RELATING & COMPARING OPERATING EFFICIENCIES OF CIVIL AIRCRAFT & MILITARY TRANSPORTS (JETS & TURBO-PROPS)

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ABSTRACT

Currently there is great emphasis on achieving efficient and optimised flight and operations. The need for overall energy savings is being felt in all spheres of defence and commercial aviation. The military scene includes many types of aircraft fulfilling diverse roles during training and in action.

An appreciation of Efficiency parameters follows from the consideration of speed (V), lift-drag ratio (L/D) and engine efficiency (SFC) with Range (R) and Payload (WP) characteristics. A range parameter X = V L/D/SFC follows. Operational aspects e.g. Air to Air Refuelling (AAR) and Close Formation Flying (CFF) also contribute. Interplaying all these leads to new designs or morphing technologies for flight optimisation. We can think in terms of sub-systems or in a more global sense, incorporating several technologies optimally.

We consider the efficiency aspects of heavy-lift, military Jet and moderate-lifting Turbo-Prop transports. Useful consistent weight fraction data is available on the Western types. Consistent data-sets on Russian aircraft are rare. We use the various weight fractions and payload range relationships.

Efficiency trends, established for civil passenger aircraft and freighter aircraft, have been described. These provide the foundation and nature of comparative aspects for a quantitative assessment of the military Jet and Turbo-Prop transports. The non-dimensional parameters introduced (e.g. PRE/X and Z = R/X) allow comparative use of data from current / older types and implied technology levels, with relative ease. This is an important feature.

Several similarities are noted in the weight ratios for the military transports and freighters. However, a surprising notable trend was that military transports use less Thrust to Weight ratio for "normal" 2.5 g flights.

Maximum Payload efficiency PRE/X occurs near range parameter Z of 0.17. The efficiency drops rapidly as Z (or range) increases and payload fraction is reduced. For military transports, operational criteria such as g limitations on performance and fuel reserve specification have a large impact on efficiency (payload-range capability shrinks). Although it is easy to have an intuitive, qualitative feel for such effects, deriving and presenting reliable quantified analysis has been painstaking but considered valuable.

The parameters can be used in future designs. For example, reducing OEW (Operating Empty Weight) or increasing X both have favourable effects in different ways on the flight envelope.

All these factors need to be viewed in the context of payload-range capability. There remains a requirement for heavy lift aircraft for transporting larger items of military equipment. Similarly, field performance capabilities (high lift, poor runway, hostile environment, etc) need to be taken into account.

A thorough appreciation of the Efficiency Parameters will allow civil / military logistics operators to maximize the performance using direct or alternative operational procedures (with planned AAR), different aircraft. Tables are presented to assist with such assessments. Similarly, future designs of transport aircraft can be biased, towards the more efficient operational procedures, as the direct changes in OEW and X begin to "level-out".

Ideas of comparative costs arising have been presented. From a matrix of payload and range capabilities for the jet and turbo-prop transport aircraft variations in fuel cost ratio (of total costs) with range and comparisons between aircraft types is given. These costs are also presented in terms of fuel cost per passenger-nm that compares directly with civil aircraft. The effect of fuel price increases on fuel cost ratio is dramatic and very significant in the current climate.

Several avenues of further work and development arise e.g. relating take-off / landing aspects with fuel efficiency. Balance between fuel efficiency and overall economics needs to be addressed along the lines indicated.

Certainly, the work programme has made us aware of what can be achieved in light of fuel efficiency concerns (that will prevail) and there are design and operational choices.

The established trends give a clear indication of "design space". We can identify the need for where the advancements e.g. by increasing the Range parameter X or by reducing the OEW thus enabling increased WP/OEW parameter.

1. INTRODUCTION

Presently there is great emphasis on achieving efficient and optimised flight and operations. Budget policies are being revised and the need for overall energy savings occurs in all spheres of defence and commercial aviation. Aircraft operating efficiency, both civil and military, has been the subject of much analysis, Refs.1-12. Particular aspects such as Air-to-Air Refuelling (AAR), Close Formation Flying (CFF) and more efficient, novel configurations are discussed in Refs.4-10. The military scene includes many different types of aircraft with the objective of fulfilling many diverse roles. The operating efficiency of military jet transports was discussed in Ref.1. In this paper we extend the analysis to include turbo-prop powered transport aircraft. There are only a few different types in current service and for many, performance data is limited. We have therefore used efficiency trends, previously established for civil passenger and freighter aircraft, to validate, quantify and compare the military aircraft data. **Fig.1** shows the Jet Transports of the USA and the Soviet countries. **Fig.2** refers to Turbo-Prop Transports. We shall first review the Payload-Range efficiency trends established for the civil passenger and freighter aircraft, before extending those to cover Military Jet and Turbo-Prop Transports.

The military jet transports considered are the Lockheed C-5 Galaxy, McDonnell Douglas / Boeing C-17 Globemaster III, Lockheed C-141 Starlifter and the Antonov An-124. The military turbo-prop transports considered are the Lockheed C-130J Hercules, Airbus Military A400M, EADS Sogerma Services C-160 Transall, Alenia Lockheed C-27J Spartan and the EADS (CASA) C-295M. Data for many other military aircraft are used to establish airframe weight and geometry trends.

2. PAYLOAD, RANGE, EFFICIENCY PARAMETERS, CIVIL PASSENGER AIRCRAFT

In Ref.2, Nangia presented results from an appreciable data exercise on modern commercial (jet) aircraft, taking into account the distinction between Maximum Payload performance, occurring at Pt A on the Payload-Range diagram, **Fig.3** and the Design Payload performance, Pt D. **Fig.3** compares the Payload-Range performance of the Boeing 757-200 and the much larger Boeing 747-400. The significance of mandatory fuel reserves has also been considered. Pt B on the Payload-Range diagram is also of interest. At Pt B the aircraft is at maximum fuel capacity with a reduced payload and at the MTOW limit. In payload terms, passenger payload is inefficient! Pt F corresponds to maximum fuel capacity with zero payload essentially for Ferrying Range.

Civil aircraft are designed, initially, for a particular passenger payload over a given Range (Pt B). Variants of the initial design may carry additional passengers (more densely seated) or additional cargo over shorter Ranges, closer to Pt A. Civil freighters are, in general, derivatives of passenger aircraft and they will not be aligned to a specific design point. Similarly, military transport aircraft will be required to operate over the entire scope of the Payload-Range envelope.

For the Civil aircraft, trends of aircraft component weight ratios (with respect to MTOW), OEW/MTOW, WP/MTOW, (OEW+WP)/MTOW, WFB/MTOW and WFR/MTOW are derived in **Fig.4.** (Pt A) and **Fig.5** (Pt D) against Range. We note the slight shift in the trends for the more modern High By-Pass Ratio (HBPR) engines.

These results have been correlated into reliable "first-order" non-dimensional trends in terms of PRE/X and Z, using the Breguet Range equation.

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% of MTOW (Ref.6).

Total Block fuel is then WFB = WFBC + WFBS.

Figs. 6-7 summarise the WFB/WP and PRE/X trends, distinguishing between A and D point operation. Green (Refs.11-12) supports the work. Radial lines of constant WFB/WP are shown. In fuel efficiency terms, aircraft perform best 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.

3. EFFICIENCY PARAMETERS, CIVIL FREIGHTERS

The work on efficiency of civil aircraft, Refs.2-3 has been extended to civil freighters, Ref.13.

The variations of freighter aircraft component weight ratios (with respect to MTOW), OEW, WP, OEW+WP, WFB and WFR at Pt A with Range are presented in **Fig.8** together with trends for the civil passenger aircraft. The OEW ratio trends for the freighter aircraft are near 10%TOW less than those of the passenger aircraft. This allows a corresponding increase in WP ratio for the freighters.

Fig.9 shows civil freighter PRE variation with Range at varying payload fractions (100%, 80%, 60% and 40% of WP_{max}). The band-widths for each payload fraction indicate scatter in the plotted data. This is partly due to variations in efficiency for freighters of varying age and design technology but may also be indicative of the accuracy of the performance data available. Also shown are "radial" lines of constant WFB/WP. This indicates that at Pt A, the freighters are achieving a WFB/WP ratio of about 0.8. When non-dimensionalised by Z, the trends of **Fig.9** take on a different emphasis, **Fig.10**. Here, PRE/X for a given payload fraction remains almost constant as Z varies. Also included in **Fig.10** is the Pt A PRE/X – Z trend for the civil passenger aircraft indicating the greater efficiency of the freighter aircraft at all payload fractions.

Fig.11 shows the civil freighter PRE/X trends with Z from **Fig.10** superimposed onto theoretical predictions using Kuchemann's model (Ref.14) with c1 and c2 parameters. We note that the civil freighter operation at Pt A equates closely to the c1+WFR = 0.30 and c2 = 1.6 trend.

Adaptation to Military Aircraft

The approach and principles outlined here allow adaptation to all sorts of situations in the local or overall sense with reference to Logistics and Mobility considerations. This includes extension to the turbo-prop transport aircraft, both civil and military. In military aircraft, depending on the mission envisaged, the OEW, WP and WFB are likely to be different from those for civil aircraft and this will imply different quantitative results from those in Ref.2. It is however, appreciated that military needs and objectives are often very different i.e. effectiveness, stealth, manoeuvrability, etc. are valued more than the fuel usage or costs over a desired time frame.

We also need to consider other issues e.g.

- Acknowledge that some military transports were adapted from the civil scene (except the heavy lifters)
- Traditionally, military aircraft are designed to specific roles – fighter, bomber, reconnaissance, land-based / carrier-based. Currently, with significant awareness of costs, multi-role designs for different operating scenarios becoming the norm.
  - Modern materials and controls will allow morphing structures to expand the flight envelopes in future (adaptive intakes, morphing wings optimised for T/O, cruise, Landing)
  - Consideration of fuel Efficiency Parameters should allow greater flexibility in the design of future transports.

General performance data for the military transports (jet and turbo-prop) have been drawn from a variety of sources, Refs.15 to 34. We note that these sources may give different emphasis to different aspects of each aircraft. Equally, data drawn from websites may not be up to date or even correct.

4. SUBSONIC MILITARY JET TRANSPORTS

Some military jet transport aircraft have been derived or converted from civil aircraft, whilst the others e.g. the Heavy lifters have been designed specifically. Of the wide range of military aircraft types in service, fighter/strike, bomber, reconnaissance, transport, etc., the military jet transports are the most amenable for efficiency analyses. Reconnaissance aircraft will provide an interesting analysis challenge for the future.

The military transports are cleared for flight at various g ratings (2.0g, 2.25g, 2.5g, 3.0g, etc.) depending upon the mode of operation anticipated. In general, civil aircraft are cleared to 2.50g. Military aircraft operating into or out of difficult airstrips may need to operate near 3.0g say, and will have their payload carrying capacity reduced accordingly. The maximum payload allowed at higher g may be limited due to several factors that include structural stress limits and payload center of mass, aircraft cg, aerodynamic center relationships, etc.

The Payload-Range capabilities depend upon the fuel reserves needed. In general, military operates with either Normal or Operational fuel reserve specifications. For comparative purposes, we have defined fuel reserves as 5% of MTOW at Pt B for the military jet transports and then calculated the effective reserves at Pt A. Where reserve fuel estimation criteria are available, the effects on operational efficiency of the various fuel reserve specifications can be shown. For the turbo-prop aircraft, fuel reserves of 4% and 7% of MTOW are considered.

When comparing performance parameters of the military aircraft directly with civil aircraft we use data from 2.5g and standard fuel reserve cases or equivalent.

Fig.12 shows the variation of aircraft wing span (feet) with MTOW (lb). Civil passenger aircraft data are shown as trend lines. These have been extended to include the Airbus A380 and the Antonov An225. In general, the civil freighter derivatives and the military subsonic jet transports considered, fall within these trends. The accompanying diagram for the turbo-prop transports includes the civil jet transport trends and military jet transport data up to 1,000,000 lb MTOW. The largest turbo-prop transport considered, An-22 Cock, lies close to the trend lines as does the current A400M. The remaining, smaller turbo-prop transports form a new trend with greater wing span for given MTOW.

The ratio of maximum static, Sea Level, thrust available over MTOW (T/W) is plotted against Range in **Fig.13**. The trends derived for the civil passenger aircraft at Pt A are in **Fig.13(a)** and for Pt B in **Fig.13(b)**. Corresponding data for the civil freighter aircraft fall within these trends. Data for the military transports are shown at various g ratings. Turbo-prop transport aircraft data are added to the trends for Pt A in **Fig.13(c)** and for Pt B in **Fig.13(d)**. There is a considerably wider variation in T/W at a given range for the turbo-prop aircraft than for the civil and military jets. This indicates a wider range of design requirements, e.g. short field performance (Saab 2000 & A400M) or older, quieter performance trends.

The variation of component weight ratios at Pt A against Range for the military jet transports are compared with those for civil freighters in **Fig.14**. These are essentially similar. These aircraft span several technology levels (years) and each has its own set of design parameters. The component weight ratios for the C-17 at Pt A lie close to the civil passenger aircraft trends. The An-124 weight ratios lie within the civil freighter trends.

We now consider the typical Payload-Range information available on C-5, C-17 and C-141. Using Breguet Range analysis, Section II, we can derive efficiency metrics for each aircraft over the whole domain of the Payload-Range envelope.

Lockheed C-5 Galaxy

Typical Payload-Range diagrams are in **Fig.15(a)** for varying g levels and alternative fuel reserves, Ref.21. Additional information allowed a 2.00g diagram to be constructed. Weight breakdown diagrams are shown in **Fig.15(b)** for Maximum (Pt A), Intermediate and Pt B Payloads and Ferry Flight for 2.0g, 2.25g and 2.5g conditions. It is interesting to note the variation in fuel burn with g limitation and TOW represented by the gradient (WFB/Range) for each case. At Pt A operation, reducing the g limitation from 2.5 to 2.0 increases the payload limit from 216,000 lb to 291,000 lb. At the nominal Design point, reducing the g limitations increases the payload limit but reduces the Range proportionally. Implementation of AMC reserves reduces the Range at any given WP as deduced from **Fig.15(a)**.

Considering the 2.50g case and Fuel Reserves (WFR) of 5% of MTOW at point B, we determine X = 14,030 nm. This "aerodynamic" efficiency is held constant over the applicable flight envelope region of interest, Pt A to Pt B. WFR at Pt A (2760 nm) then equates to 3% of MTOW. For Ranges less than 2760 nm, WFR is held constant at 3% of MTOW. WFR varies linearly between Pts A and B. For Ranges greater than 4800 nm, WFR = 5% of MTOW.

McDonnell Douglas / Boeing C-17 Globemaster III

A typical Payload-Range diagram is shown in **Fig.16(a)**, Ref.22. We note the effects of alternative fuel reserve options and g limitations on the Payload-Range envelope. Weight breakdown diagrams are shown in **Fig.16(b)** for Maximum and Design Payload and for Ferry Flight at 2.25g, 2.50g and 3.00g conditions. Ranges are for standard fuel reserves. The effect of g limitation on TOW and Range is very evident at Pt A.

At Pt A operation, increasing the g limitations from 2.5 to 3.0 reduces the payload limit from 122,200 lb to 79,500 lb and the Range from 3127 to 1463 nm. At 3.0g limitation, the MTOW is limited to 423,000 lb, implying that full fuel capacity cannot be attained (Pt B) even with zero payload.

