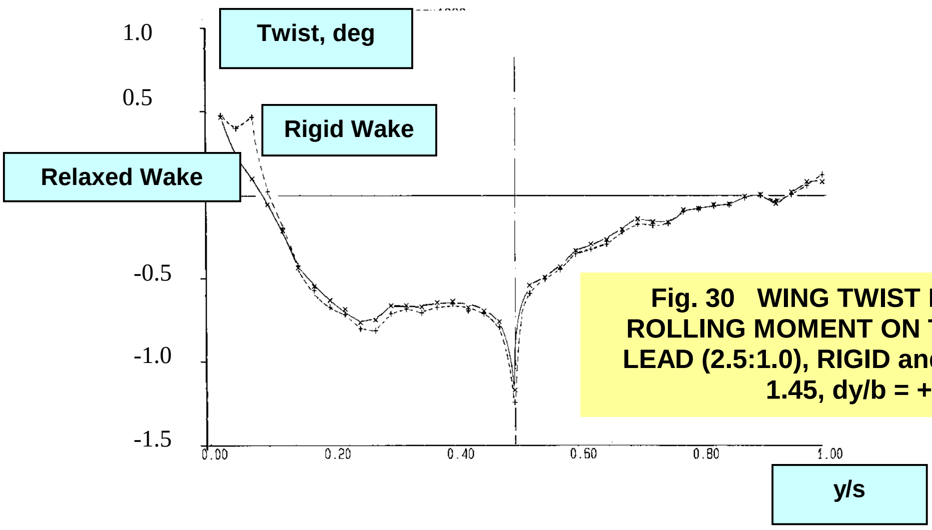


Fig. 30 WING TWIST REQUIRED TO CANCEL ROLLING MOMENT ON TRAIL AIRCRAFT, LARGE LEAD (2.5:1.0), RIGID and RELAXED WAKE, dx/b = 1.45, dy/b = +5%, dz/b = -5%

