Toronto Metropolitan University

AER715 Avionics and Systems

An All-System Theoretical Analysis of Airbus A320

Final Report

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Abstract

For the purposes of this analysis, the Airbus A320 civil aircraft was selected due to its well-known popularity and dependability, having been a mainstay in the Airbus fleet since its introduction with Air France in 1988. The airplane has a single aisle, two engines, and can carry about 190 passengers. The newest generation of aircraft is the A320neo, which has a range of 6300 km and can use up to 30% less fuel than comparable previous-generation aircraft. The aircraft's fuel system is one of its design highlights. Tanks in the wings and middle section are used for storage. The structure is completely symmetrical and essential to the aircraft's overall performance. The avionics systems and subsystems that will be examined in this paper fall into the following 7 categories: electrical systems, flight control systems, environmental control systems, engine control systems, fuel control systems, hydraulic systems, and instrumentation and crew-plane interface. The choosing of the aircraft is also covered in a quick summary.

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Introduction

The project's objective is to increase our systematic understanding of the intricate systems and avionics on a particular civil aircraft. As outlined in the proposal, the chosen model was the Airbus A320. Instruments and crew-plane interfaces, flight control systems, engine control systems, fuel systems, electrical systems, environmental control systems, and hydraulic systems are the systems described throughout this final report.

Project Plan

The following gantt chart illustrates the project schedule for our group. The two major milestones include the Preliminary Report and the Final Project Report. Each milestone has several sequential team meetings on Mondays to touch base on our individual progress, problems and to ensure that we stay on track.

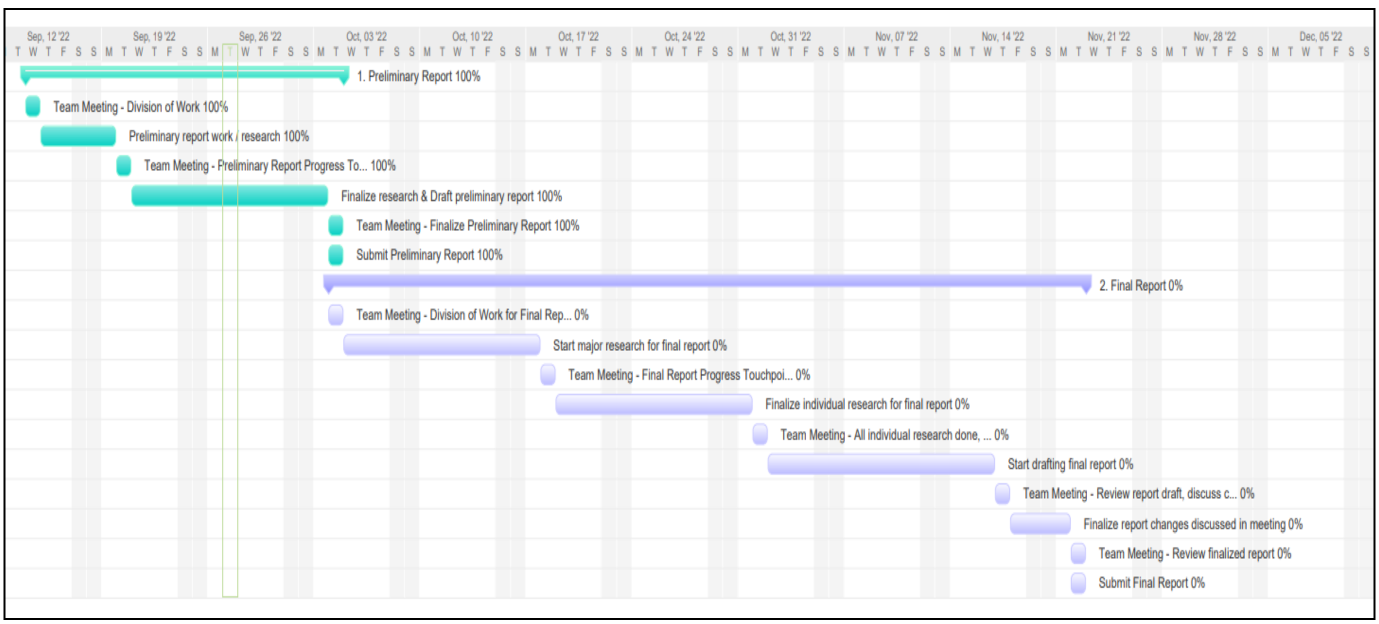


Figure 1: The Project Gantt Chart.