Considering the 2.50g case and WFR of 5% of MTOW at point B, we determine X = 13,069 nm. Holding X constant, Pt B to Pt A, results in WFR at Pt A (3127 nm) of 4% of MTOW. For Ranges less than 3127 nm, WFR is held constant at 4% of MTOW. WFR varies linearly between Pts A and B. For Ranges greater than 3950 nm, WFR = 5% of MTOW.

Lockheed C-141 Starlifter

The C-141, Ref.24, was first delivered in 1979 and was recently retired from service with the US military. A significant amount of data is available on the C-141A and B and this has been analysed to assist with establishing trends for other "less well documented" types.

Some C-141 aircraft were fitted with "intra-formation positioning sets" which enabled flights of two to thirty-six aircraft to maintain formation regardless of visibility. This technology may also be available to other aircraft types. The development of CFF techniques will be invaluable in improving fuel efficiency.

Fig.17(a) shows Payload-Range diagrams for 2.50g, 2.25g, normal and alternative fuel reserve cases. The manufacturers' Payload-Range diagrams, **Fig.17(a)** suggests additional Range limitations, on payloads above 57,000 lb at 2.50g and above 75,500 lb at 2.25g. For the 2.50g, standard fuel reserves this implies a near 6% reduction in Range at WP_{max}. In the present analysis, performance and efficiency are based upon the actual Range achieved at WP_{max}. Further analysis of efficiency without the additional Range limitations may be of value.

Weight breakdown diagrams are shown in **Fig.17(b)** for 2.50g and 2.25g limitation. The effect of alternative fuel reserve options are shown in each case. At 2.50g condition, weight breakdowns for maximum Payload (Pt A), Pt B Payload and Ferry Flight are shown. At 2.25g condition, weight breakdowns for Pt A and Pt B are shown.

Considering the 2.50g case and Fuel Reserves (WFR) of 5% of MTOW at point B, we determine X = 9600 nm. This "aerodynamic" efficiency is held constant over the Pt B to Pt A portion of the Payload-Range diagram, resulting in WFR near 5% MTOW at Pt A.

Comparisons, Military Jet Transports

The trade-off between OEW and WP for civil freighter aircraft when compared with the civil passenger trends has been noted. This trade-off is not so clearly defined for the military transports, **Fig.14**. This is partly due to their varied design specifications (high lift, high g capability, short field performance) and also the different ages of the aircraft considered.

In **Fig.18** we compare the Payload-Range diagrams for the C-5, C-17, C-141 and An-124 (2.5g operation) with those for four civil freighters (dashed lines). The military transports are designed for lift capability rather than Range efficiency. The gradient of the WP-Range curve between Pts A and B is indicative of an aircraft's adaptability. The lower the gradient the greater the Range benefits for reducing payload. In general, civil freighter gradients are shallower than military transports. This comparison does not take into account fuel efficiency. The military transports may, of course, rely on Air-to-Air Refuellling (AAR) as a matter of course to extend their operational Ranges.

The variation of PRE with Range as WP varies from 100%WP_{max} (circle symbol) to 40%WP_{max} for the military transport aircraft is shown in **Fig.19**. PRE – Range regions encompassing points of equal decrements (20%) of WP_{max} are shown the figure. Also shown are bands for similar payload fractions for the civil freighter aircraft. At a given range, the C-

141 operates at about 2/3rds PRE of the civil freighters. The C-5 compares with the best of the civil freighters. Results for the An-124 are slightly better than those for the C-5. The validity of the matched data for the An-124 is yet to be confirmed.

Also shown in **Fig.19**, are radial lines for constant WFB/WP (lb of block fuel per lb of payload). The trends for the civil freighters operating at Pt A (100%WP_{max}) achieve about 0.8 WFB/WP. At 60% WP_{max} the civil freighters achieve 2.0 WFP/WP. At Pt A operation, the C-5 achieves WFB/WP = 0.7 whereas the An-124 achieves a slightly better value near 0.6.

When non-dimensionalised by the appropriate X value for each aircraft, the data presented in **Fig.20** tend to collapse into distinct trends. We note immediately that the fractional payload trends for the civil freighters are at near constant PRE/X values as Z varies. The familiar Pt A PRE/X – Z variation for the civil passenger aircraft is shown as a dashed line. The C-5 and C-141 lie close to the civil passenger aircraft Pt A trend. The An-124 data lies at the mid-point of the civil freighter trends for all payload fractions shown. Note PRE/X – Z regions encompassing points of equal decrements (20%) of WP_{max}.

Single Point capabilities, Jet Transports

Tables 1 & 2 compare the overall performance of the military jet transport aircraft at fixed Ranges of 3000 nm and 5000 nm and at fixed payloads of 50,000 lb and 100,000 lb. These may be regarded as preliminary capability comparisons. Further tables can be produced comparing aircraft performance and capability for given payloads over specific Ranges.

It is known that AAR greatly improves efficiency. The relatively high PRE of the shorter range aircraft can be maintained over much longer ranges with suitable AAR arrangements. The tanker fuel requirements are of course taken into consideration. From the data in the above tables, several new questions arise for the logistics operator:-

Is it most fuel efficient to move 100,000 lb over 5000 nm with a C-5? Would it be more fuel efficient for the C-5 to take-off light (reserve fuel only) and then to use AAR to complete the 5000 nm? Would it be better to use smaller transport, with the payload distributed between them, in one hop or with AAR?

The current work on military transports operating under various g ratings and with alternative fuel reserve requirements has suggested variations in X (efficiency parameter) under these varying conditions. The usual definition of X (V.L/D / sfc) arising from the Breguet Range equation is applicable to the cruise condition. More accurate definitions of the Payload–Range capabilities, fuel reserves and operating conditions of the military transports may yield an improved or modified definition of X.

5. MILITARY TURBO-PROP TRANSPORTS

In general, the military turbo-prop transport aircraft have been designed and built for specific military requirements. There have been one or two notable adaptations to civil freighter use, e.g. the Lockheed L-100-30 Super Hercules. As for the military jet transports, the turbo-prop transports are cleared to various g ratings. Alternative reserve fuel options affect the payload-range specifications. The variation of aircraft wing span (feet) with MTOW (lb) was shown in **Fig.12**. The largest turbo-prop transport considered, An-22 Cock, lies close to the trend lines as does the current A400M. The remaining, smaller turbo-prop transports form a new trend with greater wing span for given MTOW. The ratio of maximum static, Sea Level, thrust available over MTOW (T/W) is plotted against Range for Pt A in **Fig.13(c)** and for Pt B in **Fig.13(d)**. There is a considerably wider variation in T/W at a given range for the turbo-prop aircraft than for the civil and military jets. This is indicative of the wider range of design requirements, e.g. short field performance (Saab 2000 & A400M) or older, quieter performance trends (Britannia).

The variations of component weight ratios at Pt A against Range for the military turbo-prop transports are shown in **Fig.21** together with military jets and civil jet aircraft trends. We note the slightly higher OEW/MTOW trend for the turbo-prop (lower range) and the corresponding reduction in WP/MTOW ratio.

We now consider typical Payload-Range characteristics information available on C-130, A400M, C-160, C-27J and the C-295M. Using analysis based on the Breguet Range equations, Section 2, we can derive efficiency metrics for each aircraft over the whole domain of the Payload-Range envelope.

Lockheed C-130J Hercules

Production of the C-130, started in 1956 and it has been continually upgraded. A significant database is available (Refs.17 to 19, 27-28, 29 & 32) but the sources emphasise different aspects and correlations are not always consistent. The Payload–Range capability of the C-130J, **Fig.22(a)**, (Ref.27) is significantly better than that of earlier versions. The requirement for wing relief fuel to be retained on landing for the higher payloads (40,000 to 48,000 lb) severely limits the range. We also note the effects of g limitations on the Payload-Range envelope.

Aircraft total weight breakdown (at 2.50g limit, standard fuel reserves) for Point A, Point B and ferry operation is shown in **Fig.22(b)**. The effect of wing relief fuel requirements (“hashed” area in figure) are severe. The dashed outline indicates the weight breakdown and range without wing relief fuel restrictions. At 2.50g operation, assuming Fuel Reserves (WFR) of 4% or 7% of MTOW at point B, we determine X = 12743 or 15322.

Airbus Military A400M

The A400M, Ref.34, has been designed to meet the European Tactical Requirements e.g. low-level operations, short and unprepared airstrip capability, steep descent and climb-out. Additional strategic airlift requirements emphasise further aspects e.g. high cruise speed with long range, large cargo capacity (bulk or “palletized”).

The weights and range data derived from Ref.33 are in the Payload – Range diagram, **Fig.23(a)**. This shows the strategic, logistic (2.25g) data (solid line) and the deduced tactical (2.50g) data (dashed line). The latter can be extended to encompass the guaranteed Payload – Range targets at 2.50g. The aircraft total weight breakdown for Point A, Point B and ferry operation (2.25g) is shown in **Fig.23(b)**. At 2.25g operation, assuming Fuel Reserves (WFR) of 4% or 7% of MTOW at point B, we determine X = 12341 or 14077.

EADS Sogerma Services C-160 Transall

The EADS Sogerma Services C-160 is a high wing, twin turbo-prop, designed for the requirements of the French, German, South African and Turkish air forces. Initial production ended in 1972 but a second series commenced production in 1977. This had improved avionics, a reinforced wing with extra fuel capacity and AAR capability.

A limited amount of data is available on the C-160. A typical Payload–Range diagram is shown in **Fig.24(a)** and general weight breakdown in **Fig.24(b)**. There was no indication of g limitations applicable. At 2.50g operation, assuming Fuel Reserves (WFR) of 4% or 7% of MTOW at point B, X is approximately 11000 or 12200.

Alenia Lockheed C-27J Spartan

The twin-engine C-27J (Refs.31, 32) first flew in September 1999 and production aircraft deliveries commenced in January 2007. The C-27J propulsion and cockpit systems are compatible with those on the C-130J Hercules. The US Army and US Air Force have selected the C-27J for the Joint Cargo Aircraft (JCA) programme, Ref.30.

A typical Payload–Range diagram is shown in **Fig.25(a).** The aircraft total weight breakdown for Point A, Point B and ferry operation, at 2.25g condition, is shown in **Fig.25(b)**. At 2.50g operation, assuming Fuel Reserves (WFR) of 4% or 7% of MTOW at point B, we determine X = 8621 or 9901.

EADS (CASA) C-295M

The EADS (CASA) C-295M, is a twin-turbo-prop transport aircraft. It is a stretched derivative of the CN-235, noted for its STOL capability. The C-295M was a contender for the Australian Defence, Ref.33.

Aircraft weight - range data have been drawn from sources e.g. Refs.16, 26, & 33. A Payload – Range diagram is shown in **Fig.26(a)**. The aircraft total weight breakdown for Point A, Point B and ferry operation, at 2.25g condition, is shown in **Fig.26(b)**. The aircraft has been analysed in detail, at both 2.50g and 2.25g. At 2.50g operation, assuming Fuel Reserves (WFR) of 4% or 7% of MTOW at point B, we determine X = 9432 or 11099.

Comparisons, Military Turbo-Props

We compare first the efficiencies of the turbo-prop transports in non-dimensional terms. This collapses the efficiency metrics into meaningful trends, consolidating older, current and projected technology levels. The turbo-props can then be compared with the military jet transports.

The Non-dimensional efficiency trends, PRE/X – Z, for the various military turbo-prop aircraft are compared, for the 2.25g, 4% of MTOW fuel reserves cases in **Fig.27**. The A-point results for the C-160, C-130J and A400M turbo-props lie very close to the civil jet transport trend. The wing relief fuel requirement for the C-130, has shifted its performance along the A-point trend to a lower Z value whilst maintaining its PRE/X level. Results for the A400M, a much larger, modern, yet to fly aircraft, appear low. This is most likely due to the limited but conservative performance data published. As expected, the smaller turbo-props (C-295M and C-27J) have high A-point PRE/X levels at low Z. These levels may be artificially inflated as a result of applying methods developed for medium to long range jet transports, to small, short range turbo-prop aircraft. However, for comparative purposes, the techniques have provided a valuable assessment basis.

Payload, Range & Efficiency Comparisons, Military Turbo-props

From the limited amount of data available, the initial indications are that the C-27J has a relatively low X value (less than 9000 nm with fuel reserves estimated at 4.0% MTOW, 2.25g rating). At similar conditions, X for the C-130J and A400M are 11300 nm and 12300 nm respectively. We note that X is a function of speed, aerodynamic efficiency (L/D) and the inverse of specific fuel consumption. Cruise speed for the C-27J is 310 – 315 kt and for the C-130J is 345 kt. From a logistical stand point, a more meaningful measure of efficiency is provided by the dimensional parameter PRE.

Payload – Range diagrams for the four larger turbo-props are compared in **Fig.28**. The diagram for each aircraft type is annotated with WPmax, MTOW and PRE values at Point A and Point B. Results for 2.25g and 2.50g limitations are included for both the C-130J and the C-27J. The effect of fuel reserve estimation is shown, **Fig.28(a)** is for WFR = 4% of MTOW and **Fig.28(b)** is for WFR = 7% of MTOW. The choice of 4% or 7% of MTOW for WFR estimation has a significant effect on the PRE values. Further work is required to more accurately determine reserve fuel quantities used under different operating procedures.

Super-imposed payload – range diagrams, with PRE isobars, for the 5 military turbo-props (2.25g, 4% MTOW fuel reserves) are shown in **Fig.29**. We note the wide range of capabilities and technologies encompassed by the 5 types. In general, the smaller types have more closely packed PRE isobars, indicating that they will achieve higher PRE values more quickly, as payload increases, than the larger types. The payload – range capability of the C-160 is very similar to that of the C-27J and is therefore partially eclipsed in this type of diagram.

Comparing Non-dimensional efficiency and performance, Military Turbo-props and Jets

The PRE/X – Z trends established for the military jet transports and civil jet freighters in Refs.1-2 are reproduced in **Fig.30**. The A-point results for the medium to large military turbo-props compare well with the trends for the military jet transports. The smaller and more modern turbo-props appear to lie on a line established by the civil jet freighters and An-124.

Single Point capabilities, Turbo-prop Transports

Table 3 presents overall performance of the military turbo-prop transport aircraft transporting either 20,000 lb or 40,000 lb over a range of 2000 nm.

A payload of 20,000 lb over 2000 nm is close to the capability limit of the C-27J at 2.25g limitation but is well within the limits of the C-130J and A400M, **Fig.28(a)**. In terms of fuel efficiency, the C-27J is far superior with WFB/WP = 0.833 (1.246 and 1.979 for the C-130J and A400M respectively). This results in PRE values of 2400, 1600 and 1010 nm for the respective aircraft. The C-27J requires a shorter runway for Take-Off. In terms of Take-Off and Landing distances the more modern A400M has better performance than the C-130J but at the expense of almost twice the fuel burn.

A payload of 40,000 lb over 2000 nm is beyond the capability of both the C-27J and C-160. It is within the limits of the C-130J and A400M. In terms of fuel efficiency, the C-130J is superior with WFB/WP = 0.733 (1.091 for the A400M), resulting in PRE values of 2728 and 1833 respectively. The C-17 would achieve PRE of 1205 nm. The data for these comparisons are presented in Table 3.

These are regarded as preliminary capability comparisons. Further tables can be produced comparing aircraft performance and capability for given payloads over specific Ranges.

