Achieving Highly Efficient Civil Aviation - Why & How with Air-to-Air Refuelling, Review & New Developments

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ABSTRACT

Over the last 70 years, Civil aviation has dominated the transport scene with growth being upwards - bigger, farther and faster on an economic productivity basis (often neglecting fuel usage). After significant efficiency improvements over the first two decades (materials, wing sweep, high by-pass ratio engines, etc.), the trends are beginning to level off. Efficiency improvements currently, are of the order of a few percent and require high technology levels and great expertise.

With awareness of environmental issues, noise, emissions and energy / fossil fuel reserves, changes will happen and possibly in an accelerating fashion, to improve the carbon balances.

The NASA and ACARE (Europe) objectives are to reduce Aviation's environmental impact by 50% or more. This paper reviews the current work towards meeting such challenging objectives. A new set of Efficiency metrics of Civil Aviation allow development of 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 new operational strategy for civil aviation provides a way forward for Fuel-efficient Civil Aviation to meet the ACARE / NASA objectives, using smaller aircraft, adopting Air-to-Air Refuelling (AAR). This fits in well with Close Formation Flying (CFF). This paper reviews the AAR. Several avenues of further work arise.

1. INTRODUCTION

The last three generations have witnessed the civil aviation industry dominating world transport. Growth has been upwards - bigger, farther and faster on an economic productivity basis, **Figs. 1 - 2** from Refs.1-2. In **Fig.2**, the fuel load is included as part of the "useful" load. The future, over the next quarter century at least, will be with subsonic aircraft (Mach 0.8-0.85 cruise).

After significant efficiency improvements over the first two decades (materials, wing sweep, high by-pass ratio engines, etc.), the trends are beginning to level off. Efficiency improvements currently, are of the order of a few percent and require high technology levels and great expertise (carbon-fibre, laminar flow, winglets, etc.).

Range and Payload are highly inter-related. The general trend for increasing seating capacity with increasing range is shown in **Fig.3** (Ref.3). The question is whether this trend continues. We have seen ever-larger or longer-range aircraft and consequently ever-larger propulsion systems. MTOW of 1.2m lb is exceeded by the Airbus A380. Another current philosophy is that smaller, long-range aircraft enable more convenient high frequency point-to-point services.

However, flying variants with large passenger payloads (e.g.350+ pax) designed for short or medium ranges are "rare". Fielding (Ref.3) mentions an A-90 aircraft study: 500-seater (double-decker) for 2000 nm range.

There is rising awareness of environmental issues, noise, emissions and energy / fossil fuel reserves (Refs.4-5). The ACARE (Advisory Council for Aeronautics Research in Europe) objectives are to reduce Aviation's environmental impact (fuel consumption, CO_2 , noise by 50% and NO_x by 80%, relative to 2000). NASA "concurs". These environmental issues will require that changes are made and these may have to occur in an accelerating fashion. This is the "**Why part**".

We need to "break-out" for a new efficiency "plateau". This brings in the "**How part**".

A proposal is that Air-to-Air Refuelling (AAR), used appropriately, is dramatically effective in reducing fuel consumption. A "**Break-out**" to a new plateau is "visible" using available technology, exploiting novel operating techniques / procedures. We propose "**what can**" be done.

This Paper

We review the current work towards meeting such challenging objectives. The efficiency metrics (based on Ref.6) allow a "unified" consistent efficiency theme, relating Payload, Range, Fuel consumed and a measure of Unit Costs. We then derive Nangia "value" (cost) and noise effective efficiencies. These decrease dramatically as the aircraft design range increases.

A strategy is outlined, for a way forward towards highly fuel-efficient Civil Aviation using smaller aircraft, and adopting Air-to-Air Refuelling (AAR) and CFF (Refs.8-9).

Both AAR and CFF have been continuously developed in Military circles and we can envisage exploitation in the civil context. For the longer ranges, AAR and CFF, in concert, can go most of the way towards NASA and ACARE objectives. Both technologies sit above evolutionary advances in aerodynamics, propulsion and structures.

2. WHY ASPECTS - SETTING THE SCENE - EFFICIENCY METRICS

The total weight of an aircraft comprises three main parts: Operating Empty Weight (OEW), Payload (WP) and Fuel (WFT). The WFT may be subdivided into Block fuel (WFB) and fuel reserves (WFR). Payload - Range capabilities are limited by the Maximum Take-Off Weight (MTOW).

2.1. Payload Range Efficiency

A measure of aircraft efficiency is Payload Range Efficiency (PRE):

PRE=WP x R / WFB (or Payload x Range / Block Fuel).

Green (Refs.4-5) presented graphs of PRE as a function of design range at maximum payload (Combi or freighter). However, reserve fuel was not accounted for. Nangia (Ref.6) conducted an independent detailed exercise on modern civil (jet) aircraft, distinguishing between maximum payload and maximum passenger payload (Points A and D, **Fig.4**) as well as including fuel reserves. The data has been analysed in several ways and a whole host of cross-plots help in understanding and credibility.

The ratios, with respect to MTOW, of the main weight variables (OEW, WFB and WP) are shown vs Range R in **Fig.5** for Pt D. For a given aircraft, Range at Pt A will be shorter than that at Pt D. These results correlate as reliable "first-order" non-dimensional trends of PRE/X vs Z. These correct the "Greener-by-Design" (GBD) work, Refs.4-5.

X = V L/D / SFC, Z = R / X

$Z = R/X = \log_e [W1 / (W2]$ where W1 and W2 signify the weights at start and end of cruise.

W2 = W1 - WFBC where WFBC is weight of the Fuel burnt during cruise.

W1 = MTOW - WFBS where WFBS refers to the Fuel used for take-off, manoeuvring additional to the cruise. This is of the order of 2.2% (Ref.5).

Total Block fuel is then WFB = WFBC + WFBS.

Figs. 6-7 summarise the WFB/WP and PRE/X trends at Pts A and D operation. Green (Ref.7) supports the work. Radial lines of constant WFB/WP are shown. In fuel efficiency terms, aircraft perform better at Pt. A and the optimum design range is about 2500 - 3500nm, depending on the aircraft range parameter X. Note that from practical size and range considerations, Pt A curves extend to Z near 0.4.

2.2. "Nangia Value Efficiency Parameters" – Cost, Noise and Emissions

The PRE/X graphs do not directly give information about aircraft structure and size (hence cost and noise). To include these we look at the Value-Efficiency trends using OEW and MTOW. We define "Nangia Value Efficiency" parameters VEO and VEM and their 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 take-off noise, emissions and hence, airport and environmental 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 point D values. Note that the short-range aircraft are strongly favoured.

Often, aircraft do not fly at full capacity (passengers and/or cargo) and the implications need to be understood.

These graphs are informative in emission / noise characteristic terms as well as costs. Note that the newer aircraft are being planned for very long ranges>8000nm with huge Engines touching 110,000 lb static Thrust each (total T/W = 0.3).

2.3. How can we Improve Fuel Efficiency?

To improve PRE, VEM and VEO, we need to:

- Increase V and / or L/D. Reduce SFC
- Reduce drag. Drag comprises several components. Peak L/D occurs when lift-induced drag is half of the total drag.
- Reduce OEW, allowing increased payload fraction. Flying wings may have a lower figure.
- Reducing SFC implies: Flying near optimum propulsive conditions e.g. Mach 0.85 for Jets with optimum bypass. Prop-fans give a lower SFC, but at the expense of higher weight / reduced cruise speeds.
- Increasing VEMPX and VEOPX: reduce the overall weight and structure per unit payload.
  - Operate at or near Point A (WPmax)
- Modify airline operating procedures.

3. TECHNOLOGY TRENDS, FUEL COSTS, CONFIGURATIONS

3.1. Current Technology Trends in Relation to ACARE Objectives

Fig.9 (Refs.10-11) shows the reducing fuel burn trend based on the 1960s Comet up to the present day. It has reached 67% currently but the rate of improvement is beginning to level off as technologies mature. It needs to be reduced by 80% by 2020 and that implies an improvement rate last seen in 1970's! Similarly, the noise reduction trend (**Fig.10**, Ref.11) shows 75% in the last 50 years and now reflects "maturity".

Fig.11 refers to distributions of stage length, fuel burn and NOX emissions (Ref.10). The cumulative fuel burn is shown in **Fig.12** (Ref.11). Most of the flight ranges are below 6200nm. Currently 35% of air transport fuel is spent on flights above ranges of 2700nm. In future, budget airlines will offer fly long ranges and shift the figure to 50%. It is remarkable the industry continues with aircraft capable of 9000nm+ range.

3.2. Impact of Fuel Costs

Fig.13 (Ref. 12) shows the volatile nature of fuel prices since 2001. The trend continues upwards in a non-linear fashion. The cost/barrel was about $30 in 2004. In May 2008, it reached $135. The corresponding costs for aviation fuel rose from 75c per USGallon in 2004 to nearly $3.25 now.

In Aircraft Cash Operating Costs terms, **Fig.14** (Ref.12) illustrates the impact of doubling the fuel cost from $1.74 to $3.48 / US gallon. Short and long -range aircraft (B737-800, B777-200ER) are considered. With doubling of fuel costs, for the short ranges, the fuel cost proportion increases from 36% to 46%. For the longer ranges, the comparable figures are 55% to 63%. Proposed Carbon Emission trading will involve such distinctions.

