THE STATE-OF-THE-ART AND THE FUTURE OF WATER MANAGEMENT WITHIN FUEL TANKS

Craig P. Lawson, Kok Meng Lim
School of Engineering, Cranfield University, MK43 0AL, UK

Keywords: *fuel contamination management water contaminant*

Abstract

Water contamination is cited as the most commonly encountered fuel contamination with the most adverse impact on aircraft operation. The current approach of combining good maintenance practice and quality control to prevent and contain the associated problems is deemed not ideal as it is labour and cost intensive. This paper focuses on the study and investigation of methods to manage the water contamination by preventing water from getting into fuel and accumulating within the fuel tank in an attempt to explore potential solutions that preferably require less or no maintenance.

The two main sources of water accumulation within fuel tanks were identified as the occurrence of the precipitation of dissolved water in the fuel and condensation of moist-air during aircraft operation. Methods to prevent water accumulation within the fuel tanks are proposed, based on the two sources identified, and their feasibility and challenges, if implemented, are evaluated and discussed in this paper. Two of the methods analysed as a potentially feasible solution, concern the development of new fuel additives and implementation of OBIGGS.

1 Background

The aircraft fuel system is deemed to be one of the most essential and safety critical airframe systems due to its important function of providing a reliable supply of required fuel to feed the engines. Aviation fuel plays an important role as efficient and safe operation of an aircraft requires clean and dry fuel. However, the aviation industry is constantly faced with the problems associated with fuel contaminations that pose challenges to both flight safety and operation.

Water contamination is commonly encountered and has the most adverse impact on aircraft safety and operation [1-4]. Water could be present in the fuel as free water, suspended water and dissolved water [5, 6]. Only free water such as water slugs or suspended water, collectively known as free phase water, is considered as a contaminant [5, 7, 8]. In fact, the presence of water has directly resulted in the occurrence of micro-biological contamination as water is essential for the growth and production of the micro-organisms [1, 9-11].

The problems arising due to water contaminations are wide ranging, including water and micro-biologically influenced corrosion, clogging of fuel filters from icing of water particles and sludge formation from the micro-organisms that could lead to fuel starvation, malfunction of the fuel quantity indication system and reduction of service life of components such as the fuel filters [8, 10, 12-15]. In addition, the by-product of corrosion, such as rust, contributes to the particulate contaminations [8, 10, 16]. The effort and cost to prevent and resolve the above mentioned problems are relatively very high [17-19].

1.1 Current Practices

Currently, the resolution of containing water contamination can be briefly divided into two main approaches, with strict Quality Control (QC) measures during fuel distribution prior to refuelling of the aircraft fuel tanks, and regular maintenance practises. Both approaches consist of detection and removal processes.

During the fuel distribution supply chain from the refinery prior to fuel entry into the aircraft fuel tanks, detection and monitoring of water contaminants is carried out, utilising commercially available kits such as Hydrokit, Shell water detector, Gammon Aqua-Tector and

Metrocator test kits. The limit of water content should not be more than 30ppm when delivered into the aircraft [20].

Water removal equipment, including filter / water separator, salt drier, water magnet and water fuse, are commonly used during fuel distribution to constantly remove any water contaminant present in the fuel. Furthermore, design features are built-into fuel storage tanks to collect water accumulated from the tank bottom and draw off fuel from the top portion of fuel in the tank with the help of a floating suction valve which prevents water accumulated at the tank bottom after settling being delivered [8, 16].

For fuel inside aircraft fuel tanks, the Clear and Bright test is carried out on a fuel sample drained from the sumps to inspect for signs of water contamination [20, 21]. Fuel tank design features are in accordance with the requirements of FAR and EASA CS - such as the availability of water drain valves located at the low points of fuel tanks for allowing any hazardous quantity of water to be drained off [22].

A maintenance requirement of daily drainage of water is recommended by aircraft manufacturers in their Aircraft Maintenance Manuals (AMM), although airline operators can vary them according to their own experiences as many factors, such as the climate in which the aircraft is operating, weather conditions and flight profile (i.e. flight duration). These factors could affect the amount of water contaminant formed. Several QC and recommendations on related maintenance practices are issued by organisations or authorities such as the ATA and JIG as guidelines to airline operators [23, 24].

In addition, most large civil aircraft have scavenging systems, designed to remove water and so reduce the amount of water accumulated in the tanks [9, 25]. The system can make use of a scavenging pump to draw water from the low point of the fuel and mix with the fuel before feeding it to the engine for combustion.