Payload, Range & Efficiency Comparisons, Military Turbo-prop and Jet Transports

Super-imposed payload – range diagrams, with PRE isobars, for the four military jet transports (2.25g, 5% MTOW fuel reserves), Ref.1, are shown in **Fig.31**. Note the different Payload and Range scales between **Figs.29** & **31**. Comparing these two figures and Tables 1, 2 and 3 it can be seen that the A400M will "bridge the gap" between the C-130 and the C-17, effectively replacing the C-141. Payloads up to 260,000 lb require an aircraft of C-5 capability. The C-17 can carry almost 170,000 lb and the C-141 95,000 lb.

Typical Costs for Military Transports (Jet and Turbo-prop)

From a matrix of different payload - range capabilities for the military jet and turbo-prop transports, information on FCR (Fuel cost per Total cost ratio) and cost in US c/pax-nm is shown in **Figs.32** and **33**. **Fig.32** shows results for 20,000 lb over ranges between 1000 nm and 5000 nm. **Fig.33** shows results for 100,000 lb payloads over 1000 nm to 4000 nm. These are plotted to base of fuel price in US$/USGal. Note that FCR rises with fuel price. For small loads, smaller turbo-props are ideal. For larger loads and longer ranges, the large aircraft come into their own. It is more economical to fly large loads over longer ranges. Here pax. is defined as 210 lb. These relationships provide an easy comparison with the usual civil scene. It will be noted that not all the aircraft are necessarily capable of the full set of ranges.

Using the block fuel figures and with assumptions of notional figures for "other" costs per flying hour, we can estimate costs for a given price of fuel, **Fig.34** . This relates payload, range and cost/ton-nm, assuming the fuel price at $4.30/USG. Such relationships allow a reliable means of obtaining the most cost effective choices for a given transport mission. As may be expected, the heavy lift jet transports are not cost efficient over small ranges or for carrying small payloads. They come into their own for carrying larger payloads to 3000 nm ranges. Although the C-17 appears somewhat more cost effective than the C-5, this may well be within the uncertainty in assumption of the "other" costs. This analysis can begin to enable informed choices for a given mission. It is emphasized that fuel and cost efficiency trends are not coincident. The "other" costs have an influence.

6. GENERAL INFERENCES & CONCLUSIONS

Currently there is great emphasis on achieving efficient and optimised flight and operations. The planned budgets and future constraints may reflect this. The need for overall energy savings is being felt in all spheres of defence and commercial aviation. The military scene includes many types of aircraft fulfilling many diverse roles during training and in action.

We considered the efficiency aspects of heavy-lift, military jet and medium-lift military turbo-prop transports. Currently, there are only a few types in service and limited consistent data is on weight fractions available. We used the various weight fractions and payload range data for deriving a set of dimensional and non-dimensional parameters.

Efficiency trends, established for civil passenger and freighter aircraft, have been described. These provided the foundation and nature of comparative aspects for a quantitative assessment of the military transports (even with data limitations). The non-dimensional parameters introduced (e.g. PRE/X and Z = R/X) allow use of data from current and older types and implied technology levels, with relative ease. This is an important feature of the work.

Several similarities were noted in the weight ratios for the military transports and freighters. However, a surprising trend was that military transports use less Thrust to Weight ratio for "normal" 2.5 g flights.

Maximum Payload efficiency PRE/X occurred near range parameter Z of 0.17 for the military jet transports. The very small military turbo-prop transports continued the maximum payload PRE/X trend of the civil freighters and military jet transports to lower Z values. The larger military turbo-props achieved relatively low PRE/X values at low Z. This may be indicative of the analysis methods and further work is envisaged for performance assessment at low ranges and with consideration of field performance. For the jet transports, efficiency dropped rapidly as Z (or range) increases and payload fraction is reduced. For military transports, operational criteria such as g limitations on performance and fuel reserves specification have large impact on efficiency (payload-range capability shrinks). Although it is easy to have an intuitive, qualitative feel for such effects, deriving and presenting reliable quantified analysis has been painstaking but considered valuable.

The established trends give a indication of "design space". We can identify where the advancements are needed e.g. by increasing the Range parameter X or by reducing the OEW thus increasing WP/OEW parameter. This works for "identifying" and assessing future designs to maximize efficiency.

A thorough appreciation of the Efficiency Parameters will allow civil / military logistics operators to maximize the performance using direct or alternative operational procedures (say with planned AAR), different aircraft. The tables presented can assist with such assessments. Similarly, future designs of heavy lift transport aircraft can be biased, towards the more efficient operational procedures, if the direct changes in OEW and X begin to "level-out".

Several avenues of further work and development have arisen e.g. relating take-off/landing aspects with fuel efficiency. Balance between fuel efficiency and overall economics needs to be addressed along the lines indicated.

Certainly, the work programme has made us aware of what can be achieved with reliable data in light of fuel efficiency concerns (that will prevail) and there are design and operational choices. Ideas of comparative costs arising have been presented.

ACKNOWLEDGEMENTS

Part of the work has been funded by AFRL-EOARD. We wish to thank Mr Dieter Multhopp for his help. The technical help of Dr. Michael Palmer is appreciated. Opportunities for collaboration are warmly invited. Opinions expressed are due to the authors.

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NOMENCLATURE

AAR — Air-to-Air Refuelling
b — = 2 s, Wing span
c1, c2 — Technology constants
CFF — Close Formation Flying
cg — Centre of Gravity
C_L = Lift Force /(q S), Lift Coefficient (C_{Lmax}, Maximum)
FCR — Fuel cost / Total Cost (Ratio)
HBPR — High By-Pass Ratio Engines
L/D — Aircraft Lift/Drag Ratio
M — Mach Number
Non-D — Non-Dimensional
OEW — Operating Empty Weight
PRE — = WP *R/WFB, Payload Range Efficiency
Pt — Point
q — = 0.5 ρ V^2, Dynamic Pressure
R — Range (nm or km)
s — Wing semi-span
S — Wing Area
SFC — Specific Fuel Consumption
STOL — Short Take-Off and Landing
TOW — Take-Off Weight (MTOW, Maximum)
T/W — Thrust to MTOW ratio
V — Aircraft Velocity
VEM — = PRE/MTOW, Value efficiency per MTOW unit
VEO — = PRE/OEW, Value efficiency per OEW unit
VEMPX — =VEM*WP/X, Non-Dimensional Value Efficiency, Section 3
VEOPX — = VEO*WP/X, Non-Dimensional Value Efficiency, Section 3
VSTOL — Very Short Take-Off and Landing
VTOL — Vertical Take-Off and Landing
WFB — Block Fuel Load
WFB / WP — Fuel Payload Fraction (FPF)
WFRes — or WFR, Reserve Fuel Load
WFT — Total Fuel Load
WP — Payload (WP_{max}, Maximum)
WP/WFB — Payload Efficiency
X — = V * (L/D) / SFC
Z — = R/X
ZFW — Zero Fuel Weight (MZFW, Maximum)
ρ — Air Density

	3000 nm		5000 nm		X (nm)
	WP (lb)	WFB/WP PRE	WP (lb)	WFB/WP PRE	
C-5	206000	0.75 4000	111700	2.15 2356	14030
C-17	122000	0.95 3158	0	-	13069
C-141	68700	1.30 2308	27500	5.00 1000	9608
An-124	221250		150000		13251

Table 1, Specific Range – Maximum Payload Capabilities and Efficiencies

	50,000 lb		100,000 lb		X (nm)
	Range (nm)	WFB/WP PRE	Range (nm)	WFB/WP PRE	
C-5	6340	6.0 1060	5200	2.5 2080	14030
C-17	4400	3.1 1420	3725	1.4 2660	13069
C-141	3935	2.2 1790	-	-	9608
An-124	~ 7100		6450		13251

Table 2, Specific Payload – Maximum Range Capabilities and Efficiencies C-5, C-17, C-141 and An-124 Jet Transports

	WP = 20,000 lb		WP = 40,000 lb		X (nm)
	Range (nm)	WFB/WP PRE	Range (nm)	WFB/WP PRE	
C-27J	2000	0.833 2400	2000	-	8621
C-130J	2000	1.246 1600	2000	0.733 2728	12743
A-400M	2000	1.979 1010	2000	1.091 1833	12341
C-17	2000	3.120 641	2000	1.659 1205	13069

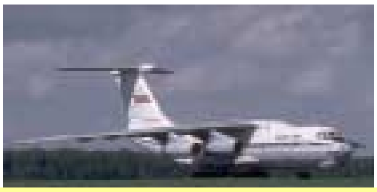
Table 3, Single Point (Payload – Range) Capabilities and Efficiencies, C-27J, C-130J and A-400M Turbo-prop and C-17 Jet Transports

C-5 Galaxy

C-17 Globemaster

C-141 Starlifter

US Jet Transports



IL-76, "Candid"
IL-78, "Midas" (Refuelling Version)

AN-124 Ruslan, "Condor"

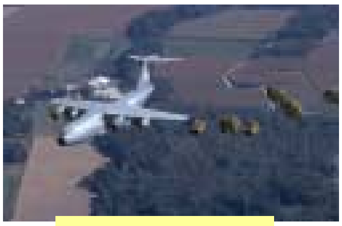
AN-225 Mriya, "Cossack"

Soviet Jet Transports

FIG. 1 JET TRANSPORTS

Lockheed C130 Hercules

Alenia - Lockheed C27J Spartan



AIRBUS A400M

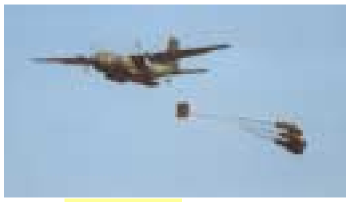


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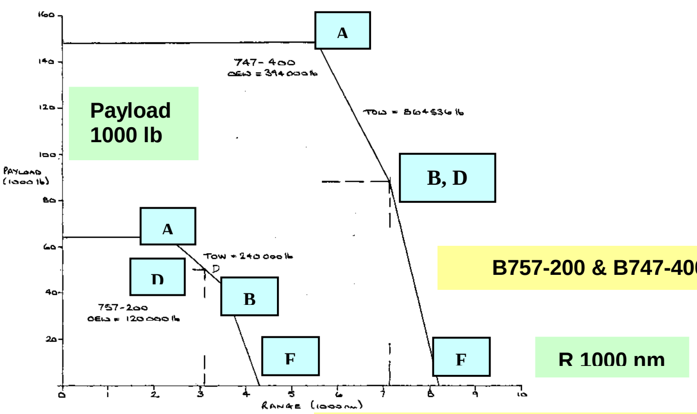
FIG. 2 TURBO-PROP TRANSPORTS



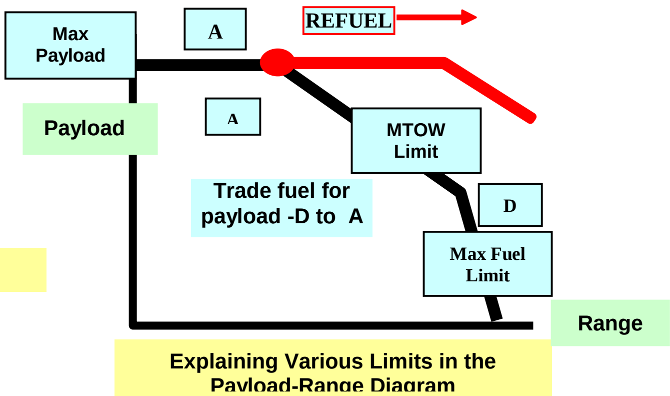
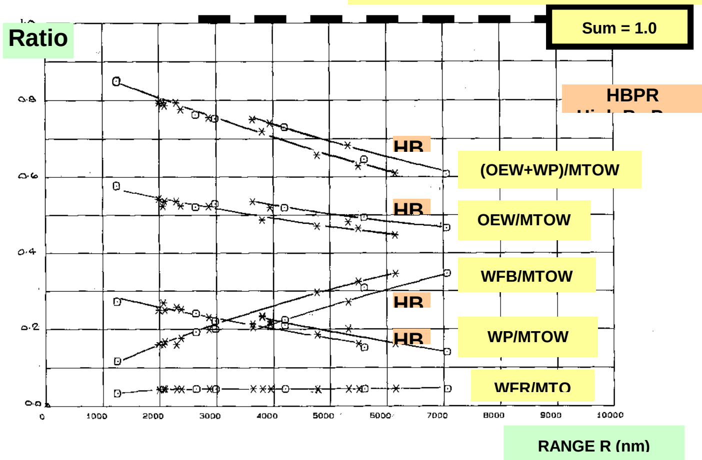


Fig. 3 Typical Payload Range Diagrams , LIMITS



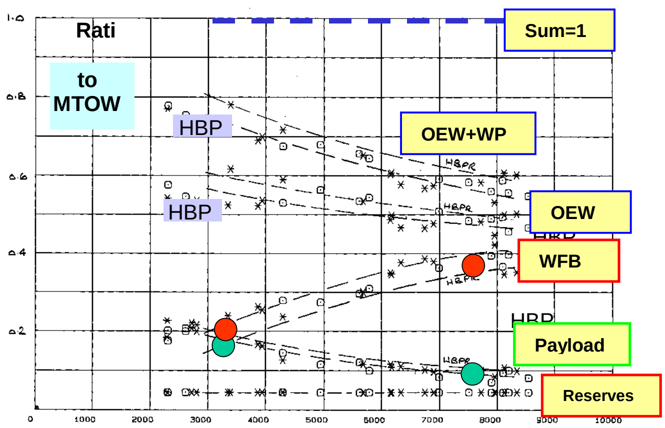


Fig. 4. Pt A, COMMERCIAL AIRCRAFT, DERIVED OEW, FUEL & PAYLOAD RATIO TRENDS

Fig. 5 Pt D, COMMERCIAL AIRCRAFT, DERIVED OEW, FUEL & PAYLOAD RATIO TRENDS

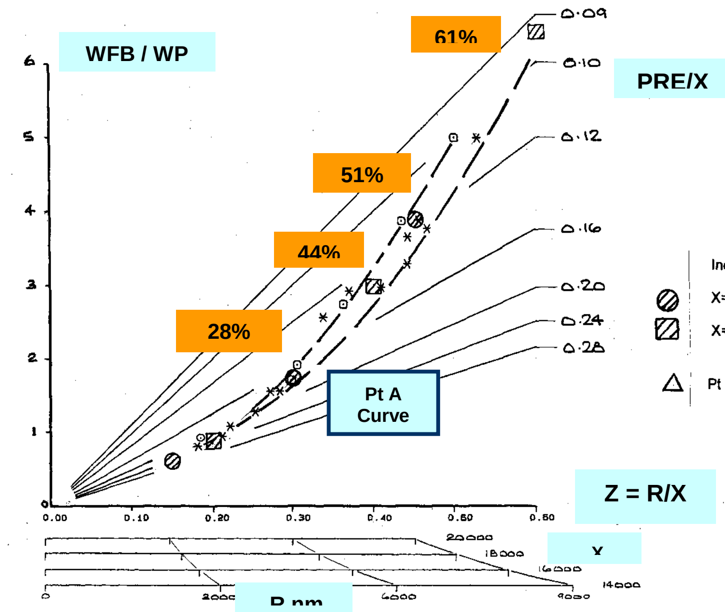


Fig. 6 WFB / WP vs Z = R/X, Pt A & Pt D
Note: Parallel Scales of R Implied for Different X Values

