AIRCRAFT FUEL SYSTEMS AND THEIR INFLUENCE ON STABILITY MARGIN

Zdobysław GORAJ
Institute of Aviation
Paweł ZAKRZEWSKI
Institute of Aviation

This paper reviews modern fuel tank systems, mainly adopted either for combat or passenger airplanes. Two important issues are addressed in the paper – an influence of fuel tanks location on the airplane trimming and longitudinal stability. It is shown that moving the fuel towards the wing tips results in a decrease of stability margin (if wings are swept back) or in an increase of stability margin (if wings are swept forward). Changing the CG position also influences on trim condition and can change elevator deflection and the overall efficiency. Examples of solutions applied for real aircraft are included into analysis. An example of fuel tanks arrangement proposed for PW-114 HALE UAV configuration, is shown and discussed.

INTRODUCTION

Fuel system is one of the main aircraft systems. Fuel system storages and delivers fuel to the engines at any conditions airplane was designed. During the century of flying, systems concepts matured, becomes more sophisticated, and his functions expanded. Now fuel systems are used not only for delivering the fuel to the engines. These systems may be used to move fuel around the aircraft to keep the center of gravity within acceptable limits, to maintain pitch and lateral balance and stability. With increasing aircraft speed, the center of lift moves aft, and its trimming using elevator or trimmer increases drag. To avoid this, the center of gravity can be shifted by pumping fuel from forward to aft tanks. Fuel tanks are sometimes placed in the wing and in such a case they can be also used to minimize the wing spanwise load distribution during flight. It can be actively controlled due to optimal order of tank's empting.

1. REVIEW OF THE SYSTEMS IN USE

In the early days of aviation the supply of fuel was simple. It was a gravity tank above the engine on the upper wing. When the low wing monoplane arrived there was no alternative but to fit engine driven pumps. During the Second World War, larger engines with greater fuel demands led to the use of electric pumps in the tanks to provide an artificial head at the engine pump. With the arriving of jet engine the use of immersed in tanks electric pumps was retained. Construction, destiny and type of airplane determines what type of fuel system is applied.

- Gravity fuel system. Gravity systems rely on the force of gravity to deliver fuel from the tank to the carburetor, which limits them to high wing light airplane applications (Fig. 1). Such type of system, is very simple, relatively inexpensive and does not require the pump or only one pump may be required. The most significant disadvantage to the gravity system is possibility of vapor lock. The fuel lines, filled with vapor, are unable to supply sufficient fuel

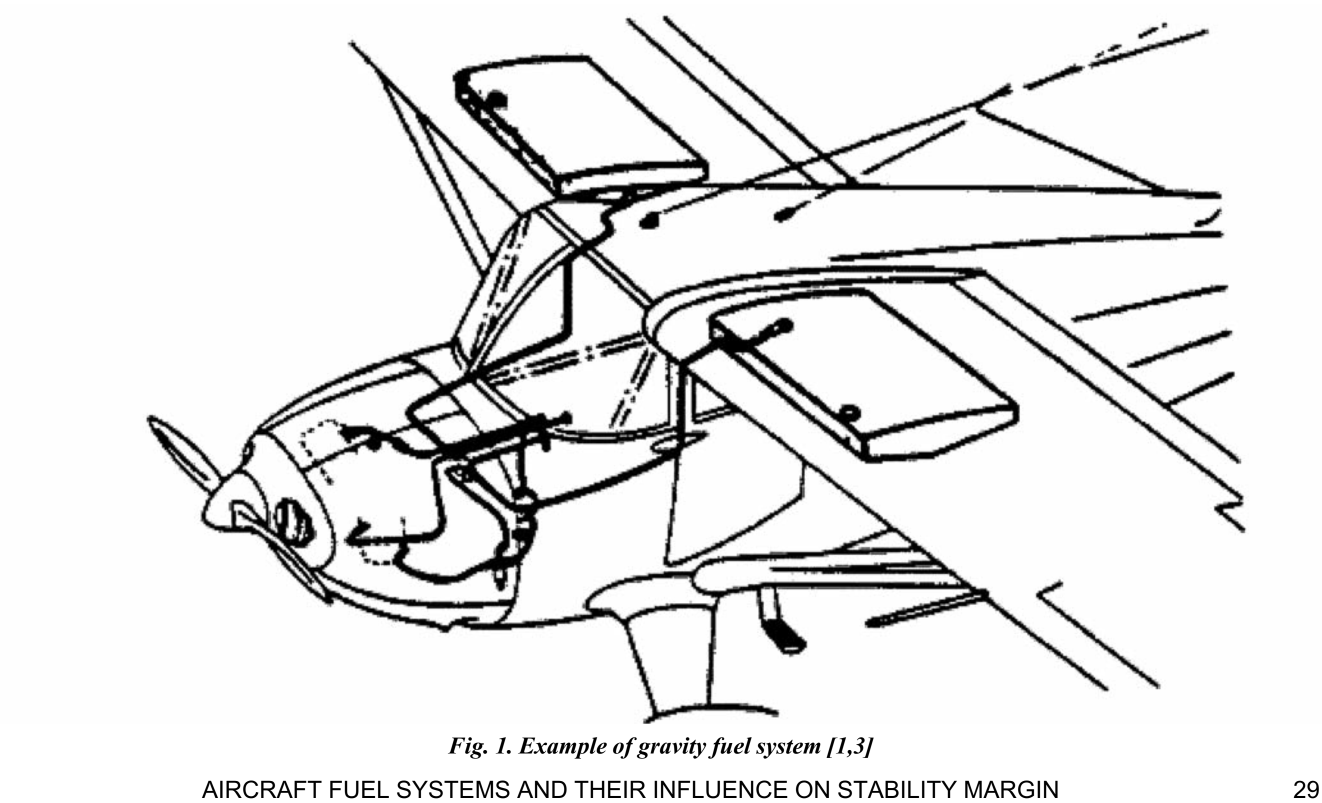

Fig. 1. Example of gravity fuel system [1,3]

to the engine. Vapor lock is caused by excessive fuel temperature, or high altitude operations. Fuel vaporization is the result of shutting down an engine on a hot day. High altitude operation also may induce vaporization at a lower temperature. The solution to the problem of vaporization is to provide positive pressure with a fuel pump.

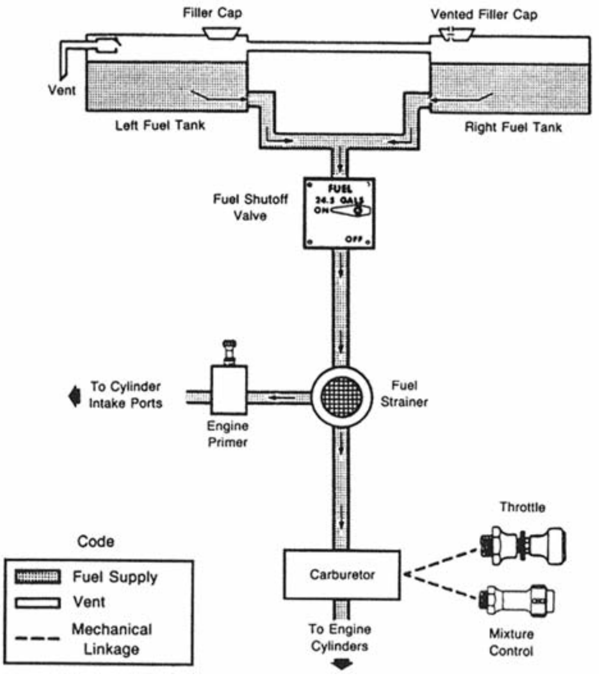

Fig. 2. Cessna 152 gravity fuel system [6]

- Pressure fuel system. In this type of system at least two fuel pumps are required. System may be applied in low wing airplane (Fig. 3). In the pressure system, the engine driven pump delivers fuel from tanks located anywhere in the airplane to the carburetor. This permits greater flexibility in tank utilization and minimizes vapor lock potential. Twin engine aircraft has a more complex fuel system (Fig. 4, 5).
- Fuel system for maneuverable aircraft designed for inverted gravity operations. Tank on Fig. 4 has inner tank which is equipped with flapper valves which trap fuel around the pump during inverted flight.

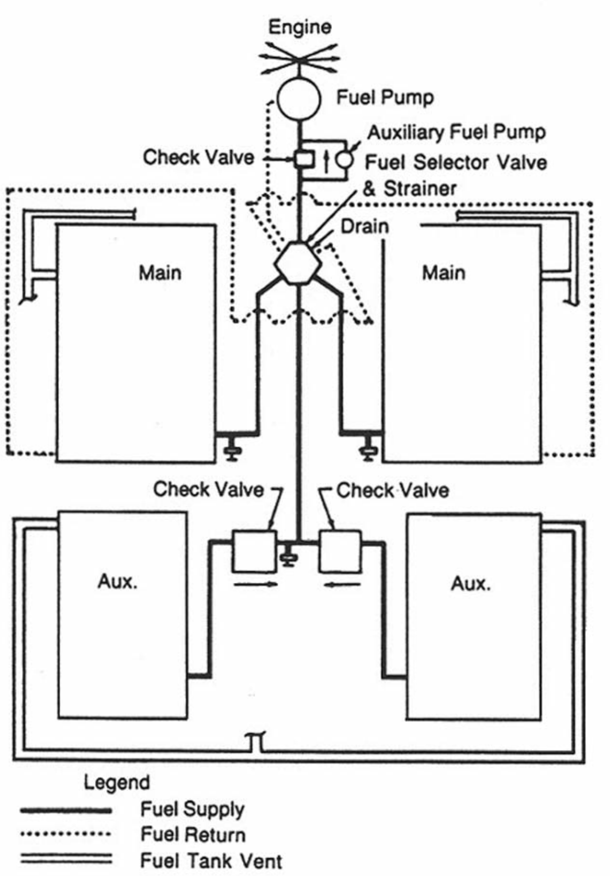

Fig. 4. Beech Bonanza K35 fuel systems [6, 7]