1.2 Research Applicability

Although currently, the combination of strict QC and good house maintenance practices is still the most effective way to control and minimise the occurrence of problems resulting from water contamination, accumulation of significant amounts of water is still sometimes being reported within the aircraft service. All these measures are deemed to very labour intensive and hence result in an increase in operating cost and aircraft down time as well.

More importantly, due to the current highly competitive commercial aircraft industry environment, and coupled with the hike in fuel prices that increases their operating costs [26], airline operators are exploring every means to reduce expenses and maximise aircraft usage in order to generate more revenue and so ensure their business remains profitable. And it is no surprise that maintenance expenses incurred by the airline operators is ranked the most important aircraft evaluation and selector factor [27].

Therefore, there is a motivation factor to re-examine and investigate ways and methods to overcome any labour intensive maintenance tasks, especially those related to water management within the fuel tanks. With the advances in technology, solutions that were previously not available could soon be present or are now in the process of development. Hence, there have been studies conducted into the water management of fuel tanks, including at Cranfield University [28].

3 Main Causes of Water Contamination and Potential Solutions

The mechanisms that result in the accumulation of water within the fuel tanks during aircraft operation are identified with their main causes in this paper. They were identified as;

1) the precipitation of dissolved water due to the reduction of water solubility in fuel as the fuel temperature drops as the aircraft climbs and cruises at high altitude [5, 9], and
2) the condensation of air (with water vapour / moist air) as ambient air vent into the fuel tank

due to the pressure difference between the inside and outside of the fuel tank during aircraft descent [9].

Fundamental questions were asked by the authors, as shown in Fig 1, to explore how the above occurrences that result in water accumulation within fuel tanks could be minimised or prevented, with each potential solution being investigated to assess if they could provide a solution to these questions and in return, minimise or prevent water contamination.

3.1 Prevention of Precipitation of Dissolved Water in Fuel

The mechanism which resulted in a significant portion of water accumulated is due to the precipitation of dissolved water in fuel when the fuel temperature reduces during aircraft operation at high altitude [8]. The water solubility of the fuel decreases exponentially when fuel temperature is reduced [10], and for large civil transportation aircraft with large fuel volumes carried on board, the amount of water precipitated could be quite significant. Therefore, if there is method to either reduce the amount of water being dissolved in the fuel in the first place or to prevent the water from precipitating, the accumulation of water could be significantly reduced.

It is commonly cited that fuel is hygroscopic and water is always present in the fuel to some extent, but further details on why this is so is not readily explained in literature. Upon further investigation by the author, it has become apparent that the aromatics content in the fuel is the main contribution that results in the hygroscopic nature of the fuel as this content has the highest water solubility property [8, 29]. Although the detailed chemical explanation of the water, hydrocarbon mixtures at molecular level, remains largely unknown, if this content could be reduced in the fuel, water accumulated due to precipitation could be reduced as well. The main possible approaches identified as follows;

1) Variation of Cut-point Range of Fuel Distillation
2) Usage of Alternative Fuel
3) Usage of Fuel Additives
4) Prevention of Reduction of Fuel Temperature during aircraft operation

3.1.1 Cut-point Range of Fuel Distillation

Fuel consists of different hydrocarbon compositions with different boiling points and is being produced by distillation with a pre-defined range of boiling points, the amount of aromatics content in the fuel could be reduced by varying the cut-point range of distillation.

The aromatics content in AVTUR is mainly constrained by the back end cut-point (the upper boiling end) [30], and if the extent of the boiling range is reduced by having a higher back end cut point, the amount of aromatics content in AVTUR could be reduced accordingly. This could result in lower water solubility in the fuel and hence the amount of dissolved water that could be precipitated during aircraft operation would be reduced.

However, there are two major barriers to utilising this method. Firstly, although reduction of aromatics content in the fuel will also have a positive effect on engine combustion due to lower carbon content and smoke point [30], it also reduces the swelling effect that the aromatics content has on seals, O-rings and elastomer materials. Aromatics content is known to chemically react with these materials and results in the swelling of the materials that prevent fuel leakage in both fuel and engine systems - designers have taken this swelling effect into consideration when designing the systems. Hence, by reducing the aromatics content, fuel leakage could occur that results in additional maintenance tasks and may even pose safety concerns. Another major impact on the aviation industry by adopting the approach of reducing the defined range of the fuel boiling points in order to reduce the aromatics content is that the fuel availability for AVTUR would be reduced as well. This reduction of fuel availability will surely have a big impact on the already high fuel prices that are resulting in higher operating costs for the airline operators. As a result, this approach is assessed to be neither feasible nor recommendable.

