Predicting the certification basis for airliner air-to-air refuelling

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ABSTRACT

The premise is that in the future civil Air-to-Air Refuelling (AAR) will become an economic necessity if popular mass air travel is to continue. What is attempted is to provide a contemporary view of how such future operations could be safely undertaken. The intention is to predict the certification basis for demonstrating safe AAR operation of Cruiser-Feeder concepts. The necessary systems and aircraft functions are treated very much as they are today when civil certifying a large aeroplane type. The compliance demonstration required for environmental conditions, flight envelope, systems providing the necessary functionality, structural integrity, weight and balance are discussed.

Applicable existing civil certification requirements are identified and where necessary expanded in scope to accommodate AAR operation. Where contemporary material does not supply appropriate guidance then corresponding safety criteria are proposed to address the deficiency. Lessons learnt from military AAR include the drive for interoperability. This has resulted in extensive efforts to standardise equipment and systems, which are equally applicable to civil AAR. Extremely useful advisory material exists, ranging from flight testing techniques to related safety.

The importance of ensuring the consistency of failure condition categorisation at system and aircraft level is highlighted. The treatment of failures when two aircraft are in close proximity is something not considered by civil functional hazard analysis. The concept of AAR as an

Paper No. 4306. Manuscript received 15 December 2014, revised version received 12 April 2015, accepted 29 June 2015.
This is an adapted version of a paper first presented at The 2014 Royal Aeronautical Society Biennial Applied Aerodynamics Research Conference, *Advanced Aero Concepts, Design and Operations*.

https://doi.org/10.1017/S0001924000011209 Published online by Cambridge University Press

additional flight phase is introduced and affected system safety analyses identified. Examples of failure conditions that are not catastrophic at system level, but potentially could be at aircraft level during AAR are provided. Rendezvous scenarios are described to illustrate their influence on the certification basis. Combining such considerations with the factors that influence aircraft design leads to ramifications for handling qualities, performance and fuel system design. A viable and certifiable AAR configuration is consequently proposed. Consideration is given to treating operational certification in a progressive manner similar to existing LROPS (Long Range Operations).

NOMENCLATURE

AAR	Air-to-Air Refuelling
AC	Advisory Circular
AMC	Acceptable Means of Compliance
APU	Auxiliary Power Unit
AGARD	Advisory Group for Aerospace Research and Development
ARSAG	Aerial Refuelling System Advisory Group
AWACS	Airborne Warning and Control System
BDA	Boom-Drogue Adaptor
CG	Centre of Gravity
CS	Certification Specifications
DAL	Design Assurance Level
EASA	European Aviation Safety Agency
ECS	Environmental Control System
ETOPS	Extended Twin Operations
FGS	Flight Guidance System
FQI	Fuel Quantity Indication
FMS	Flight Management System
g	Acceleration due to gravity
HDU	Hose Drum Unit
KIAS	Knots (Indicated Air Speed)
LROPS	Long Range Operations
nm	nautical mile
STANAG	Standardised NATO Agreement
TACAN	Tactical Air Navigation

1.0 INTRODUCTION

Imagine that in twenty years fuel resources are such that the AAR of airliners has become necessary. As part of an initial feasibility study this document has been retrieved from the archives. The following should be read in this context as it attempts to provide today's contemporary knowledge and experience. In Ref. 1 Nangia presented the case for significant fuel savings on long range journeys by replacing the large long-range aircraft with short range equivalents utilising AAR. The study concluded that enabling 3,000nm range aircraft to complete long-range flights by AAR would provide fuel savings of 30-40% and financial benefits of 35-40%.

The approach to airworthiness must address certification as an aircraft level operation. The systems and aircraft functions necessary for providing safe AAR operation should be treated much

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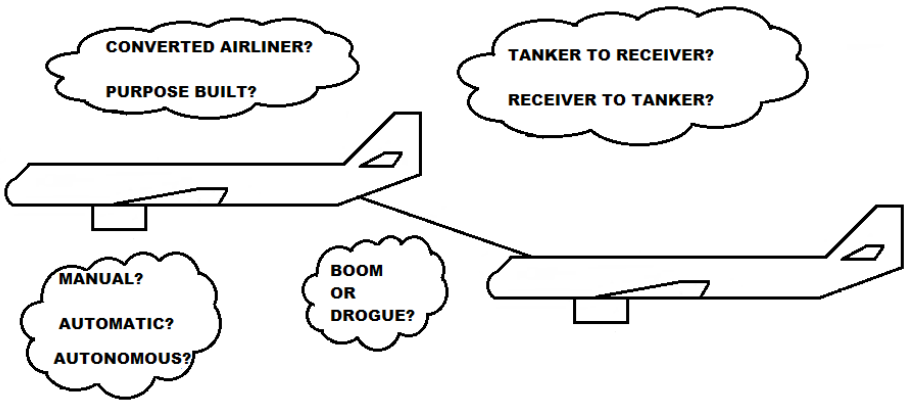


Figure 1. Concept of Airliner AAR.

as they are today when certifying a new aircraft type in accordance with Ref. 2. This paper does not address future operational requirements analogous to Ref. 3 for the adequate supervision and certification of civil AAR operators. The concept of operation and resulting aircraft configurations will introduce specific airworthiness considerations. Contemporary military AAR operations have the Tanker in front of the formation, not necessarily the case for future civil AAR. Current fuel dispense system technology comprises two methodologies, hose/drogue and boom. Figure 1 illustrates conceptual considerations and Fig. 2 how AAR can perpetuate fuel reserves allowing a trade-off between fuel and payload that facilitates an extension in range.

