Highly Efficient Civil Aviation - An Opportunity for Present & A Vision for Future

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ABSTRACT

Civil aviation has dominated the transport scene with growth being upwards - bigger, farther and faster on economic productivity basis (often neglecting fuel usage). With increasing awareness of environmental issues, noise, emissions and energy / fossil fuel concerns, changes may accelerate.

The ACARE objectives are to reduce environmental impact due to Aviation by up to 50%. This paper addresses "unified "Efficiency issues (metrics) of aircraft, relating Payload, Range and fuel consumed and first-order costs. All efficiencies, including the "value" (cost) and noise effective efficiencies decrease dramatically with increasing Range. This leads to an innovative strategy for attaining high efficiency from Civil Aviation, using smaller aircraft, adopting Air-to-Air Refuelling (AAR) and Close Formation Flying (CFF), possibly in concert. For longer ranges, this strategy could go a long way towards meeting the ACARE objectives, present and future.

1. INTRODUCTION

The last 70 years have witnessed civil aviation dominating the transport scene with increasing growth - bigger, farther and faster on an economic productivity basis (often neglecting fuel usage), **Fig.1**, Refs1-2. With awareness of environmental issues, noise, emissions and energy / fossil fuel reserves, changes will happen, possibly quickly. In the UK, the Greener-By-Design (GBD) group has isued a series of reports e.g. Refs.3-4.

The ACARE objectives are to reduce environmental impact due to Aviation by up to 50%. This brings us to Efficiency issues (metrics) of Aircraft operating over different ranges, before looking at Innovative concepts for future air transport.

2. EFFICIENCY CORRELATIONS & INFERENCES

Nangia (Ref.5) presented results from a data exercise on modern commercial (jet) aircraft (typical Payload – Range diagrams, **Fig.2**), distinguishing between maximum payload (Point-A, Combi, freighter), and design payload (Point-D) and including fuel reserves. Further, the results have been correlated into reliable "first-order" non-dimensional (non-D) trends.

In the well known Breguet Range Equation (for cruise flight), 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 that relates the flight speed, aerodynamic efficiency and power-plant technology (V, lift-drag ratio (L/D) and Specific Fuel Consumption (SFC)). It has units of length. In turn, it leads to the non-D form for range, Z.

$$X = V\,L/D\,/\,SFC, \quad R = X \log_e (W1/W2),$$

$$Z = R/X = \log_e [W1/(W1\text{-}WFB)].$$

A measure representing "useful work done" for unit fuel used is the Payload Range Efficiency (PRE ie. Payload x Range / Block Fuel). This can be a function of Range either at Point A or D. **Figs.3-5** (Ref.5) summarise the fuel burnt ratio WFB/WP and PRE trends. The trends on a non-D basis are fairly "smooth". Selected points are for Range = 3000, 6000 and 9000 nm at X = 15000 and 20000 nm. Green (Ref.6) supports the analysis.

The "Nangia" Value Efficiency graphs (**Fig.5**) are particularly informative in depicting emissions and noise characteristics as well as costs relationships. Often aircraft do not fly at full capacity and the implications of this can be inferred directly.

From the viewpoint of fuel efficiency, the optimum design range is in the region of 2500 - 3500nm, depending on the Aircraft range parameter X (=V L/D /sfc). It follows that we need to:

- Increase V and L/D or reduce SFC
- Reduce drag
  Drag comprises several components
  Peak L/D occurs when lift-induced drag is about half the total drag.
- Reduce Empty weight, allowing increased payload fraction.
  Flying wings have low Empty weight fraction.
- Reducing SFC implies
  Flying near optimum propulsive conditions e.g. Mach 0.85.

An obvious solution proposed by the GBD group (Refs.3-4) is to fly the longer ranges in short hops using more efficient 3000 nm range aircraft. The idea however remains unattractive because of additional overall journey time (descent, taxiing, refuelling, take-off and ascent at each stop), extra fuel usage and more wear and tear – extra take-offs and landings. Airport congestion is not necessarily eased unless all-new "staging" airfields are built. Further, Air Traffic Control (ATC) operations at intermediate airfields would increase as would costs of airport usage.

With some lateral thinking, we can offset most of the concerns in one stroke, using currently proven available technology. AAR is a well implemented daily routine in military operations, **Fig.6**. It has reached a level of autonomy with advances in night vision, control systems and differential GPRS and navigation.

3. AIR TO AIR REFUELLING (AAR)

The approach is to design representative aircraft for carrying the same payload of 250 passengers (pax) over 6000, 9000 and 12000 nm (Ref.7) and estimate the fuel saved by using the base 3000 nm range aircraft with AAR over the longer ranges.

The Breguet range equation is 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 3000 and 6000 nm aircraft we used SFC of 0.65 lb/hr/lb with the Range parameter X as 15,077 nm. For the 9000 nm aircraft we used a "more efficient" SFC = 0.57 lb/hr/lb and X as 16,897 nm.

The base aircraft weight variation over 3000 nm is shown in **Fig.7**, MTOW = 261,932 lb. Block fuel is 46,147 lb. A 6000 nm aircraft, **Fig.8**, MTOW = 505,438 lb uses 161,269 lb fuel (double range requires more than treble the fuel). The extra fuel, above that for double the range, is needed for the additional aircraft weight (tankage, structure and larger landing gear). **Fig.8** also compares the weight variations with range for the 6000 nm aircraft and the 3000 nm aircraft refuelled at 3000 nm. Also shown are Fuel used and savings offered by AAR (43% over 6000 nm). A 9000 nm aircraft, **Fig.9**, MTOW = 656,262 lb, uses 263,073 lb fuel. A comparison weight breakdown for a 3000nm aircraft with two AAR operations (block fuel 138,441 lb, saving of 47%) is included.

The relative sizes of aircraft designed for 250 pax over 3000, 6000, 9000 and 12000 nm are in **Fig.10**. The fuselage size remains almost constant but the wing area increases rapidly to accommodate the fuel requirements and maintain design C_L.

Fig.11 shows the block and total (block + reserve) fuel trends with range. Note the potential for fuel savings with AAR.

AAR applies to 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 favour the 250-seaters. All this points towards further interesting studies.

Tankers & Operations

Military tankers essentially operate as "garages in the sky" requiring long endurance. A key feature of civil tanker operation is that it will be "focussed" and shorter, efficient flights are envisaged. Each tanker may accomplish 3-4 operations in a mission and then land at a suitable airfield, **Fig.12**. In this way, tanker offload fuel is 4-7 times greater than that consumed.

Fig.13 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 (250 pax). 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. Other ranges between 3000 and 6000 nm could be explored.

Reasonably efficient tanking with RT near 4-5, should be adequate. There is little need for extensive advances in tanker design. Currently available tankers will allow significant fuel savings to be made on refuelled aircraft over longer ranges.

Note from **Fig.14**, the increase in PRE/X achieved by the refuelled 3000 nm design aircraft over the PRE/X for 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 RT = 4, we are touching gains in PRE/X of 60% for 6000nm and 80% for 9000nm ranges.

The adoption of AAR leads to several other possible benefits.

Laminar (Boundary Layer) Flow Aircraft

Although advantages (e.g. 10-15% better VL/D) of hybrid laminar flow applications have been demonstrated in flight, the complex technologies are not fully proven. Extra fuel reserves would be carried by laminar flow aircraft to ensure safe diversion in the event of system failure or laminar flow becoming turbulent (surface contamination). The carriage of extra reserves could affect the full benefits and economics.