3.3. Possible Future Configuration Technology

Exploiting natural or hybrid laminar flow (to reduce skin friction drag) has been studied and demonstrated over many years. Several configurations (**Fig.15**) have been proposed. Perceived integration and practical difficulties have prevented its application.

Advanced configurations employing Blended Wings (BWB) have been proposed, **Fig.16**. These could offer lower empty weight for large aircraft. Propulsion integration remains challenging.

The Oblique Flying Wing (OFW) has been revived (DARPA and USAF). A prototype to demonstrate supersonic flight is being built in USA by Northrop Grumman. We have recently undertaken studies into such wings. A subsonic / transonic configuration on the lines of **Fig.17**, but with fixed sweep, may be attractive for long and short range applications (Ref.13). This will avoid pivot penalties and exploit a simple lighter wing structure. Control problems have been solved during the NASA work on the AD-10 in the 1980's.

For short-range aircraft, Open fans may be a viable way forward for improving SFC by 10-15% by 2020, **Fig.18** (Ref.12). There are significant challenges about noise, maintenance, reliability and configuration integration. Further, cruise speed is lower. Range Parameter X may not be appreciably increased in relation to the conventional jets.

3.4. Exploiting Operational Technologies – "Out of the Box" Thinking

One obvious solution proposed (GBD) in Refs.4-5 is to fly long range in a series of short hops, refuelling at intermediate airports. Although at first sight, this seems fuel-efficient, using the much more efficient 3000 nm range aircraft, it 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 due to additional take-offs and landings per journey. Airport congestion is not necessarily improved unless all-new "staging" airfields are built. Further, Air Traffic Control (ATC) operations at intermediate airfields would increase. Costs associated with intermediate airport usage would need to be offset.

With some **lateral** thinking (Refs.14-15), we can deal with most of these concerns in one stroke, availing of a current proven technology. AAR is a common place, daily routine in military operations, **Fig.19**. It has reached a level of autonomy with advances in night vision, control systems and differential GPRS. Wet autonomous hook-up is planned for 2009 with RARO system. A significant development from the Netherlands is the Tanker Remote Vision System (TRVS). This gives 230° stereoscopic field-of-view of the refueling operation. With RARO the new TRVS offers 10 times better stereo acuity than the existing system (3.3 times better then the human eye).

The AAR technology complements CFF, used to great advantage in nature.

We are now in the "**How-part**". Benefits arise.

4. HOW – WITH AIR TO AIR REFUELLING (AAR) IN CIVIL AVIATION

4.1. Using 3000nm Aircraft for AAR over Longer Ranges

The approach is to design representative aircraft (using Ref.16) for carrying the same payload of 250 pax. over 6000, 9000 and 12000 nm (**Fig.20**) and then estimate the fuel saved by using the 3000 nm range aircraft with AAR over the longer ranges. This ensures that we **compare** "like with like" – **same technology level**. **Figs.21-23** show relevant results. All this points to substantial fuel savings – of the order of 30-50% depending on range, **Fig.24**. Further, the 3000nm aircraft gain less altitude during cruise-climb (constant CL) - useful for control and reducing off-design penalties.

Further, over a 3000nm interval, the gain in altitude during cruise-climb (constant CL) is less than for the longer range aircraft. This is useful for control and reducing off-design penalties.

Tankers for AAR, Tanker Fuel Off-load Efficiency

A key issue is that Tankers for civil work operate in a different way to Military ones. Whereas the latter essentially operates as a "garage in the sky" (long endurance), the civil ones will be "purposeful" and shorter, more efficient flights are envisaged. Tankers can be based away from civil airports (origin or destination) e.g. on un-congested airfields, close to fuel supplies.

In a typical civil AAR scenario, **Fig.25**. a tanker takes off (1) and refuels receiver one, East bound (3-4). It then manoeuvres to refuel receiver two, West bound (5-6) and then receiver three, also West bound (7-8). The off-load factor for the tankers (factor RT) is 3-6 times their own usage.

Using a 3000nm aircraft, **Figs.26-27** show the substantial savings in fuel and increases in PRE/X vs Range with tanker off-load RT efficiency.

This implies that reasonably efficient tanking, giving RT near 4, is adequate for substantial overall efficiency gains. Beyond RT=4, the gains are small. Although it helps to have better performing tankers, extensive advances are not required for adequate tanker off-loads. Current tankers will allow significant fuel savings to be made on aircraft refuelled over longer ranges.

At this level of RT = 4.0, the gain in PRE/X is about 60% at 6000nm. The corresponding figure for 9000nm is 80%.

4.2. Part Range Refuelling and Maximum Pt A Payload, Taking off Lighter

We have taken as examples the B757-300 (MTOW 270,000 lb) and the A330-200 (MTOW 507,065 lb) to assess the effect of part-range refuelling, flying with maximum Point A payload (best efficiency).

The B757-300 can shift its maximum payload of 68,200 lb over a range of 2388 nm (Point A operation) without AAR. A typical weight breakdown is in **Fig.28(a)**. **Fig.28(b, c & d)** shows the weight breakdown starting off with different take-off weights (Light, Intermediate and MTOW) and a single refuel of 47,850 lb (WFREF) at the respective ranges completed. After AAR the aircraft are at MTOW and can complete a further 2388 nm. **Fig.28(e & f)** shows the weight breakdown starting off at MTOW and then refuelling after 2388 nm with either 10% or 50% WFREF.

The A330-200 could transport its maximum payload of 106,800 lb over a range of 4200 nm (Point A operation) without refuelling. **Fig.29(a)** shows typical weight breakdown. The above exercise is repeated for the A330-200 in **Fig.29(b-f)**. WFREF is 113,730 lb.

Fig.30 shows the PRE / X - Z relationships for both the A330-200 and the B757-200 with AAR. For each type, the lower line results from taking off at less than MTOW and then refuelling with 100% WFREF. The upper line results from taking-off at MTOW and then refuelling with various fractions of WFREF. Note the substantial improvements c.f. the current PRE/X trends for Pt A and Pt D. Further work is needed with other aircraft.

4.3. Associated Benefits

Operational issues will, no doubt, need to be solved. 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:

- a “life-line” / safety-net to newer technologies e.g. laminar flow designs.
- Lighter, quieter, safer T/O
- Supersonic flight (T/O light -inefficient low speed phase),
- More efficient Business jet usage
- Greater use of Regional Airports, less intense ATC activity,
- A to B operations and flexibility,
- Single design for all routes. One-off certification for flight crew, ground staff, maintenance staff, etc. One engine type per airline fleet.

4.4. What Can or Needs to be Done

Conclusions and recommendations will create an element of surprise. If Aviation is to be serious about fuel saving, then several topics can be initiated immediately:

(1). Design Smaller Aircraft (with 40-50% savings in MTOW) for shorter / medium ranges giving more Efficiency - Fuel-wise and Value-wise,

(2). Set up simulations using AAR for long ranges. No doubt, there will be operational and regulatory problems to be studied and solved.

(3). Initial trials to establish fuel savings using cargo fleet operators. Possibility of short-term subcontracting of cargo operations to military to make best use of established AAR routines.

With acceptance of these ideas, we can make a “**plateau**” jump (Ref.17) in Aviation Efficiency and Operations. New cost-economic, efficient Aircraft with lower propulsion needs and new designs of task-specific Tankers will emerge. We look to renewed collaboration amongst academia, research and industry. AAR sits on top of any technology advances in propulsion, structural & aerodynamics.

5. GREENER ENVIRONMENT - CIVIL AAR

In an integrated environment of passenger travel and fuel delivery etc, it is interesting to assess the effect of AAR on fuel usage for carrying 250 passengers over different flight ranges with typical, mean travel distances to and from the airports.

The schematic of **Fig.31** shows the total fuel used to transport 250 passengers over a flight range of 6000 nm without AAR is 173,053 lb. This comprises 161,269 lb aircraft block fuel, 11,200 lb passenger surface travel fuel and 1,034 lb road tanker delivery fuel. With AAR, using a 3000 nm aircraft, the total fuel consumed is 107,041 lb, **Fig.32**. This includes AAR tanker fuel. This implies a saving of 38%.

For the 9000 nm service, **Figs.33 & 34**, show the breakdown of total fuel used without and with AAR respectively. For this range, AAR offers a fuel saving of 41%.

Using smaller aircraft reduces wake problems at the airport and allows increased movement rates. Pressure on hubs can be lessened by using regional airports for the longer range. **Fig.35** represents a first attempt at refuelling zones.for some routes.

6. TYPICAL ISSUES

It is worth listing the issues perceived.

Civil Scene Different from Military

- Civil operational requirements are more stringent.
- Utilisation may be more intense
– Fuel system design capabilities

– New Training phases.
– Reliability has economic implications.

Considerations & Systems

- Contact (Tanker / receiver / boom).
- Anti-collision system (TCAS) modified
- Adequate diversion procedures similar to twins.
- Propulsion limitations and handling qualities
- Wake interactions
- Passengers (AAR operation in view or not!)
- Electro-static charges
- Ensure that fuel leakages are safe
- Allow for speed or altitude
- IFR Conditions

Typical Refuelling Operation

During a specified time-frame, the Tanker controls the AAR operation, providing relative position, speed and attitude data. Receiver obeys via autopilot data-link, monitors its fuel but is required to carry out only minimal trim corrections. Receiver can break off contact as needed. This way, training is minimized for the receiver crew.

Research Areas

Presently, the tanker off-load capability is about 10-12,000 lb /min. A larger diameter boom could achieve 15-18,000 lb/min. For 45,000 lb transfer, a 3-minute hook-up can be envisaged. The tanker needs to be capable of high thrust levels for short periods. However, the demand gets lower as the fuel off-load continues.

