‘Greener’ civil aviation using air-to-air refuelling – relating aircraft design efficiency and tanker offload efficiency

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NOMENCLATURE

AAR	air-to-air refuelling
ACARE	Advisory Council for Aeronautics Research in Europe
ATC	air traffic ccontrol
D	drag force
kt	knots, nm/hr
L	lift force
L/D	lift to drag ratio
M	Mach number
MTOW	maximum take-off weight
OEW	operating weight empty (also WOE)
OEWR	OEW/MTOW
Pax	passengers
PRE	payload range efficiency WP*R/WFB
R	range
RT	fuel off-loaded/fuel used by tanker
S	reference area
SFC	specific fuel consumption, lb (of fuel)/hr/lb (thrust) = 1/hr
TOW	take-off weight
V	airstream velocity, k
WP	payload
WF	fuel load (block + reserves = total)
WFB	block fuel
WFT	tanker fuel
X	$V\,L/D$/SFC, range parameter
Z	R/X, non-dimensional range

1.0 INTRODUCTION

The aircraft industry, as a whole, is striving to limit its impact on the environment. Improved engine design and operation may offer a reduction in emissions of a few percent. More efficient air traffic control (ATC) may offer a limited reduction in overall fuel burn. Improvements in aerodynamic design and materials available (e.g. on A350XWB, B787) might achieve a few percent increases in efficiencies. The use of alternative fuels is some way off. The ACARE objectives present a stiff challenge.

Our recent studies have shown that air-to-air-refuelling (AAR), well established in military circles, introduced to civil aircraft operations would provide fuel savings of the order of 30% – 40%. AAR will allow smaller (3,000nm range), more efficient (greener) aircraft, operating from shorter runways, to fulfil long-range route requirements. In addition, the ‘safety-net’ afforded by the availability of AAR will enable a host of hitherto borderline technologies to be accepted and utilised in future aircraft designs. Laminar flow will provide fuel savings and increased efficiency in its own right provided it is enabled within a civil AAR environment. Similarly, supersonic transport becomes an acceptable economic option.

As a result of our previous publication in the RAeS *The Aeronautical Journal*, November 2006(1), a few more interesting aspects have emerged with regard to tanker design and operation and the magnitude of the fuel off-loads available and relating them to overall fuel savings and gains in payload range efficiency (*PRE*).

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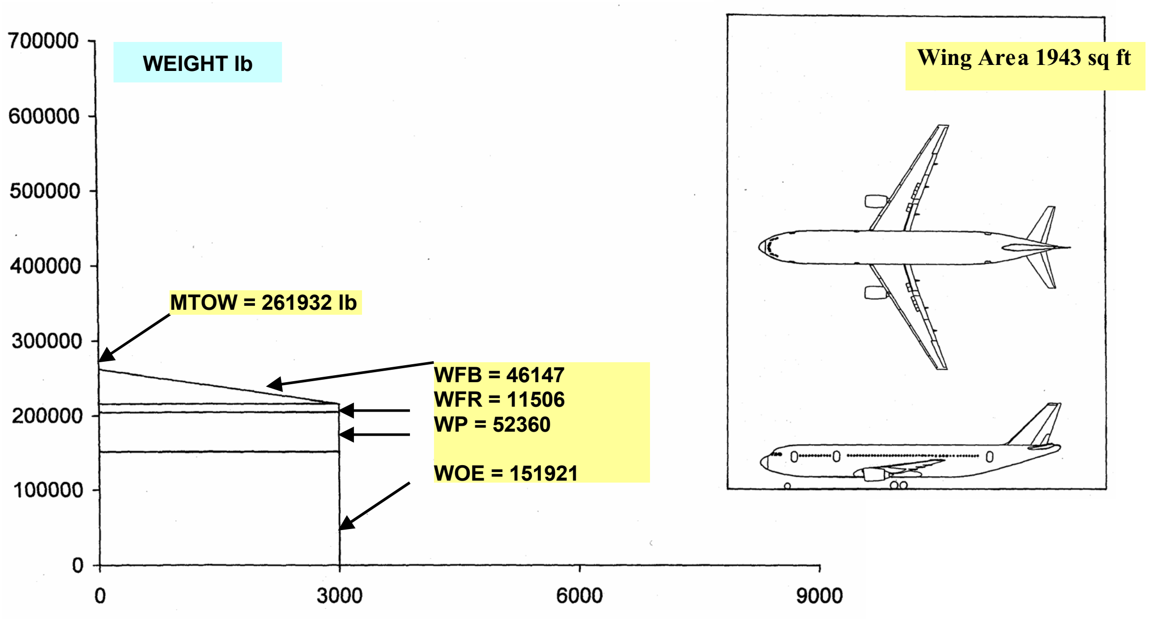