2.0 ENVIRONMENTAL CONDITIONS

2.1 Lightning strike risk and static electricity

AAR is prohibited in a known lightning environment. Even so the manufacturer would have to submit a qualitative analysis of the design precautions taken against inadvertent lightning strike. The expected lightning discharges are described in Ref. 4. With the possibility of an increasingly

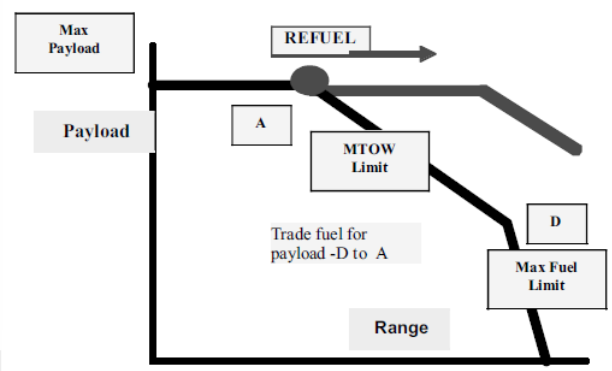


Figure 2. AAR perpetuates fuel reserves and extends range (courtesy of Nangia).

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energetic atmosphere these discharge intensities and action integrals might have to be revisited. Compliance against CS 25.581 Lightning Protection and CS 25.899 Electrical Bonding and Protection against Static Electricity[2] would have to be demonstrated. Static discharge would have to be addressed during approach and contact. It would be the responsibility of the AAR formation leader (presumably the Tanker captain) to obtain weather forecasts at the departure airport, rendezvous point, diversion and arrival airport. Both the Receiver and Tanker aircraft should use Doppler shift weather radar to detect and display wind shear patterns and water precipitation droplets associated with lightning conditions.

2.2 Icing conditions

AAR operation would only be certified when the Receiver or Tanker was not accreting ice in accordance with CS 25.1419 Ice Protection[2]. AAR would be allowed until ice accretion was detected by means of an ice detector and/or visual check. The primary concern would be shedding accreted ice and the risk of it striking an aircraft. Flight testing would determine the extent of ice accretion at the point of first detection. Once the weight of accretions was known it could be demonstrated that the trajectories of any shed ice and subsequent impacts were not critical for airframe and engine. AAR capability would have to be recovered as soon as possible after leaving icing conditions. Reference 5 considers worse case icing conditions to be at 15,000ft altitude at –10°C, typical of a holding pattern, however icing conditions may exist up to a typical maximum operational ceiling of 40,000ft. Updrafts in a thunderstorm support abundant liquid water with relatively large droplet sizes. Clear icing can occur at any altitude above freezing level. At high altitudes icing from smaller droplets may be rime or mixed rime and clear. The abundance of large, super-cooled water droplets makes clear icing accumulation very rapid between 0°C and –15°C. Thunderstorm icing can therefore be very dangerous.

2.3 Vulnerability of AAR operations to severe weather in the refuelling zone

AAR operations require stable aeroplane platforms in approach to contact and during fuel transfer. Large weather systems may disrupt these conditions. The certification basis of a contemporary tactical tanker specifies airframe loading in the hoses extended flight phase as:

- Symmetric manoeuvres from 0·5 to 2g
- Gusts of intensity equal to ½ of the intensity specified in CS 25.341 Gust and turbulence loads[2] as applicable at the Tanker's design cruising speed.

Flight planning would have to establish rendezvous points that avoided severe weather conditions that lead to exceeding this envelope.

2.4 Flight envelope

2.4.1 Normal AAR flight envelope

The manufacturer would provide a detailed AAR envelope for speed, altitude, Mach number, g-load, aircraft gross weight, environmental conditions and docking speed for the Receiver/Tanker combination. Tests would be made utilising flight control laws that gave a stable AAR platform in smooth and turbulent conditions. In accordance with DEF STAN 970 Chapter 916 13.4 Extension and Exploration of the AAR Envelope[6] the Receiver/Tanker combination should make smooth entries to and recoveries from turns at bank angles of up to ±30°. Likewise smooth entry to and recovery from descent rates of up to 500ftmin^{-1} should be possible. Accurate speed holding over the

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intended receipt range would be needed. Different weights and centres of gravity (CG) will influence the resulting wing trailing-edge downwash, vortices and level of engine thrust of the lead aircraft. These parameters will determine the level of induced drag and handling qualities effects on the aft aircraft. To establish a certified flight envelope for the Receiver/Tanker combination the manufacturer should establish flight test points in terms of Tanker and Receiver weights, CGs, altitudes, speeds and flap configurations. Flight testing should start with conservative aircraft configurations (medium to light mass, mid CG, clean configuration) before moving to the corners of the flight envelope. As the Tanker transfers fuel to the Receiver it will become lighter and the Receiver will become heavier, changing the airflow environment for the aircraft. Reference 7 describes the points that need to be considered when planning AAR trials to clear a new Tanker or a new Receiver aircraft for Service use.

2.4.2 Engine(s) Out AAR flight envelope

Controllability of the Receiver and Tanker under the condition of engine(s) failure when in the AAR bracket would be demonstrated. If it proved necessary to develop a dedicated AAR disconnect procedure following engine(s) failure then it would have to be approved by the certifying authority. The manufacture would also provide advice as regards reconnection if essential for mission completion.

3.0 AIR-TO-AIR REFUELLING OPERATION

3.1 AAR – General

AAR requires Receiver/Tanker compatibility while in formation, pre-contact, contact and withdraw from contact. The dispense/refuelling systems must also be compatible. The manufacturer would provide an AAR Operation Compliance Summary that referred to the certified Type Design Definition for the hardware and software standards for the major systems used in the AAR operation such as Fuel Control and Monitoring, Flight Warning System, Flight Management System, Flight Guidance System and Central Display System. A list of limitations and restrictions for the AAR operation would be extracted from the System Safety Assessments (SSA) of the Tanker and Receiver's systems providing the necessary AAR functionality. Reference 8 Appendix to Annex BA provides good starting points for identifying the systems necessary for AAR.