For new tanker designs, high speed and high altitude refuelling could be introduced. Off-centre refuelling in a favourable upwash field can be envisaged, e.g. efficient tanker booms nearer the wing tips – joined wing type with stiff wings. Forward projecting centerline probes may be subject to Aero-elastic effects.

An efficient twin-aisle aircraft for medium ranges is required. This may be based on the A300. New aircraft purchases would be with AAR specifically in mind.

Navigation and Communications need to be developed for AAR operations. These include Transponders, TCAS using special AAR mode (Link-up, Homing devices and Monitoring CCTV).

Spatial awareness techniques need to be developed in view of aerodynamic interferences and wakes/propulsion exhaust proximities.

7. CONCLUDING REMARKS

For the last 70 years, the civil aviation has dominated the world transport. 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.). In the near future, environmental issues will force aviation to cut emissions, either by further technological advances or by reducing operations.

We have mentioned 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 naturally to proposing AAR within civil aviation.

The benefits of commercial AAR lie in reduced mission fuel burn and the ability to have virtually unlimited range from almost any airport. Tankers can be based away from origin or destination e.g. on un-congested airfields, close to fuel supplies.

Certification requirements, safety issues, logistics and public opinion would require civil AAR to be phased-in over a period of time despite the enormous economic and social benefits.

Military operators (NATO, US, UK, etc.) already have a proven and effective AAR network. Initially, this could be utilised by civil cargo carriers. Once the AAR safety issues have been addressed and the fuel savings ratified with cargo aircraft, AAR could be phased in on the civil passenger scene. Operators would modify their existing aircraft for AAR.

Commercial AAR operations however, differ from military operations, particularly in safety standards. The civil tankers are more "purposeful".

We need to take a new, objective and unbiased viewpoint. The studies 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 AAR, no amount of predictive work is capable of giving a complete insight into possible implementation. Military has vast experience on AAR and close proximity flying. There are significant advances in differential GPS, navigation, ATC, autonomous flying that could ease CFF and AAR into the civil world.. 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 satisfying ACARE objectives.

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NOMENCLATURE

AR	Aspect Ratio
ATC	Air Traffic Control
b	= 2 s, Wing span
c	Local Wing Chord
c_{av}	= c_{ref} = S/b, Mean Geometric Chord
C_A	= Axial force/(qS), Axial Force Coefficient
C_{AL}	Local Axial Force Coefficient
C_D	= D /(q S), Drag Coefficient
C_{Di}	Lift Induced Drag Coefficient
C_{DL}	Local Drag Coefficient
C_L	= L/(q S), Lift Coefficient
C_{LL}	Local Lift Coefficient
C_m	=m/(qS c_{av}), Pitching Moment Coeff.
C_{mL}	Local Pitching Moment Coefficient
C_P	Coefficient of Pressure
D	Drag force
DOC	Direct Operating Cost
GPS	Global Positioning System
kt	Knots, nm/hr
L	Lift Force
L/D	Lift to Drag Ratio
m	Pitching moment
M	Mach Number
MTOW	Maximum Take-Off Weight (=TOW)
OEW	Operating Weight Empty (also WOE)
OEWR	= OEW / MTOW
Pax	Passengers
PRE	Payload Range Efficiency WP*R/WFB
q	= 0.5 ρV^2, Dynamic Pressure
R	Range
s	semi-span
S	Reference Area
SFC	Specific Fuel Consumption, lb (of fuel)/hr / lb (thrust) = 1/hr
T/W	Thrust to Weight Ratio
V	Airstream Velocity (kt)
WP	Payload (W_P)
W_F	Fuel Load (Block + Reserves = Total)
WFB	Block Fuel
WFREF	Maximum Refuel Load
WFT	Tanker Fuel
x,y,z	Orthogonal Co-ordinates, x along body
X	= V L/D / SFC, Range Parameter
Z	= R / X, Non-Dimensional Range
α	AoA, Angle of Attack
λ	Taper Ratio, c_t/c_r
Λ	LE Sweep Angle
η	= y/s, Non-dimensional spanwise distance
ρ	Air Density

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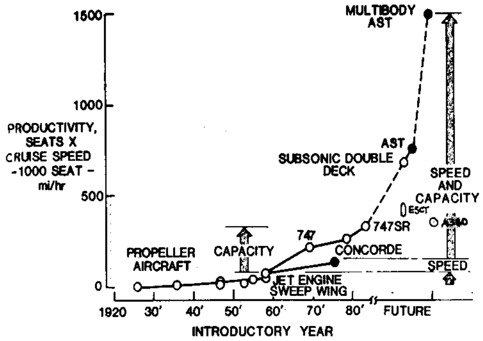


Fig. 1 IMPROVEMENTS IN PRODUCTIVITY OF LONG-RANGE TRANSORT AIRCRAFT (Dollyhigh et al, Ref.1)

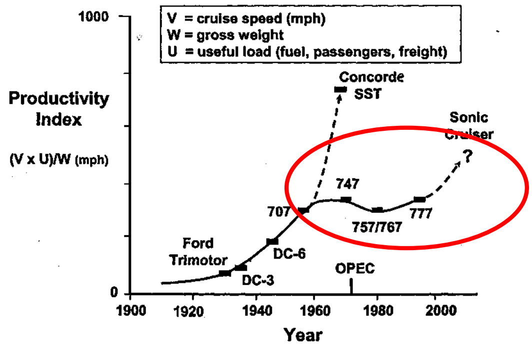


Fig. 2 EVOLUTION IN THE PRODUCTIVITY OF COMMERCIAL AIRCRAFT (McMasters, Ref.2)

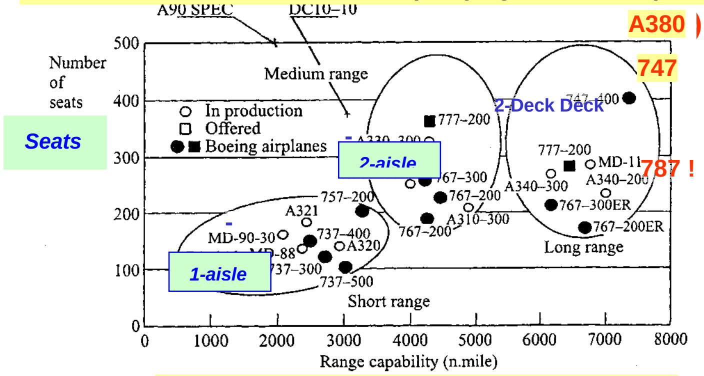
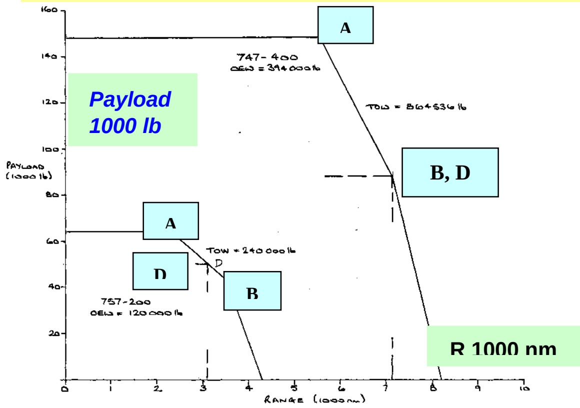


Fig. 3 SEAT & RANGE CAPABILITY



B757-200 & B747-400

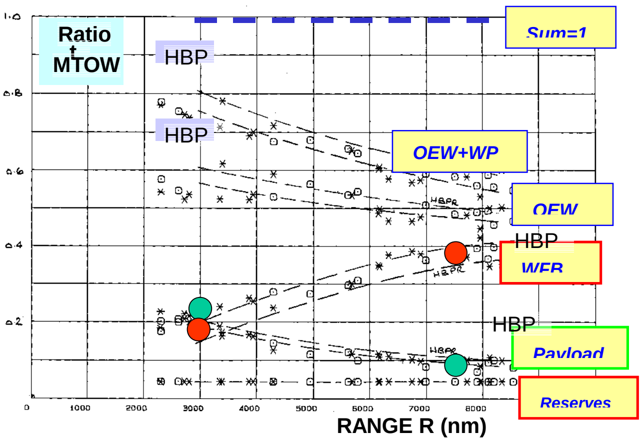
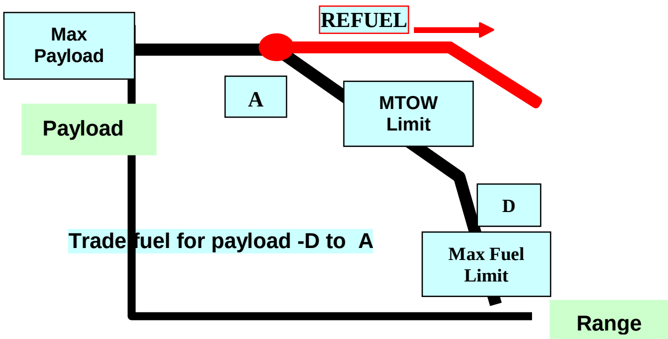