In additional, the conservative approach adopted in the aviation industry, given their good experience and knowledge, current confidence level with the fuel performance and safety considerations, nobody would want to compromise aircraft safety with any unnecessary fuel composition change due to the uncertainty posed. Furthermore, the cons of having reduced aromatics, such as the reduction of fuel availability, the requirement of an extensive evaluation and approval programme, the problem of water contamination is deemed not significant enough to result in the industry making such a major change to the fuel composition specification.

3.1.2 Alternative Fuel

Currently, there is focus by the aviation industry on exploring and developing suitable alternative fuels to overcome the fuel sustainability constraints and environmental impact [31], these new sources of fuel could offer a different insight and effect in terms of water contaminations.

One of the potential alternative fuels, the synthetic fuel produced by the Fisher-Tropsch process, is reported to have low aromatics content and low hygroscopic properties [30, 32]. Hence, the amount of water that could be dissolved in this fuel is expected to be less and in turn, less water accumulated within the fuel tanks due to precipitation. The usage of the synthetic fuel is unlikely to pose sustainability problems in contrast to the current aviation fuel distillation from crude oil.

However, there is still the concern about the absence of swelling effects that may cause leakage, but researchers have claimed to have found a suitable compound that could be used as a fuel additive to create the similar swelling effect resulting from the aromatics content and hence, prevent the potential leakage [33]. As the development and selection of such alternative fuel is still in the evaluation stage, there will be a need to continue to monitor the progress and assess its effect on water contamination, may it be for better or worse, for improved awareness.

3.1.3 Use of Fuel Additives

One more approach identified is to attempt to alter the hygroscopic nature of the fuel by external means with the use of fuel additives. There is a trend of utilising fuel additives to achieve the desired property of the fuel and improve the performance [10, 34, 35]. Hence, the approach to develop fuel additives to overcome the occurrence of water contamination, such as by preventing dissolved water from precipitation, could be explored. Potential additive candidates were identified by the authors to support the analysis that the approach of utilising fuel additives could offer a potentially feasible solution.

One of the potential candidates analysed to be promising is the TP additive [36]. This particular fuel additive has been tested in fuel during its storage over a period of one year. When compared with fuel without this additive, the fuel with the TP additive blended showed positive results of no water accumulation during the period of testing, whereas fuel stored in a similar fuel storage tank was observed with increased water contaminant over time and formation of ice crystals during the winter period (see Table 1). There was no observation of ice crystal formation in the fuel with the additive during the winter. In this case the absence of the formation of ice crystals in fuel is an indication that there is no water particles suspended within the fuel.

Period of Storage (month)	**Water Accumulation settled in the RT fuel at the bottom of the fuel storage tank (mm)**	
	Without TP Additive	**With 0.02% (by weight) of TP additive**
4	Traces	Nil
6	7	Nil
8	10	Nil
10	25	Nil
12	33	Nil
Observation during winter	Formation of ice crystal within the fuel storage tank	No ice crystal was observed

Table 1. Experimental Results of Fuel with TP additive (tabulated from data in [36])

Another additive which may offer a solution to overcome water contamination is based on Lipophillic Organic Compound [37]. This additive is known to prevent water separation from the fuel. Any water just about to be precipitated from the fuel will be 'absorbed' by this compound which is soluble in the fuel. Although this additive is currently only being used in the automotive industry, it may be worth further analysis to see if this compound could have a similar effect on the water contaminant in aviation fuel.

The challenges posed for adopting this approach include not only the compatibility concerns, but also the costly and time consuming certification and approval processes [38, 39]. Any newly developed fuel additive must be tested at 4 times the recommended dose [40], to check for adverse effects on the fuel performance, reaction with previously approved additives, and all materials that the additive blended fuel will come into contact with in both the fuel and engine systems.

Therefore, from the above analysis of trends and observations, the usage of fuel additives specially developed to overcome problems associated with water contamination is deemed to be potentially possible and feasible in the near future.

