Operations and aircraft design towards greener civil aviation using air-to-air refuelling

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SUMMARY

As civil aviation expands, environmental aspects and fuel savings are becoming increasingly important. Amongst technologies proposed for more efficient flight, air-to-air refuelling (AAR), 'hopping' and flying in close formation (drag reduction), all have significant possibilities. It will be interesting to know also how these technologies may co-exist e.g. AAR and formation flying.

In military use, AAR is virtually indispensable. Its benefits are real and largely proven in hostile and demanding scenarios. We present a case for applying AAR in a civil context to show that substantial reductions in fuel burn for long-range missions are achievable. Overall savings, including the fuel used during the tanker missions, would be of the order of 30-40% fuel and 35-40% financial. These are very significant in terms of the impact on aviation's contribution to reducing atmospheric pollution.

AAR allows smaller, efficient (greener) aircraft optimised for about 3,000nm range to fulfil long-range route requirements. This implies greater usage of smaller airports, relieving congestion and ATC demands on Hub airports. Problems due to shed vortices and wakes at airports are reduced. Smaller engines will be needed.

Integrated (accepted) AAR could lead to further benefits. Aircraft could take-off 'light', with minimum fuel and reserves and a planned AAR a few minutes into the flight. The 'light' aircraft would not require over-rating of the engines during take-off and would therefore be less noisy during take-off and climb-out, permitting more acceptable night operations.

The availability of civil AAR will enable opportunities for hitherto borderline technologies to be utilised in future aircraft. Laminar flow will provide fuel savings and increased efficiency in its own right but could be significantly enhanced within a civil AAR environment. Similarly, supersonic transport may become an acceptable economic option.

AAR affords the possibility of a complete widening of the design space and this should appeal to the imagination of current and future designers.

NOMENCLATURE

AAR   air-to-air refuelling
ACARE Advisory Council for Aeronautics Research in Europe
$ASNM$ available seat nm
ATC   Air Traffic Control
C_D = $D/(q\,S)$, drag coefficient
C_L = $L/(q\,S)$, lift coefficient
D Drag force
DOC direct operating cost
GPS   Global Positioning System
IPCC   Intergovernmental Panel on Climate Change
kt   knots, nm/hr

L	lift force
L/D	lift to drag ratio
M	Mach Number
$MTOW$	maximum take-off eight (TOW take-off weight)
OEW	operating weight empty (also WOE)
$OEWR$	OEW/MTOW
Pax	passengers
PRE	payload range efficiency $WP*R/WFB$
q	$= 0 \cdot 5 \, \rho \, V^2$, dynamic pressure
R	range
S	reference area
SFC	specific fuel consumption, lb (of fuel)/hr/lb (thrust) = 1/hr
SST	supersonic transport
T/W	thrust to weight ratio
V	airstream velocity, kt
WP	payload
WF	fuel load (block + reserves = total)
WFB	block fuel
WFT	tanker fuel
x,y,z	orthogonal wing co-ordinates, x along body axis
X	$= V \, L/D/SFC$, range parameter
Z	$= R/X$, Non-dimensional range
ρ	air density

1.0 INTRODUCTION

The volume of passengers and cargo transported by air continues to grow worldwide. This growth translates into the world fleet airframe trends shown in Fig. 1[1], indicating that the number of aircraft worldwide will have doubled in the twenty years from 2004 to 2024. An increasing proportion of these will be larger capacity, longer-range aircraft. Air travel growth is typified by Fig. 2[1,2], showing the trends for passengers, airports and frequencies of travel. The events of 11 September 2001 result in a significant delay in predicted growth trends. The demand for aviation fuel will also increase. Society may view this demand as potentially unacceptable in terms of eroding natural resources, atmospheric pollution generated, Greenhouse effects, etc.

The trend, worldwide, has been, in general, for Regional airports to cater for short to medium range aircraft whereas Hub airports with longer runways cater for large capacity long-range aircraft. Hub airports are reaching 'saturation' point in terms of aircraft movements and passenger accessibility. This concentration of air and ground traffic leads to high pollution levels, a large proportion of which arises from surface traffic. Highly topical and controversial debates ensue all over the world on issues of new airport sites or additional runways. The expansion of existing airports will lead to an increase in the already high levels of pollution (noise and gaseous).

The development of Regional airports allows passengers greater choice and the possibility of near direct A to B (door to door) transportation. Surface travel to and from the airports of departure and arrival is reduced. Aircraft such as the B787 and the A350 are planned. These have been designed for the longer routes, up to 9,000nm. The use of Hub airports implies significant amounts of surface or connecting travel for the majority of passengers.

Over the past 50 years, technology has kept pace with demands for improved efficiency, cost reduction and more environmentally friendly aircraft. Significant advances are still being made. For example, reduced specific fuel consumption (SFC) in the latest Rolls-Royce engines for the A350 and the Boeing 787 and reduced structure weight due to the increased application of carbon fibre composites and advanced metallics in those aircraft. However, the benefits due to evolving technologies associated with air transport are slowing down.

In the UK, the Greener by Design (GBD) group has issued reports on the impact of environmental concerns for the future aviation scene[3,4]. Several implications and trends have been shown. For example, fuel efficiency peaks at 2,500 – 3,000nm range. It was noted that significant fuel savings on long-range journeys could be achieved by replacing the large long-range aircraft with short-range equivalents refuelling at intermediate airfields or utilising air-to-air refuelling (AAR). Following the efficiency parameters correlations paper by Nangia[5], it was recommended that fuel reserves must be allowed for. These can amount to 40-50% of the payload for the long-range aircraft. Green[6] has published a technical note revising the earlier work of Refs 3 and 4. References 3-5 recommended a look at AAR. It is useful first to review the efficiency issues.

1.1 Air transport efficiency – fuel availability and concerns

The efficiency of transport systems needs to be judged in terms of speed, range and economics. For air transport, the latter should include the costs of airframe manufacture, maintenance, operations and fuel. Fig. 3[7] shows the near linear, increasing trend of aircraft purchase price with operating empty weight (OEW). From an environmental viewpoint, the quantity of fossil fuel used needs to be considered or the impact on the environment of alternative fuels. Fossil fuel is threatened by availability, cost and environmental impact. First thoughts are that we can imagine Kerosene being reserved for air travel as surface transport (road, rail and sea) more easily converts to other 'greener' technologies. Obviously there will be accompanying political and governmental pressures to consider in all this!

In view of the expansion of air travel, significant reductions in fossil fuel consumption will be needed to reduce the environmental impact. For example, the objectives of the Advisory Council for Aeronautics Research in Europe (ACARE) are to reduce the aviation fuel usage (over all sectors) by 50% based on 2,000 levels. This may be achieved by improved efficiency through aerodynamic design, engine design and operational procedures. Answers may be in combining technologies e.g. AAR, 'Hopping' and Close Formation Flying (drag reduction). High efficiency prop-fans may be applicable to short ranges. Development of laminar flow aircraft has also been proposed.

2.0 PAYLOAD RANGE, EFFICIENCY AND POSSIBLE AAR SCENARIO

2.1 Payload range considerations

Figure 4 explains the various limits operating on the payload range diagram and also compares a small and a large aircraft. The payload cannot be increased above the maximum payload limit due to structural and volume limitations. The maximum take-off weight (MTOW) is also limited by structural considerations, mainly for the wing and landing gear. The maximum fuel volume limit is self-explanatory and it includes non-usable (residual) and reserve fuel.

Point A denotes the maximum range for maximum payload. Maximum payload is achieved, typically, by all-cargo and combi (part passenger, part cargo) variants, and is sometimes approached (say to 80% or so) by stretched variants carrying increased passenger numbers in a one-class single-aisle economy layout. Pt A denotes the highest payload efficiency parameters for a given aircraft.

Point D is the more usual prime design point, typically for full passenger load plus baggage in a two or three class cabin configuration. The range at Pt D is always more than that at the maximum payload design point Pt A.
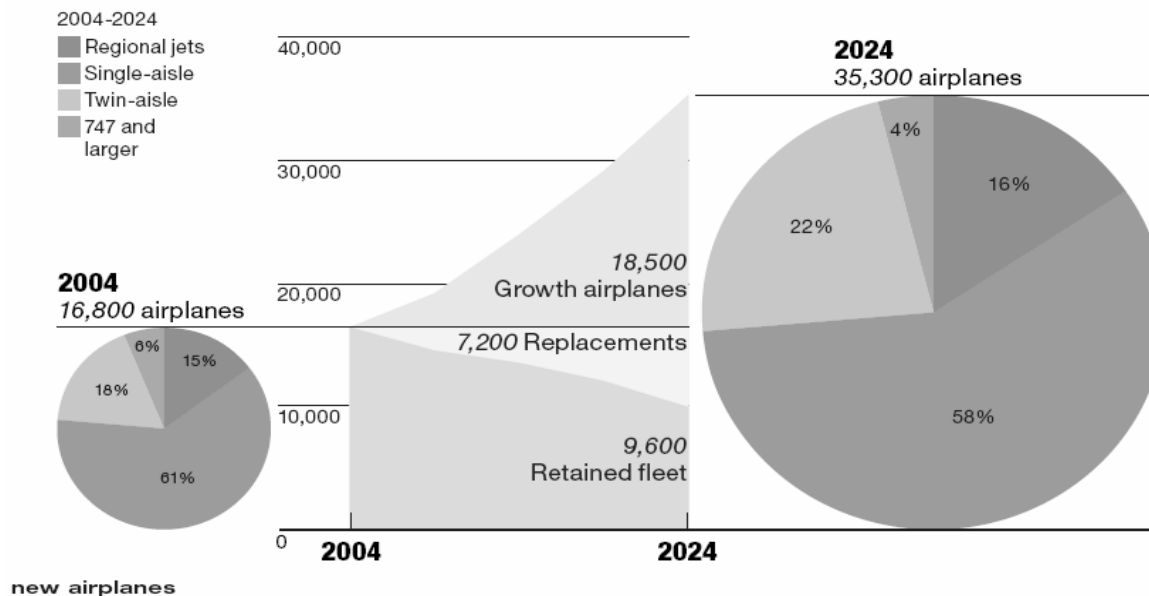
The World Fleet Will More Than Double

