7 Fuel (ATA28)

7.1 Definition

Those units and components which store and deliver fuel to the engine. Includes engine driven fuel pumps for reciprocating engines, includes tanks (bladder), valves, boost pumps, etc., and those components which furnish a means of dumping fuel overboard. Includes integral and tip fuel tank leak detection and sealing. Does not include the structure of integral or tip fuel tanks and the fuel cell backing boards which are ... [part of the structure], and does not include fuel flow rate sensing, transmitting and/or indicating, which are covered ... [by the power plant systems]. (**ATA 100**)

7.2 Fuel General

The purpose of the fuel system is to provide reliably the proper amount of clean fuel at the right pressure to the engines during all phases of flight and during all maneuvers.

The fuel system includes (**ATA 100**) all components necessary to achieve

- **fuel storage** (tanks, components for tank ventilation, over-wing filler necks and caps)
- **fuel distribution** (all components from the filler to the tank and form the tank to the engine quick disconnect: plumbing, pumps, valves, and controls)
- **fuel dump** (all components used to dump fuel overboard during flight)
- **indicating** (all components used to indicate the quantity, temperature, and pressure of the fuel).

Without fuel supply, powered sustained flight would not be possible. For this reason, the fuel system together with the flight control system and the landing gear, can be considered the most essential systems of an aircraft. This fact is also reflected in the many sections of the certification requirements dedicated to the fuel system: For transport category aircraft these are section 951 through section 1001 of **JAR-25** and **FAR Part 25**.

All **aircraft** use hydrocarbon **fuels**. Piston engine aircraft use a high-octane number *gasoline*. Common for these aircraft is AVGAS 100LL. Jet engine aircraft use *kerosene*. Depending upon the application (civil or military), various grades are utilized. Common jet fuel for civil applications is JET A-1. Table 7.1 contains some **fuel data** relevant to aircraft fuel systems.

Table 7.1 Fuel characteristics related to aircraft fuel systems

	AVGAS 100LL gasoline for piston engines	**JET A-1** kerosene for jet engines
flashpoint (at standard sea level pressure)	- 40 °C (- 40 °F)	+ 38 °C (+ 100 °F)
vapor pressure (REID standard conditions)	500 hPa (7.25 psi)	10 hPa (0.145 psi)
density (at 15 °C)	720 kg/m³ (6.0 lb/USgal)	810 kg/m³ (6.7 lb/USgal)
heating value	43.5 MJ/kg (18700 BTU/lb)	42.5 MJ/kg (18300 BTU/lb)

Kerosene has a sufficiently high **flashpoint**. At sea-level pressure and normal temperatures, kerosene can be considered a "safe fuel". Gasoline, in contrast, could easily ignite and needs to be handled especially careful.

When fuel in the fuel lines is heated enough to cause it to vaporize, a bubble of fuel vapor appears, blocking the fuel from flowing to the engine. Such a situation is called *vapor lock* and must obviously be avoided. The **vapor pressure** is a measure showing if a fuel is prone to vapor lock.

Fuel contains a certain amount of energy per unit mass known, as *specific heat* or **heating value** *H*. The fuel tank offers a limited fuel *volume V*. Hence, fuel *mass m* and fuel *energy E* in the fuel tank vary with fuel **density** ρ

$$m = \rho \cdot V \qquad E = m \cdot H \qquad E = \rho \cdot V \cdot H \quad .$$

Since fuel density decreases with increasing temperature, so do storable fuel mass and energy. For aircraft operation, the amount of energy on board is of importance. Accordingly, *indicating fuel mass* to the pilots does make sense (in contrast to *indicating fuel volume*). The draw back: not only measurements of fuel level and hence fuel volume are required, but additionally, measurements of fuel density.

Water may be contained **in the fuel** dissolved, entrained, or free. As fuel is taken from the tank, air (at given humidity) enters the space above the fuel in the tank. With decreasing temperature, water condenses from this air and enters into the fuel. During flight at high altitudes and low temperatures, ice crystals can form that clog *fuel filters*. To prevent clogging, the fuel may be passed through a *fuel heater* prior to entering the filter. Fuel systems must be capable of sustained operation with a specified amount of free water under critical conditions for icing (section 951). With the aircraft at rest, water in the fuel collects in the fuel tank sump that is the lowest part of the fuel tank. This happens because density of water (1000 kg/m³) is greater than fuel density. "Each fuel tank sump must have an accessible drain" (section 971). *Water drain valves* are used to extract the water.