3.1.4 Prevention of Reduction of Fuel Temperature

The usage of a heat source, such as a fuel heater utilising engine oil and bleed air to maintain fuel temperature when the aircraft is operating at high altitude, could prevent or reduce the dissolved water from precipitation and hence reduce the amount of water accumulated. However, this approach is expected to require massive energy to maintain the fuel temperature of the large volume of fuel for civil transport aircraft. In addition, the rate of fuel evaporating could be increased due to the rise of fuel temperature [30] and, coupled with the heat source; it poses safety concerns, especially after the TWA 800 accident [41]. Hence, the author anticipates this approach will not be advisable or acceptable to the industry.

3.2 Prevention of Water Condensation in Fuel Tanks

The other mechanism that results in water accumulation within fuel tanks is due to the condensation of moist air during aircraft descent. The pressure difference between pressure within the fuel tanks and the ambient results in moist air entry into the fuel tanks as the aircraft descends. Furthermore, this moist air is also relatively warm as the aircraft descends and the altitude reduces. As a result, when this warmer moist air comes into contact with the much colder surfaces within the fuel tanks, condensation takes place [10]. Therefore, if both the relative humidity and the amount of moist air entering into the fuel tanks could be reduced, the amount of water accumulated could be reduced accordingly.

3.2.1 OBIGGS

The integration of OBIGGS was analysed to have a positive effect on water contamination occurrence within fuel tanks by reducing water condensation through achieving constant low humidity in the ullage, and the reduction of ambient air venting into the fuel tanks during descent. The above conclusion is based on the ability of the OBIGGS to remove water vapour from the air while producing inert gas in the fuel tanks [42], and from the analysis of flight test data collected from FAA's OBIGGS evaluation flights which reveal a reduction of air entering into the fuel tanks during aircraft descent (See Fig.2) [41, 43].

The application of OBIGGS may also pose the possibility of a higher fuel temperature in flight due to the ability to control and supply a higher temperature of the inflow of dry nitrogen rich gas into the fuel tanks [41], as compared to fuel in fuel tank without OBIGGS in operation, hence achieving reduced water precipitation as well.

The challenges for implementing new systems such as the mentioned OBIGGS, is to justify the performance penalty due to the additional weight and hence increased fuel consumption. Although FAA has reported the OBIGGS based on the Hollow Fibre Membrane (HFM) is cost effective, no figures have been published. However, it should be noted that the primary role of an OBIGGS is to provide inert gas for safety reasons and any positive effect on water contamination could be treated as a 'bonus feature', hence any penalties resulting from modification should not be fully borne from the water contamination aspect.

It is interesting to note that Boeing Dreamliner 787 has claimed to have significantly less maintenance requirements, including those related to water contamination, such as water drainage which is deemed to be labour intensive. From the author's assessment, the implementation of the OBIGGS system could play a part in Boeing overcoming and/or minimising the labour intensive water contamination related tasks.

Although the FAA's proposal for fuel tank inerting is only applied to the centre fuel tank (in 2007), Boeing 787 will be the first commercial aircraft to have all the fuel tanks inerted by the application of OBIGGS. This decision will incur approximately an additional 90 kilograms on the aircraft weight and consume about 40 kilowatts which results in a greater performance penalty compared to if the OBIGGS is only provided to the centre fuel tank.

The primary motivation factor for Boeing to provide OBIGGS for all the 787's fuel tanks is reported to be for safety reasons by reducing the flammability of the tank. It is also of great importance for an aircraft like the 787, with composite wing and fuselage, to be equipped with OBIGGS due to the much lower thermal conductivity that could result in any potentially flammable fuel vapour remaining in the tank for a longer period of time. However, there could also be other supporting factors that motivate Boeing to provide inert gas to all the fuel tanks.

One of the probable factors could be the essential need to remove water contaminants in the fuel tank, as any potential accidental ingress of moisture into composite materials could affect the structural stiffness significantly. Coupled with the advantages of reduced maintenance requirements related to water contamination, all these factors could justify the decision of Boeing to trade off the penalty of additional weight and power consumption. In addition, Boeing could also have built upon their experience of water contamination from large military aircraft with the OBIGGS system incorporated. This example illustrates the common trade off design consideration during the aircraft design and development phase. Hence, an in-depth study should be carried out to further analyse the impact of OBIGGS on water contamination.

Additional effort should be placed on examining the aspects of implementing the OBIGGS for all fuel tanks. Although the current FAA proposal only affects the wing centre fuel tank, and not all fuel tanks, this decision could partly be due to the pressure from airlines and aircraft manufacturers due to the additional cost, including from the resulting aircraft down time to be incurred.