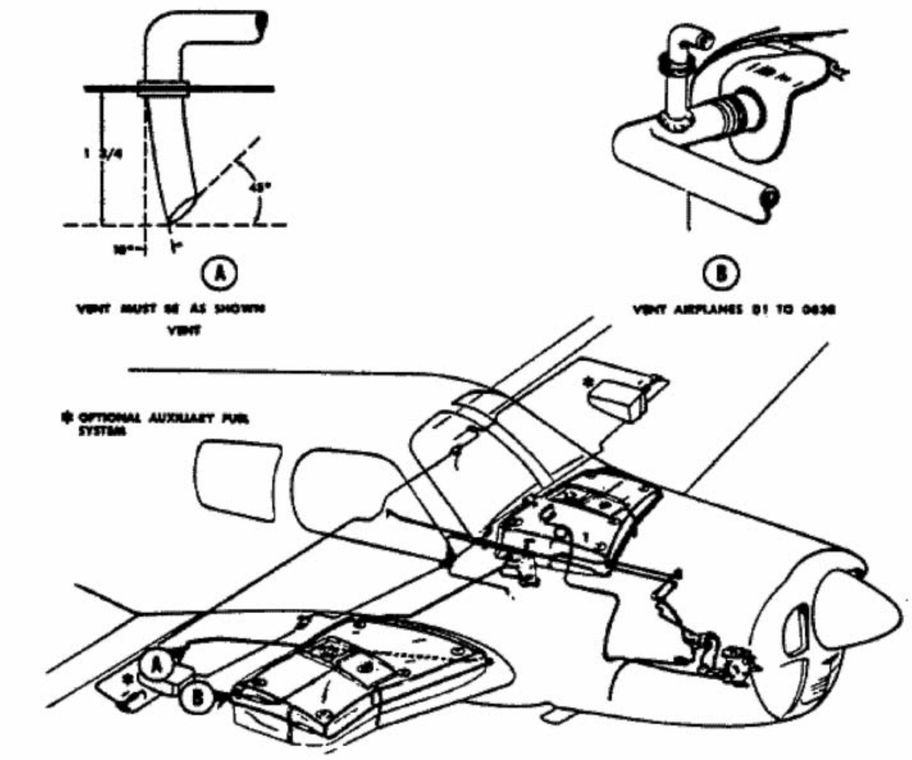

Fig. 3. Fuel system for low wing aircraft [1]

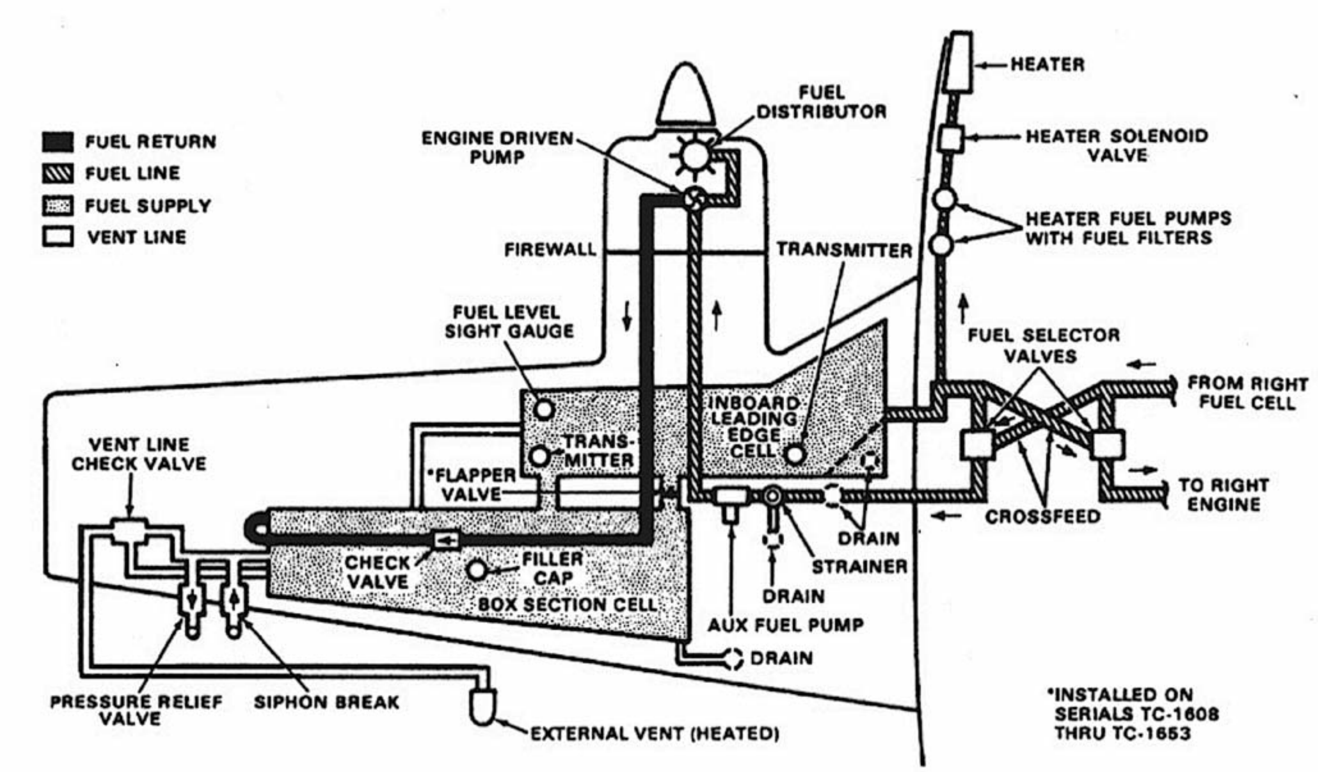

Fig. 5. Beech Baron B55 fuel system [6]

2. FUEL TANKS

Fuel tanks have all shapes and locations. All tanks must be protected from vibration, principle cause of deterioration and leakage, and must be able to handle fuel expansion as a results of heat. Most fuel tanks are made of either pre shaped, riveted aluminum alloy or synthetic rubber. The aluminum wet-wing tanks use a sealant along their seams to prevent leakage.

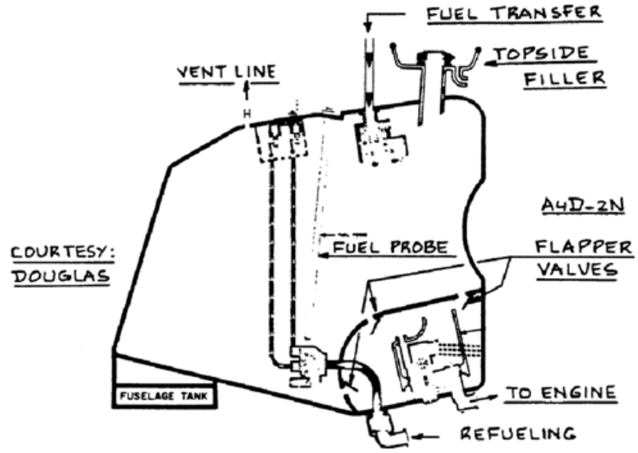

Fig. 6. Fighter fuselage tank [1,10]

Bladder tanks are made by stuffing a shaped rubber bag into a cavity in the structure. The rubber bag is thick, causing the loss of about 10% of the available fuel volume. Bladders are widely used because they can be made „self-sealing". This offers a major improvement in aircraft survivability. Flexible bladder fuel cells were used widely in the 1950s and are still used as fuselage tanks. Their advantages are ease of installation through access doors, ease of repair by turning the tanks inside out, self sealing for small caliber weapons, crash and vibration resistance. High cost and additional weight are their major disadvantages. The shapes of wing tanks are fairly simple, fuselage tanks (Fig. 6) are complex. They and their systems have to compete fiercely with other components for the limited volume within the fuselage profile.

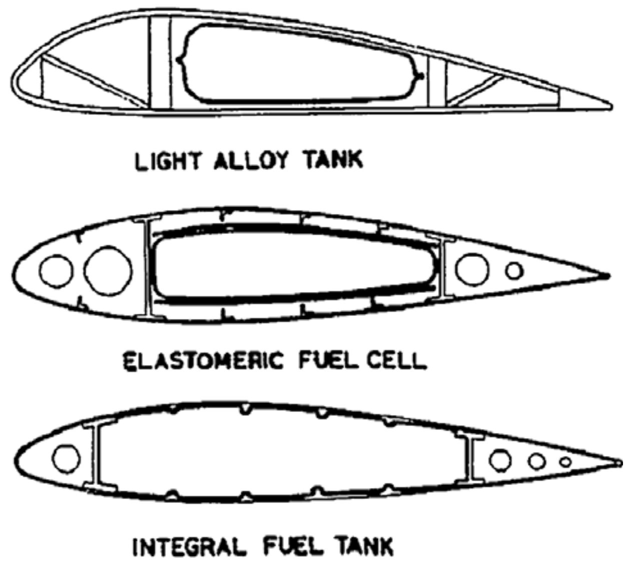

Fig. 7. Fuel tanks types [7]

Integral tanks are cavities within the airframe structure that are sealed to form a fuel tank, Fig. 7. Ideally, an integral tank would be created simply by sealing existing structures such as wing boxes. Integral wing tanks had gone in use when aircraft structures had become more stiff due to requirements of higher flight performance in 1950s. The use of carbon-fibre composites has provided complex shaped integral fuselage tanks with the advantage of increasing fuel capacity by 10 to 15%. Evolution of fuel tanks in fighters is shown on Fig. 9 on example of Mystere B2 (flexible tanks), Mirage IIIE (integral wing tanks, flexible tanks in fuselage) and Mirage 2000 (integral tanks).