Figure 1. Aircraft weight variation with flight distance for 3,000nm range no refuelling, 250 PAX, OEWR = 0·58, X = 15,077nm.

2.0 TANKERS & FUEL OFFLOADS DEFINITION

We define a factor RT for tanker off-load fuel ratio (efficiency):

RT = fuel off-loaded/fuel used by tanker

Ratios of about 5:1 should be achievable in the commercial AAR scenario. The overall tanker operating efficiency will depend upon the availability of tanker operating bases and their proximity to scheduled service routes. Commercial routes could be modified to make best advantage of AAR.

3.0 BRIEF REPRESENTATION OF WORK OF REF. 1

The symbol notation including the payload range efficiency (*PRE*) is defined in the list of symbols in Ref. 1. Since the range parameter X depends only on the propulsive and aerodynamic efficiencies of the aircraft, the ratio PRE/X is a measure of the effect on fuel efficiency of range and of the ratio of empty weight to payload.

We now refer to Figs 9 and 10 of Ref. 1 reproduced here as Figs. 1 and 2 supported by Fig. 3 that should have been Fig. 11 in Ref. 1, and Fig. 12 of Ref. 1 reproduced as Fig. 4 here.

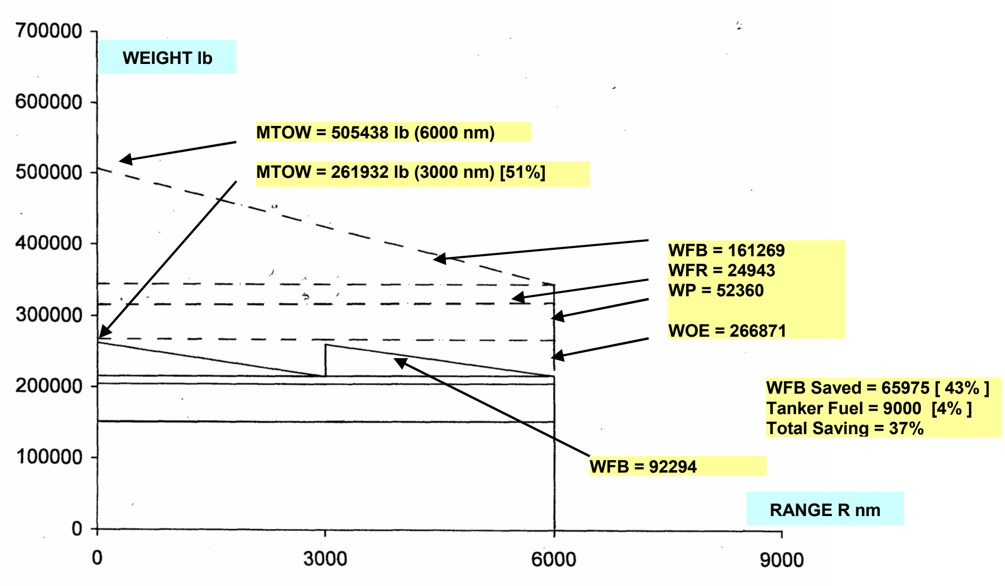


Figure 2. Aircraft weight variation with flight distance for 6,000nm range aircraft, refuelling once cf aircraft without refuelling, OWER – 0·528, 250 PAX, 3,750ft^2, X = 15,077nm.