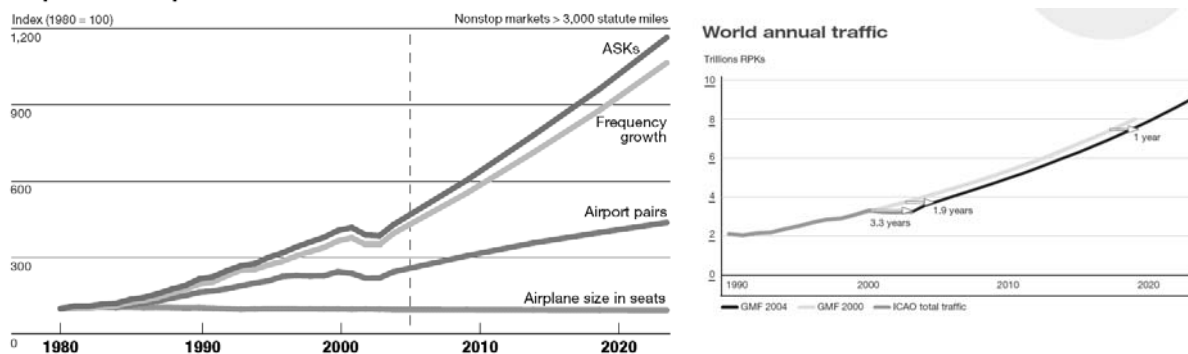Figure 1. World air traffic forecasts 2004-2024.
(Boeing)

Figure 2. Passenger, airports, frequency trends.
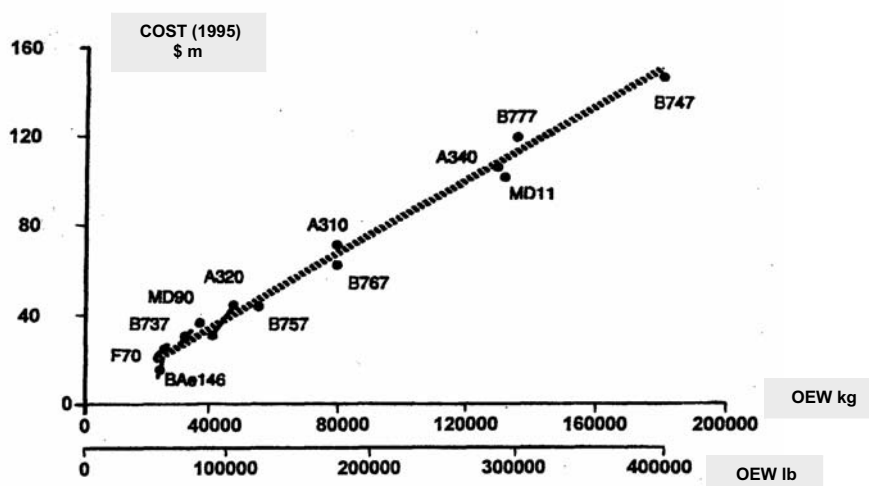**(Boeing and Airbus)**

Figure 3. Aircraft purchase price – OEW, 1995 (Avmark)[7].

2.2 Possible refuelling scenarios

If an aircraft, carrying its maximum payload, were refuelled at the end of its maximum payload range Pt A, the effective range could be extended whilst still maintaining highest efficiency.

Alternatively, an aircraft could take-off with maximum payload at a lighter weight (minimum fuel on board), keeping the noise down and then refuel a little later at convenience, extending the range as required. This will be detailed later in Section 4.

2.3 Non-dimensional efficiency parameters and range relationships

In Ref. 5, Nangia presented a series of efficiency parameter correlations on commercial aircraft operating at Pts A&D. The correlation parameters related payload (WP), fuel burnt (WFB), maximum take-off weight ($MTOW$), operating empty weight (OEW) and range (R). We summarise the main inferences as these help in appreciating the trade-offs in efficiency, noise, emissions and costs, with respect to range.

The range parameter (X) follows from the usual Breguet range equation. It relates the aircraft flight velocity V and aerodynamic (L/D) and propulsion (SFC) efficiencies and is defined as $X = V L/D/SFC$ (nm). This then allows definition of a non-dimensional Range Parameter, $Z = R/X$. The various efficiency parameters can be plotted against Z as in Fig. 5(a-c). Here we are concerned with Pt D correlations.

The ratio of fuel burnt per payload carried (WFB/WP) is shown in Fig. 5(a). The non-dimensional Payload Range Efficiency (PRE/X) is shown in Fig. 5(b) where $PRE = WP*R/WFB$ (nm).

From Figs 5(a-b), using differing values of X, we have derived PRE/X and WFB/WP variations with range R (reference range is 3000nm). The % changes are summarised in the following table. X varies from 20,000 to 15,000 (higher % occur at lower X).

		6,000nm	9,000nm
PRE/X:	% Decrease	28-44	51-61
PRE/X:	% Improvement Required	39-78	105-159
WFB/WP:	% Increase	28-44	51-61

At $X = 15,000$, 44% of the fuel consumed by a 6,000nm aircraft would be saved by using a 3,000nm aircraft in two stages. This directly relates to a decrease in PRE/X, Fig. 5(b), of 44%. An efficiency improvement of 159% would be required for a 9000nm range aircraft (at $X = 15,000$) to achieve the same PRE/X level as a 3,000nm 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 a 3,000nm range aircraft with hops or with AAR (allowing of course, in the latter case, for the fuel used by the tanker).

Relating the non-dimensional Payload Range Efficiency PRE/X and the factor OEW/WP, we can define a non-dimensional 'Nangia Value Efficiency' parameter $VEOPX$:

$VEOPX = (PRE/X)/(OEW/WP) = (PRE/X) * (WP/OEW)$.

This parameter, Fig. 5(c), denotes the work efficiency per structure weight per unit payload, which can be related to the purchase cost per unit payload using the cost (price) versus OEW relationship of Fig. 3. Parameter $VEOPX$ also serves as a measure of approach and landing noise. A higher value is better for lower structure weight, lower costs (acquisition and operating) and lower landing noise.

Similarly using $MTOW$ as a simple measure of take-off noise and emissions, we define the 'Nangia Emissions Efficiency' parameter $VEMPX$:

$VEMPX = (PRE/X)/(MTOW/WP) = (PRE/X)*(WP/MTOW)$.

This parameter, Fig. 5(c), denotes the work efficiency per total weight per unit payload. Parameter $VEMPX$ also serves as a measure of airport and other fees. A higher value is better for lower noise emissions and lower operating costs.

These parameters indicate feasible ways of understanding and improving efficiency in fuel usage, economic and environmental terms. The graphs of $VEMPX$ and $VEOPX$ provide a reasonably 'realistic' measure of the efficiency of a given configuration as all the components of $MTOW$ are included. Reference. 5 summarises the important trends.

It is worth noting that the thrust/$MTOW$ level of all the aircraft is of the order of 0·3[5].

Considering $VEMPX$ and $VEOPX$ from Fig. 5(c), ($X = 15,000$), we compare the performance of an aircraft designed to carry 250 passengers over 6,000nm with that of a smaller aircraft carrying the same payload over two 3,000nm stages and deduce the following factors. The 6,000nm aircraft produces 3·1 times the noise of the 3,000nm aircraft and 1·6 times the emissions. The 6,000nm aircraft is 50% more expensive than the smaller aircraft. Similarly, for a 250 passenger payload over 9,000nm, the 9,000nm designed aircraft produced 6·2 times more noise than the 3,000nm aircraft, 2·1 times the emissions and is 70% more expensive.

We now have a reasonably good idea of the costs and environmental benefits. The major reasons for the much higher efficiency of the 3,000nm aircraft are the lower structure weight as well as the more obvious one of not carrying the weight of the fuel for the latter parts of the mission.

In future, it will be worthwhile taking a further general look at efficiency implications and how, in some cases, benefits can be taken, using current aircraft.

Many factors may contribute towards improved efficiency. These include more advanced materials, improved manufacturing techniques, design improvements and better design methods and improved operating procedures. These will continue to have an impact during the life cycle of a given type.