Fig. 5 DERIVED WEIGHT RATIO TRENDS



Explaining Various Limits in the Payload-Range Diagram

Fig. 4 Typical Payload Range Diagrams , LIMITS

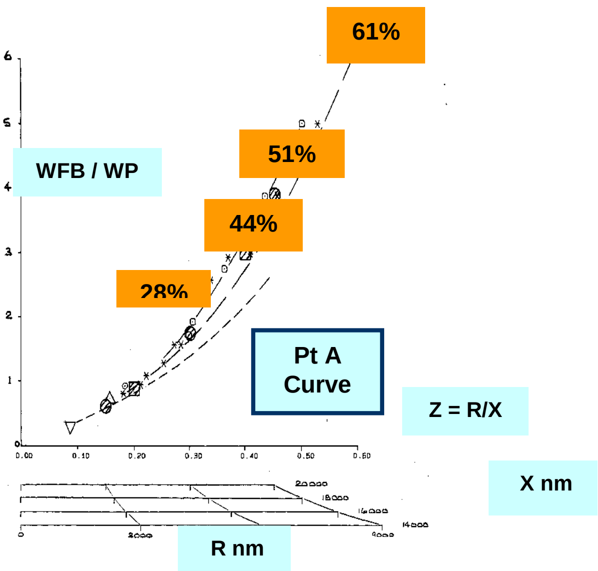


Fig. 6 WFB / WP vs Z = R/X, Pt A & Pt D

Note: Parallel Scales of R Implied for Different X Values

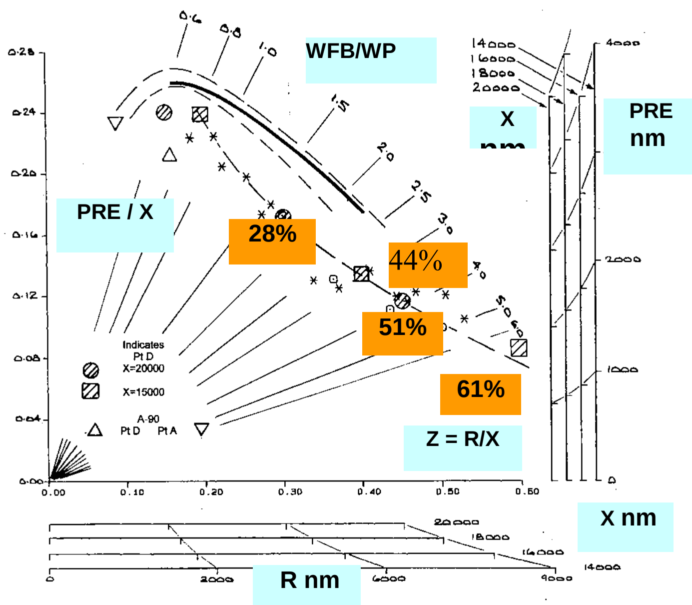


Fig. 7 PRE/X vs Z = R/X, Pt A & Pt D

Note: Parallel Scales of PRE Implied for Different X

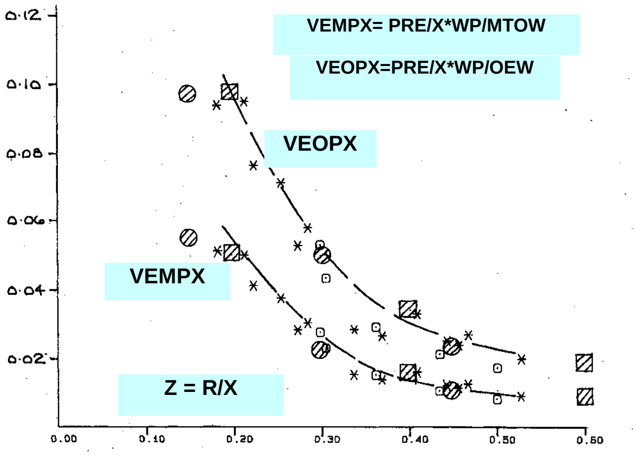


Fig. 8 CIVIL AIRCRAFT, NON-DIMENSIONAL EFFICENCY PARAMETERS VEMPX & VEOPX AT Pt D, BASED ON Ref.5

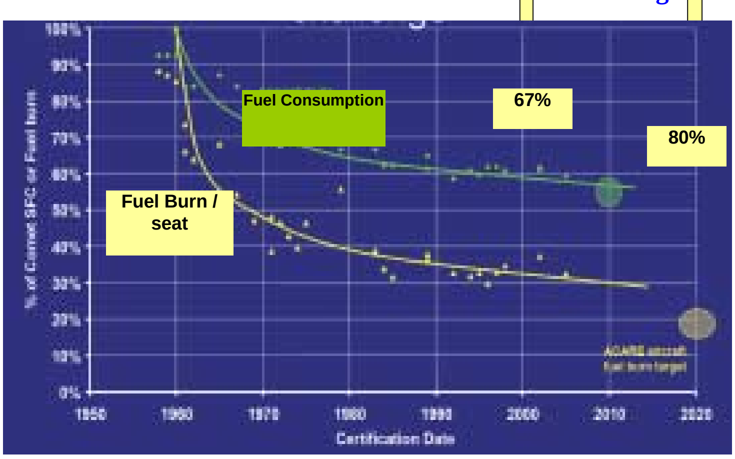


Fig. 9 REDUCING FUEL BURN TREND, 1960 TO 2000

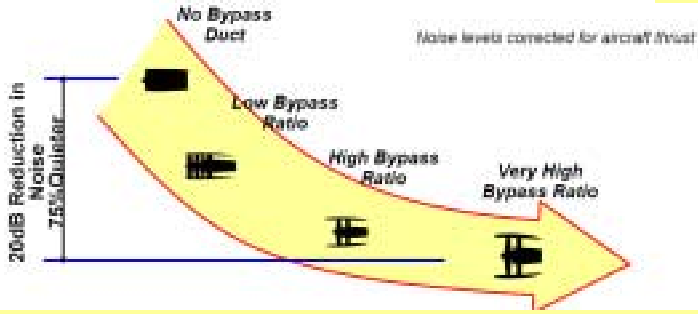


Fig. 10 ENGINE NOISE REDUCTION, 1960 to PRESENT

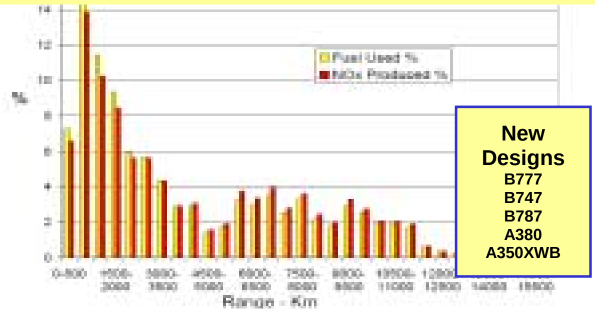


Fig. 11 DISTRIBUTION OF STAGE LENGTH, FUEL BURN & NOX EMISSION

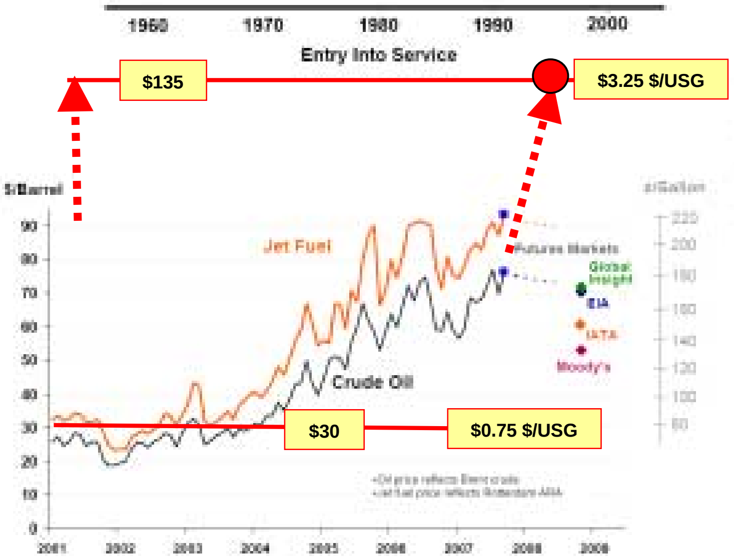


Fig. 13 FUEL COST ESCALATES (from 2001,Moody, IATA & Ref.10)

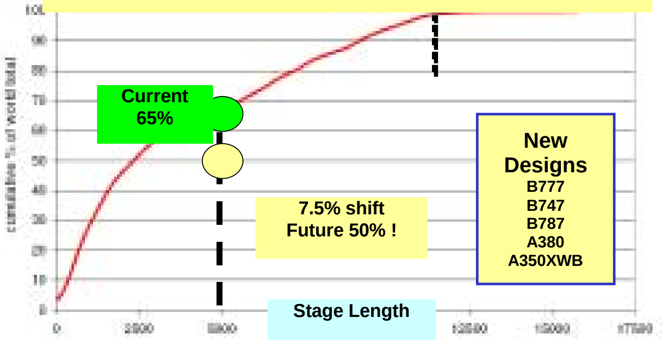


Fig. 12 CUMULTIVE WORLD FUEL BURN vs STAGE LENGTH

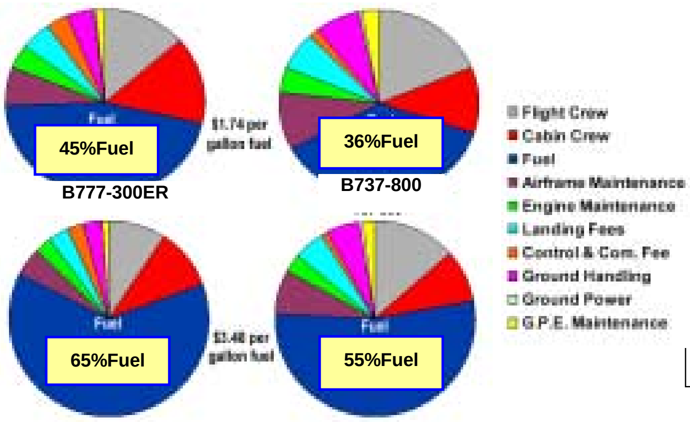


FIG. 14 IMPACT OF FUEL COSTS ON AIRCRAFT CASH OPERATING COSTS, 737 & 777 SERIES (Ref.10)