Microorganisms, bacteria or fungi, may grow **in jet fuel** tanks. These organisms live and multiply in the water contained in the fuel and feed on the hydrocarbons. The buildup of microorganisms not only interferes with fuel flow and quantity indication but can start electrolytic corrosion. The organisms form a dark slime on the bottom of the lowest parts of the fuel tank, especially near water drain valves. Regularly draining water from the fuel together with fuel additives may solve the problem of microbial growth.

Unintended ignition of fuel must be prevented. Therefore section 954 of **JAR-25** and **FAR part 25** reads: "The fuel system must be designed and arranged to prevent the ignition of fuel vapour …" by lightning strikes or other effects at outlets of the vent and jettison systems or directly through the structure.

7.3 Fuel Storage

Fuel **tank location** can be in the wing, fuselage, horizontal stabilizer, or fin. Tanks can be permanently attached or mounted onto the wing tip (*tip tank*). In the case of combat aircraft, additional tanks can be under-wing mounted, over-wing mounted, or belly mounted. Transport aircraft often use the center section of the wing for a *center tank* (Figure 7.3). These aircraft may trade payload versus fuel capacity (i.e., maximum range) by using part or all of the cargo compartment for *additional center tanks* (ACT).

"Fuel tanks must have an **expansion space** of not less than 2% of the tank capacity. It must be impossible to fill the expansion space inadvertently with the aeroplane in the normal ground attitude" (section 969). A 2% expansion is equivalent to an increase in fuel temperature of 20 °C.

Fuel initially filled into the empty tanks cannot practically be expected to be taken out again "to the last drop" under all operating conditions. The amount of fuel that remains in the tank is called **unusable fuel**. "The unusable fuel quantity for each tank and its fuel system components ... [is] the quantity at which the first evidence of engine malfunction occurs under the most adverse fuel feed condition for all intended operations and flight manoeuvres ..." (section 959). Aircraft manufacturers try to reduce the unusable fuel volume as much as possible. So-called *scavenge pumps* are used to collect fuel from different areas of the tank.

The fuel in the fuel tanks can be used for **center of gravity** (CG) **control**. *Supersonic aircraft* may use CG control **to minimize trim drag** that is caused by the rearward shift of lift at supersonic speeds. The Concorde uses trim tanks in the forward part of the wing for CG control. *Subsonic aircraft* may use a trim tank in the empennage to maintain an optimum rearward CG in cruise. An aft CG reduces trim drag and thus enhances aircraft performance.

The Airbus A340 applies a trim tank in the horizontal tail to move the CG in cruise back to approximately 2% mean aerodynamic chord (MAC) forward of the certified aft limit.

The **weight of fuel** in the wings directly balances lift. This **reduces wing-bending moments** and allows for the design of a lighter structure. In order to make as much use as possible of this phenomenon, fuel is preferably taken from the center tank or an inner wing tank first, whereas the fuel in outboard wing tanks is used only during the last part of the flight. During the last part of the flight, lift is already reduced anyway due to a reduction of aircraft weight as a result of fuel consumption.

Fuel tank construction can be divided into three basic types: *rigid removable*, *bladder*, and *integral*.

A **rigid removable fuel tank** is one that is installed in a compartment designed to hold the tank. The tank must be fuel-tight, but the compartment in which it fits is not fuel-tight. The tank is commonly made of aluminum components welded together or composites. Rigid fuel tanks are used on small aircraft or as additional center tanks (ACT). ACTs inside the fuselage must be double-walled.

A **bladder tank** is a reinforced rubberized bag placed in a non-fuel-tight compartment designed to structurally carry the weight of the fuel. Bladder tanks are found on medium- to high-performance light aircraft or inside a rigid ACT structure to produce a double-walled tank.