However, the National Transportation Safety Board had commented that to provide inert gas to only the centre fuel tank is insufficient, and all fuel tanks should be supplied, as an important transportation safety improvement. Hence, the possibility of the FAA-required inerting of all fuel tanks is not impossible in the future, which may actually help to minimise the occurrence of water contamination and its adverse impact

4 Further Work

Following on from the research reported in this paper, three main areas of work are proposed to further improve the study and research behind this work on the topic of water management within fuel tanks, related to water contamination. The recommendations are also for the benefit of future investigations and activities to seek solutions to resolve the challenges posed by water contamination in aviation fuel. These recommendations are briefly described in the following sub-sections.

4.1 Fuel Additives

One of the promising potential methods analysed to be able to overcome the main causes of water contamination by the prevention of water separation from the fuel is with the usage of specifically developed fuel additives. Although potential candidates have been identified in this paper for further analysis, it is essential for the users to have a full understanding of the chemical working principles of the additives. Hence, further in-depth research and study focusing on the fuel-additive chemistry and interactions with relevant materials is to be included in future works for gaining a comprehensive understanding of the subject. Although such information may not be readily available, partnership or revealing intent of interest as a potential customer with the additive developers could be an approach in order to gain the essential information required.

4.2 Alternative Fuel

From the analysis carried out in this project, the approach to reduce the fuel cut-point range during fuel distillation in order to reduce the fuel's aromatic content and so to minimise the amount of water being dissolved in the fuel in the first place is deemed to be infeasible. However, with the development and evaluation of the alternative fuels recently, these newly explored and developed fuels may have a different impact due to water contamination and this is probably due to the different fuel composition as compared to current aviation fuel. Current focus on these alternative fuels is on their impact on the environment and to achieve sustainability. Monitoring of the impact of water contamination on alternative fuel, such as synthetic fuel, is advised for better awareness as the approach and method for seeking the solution to resolve water contamination may be need to be altered accordingly.

4.3 OBIGGS

Another potentially feasible solution to overcome, or at least minimise, the occurrence of water contamination is the implementation of OBIGGS, as discussed in this paper. Further detailed quantifications of the above advantages offered by OBIGGS are strongly recommended. Data collection and analysis of the relative humidity percentage in the ullage, amount of water accumulated and the variation of fuel temperature are recommended to be included in subsequent flight testing on the evaluation of the OBIGGS, to be conducted by FAA in conjunction with aircraft OEMs.

Comparison of flight data with and without OBIGGS on similar flight test profiles and conditions could then be carried out in order to perform a more in-depth quantification on the advantages offered by OBIGGS. Existing test data may be available, collected on the measured temperature of fuel by FAA on previous OBIGGS evaluation flight tests, conducted for further analysis and verification of the author's hypothesis that higher fuel temperature could be maintained in flight as the result of the temperature controlled supply of dry nitrogen gas delivered to the fuel tank.

The investigation results from the above recommended analysis could be used for future assessment to decide if it is justifiable to incorporate OBIGGS for all fuel tanks based on the impact on the performance and cost benefit analysis (from reduction of maintenance man hours and potentially corrective actions required due the problems resulting from water contamination).

The OBIGGS's Air Separation Module based on Hollow Fibre Membrane (HFM) technology could remove water vapour from the air. Hence, a feasibility study is also recommended for exploring modification to the aircraft vent system by incorporating the HFM Gas Separation unit at the vent valves to allow only dry air to be vented into the fuel tanks during aircraft descent, as a potential alternative to implementing the OBIGGS for all the fuel tanks.

One possible conceptual design could have a check valve incorporated (fail-safe design, with failed in open), and air in the ullage is allowed to pass through this valve to the atmosphere during refuelling or aircraft climbing. During defuelling or aircraft descent, the air will need to pass through the HFM unit to have its water vapour removed before entering into the ullage. Areas of assessment must include the considerations for meeting the FAR/EASA CS requirements (25.975 Fuel tank vents) when exploring the conceptual designs and implementation of the vent systems. There is also a need to assess if the differential pressure required during aircraft descent is sufficient to feed the pressurised air into the HFM in order to produce the dry, nitrogen rich air in the fuel tanks.