Table 1: Peer Evaluation.

Name	Task/Responsibility	Contribution
Jack	Instruments and Crew-Plane Interface	16.67%
Shae-Lin	Environmental Control System	16.67%
Aman	Engine Control System, Electrical Systems	16.67%
Joshua	Flight Control System	16.67%
Ronak	Hydraulic System	16.67%
Shadab	Fuel System	16.67%

The above table is a representation of the work-distribution for this case study of the Airbus A320's general systems. It evaluates the tasks completed by each member for the report. All members are responsible for analyzing the aircraft system for the final report.

1. Instruments and Crew-plane Interface

The Airbus A320 is one of the most successful medium-haul aircraft and it is one of many aircraft using the newer Fly-by-wire (FBW) technology. As a short explanation, fly-by-wire means that the manual input through the pilot's sidestick is converted to an electrical signal that is sent to a flight computer which then tells the aircraft how to move as desired [1]. A more detailed explanation will be given in the Flight Control System section. However, this is important because since the aircraft flies through a computer, the importance of Instruments and Crew-plane interfaces becomes paramount.

1.1 Cockpit Design Requirements and Philosophy

Before the important instruments of the cockpit are discussed, the design requirements and philosophy that drove the design choices made by Airbus must be discussed. Airbus has outlined 10 main high-level design requirements that dictate the design of the cockpit [2]. These requirements also include operational and human factors that are key to cockpit design [2]. The requirements are [2]:

1. The pilot is responsible for the safe operation of the aircraft.
2. The pilots should be able to exercise their full authority, if required, through intuitive actions while also removing the risk of overstress or overcontrol
3. The cockpit is designed in such a way that it allows pilots with different skill sets and experiences to become easily accustomed to the cockpit.
4. The factors of safety, passenger comfort and efficiency are prioritized in that order.
5. The cockpit should look at simplifying tasks for the flight crew by enhancing situation and aircraft status awareness.
6. Automation is an additional feature available to the crew who can decide when to delegate and the assistance they require.
7. Human-machine interfaces consider the systems' features and flight crews' strengths and weaknesses.
8. Modern Human factors considerations are applied in the system design processes.
9. Overall cockpit design contributes to and enhances flight crew communication.
10. The implementation of and use of new technology and features are imposed by
    a. Safety benefits

b. Obvious operational advantages
c. Clear response to the needs of the flight crew.

These 10 requirements are especially important to the cockpit design and are heavily based on the safety of aircraft and human and operational factors. For Airbus, safety is a top priority, and this can be seen in the first, second and fourth requirements.

The 10 requirements heavily influence the design philosophy of the cockpit of the A320 and its layout. For instance, requirement 2 can be seen in the design of the push-buttons of the A320 instruments. Common sense dictates that when a button is pressed and remains depressed it means that it is on and when it is no longer depressed it is off. This common sense is applied to the push-buttons, as when they are depressed it means that they are 'on,' 'open' etc. When they are no longer depressed it means it is 'off,' 'closed' etc. [3]. The whole intuitive nature of the buttons also extended to the colours that are displayed on the buttons. Red means, warning there is a failure requiring immediate attention, amber indicates, caution a failure that does not need immediate attention has occurred, green means that the system is operating normally, and blue indicates that a temporary system that is used is operating normally [3]. Requirement 3 also features heavily in the design of the A320. The A320 cockpit design "shares commonality with other Airbus fly-by-wire aircraft" [4]. Pilots who fly the A320 can easily transfer to A319, A321 and with a little more training, to other Airbus aircraft [4]. This is an excellent design choice by Airbus as it allows airlines to be flexible with their pilots. Not only is this a clever design from an engineering perspective, but it is also a good design from a business perspective.