An **integral fuel tank** is a tank that is part of the basic *structure* of the aircraft. Integral fuel tanks, e.g., in the wing, use structural members of the wing and *sealing materials* where members join to form a fuel-tight tank. Tank *access panels* seal the oval cutouts in the lower wing surface used for tank inspection. *Baffles* are frequently installed inside fuel tanks to reduce fuel sloshing. Baffles may have *check valves* that open in the inboard direction only. These check valves keep fuel in the inboard part of the tank, where the pumps are located.

The **tank vent system** "maintains acceptable differences of pressure between the interior and exterior of the tank" (section 975) under all operating conditions, including:

- cruise (fuel burn)
- maximum rate of climb and descent (change of outside pressure)
- refueling and defueling

Overpressure and underpressure in the tanks can cause structural damage. Underpressure can cause engine fuel starvation. The vent system for a light aircraft may be as simple as a hole drilled into the fuel cap. Large aircraft connect each main tank via *vent pipes* with a *vent surge tank* for tank venting (Figure 7.4). The vent surge tanks take up any overflow fuel from the main tanks and direct it back to these tanks through *vent float valves*. The vent surge tanks are each connected to the outside via a NACA air intake, which achieves a pressure in the fuel tank slightly above ambient pressure.

Aircraft fuel is also used as a heat sink. The hydraulic system and the air conditioning system, especially of jet fighters, use fuel **for cooling purposes**. It is obviously important to monitor the fuel temperature carefully in order to avoid over temperatures.

7.4 Fuel Distribution

The fuel distribution system may consist of:

- the engine feed system
- the fuel transfer system
- the crossfeed system
- the refuel / defuel system

Engine feed, i.e., fuel flow to the engines may be either *gravity feed* or *pressure feed*.

In the case of **gravity feed**, the fuel flows by gravity to the engine. This is possible if the tank is located sufficiently above the engine. Gravity feed is used on small high-wing aircraft and on large aircraft in emergency cases with system fuel pumps inoperative (suction provided from engine fuel pumps).

In the case of **pressure feed**, *fuel pumps* are used to move fuel through the fuel system. For turbine-engine fuel systems there must be one *main pump* for each engine (section 953) and one *emergency pump* (section 991) immediately available to supply fuel to the engine if the main pump fails. Various fuel pump principles exist including: *vane pump*, *centrifugal pump*, and *ejector pump*.

The **centrifugal pump** (Figure 7.1) draws fuel into the center inlet of a centrifugal impeller and expels it at the outer edge. Fuel can flow through the pump when the pump is not in operation. This eliminates the need for a *bypass valve.*