However, for long ranges, the possibility of up to 10-15% fuel burn improvement from laminar flow technology in its own right, coupled with the potential for further 30% to 40% fuel efficiency improvements from AAR could be attractive.

Established AAR could offer the "safety net" needed by laminar flow aircraft. Contingencies for loss of laminar flow, no longer have to be "designed-in". Much smaller, lighter and therefore more efficient laminar flow aircraft can be designed. In the event of loss of laminar flow en-route, extra AAR would allow the aircraft to reach its original destination.

Regional Airports, Reduce Demand on Hubs, Tanker Bases

AAR enables smaller aircraft operating from Regional airports to fly longer ranges. Increased use of Regional airports worldwide would result in less surface travel by passengers at either end of their flight (point A to point B flexibility). This reduces congestion at Hub airports, saving time, effort, energy and fuel. Less fuel needs to be transferred to (road tanker or pipeline) or stored at the Hubs. Future increased capacity may be provided through new airports, sited where needed.

AAR will allow the ATC workload to be shared more evenly.

The smaller aircraft produce less intense and less persistent wakes allowing an increase in operating frequency.

Tanker bases could be located near refineries or fuel depots, away from environmentally sensitive or populated areas. All these facts have beneficial environmental and security aspects.

One Design range Aircraft to operate on all Routes

The fuel efficiency is optimum for 3000nm designs and independent (first-order) of the payload. This suggests possibilities for medium range aircraft in different seat variants. Each variant is capable of all ranges with AAR. If required, the development of larger, high capacity medium range aircraft will occur, solely for traffic demands rather than as a by-product of increasing range. This would focus the efforts of industry, resulting in larger, economical production runs. Developments and upgrades need only be applied to a few types.

A single aircraft type within an operator leads to easier scheduling, easier maintenance, reduced type certifications (aircrew, ground / maintenance crew), yielding cost savings in training, servicing, maintenance and spares. Safety will improve.

Reduced Requirement for Larger Engines

With 250 seats, the 3000nm aircraft requires two engines of about 40,000 lb thrust each c.f. 80,000 lbs each for 9000 nm aircraft (Ref.5). With smaller aircraft flying the longer routes as a result of AAR, the requirement for larger engines reduces.

The expertise gained as engine manufacturers strive to keep ever-larger engines within noise / emissions limitations could be employed in further reducing noise and emissions on the smaller developing engines. The benefits for night-time and increased frequency operations are again evident.

Safer and Quieter Take-Off and Climb-Out Procedures

Take-off is usually a demanding phase of flight. The aircraft is heavy with payload and fuel. The engines operate close to the maximum output.

If an aircraft is required to refuel at least once to complete a 6000 nm flight, or twice to complete a 9000 nm flight, then an additional AAR operation shortly after take-off could be easily accomodated. In this scenario, the aircraft, capable of and with the tank capacity to carry 250 pax over 3000 nm, would take-off light (minimum fuel). It would be more aerodynamically efficient and not operating near its performance limits, directly reducing noise pollution. After 20-30 minutes, the aircraft would rendezvous with a tanker and take on sufficient fuel to reach the next rendezvous.

This enhanced operating procedure will require further analysis of the balance between offering improved safety at take-off versus the introduction of an additional operation. Available data indicates that AAR operations between similar sized aircraft (Tristar – Tristar, VC10 – VC10, VC10 – Tristar, etc) are not difficult or hazardous.

Greater Flexibility with Existing Long-Range Aircraft

We consider a typical 250 passenger, 6000 nm aircraft. With a full passenger complement at MTOW, the aircraft would probably have payload capacity to spare and would not be carrying its maximum fuel capacity. With AAR available, the aircraft could take-off with minimum fuel onboard, a full complement of passengers and the payload capacity topped up with revenue earning cargo, Point A operation. Once airborne, the aircraft could refuel as needed to complete the schedule. In general, Point A operation could be up to 30% more fuel efficient than Point D operation.

Advantages vs Disadvantages

We have studied the AAR concept over an appreciable period, taking into consideration, the environment, demands for air travel growth, technology trends, safety, efficiency and practicality. The disadvantages: passenger acceptance and additional crew operations are far outweighed by the advantages: fuel savings, reduced costs, greater airline efficiency, reduced congestion, reduced pollution, regeneration of disused military airfields, greener environment. Operational issues will need to be solved no doubt, See Ref.7.

If the world truly wants to be greener, with more efficient air travel, along with other areas currently being advanced, AAR promises a really valuable and readily available contribution.

4. CLOSE FORMATION FLYING (CFF)

The possibility of using CFF to reduce lift-induced drag and hence to reduce fuel usage or to extend range is well known. It is important to assess its implementation. Aircraft formations, **Figs.15 & 16** occur for several reasons e.g. during displays or in AAR but they are not maintained for any length of time from the fuel efficiency perspective. Recently NASA conducted tests on F/A-18 aircraft formations (Refs.8-9 & **Fig.16**), showing that benefits occur at certain geometry relationships e.g. the trail aircraft overlaps the wake of the lead aircraft by 10-15% semi-span (see also Ref.10). The NASA work was partly inspired by the sizeable German work programme including flight-tests (Hummel et al, See Nangia paper, Ref.11).

For civil aircraft, Jenkinson, in 1995 (Ref.12), proposed CFF of several large aircraft as being more efficient, contrasting with flying a very large aircraft. Aircraft could take off from different airports and then fly in formation over large distances before peeling away for landing at the required destinations.

Formations can comprise large and small aircraft, **Fig.17**. Each aircraft will experience off-design forces and moments. It will be pre-requisite that these are 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. Several results are available for CFF using idealized approaches e.g. vortex lattice formulations (Ref.10). 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.13-14) applicable to wings with or without winglets. This approach starting with 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. 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, usually in less than five design iterations. A number of flight formations with aircraft of varying size and relative location have been studied. Predictions show 30% or more benefits in lift-induced drag (Refs.11 & 15).

Fig.18 refers to 2 equal-sized aircraft in CFF with streamwise displacement dx/b = 1.45, spanwise over lap dy/b = 10% and vertical displacement dz/b = 0%, Case 3. Results on the Trail wing are in the presence of a Lead wing relaxed wake. Spanwise loadings (Lift, Drag and Pitching Moments) are shown in **(a)**, Cp distributions in **(c-d)**. Increased loading on the left wing, before redesign, is evident in both spanwise and chordwise distributions. The original and redesigned cambered and twisted surfaces are compared in **(b)**. 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.

First-Order Relative Size Ratio Effects

We consider: Lead : Trail linear scale ratios of 0.8, 1.0 and 2.5.

Fig.19 refers to 2 unequal-sized aircraft (Lead: Trail linear scale ratio 2.5) in CFF with displacements dx/b =1.45, dy/b = 5%, dz/b = -5%. It shows spanwise loadings on the Trail wing before and after redesign in the presence of a relaxed Lead wing wake. The resulting Trail wing twist changes for these cases are shown in **Fig.20**. Re-designing in the presence of a relaxed Lead aircraft wake has resulted in a slightly smoother twist variation across the Trail wing.

For dz/b = -5%, the variation of ΔC_{VM} (vector addition of ΔC_L% and ΔC_{Di}% prior to redesign, solid line) is plotted against location across the Lead aircraft span in **Fig.21** 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 . Note 30 to 60% reductions.