3.2 Fuel receipt and dispense systems

Reference 2 would apply to the certification of the fuel dispense and receipt systems. For safe operation alerts and advisories relating to the respective fuel systems should be provided to the flight crew as compliance against CS 25-1309(c) Equipment Systems and Installations[(2)]. The information would include aircraft fuel quantity, CG, fuel required to complete the flight, transfer between tanks and possible fuel leaks. The maximum surge pressures arising from AAR operation would have to be accounted for in the fuel system design. The 'holy grail' for today's drogue/hose AAR systems is to standardise the coupling interface pressure. References 9 and 10 set pressure standards at normal and stall flow rates. What is proving to be problematic is standardising the interface pressure in the event of the failure of one of the pressure regulating devices. ARSAG (Aerial Refuelling System Advisory Group) has been driving attempts to revise these documents in this respect. An interface pressure standard that fully addressed stall pressure, normal operation and regulator failure cases would have to be established at the onset of civil AAR. It would be an extrapolation of the current ground refuelling pressure requirement of 50 ±5lb Sin^2. Figure 3 illustrates boom and Fig. 4 hose/drogue refuelling.

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Figure 3. Boom refuelling.



Figure 4. Centre-line drogue/hose AAR.

Current practice is to ground test Receiver/Tanker combinations before flight trials. It makes senses to first check on the ground for excessive surge pressure with the Receiver's fuel tanks reaching full and closing isolation valves. It is obvious that it is safer to discover excessive surge pressures on ground than in flight. The maximum likely surge pressures arising from AAR would have to be certified in accordance with CS 25.979(d) Pressure refuelling system[2]. Current practice for boom to receptacle AAR combinations is to use an adapter for connection during ground testing. Reference 7 provides comprehensive and pragmatic guidance material for ground testing Receiver/Tanker combinations and Fig. 5 illustrates ground compatibility testing.

Civil certification of a fuel system ideally suited to AAR is entirely viable. If boost pumps pressurise all transfer galleries to ensure internal fuel transfer integrity then the control and indication of an AAR dispense fuel isolation valve is just another aspect of this civil certification. The fuel receipt system is just an extension of ground pressure refuelling. A diverter valve is added to the refuel gallery to receive fuel via the connection device. All this can easily be encompassed by civil certification.



Figure 5. Ground compatibility testing for AAR.



Figure 6. TriStar Tanker HDU signalling lights and testing for AAR alignment markings.

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3.3 Flammable fluid and fire precautions

The manufacturer would submit an analysis of fuel spillage during the AAR flight phase. It should address the effects of fuel spillage on both aircraft and possible fuel auto-ignition sources such as external lights, heated windscreen and air data sensors. It would include the effects of fuel ingestion by the engine, Auxiliary Power Unit (APU) and Environmental Control System (ECS) intakes. The starting point would be identification of all possible failure conditions leading to fuel spillage during AAR and then determination of what areas of the aircraft were impacted by such spillage and in what quantities. Extensive regulatory work such as Ref. 11 has been undertaken following the loss of flight TWA 800 off New York in 1996, but has explicitly focused on preventing fuel tank explosions. In this context the fuel auto-ignition temperature has been taken as 200°C derived from the FAA Advisory Circular AC 25-8 Auxiliary Fuel System Installation, the AC having been raised with the introduction of auxiliary cargo fuel tanks. Simply applying this auto-ignition temperature criterion for fuel spillage during AAR would be naive.

American research into fuel safety was triggered after the fire on board the USS *Forrestal* in 1967 off the Gulf of Tonkin. An extremely serious fire on the carrier's flight deck followed after a rocket was accidently fired from a F-4 and hit a Skyhawk's drop tank. In the aftermath MIL HBK 221 Fire Protection Design Handbook for US Navy Aircraft powered by turbine engines was produced. The significance of this event and subsequent research is that both aircraft carrier and AAR operations are conducted with aircraft in close proximity. US research continued into the 1980s. One landmark piece of research into hot surface fuel ignition was made at Wright-Patterson Air Force Base. The testing was extremely realistic utilising an F-16 engine compartment and F100 engine. Various flammable fluids were dripped and sprayed into the compartment. A hot air pipe running through the set-up provided the ignition source. Parameters of ventilation air pressure, temperature and speed were varied and minimum hot surface ignition temperatures determined. It provides very useful data for particular risk analysis of fuel spillage into systems such as ECS. Details of the work are provided by Ref. 12. Only one engine fuel ingestion test is known at present. In 2001 Rolls-Royce performed fuel ingestion tests on an Olympus 593 engine built from life-expired parts[13]. The tests were conducted at the original Shoeburyness test stand as part of the Concorde return to service programme. Tests showed that with fuel in the form of a spray, which is more representative of spillage during AAR, the engine would accept flow rates as high as 1·6 litres per second without surging.

3.4 Structural integrity

Load cases encountered during AAR would be identified in the Loads Manual. Tanker and Receiver masses and inertial forces will change in-flight during AAR. The structural integrity of the airframe and fuel system installations would have to comply with the relevant Ref. 2 requirements for such load cases. AAR a few minutes into the flight could allow lighter weight take-offs reducing the take-off airframe loads. The corresponding certification requirements are given in SUBPART C – Structure of Ref. 2.

3.5 Aero-elasticity

It would have to be demonstrated that there was no flutter excitation due to trailed AAR devices and that the aircraft in the AAR configuration was free from vibration and buffeting that prevented continued safe flight in accordance with CS 25.629 Aero-elastic stability requirements and CS 25.251 Vibration and buffeting[2].