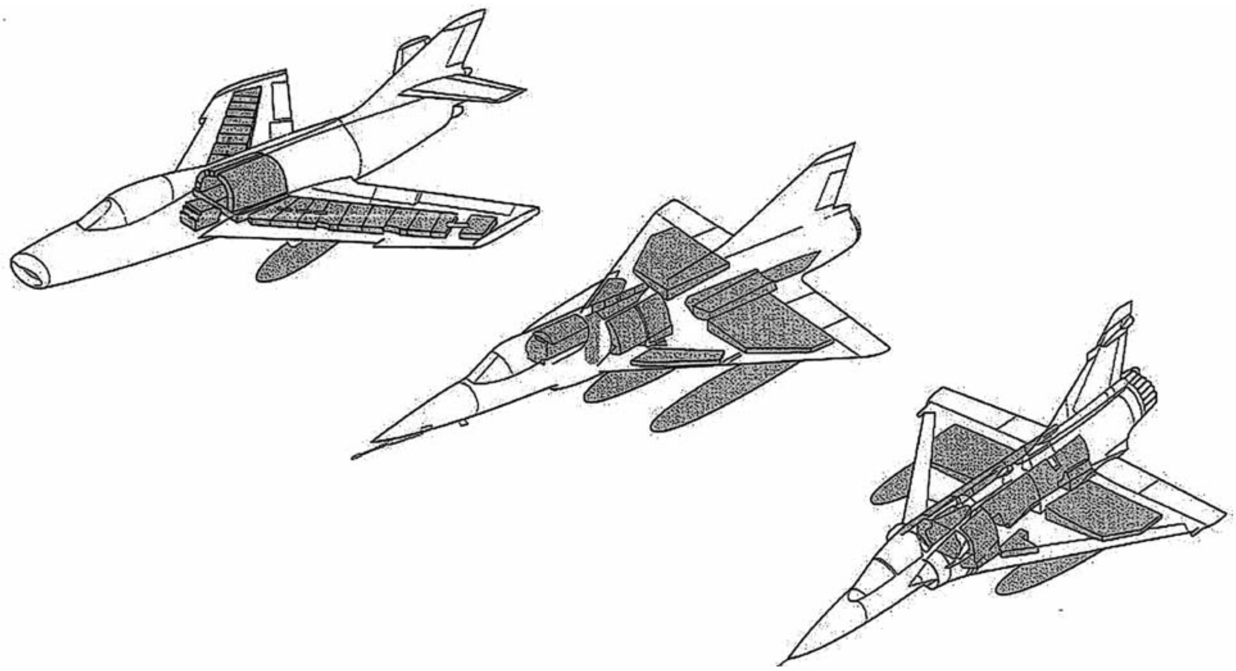

Fig. 8. Evolution of typical fuel tank layouts in military aircraft. [10]

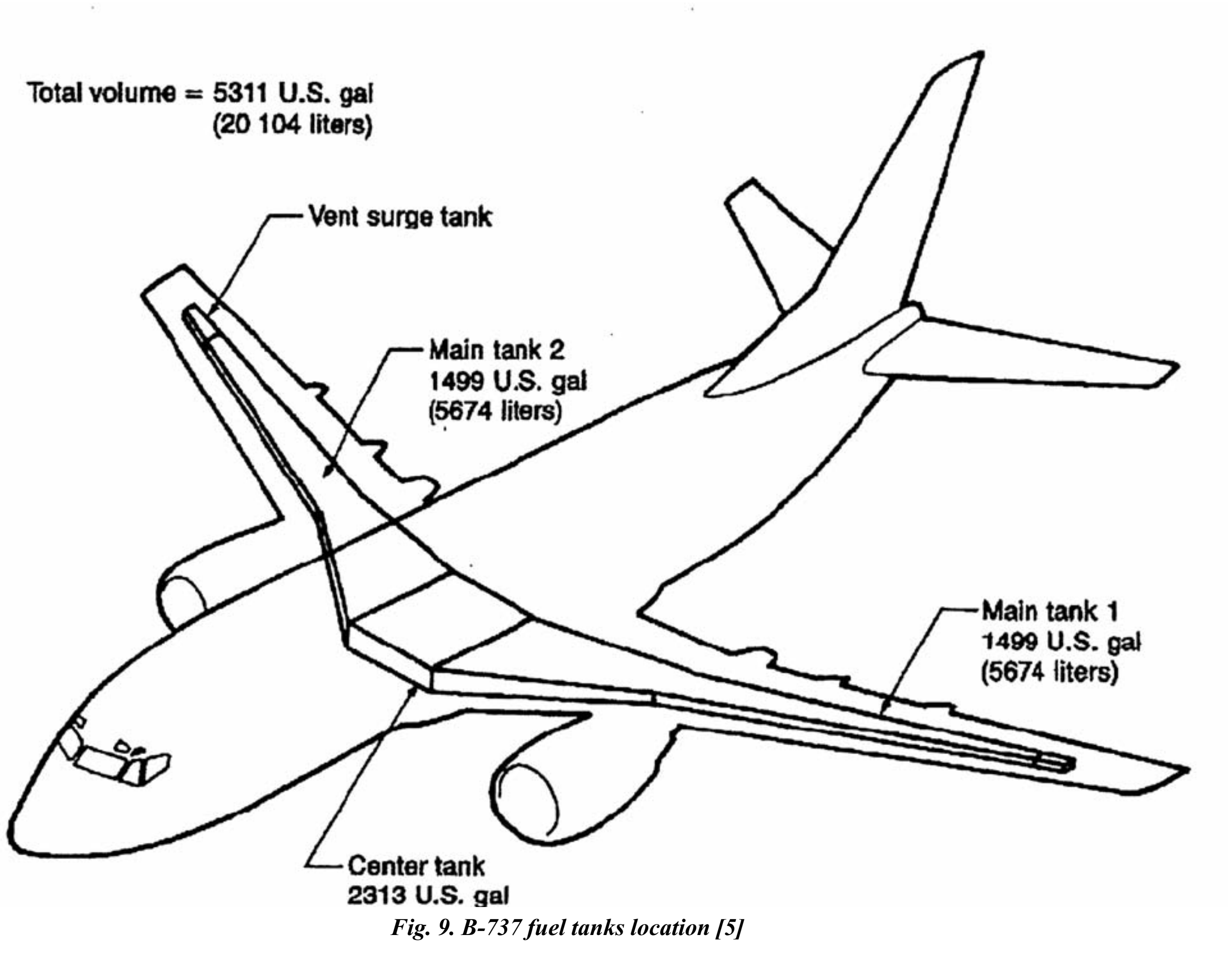

Fig. 9. B-737 fuel tanks location [5]

In transport airplanes surge tanks are installed to collect and condense any excess fuel vapor before it exits through the overboard fuel vents.

3. EXAMPLES OF FUEL SYSTEMS SOLUTIONS

Boeing 737

B-737 fuel system (Fig. 9) includes 3 tanks, boost pumps, flapper valves, shutoff valves, fuel lines and another elements needed to storage, capacity indication and fuel transfer.

Fuel tanks

There are three fuel tanks, one center tank in center wing, and two in the wings structure between forward and rear spar (Fig. 10). All wing tanks are of integral type fuel tanks. There is a vent surge tank in the wing tip.

When all tanks are full, both engines are fed from the center tank. When center tank is empty, engine 1 and APU are fed from main tank 1 and engine 2 is fed from main tank 2. There is emergency cross feed valve to feed all engines from all tanks (Fig. 11).

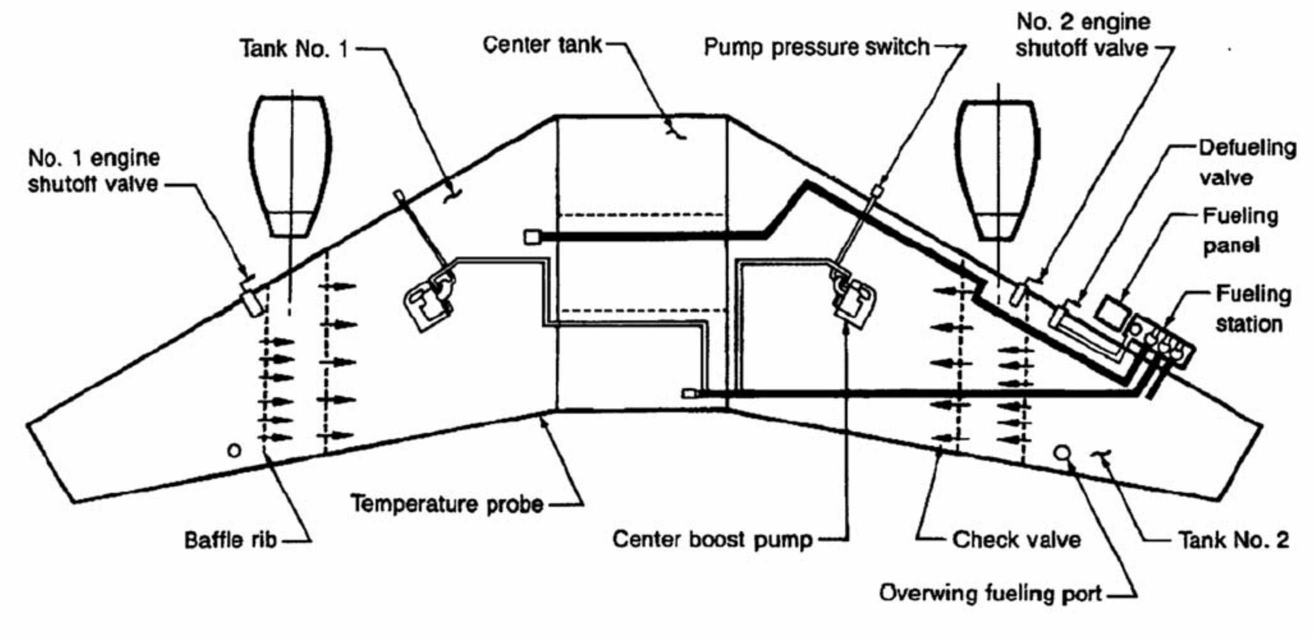

Fig. 10. B-737 fuel system [5]