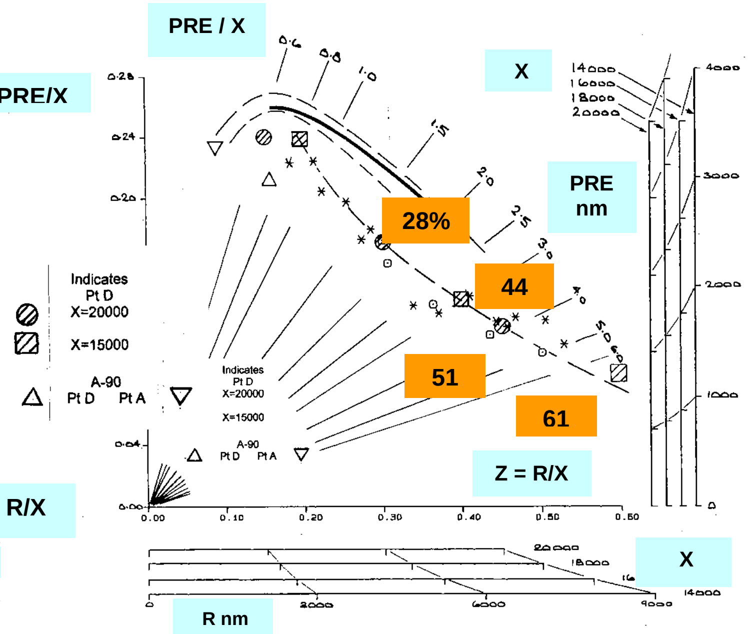


Fig. 7 PRE/X vs Z = R/X, Pt A & Pt D
Note: Parallel Scales of PRE Implied for Different X

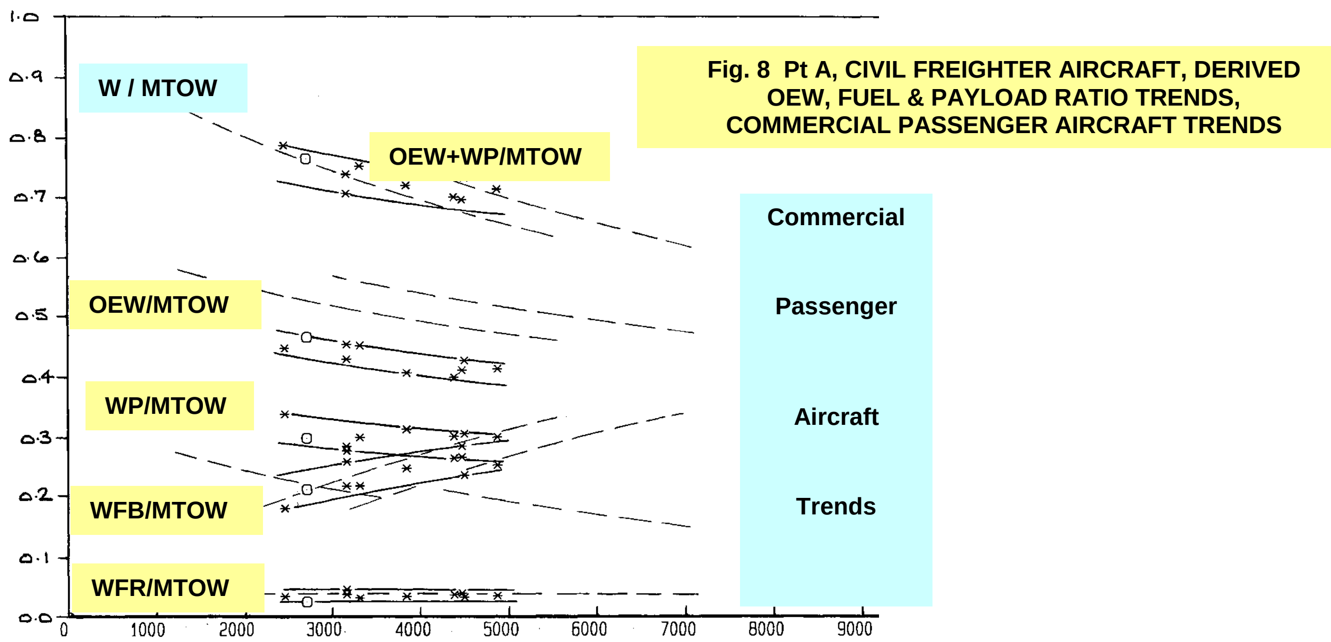


Fig. 8 Pt A, CIVIL FREIGHTER AIRCRAFT, DERIVED OEW, FUEL & PAYLOAD RATIO TRENDS, COMMERCIAL PASSENGER AIRCRAFT TRENDS

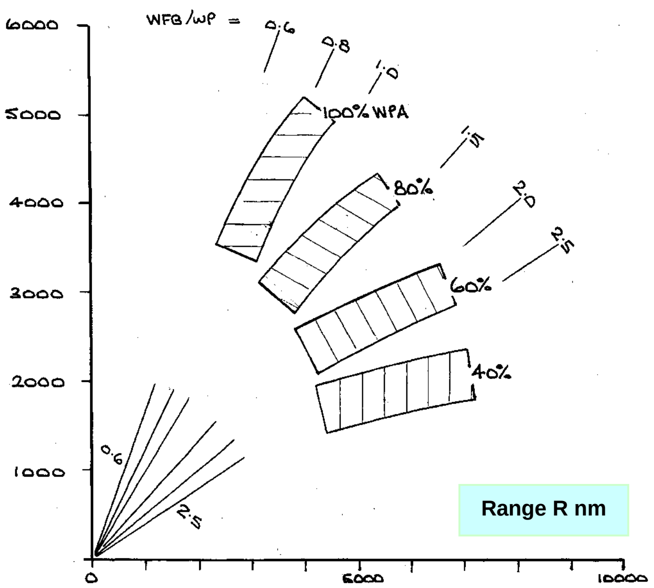


Fig. 9 PRE vs RANGE, BANDS FOR VARYING PAYLOAD FRACTION, FREIGHTERS, Constant WFB/WP (Radial lines)

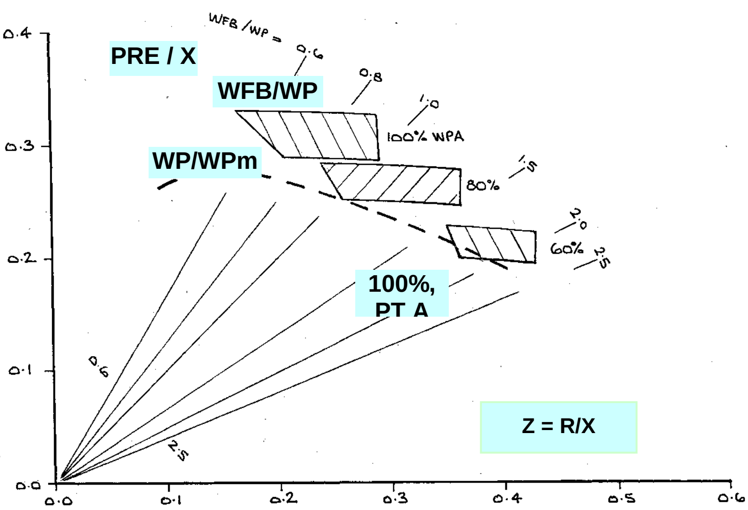


Fig. 10 PRE/X vs Z, BANDS FOR VARYING PAYLOAD FRACTION, FREIGHTERS, Civil Aircraft Pt A Trends, Constant WFB/WP (Radial lines)