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3.6 Crashworthiness

Emergency landing analysis for AAR fuel system installations would be made in accordance with the inertial accelerations specified in CS 25.561(b)(3) Emergency Landing Conditions[2]. These requirements relate to landings with one or more landing gear known to have not locked down. AAR fuel system installations must avoid fuel spillage adjacent to emergency exits and susceptible elements must not be located at the point of maximum fuselage bending during a wheels-up landing.

3.7 Lighting system

Safe AAR operation during all lighting conditions would have to be ensured by means of adequate aircraft lighting and AAR light signalling. Reference 14 provides the current standard for drogue refuelling signal lights. Figure 6 illustrates HDU signalling lights. Such lighting should not dazzle the pilots during night time AAR. White LED illumination technology should be avoided if operations performed at night are to rely on human vision dark adaptation, the use of such bright point sources causing disability glare. Loss of naked eye adaption for night vision would also invalidate fuel leak procedures where the crew looks out of the aircraft to try and locate the leak. White LED technology is however compatible with use of NVGs (Night Vision Goggles), having a much sharper cut-off in the red part of the spectrum compared with a black body radiator and therefore easier to filter.

3.8 AAR Markings

External markings would have to be provided for guiding the approaching aircraft into AAR contact. Figure 6 illustrates such markings and DEF STAN 970 Chapter 916 7.3 Night Lighting, Visual References and Line-up Markings[6] explains their use and the lighting conditions under which they should be evaluated.

3.9 Handling qualities and flight control laws

Handling qualities should be suitable for the certified AAR flight envelope in free air, approach to contact, contact, fuel transfer, normal and emergency disconnect. Smaller and lighter aircraft with more efficient lift/drag coefficients would minimise bow wave effects. Heavier aircraft in front would induce more drag on the aircraft behind. Contemporary flight testing has shown that the aft aircraft requires between 15 to 20% more engine power when in contact. The bow wave effect has been determined to decrease the power needed on the aircraft in front by 3%. Refuelling while in a gentle descent of up to 500ft/min^{-1} requires only low power for the leading aircraft. Any dedicated AAR flight control laws would have to be tuned by flight testing before being certified as part of the primary flight control system. The Receiver could be flown manually but may have additive terms in the flight control laws to ease the handling relative to the Tanker. Pitch control might involve direct lift kinematics as symmetrical deflection of ailerons and spoilers in proportion to the elevator improves vertical acceleration response times. This would require spoiler pre-deflection. Roll control may involve restored positive spiral stability. A hard stick-over manoeuvre would cause immediate reversion to normal control laws. The Tanker would fly in selected mode. The applicable CS 25[2] Control and Stability requirements would be:

- CS 25.143 General
- CS 25.147 Directional and lateral control
- CS 25.149 Minimum control speed
- CS 25.161 Trim

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- CS 25.171 General Stability
- CS 25.175 Demonstration of static longitudinal stability
- CS 25.177 Static directional and lateral stability
- CS 25.181 Dynamic stability
- CS 25.201 Stall demonstration
- CS 25.203 Stall characteristics
- CS 25.207 Stall warning

3.10 Performance

High speed performance calculations would be required from a validated Flight Performance Tool and the results then embedded in the Electronic Flight Bag or similar for pilot reference, including performance data for flying in clean configuration with AAR system trailed. The following CS 25 (2) requirements would apply:

- CS 25.101 General Performance
- CS 25.123 En-route Flight Path
- CS 25.125 Landing – landing with AAR devices trailed would be a failure condition covered by CS 25.1309(b)

3.11 Weight and balance

The key point for the Weight and Balance Manual would be to ensure refuelling and defueling vectors remained within forward and aft CG limits including allowance for Fuel Quantity Indication (FQI) accuracy. Fuel quantity and distribution are key for determining CG position therefore CG monitoring should be part of the Fuel Control and Monitoring System.

The approved Weight and Balance Manual would have to show compliance against the following CS 25 requirements for Tanker and Receiver aircraft configurations:

- CS 25.023(a) Range of Weights
- CS 25.025(a) Maximum Weights and CS 25.025(b) Minimum Weights
- CS 25.027 (a) Centre of Gravity Limits (selected by manufacturer), CS 25.027 (b) Centre of Gravity (proven for structures) and 25.027 (c) Centre of Gravity (flight requirements)
- CS 25.029 Empty Weight and Centre of Gravity
- CS 25.159 Weight, Centre of Gravity and Weight Distribution
- CS 25.1583 (c) Weight and Loading Distribution

3.12 Flight guidance system

Current civil Flight Management Systems (FMS) do not guarantee that the aircraft will turn at constant bank angles or flying from waypoint to waypoint without roll corrections. As an alternative selected mode inputs into the Flight Director and the Autopilot could be used during AAR as follows:

- Selected altitude, vertical speed and flight path angle for vertical control
- Selected heading, track, navigation and bank angle for lateral control
- Selected speed for automatic thrust control.

Flight to the Rendezvous Point would be in FMS managed mode.

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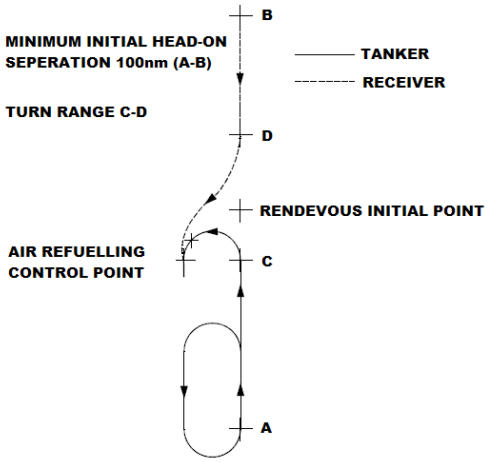


Figure 7. Head-on rendezvous.