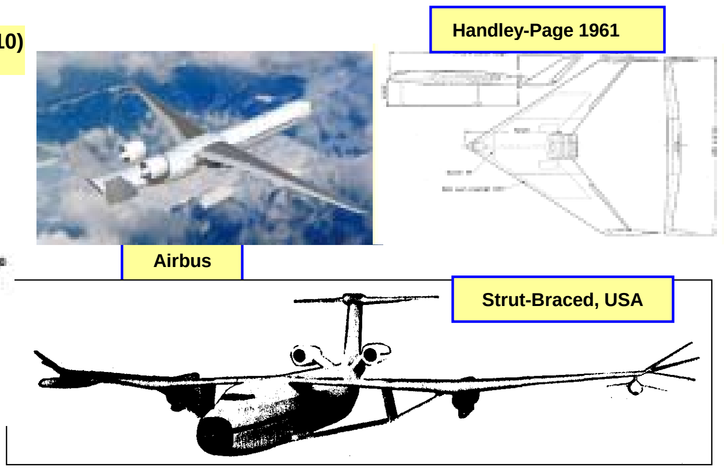


Fig. 15 EXPLOITING LAMINAR FLOW - PROPOSALS

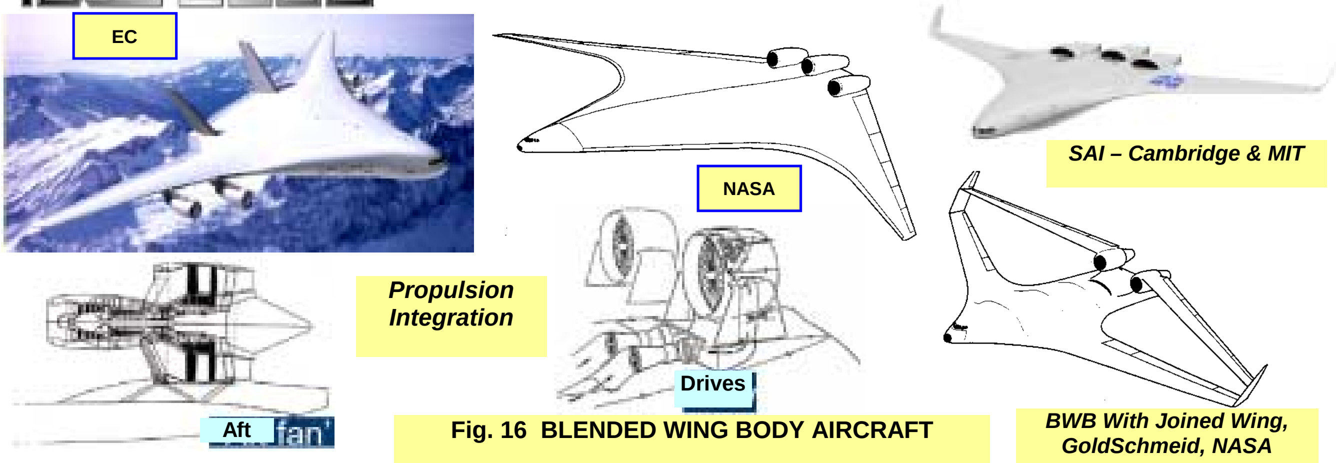


Fig. 16 BLENDED WING BODY AIRCRAFT

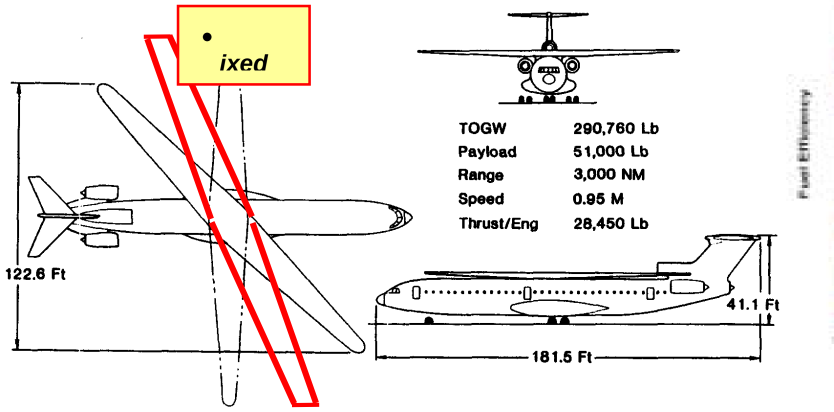


Fig. 17 FIXED OR VARIABLE SWEEP OBLIQUE WING CONFIGURATIONS

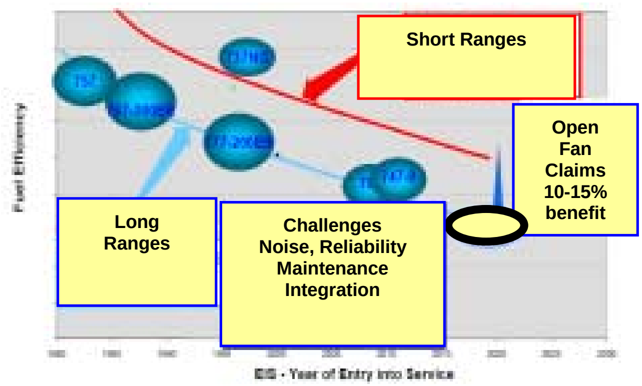


Fig. 18 OPEN FANS WORTH CONSIDERING ! (VerWay)