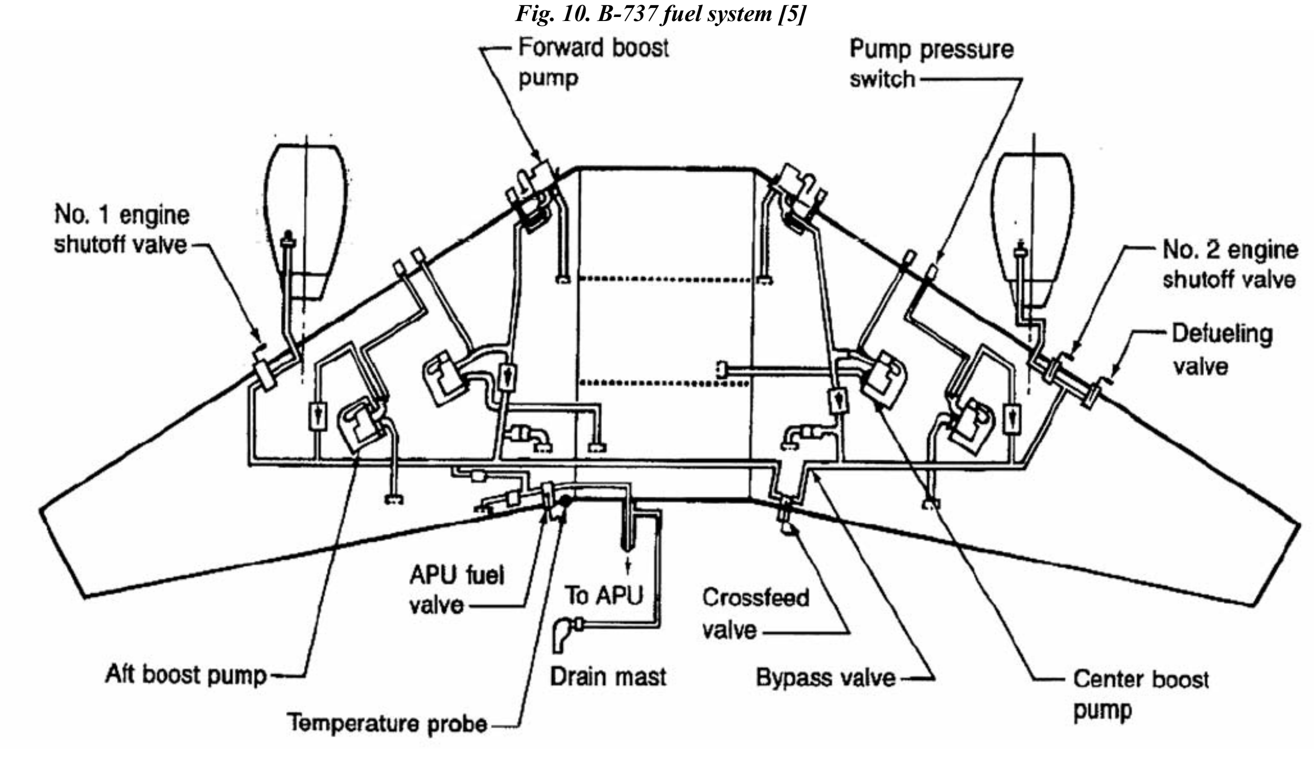

Fig. 11. Engine and APU fuel feed system [5]

Boeing 767

Boeing 767 has 3 fuel tanks, and complex fuel pumps, valves and venting system (Fig. 12). Vent lines are equipped with flame arrestors (Fig. 15). In B-767 advanced fuel indication system is applied. Like other airplanes there are dry bays behind the engines.

Fuel tanks

B-767 fuel tanks are integral wing tanks. Center auxiliary fuel tank is located in central part of the wing, near fuselage. Center wing is dry (Fig. 13).

Engines are fed from corresponding tanks, but there is possibility to feed any engine from any tank. Engine fuel feed system is shown on Fig. 14. There is dual element main boost pump. Each element of the boost pump can provide maximum fuel flow to engine. Each element is driven by different electrical system. Override pump insures center auxiliary tank is pumped first. Fuel may be pumped by APU drive pump for starting. Imbalance condition can be relieved by control boost pumps and crossfeed valve.

B767 is equipped with surge tanks in the wing tips. These surge tanks are not normally filled with fuel. The overfill sensor installed in the surge tanks prevents overfilling and overpressuring of the fuel tanks.

Embraer EMB-145

The fuel system of the EMB-145 consists of two tanks, electric fuel pumps, shutoff and check valves, and transfer ejector pumps. The system was developed to assure sufficient fuel supply to the engines and APU under all operating conditions, while minimizing the unusable fuel.

Fuel tanks

The Embraer 145 has two integral type fuel tanks

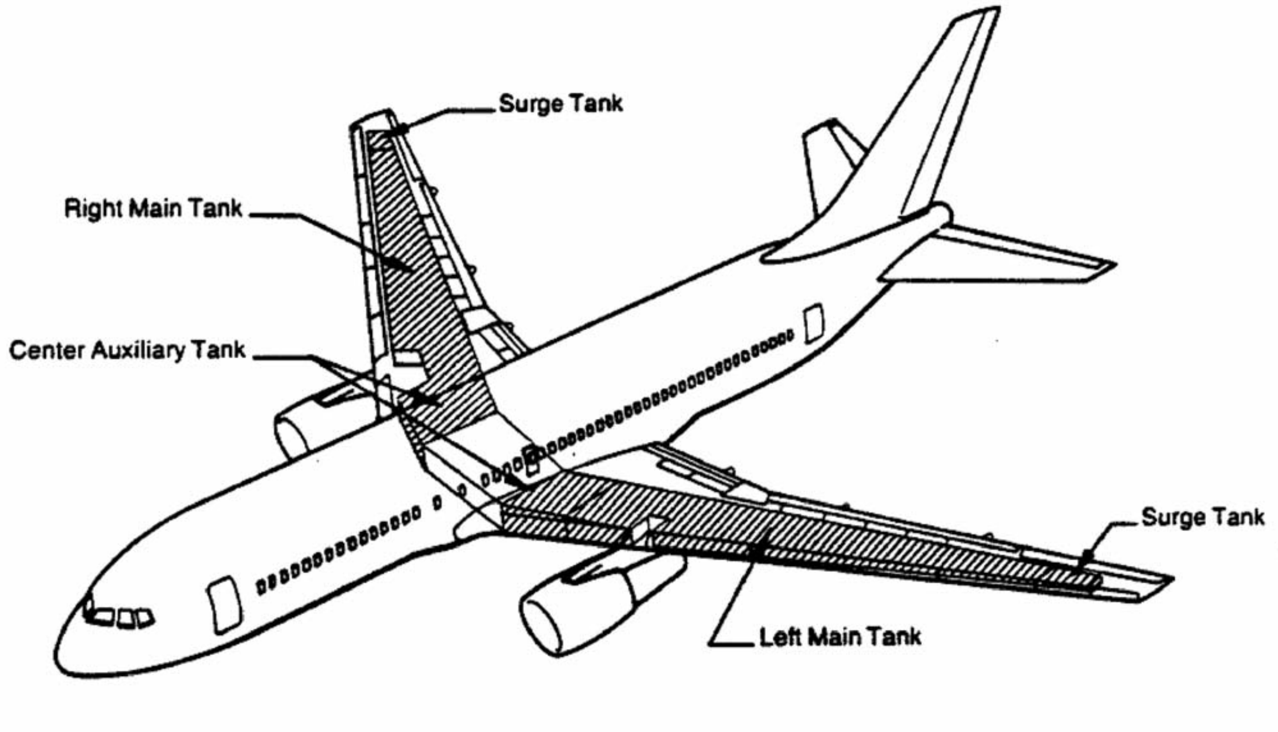

Fig. 12. Tanks location in Boeing 767 [1]

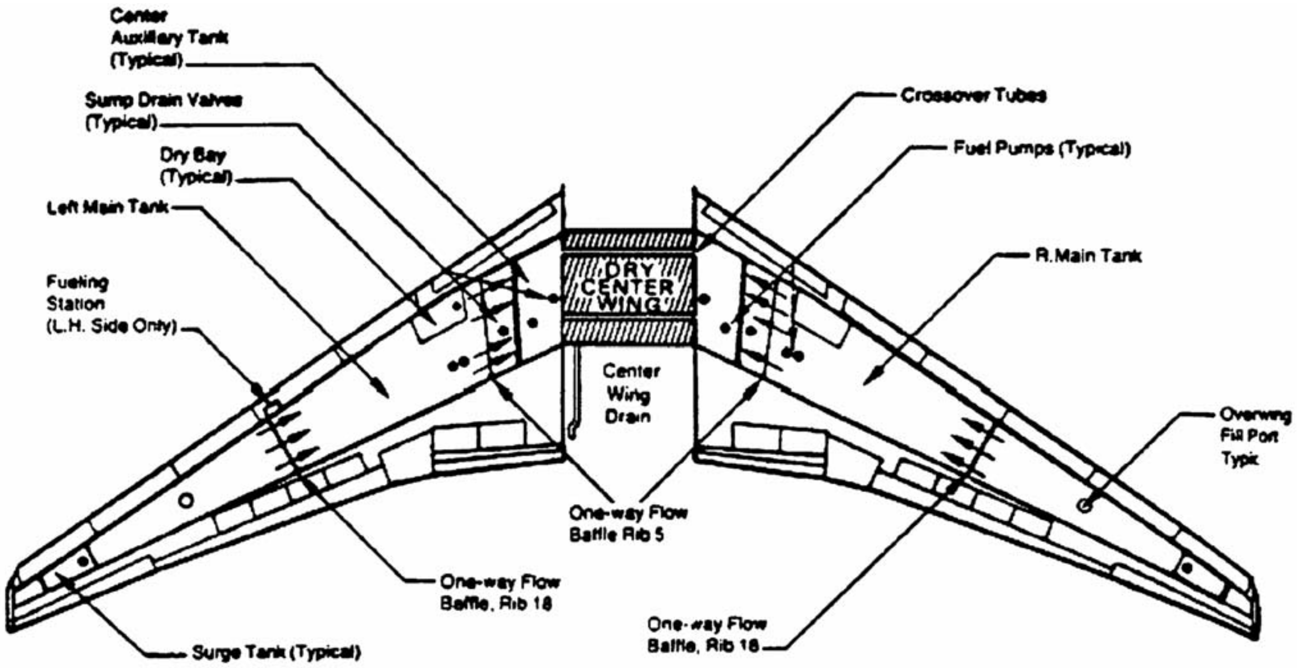

Fig. 13. B-767 Fuel system schematic [1]

(Fig. 16). These tanks have a capacity of 4600 lbs (2800 kg). Partial closure of a wing rib in each restricts fuel movement within the tank.

Flap valves installed on this rib prevent fuel flow from wing root to wing tip at the lower tank surface during maneuvers. Passages at the upper tank surface are kept open.

The wing fuel tanks contain a NACA air intake on the lower wing surface, a surge vent tank in the wing tip, and a collector box at the wing root. The NACA air intake equalizes pressure between the vent tank and the atmosphere to prevent wing structural damage. The surge vent tank collects fuel during wing down maneuvers, and after the end of the maneuver, returns it to the main fuel tank. Float valves connect the vent tank with the main tank (Fig. 17).

Fuel distribution

The fuel distribution subsystem (Fig. 18) consists of the following systems:

- engine feed.
- APU feed.
- fueling/defueling.

Engine feed system

The engine fuel feed system performs following functions:

- engine fuel supply during start and all operational phases,
- fuel transfer to the collector boxes,
- Tank pressure control,
- Engine crossfeed,
- Isolate fuel flow in case of engine feed line leakage,
- Isolate fuel flow in case of engine fire.