3.13 Flight management system

Civil FMS functionality would have to be adapted for AAR. If used without modification Receiver fuel to destination predictions would indicate negative fuel quantities when approaching rendezvous. Predicted Tanker fuel reserves at the end of the flight would be erroneously high. Reference 8 defines 'bingo' fuel as a predetermined quality of Receiver fuel which is insufficient to complete the mission as planned. FMS functionality would have to be expanded beyond just calculating fuel used at each waypoint. It would have to trigger a 'bingo' fuel warning to divert if the rendezvous was not achieved. Such a system may well require a Design Assurance Level of DAL A in accordance with Ref.15 as fuel exhaustion would be catastrophic. FMS development might allow the aircraft to fly pre-programmed automatic AAR patterns, interfaced with the FGS to ensure constant bank turns that exit on pre-set headings.

The amount of excess fuel burnt by the Receiver because of AAR must be minimised. AAR efficiency (payload x range/fuel used) tends to peak at about 2,500 to 3,000nm according to Nagia's parametric studies (1). Nagia's base-line aircraft has a payload of 250 passengers that requires less than 50,000lb of fuel per 3,000nm leg. Using contemporary refuelling technology delivering 1,800kg of fuel per minute would infer a refuelling time of around 12 minutes for each 3,000nm leg. During AAR the Receiver would have to slow from cruise speed to that for deploying AAR equipment. The current maximum speed for drogue trailing is around 350 KIAS.

Reference 8 lists seven types of rendezvous patterns along with any necessary details for turn range and speed corrections for intercepts. Consideration should be given to patterns that allow en route refuelling so as to minimise excess fuel burn due to AAR. Figure 7 illustrates a head-on rendezvous that is suited to Receivers equipped with airborne intercept radar. Once the Air Refuelling Control Point was reached AAR could continue en route albeit at reduced speed compared with cruise. FMS development would allow the aircraft to fly such a pre-programmed pattern.

Reference 16 describes successful Northrop Grumman station-keeping flight tests between a Learjet and Boeing K707 Tanker. The Learjet was piloted to a rendezvous point approximately one mile from the Tanker before the pilot transferred control to an autonomous flight control processor, allowing control of the 'Receiver' by the Tanker or ground station at pre-contact, contact and

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post-contact AAR positions. Autonomous control might be combined in the future with a hybrid GPS/ vision based relative trajectories system to maintain a precision distance between the aircraft in AAR contact. Such systems would have to be DAL A in accordance with Ref. 15. This would represent an unprecedented level of system integration, further complicated by the complexity of integrating the systems of two individual aircraft operating in unison. Compliance against Ref. 2 would require showing that there was no single catastrophic failure condition and that a chain of failures, including latent failures, was extremely improbable i.e. not likely to occur within 10 to the power 9 flight hours.

3.14 Communication and radio navigation

Reference 8 describes compatibility between Receiver and Tanker navigation systems. Current AAR operation relies on TACAN (Tactical Air Navigation) switched to the assigned frequency for the bearing and distance to get visual contact. TACAN is a more precise military version of the civil VOR/DME (VHF Omni-directional Range/Distance Measuring Equipment). Differential GPS (Global Positioning System) is currently not used in AAR operation. It has been used in proximity flight tests to investigate the possibility of helicopter AAR. Adaptation of differential GPS might provide an input for automatic or autonomous control of AAR.

3.15 Electrical power

Tests would have to demonstrate sufficient electrical power for the AAR system and its correct functioning under maximum harmonic voltage distortion from the electrical buses by showing compliance against CS 25.1363 Electrical System Tests[(2)].

3.16 Hydraulic system

The manufacturer should demonstrate that there is sufficient hydraulic flow and pressure to power hydraulically driven AAR dispense pumps and flight control surface actuators during the AAR flight phase in accordance with CS 25.1435 Hydraulic System[(2)]. Hydraulically powered fuel pumps currently allow high fuel dispense rates in the order of 1,800kg/min. Availability of hydraulic pressure and flow would have to be considered in trade-off studies between using large diameter AAR equipment utilising lower pump pressure or smaller diameters that would require higher pressures.

3.17 Uncontained engine and auxiliary power unit rotor failure

A qualitative analysis for the AAR fuel system in accordance with AC 20-128A Design Considerations for Minimising Hazards caused by Uncontained Engine and Auxiliary Power Unit Rotor Failure[(2)] would be required. Turboprop engines introduce the complication of propeller blade release. Open rotor configurations would need minimum clearance criteria for AAR. Contemporary helicopter proximity flight testing for AAR suggests that rotors should not be within 7 metres of any part of the Tanker in anticipation of emergency breakaway. Compliance against CS 25.903(d) (1) Engine Rotor Burst[(2)] would be required.

3.18 Aeroplane flight manual

The manufacturer would have to supply any limitations necessary for safe AAR operation in the Aeroplane Flight Manual and they would have to be approved by the certifying authority under CS 25.1583 Operating Limitations[(2)].

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3.19 Human factors

AAR operation must not cause excessive workload for the crews under normal and abnormal operating conditions. Currently civil airliners converted to the Tanker role require a flying officer with his or her own dedicated flight refuelling station. Automation of the AAR operation would allow the mission to be flown by two person crews but careful workload studies would be required. Workload peaks would have to be investigated by qualified pilots on flight simulators with all systems at the certified standard.