3.0 NEED FOR EFFICIENT AND GREENER AVIATION IN FUTURE, FORMATIONS, HOPPING AND AAR

It may be postulated that in the future, most of the short-haul journeys will ideally be via surface transport and medium to long-range journeys by air. We need, therefore, to focus on making the long-range journeys more efficient. One obvious solution proposed by the 'Greener by Design' group[3,4] is to segment long-range air travel into a series of short hops, refuelling at intermediate airports. Although this seems fuel-efficient, using the much more efficient 3,000nm range aircraft, it remains unattractive because 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. 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, we can deal with most of these concerns in one stroke, availing of a current proven technology. AAR is a daily routine in military operations[6]. Every step that has allowed a large bomber (B-52) to be refuelled in flight by a tanker (KC-10) is readily available and achievable in the civil scene: location, positioning, formation flying, connection and fuel transfer. In the early days, AAR was used for record-breaking feats of range and endurance. It is now routinely used by the military to extend range and endurance and increase operational payload. AAR is indispensable and most military aircraft are designed assuming its availability.
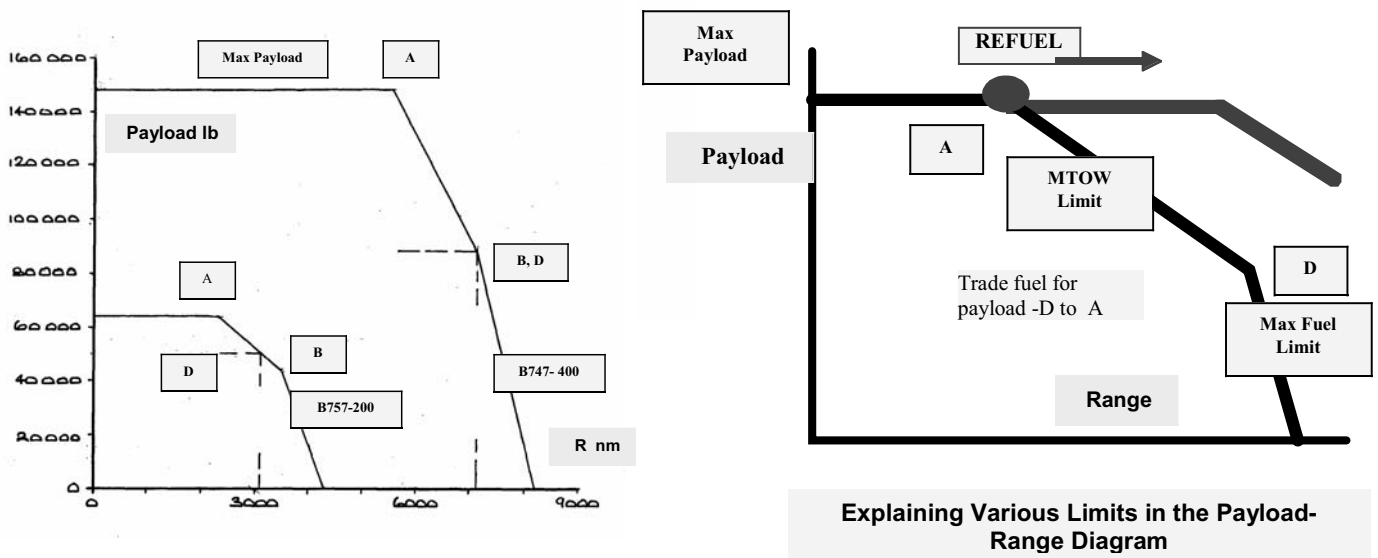
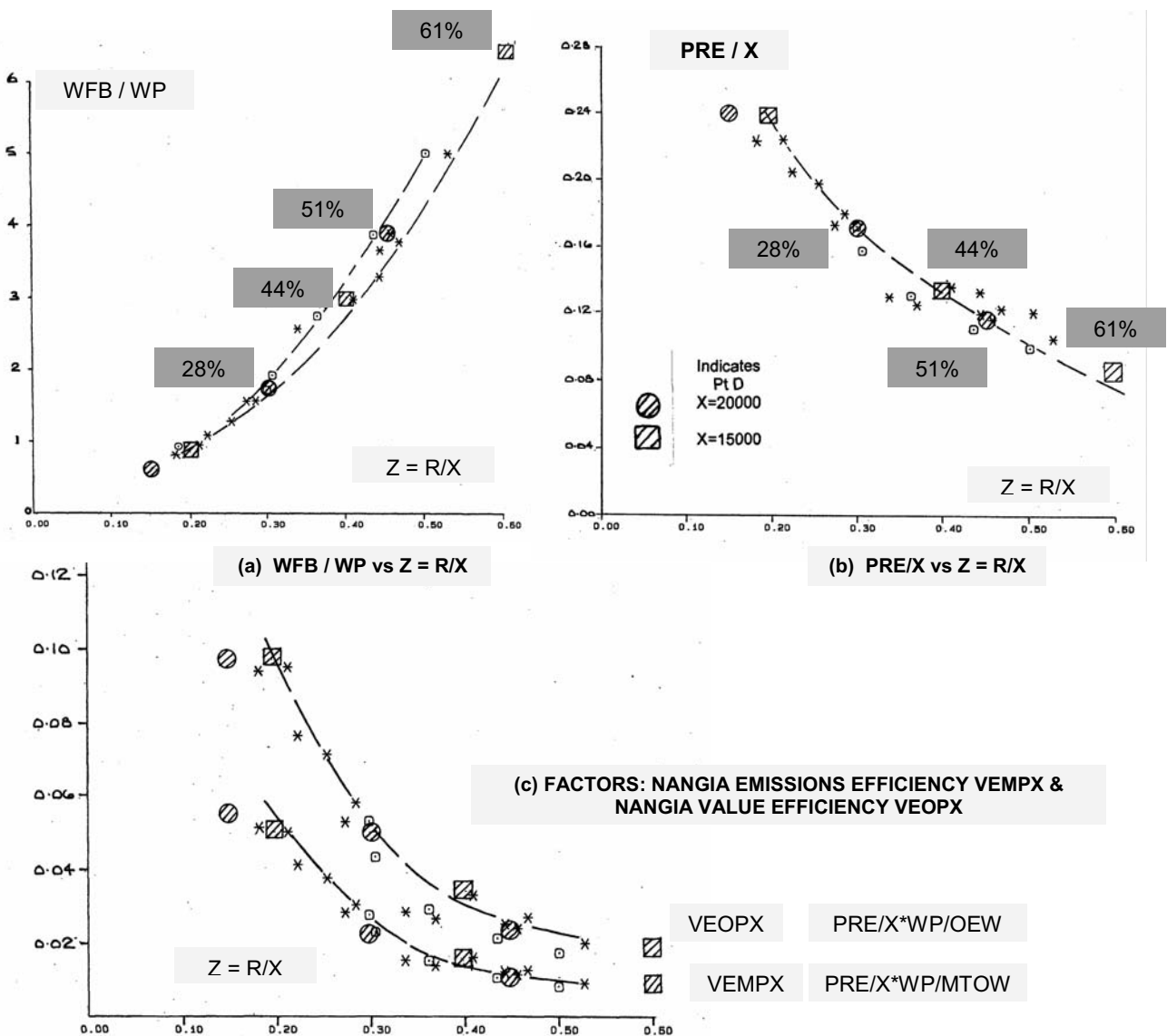Figure 4. Typical payload range diagrams and limits.

Figure 5. Commercial aircraft, non-dimensional efficiency parameters at Pt D, based on Ref. 5.

We appreciate that it is one thing to have acceptable AAR military techniques with trained pilots and quite another to have it accepted for civil work with airline pilots trained to civil standards. Safety, reliability and all weather capability take on different degrees of importance within the two situations. It is fairer to say that the standards now achieved by the military operation point the way to civil acceptance, and if the AAR case is proved, it should drive the research required to make it happen (such as autonomous station keeping between two aircraft).

3.1 Observations on refuelling formation, drag, altitude and thrust implications

There are many possible alternatives relating the sizing and positioning of the tanker and receiver aircraft. Each will have to be assessed on its own merits.

- 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.

In Fig. 6, a number of refuelling locations can be inferred. Some of these locations are more favourable than others. We briefly discuss the drag implications.

The cruise drag of an aircraft comprises several components, Fig. 7. The major components are: friction (48%) and lift-induced (35%). This is subject to interference effects in close aircraft formations. Using a simple horse-shoe vortex model, Blake and Multhopp[8] have published 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. 8. Both wings are unswept and are of the same size. Although subject to chordwise location effects, it is shown that 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.

In the symmetric refuelling formation (0% lateral spacing), a lift induced 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 changes in drag are accompanied by interference effects e.g. in pitch, roll and yaw. In our recent work, we have analysed such formation aspects with more detailed flow models on representative swept-back wings, including aircraft size differences [9,10]. Such considerations will be important in practical operational terms.

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.

We now give examples of how AAR can be adapted to remove most of the objections and concerns that continued expansion of air travel is likely to raise. At the same time it will enable acceptance of technologies that have hitherto been unacceptable on the grounds of safety, cost, economic and environmental impact, e.g. laminar flow, supersonic transport and supersonic business jets, etc.

4.0 EXPLOITING AAR IN THE CIVIL SCENE

We look briefly at the practicalities of incorporating AAR equipment and operating procedures into civil operations. We then look at fuel savings afforded by AAR on 6,000, 9,000 and 12,000nm flights

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

AAR works with any size of aircraft (payload). Efficiency (payload x range/fuel used) tends to peak at about 2,500 to 3,000nm. For the current exercise, we opted for a payload of 250 passengers and a design range of 3,000nm for our base aircraft. Such an aircraft requires less than 50,000lb of fuel per 3,000nm leg and that is dispensed fairly easily from a tanker. Each tanker may then accomplish 3 – 4 operations in a single flight and then land at the nearest suitable airfield (Section 5).

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 approach is to design representative aircraft to carry the same payload over 6,000, 9,000 and 12,000nm and estimate the fuel saved by using the base 3,000nm range aircraft with AAR over these longer ranges. Our 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.)[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 [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 36,000ft). For the 3,000nm and 6,000nm aircraft we have used SFC of 0·65lb/hr/lb. The range parameter $X = V \, L/D/SFC$ is then 15,077nm.
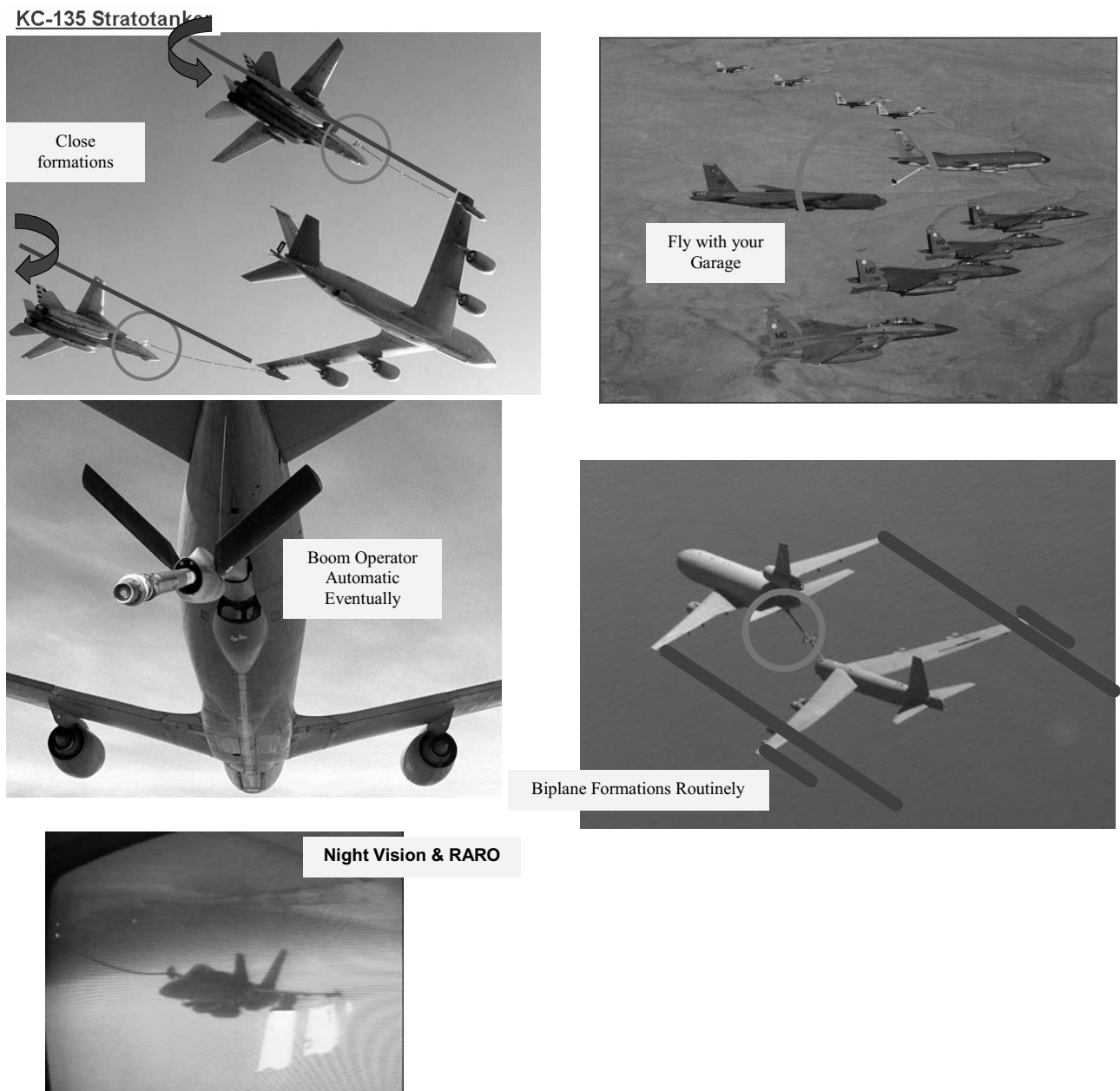
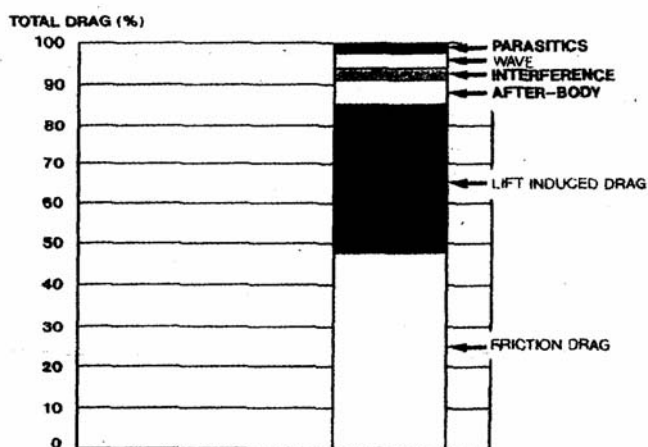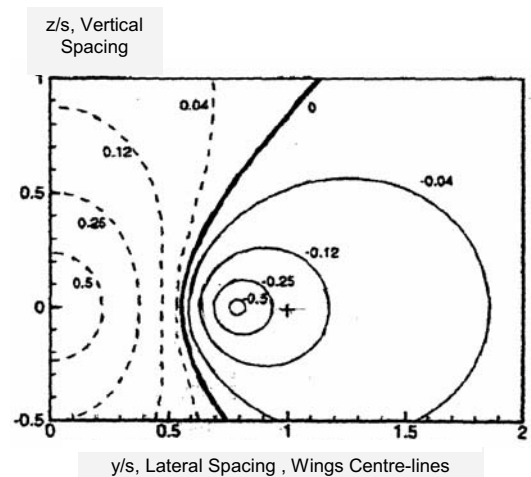Figure 6. Typical, everyday military AAR activities.