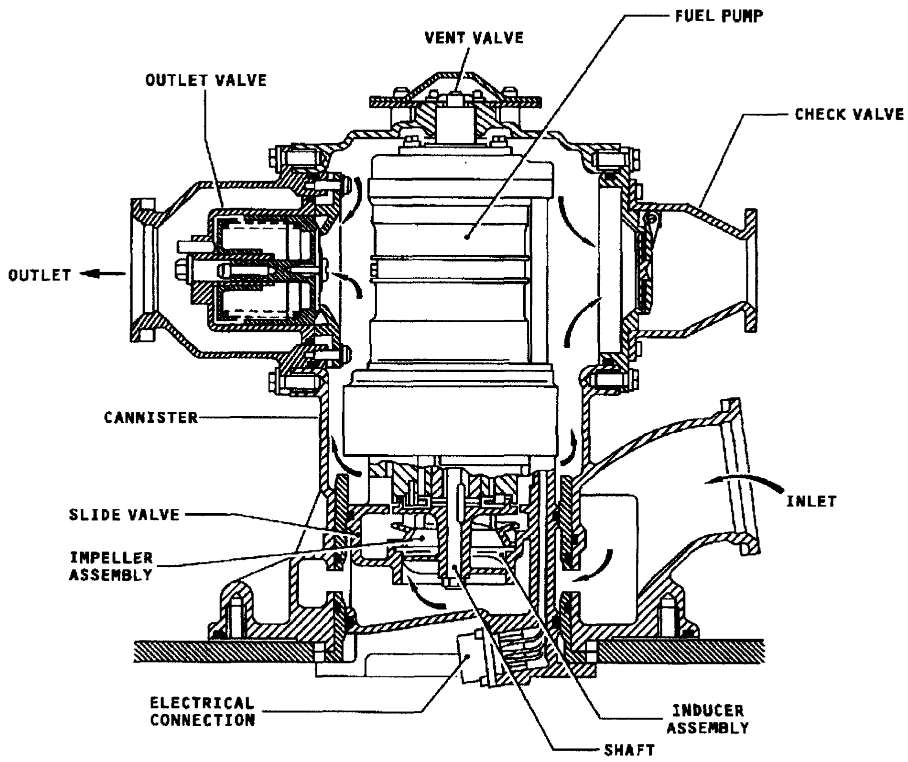

Figure 7.1 Centrifugal fuel pump (A321)

An **ejector pump** (Figure 7.2) is used to scavenge fuel from other areas of the fuel tank or from adjacent fuel tanks. This type of pump has no moving parts, instead, it relies on the fuel flow from a main pump.

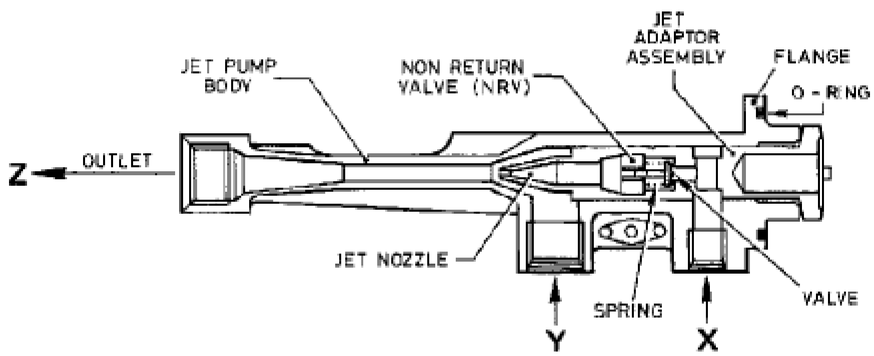

Figure 7.2 Jet pump (A321)
X: input from main pump
Y: suction input
Z: output

Fuel selector valves provide means to select a tank from which to draw fuel in a multiple-tank installation, transferring fuel from one tank to another and directing fuel to one or more engines. A **shutoff valve** (section 1189) disconnects fuel flow to an engine. The shutoff valve is also closed by the fire handle in case of engine fire. "There must be a **fuel strainer** or **filter**..." (section 997).

The **fuel transfer system** allows fuel to be pumped from one tank into another. The main feature of the *crossfeed system* is its fuel manifold. Fuel is supplied form the tanks to the *crossfeed manifold*. *Crossfeed valves* on the crossfeed manifold can be set such that each engine can be fed from all tanks.

There are two basic **refuel procedures** for aircraft: *over-wing refueling* and *pressure refueling*. In addition, some aircraft are able to use *in-flight refueling*.

The historical form of refueling an aircraft from above simply by gravity is called **over-wing refueling**. Small aircrafts apply this simple method. It is slow, and depending on aircraft size and wing location it may be difficult to reach on top of the wing.

Pressure refueling uses pressure form the fueling station or truck to force fuel into the aircraft tanks. This is usually done through a fueling coupling located under the wing at the right wing leading edge. Pressure refueling is fast and the refuel coupling is in easy reach.

During **in-flight refueling**, a military aircraft is supplied with fuel in the air from a tanker aircraft. Tanker aircraft are converted large civil transports. The connection between the receiving and providing aircraft can be established with a flexible hose or a rigid boom. In-flight refueling was first used for fighter aircraft to extend their limited range capabilities. Later, in-flight refueling was applied to cover large distances in global conflicts or to maintain constant combat air patrol.

Defueling is the opposite of refueling: fuel is pumped out of the aircraft fuel tanks and back into the station or truck. During **fuel ground transfer**, fuel is pumped from one aircraft tank into another tank. Defueling and fuel ground transfer may become necessary prior to tank maintenance.