Human Factors will significantly influence the selection of a viable operational configuration for AAR. In any operational scenario safety depends on reducing human error. Human error depends upon both the amount and stability of workload. The starting premise is that AAR would be first introduced as an automatic procedure. Crew monitoring of the necessary automatic devices will increase workload. Responsibility for controlling engagement with the drogue or boom must be placed with the Tanker pilots who would be trained to routinely perform such tasks.

In Ref. 17 Thomas proves the hypothesis that aircraft using the boom method of refuelling have a substantially higher percentage of mishaps caused by aircrew when compared to aircraft refuelled with the Boom Drogue Adaptor (BDA) method. Boom refueling requires continuous interaction between the Receiver pilot and the boom operator. In the BDA method the Receiver pilot is responsible for flying the probe into the drogue. It should be noted that Ref.17 was based on the study of KC-135 operations. The KC-135 is not equipped with a centre-line Hose Drum unit (HDU) but with a BDA to allow probe equipped Receiver aircraft to join on the centre-line. This operational scenario is very similar in that the Receiver connects to a trailed drogue using its probe.

What emerges from these considerations for minimising and ensuring stable workload is a distinct AAR operational configuration given contemporary AAR technology. The Receiver would trail a hose and drogue. The Tanker would then connect by flying its probe into the trailed drogue. Trained and experienced Tanker pilots would routinely make the connection. Airliner (Receiver) pilots would passively trail the drogue.

Reference 7 recommends checking deployment, use and recovery of AAR equipment for the intended range of aircraft weight, airspeed and Mach number. One consequence of such testing is that the drogue can be assessed as a steady target and refined if necessary by subsequent modification. In this respect workload may be significantly reduced through successive design and test iterations of the trailed drogue.

4.0 FUNCTIONAL HAZARD AND SYSTEM SAFETY ANALYSES

The manufacturer will have to ensure that failure condition categorisations at system and AAR aircraft operation levels are consistent. All Functional Hazard Assessments should consider the AAR flight phase when showing compliance against CS 25.1309(b) Equipment, systems and installation using the advice given in AMC 25.1309[(2)]. Particular attention will be paid to any failure condition that can cause inadvertent acceleration, deceleration or trajectory change that might lead to collision during AAR contact. The manufacturer will have to demonstrate that any such failure will not result in collision within five seconds of the failure given the aft aircraft taking no avoiding action whatsoever. The ‘five second’ criterion is based on the aft pilot’s reaction time irrespective of any breakaway call or red light signal from the lead

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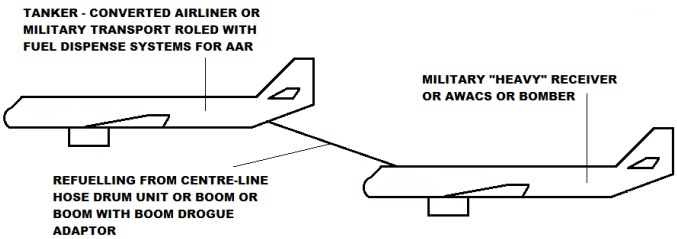


Figure 8. Current configurations for AAR of 'heavy' military receivers.



Figure 9. VC10 to AWACS military aircraft AAR.

aircraft. Five seconds or longer is sufficient for the aft aircraft's crew to perceive that there is an abnormal situation and to take the necessary evasive action, manually over-riding any automatic or autonomous AAR systems. Mathematical flight trajectory models combined with animated digital mock-ups of the two aircraft would determine the time to collision. Any failure conditions that could not meet this 'five second' rule would have to be demonstrated as being extremely improbable.

Examples of failure conditions that could cause the forward aircraft to decelerate are:

- Inadvertent deployment of landing gear
- Inadvertent deployment of spoilers
- Engine fuel starvation

Examples of failure conditions that would cause the aft aircraft to accelerate are:

- Inadvertent take-off and go-around thrust
- Loss of Tanker flight control laws

5.0 AIRCRAFT CONFIGURATIONS AND AIRWORTHINESS

Figures 8 and 9 illustrate the current configurations for the AAR of large military aircraft. Current military AAR of 'heavy' Receivers is with the Tanker in the forward position. Refuelling is in line astern to minimise the proximity between the two aircraft. Refuelling A 'heavy' Receiver from a wing fuel dispensing pod is too close for safe operation. AAR operations are therefore in line astern using one of three methods:

- Boom and receptacle refuelling that requires an operator station on the Tanker to fly the boom and make contact with the receiver's receptacle.

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- Drogue and probe refuelling that requires the tanker to passively trail a hose from a centre-line Hose Drum Unit. The Receiver is then responsible for connecting its probe to the Tanker's trailed drogue.
- Boom equipped tankers that utilise a Boom-Drogue Adaptor (BDA) to allow probe equipped Receivers to connect. Reference 17 substantiates that BDA refuelling is more susceptible to mishaps compared to the boom method, this being attributed to the more delicate components of the BDA equipment.

Civil AAR operations would allow contemplating alternative AAR aircraft configurations leading to specific airworthiness considerations. It is extremely unlikely that future aircraft dedicated to the Tanker role would be anything other than existing transport aircraft. It is not realistic to consider futuristic purpose designed tankers such as the 'box wing' or 'slim fuselage' concepts at this stage.

What follows from the discussion above is that a viable and certifiable civil AAR configuration would consist of the following:

- Existing airliner modified for the receiver role and equipped with a HDU.
- Receiver as the lead aircraft in the formation.
- Existing airliner modified by addition of AAR probe and fuel dispense system to a dedicated Tanker role.
- Tanker flown astern manually with additive terms in flight control laws to ease handling relative to Receiver.
- Tanker pumping fuel 'uphill' against the fuel pressure head.
- Higher refuelling speed to reduce the height of the hose catenary and corresponding pressure head.