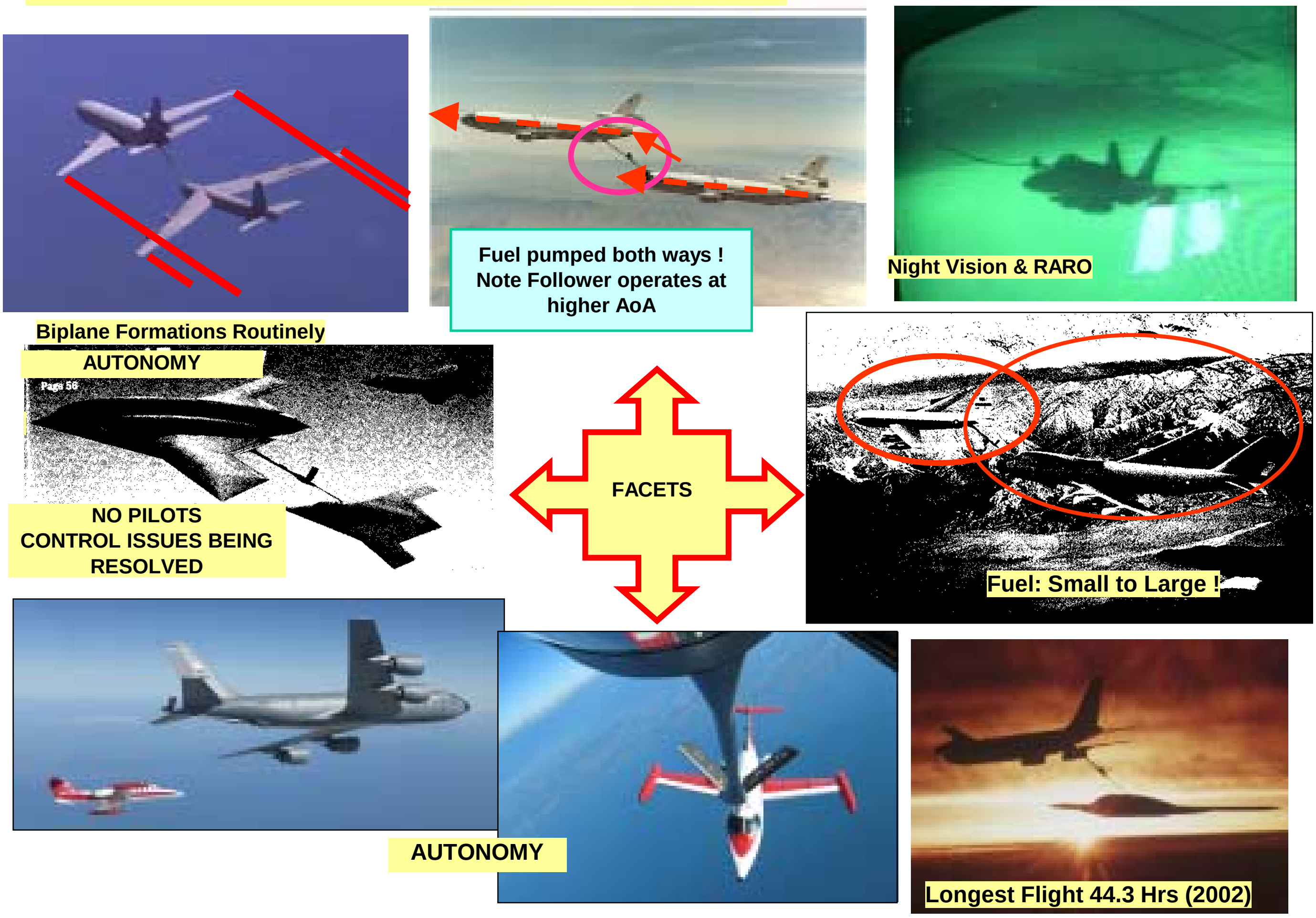


Fig. 19 TYPICAL AAR OPERATIONS, MILTARY

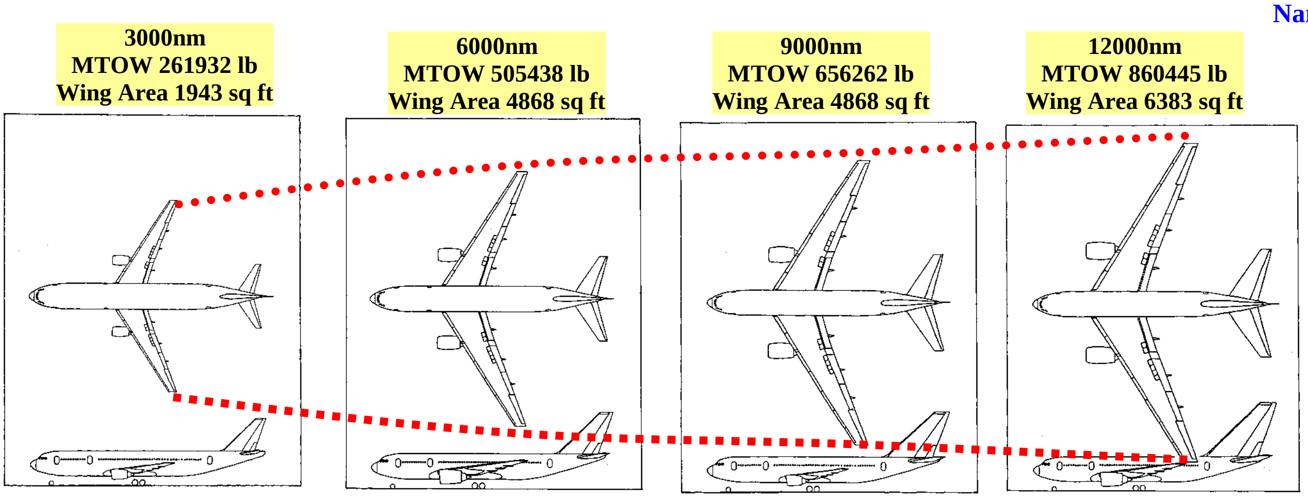


Fig. 20 COMPARING AIRCRAFT DESIGNED FOR DIFFERENT RANGES, 250 Pax.

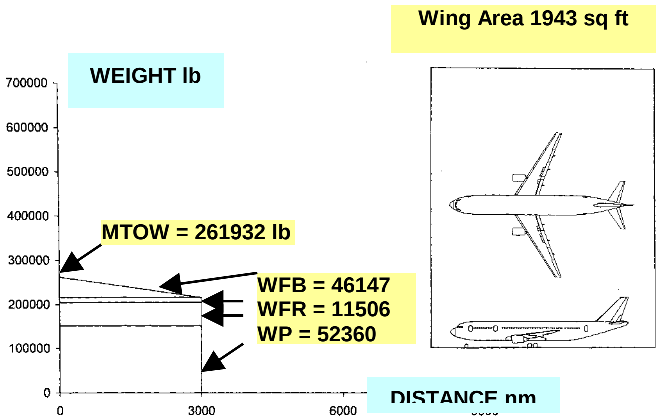


Fig. 21 AIRCRAFT WEIGHT VARIATION WITH DISTANCE FOR 3000 nm RANGE NO REFUELLING, 250 PAX., OEWR = 0.58, X = 15077 nm

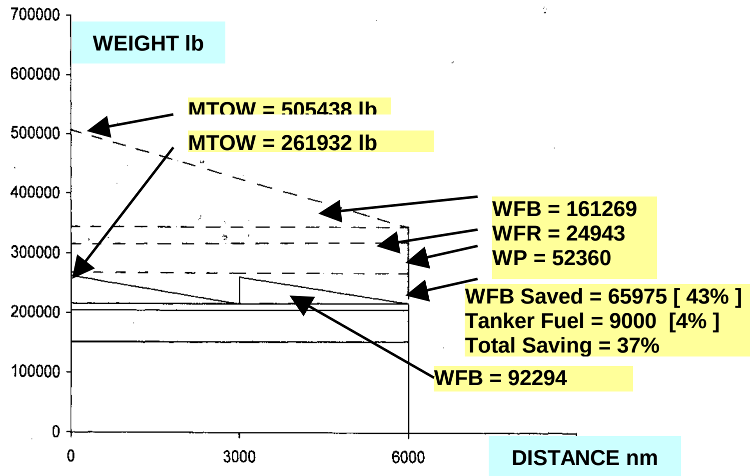


Fig. 22 AIRCRAFT WEIGHT VARIATION WITH DISTANCE FOR 6000 nm RANGE AIRCRAFT, REFUELLED ONCE cf AIRCRAFT WITHOUT AAR, OEWR = 0.528, 250 PAX. 3750 ft^2, X = 15077 nm

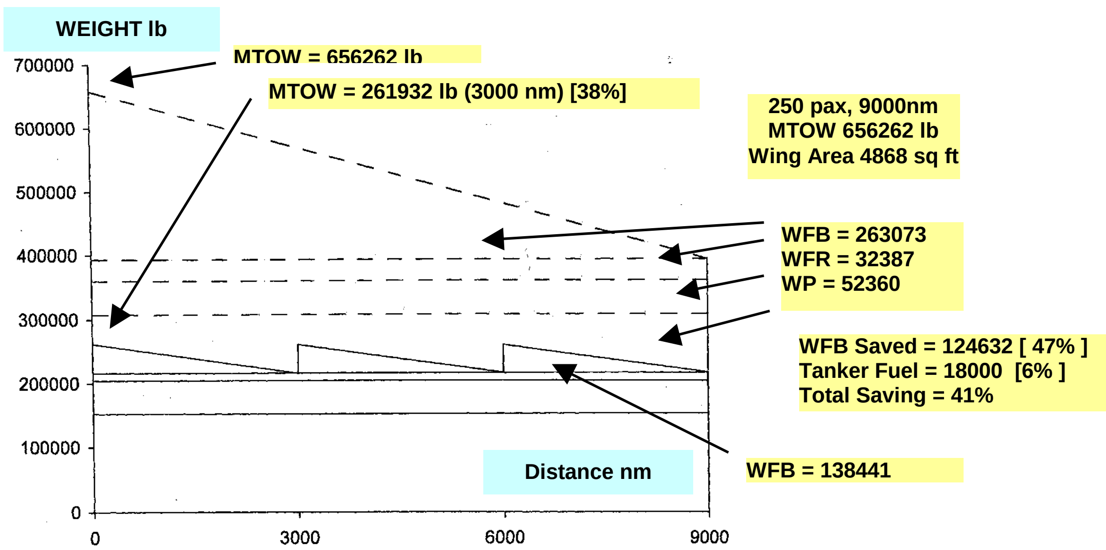


Fig. 23 AIRCRAFT WEIGHT VARIATION WITH DISTANCE FOR 9000 nm RANGE AIRCRAFT (X = 15077nm) REFUELLED TWICE cf AIRCRAFT WITHOUT REFUELLING, OEWR = 0.47, 250 PAX., S = 4968 ft^2, X = 16897

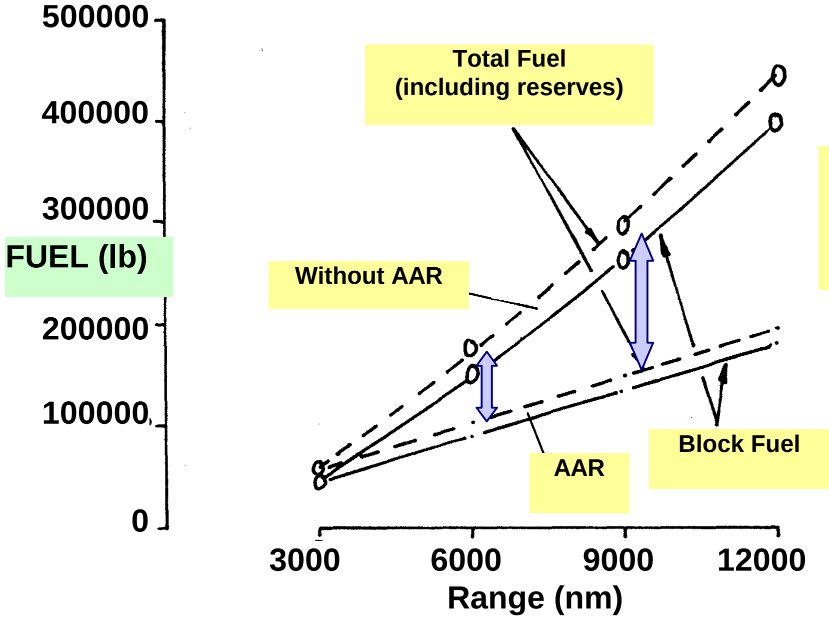


Fig. 24 FUEL SAVED FOR FLYING 6000 nm, using AAR on 3000nm Aircraft, INCLUDING TANKER CHARACTERISTICS, 250 Pax