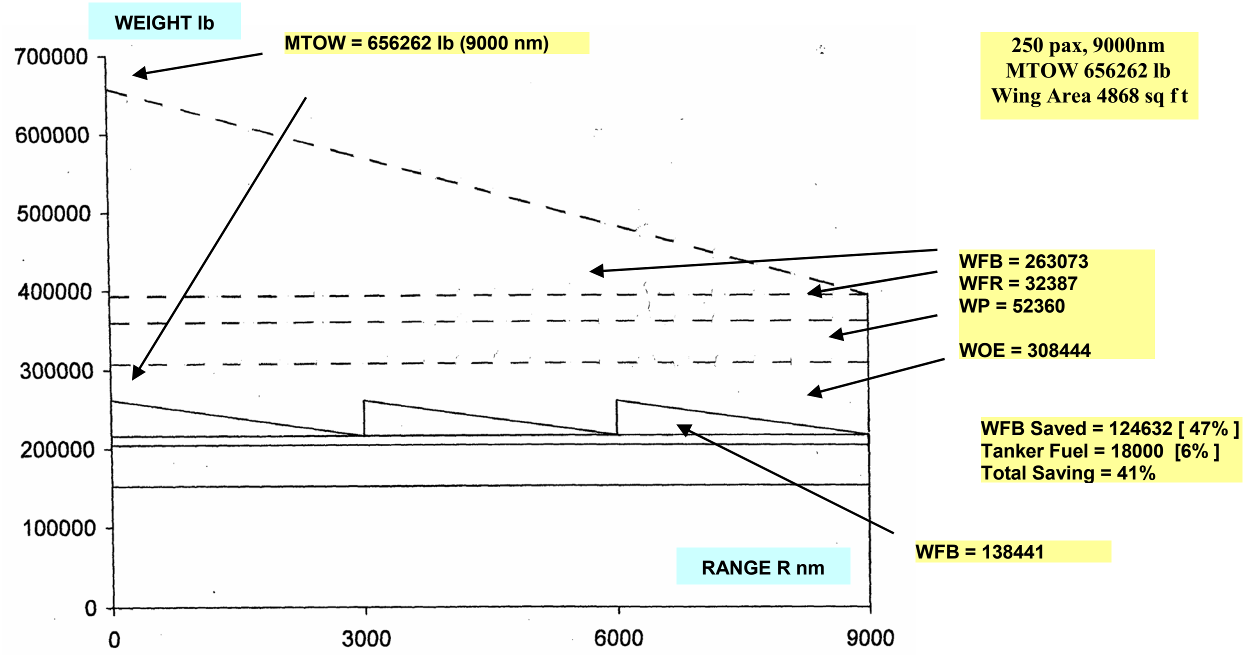


Figure 3. Aircraft weight variation with flight distance for 9,000nm range aircraft, (X = 15,077nm) refuelled twice cf aircraft without refuelling, OWER – 0·47, 250 PAX, S = 4,968ft^2, X = 16,897.

The approach followed was to design representative aircraft to carry the same payload (250 passengers) over 6,000, 9,000 and 12,000nm and estimate the fuel saved by using the base 3,000nm range aircraft to carry the same payload but using AAR to complete the longer ranges.