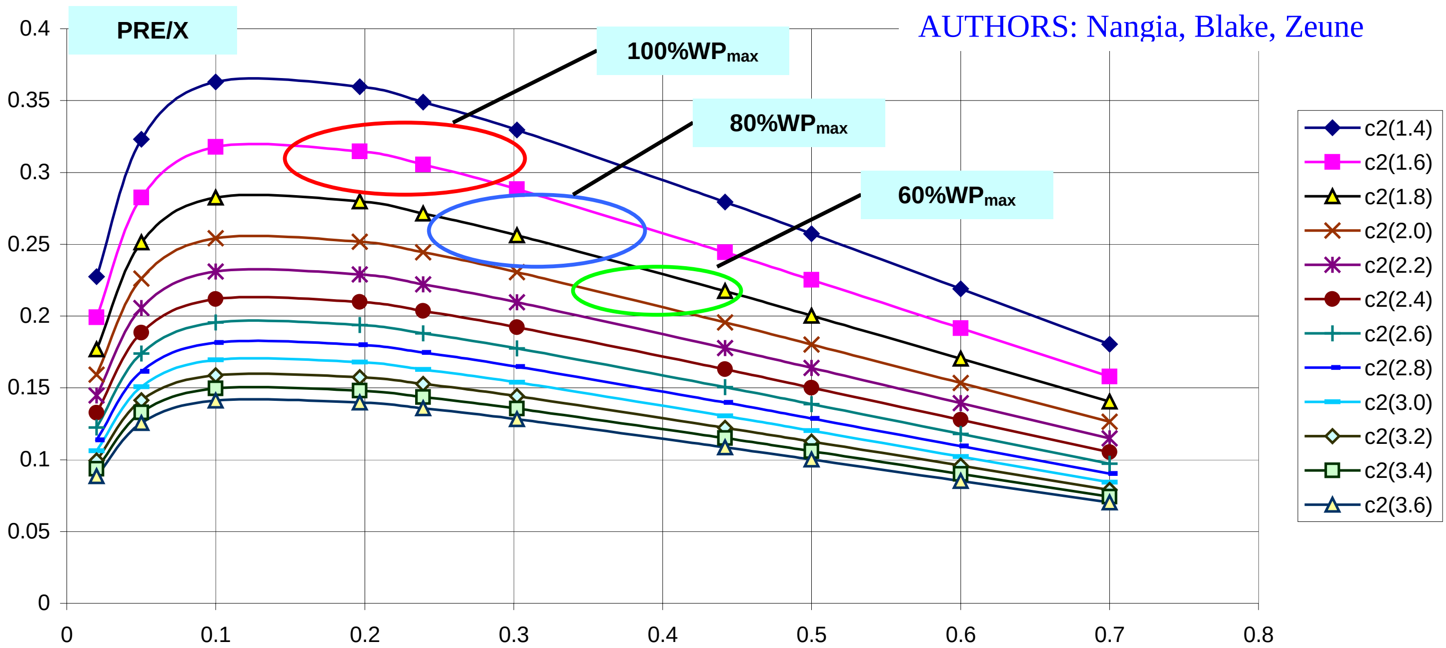


Fig. 11 PRE/X vs Z, c1 +WFR/MTOW = 0.30, c2 VARIES, BANDS FOR FREIGHTER AIRCRAFT VARYING PAYLOAD FRACTION

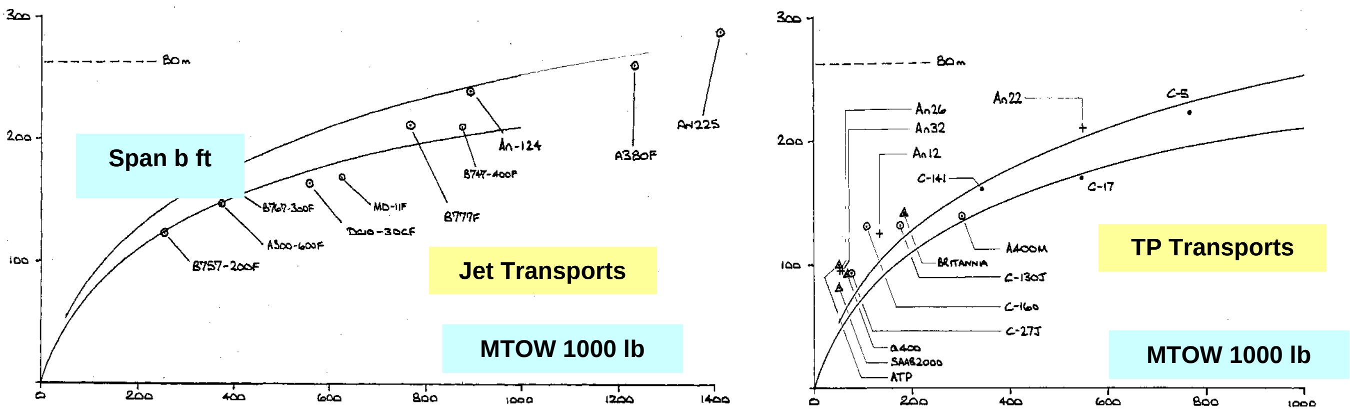


Fig. 12 SPAN v MTOW, CIVIL PASSENGER AIRCRAFT TRENDS, CIVIL FREIGHTERS and MILITARY TRANSPORT AIRCRAFT

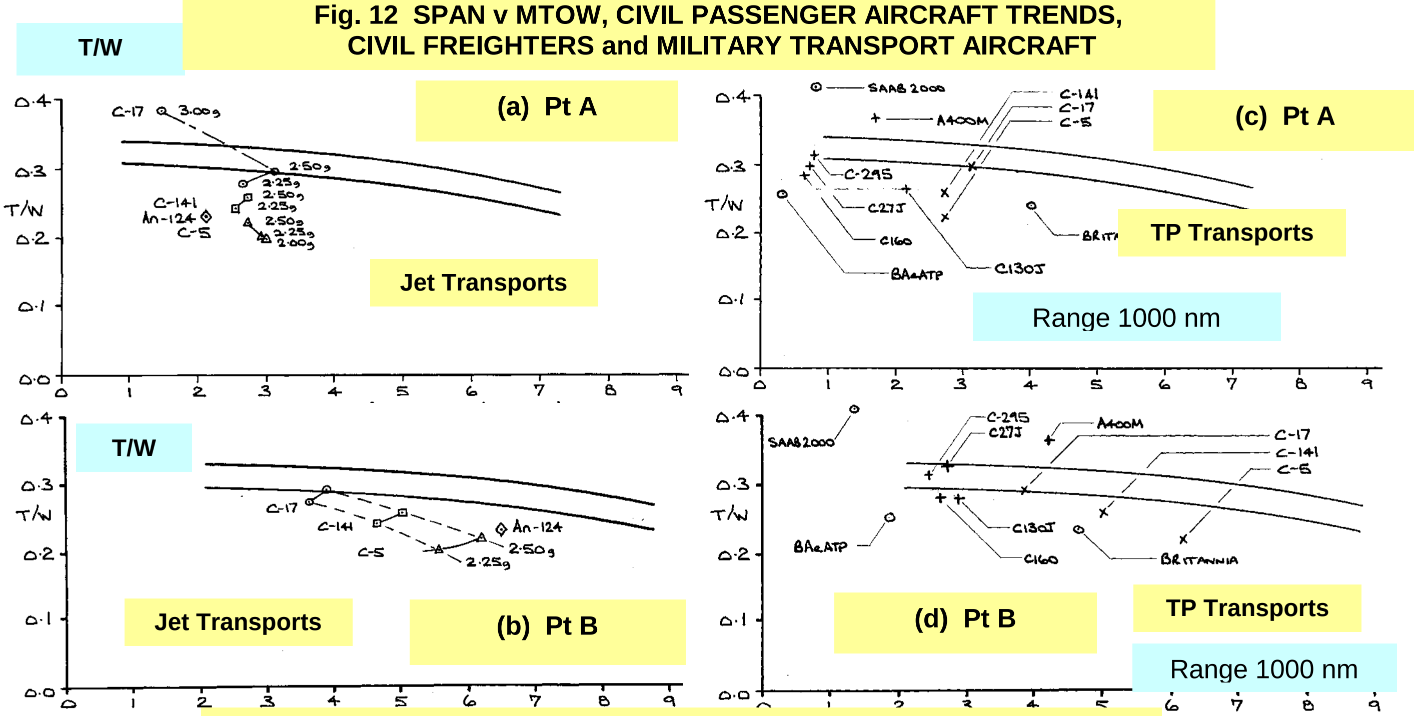


Fig. 13 T/W - RANGE, CIVIL PASSENGER AND FREIGHTER AIRCRAFT TRENDS AND MILITARY TRANSPORT AIRCRAFT

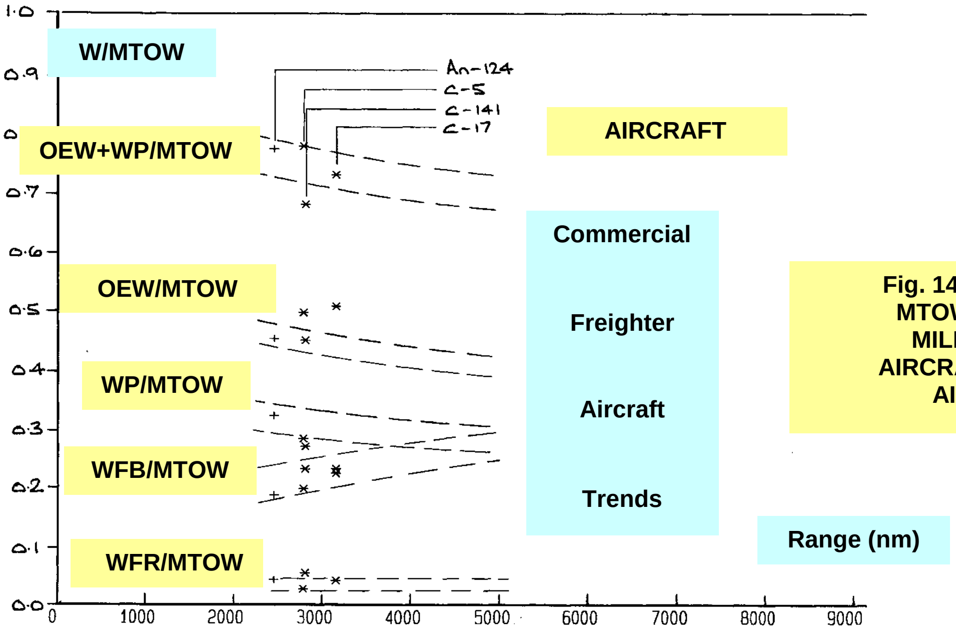
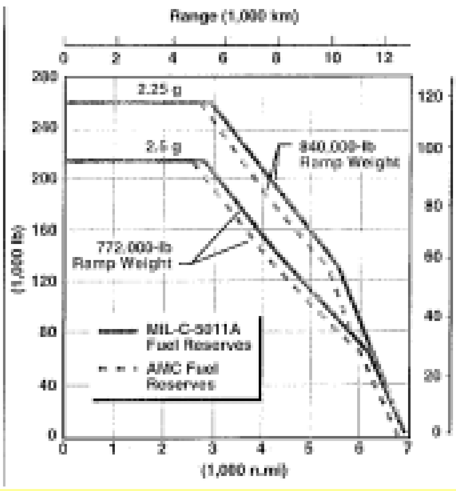
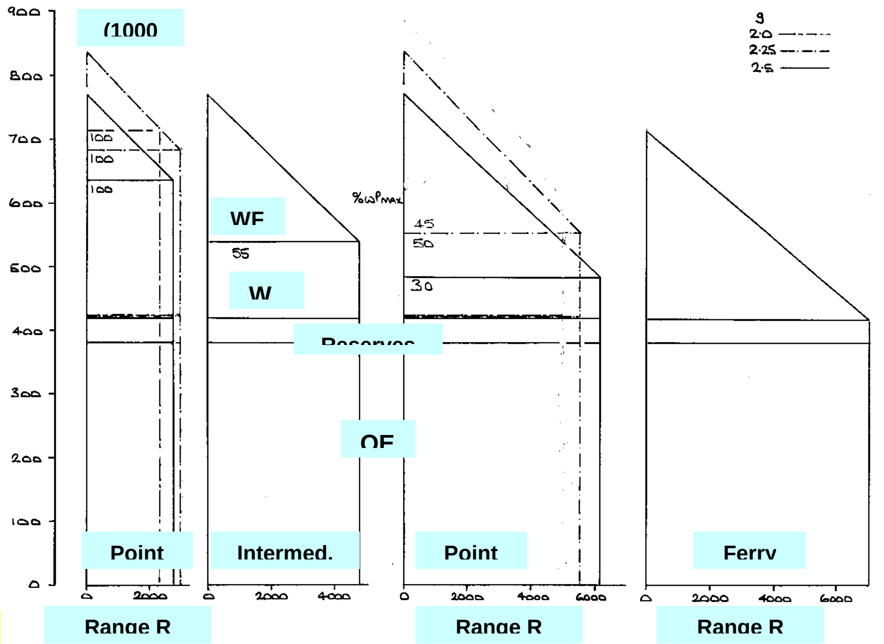


Fig. 14 WEIGHT RATIOS wrt MTOW v POINT A RANGE, MILITARY TRANSPORT AIRCRAFT WITH FREIGHTER AIRCRAFT TRENDS 2

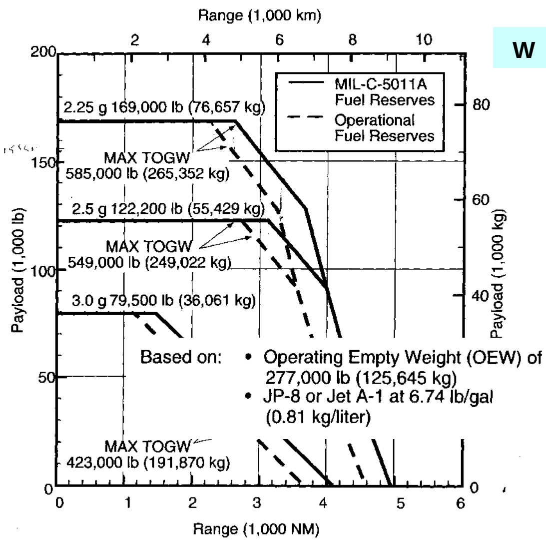


(a) WP – Range, 2.50g & 2.25g



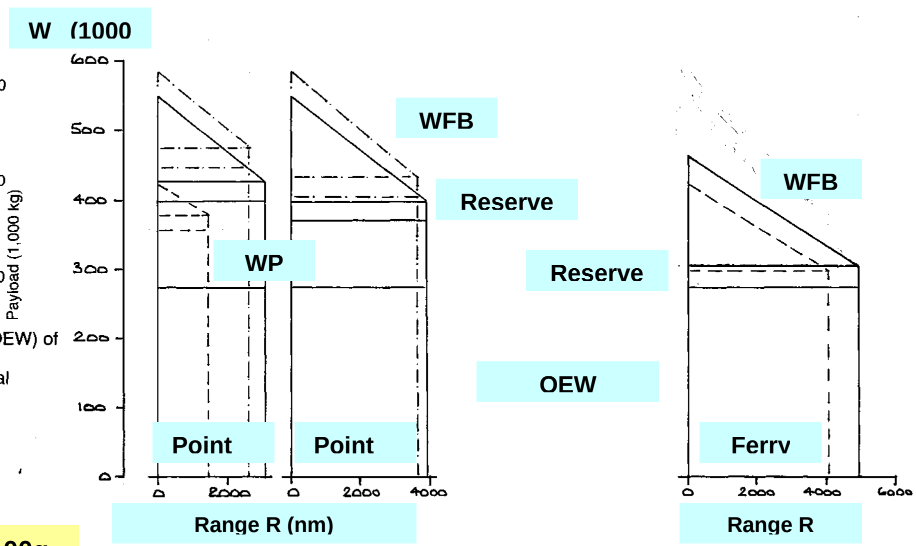
(b) WEIGHTS BREAKDOWN, g LIMITATION EFFECTS

FIG.15 C-5 GALAXY, Ref.20
MIL-C-5011A & AMC Reserves

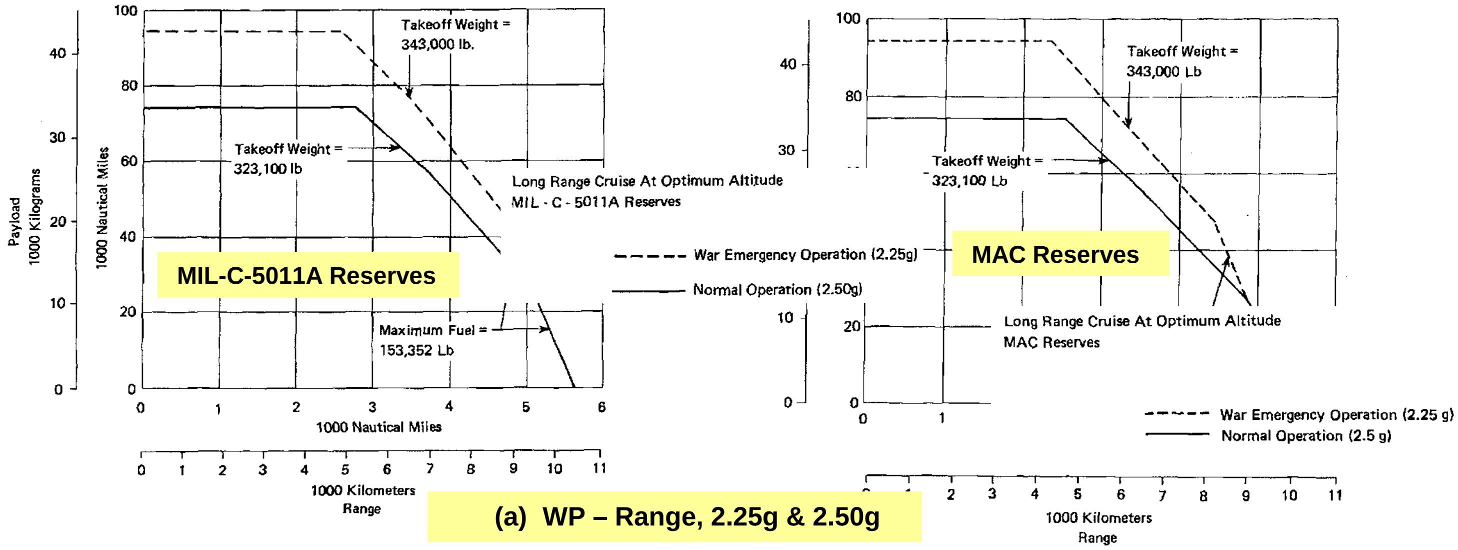


(b) WP – Range, 2.00g, 2.25g & 3.00g

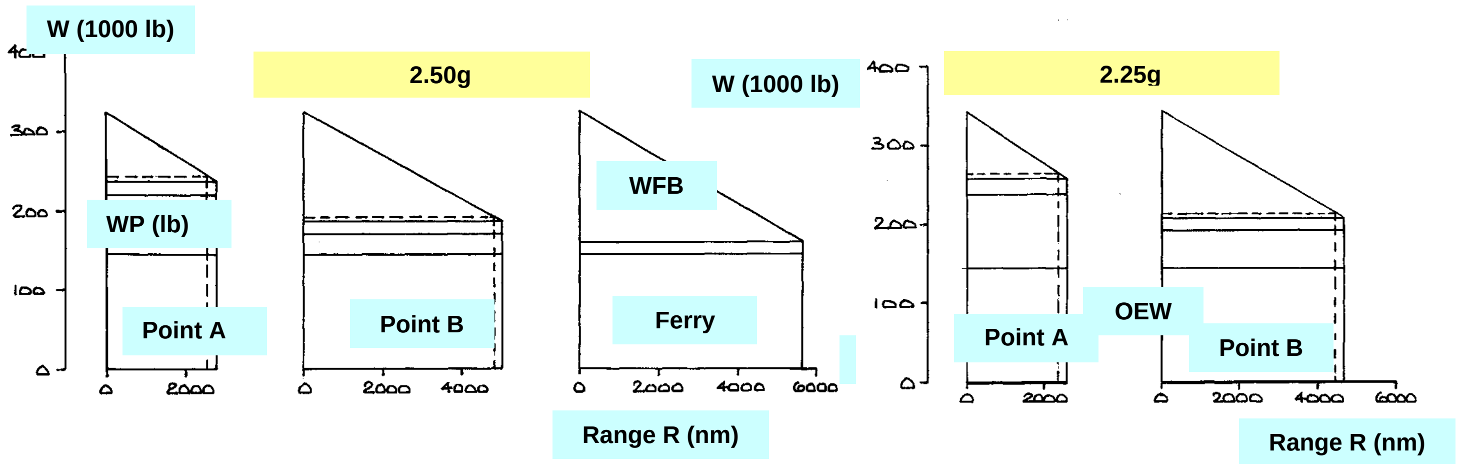
Fig. 16 C-17 GLOBEMASTER III
MIL-C-5011A & AMC Reserves