5 Conclusions

The fact that water is accumulated within the fuel tanks through two different mechanisms; by precipitation of dissolved water, and the condensation of moist air, there is unlikely to be one solution that could resolve both the causes fully at the same time. However, based on the investigation and analysis carried out by the authors, both the usage of specifically developed fuel additives for the prevention of water separation from fuel and the application of OBIGGS seemed to offer potentially feasible solutions to overcome problems of water contamination in the near future. Last but not least, even with the implementation of fuel additives and OBIGGS, a monitoring system to check for excessive water contamination will still be required to serve as a warning indicator in case of maintenance human error or systems failure.

This approach and methods to enable the reduction of the current labour-intensive maintenance requirements were assessed. The maintenance results from the regular processes of monitoring, detection (involving fuel sampling checks) and removal of water contamination (such as the daily recommended water draining from sumps). When the occurrence of water contamination is reduced or eliminated, the maintenance burden due to the corrective tasks such as the repair of structural damage due to corrosion, removal of micro-organisms due to the presence of water, frequent replacement of faulty equipment such as malfunctioned fuel indication systems and fuel filter, is expected to be significantly reduced.

The main initial objective of this research was to explore potential methods to overcome the water accumulation within fuel tanks that enables the reduction or elimination of the related maintenance requirements. This goal has been met as potential feasible solutions have been identified and, with their feasibility and challenges for their application analysed, recommendations have then been provided for further work.

References

1. Vihelmo Velapatino, *The Water Contamination in Fuel Aviation and their Solution - Contamination and Cleanup*. 2007, http://www.monografias.com/trabajos44/the-water-contamination/the-water-contamination.shtml.
2. J.D. Rogers, J.A. Krynitsky, and A.V. Churchill, *Jet Fuel Contamination: Water, Surfactants, Dirt and Microbes.* SAE Transactions 1963. **71**: p. 281-292.
3. Howard L.Chesneau, *Fuel System Contaminants: An Introduction*, in *Distillate Fuel Contamination, Storage, and Handling*, Chesneau and Dorris, Editors. 1998, ASTM: Philadelphia. p. 1-5.
4. A.V. Oreshenkov, *Accumulation of Water in Jet Fuels - Mathematical Modeling of the Process.* Chemistry and Technology of Fuels and Oils, 2004. **40**(5): p. 320-325.
5. US Federal Aviation Administration (FAA), *Water In Aviation Fuels* Advisory Circular No. 20-125, 12 October 1985.
6. U.S. Department of Transportation - Coast Guard, *USCG Aviation Fuel Handling Procedures Manual COMDTINST M13001.1*. June 2000.
7. C.Lawson, *Aviation Fuels and Aircraft Fuel Systems - AVD 0502/1 (Airframe Systems Lecture Notes)*. 2006/07, School of Engineering, Cranfield University.
8. Greg Hemighaus, et al., *Aviation Fuels Technical Review*. 2006, Chevron.
9. International Air Transport Association (IATA), *Guidance Material on Microbiological Contamination in Aircraft Fuel Tanks*. 2nd Edition, 1 February 2005.
10. Coordinating Reseach Council, *Handbook of Aviation Fuel Properties (CRC Report No. 635)*. 2004 3rd Edition, SAE.
11. Steven T.Swift, *Identification and Control of Microbial Growth in Fuel*

Handling Systems, in *Distillate Fuel Contamination, Storage, and Handling*, Chesneau and Dorris, Editors. 1988, ASTM: Philadelphia. p. 15-26.