It is emphasized that this is very much a first order assessment and analyses 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-design (camber control), the ΔC_L levels are less than 1%. The resulting ΔC_{Di} % are plotted as dashed lines in **Fig.21**. 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 Symmetric V-Shape CFF

For dx/b=1.45, dy/b=5%, dz/b=-5%, **Figs.22 & 23** show Euler results before and after camber control, respectively. The Mach and Cp contours, in **Fig.22**, show the more significant spanwise extent of the differential loading on the Trail wing. In **Fig.23**, after re-designing, the loading is evidently more symmetrical.

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 consideration.

For longer ranges, AAR and CFF could go most of the way towards satisfying ACARE objectives.

5. INFERENCES & CONCLUDING REMARKS

Civil aviation has dominated the transport scene for the last 70 years with increasing growth - bigger, farther and faster on economic productivity basis (often neglecting fuel usage). With awareness of environmental issues, noise, emissions and energy / fossil fuel reserves, it is realised that changes will happen and possibly in an accelerating fashion. The ACARE objectives are to reduce environmental impact due to Aviation by up to 50%.

We have addressed "unified" Efficiency issues of aircraft, relating Payload, Range and fuel consumed and first-order costs. All efficiencies, including the "value" (cost) and noise effective efficiencies decrease dramatically with increasing Range.

It has been shown that significant increases in efficiency can be gained using innovative strategies in Civil Aviation. Depending on range, AAR offers 30% - 50% reduction in fuel burn using smaller (with 40-50% savings in MTOW) short - medium range aircraft to complete long range services. CFF offers 10 – 15%

increase in Range or a comparable reduction in fuel burn. In conjunction, AAR and CFF will offer cummulative benefits.

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 alone. Integration and knowledge transfer are key factors. For the ACARE objectives, civil aviation will need to take a new, objective unbiased view.

We need to broaden the analysis to include all types of aircraft in service now and what may be on offer in the future, e.g. BWB, Oblique Flying Wing (OFW), Propfans etc. The question of how these new designs line up on the efficiency metrics basis becomes important. Are the metrics adequate?

Flight simulations of civil AAR and CFF need to be conducted to highlight any technical or operational issues, e.g. fuel transfer aspects, tanker / receiver formation relationships, etc.

Conference Goals Met

All this provides the motivation for continuing the exciting work programmes that fit in with the goals of the conference: **Innovative concepts for future air transport,** and **Environment and technologies for environmental aspects in aeronautics and space.**

With acceptance of these ideas, we can progress towards the two other major goals of the Congress, benefitting from: **International cooperation among academia, research and industry** ensuring interesting work during: **Education / training for aeronautics and space; attracting young engineers.**

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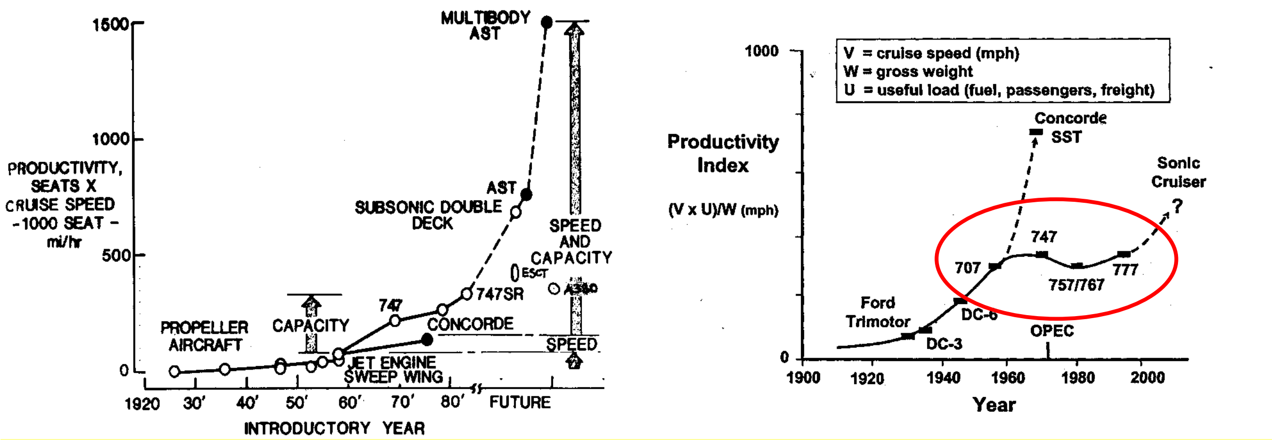
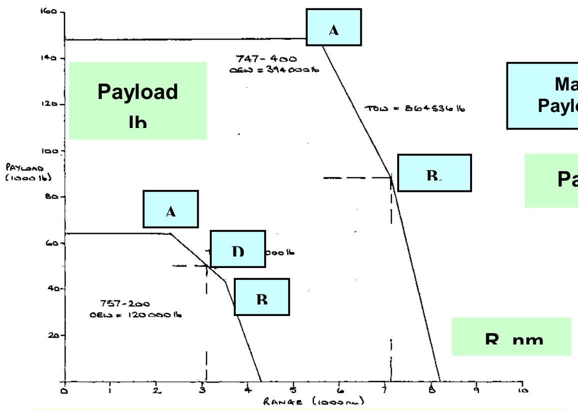
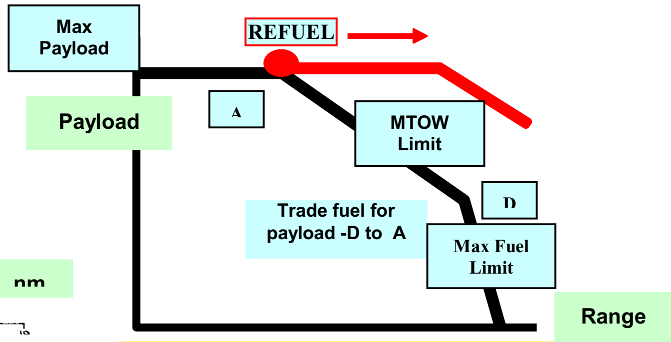


Fig. 1 PRODUCTIVITY OF LONG-RANGE TRANSPORT AIRCRAFT (Dollyhigh et al, Ref.1 & McMasters, Ref.2)



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



Explaining Various Limits in the Payload-Range Diagram

Fig.2 TYPICAL PAYLOAD RANGE DIAGRAMS & LIMITS

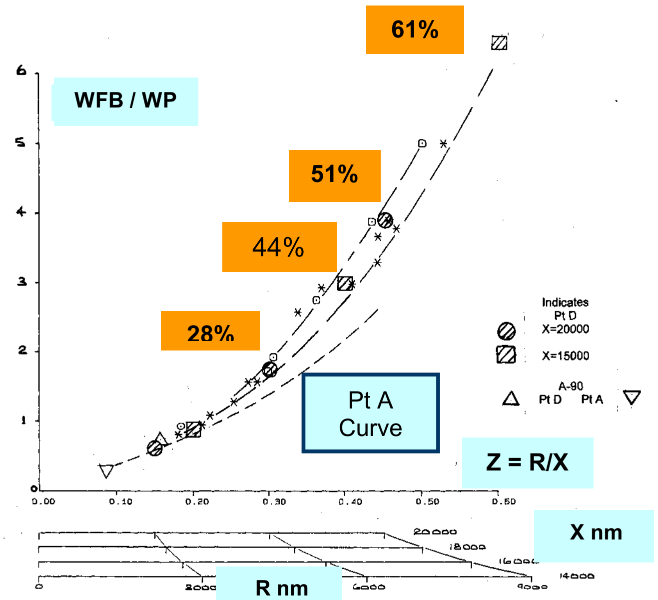


Fig. 3 CIVIL AIRCRAFT, WFB / WP & Z = R/X RELATIONSHIPS, Pt A & Pt D
Parallel Scales of R for Different X Values