(b) WEIGHTS BREAKDOWN, g LIMITATION EFFECTS



(a) WP – Range, 2.25g & 2.50g



(b) WEIGHTS BREAKDOWN, g Limitation and Reserve Fuel Effects

Fig.17 C-141 STARLIFTER, MIL-C-5011A & MAC Reserves

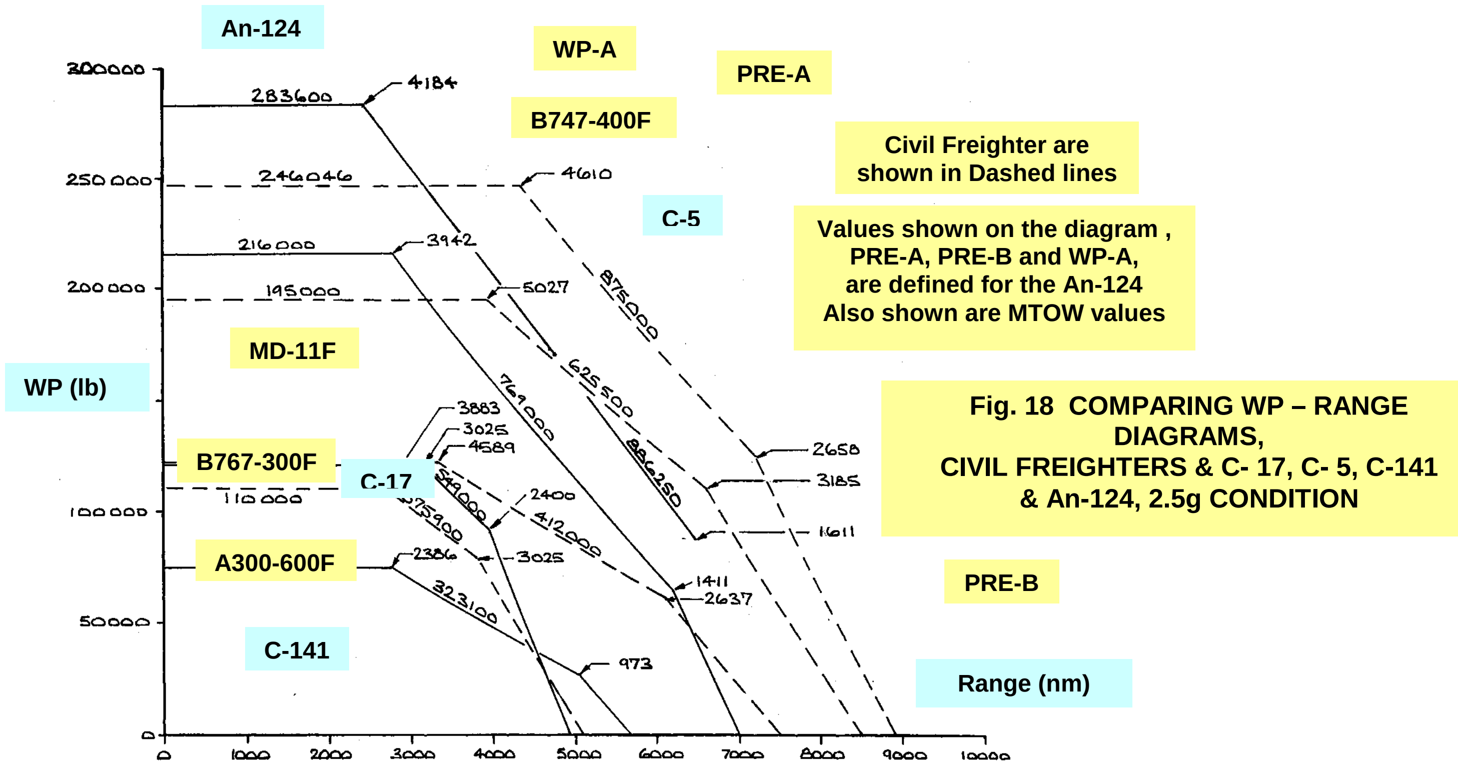


Fig. 18 COMPARING WP – RANGE DIAGRAMS,
CIVIL FREIGHTERS & C- 17, C- 5, C-141 & An-124, 2.5g CONDITION

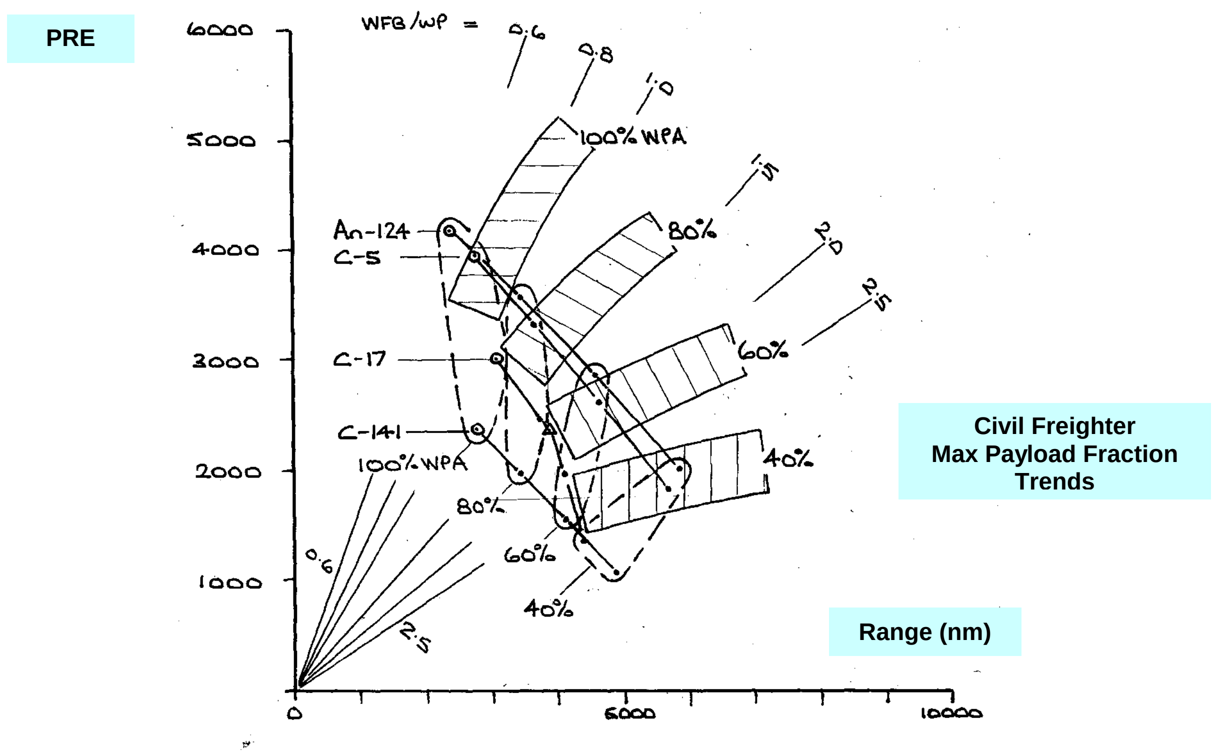


**Fig. 19 PRE – RANGE, MILITARY TRANSPORTS,
CIVIL FREIGHTER AIRCRAFT MAX PAYLOAD FRACTION TRENDS,
CONSTANT WFB/WP (RADIAL LINES)**

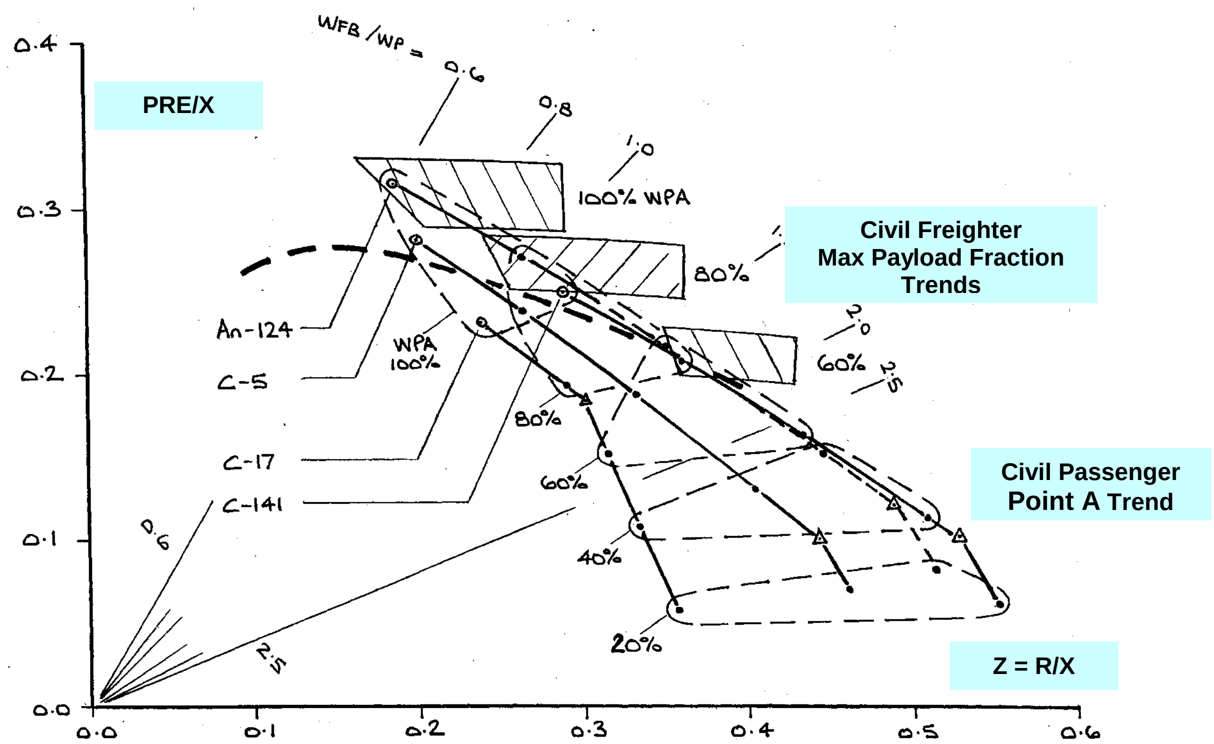


**Fig.20 PRE/X – Z, MILITARY TRANSPORTS,
CIVIL PASSENGER AIRCRAFT POINT A TREND,
CIVIL FREIGHTER AIRCRAFT MAX PAYLOAD FRACTION TRENDS,
CONSTANT WFB/WP (RADIAL LINES)**

AUTHORS: Nangia, Blake, Zeune

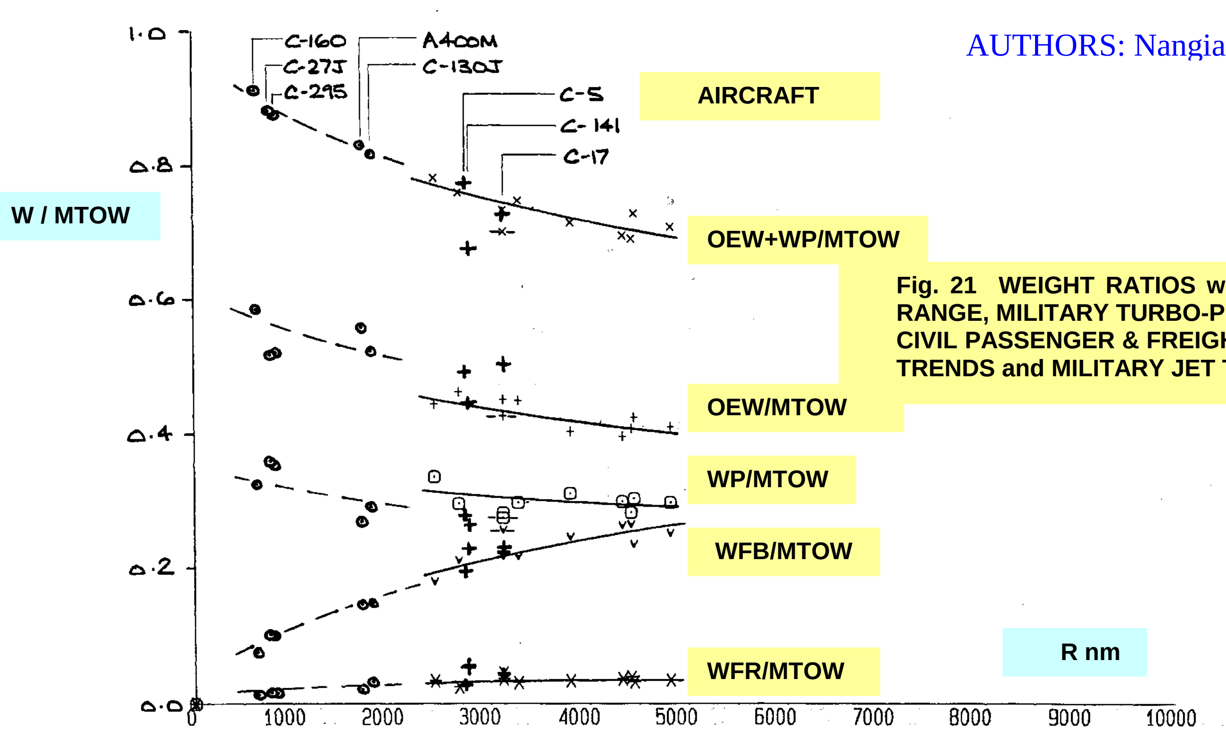
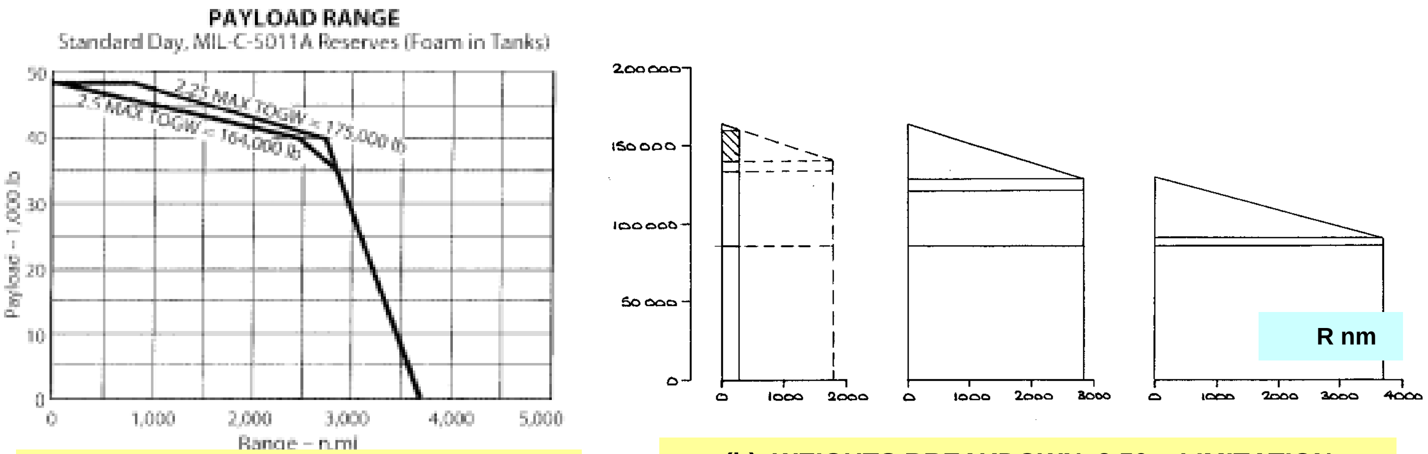


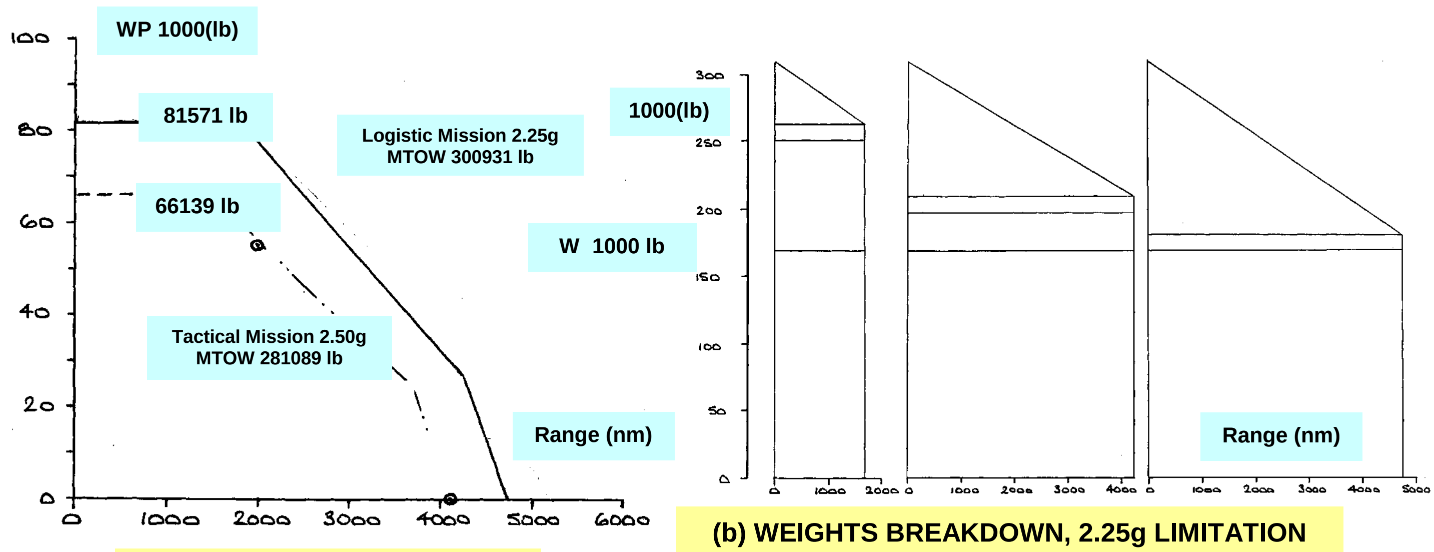
Fig. 21 WEIGHT RATIOS wrt MTOW v POINT A RANGE, MILITARY TURBO-PROP AIRCRAFT, CIVIL PASSENGER & FREIGHTER JET AIRCRAFT TRENDS and MILITARY JET TRANSPORTS