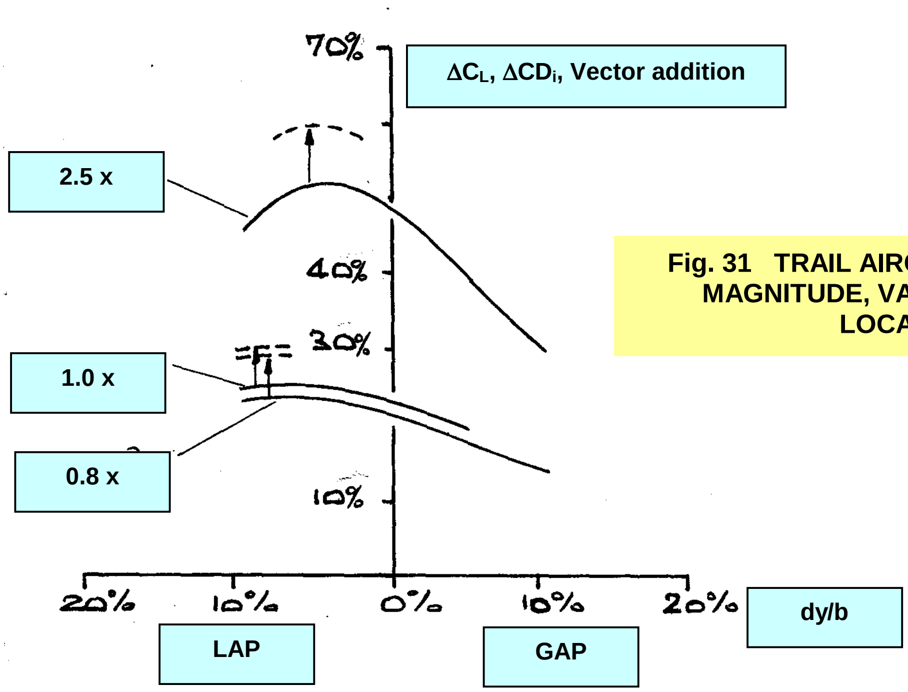


Fig. 31 TRAIL AIRCRAFT ΔC_L and ΔC_{Di} VECTOR MAGNITUDE, VARIATION WITH SPANWISE LOCATION, dz/b=-5%

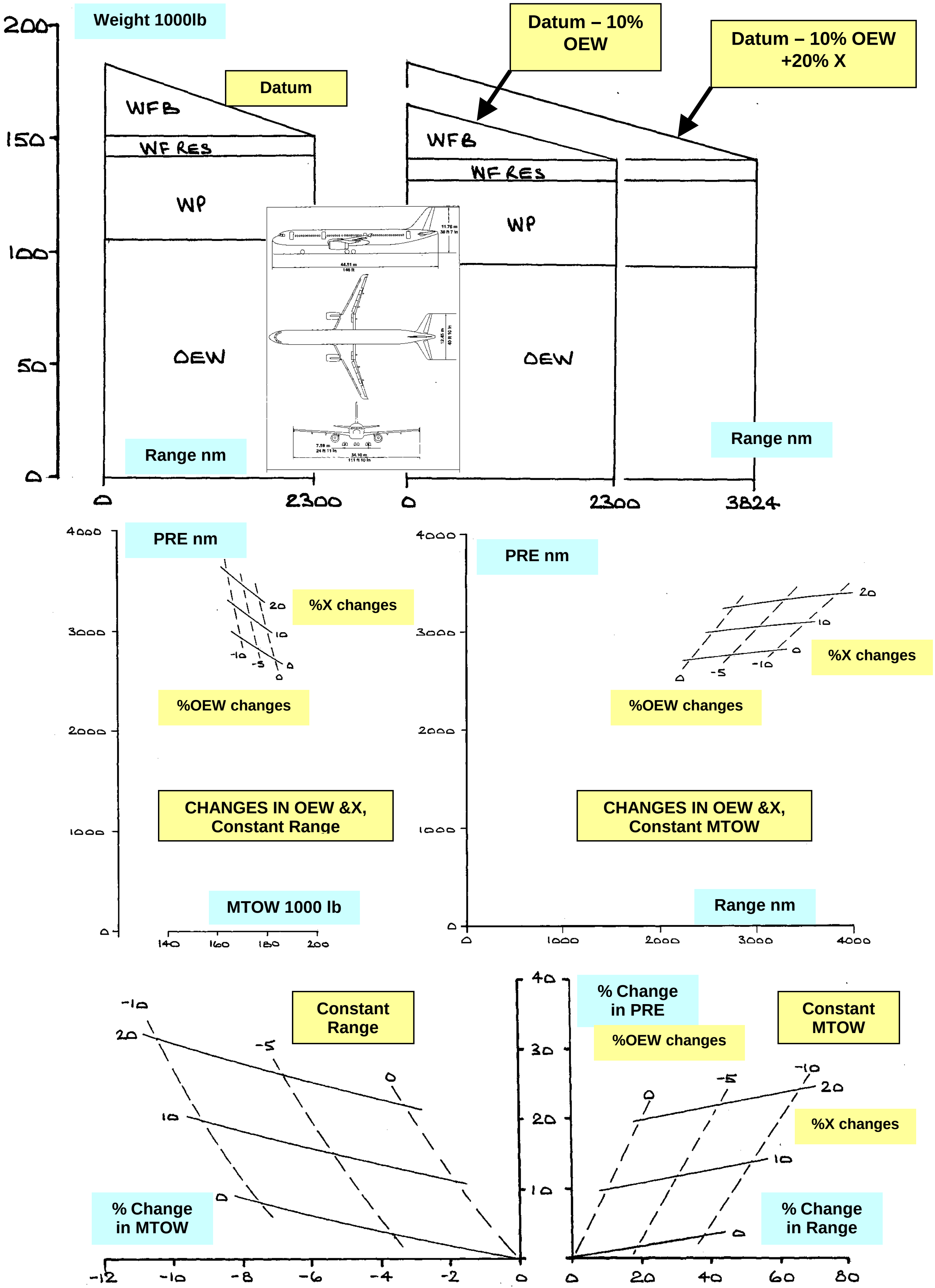


Fig. 32 ASSESSING THE EFFECT OF % CHANGES IN OEW & SFC ON A A321-100 sized AIRCRAFT

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