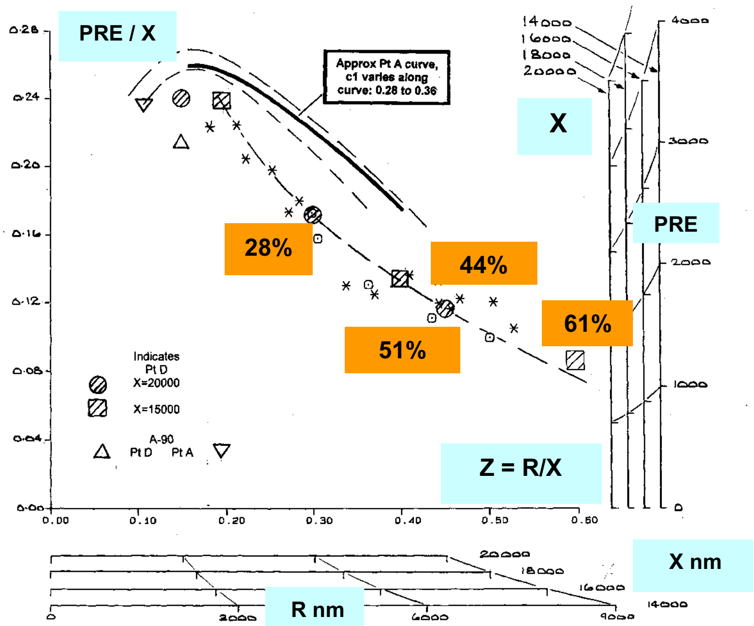


Fig. 4 CIVIL AIRCRAFT, PRE/X & Z = R/X RELATIONSHIPS, Pt A & D
Parallel Scales of PRE Implied for Different X Values

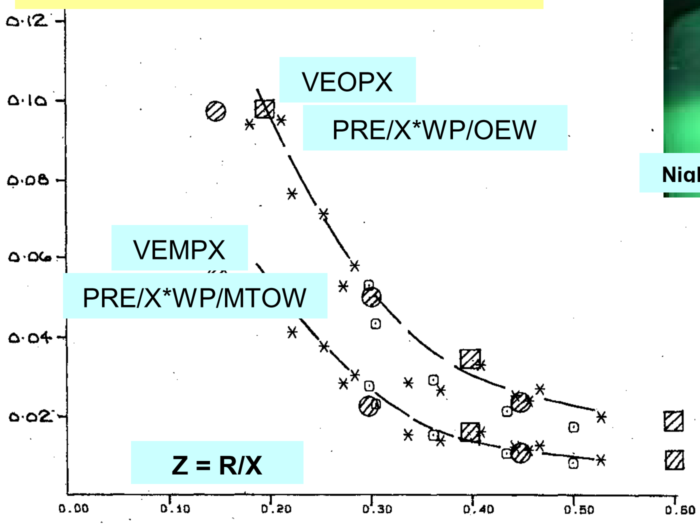


Fig.5 FACTORS: NANGIA EMISSIONS EFFICIENCY VEMPX & NANGIA VALUE EFFICIENCY VEOPX AT Pt D

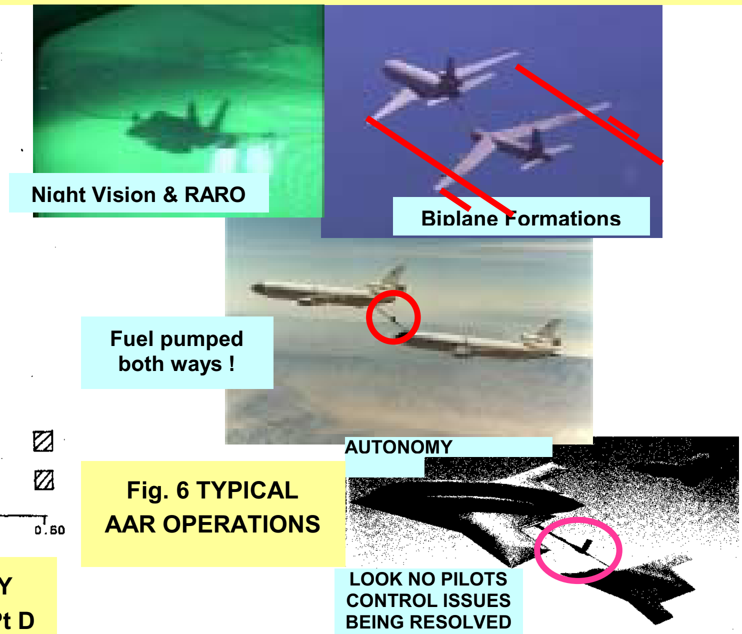


Fig. 6 TYPICAL AAR OPERATIONS

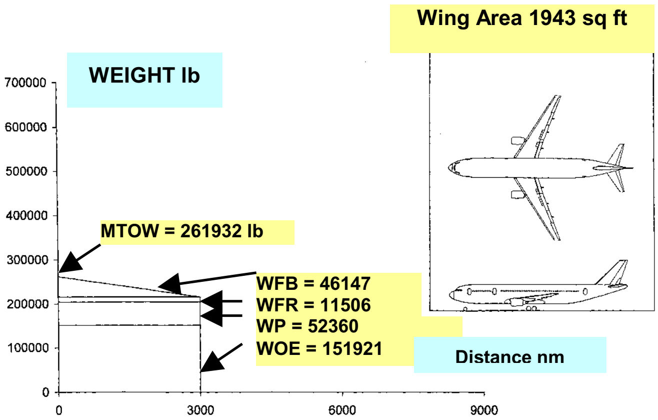


Fig. 7 AIRCRAFT WEIGHT VARIATION WITH DISTANCE FOR 3000 nm RANGE NO REFUELLING, 250 PAX., OEWR = 0.58, X = 15077 nm

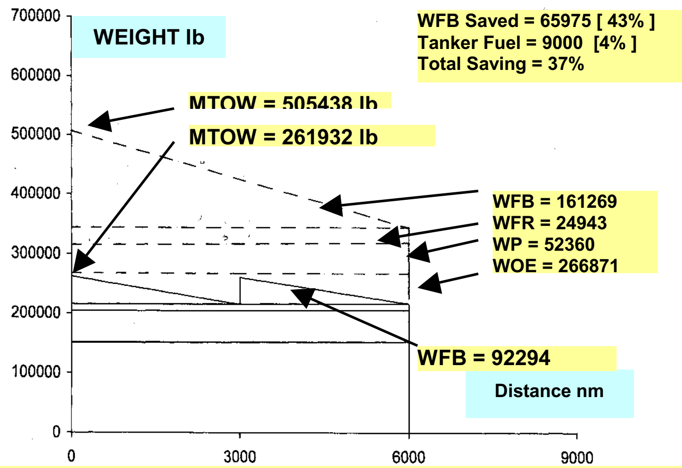


Fig. 8 AIRCRAFT WEIGHT VARIATION WITH DISTANCE FOR 6000 nm RANGE AIRCRAFT, REFUELLED ONCE cf AIRCRAFT WITHOUT REFUELLING, OEWR = 0.528, 250 PAX. 3750 ft², X = 15077 nm