7.5 Fuel Jettison

Fuel weight amounts to a large fraction of aircraft gross weight, especially at the beginning of a long-range flight (with a long-range aircraft). If an **emergency** occurs shortly after takeoff, the aircraft may be forced to return and land as soon as possible. In such a situation the present aircraft weight will still be considerably above maximum landing weight. An overweight landing might unduly stress and endanger the aircraft, and in case of a discontinued approach, the heavily laden aircraft will not be able to fly a successful go-around maneuver with sufficient climb rate (section 1001).

A fuel jettison **system** (fuel dump system) helps to solve the situation. The fuel jettison system allows dumping of all but some reserve fuel over board in not more than 15 minutes.

This now brings the aircraft weight down quickly as a prerequisite for a successful emergency landing.

Two fuel-jettison **principles** have been used: Systems can work with gravity or with pump pressure. A *gravity jettison system* is equipped with long *dump chutes* that are deployed at both wing tips. The long chutes produce the necessary pressure differential for the flow. A *pump jettison system* is equipped with *dump nozzles* at both wing tips.

7.6 Indicating

Quantity, *temperature*, and *pressure* of the fuel can be measured for the fuel system. Other fuel parameters are measured by the engine.

A **fuel quantity indicator** can be a *mechanical* quantity indicator, a *resistance* quantity indicator, or a *capacitance* quantity indicator.

A **capacitance quantity indicator** is a condenser installed in the tank, so that the condenser is immersed in the fuel. Fuel respectively air in the tank serve as dielectric material for the condenser. When the probe is dry, its capacitance value is low, but as fuel moves up the probe, its capacitance value increases. A controller monitors the capacitance value and converts it into a fuel volume.

In addition to the fuel quantity indicator, which is primarily used in flight, it is desirable to have an alternative provision to **determine the fuel quantity visually**. On light aircraft this may be accomplished by *viewing the fuel surface* through the fuel filler cap opening, but on large aircraft this would be extremely difficult. For this reason, calibrated hollow fiberglass *dripsticks* have been used that are unlocked and slowly lowered from under the wing. The position of the stick when it "drips" marks the fuel level inside the tank. More sophisticated are *magnetic level indicator* (MLI). The MLI are also unlocked and lowered from under the wing. A magnetic float on the fuel surface gets hold of the magnetic top of a stick. The position of the stick attached to the float determines the fuel level.

7.7 Example: Airbus A321

The Airbus A321 has **three fuel tanks** (Figure 7.3):

- the left wing tank
- the right wing tank
- the center tank.

The total usable fuel capacity of these tanks is 23700 l. The total unusable fuel capacity is 89.7 l. This is less than 0.4%.

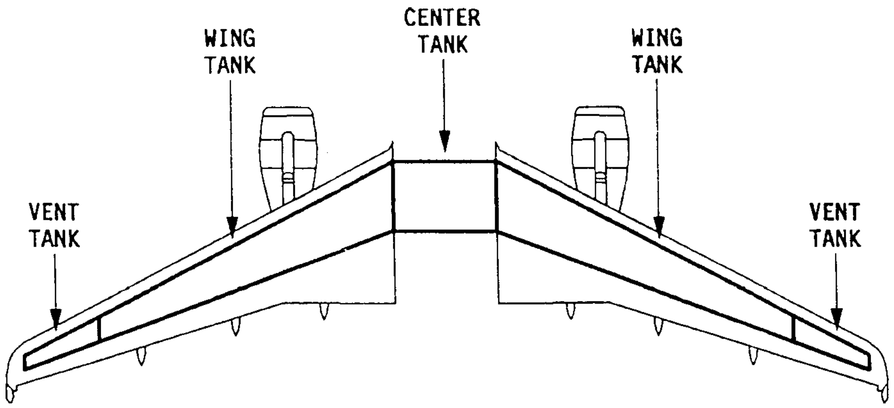

Figure 7.3 A321 fuel tanks

The **vent surge tanks** (Figure 7.4) do not normally contain fuel. They are connected to the wing tank and center tank through the *stringer vent duct* and the *center tank vent pipe*. The vent surge tanks can vent these tanks because they are open to the external air through a *vent duct*. The vent duct contains a *vent protector* with a *flame arrestor* and an *ice protector*. The vent duct is connected to a NACA intake on the bottom of the tank. The vent surge tanks are also a temporary reservoir for the fuel that could enter through the vent pipes. This fuel is drained back to the wing tanks through vent *float valves* (clack valves). In case of an obstruction in the vent duct, the *overpressure protector* ensures that the pressure in the vent surge tank does not exceed specified limits.