(a) WP – Range, 2.25g & 2.50g

(b) WEIGHTS BREAKDOWN, 2.50 g LIMITATION

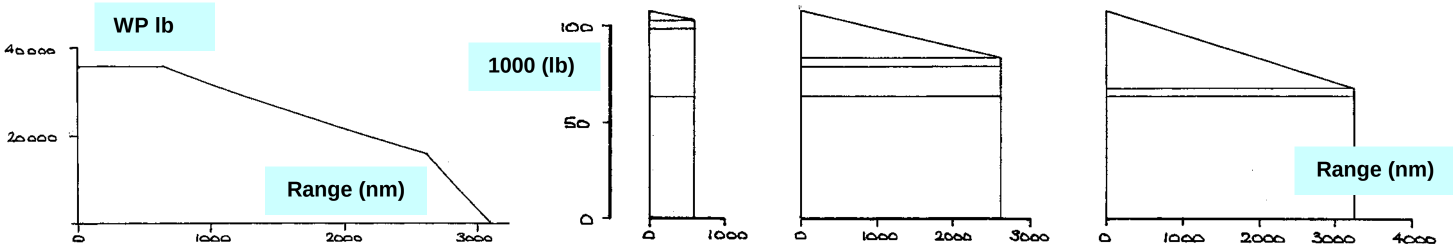
Fig. 22 C-130J HERCULES, MIL-C-5011A Reserves



(a) DERIVED WP – RANGE, 2.25g & 2.50g (Estimated)

(b) WEIGHTS BREAKDOWN, 2.25g LIMITATION

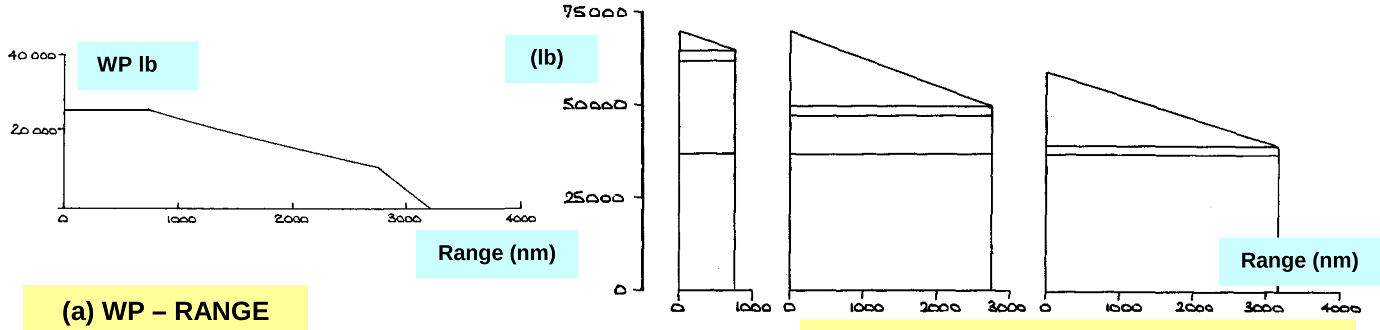
Fig. 23 A400M



(a) WP – RANGE

Fig.24 C-160

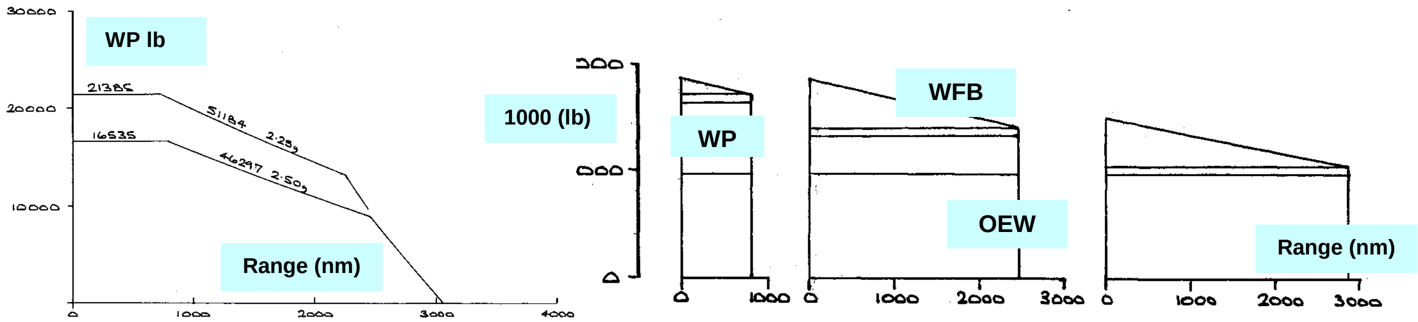
(b) WEIGHTS BREAKDOWN



(a) WP – RANGE

Fig. 25 C-27J, 2.25g LIMITATION

(b) WEIGHTS BREAKDOWN



(b) WEIGHTS BREAKDOWN

(a) WP – RANGE

Fig. 26 C-295M

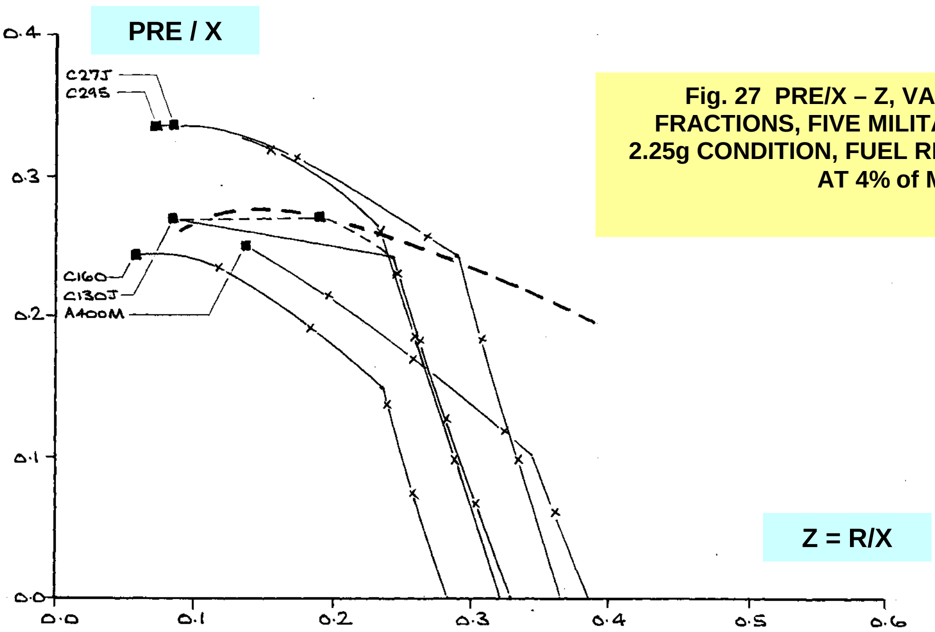


Fig. 27 PRE/X – Z, VARYING PAYLOAD FRACTIONS, FIVE MILITARY TURBO-PROPS 2.25g CONDITION, FUEL RESERVES ESTIMATED AT 4% of MTOW

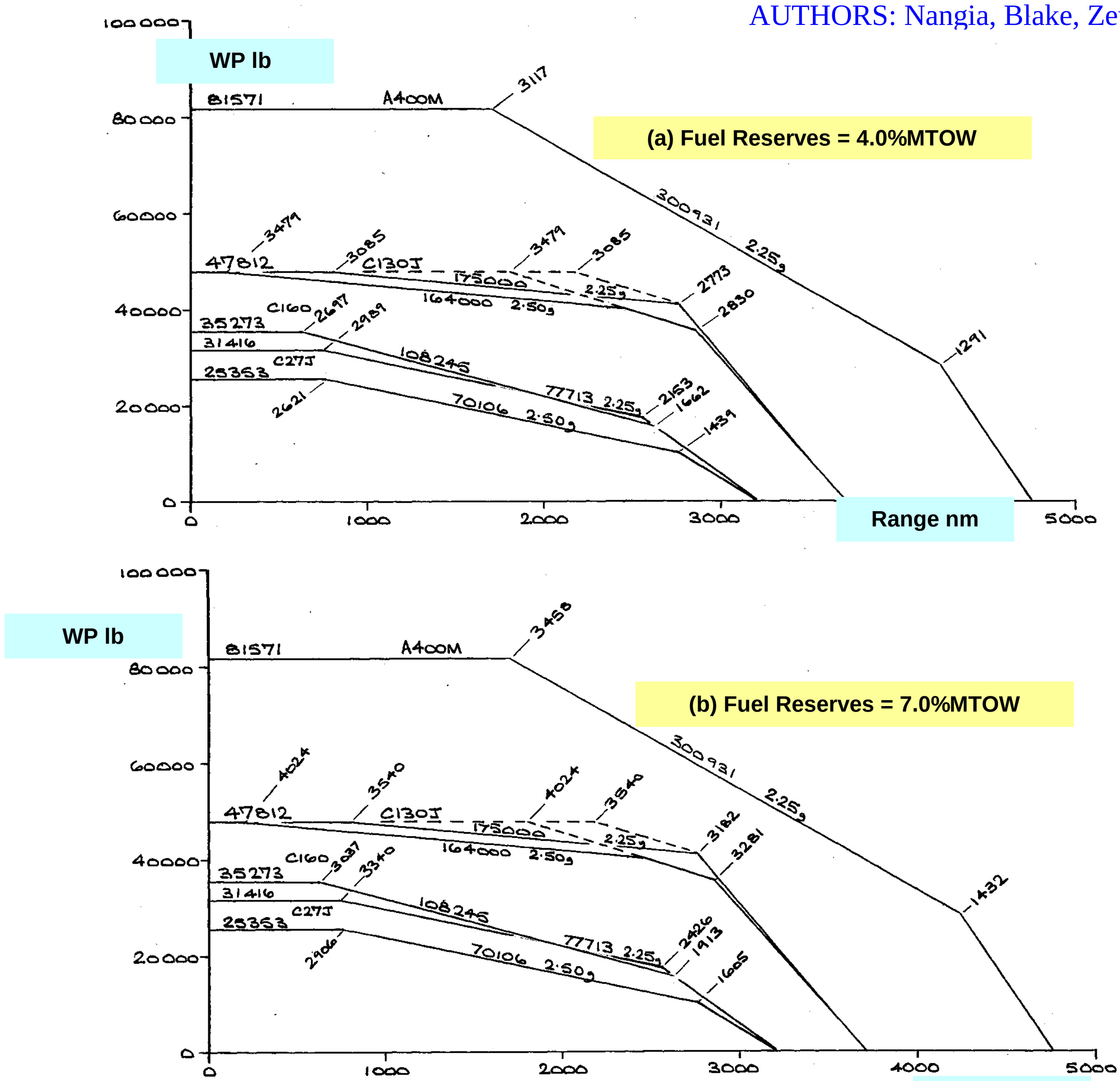


Fig. 28 WP – RANGE, FOUR MILITARY TRANSPORT TURBO-PROPS CONSIDERED, EFFECT OF FUEL RESERVES ON PRE

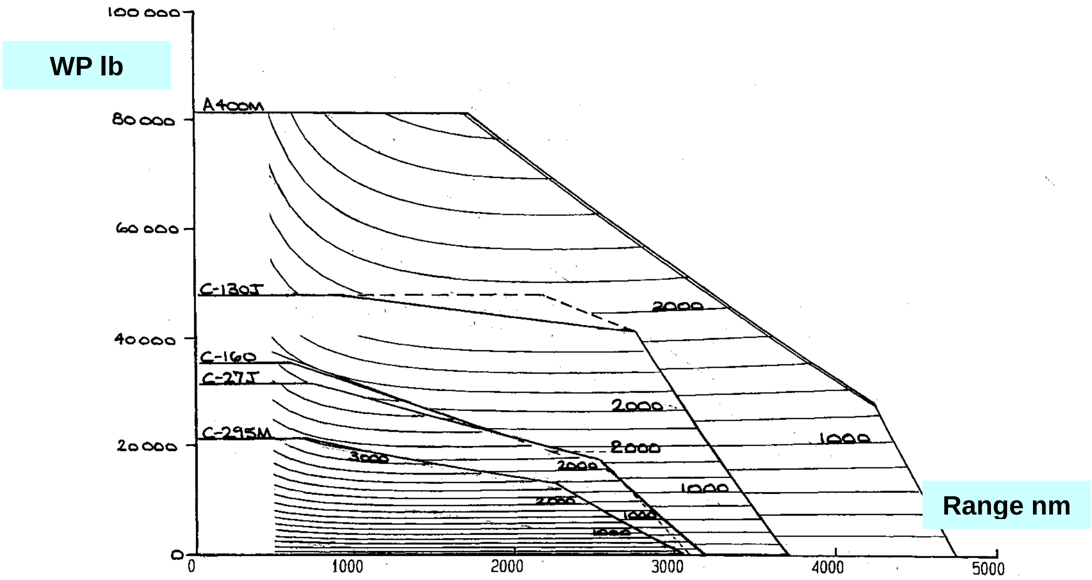


Fig. 29 WP – RANGE, FIVE MILITARY TURBO-PROP TRANSPORTS COMPARED, ISO PRE LINES

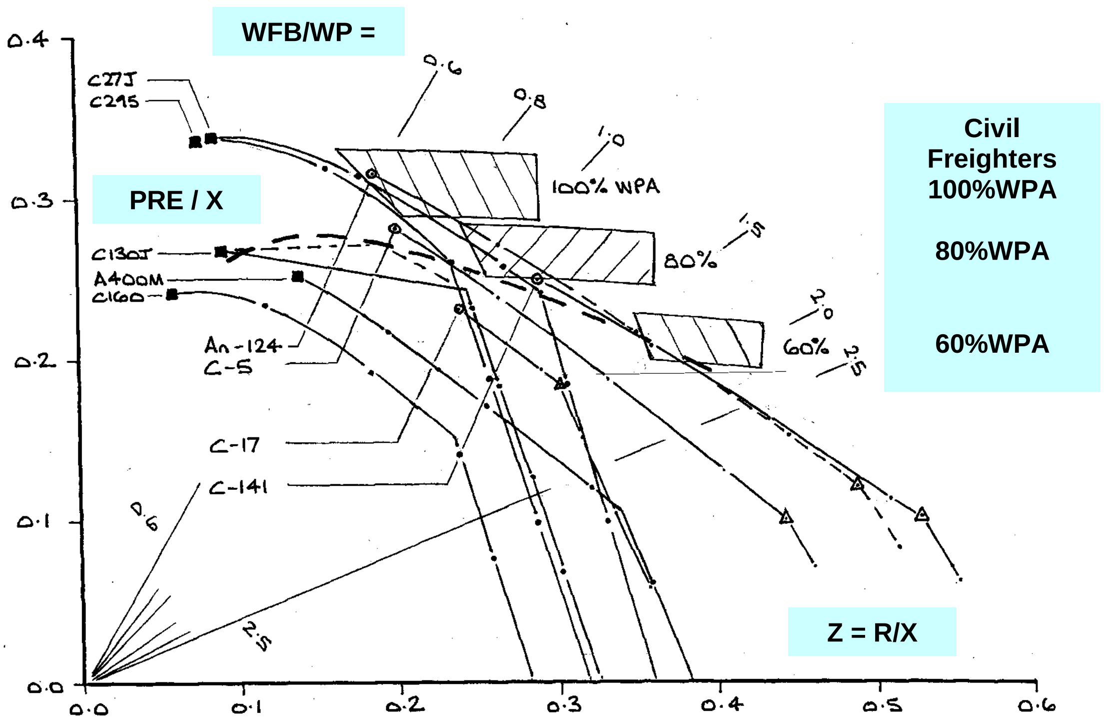


Fig. 30 PRE/X – Z, VARYING PAYLOAD FRACTIONS, MILITARY TRANSPORTS, 2.25g CONDITION FUEL RESERVES ESTIMATED AT 4% of MTOW - TURBO-PROPS & 5% of MTOW - JETS