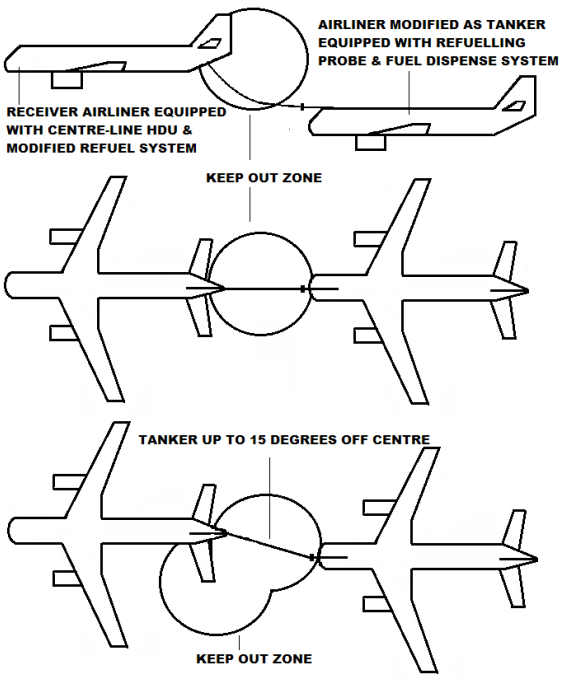


Figure 10. Viable and certifiable AAR configuration.

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- Tanker flight crew trained specifically for AAR.
- Formation nominally line astern but with Tanker handling explored within a 15° 'cone' about the optimum contact position with hose attached in accordance with Ref. 6

Figure 10 illustrates this configuration.

6.0 LESSONS LEARNT FROM ETOPS (LROPS) CERTIFICATION

The philosophy of ETOPS (extended twin operations) and LROPS (long range operations – triple and quad engine equivalent to LROPS) could be extended to the concept of civil AAR. ETPOS (LROPS) allows a particular airliner model to be certified for a specific flight time to a diversion airfield, regardless as to whether the diversion is over land or water. Such certifications are progressive in that the ETOPS (LROPS) flight times are increased step-by-step by demonstrating the operational reliability of the aircraft's engines and systems. This approach could be adopted for civil AAR operations. The radius of rendezvous points centred on the Tanker's home hub point might be progressively lengthened and certified after the demonstration of AAR operational reliability. Certification consideration could be given for two Tanker hubs with overlapping radii or operation. The certified radius of operation could then consider rendezvous points for Tankers operating from both hubs.

7.0 CONCLUDING REMARKS

In the author's personal opinion there is sufficient military AAR experience to adapt civil certification requirements and demonstrate safe AAR of airliners. The technologies and aircraft configurations used will have a pronounced influence on the certification of such operations:

- Adapting conventional civil Flight Management Systems for AAR may involve the introduction of DAL A functionality. Care will have to be taken in selecting a supplier who is capable of delivering such a level of system integrity.
- Autonomous AAR is still at the flight demonstrator stage. From a certification perspective it would be more conservative to first consider automatic AAR utilising Flight Guidance, Station-keeping and Flight Management systems with specific functionality for AAR. Autonomous AAR would be for the next generation of civil AAR operations.
- The importance of ensuring the consistency of failure condition categorisation at both system and AAR operational level cannot be over emphasised. It is anticipated that civil system designers will tend to focus more on the categorisation at system level. This can only be addressed by clear and concise top-level engineering requirements at the beginning of any civil AAR project being cascaded to the system design teams.
- A HDU equipped Receiver in front and probe equipped Tanker joining from astern is the only acceptable configuration from a human factors perspective. Both Receiver and Tanker would be derived from the conversion of existing transport aircraft.

Consideration of civil AAR is based on the premise that it will at some point in the future be needed out of economic necessity. It is the author's opinion that the civil aircraft industry should formulate an appropriate strategy to address this challenge. Which of the existing aircraft in the 3,000nm fleet will still be operating at some future point in time and what would be the design effort needed to convert them for the Tanker or Receiver role? Should future airliner designs incorporate features

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in the major components of the airframe needed for modification to the AAR Receiver or Tanker role? The intention of this paper has been to assist in answering these questions.

ACKNOWLEDGEMENTS

The author would like to gratefully acknowledge Dr Raj Nangia and Roger Taplin for their immense patience in coaxing this prediction of a civil AAR certification basis out of him. Without their help this paper would never have progressed beyond a simple set of proposed compliance statements. All of their suggestions, comments and thoughts have been very much appreciated and used extensively. This work would not have been possible without their wealth of total aircraft experience. In the same context the author would like to thank George Robinson who not only shared his experiences as VC10 Tanker flight test engineer but also taught the author the basics of flight control laws. Finally in the spirit in which this paper was written it is hoped that with foresight a future design team can be acknowledged for achieving certified civil AAR.