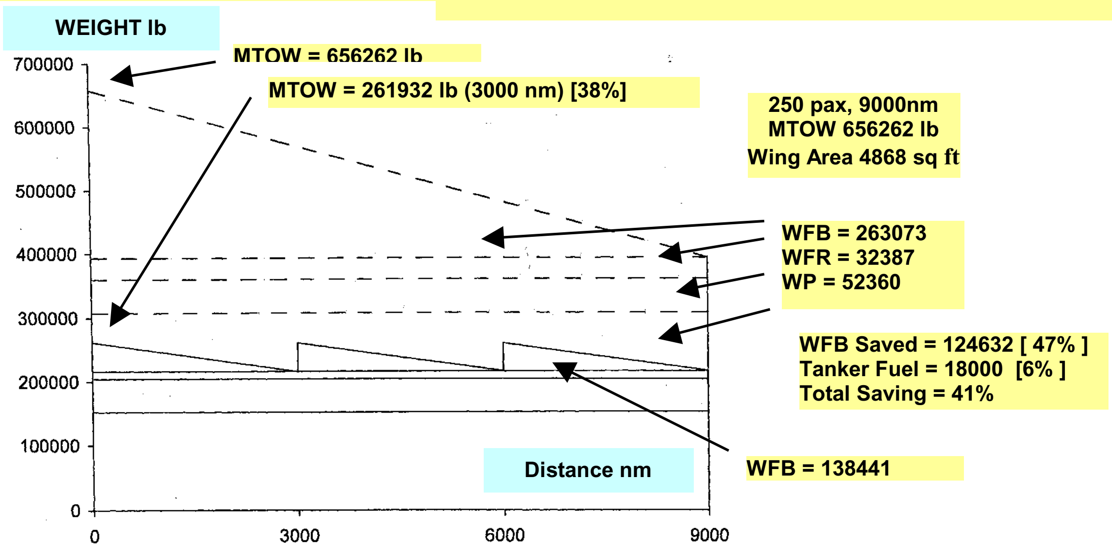


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Fig. 9 AIRCRAFT WEIGHT VARIATION WITH DISTANCE FOR 9000 nm RANGE AIRCRAFT (X = 15077nm) REFUELLED TWICE cf AIRCRAFT WITHOUT REFUELLING, OEWR = 0.47, 250 PAX., S = 4968 ft², X = 16897

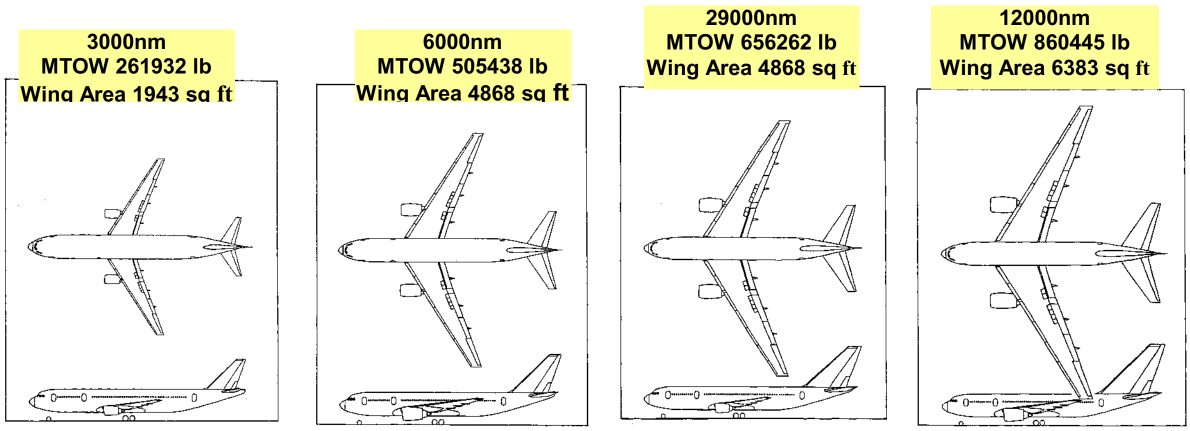


Fig. 10 COMPARING AIRCRAFT DESIGNED FOR DIFFERENT RANGES, 250 Pax.