12. Christopher McGregor, *Fuel Contamination - Prevention and Maintenance Actions*. Airbus FAST Magazine, July 2006(38): p. 26-31.
13. L.C. Quigg (Lockheed Corporation). *Handling Problems Associated with Jet Aircraft Fuels*. in *33rd Annual International Air Safety Seminar - The Safe and Efficient Management of Energy*. 15-18 September 1980. Christchurch, New Zealand.
14. Harold W.Graef, *An Analysis of Microbial Contamination in Military Aviation Fuel Systems*, in *Air Force Institute of Technology*. March 2003, USAF Air University: Ohio.
15. Z.D. Liang, *Corrosion of Aluminum Alloy in Aircraft Fuel Tank Compartments Due to Condensed Water*. The Journal of Science and Engineering - Corrosion, June 1992. **48**(6): p. 514-517.
16. E.M. Goodger, *Hydrocarbon Fuels - Production, Properties and Performance of Liquids and Gases*. 1975, London: Macmillan Press Ltd.
17. Mike Gamauf, *What's That Ick In Your Tank?*, in *Business & Commerical Aviation*. November 2004.
18. J.A. Scott, *Microbiological Contamination of Aircraft Fuel Tanks - Airframe Consideraions*, in *National Air Transportation Meeting*. 1971, SAE: Atlanta, Georgia, USA.
19. Christine C. Gaylarde, Fatima M. Bento, and Joan Kelley, *Microbial Contamination of Stored Hydrocarbon Fuels and its Control - Mini Review*. Revista de Microbiological 4 Feburary 1999. **30:01-10**.
20. International Air Transport Association, *Guidance Material for Aviation Turbine Fuels Specifications*. 5th Edition, 1 January 2004.
21. ExxonMobil Aviation International Limited, *Aviation Fuelling Guide*. 2003.
22. *Certification Specifications for Large Aeroplanes, CS-25, Amendment 2*, European Aviation Safety Agency, Editor. 2 October 2006.
23. Air Transport Association of America, *Specification 103 - Standards for Jet Fuel Quality Control at Airports (Revised)* 2004.
24. Joint Inspection Group, *Guidelines for Aviation Fuel Quality Control & Operating Procedures for Jointly Operated Supply & Distribution Facilities (Issue 9)*. January 2004.
25. Terry Ford, *The Boeing 777 Fuel System*. Aircraft Engineering and Aerospace Technology, 1998. **70**(3): p. 199-202.
26. Association of European Airlines (AEA), *Summary Report - Operating Economy of AEA Airlines 2006*. December 2006.
27. Paul Clark, *Buying the Big Jets: fleet planning for airlines* 2001, Aldershot, England: Ashgate Publishing Ltd.
28. Lim Kok Meng, *Water Management within Fuel Tanks*, in *School of Engineering*. 2007, Cranfield University.
29. V.I. Primenko and O.E. Poboiskii, *Influence of Dissolved Water on Static Electrication of Jet Fuel*. Chemistry and Technology of Fuels and Oils, January 1976. **12**(1): p. 33-34.
30. FAA Aviation Rulemaking Advisory Committee (ARAC), *Report to the Fuel Tank Harmonization Working Group of the FAA ARAC on Fuel Properties - Effect on Aircraft and Infrastructure (Task Group 6/7)*. 1998, ARAC.
31. D. Daggett, et al., *Alternative Fuels and Their Potential Impact on Aviation (NASA/TM - 2006-214365)*. October 2006, National Aeronautics and Space Administration: Glenn Research Centre, Ohio, USA.
32. The National Non-Food Crops Centre, *Position Paper : The Potential for Renewable Aviation Fuels*. February 2007.
33. Charles E.Taylor, et al., *Clean Fuels - Fischer-Tropsch Fuels (R&D Facts)*,

U.S. Department of Energy - Office of Fossil Energy - National Energy Technology Laboratory, Editor. April 2007.
34. PROACT, *Petroleum Fuels: Basic Composition and Properties*. August 2005, The Air Force Center for Engineering and the Environment. www.afcee.brooks.af.mil/pro-act: Brooks City-Base, Texas.
35. A.M. Danilov, *Fuel Additives - Development and Use in 2001-2005.* Chemistry and Technology of Fuels and Oils, 2007. **43**(2): p. 155-171.
36. V.N. Zrelov, et al., *Additives for the Prevention of Water Separation from Jet Fuels during Storage.* Chemistry and Technology of Fuels and Oils, September 1996. **31**(5): p. 230-233.
37. Jeremy D. Peter-Hoblyn, Barry N.Sprague, and James M.Valentine, *Platinum Metal Fuel Additive for Water-Containing Fuels*, in *United States Patent 5693106*. December 1997, Platinum Plus, Inc.
38. E.C. Hill, *The Control of Micro-organisms in Aircraft Fuel Systems.* Journal of The Institute of Petroleum, May 1970. **56**(594): p. 138-146.
39. ASTM International, *Work Item - WK4279 Revision of D4054-93 (2003) - Standard Practice for Evaluating the Compatibility of Additives with Aviation-Turbine Fuels and Aircraft Fuel System Material*. 2 May 2004 (Initiated).
40. ASTM International, *D4054-93 (2003) - Standard Practice for Evaluating the Compatibility of Additives with Aviation-Turbine Fuels and Aircraft Fuel System Materials*. 2003.
41. Michael Burns, et al., *Evaluation of Fuel Tank Flammability and the FAA Inerting System on the NASA 747 SCA - DOT/FAA/AR-04/41*. December 2004, US Department of Transportation, FAA: Virginia, US.
42. Michael Burns and William M. Cavage, *Inerting of A Vented Aircraft Fuel Tank Test Article with Nitrogen-Enriched Air - DOT/FAA/AR-01/6*. April 2001, US Department of Transportation, FAA: Virginia, US.
43. Michael Burns, et al., *Flight-Testing of then FAA Onboard Inert Gas Generation System on an Airbus A320 - DOT/FAA/AR-03/58*. June 2004, US Department of Transportation, FAA: Virginia, US.