The commonality of the cockpit design of the A320 and other Airbus aircraft reduces the operational and training costs for pilots because airlines do not have to spend substantial amounts of money training new sets of pilots or retraining experienced crews. This makes it highly attractive from a business standpoint as all businesses love to reduce costs. The commonality design philosophy of the A320 cockpit "also extends into the passenger cabin, with similar systems, control panels and procedures across the Airbus single-aisle and widebody families" [4]. The overall design of the cockpit also has features that increase safety, ergonomics, and crew comfort too. For safety and ergonomic reasons, the cockpit is designed with the dark cockpit concept or lights out concept [3]. This allows the pilots to easily see the controls and buttons of the aircraft allowing them to properly control the aircraft. Which is further enhanced by the glareshield above the main instrument panel [3]. Additionally, crew comfort is considered which by extension increases safety because the crew is not distracted and stressed. The cockpit has adjustable seats for the captain and first officer, as well as the possibility for third and fourth-occupant seats depending on configuration [3]. The cockpit is furnished with various accessories and equipment that improve "the comfort, convenience and safety of the occupants" [3]. In all, the A320 cockpit is designed to account for the various requirements and factors which make it a highly excellent designed cockpit. Figures 2 and 3 show the plan view of the cockpit and the general arrangement of the rear part of the cockpit which shows the implementation of the design philosophy discussed above.

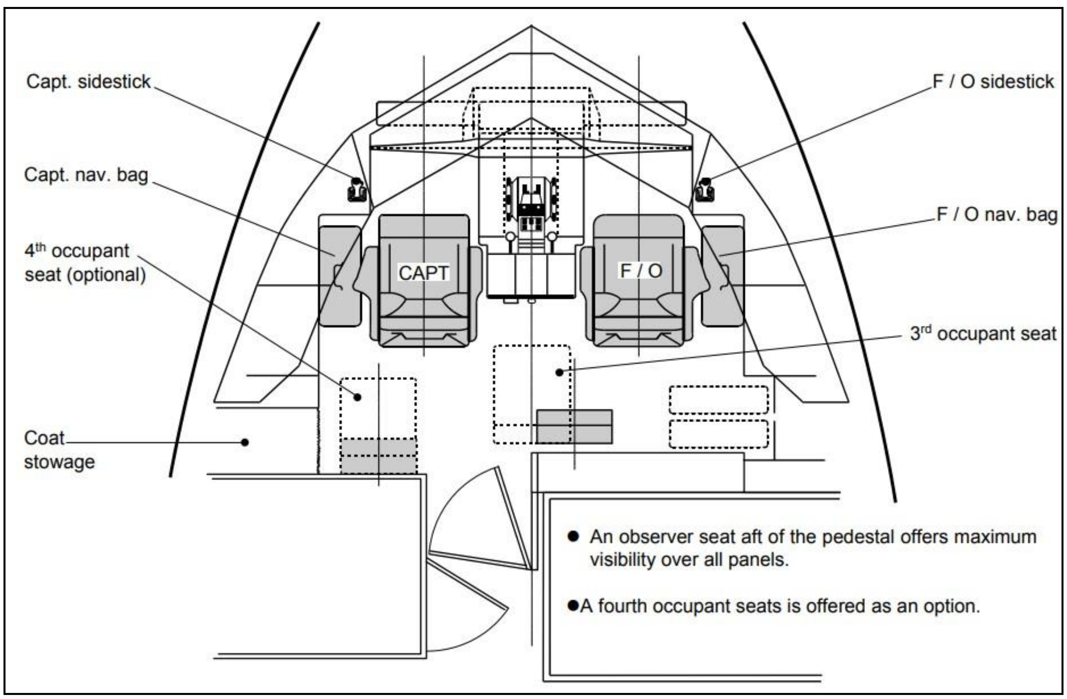


Figure 2: The plan view of the A320 Cockpit [5].