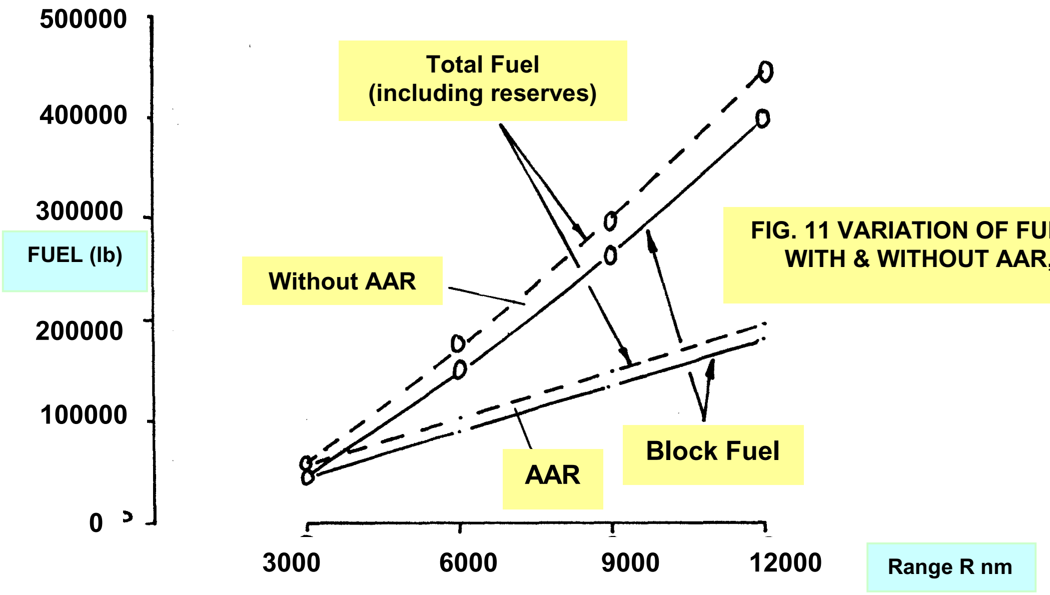


FIG. 11 VARIATION OF FUEL USED WITH RANGE, WITH & WITHOUT AAR, 250 PAX AIRCRAFT

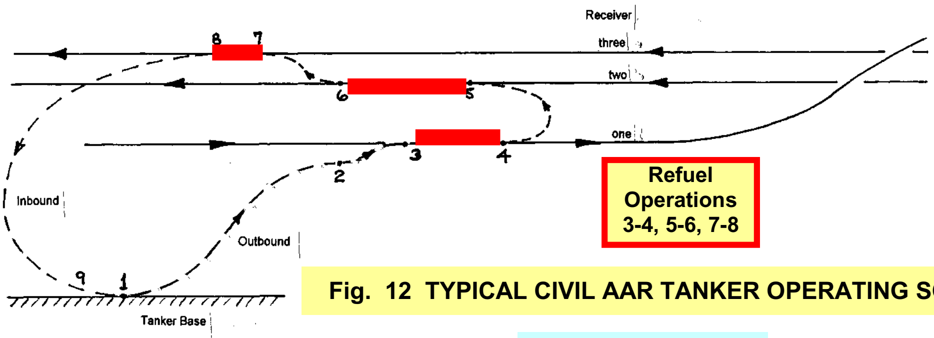


Fig. 12 TYPICAL CIVIL AAR TANKER OPERATING SCENARIO

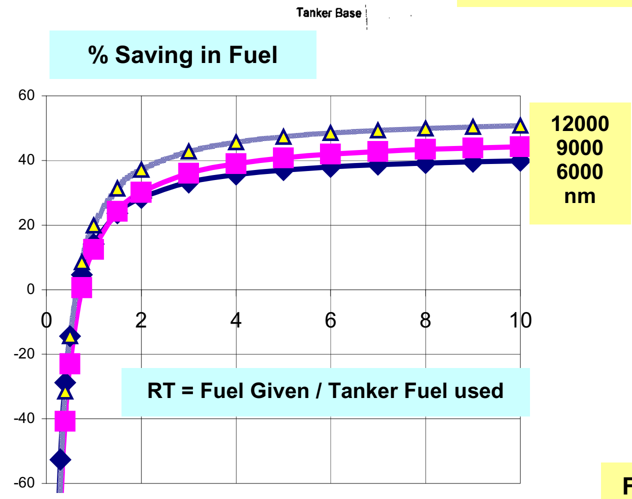


FIG. 13 SAVING IN TOTAL FUEL CONSUMED

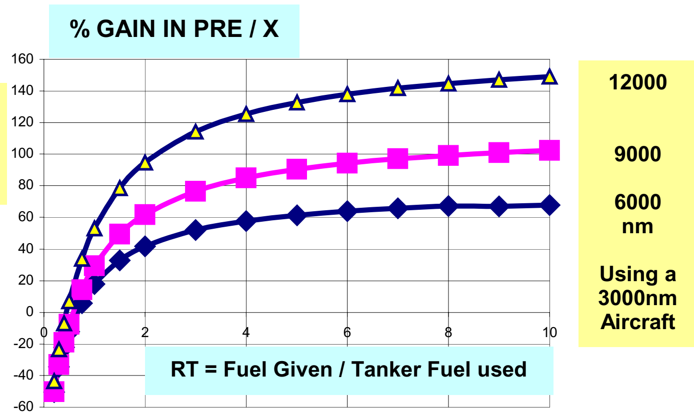


FIG. 14 % IMPROVEMENT IN PRE / X USING a 3000 nm AIRCRAFT WITH AAR, VARIATION WITH TANKER FUEL OFF-LOAD

Fig. 15 DISPLAY FORMATION

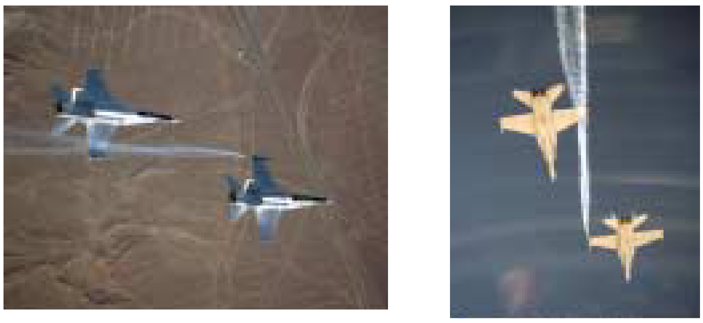
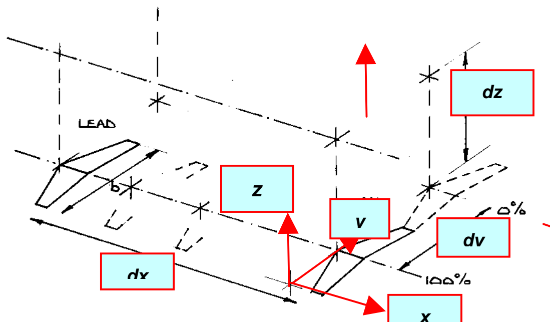