Figure 7. Drag breakdown of a typical transport aircraft[2].

Figure 8. Induced drag as function of relative position, two equal sized unswept wings.
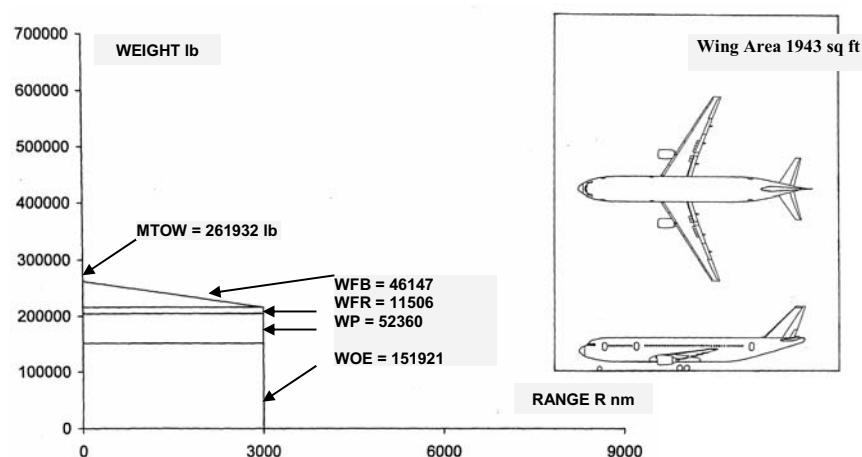
Figure 9. Aircraft weight variation with flight distance for 3,000nm range (no refuelling), 250 PAX., OEWR = 0·58, S = 1,943ft^3, X = 15,077nm.
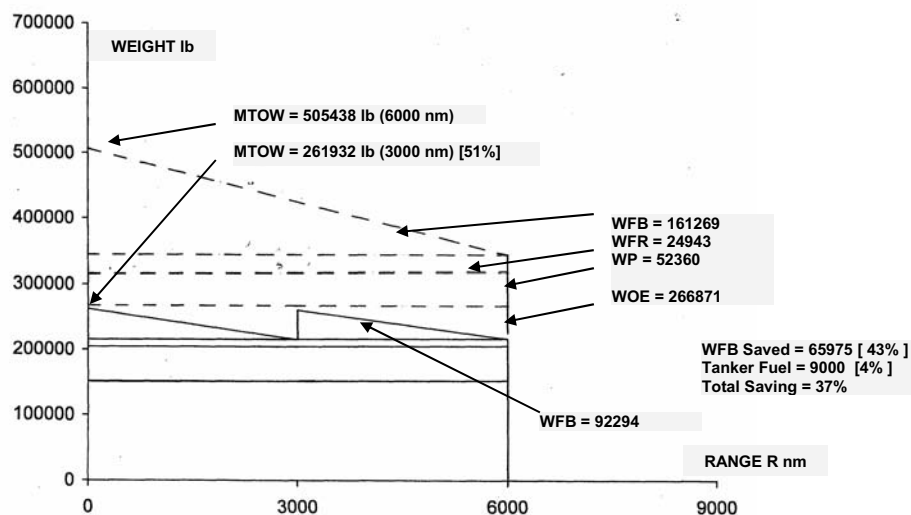

Figure 10. Aircraft weight variation with flight distance for 6,000nm range. Aircraft, refuelled once cf aircraft without refuelling, 250 PAX., OEWR = 0·528, S = 3,750ft^2, X = 15,077nm.
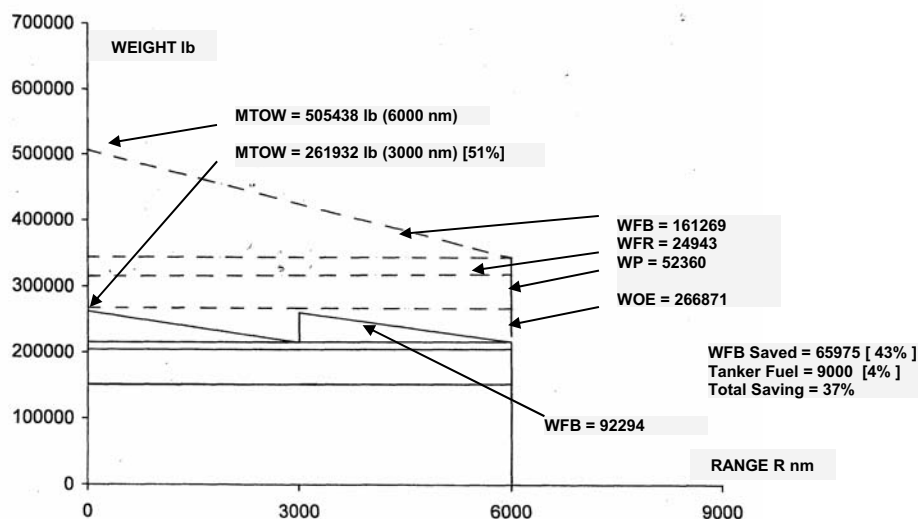

Figure 11. Aircraft weight variation with flight distance for 9,000nm range. Aircraft (x = 15,077nm) refuelled twice cf aircraft without refuelling, 250 PAX., OEWR = 0·47, 4,968ft^2, X = 16,897nm.
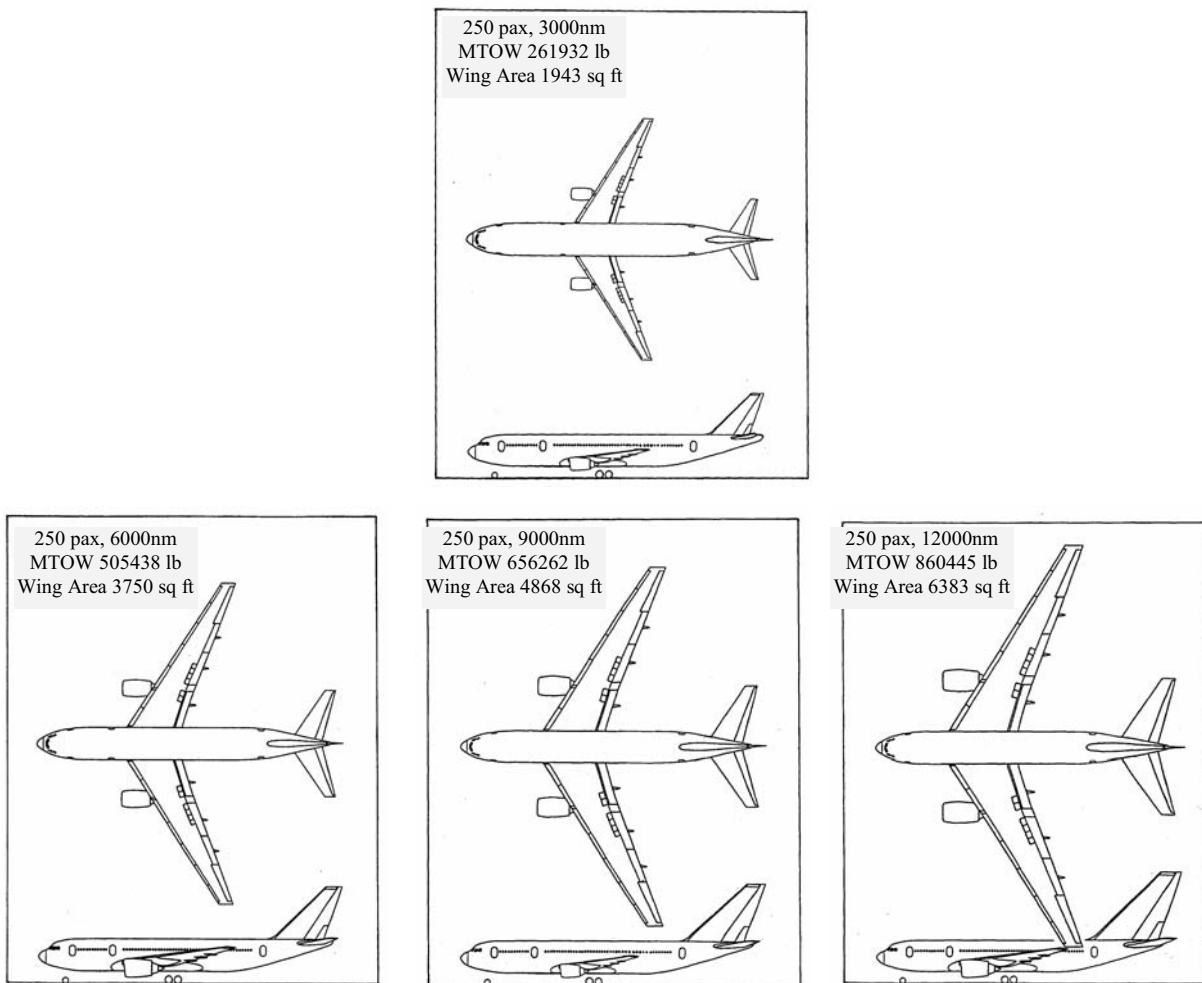
Figure 12. Comparing (approximately) the aircraft designed for different ranges, without refuelling, 250PAX.