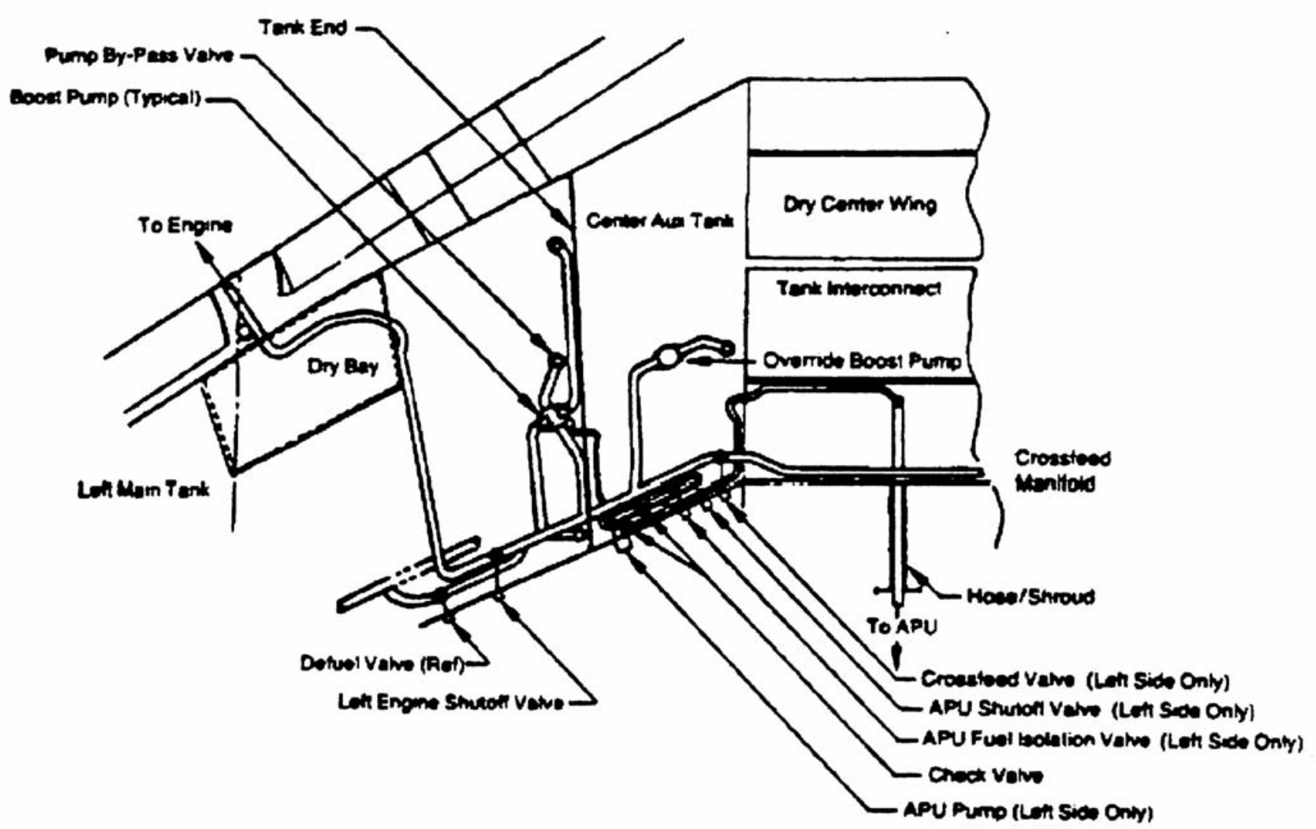

Fig. 14. B-767 Engine fuel feed system [1]

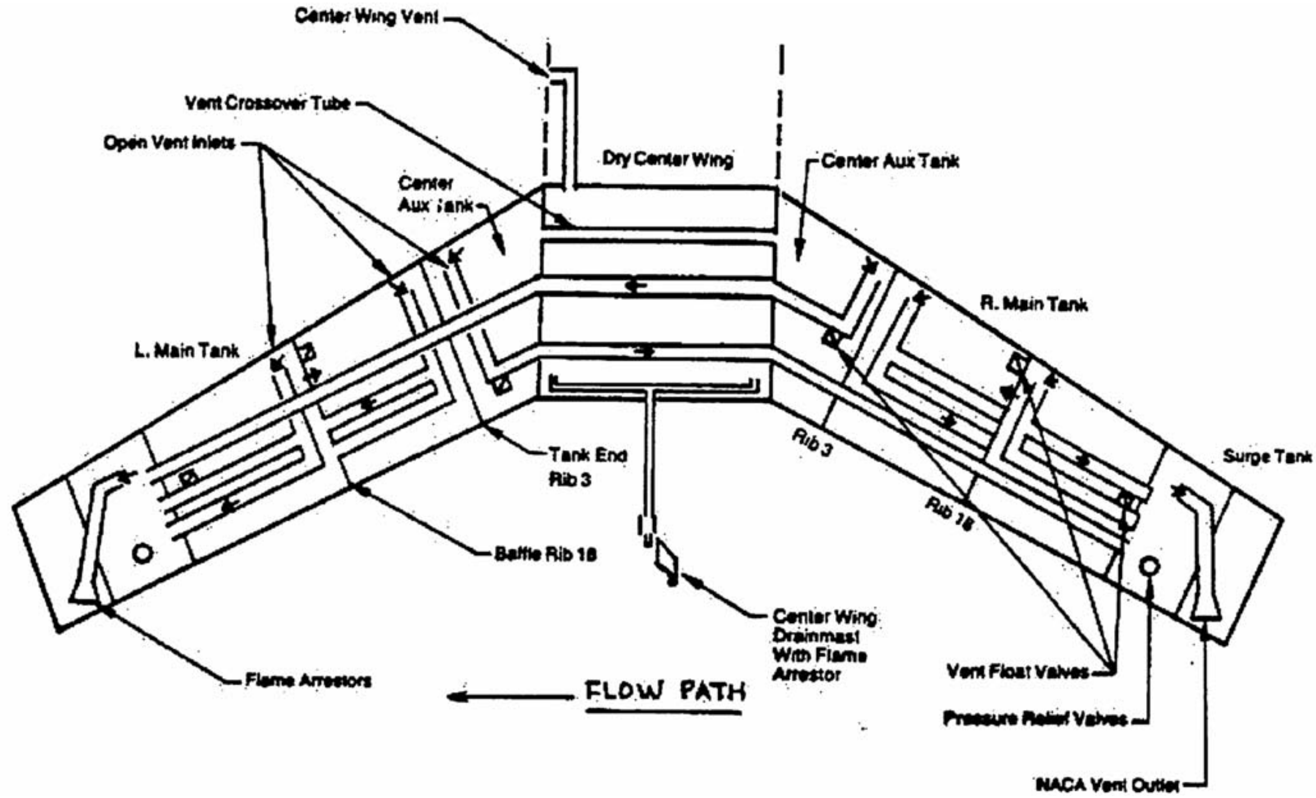

Fig. 15. B-767 Fuel tank vent system [1]

The engine fuel feed system controls the fuel to the engines during all operating conditions within pressure limit requirements of the engine manufacturer. Each engine has dedicated components, plus interfacing components for engine crossfeed.

4. FUEL LOCATION EFFECT ON CENTER OF GRAVITY

Location of the fuel tanks effects on the position of the center of gravity location of the airplane. It’s important to correctly estimate effect of fuel weight on center gravity location also during flight when fuel is partially burned. Fuel volume plot shown on Fig. 19 allows the estimation of the center of gravity for each tank.