Fig. 16 F/A-18 FORMATIONS, NASA



GEOMETRY DEFINITIONS IN FORMATION FLYING

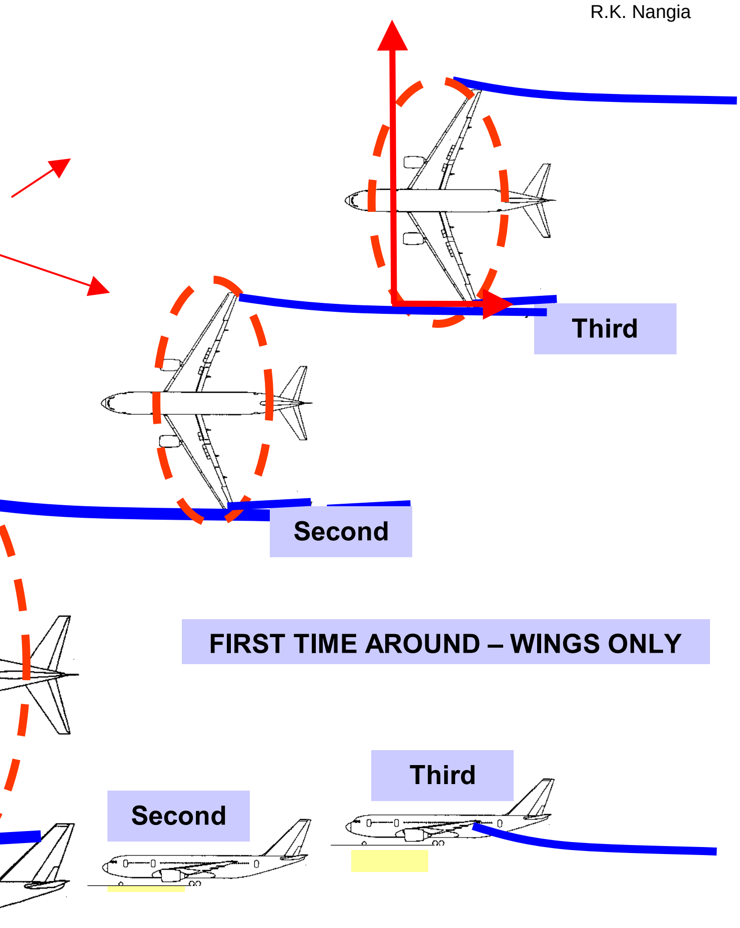


Fig. 17 FORMATION, 3 UNEQUAL SIZE AIRCRAFT

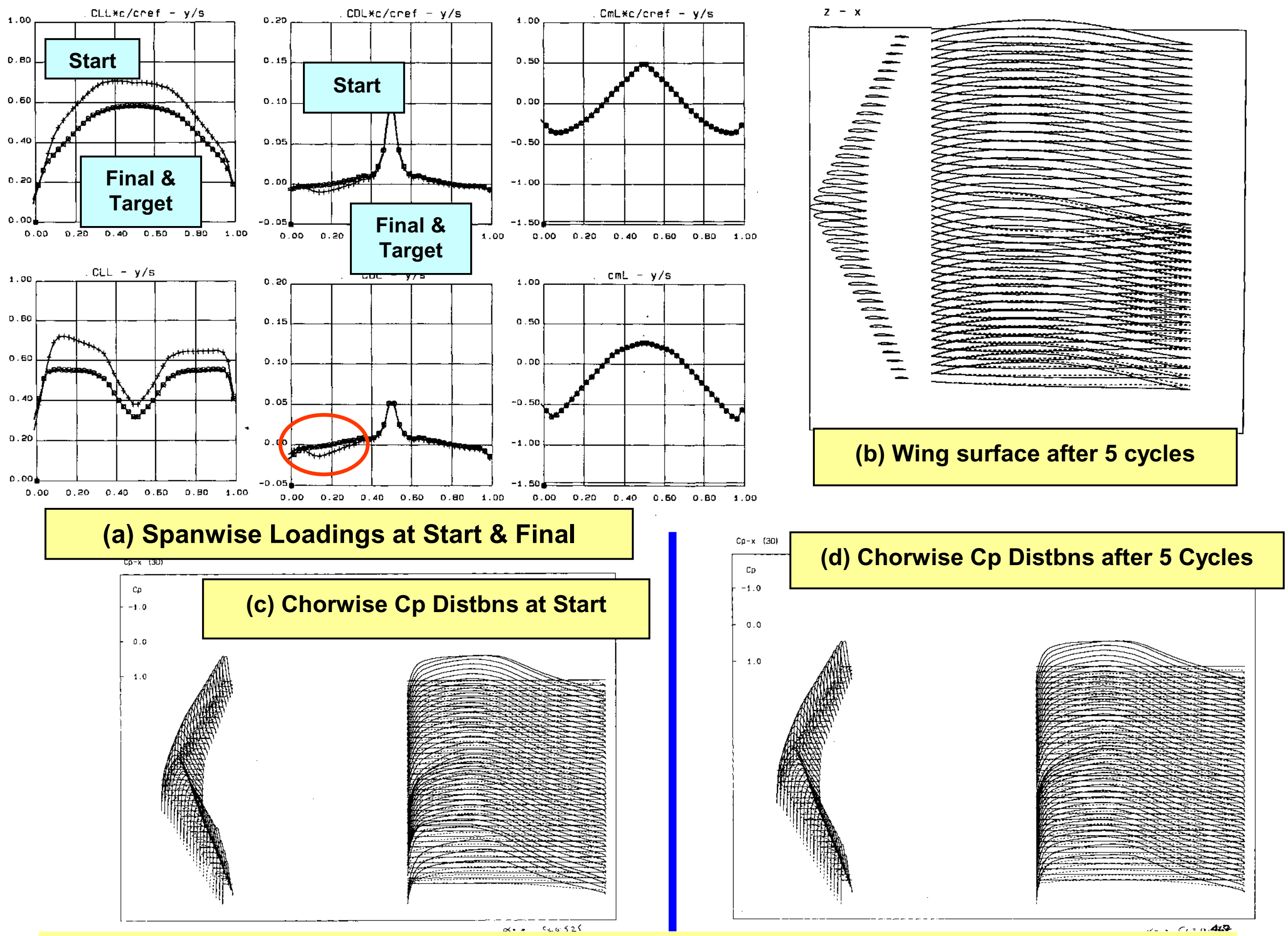


Fig. 18 2- Aircraft Formation, Typical CASE, RELAXED WAKE of LEAD AIRCRAFT
delx/b = -1.45, dely/b = -10%, delz/b = 0%

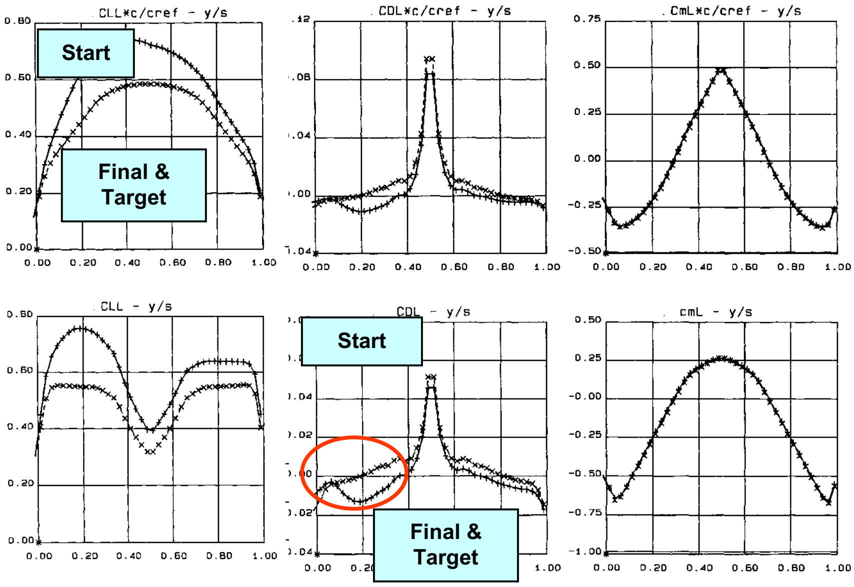


Fig. 19 LARGE LEAD (2.5:1.0), RIGID WAKE, Spanwise Loadings at Start & Final / Target, dx/b = 1.4, dy/b = +5%, dz/b = -5%

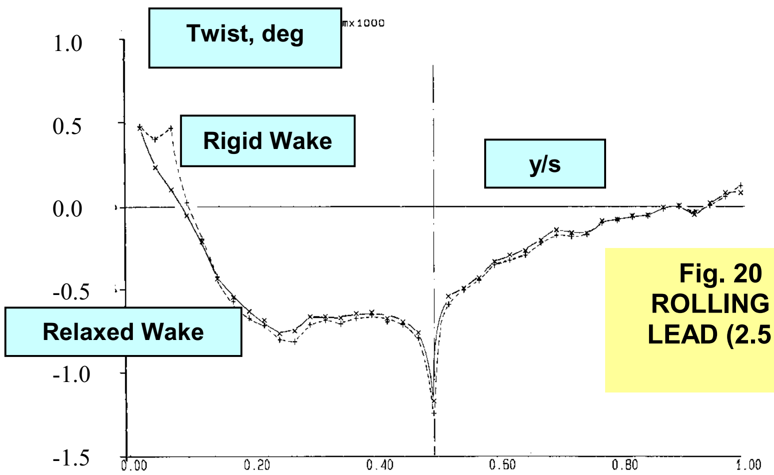


Fig. 20 WING TWIST REQUIRED TO CANCEL ROLLING MOMENT ON TRAIL AIRCRAFT, LARGE LEAD (2.5:1.0), RIGID and RELAXED WAKE, dx/b = 1.45, dy/b = +5%, dz/b = -5%

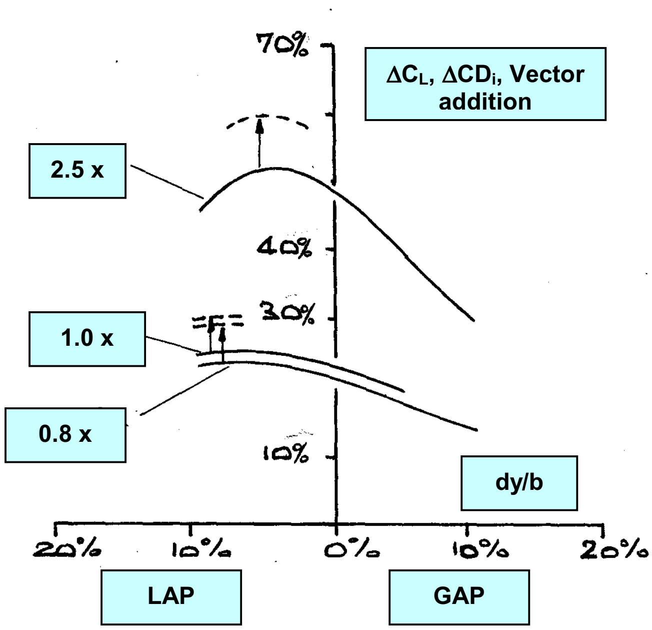


Fig. 21 TRAIL AIRCRAFT ΔC_L and ΔC_{Di} VECTOR MAGNITUDE, VARIATION WITH SPANWISE LOCATION, dz/b=-5% EFFECT OF LEAD AIRCRAFT SIZE, M=0.8