For the 9,000nm aircraft we have used a 'more efficient' SFC = 0·57lb/hr/lb. The Range Parameter X is then 16,897nm.

The base aircraft weight variation over 3,000nm is shown in Fig. 9. The block fuel used to carry 250 passengers over this range is 46,147lb (MTOW = 261,932lb). An aircraft designed to carry the same payload over 6,000nm, Fig. 10, uses 161,269lb fuel (doubling the range has more than trebled the fuel required, $MTOW$ = 505,438lb). 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. 10 also compares the weight variations with range for the 6,000nm aircraft and the 3,000nm aircraft refuelled at 3,000nm. Fuel used and the savings offered by AAR (41% over 6,000nm) are also shown.

Figure 11 refers to the comparisons for 9,000nm range. An aircraft without a refuelling option would have MTOW of 656,262lb, and consume 263,073lb of fuel carrying 250 passengers. With two AAR operations, using the 3000nm aircraft, the block fuel would be 138,441lb, a saving of 47%.

The relative sizes of aircraft designed for 250 passengers over 3,000, 6,000, 9,000 and 12,000nm are shown in Fig. 12. The fuselage size remains almost constant but the wing area increases rapidly to accommodate the fuel requirements and maintain design CL.

Fig. 13 shows the rapid rise in MTOW, as range increases, for aircraft with 250 passenger payload, (L/D = 20) and not using AAR. If AAR were available, our base aircraft, L/D = 20, could complete any range required as shown. For a range of 6000nm, with AAR, a relatively inefficient aircraft (L/D < 14) would still have a lower MTOW than an aircraft designed for that range with L/D = 20. Figure 14 shows the block and total (block + reserve) fuel trends with range. We can immediately see the potential for fuel savings with AAR. We need to consider now the additional costs, both financial and fuel consumed, in carrying out the AAR services.

5.0 DEDICATED TANKERS, REFUELLING SCENARIO

In the current economic scene, military air tankers are dual role (tanker/transport). They are either conversions of ex-civil aircraft or dual role options of current designs. A considerable amount of work has already been carried out by industry into future tanker designs. Lockheed Martin propose that truly dedicated tanker designs would be smaller and cheaper than modified commercial airframes. Fig. 15 shows a concept studied by Lockheed Martin. This concept, in comparison with the KC135 tanker, has a minimal fuselage, improving cruise speed and reducing drag, with only the cockpit area being pressurised. The engines are fuselage mounted to reduce interference with the receiving aircraft and have half the fuel burn rate of current cruise engines. The OEW = 41,200 kg, would be 50% less than a KC135. Joined-Wing concepts have been proposed that allow wing-tip refuelling in favourable aerodynamic interference flow.

With advances in GPS, collision avoidance technology and navigation/communication techniques, tanker/receiver mutual contact is not likely to raise any significant difficulties. Indeed, a robotic refuelling system for the USAF is being developed[15]. Actual AAR methods are continually being refined. A remote aerial refuelling operation (RARO) system has been introduced in the US, [2], for safer operation both day and night and automated AAR is currently being developed for unmanned aircraft.

With the adoption of civil AAR, dedicated and efficient air tankers would become economically viable. Fig. 16 shows a typical civil AAR tanker operating scenario. At a scheduled time, the tanker leaves its base (1) fully laden and flies a minimum outbound leg to its first rendezvous (2). A few minutes elapse whilst the aircraft position themselves (2-3). Fuel is discharged from tanker to receiver (3-4). The tanker then re-positions (4-5) onto a second receiver for refuelling (5-6). In this scenario, a third receiver is refuelled (7-8) before the tanker returns to base (8-9). The destination tanker base need not, of course, be its original departure base. During daily operations the tankers could refuel at any suitable base, as often as required, before returning to their home base at the end of the crew shift.

We consider now a dedicated tanker design by adapting the usual Breguet range equation to allow for the specialized tanker operating mode. Conventionally, reserve fuel is added as percentage of the design range with allowances for hold and diversion. Instead of adding reserve fuel we have factored the take-off and landing ranges by 1·4 and 1·2 respectively to allow for fuel consumed during ground manoeuvres, extra fuel burn at take-off rating, etc. The other factors used in the Breguet range equation are: $OEW/MTOW = 0·45$, $SFC = 0·65$, $L/D = 20$, $V = 490$kt. Fig. 17 shows the total weight variation for tankers making 4, 3 or 2 offloads of 50,000lb (5,000lb/min) with an effective positioning time of 10 min per refuel and take-off and landing sectors of 30 min each. The points marked 1 to 9 in the refuelling scenario in Fig. 16 correspond to points 1 to 9 in Fig. 17 for the three-offload case. For the four-offload case, the ratio of fuel supplied to fuel consumed (WF/WFT) is 7·1. As we reduce the number of refuelling operations, increases to 8·3 and 9·8 respectively. These trends are summarised in Fig. 18 which shows WF/WFT variation with tanker $MTOW$ for various flow rates, offload quantities and positioning times. WF/WFT maximises for higher transfer rates, shorter positioning times and, surprisingly, minimum refuelling operations.

We need to consider the tanker operating costs which must include capital costs, depreciation, insurance, crew costs, navigation and airport charges, etc. Fig. 19 summarises the variation of the additional 'tankerage' cost of fuel delivered ($/lb) with tanker $MTOW$ for various offload quantities and frequency, fuel transfer rate and positioning time. Within the range of parameters considered, it is most economical to design and operate a tanker delivering two offloads of 100,000lb each at 10,000lb/min with 6·25 min positioning time. This would require a tanker MTOW of 400,000lb. If we restrict the offload to 20,000lb (dictated possibly by the receiver aircraft), without changing any other parameters, the minimum additional fuel costs occur at five refuelling operations (total offload 100,000lb) from a tanker with $MTOW$ of 210,000lb. The final optimised tanker design will be determined by receiver aircraft operational requirements, fuel transfer technology, ATC technology, etc.

So far we have focussed mainly on AAR applied to 250-seater receiver aircraft. The tankers assumed are 'conventional' and may off-load 50,000lb of fuel during each docking operation. Larger and smaller and more up-to-date (possibly unconventional) aircraft need to be included in studies to ascertain the most advantageous situations. More efficient, dedicated tankers will have a dramatic favourable effect on AAR.

6.0 GREENER ENVIRONMENT WITH CIVIL AAR

It is interesting to view the perspective of how AAR may fit into the overall civil aviation scene.

In general, civil aviation is growing over all range sectors. The low cost airlines have encouraged the short-range sector to grow at a remarkable pace – with passengers shunning the often more logical and time-efficient surface transport alternatives.

To tackle the ACARE overall objectives (50% reduction in aviation fuel usage), multi-faceted solutions will be needed. It can be proposed that by using efficient propeller systems, the short-range flights could become more efficient. AAR will tackle the longer-range sectors. Although not considered in detail here, formation flying integrates effectively with AAR and this will benefit the medium and long range sectors.

Structure weight reductions will have an effect across the board, probably skewed to longer ranges. Laminar flow and improved engine SFC will have similar effects. Further work needs to be done to quantify the technology benefits and their integration. The benefits from some of the new technologies may well be less than in previous years but the trends have by no means flattened off.

It is implied in our work that civil AAR begins to improve efficiency as soon as it is introduced. The following table summarises the fuel requirements for 250 passengers ($WP = 52,500$lb) on journeys of 3,000, 6,000 and 9,000nm. For each range, the fuel used by the passenger aircraft is itemised, and in the case of AAR operations, the fuel used by the air tanker. Percentage fuel savings over equivalent conventional aircraft are shown in brackets [ ].

	FUEL	Range 3,000nm	Range 6,000nm	Range 9,000nm
Aircraft L/D = 20 Conventional	Aviation Block	46,147	161,269	263,073
With AAR	Aviation Block		92,294 [43%]	138,441 [47%]
Air Tanker			9,000	18,000
TOTAL			101,294 [37%]	156,441 [41%]

Based on the WFB/WP – Z trends of Fig. 5(a), Fig. 20 shows the effect of payload (WP) and Range Parameter (X) variations on the fuel used (WFB) with range (R). We can depict graphically the total aviation fuel savings (block fuel saved – tanker fuel required) offered by AAR for the 250 seaters. Such a figure also allows an idea of fuel savings with different payloads.

Certification requirements, safety issues, logistics and, above all, public opinion would require that civil AAR be phased-in over a period of time reaping slowly the economic and social benefits. Military operators (NATO, US, UK, etc.) already have a proven and effective AAR network. Initially, for example, 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 medium (3,000nm) range aircraft for AAR operation and re-consider the usage of their longer range fleet in a more efficient way using AAR.