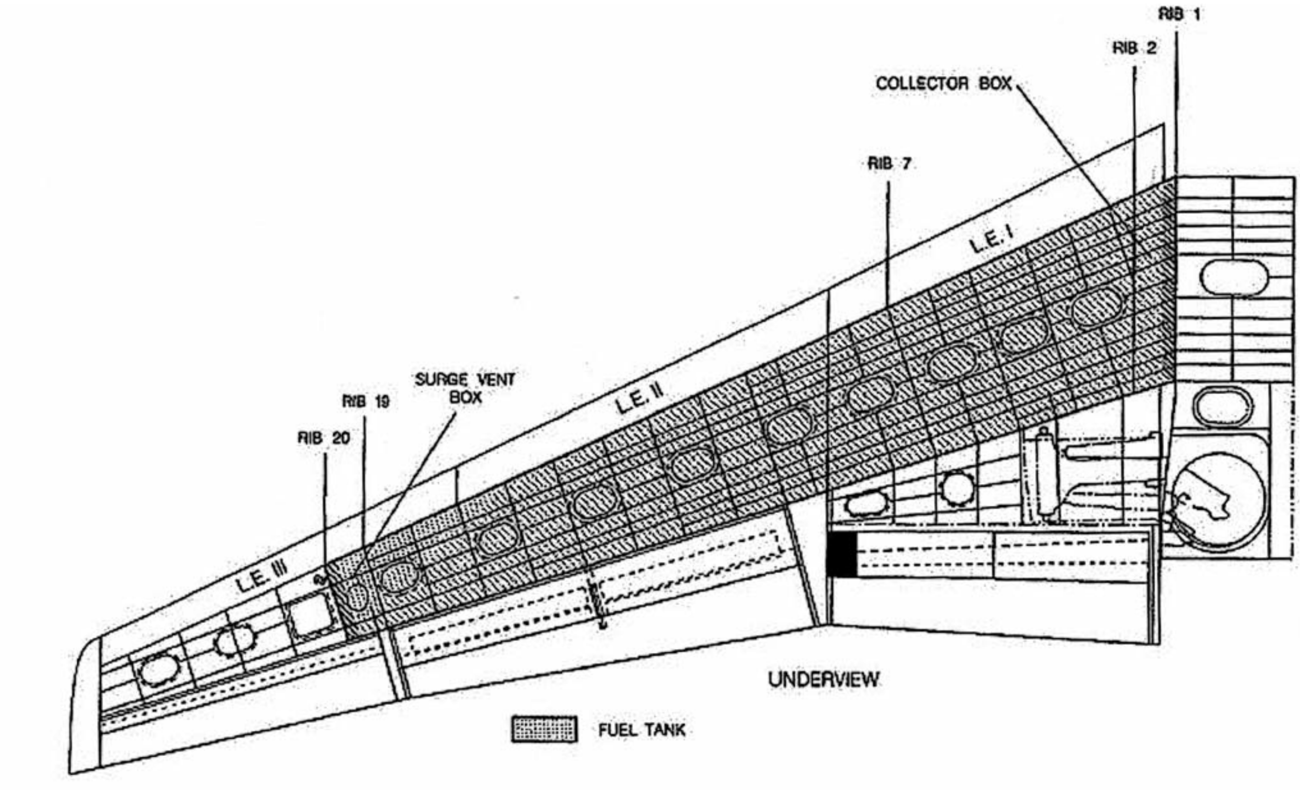

Fig. 16. E-145 Fuel tank

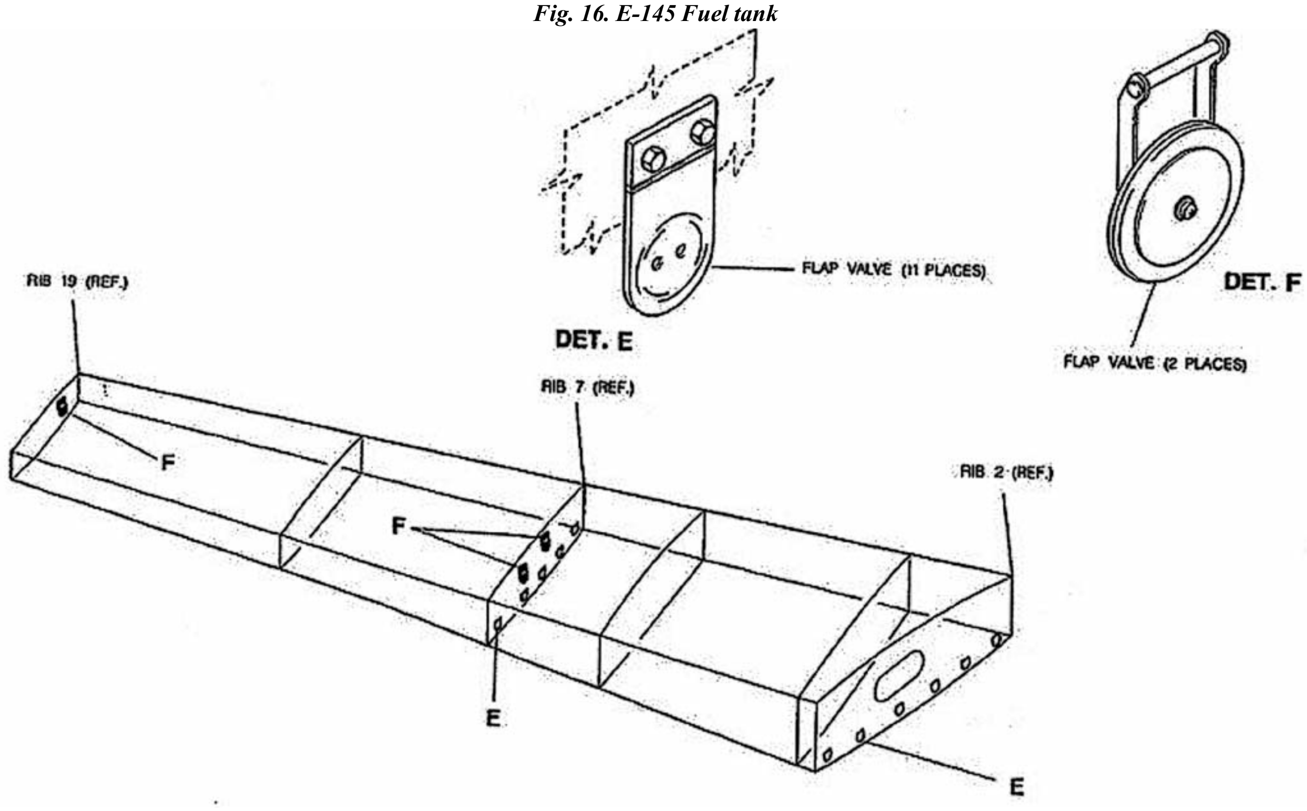

Fig. 17. EMB-145 Fuel tank components

Center of Gravity and Fuel Transfer

The aircraft might need of application of fuel tanks control system which controls and manages priority of empting tanks to maintain correct CG location. This systems is described on following example when trim tank is used to control location of CG during normal airliner operation.

The fuel transfer system controls the CG position of the aircraft. When the aircraft is in cruise the system optimizes the CG position to increase the fuel economy by reducing the drag of the aircraft. The system transfers fuel to the trim tank or from the trim tank (Fig. 20). This movement of fuel changes the CG position of the aircraft. Normal operation is automatic but the crew can manually control fuel transfer.

The flight management computer (FMC) calculates the CG of the aircraft and compares the result to a target value. From this calculation the FMC decides the quantity of fuel to be moved aft or forward in flight (usually only one aft fuel-transfer is carried out during each flight).

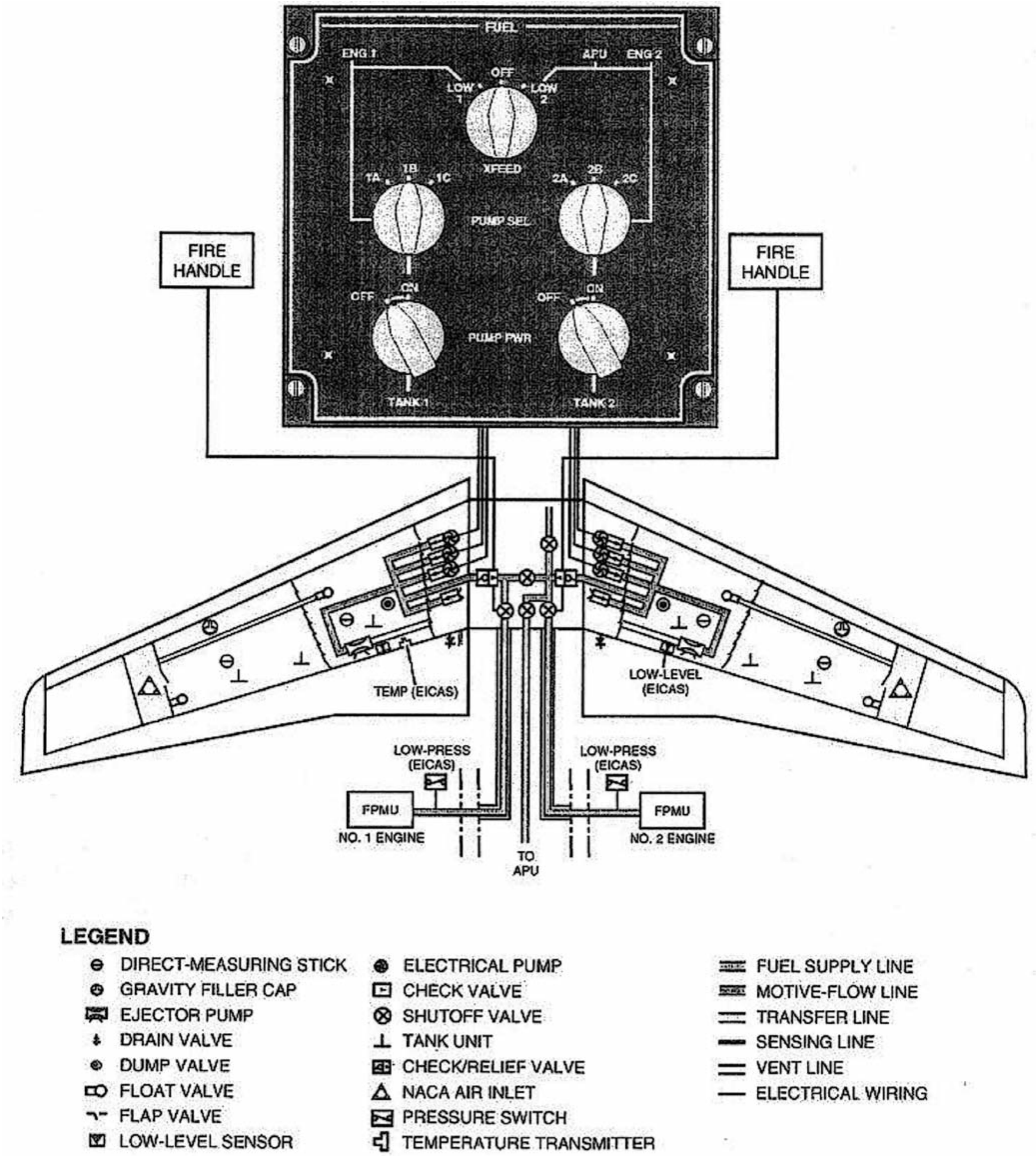

Fig. 18. EMB-145 Fuel distribution

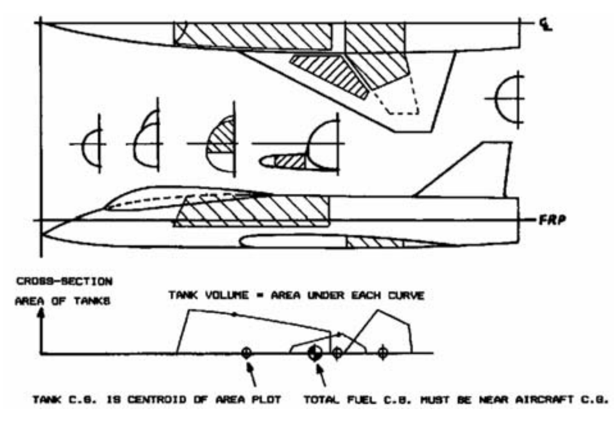

Fig. 19. Estimation of the center of gravity for each tank [2]

Another example is CG control during supersonic flights of Concorde, Fig. 21. Concorde, has multiple fuel tanks. During the flight fuel is transferred from tank to tank to maintain trim and balance of the aircraft as it does not have a full tail plane which would be used on a subsonic airliner to perform this task. Also for supersonic flight the Center of Gravity is critical and required to be moved for different speeds.

The center of gravity location on Concorde is critical to it being able to maintain supersonic speeds. The center of lift of the aircraft, when flying at Mach 2, can move by 6 feet. On a traditional subsonic aircraft the control surfaces would be moved to trim the aircraft correctly, but on Concorde this would be unacceptable due to the drag it would cause and also very little movement left to control the aircraft.