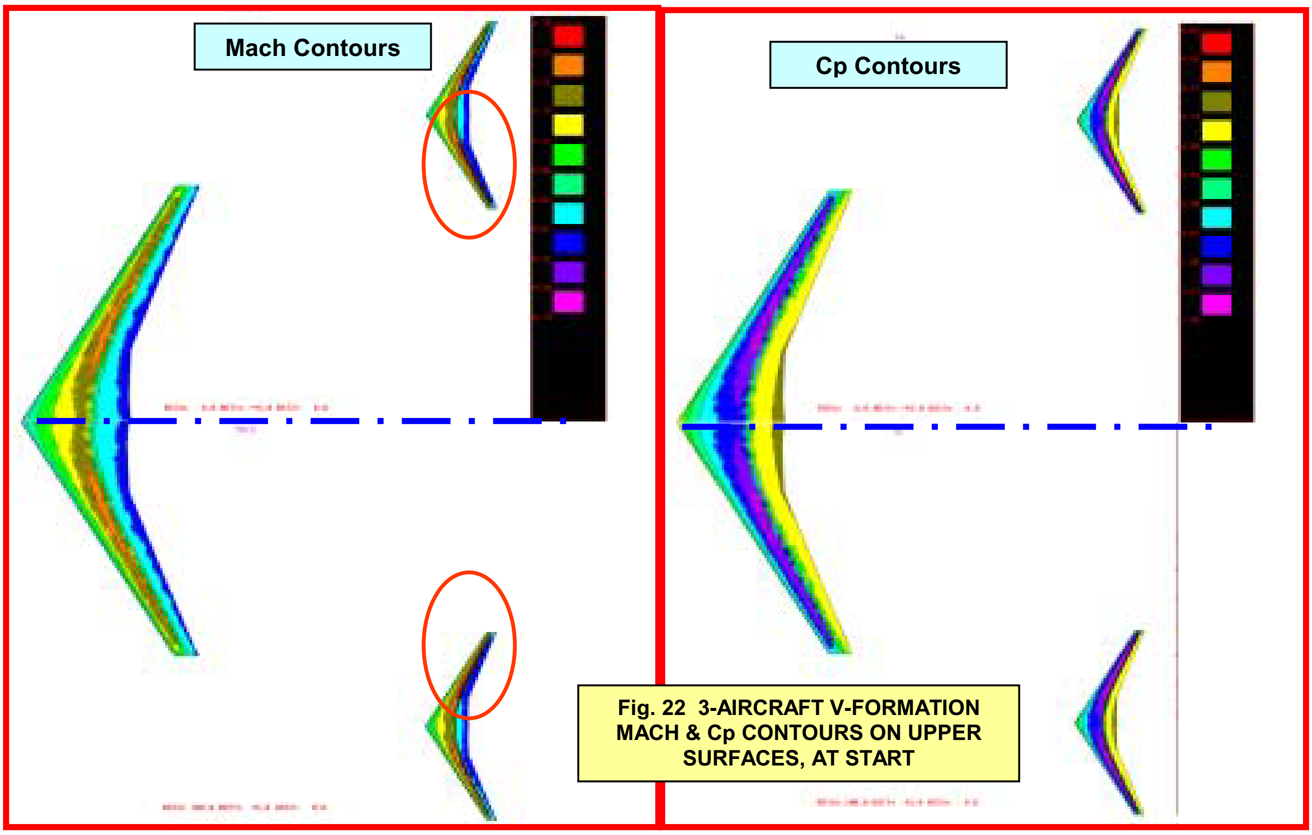


Fig. 22 3-AIRCRAFT V-FORMATION MACH & Cp CONTOURS ON UPPER SURFACES, AT START

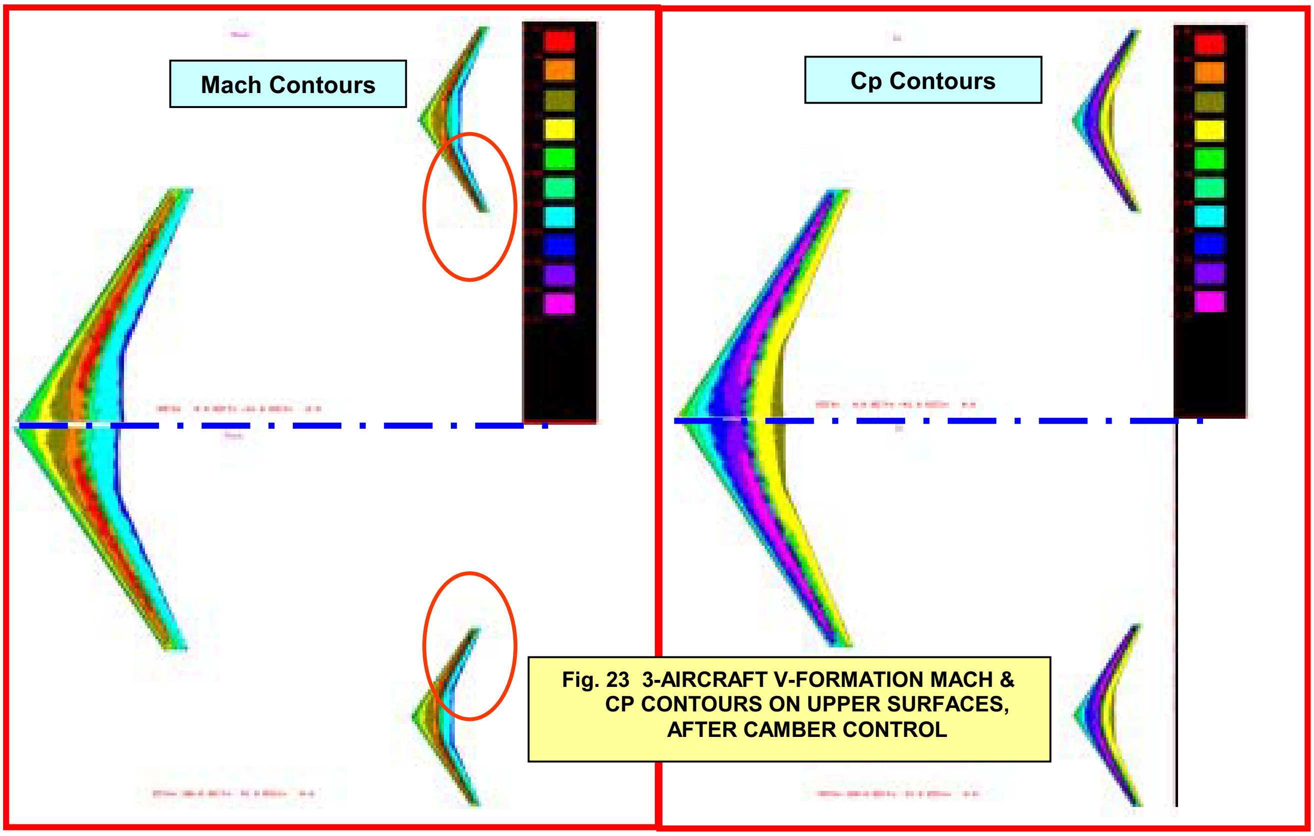


Fig. 23 3-AIRCRAFT V-FORMATION MACH & CP CONTOURS ON UPPER SURFACES, AFTER CAMBER CONTROL