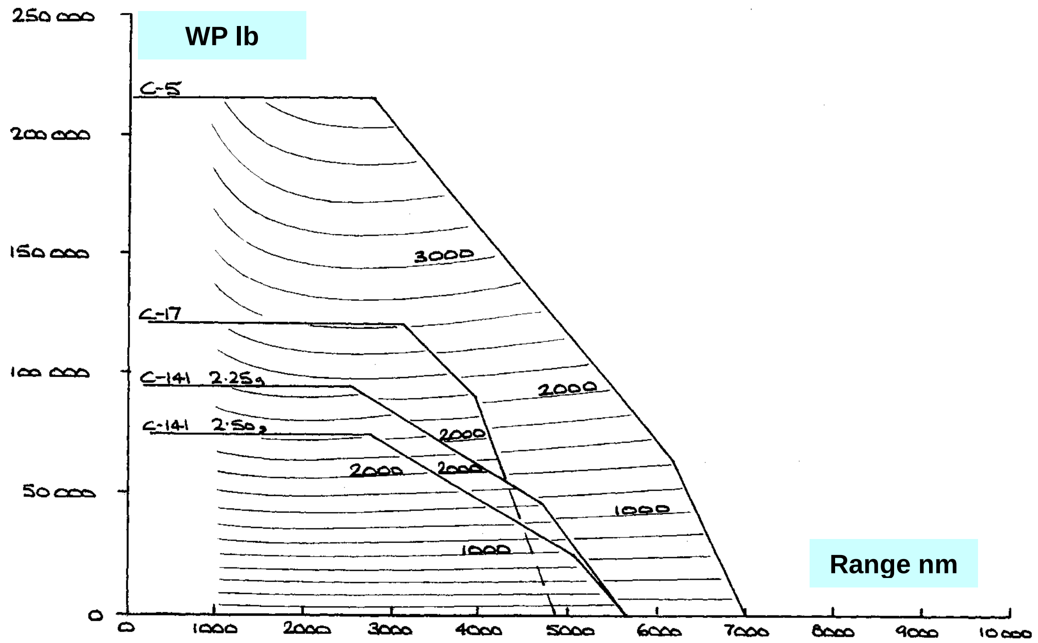


Fig. 31 WP – RANGE, THREE MILITARY JET TRANSPORTS COMPARED, ISO PRE LINES

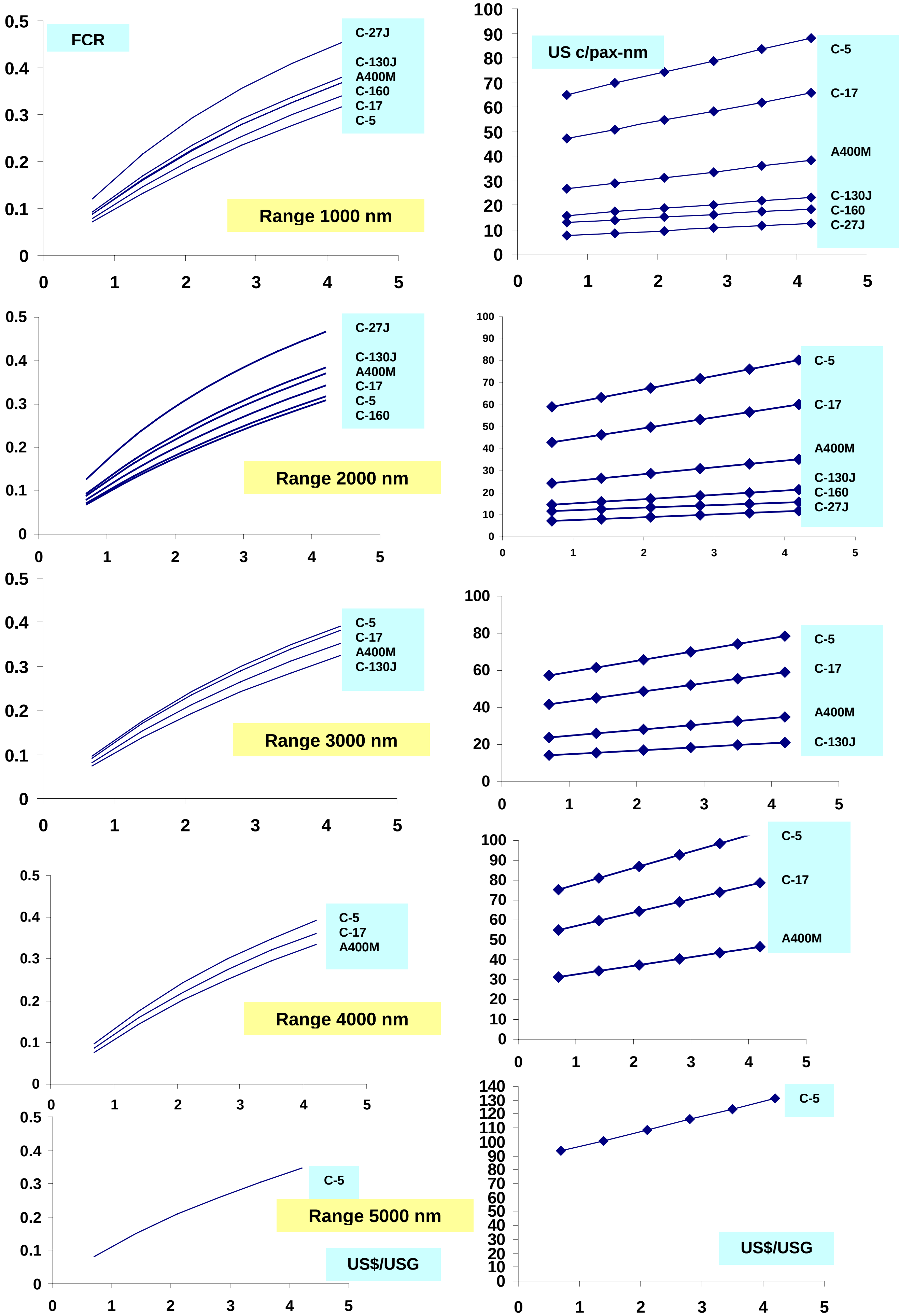


Fig. 32 Transporting 20,000 lb over DIFFERENT RANGES, FCR & cost / pax-nm Relationships with Fuel Price

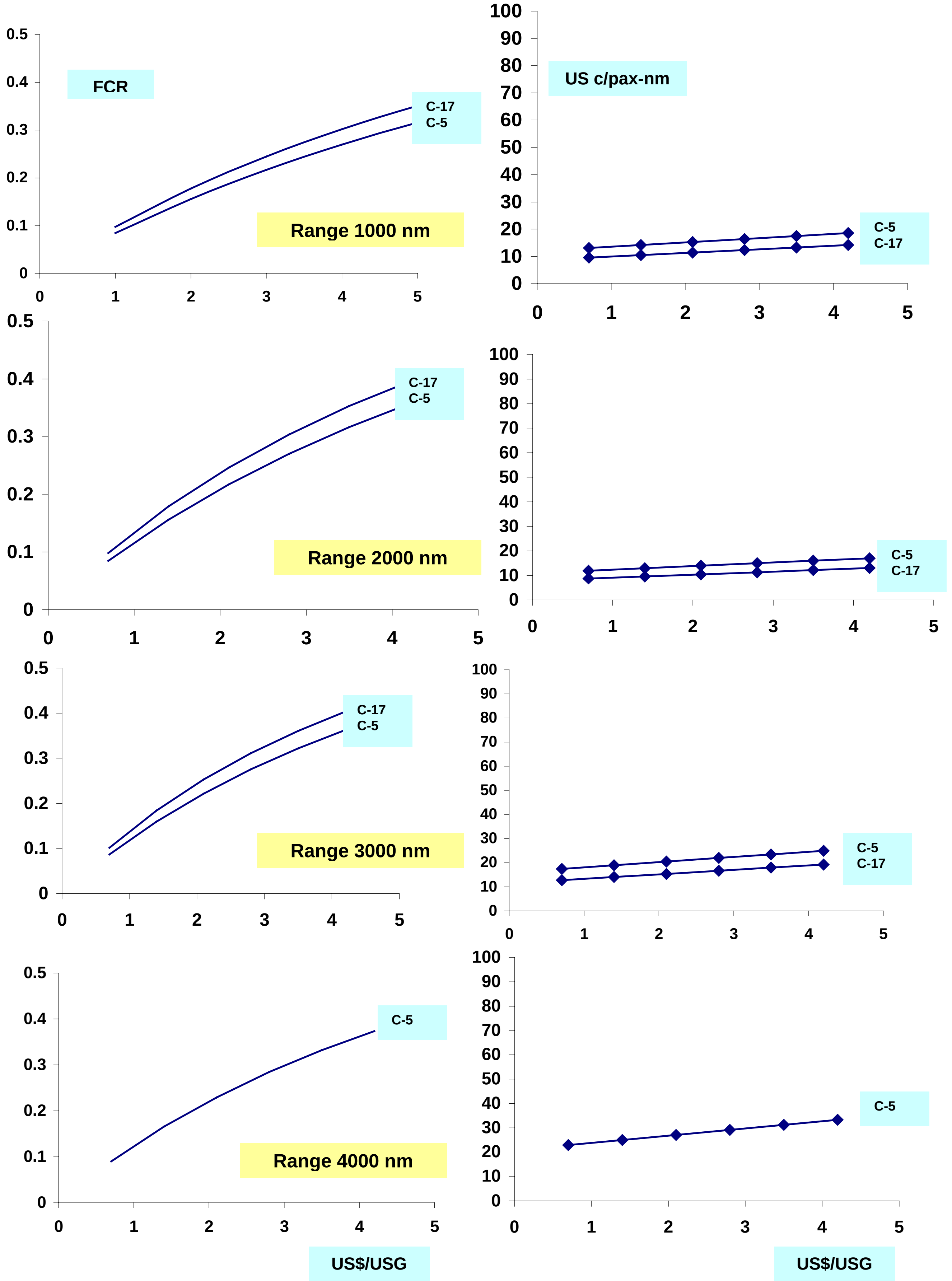


Fig. 33 Transporting 40,000 lb over 2000 nm, FCR & cost / pax-nm Relationships with Fuel Price

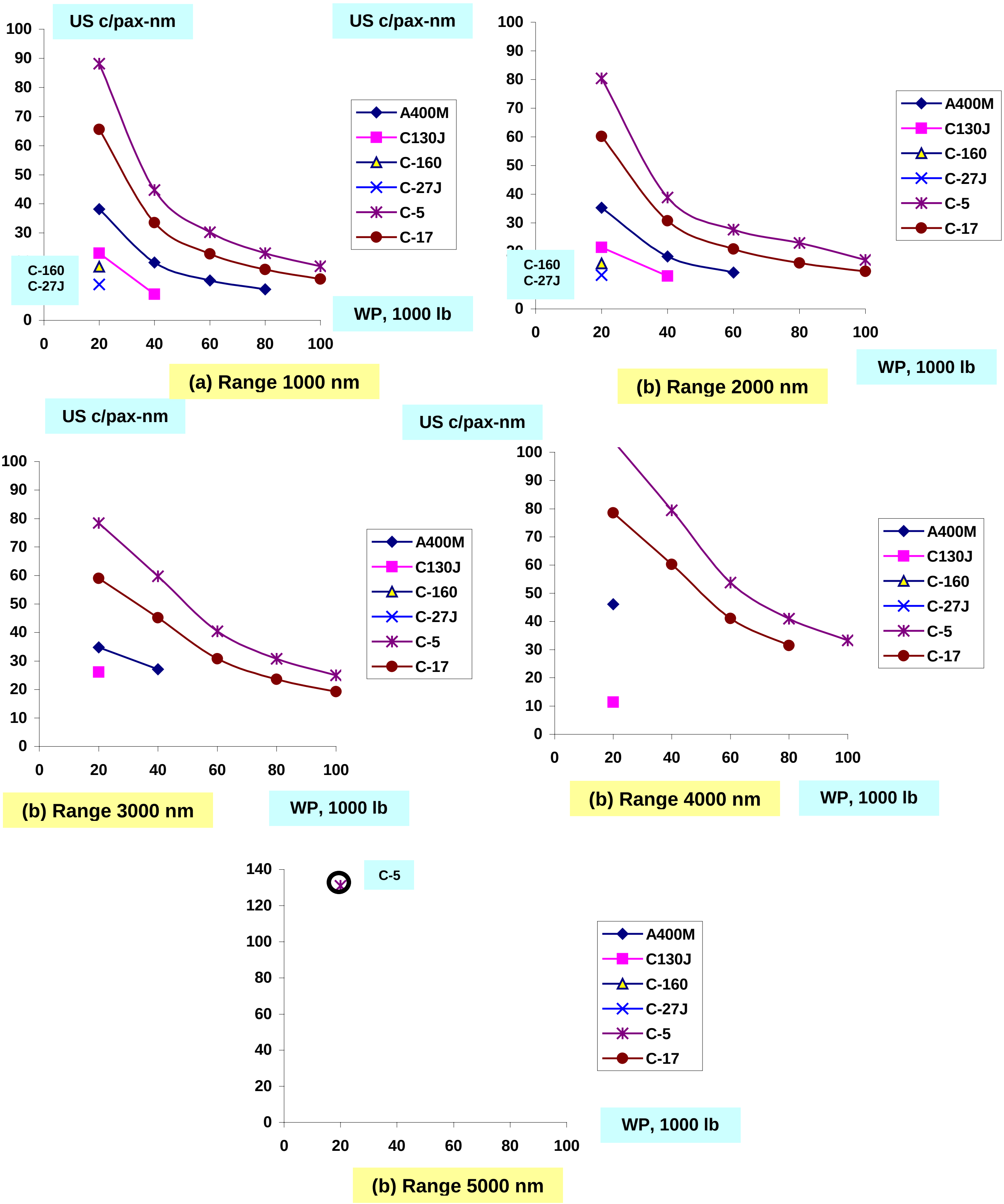


Fig. 34 "Summary" Figure Relating Payload, Range & Cost/pax-nm, Fuel price US$ 4.30/USG