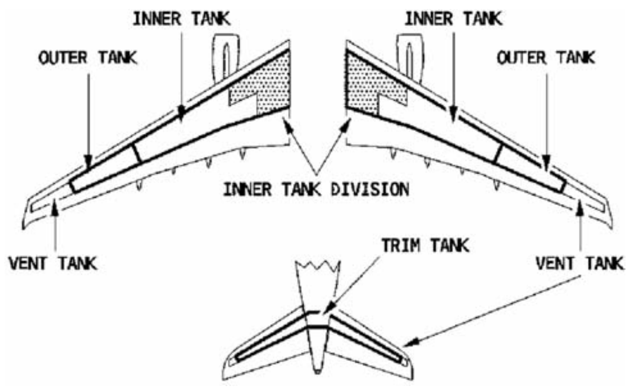

Fig. 20. Fuel tanks location of example airliner [7]

The way the change in the center of lift from the wings is trimmed out on Concorde is to compensate either by moving the weight distribution, or CG, by pumping fuel from the forward trim tanks to the rear trim tanks. The trim tanks make up around 33 tons of fuel that can be moved around the aircraft (there are 95 tons of fuel in the main tanks).

Before take off and during the acceleration through Mach 1 to an eventual Mach 2, fuel is pumped out of the forward trim tanks to the rear trim tanks and the collector tanks in the wings (Fig. 22). Around 20 tons of fuel is moved in the process and results in a rearward shift of the CG by 2 m.

At the end of the Cruise during the deceleration fuel is pumped forward to the wing transfer and even the forward trim tanks is necessary to moving the center of gravity forward again as the center of lift moves reward (Fig. 23).

The movement of fuel also provides additional benefits at lower speeds: by making the aircraft rearward heavy during take off and landing, this causes the elevators control surfaces to move downwards to counteract this weight and increases the camber of the wing generating more lift at lower speeds. Another feature is the ability to move fuel across the aircraft between tanks 1 and 4. This allows the aircraft roll trim to be set without having slightly different deflection on the elevators, which again adds drag and reduces performance.

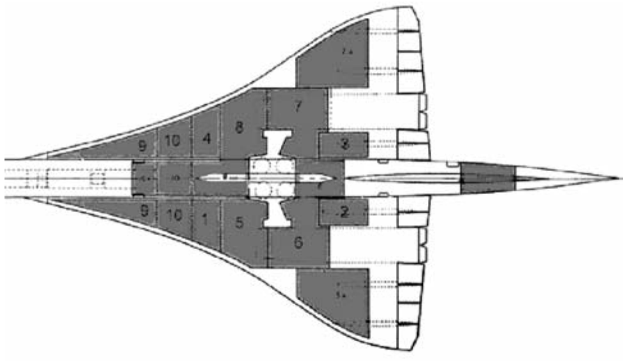

Fig. 21. Location of Concorde's fuel tanks. [8]

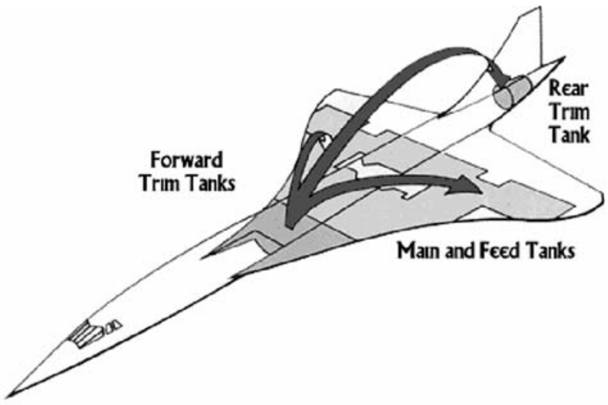

Fig. 22. Fuel transfer during take-off and acceleration [8]

Diagram at Fig. 24 shows the range where the center of gravity on Concorde must be moved for different speed profiles.

Center of gravity shift, controlled by internal fuel transfer may be used to maintain relaxed static stability. Program-

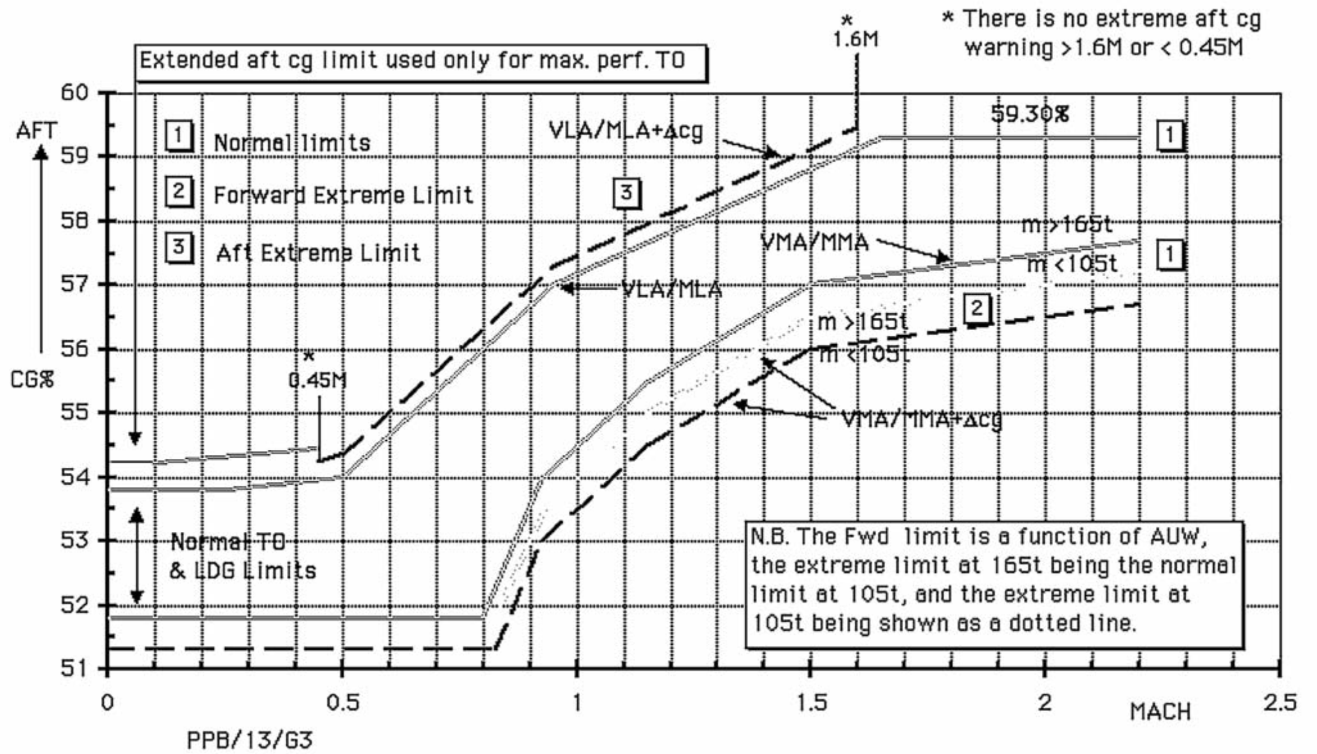

Fig. 24. Center of gravity movement versus speed [8]

med fuel transfer can be applied to conventional subsonic aircraft to reduce an overlarge static stability during cruise. For a conventional transport airplane the gain in the aerodynamic efficiency due to relaxed stability is anticipated between 3% and 5%. The gain in efficiency is much larger for a tailless configuration. Aerospatiale made some experimental flights on Concorde and obtained 10% gain on the lift-drag ratio during unstable flight in subsonic regime, Fig. 25. Experiments completed by Airbus Industry on modified experimental A300 have demonstrated fuel saving of about 2.5% due to such fuel transfer concept.

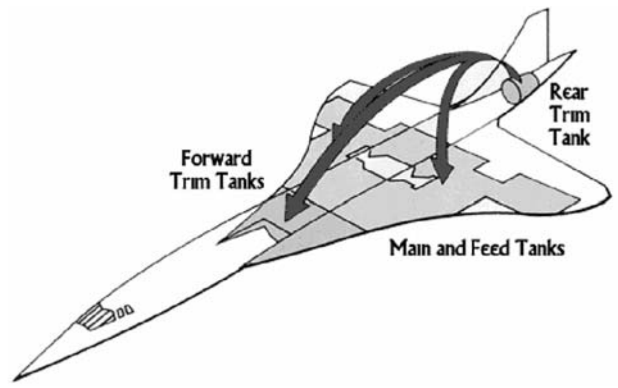

Fig. 23. Fuel transfer during deceleration [8]

Arrangement of fuel tanks, pipes, pumps, filters and regulators are especially important for long endurance airplanes, including HALE UAV. Let consider one of such airplanes, PW-114 developed within CAPECON V Framework European Project [11]. Fuel system of PW-114 consists of seven tanks Fig. 26 and fuel distribution installations, Fig. 27. Engines are supplied by two independent installations. Each fuel tank is equipped with independent installation consisting of two pumps, system of sensors and venting line. Sensors are measuring the level of fuel in the limiting points of the tank. Venting line leads to the common valve in the rear of central fuselage section. The fuel is directed to two auxiliary tanks located in the fuselage. Pumps are delivering the fuel from the auxiliary tanks to adequate engines. Valves connect all fuel tanks to enable fuel transfer between tanks. Common valve for pressure refuelling is located in the fuselage. Overpressure in the tanks prohibits fuel cavitations.

Tab. 1. Fuel tanks capacity

Tank 1	2000 l
2 x Tank 2	1500 l
2 x Tank 3	1400 l
2 x Tank 4	700 l
Total capacity	5600 l

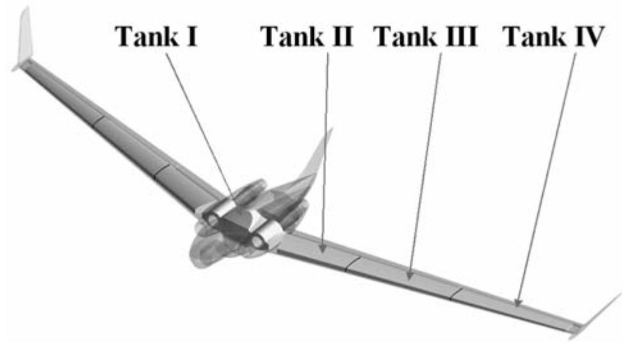

Fig. 26. PW-114 – fuel tanks[11]

The fuel is located in the integral fuel tanks in the wing torsion box and in the fuselage between first and third main frame. Each wing contains three independent tanks and has an independent installation of pipes. Fuel is used from tanks in the following sequence: from 1st and 4th together, then from 2nd and finally from 3rd.