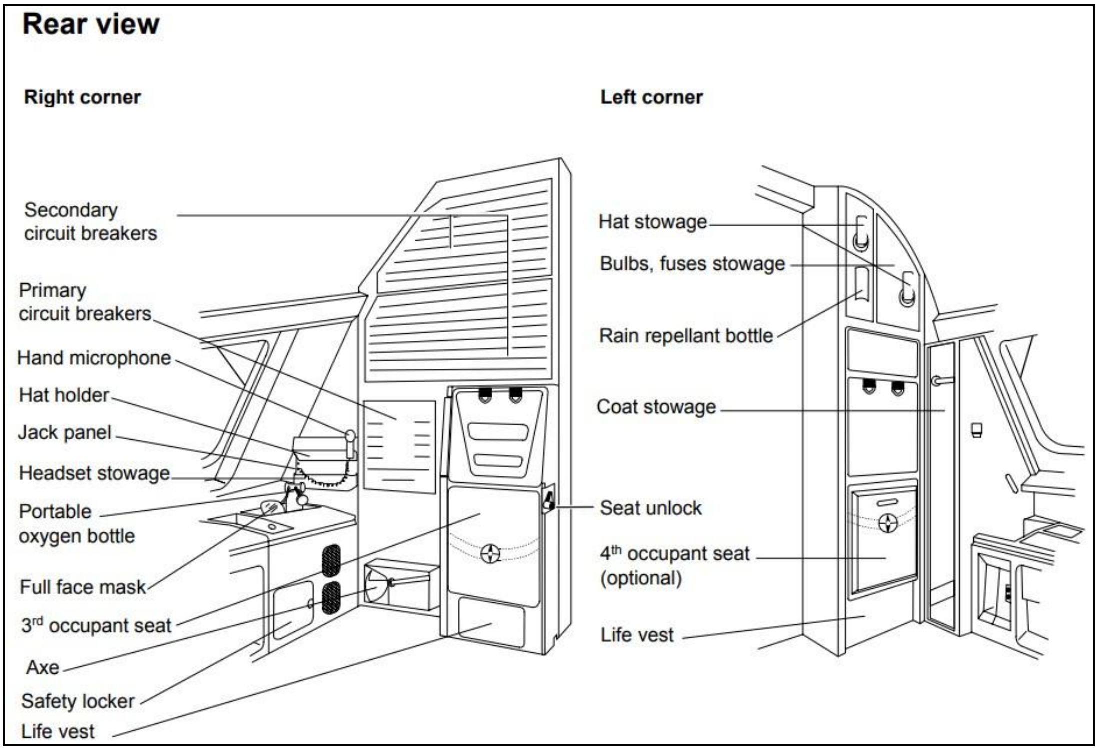


Figure 3: The general arrangement of the rear of the cockpit of the A320 [5].

1.2 General Layout

The cockpit of the A320 consists of a few key important pieces required for any aircraft. The first aspect of the cockpit is the overhead panel which contains many key functions like the system panels and the circuit breaker [3]. The next aspect of the cockpit is the glareshield which contains the flight control unit and the master warning and caution lights. Below the glareshield is the main instrument panel which contains all the displays and other key features for flying an aircraft [3]. Under the main instrument panel is the central pedestal with many prominent features. Lastly, the side console is another important aspect of the cockpit. It contains the Side Stick Controller used to control the aircraft [3]. As mentioned before the aircraft uses the FBW system which means that the traditional yoke seen in other aircraft is not present [3]. Figure 4 below shows the general layout of the cockpit that the pilots use.

Figure 4: The cockpit layout of the Airbus A320 [2].