REFERENCES

1. NAGIA, R. Operations and aircraft design towards greener civil aviation using air-to-air refuelling, *Aeronaut J*, November 2006, **110**, (1113), pp 705-721.
2. European Aviation Safety Agency Certification Specifications part 25 Large Aeroplanes, amendment 15, 21 July 2014, Annex to ED Decision 2014/026/R.
3. Council Regulation (EEC) No 3922/91 on the harmonisation of technical requirements and administrative procedures in the field of civil aviation.
4. EUROCAE document ED-84 Aircraft lightning Environment and Related Test Waveforms.
5. European Aviation Safety Agency Certification Specifications part 25 Large Aeroplanes, Acceptable Means of Compliance AMC 25.1419 Ice Protection.
6. UK Ministry of Defence, DEF STAN 00-970, Chapter 916 *Air-to-Air Refuelling*, amendment 7, May 1988.
7. The Testing of Fixed Wing Tanker and Receiver Aircraft to Establish their Air-to-Air Refuelling Capabilities, AGARD (Advisory Group for Aerospace Research and Development) Volume 11 ISBN 92-835-06987.
8. NATO Allied Technical Publication ATP-56(B) (AJP 3.3.4.2), *Air-to-Air Refuelling*, 22 January 2010.
9. Aerial Refuelling Equipment Dimensional and Functional Characteristics, STANAG 3447 edition 3, 25 September 1990.
10. MIL-PRF-81975C Performance Specification Couplings, Regulated, Aerial Pressure Refuelling Type MA-2, Type MA-3 and Type MA-4, 22 January 2008, 3.8.11 Regulation capability (MA-3 and MA-4) couplings.
11. INT/POL/25/12 EASA policy statement on the process for developing instructions for maintenance and inspection of fuel tank system ignition source prevention, 5th August 2005.
12. AGARD Conference Proceedings No.467 Aircraft Fire Safety ISBN-92-835-0529-8/AD-A217575 – CLODFELTER, R. Hot surface ignition studies of aviation fluids.
13. www.concordesst.com/returntoflight/rts/chapter5.html
14. STANAG 7215 Edition 2, Signal Lights in Drogue Air-to-Air Refuelling Systems, 31 March 2010.
15. SAE Aerospace Recommended Practice ARP4754, Revision A, Guidelines for Development of Civil Aircraft and Systems, December 2010.
16. http://www.spacedaily.com/reports/Northrop_Grumman_US_Navy_Test_Autonomous_Aerial_Refueling_for_Unmanned_Combat_Air_System_Demonstration_999.html
17. THOMAS, M. Analysis of the causes of inflight refueling mishaps with the KC-135, Air Force Institute of Technology, AFIT/GSM/LSM/89S-41, September 1989.

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APPENDIX: AUTONOMOUS VS AUTOMATIC AIR-TO-AIR REFUELLING

The paper has not considered the feasibility of autonomous or automatic air-to-air refuelling (AAR). This appendix addresses this important point separately by defining such operations and then then examining viability in the context of contemporary AAR capability.

Automatic – take the existing perimeter of civil and military certification enhanced with AAR specific Flight Management and Guidance Systems

Autonomous – one aircraft in the bracket controlled by either the other aircraft or a ground station

Civil fuel systems have been certified up to the point of installing AAR equipment. Flight controls and handling qualities of modern fly-by-wire aeroplanes can safely accommodate AAR flight phases. Current military operations ensure avoidance of fire hazards and take full advantage of light and radio signalling. Military navigation aids such as TACAN (Tactical Air Navigation) allow making visual contact with the tanker. Flight management is aided in most cases by the addition of a third crew member stationed at a dedicated Fuelling Officer workstation.

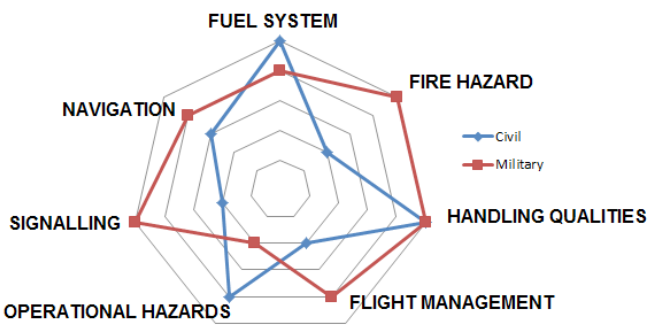


Figure 1. Comparison of civil and military capabilities.

Figure 1 qualitatively compares the current civil and military key capabilities necessary for AAR.

Fuel systems and the prevention of fire hazards are not impacted as they remain within the perimeter of the individual aircraft. In all other aspects the integrity of existing system functionality is in no way sufficient for autonomous AAR. Figure 2 illustrates this point by correlating the existing envelope of civil and military capabilities with the given definitions of automatic and autonomous AAR.

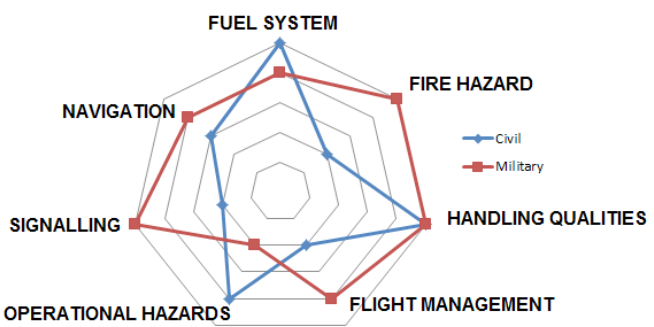


Figure 2. Contemporary capability for automatic and autonomous AAR.

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Automatic AAR certified operations are viable with today's technology. The on-going development of civil flight management and station keeping systems and perhaps the adaptation of infrared landing system technology to facilitate automatic docking would complete the capability. Certification of civil automatic air-to-air refuelling operations will be entirely feasible once such system functionality is at a serial production standard. Such operations could be routinely flown by two person crews without any increase in cockpit workload. Emergency disconnect procedures and the responses to indications of abnormal operating conditions would be part of flight crew training.

Autonomous AAR will require a fundamental change to the way in which system safety analyses are conducted. Where should autonomy be introduced into the system and what would be the cognitive effects on the pilot? Would autonomous systems have failure modes that are not known yet? It may very well be that the military again takes the next step in AAR, not directly but in its development of drones. The Final Report of the Defence Science Board Task Force on the Role of Autonomy in Department of Defence Systems, dated 11 June 2012 provides some insight into the current thinking on how to safely use autonomous systems in general.

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