Copyright Statement

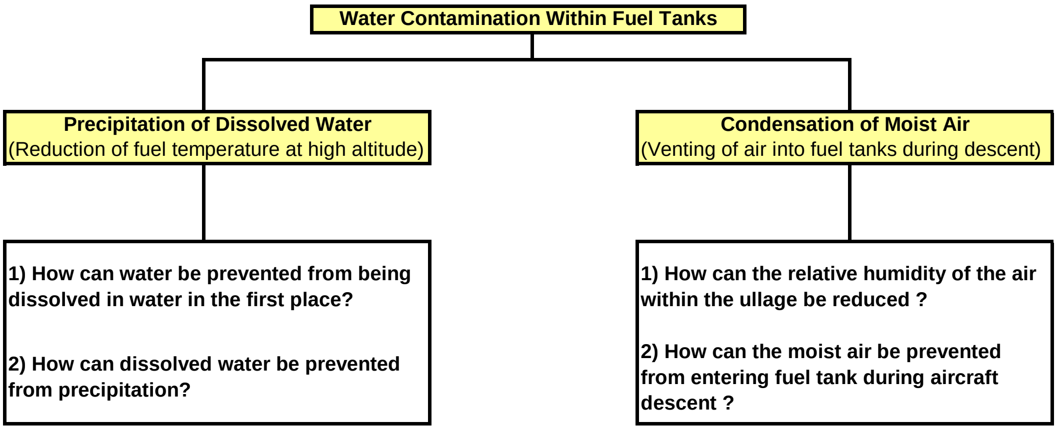

Fig 1. Approach on Identification of Potential Solutions

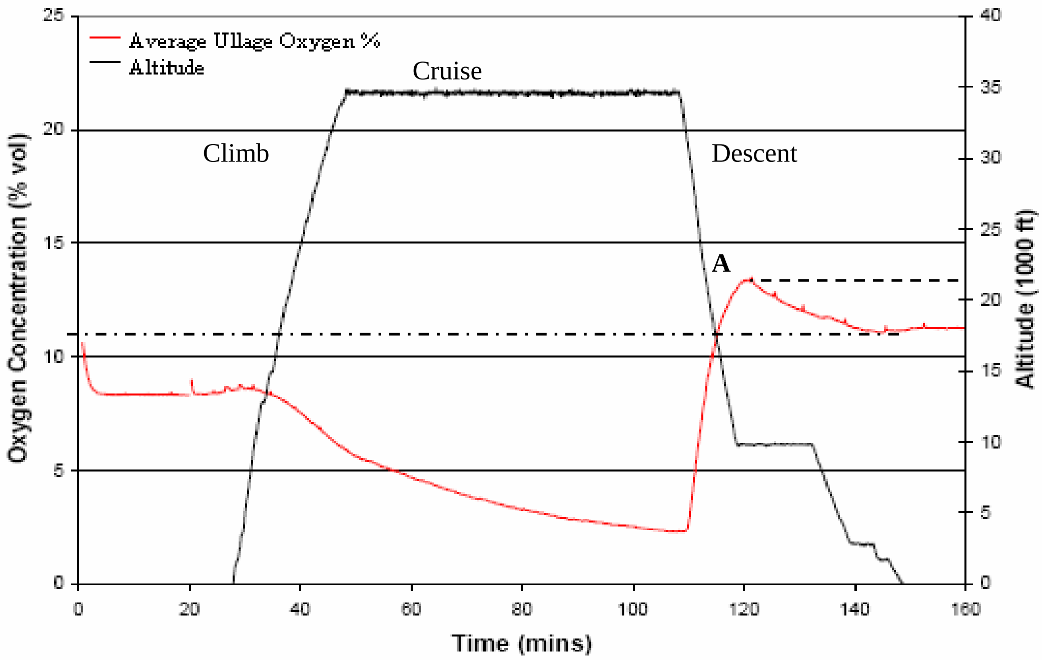

Fig. 2 Average Ullage Oxygen Concentration during a Flight Cycle (Reference [41])