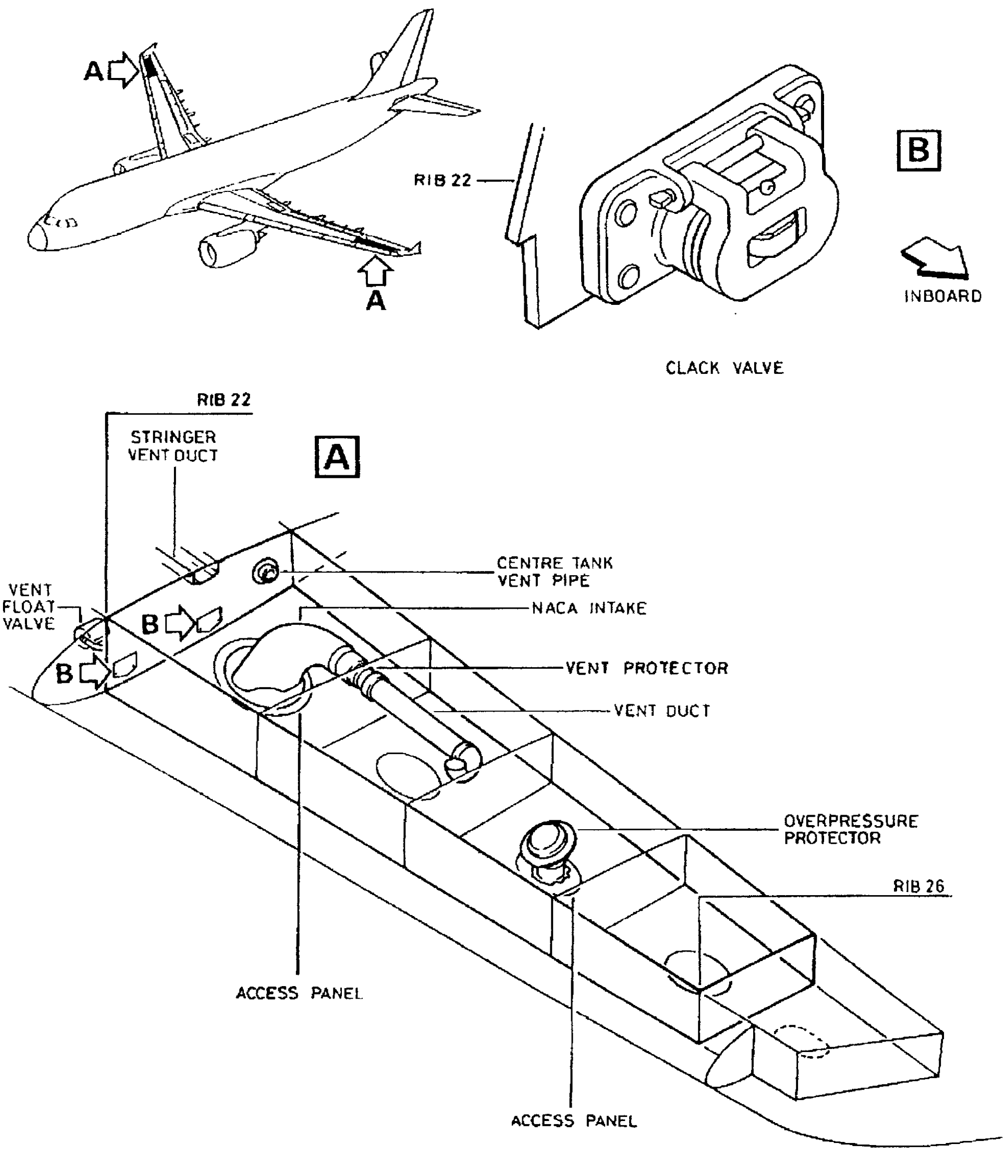

Figure 7.4 A321 vent surge tank

The **fuel distribution system** of the A321 is shown in Figure 7.5:

- The *engine feed system* takes fuel from the wing tanks and supplies it to the engines. Two main pumps (Figure 7.1) are located in each wing tank.
- The *main transfer system* enables transfer of fuel from the center tank to the left and right wing tank. This fuel transfer is a normal procedure necessary to make use of the fuel in the center tank. Fuel transfer is achieved with ejector pumps (jet pumps). The jet pumps in the center tank are driven by fuel form the main pumps.
- The *crossfeed system* connects the left and right fuel feed system. The engine feed line has a crossfeed valve that permits the isolation or interconnection of the left (engine 1) and right (engine 2) fuel supply system. Under normal conditions, the crossfeed valve is closed.

- The *refuel / defuel system*:
    - o Refueling: Fuel is supplied to the fuel tanks via the refuel coupling in the right wing. A second refuel coupling in the left wing is optionally available.
    - o Defueling: Fuel is pumped out of the tanks by way of the refuel coupling. The defuel transfer valve is open.
    - o Fuel transfer: The system may be used to transfer fuel from one tank into any other tank. The defuel transfer valve is open.
- The *APU feed systems* takes fuel from the engine feed line and supplies fuel to the auxiliary power unit (APU).

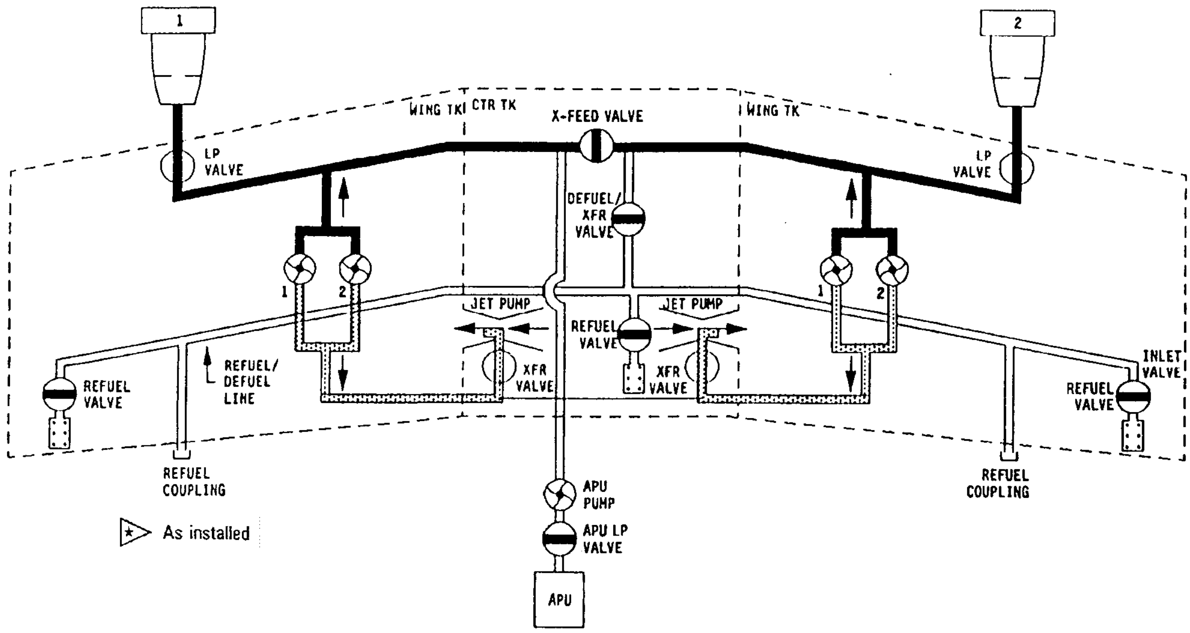

Figure 7.5 A321: Overview of the fuel distribution system

black lines	engine feed system
gray lines	main transfer system
white lines	refuel / defuel system and APU feed
X-FEED	crossfeed
XFR	transfer