Figure 21 shows fuel burn rates and efficiency ($WP*R/WFB$) for long-range and short-range B747s operated by JAL[3]. The high density, short-range, aircraft are twice as efficient as the long-range aircraft. With AAR, this efficiency could be maintained over any range required as emphasised in the $PRE = WP*R/WFB$ plot. However, to maintain an acceptable level of comfort over the longer ranges, the seating density would need to be less dense. As required, new aircraft purchases would be with AAR specifically in mind.
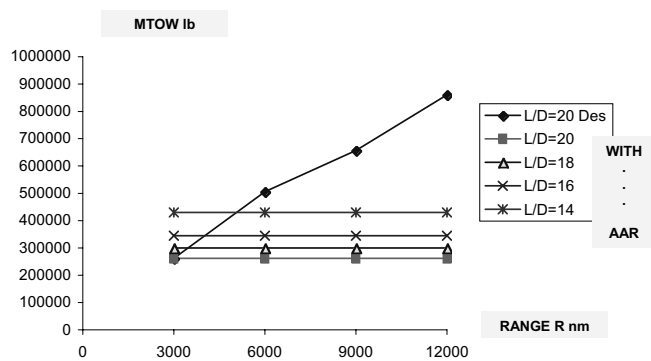
Figure 13. Variation of MTOW with range, No AAR, *L/D* = 20, compared witth AAR aircraft with *L/D* from 14 TO 20.
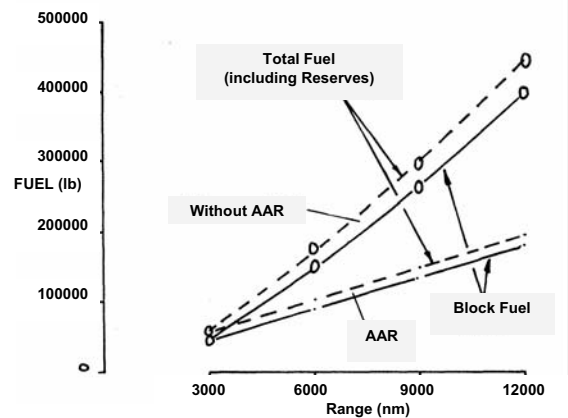

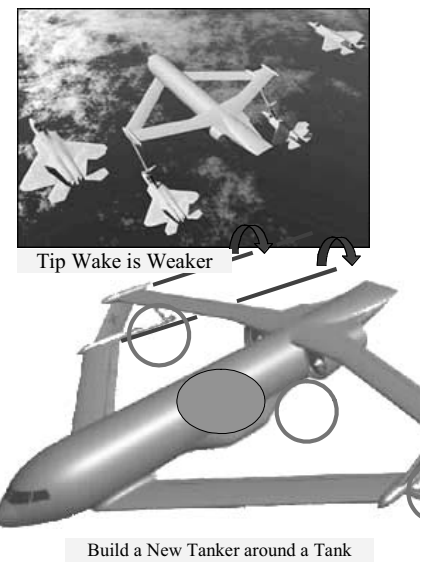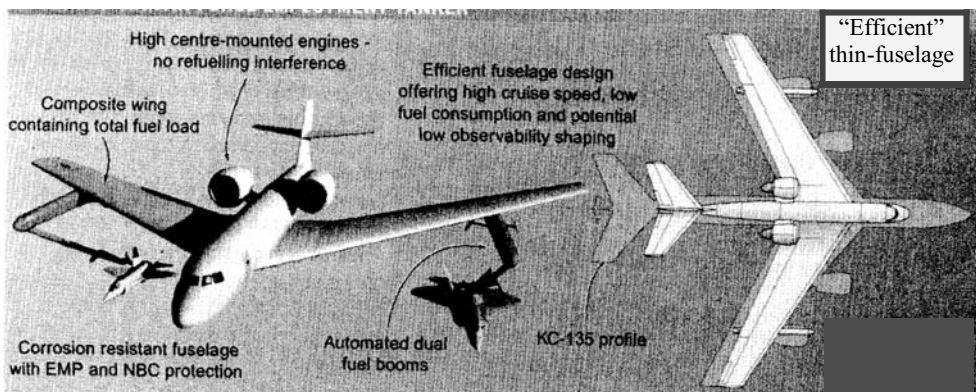Figure 14. Variation of fuel used with range, with and without AAR 250 PAXAircraft.

Figure 15. More efficient tankers being considered, comparison with KC-135, (Lockheed & *Flight International*) and joined-wing tankers.
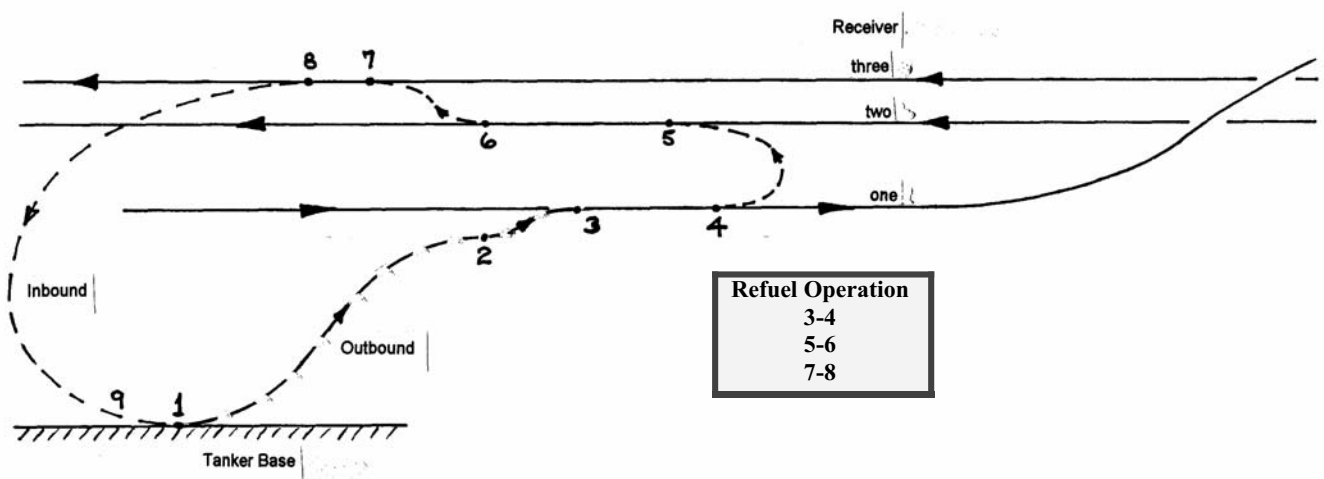

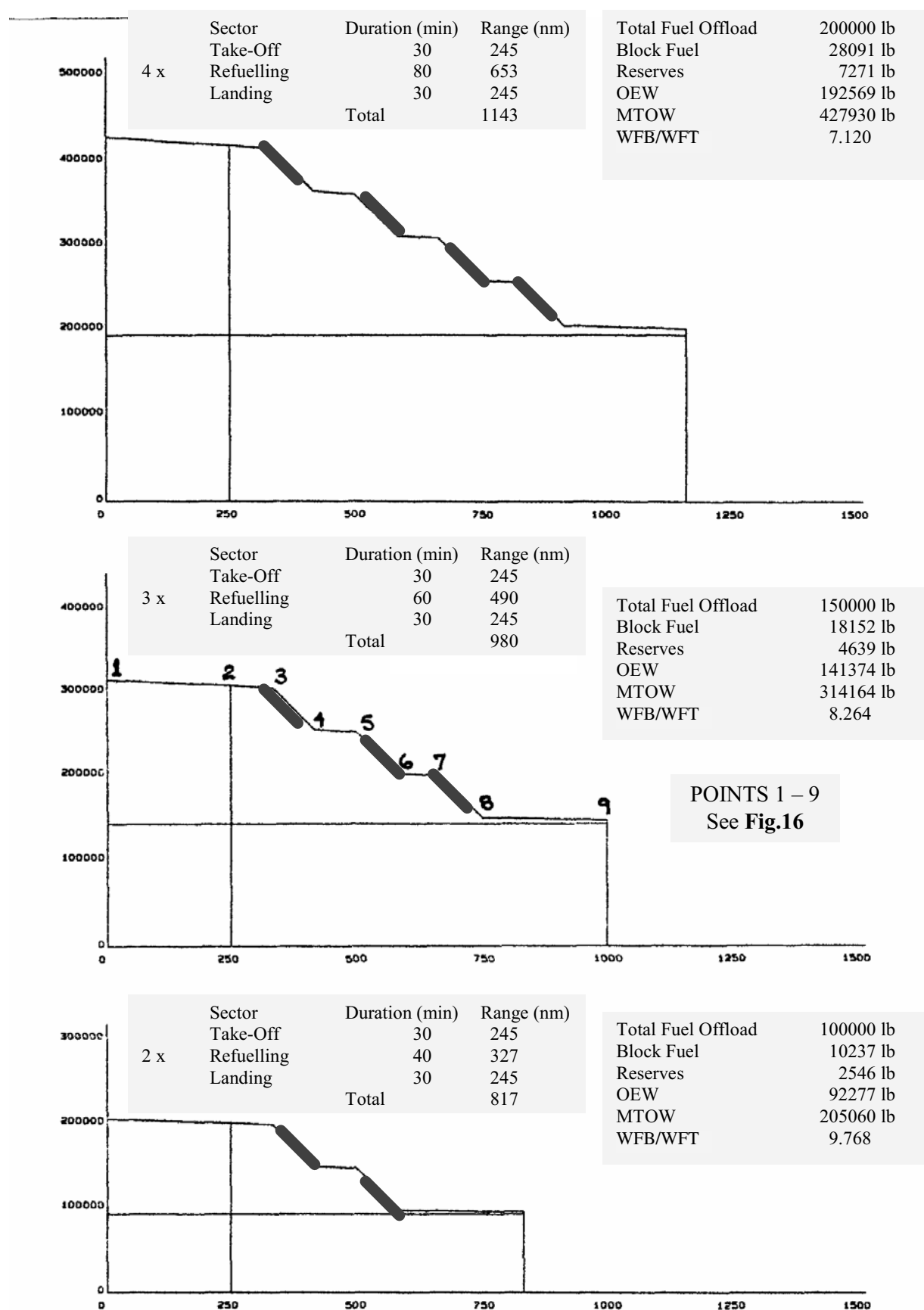Figure 16. Typical civil AAR tanker operating scenario.

	Sector	Duration (min)	Range (nm)
	Take-Off	30	245
4 x	Refuelling	80	653
	Landing	30	245
	Total		1143

Total Fuel Offload	200000 lb
Block Fuel	28091 lb
Reserves	7271 lb
OEW	192569 lb
MTOW	427930 lb
WFB/WFT	7.120

	Sector	Duration (min)	Range (nm)
	Take-Off	30	245
3 x	Refuelling	60	490
	Landing	30	245
	Total		980

Total Fuel Offload	150000 lb
Block Fuel	18152 lb
Reserves	4639 lb
OEW	141374 lb
MTOW	314164 lb
WFB/WFT	8.264

POINTS 1 – 9
See **Fig.16**

	Sector	Duration (min)	Range (nm)
	Take-Off	30	245
2 x	Refuelling	40	327
	Landing	30	245
	Total		817

Total Fuel Offload	100000 lb
Block Fuel	10237 lb
Reserves	2546 lb
OEW	92277 lb
MTOW	205060 lb
WFB/WFT	9.768

Figure 17. Tanker weight variation with range, 4, 3 or 2 off- loads of 50,000lb fuel at 5,000lb/min.