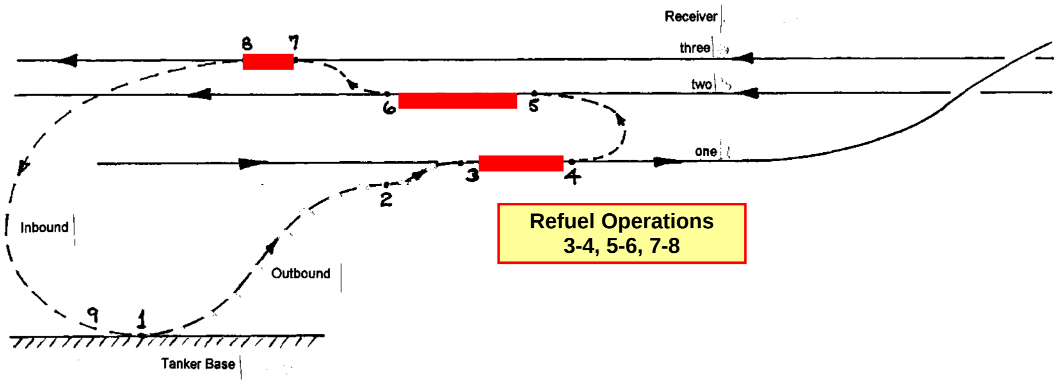


Fig. 25 TYPICAL CIVIL AAR TANKER OPERATING SCENARIO

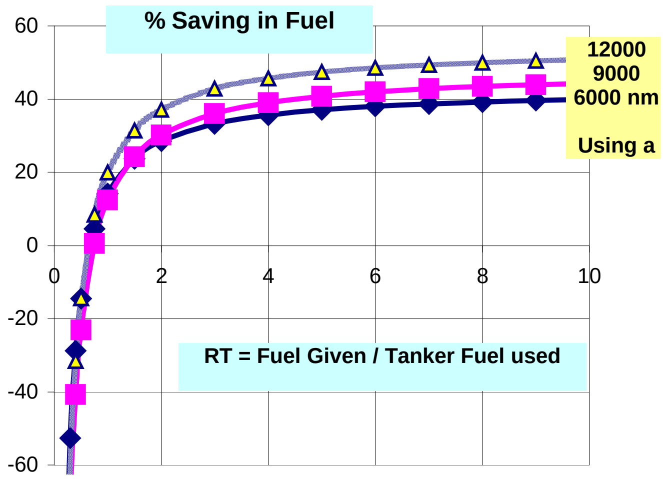


Fig. 26 SAVING IN TOTAL FUEL CONSUMED (%) USING A 3000 nm AIRCRAFT WITH AAR, VARIATION WITH TANKER FUEL OFF-LOAD EFFICIENCY (RT)

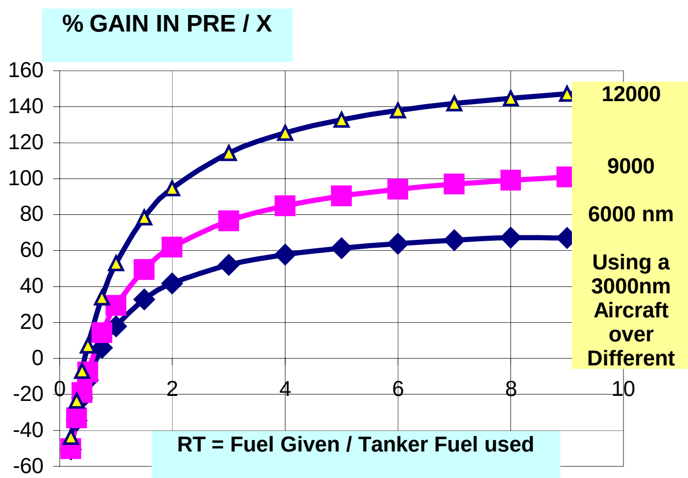


Fig. 27 % IMPROVEMENT IN PRE / X USING a 3000 nm AIRCRAFT WITH AAR, VARIATION WITH TANKER FUEL OFF-LOAD EFFICIENCY (RT)

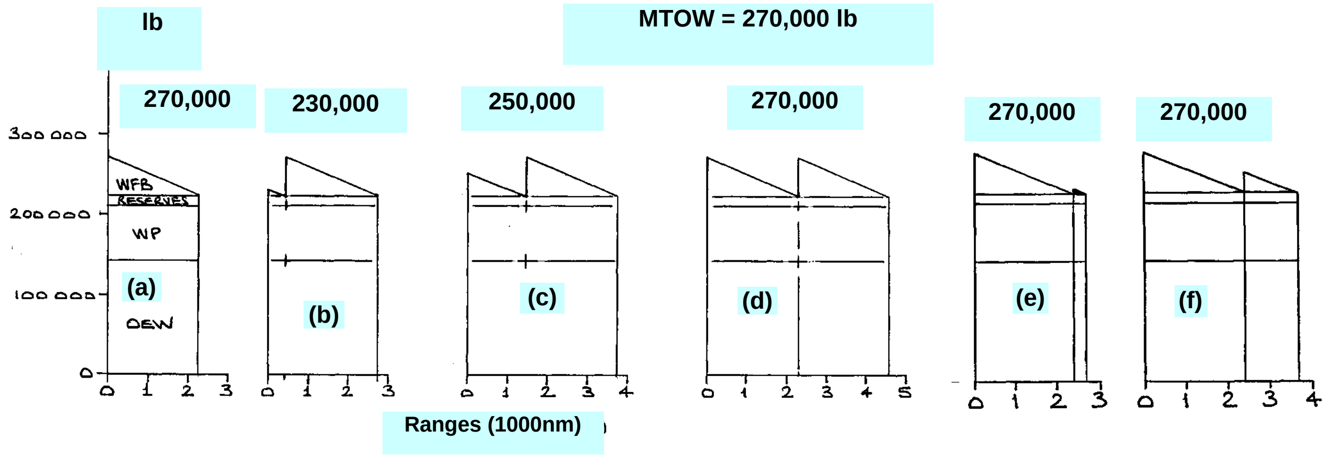


Fig. 28 VARIATION OF WEIGHT WITH DIFFERENT REFUELLING OPTIONS ON B757-300, One Refuel, 47850 lb, Flying Lighter

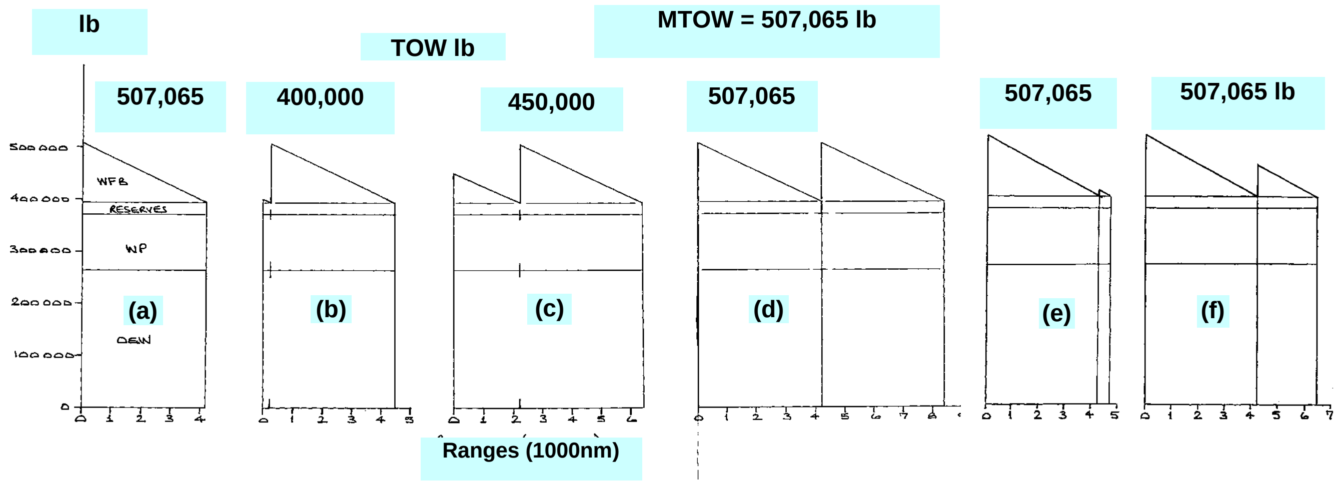


Fig. 29 VARIATION OF WEIGHT WITH DIFFERENT REFUELLING OPTIONS ON A330-200, One Refuel, 113,730 lb, Flying Lighter