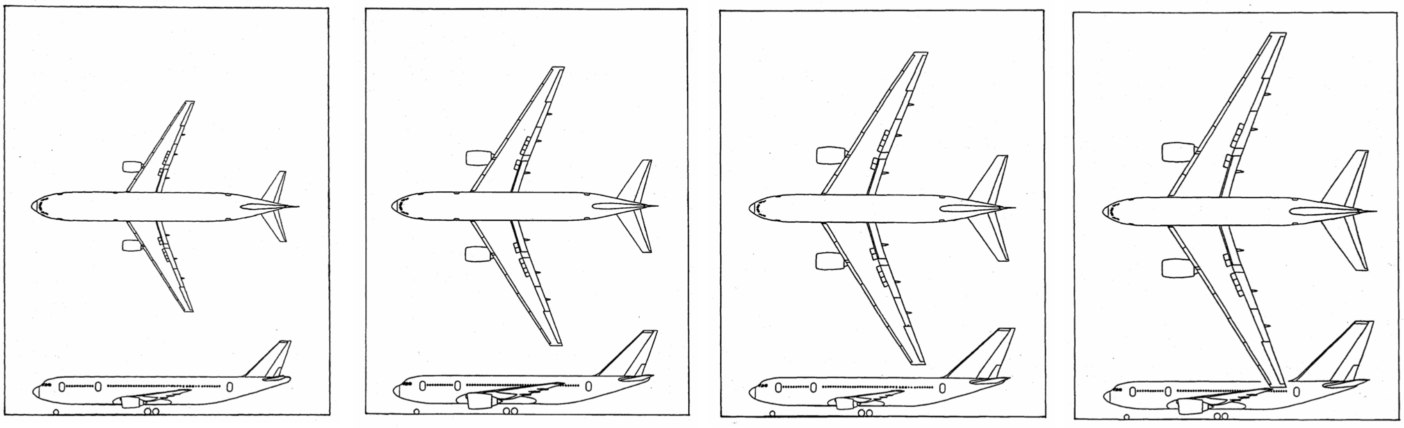
Our prediction methods and models are based on correlated data from current in-service aircraft and include likely aerodynamic improvements (L/D up to 20). The Breguet range equation has been used to relate the main parameters. The aerodynamic parameters are: L/D = 20, V = 490kt (cruise M = 0·85 at 36,000ft). 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. The PRE/X values are 0·212 and 0·125 for the 3,000nm and 6,000nm respectively.

For the 9,000nm aircraft we have used a 'more efficient' SFC = 0·57lb/hr/lb. The Range Parameter X is then 16,897nm and PRE/X value is 0·102.

The base aircraft weight variation over 3,000nm is shown in Fig. 1. 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. 2, 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. 2 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 3 refers to the comparisons for the 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 3,000nm 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. 4. It is realised that 12,000nm range is somewhat academic, slightly longer than the great



250 pax, 3,000nm
MTOW 261,932lb
Wing area 1,943sq ft

250 pax, 6,000nm
MTOW 505,438lb
Wing area 3,750sqft

250 pax, 9,000nm
MTOW 656,262lb
Wing area 4,868sqft

250 pax, 12,000nm
MTOW 860,445lb
Wing area 6,383sqft

Figure 4. Comparing (approximately) the aircraft designed for different ranges, without refuelling, 250 PAX.

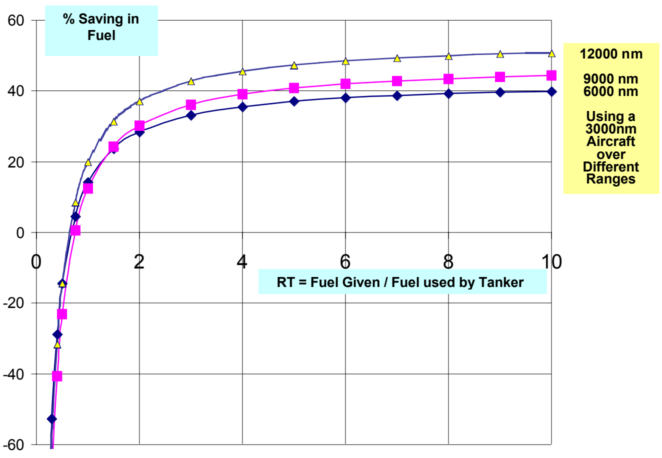


Figure 5. Savings in total fuel consumed (%) using a 3,000nm aircraft with AAR, variation with tanker fuel off-load efficiency (RT).