7.0 AAR AS AN ENABLER (OPPORTUNITIES)

7.1 Laminar (boundary layer) flow

In the past 15 years, hybrid laminar flow (sucked ahead of the front spar) has been well demonstrated on the B757 wing and the A320 fin, with quite adequate sweepback. Improvements in *ML/D* of at least 10-15% should be achieved, with the downside of extra system complexity and cost. Because the technology is not yet fully proven, extra fuel reserves would almost certainly need to be carried by aircraft utilising laminar flow to ensure safe diversion in the event of system failure or laminar flow becoming turbulent (e.g. due to surface contamination). The carriage of these additional reserves could reduce the environmental benefits and further worsen the 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 further 30% to 40% fuel efficiency improvement offered by AAR could be an attractive proposition.

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 with AAR availability. In the event of loss of laminar flow en-route, additional AAR would be used to allow the aircraft to continue to its original destination. Again there is scope for much further study on these possibilities.

7.2 Supersonic transport

Many factors currently prevent the economic operation or development of civil SSTs. The optimum cruise design shape is very inefficient at low speed (take-off and landing). Consequently, for operation from existing airports, rapid acceleration and high engine thrust levels are required. This implies high noise levels and high fuel consumption rates during take-off and climb-out in the vicinity of the airfield and local population.

In an SST, 20% of the total fuel onboard is used up in the first 20 minutes of flight. With AAR available, the aircraft would take-off with minimum fuel onboard, sufficient to get it to altitude and away from populated areas. Along the philosophy of SR-71, the SST would be designed with enough fuel tank capacity (thinner wings implication) to complete a suitable supersonic design range with AAR immediately before transonic acceleration and after deceleration, if required. The resulting, smaller SST has many advantages that may be accrued in a variety of ways; reduced take-off speed, reduced thrust, or reduced runway length or reduced C_L at same speed (hence higher *L/D*). Lower take-off thrust level will be beneficial in reducing engine emissions, especially noise.

7.3 More efficient business jet usage

Business Jets (BJ) are currently operated by large corporations and leasing companies. These are relatively inefficient in terms of fuel usage. Within a global AAR network, long range BJ could benefit. However, the contribution of BJ to climate change is relatively small.

8.0 INFERENCES, IMPLICATIONS AND GLOBAL BENEFITS OF CIVIL AAR

We have shown that AAR offers fuel savings on longer-range flights. Less fuel consumed implies reduced emissions released into the atmosphere. The global benefits resulting from the introduction of AAR to the civil transport scene are extensive, compound and assume a snowballing effect. The disadvantages appear minimal, on the whole only perceived and on balance far outweighed by the economic, environmental and safety benefits.
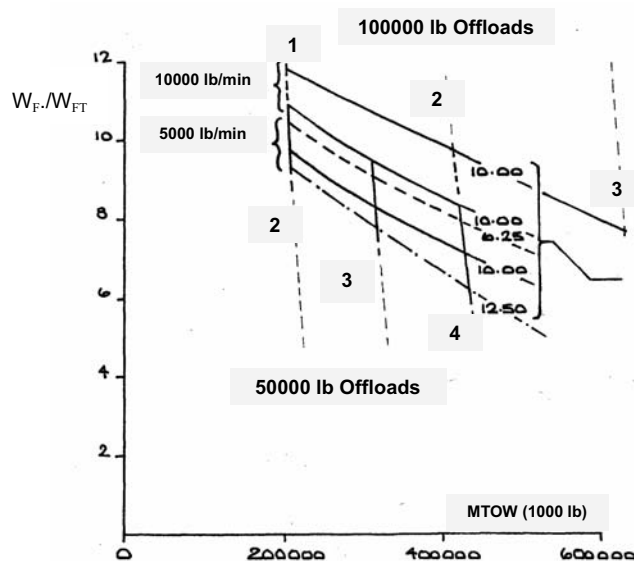

Figure 18. Tanker efficiency (WFT/WF),
varying transfer rates, offload, positioning time.

In this section we present a discussion of the overall scope of AAR. It is hoped that this will deal with the first-level questions arising.

8.1 Development of regional airports, reducing demands on hubs, tanker bases

AAR enables smaller aircraft to complete longer ranges, operating from smaller Regional airports. 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 also reduces congestion at Hub airports thereby saving time, effort, energy and fuel. Less fuel needs to be transferred to (by road tanker or pipeline) or stored at the Hub airports. Future, increased capacity may be provided through new airports, sited exactly where needed, rather than relying on continual development of already overloaded Hubs.

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.

8.2 Pilot workload, AAR operations

AAR will involve one or two additional crew operations on each long-range flight. These operations could be argued to be simpler than take-off and landing. The closing speed prior to refuelling is of the order of 1kt compared with 'meeting your image' on landing at 140kt horizontally and 5 to 10kt vertically. AAR easily offers more than one chance of establishing the objective.

The military AAR scene, even though in demanding and hostile circumstances, reports a good safety record. Automated AAR is currently being developed both for conventional and unmanned aircraft. Collision avoidance, navigation and global positioning technologies are continually being developed and all these will be available to future AAR activities.

The relative positioning of the tanker and receiver (above/below, in front/behind, in-line/tip-to-tip) for civil aircraft will need further

detailed work to ensure AAR operational availability over a wide flight envelope.

8.3 Airline operational developments, voluntary or mandatory?

The adoption and integration of AAR involves a rethink of the whole scenario of long-range air travel. Bearing in mind the 'natural' resistance to change, initial reactions may be the fear of extra costs and reduced profits. We have shown that AAR increases efficiency and hence increases profit.

It would be appear that no single sector within the aviation industry will opt for the first step. It is more likely that such a change will come about through fuel conservation pressures, governmental and international encouragement or demands.

8.4 Immediate benefits

Obviously, it will take a decade or more to achieve a reasonable level of integrated civil AAR. It could be introduced, almost immediately in specific areas of aviation e.g. cargo aviation, affording large improvements in fuel savings, reduced pollution and increased profits. This will provide a valuable pre-cursor experience for the full adoption of AAR.

8.5 One design range aircraft to operate on all routes

The fuel efficiency is optimum for 3,000nm designs and independent (first-order) of the payload. This suggests possibilities of medium range aircraft in different seats versions. Each version is capable of all ranges with AAR. If required, the development of larger, high capacity medium range aircraft will occur, solely for the traffic demands rather than as a by-product of increasing range.

This would focus the efforts of industry, resulting in larger, more economical production runs. Developments and upgrades need only be applied to a few types.

A single aircraft type within one operator would lead to easier scheduling, easier maintenance, reduced type certifications for aircrew, ground and maintenance crew. This would result in cost savings in training, servicing, maintenance and spares. Safety will improve.

8.6 Reduced requirement for larger engines

Assuming 250 seats, the 3000nm aircraft will require two engines of about 40,000lb thrust each c.f. 80,000lbs each for 9,000nm aircraft[5]. With smaller aircraft capable of servicing the longer routes as a result of AAR, the requirement for larger engines would be reduced.

The expertise currently being 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.

8.7 Reduced noise at airports

AAR would reduce the need for larger long-range aircraft. The consequent noise reductions would reduce or even remove night flying restrictions. The problems caused by take-off and landing shed vortices at airports would also reduce, allowing increased frequency.

8.8 Safer and quieter take-off and climb-out procedures

Available data indicates that AAR operations between similar sized aircraft (TriStar – TriStar, VC10 – VC10, VC10 – TriStar, etc.) are not difficult or hazardous. If an aircraft is required to refuel at least

once to complete a 6,000nm flight, or twice to complete a 9,000nm flight, then there should be no difficulty in introducing an additional AAR operation shortly after take-off. In this scenario, the aircraft, capable of and with the tank capacity to carry 250 passengers over 3,000nm, would take-off with only a minimum amount of fuel onboard (equal to the normal flight reserves). After 20-30 minutes, the aircraft would rendezvous with a tanker and take on sufficient fuel to reach the next rendezvous.

Take-off has always been regarded as one of the most demanding phases of any flight. The aircraft is heavy with payload and fuel. The engines are operating close to the maximum output. With the option of AAR, the aircraft could take-off very light. It would be more aerodynamically efficient and not operating anywhere near its performance limits. Engine power requirements would be reduced, directly reducing noise pollution. This enhanced operating procedure will require further statistical analysis to review the balance between offering improved safety at take-off versus the introduction of an additional, potentially hazardous, operation.

8.9 Greater flexibility with existing long-range aircraft

We consider a typical 250 passenger, 6,000nm 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.

8.10 Advantages *v* 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. If the world truly wants to be greener, with more efficient air travel, along with other areas of advance currently being researched, AAR appears to give a really valuable contribution.

9.0 CONCLUDING REMARKS

World air traffic, both passenger and cargo, will continue to grow. Estimates suggest a two to three fold increase in 25 years time. At current trends, pollution (noise and gaseous) and congestion will rise beyond what are already seen as unacceptable levels, particularly on Hub airports.

This raises many questions for the air transport industry: Do we allow air traffic to grow? Can it continue at present rates? Do we insist on Hub airports or 'diffuse' to Regional airports? Can the effects on the environment be reduced or eliminated?

- AAR will provide fuel savings of 30-40% and financial benefits of 35-40%. Formation flying also offers significant fuel savings. It is envisaged that a degree of integration between AAR and formation flying would provide compound benefits.

- The introduction of AAR into civil aviation will enable smaller, quieter, 3,000nm range aircraft to complete long-range flights.