CONCLUSION

Fuel systems are essential for aircraft operation and highly influence on safety. They must be reliable, redundant and easy to maintain. Very often they may be used to move fuel around the aircraft to keep the center of gravity within acceptable limits, to maintain pitch and lateral balance and stability. Fuel system also can be used to optimize the wing span load distribution during flight. It can be achieved due to optimal tanks allocation and due to empting the tanks in predefined order.

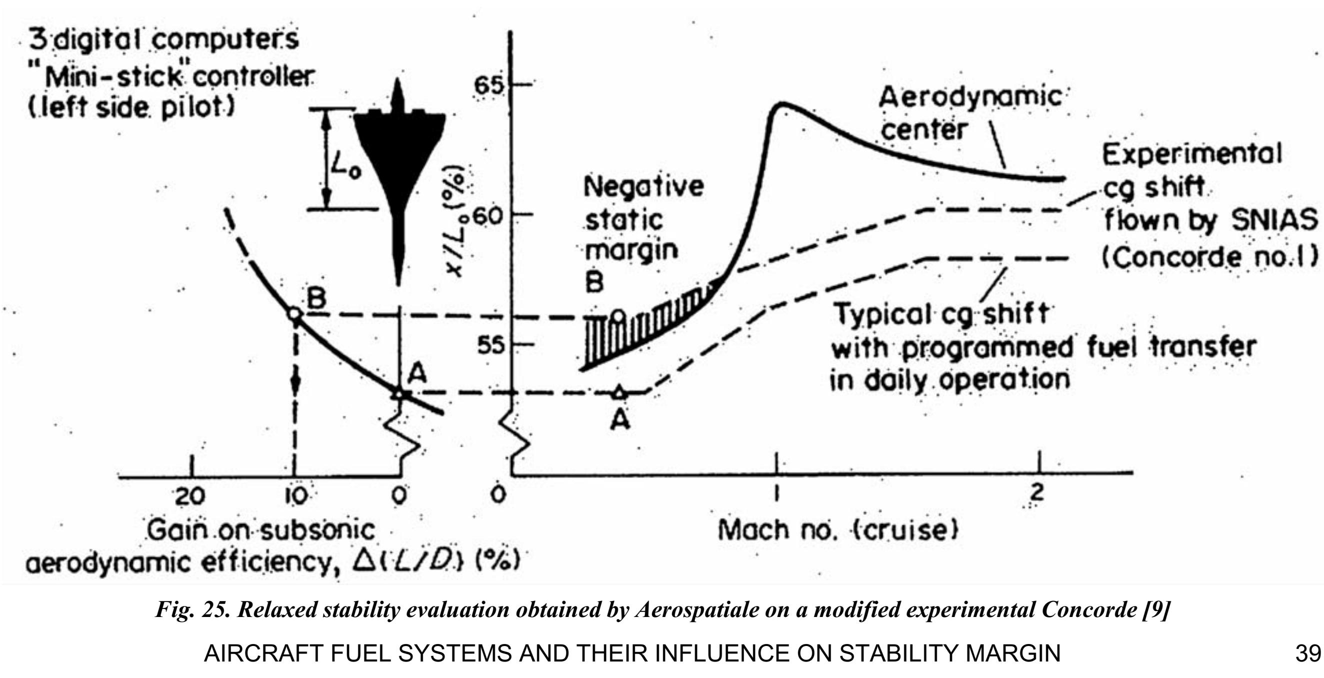

Fig. 25. Relaxed stability evaluation obtained by Aerospatiale on a modified experimental Concorde [9]

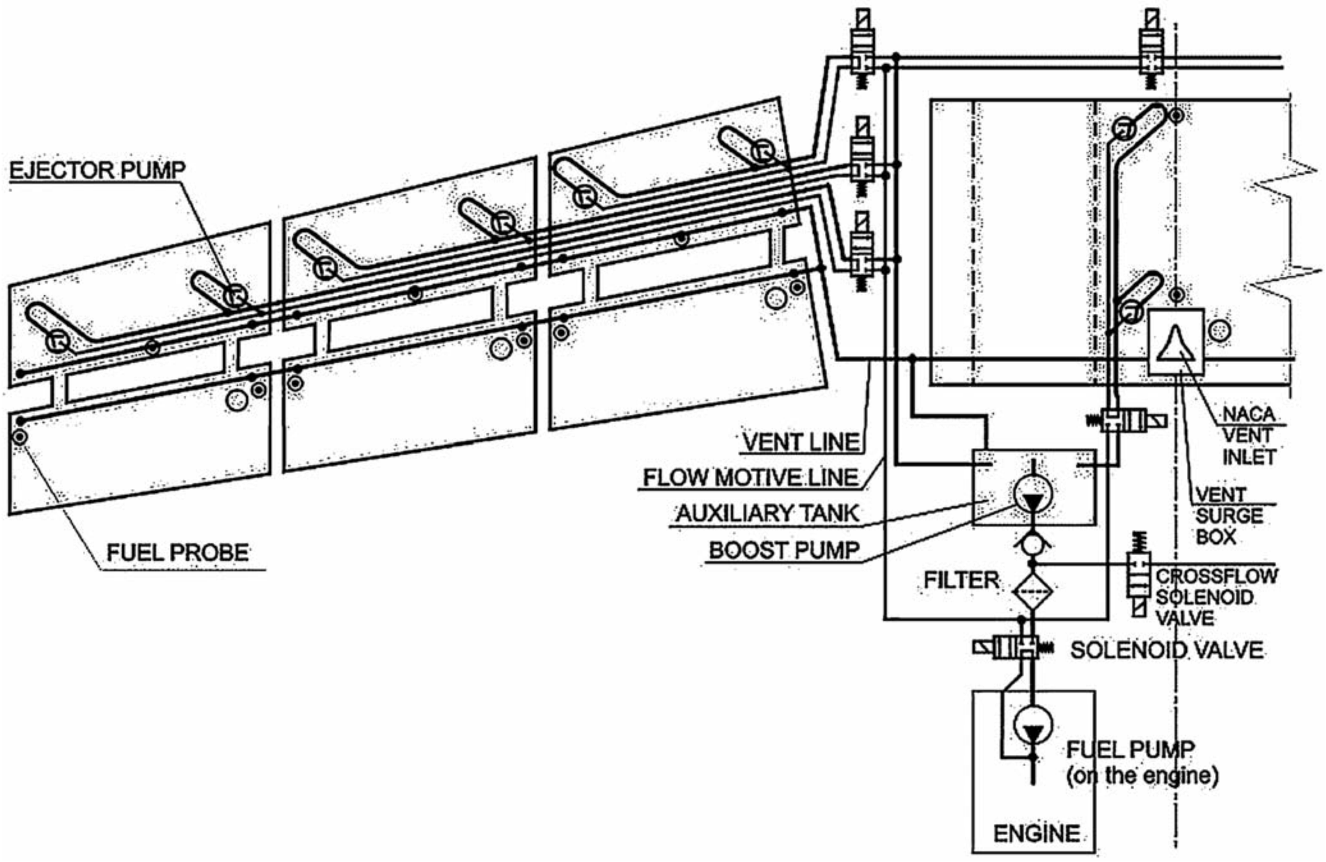

Fig. 27. HALE PW114 fuel instalation

REFERENCES

[1] **Roskam J.:** *Airplane Design.* Part 4, DarCorporation, Lawrence, Kansas 2000.

[2] **Raymer D.:** *Aircraft Design: A Conceptual Approach.* AIAA Educational Series, AIAA 1992.

[3] **Torenbeek E.:** *Synthesis of Subsonic Airplane Design.* Delft University Press1982.

[4] **Corke Thomas:** *Design of Aircraft.* Prentice Hall 2003.

[5] **PLL LOT:** *Boeing B737 – 300/400/500.* Maintenance Manual 2000.

[6] **Lombardo D.:** *Aircraft Systems*. McGraw-Hill, London 1999.

[7] **Lombardo D.:** *Advanced Aircraft Systems.* TAB Books Imprint of McGraw-Hill, New York 1993.

[8] *International Aviation Safety Association* – www.iasa.com.au

[9] *Concise Encyclopedia of Aeronautics & Space Systems,* ed.M. Pelegrin, W.Hollister, Pergamon Press, Oxford 1993.

[10] **Whitford R.:** *Fundamentals of Fighter Design.* Airlife Publishing Ltd, London 2000.

[11] *CAPECON Project No GRD1-2001-40162* (Civil UAV Applications and Economic Effectivity of Potential CONfiguration Solutions), Technical documents 2002-2004. V FR of European Union.

Zdobysław Goraj, Paweł Zakrzewski

UKŁADY PALIWOWE SAMOLOTÓW I ICH WPŁYW NA ZAPAS STATECZNOŚCI

Artykuł omawia nowoczesne układy paliwowe, instalowane w samolotach wojskowych i cywilnych. Artykuł porusza dwa problemy – wpływ położenia zbiorników paliwa na wyważenie samolotu i jego stateczność podłużną. Wykazano, że przemieszczenie paliwa w kierunku końcówek skrzydła zmniejsza zapas stateczności (dla skrzydeł skośnych do tyłu) lub zwiększa zapas stateczności (dla skrzydeł skośnych do przodu). Zmiana położenia środka ciężkości wpływa również na warunki wyważenia samolotu i mogą zmienić zakres wychyleń steru wysokości i sprawność ogólną samolotu. Analiza zawiera przykłady zastosowań w rzeczywistych konstrukcjach lotniczych. Pokazano i omówiono konfigurację położenia zbiorników paliwa dla samolotu PW-114 HALE UAV

З. Горай , П. Закшевски

ТОПЛИВНЫЕ СИСТЕМЫ САМОЛЕТОВ И ИХ ВЛИЯНИЕ НА ЗАПАС УСТАЙЧИВОСТИ

В стате обсуждаются современные топливные системы, устанавливаемые в воснных и гражданских самолетах. Затронуты две проблемы – влияние положения топливных баков на балансировку самолета и его продольную устайчивость. Показано, что перемешение топлива в направлении конца крыла уменьшает запас устайчивости (для крыльев прямой стреловидности) или увеличивает запас устойчивости (для крыльев обратной стреловидности). Изменение положения центра тяжести влияет также на условия балансировки самолета и могут изменить диапазон отклонений руля высоты и полный коэффициент полезного действия. Анализ содержит примеры применений в реальных авиационных конструкциях. Показана и обсуждена конфигурация положения баков топлива для самолета PW-114 HALE UAV.