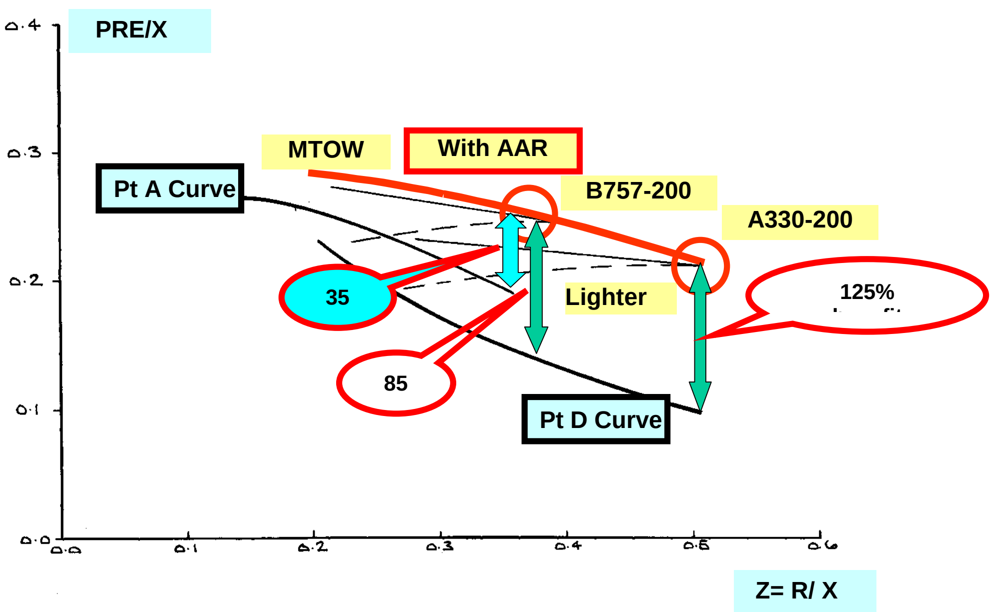


Fig. 30 PRE/X – Z, CURRENT A & D POINT TRENDS (Fig.5) AND
VARIATION WITH DIFFERENT REFUELLING OPTIONS FOR A330-200 and B757-300
Note the Benefits with respect to PT A & Pt D Curves

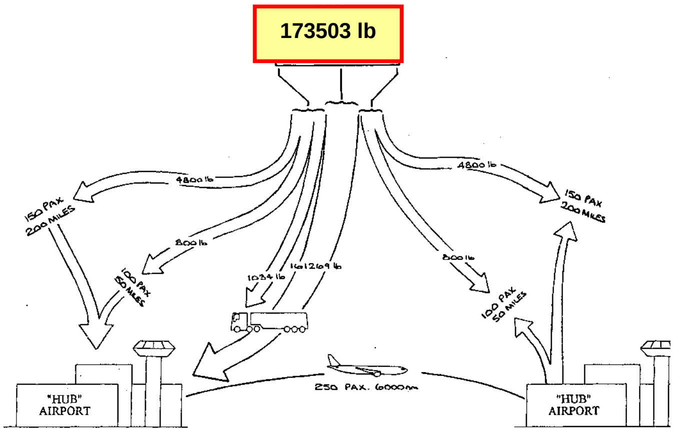


FIG. 31 SCHEMATIC BREAKDOWN OF TOTAL FUEL USED 250 PAX OVER 6000 nm WITHOUT AAR

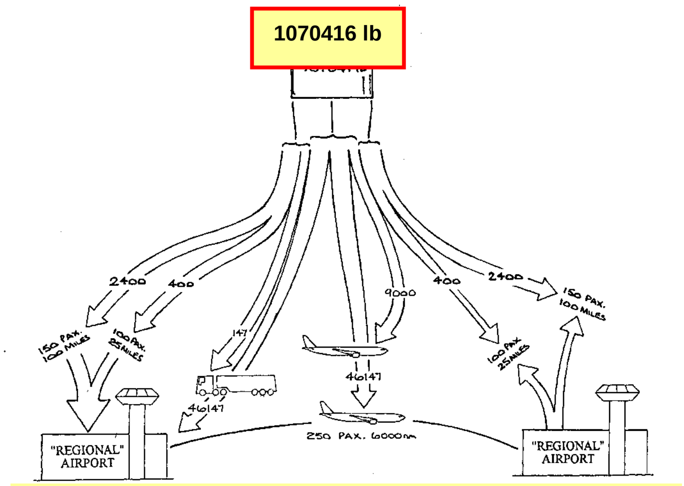


FIG. 32 SCHEMATIC BREAKDOWN OF TOTAL FUEL USED 250 PAX OVER 6000 nm WITH AAR

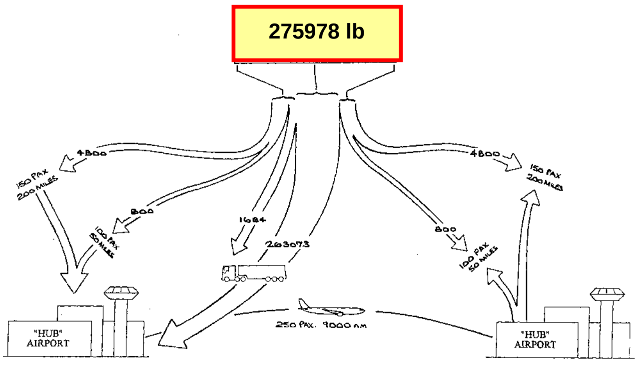


FIG. 33 SCHEMATIC BREAKDOWN OF TOTAL FUEL USED 250 PAX OVER 9000 nm WITHOUT AAR

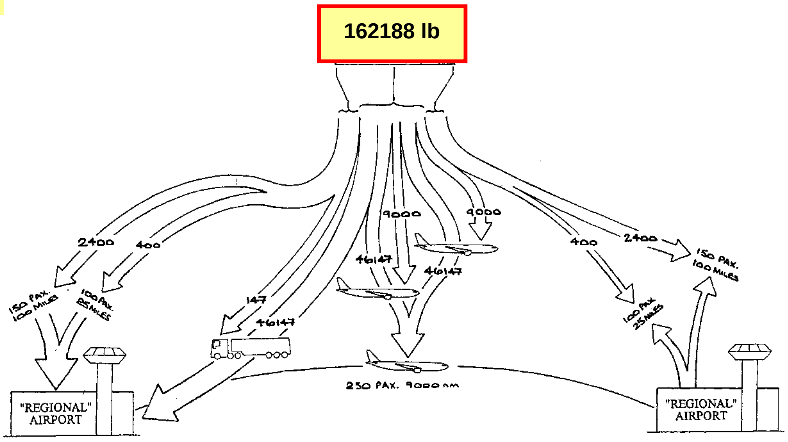


FIG. 34 SCHEMATIC BREAKDOWN OF TOTAL FUEL USED 250 PAX OVER 9000 nm WITH AAR

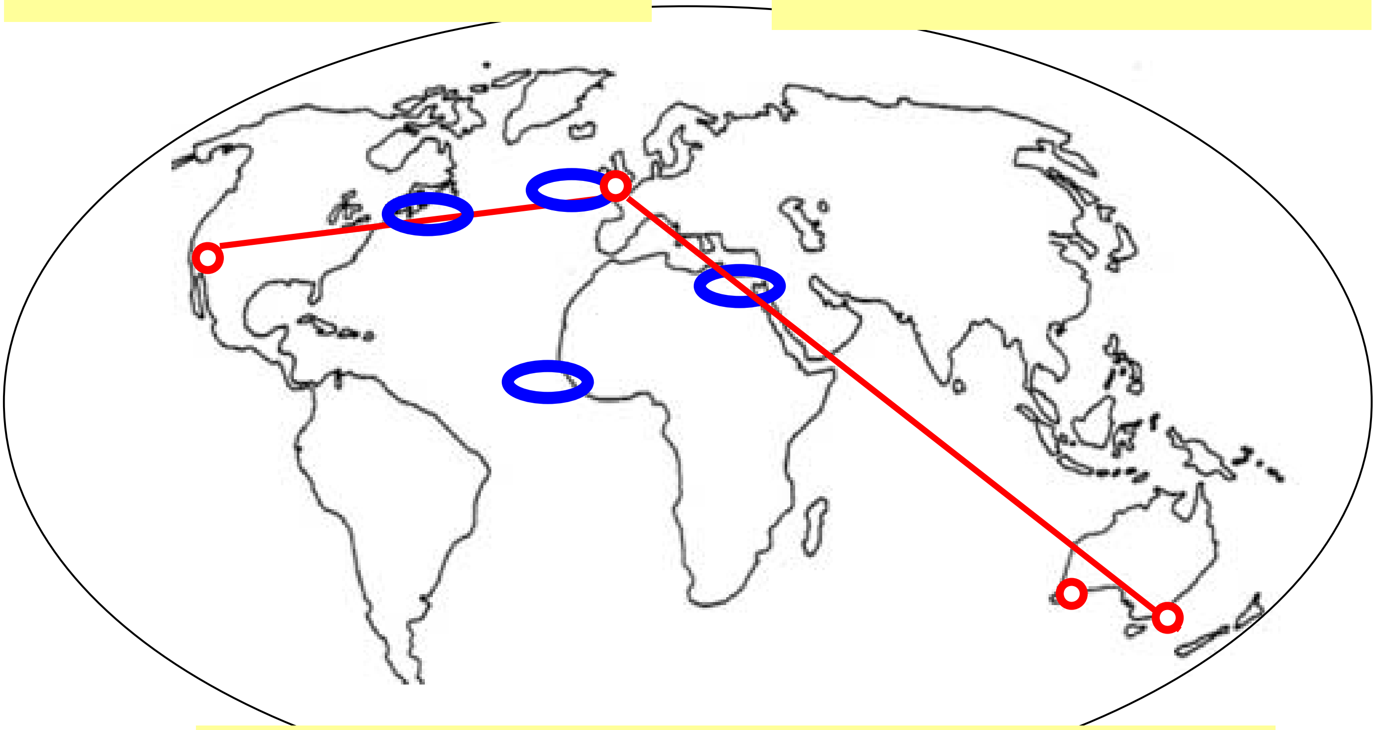


FIG. 35 SOME ROUTES & POSSIBLE REFUELLING ZONES