- Hub airports are nearing capacity limits in terms of flight frequency, pollution levels and accessibility. AAR will allow the smaller, more abundant and accessible Regional airports to handle long-range flights. Smaller aircraft, with smaller engines, produce less noise and pollution. Their wakes are less intense and less
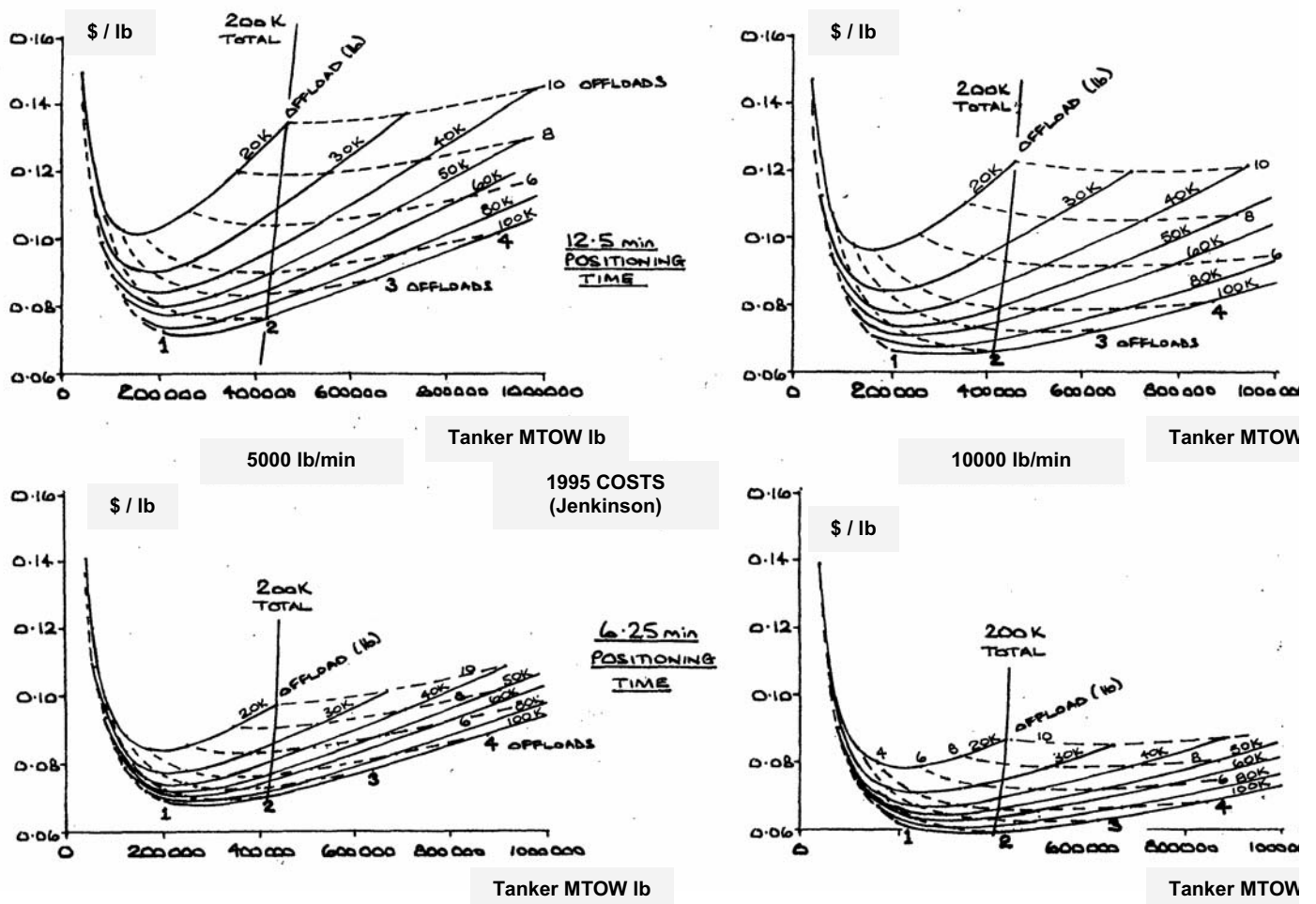
Figure 19. Additional fuel cost variation with MTOW for different tanker capabilities, costs based on 1995 prices.
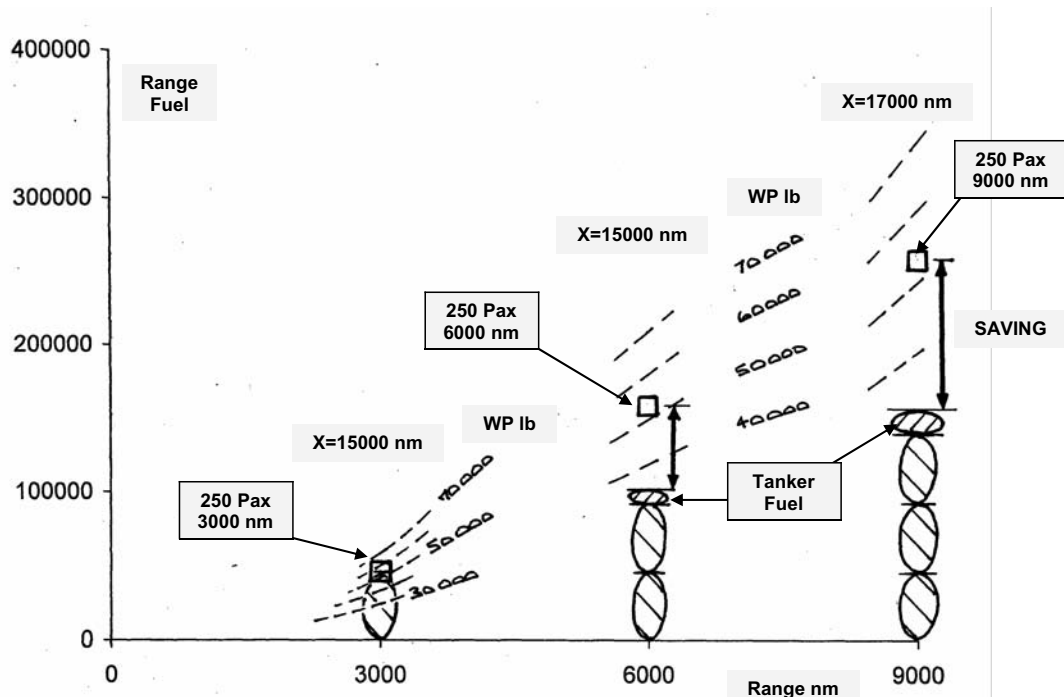

Figure 20. Variation of fuel used with range, payload and *X V* variations, fuel saving with AAR square symbol, are for 250 PAX.
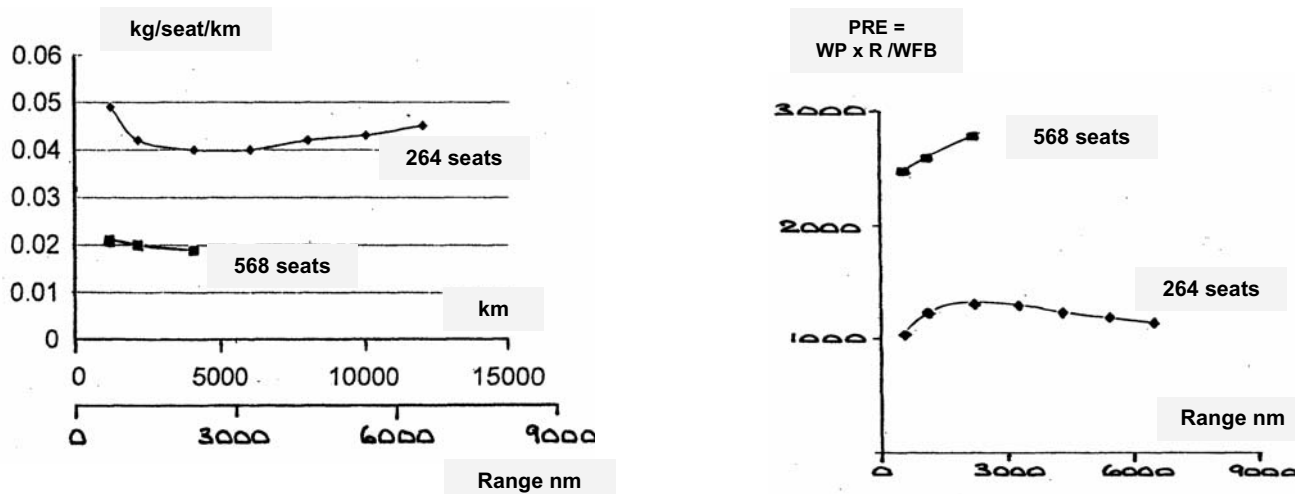
Figure 21. Variation of fuel burn rate and work done efficiently,with range and PAX density effects
(JAL, Green)

persistent allowing increased frequency and greater operational flexibility. Further, night flight restrictions could be eased. The demands on ATC at Hub airports will be alleviated.

● Take-off with maximum payload, minimum fuel, and refuelling soon after will imply less noise and higher aerodynamic and mechanical safety margins. The flight itself will be at high PRE.

● Military AAR is an established, proven operational activity. By providing a 'garage in the sky', AAR increases the capability of modern military operations. Its effectiveness outweighs the costs.

● Dedicated civil tanker designs with slim fuselages and fuel tanks in wings (or joined wings) could offer high *L/D*. High fuel transfer rates would further improve efficiency. The tankers would be scheduled to carry out, closely coordinated, multiple refuelling operations in each flight. Integrated civil AAR will therefore be very different from current military usage. Receiver aircraft larger than the 250 passengers – 3,000nm range example considered here will require larger tankers. The balances and trade-offs need to be examined in more detail.

● The acceptance of civil AAR will enable hitherto borderline technologies to be utilised. Laminar flow, with AAR as a 'safe-guard', offers increased efficiency. Supersonic transport may become an acceptable economic option with benefits afforded by AAR.

● Fuel burn savings afforded by AAR (of the order of ten times those offered by possible technological advances) will have a significant impact on aviation's contribution to reducing atmospheric pollution. Public opinion will be wooed with benefits of a greener environment, safer and quieter take-offs, quieter climb-out, noise reductions, lighter and more efficient aircraft and fare reductions!

With regard to ACARE's overall objectives, a 50% reduction in aviation fuel usage, multi-faceted solutions will be needed. By using efficient propeller systems, the short-range flights could become more efficient. AAR will tackle the longer-range sectors. Formation flying integrates effectively with AAR and this will be also benefit medium and long-range sectors.

10.0 THE WAY AHEAD

AAR affords the possibility of a complete widening of the design space. This should appeal to the imagination of current and future designers.

Having set out the possibilities and potential for civil AAR we need to establish a plan for further development, proving and acceptance of the ideas. Before flight demonstrations, a full rigorous system study will be required with aircraft optimised for 3,000nm range and dedicated tankers and infra-structure as needed.

Here is a possible list of topics that need to be focussed on and prioritised.

● establish economic gains with up-to-date data (aircraft performance, fuel costs, etc)

● re-evaluation of economic gains with different payload combinations with optimised 3,000nm range aircraft and dedicated tanker designs and infra-structure

● feasibility studies with technology providers and users (AAR companies, RAF, manufacturers, airlines, airports, governments

● further review of safety aspects (ATC, CAA, FAA, airports, local authorities, governments)

● initial proving exercises with current air force (RAF) deployments.

● subsequent commercial proving could be undertaken with freight carriers.

● establish basic tanker network in conjunction with air forces (move towards civil operation of air force tankers) and freight carriers

● design, manufacture and deployment of dedicated tankers

● design, manufacture and deployment of optimised 3000nm range aircraft

● mutual interference, control aspects

● development of global tanker network

Also required is a full analysis of further technology requirements (where certainly the military should be involved) to work up proposals for European or UK research programmes (obviously moving through to the demonstration phase).

It is hoped that this document has addressed the AAR option in sufficient detail to encourage objective assessments and further work towards detailed proving.

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