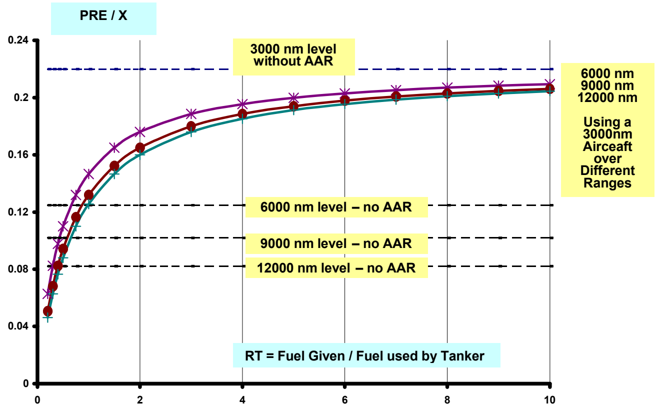


Figure 6. *PRE*/X using a 3,000nm aircraft with AAR, variation with tanker fuel off-load efficiency (RT).

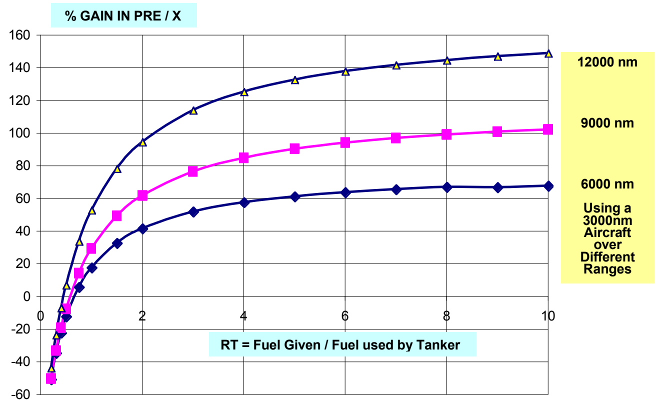


Figure 7. Improvement in *PRE*/X using a 3,000nm aircraft with AAR, variation with tanker fuel off-load efficiency (RT).

circle route, half way around the world – perhaps not likely to be flown often! The current design scene is aiming the aircraft more towards the 9,000nm range. The fuselage size remains almost constant but the wing area increases rapidly to accommodate the fuel requirements and maintain design C_L.

4.0 CURRENT WORK WITH TANKERS & FUEL OFFLOADS

Figure 5 shows the fuel saving (%) achieved by using a 3,000nm design aircraft, with AAR, over aircraft specifically designed for the 6,000, 9,000 and 12,000nm ranges, all carrying the same payload. It is interesting to note that we begin to make fuel savings with RT slightly less than 1 and beyond. For RT values about three, we are close to being within 5 – 7% of the maximum benefit obtainable. It is worth noting that we need to explore ranges between 3,000 and 6,000nm. This aspect opens up further discussion and work regarding stage length variation.

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

Following Ref. 2, we have derived non-dimensional payload range efficiency curves for refuelled aircraft in terms of *PRE/X*. These are plotted against RT in Fig. 6. Comparisons are made against base levels shown for the aircraft designed to carry 250 passengers over each of the ranges (3,000, 6,000, 9,000 and 12,000nm) level. Note that all the refuelled cases tend towards the 3,000nm range aircraft as RT increases.

It is interesting to note from Fig. 7, the increase in *PRE/X* achieved by the refuelled 3,000nm design aircraft over the *PRE/X* achieved by the aircraft designed for that range as a percentage of the *PRE*/X achieved by the aircraft designed for that range. The improvements are large and higher for the longer range situations. For a 'reasonable' RT value of four, we are touching gains in *PRE/X* values of 60% for 6,000nm and 80% for 9,000nm ranges.

5.0 CONCLUDING REMARKS

It is hoped that the contents of this note, by laying out the tanker requirements, add strongly to the discussion in Section 5 in Ref. 1.

So far we have focussed on 250 seaters in this document with refuelling half-way for the longer ranges. Many other situations arise and they will need to be studied.

The work continues to emphasise the significance of AAR and the need for introduction in in civil aviation. It certainly brings us nearer to fulfilling the objective need for its introduction into ACARE.

ACKNOWLEDGEMENTS

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1. NANGIA, R.K. Operations and aircraft design towards 'Greener' civil aviation using air-to-air refuelling, *Aeronaut J*, November 2006, **110**, (1114), pp 705-721
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