1.3 Overhead Panel

The overhead panel is divided into 2 main sections, the fwd. section, and the aft section [3]. The fwd. section contains controls and push-buttons for a variety of the A320's systems. Specifically, the electrics, hydraulics, bleed air, engine fire indication, lighting, air conditioning and many more [6]. The aft section contains circuit breakers and the maintenance panel of the overhead panel [6]. See figure 5 for the full layout and list of the controls of the overhead panel. The design of the overhead panel is intuitive, and ergonomic and contains many of the design philosophies discussed in the Cockpit Design Requirements and Philosophy subsection. The overhead panel is designed as a "single slope" [5]. This allows the pilots to naturally follow the shape of the overhead panel making it highly intuitive. Part of the intuitive and ergonomic design of the overhead panel is the ability for the overhead panel controls to be reached by either pilot [5]. This allows pilots to easily reach the overhead panel controls without having to struggle or have the other pilot do it from their seat. Furthermore, this design choice increases safety because it ensures that at least one pilot has their hand on the sidestick for manual operation of the aircraft in case of an emergency, while the other pilot can press the buttons that require attention. As stated before the overhead panel is separated into 2 sections, which is a brilliant design choice because it follows common sense. The 2 sections are even separated by a buffer pad to help pilots distinguish between the 2 sections [5]. The fwd. section as mentioned before contains all of the important controls which makes sense because they are the most frequently used and hence why they are located in the front [5]. This further shows the intuitive design of the control panels. Even the controls are laid out in a logical fashion making it easier for the pilots. The controls are arranged in 3 rows, with the central rows containing engine-related systems and the other 2 rows containing other systems [5]. The aft section of the control panel contains controls not critical for flying the aircraft or used during the flight [5]. That is why it contains circuit breakers and a maintenance panel. Additionally, the overhead panel follows the push-button philosophy that was discussed in the Cockpit Design Requirements and Philosophy with different coloured lights and different button positions [5]. The overhead panel push-buttons were designed so that the indicator lights would not turn if the system were running normally. They would only turn if there was an issue [3]. This was a deliberate design choice for ergonomic reasons allowing the pilots to immediately see that there is an issue with the system [3]. The overall design of the overhead panel ensures that there would be minimal chances of errors and that it would be easy for pilots to use [2].

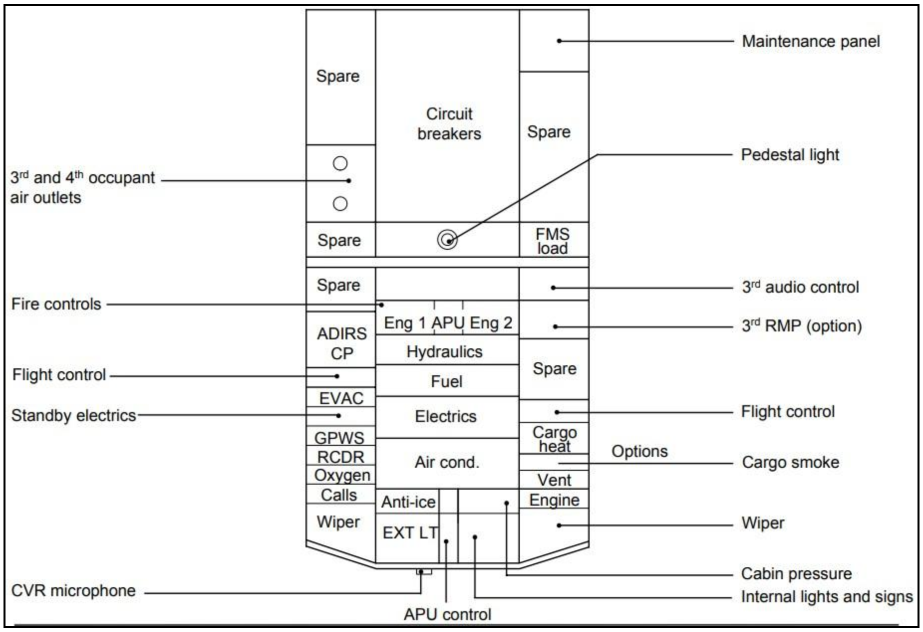


Figure 5: Schematic diagram of the overhead panel [5].

1.4 Glareshield

The glareshield, which is located just above the main instrument panel, protects the main panel from glare from the sun and reflections. This is to ensure that the pilots can see the main instrument panel reliably. The glareshield serves an important safety function because if the pilots could not see the main instrument panel which contains critical flight information due to glare or reflections, it could lead to serious issues or even disaster. Apart from the safety function, the glareshield also contains the flight control unit (FCU), Electronic Flight Instrument System panels (EFIS-Panels) and the Warning-Panels [6]. The design of the glareshield is that of a mirrored design. At the center of the glareshield is the FCU and to the left and right of the FCU are the EFIS-Panels. There are 2 EFIS-Panels, which are identical because it allows the pilots to adjust their own Navigation Display (ND) to their liking and allows both pilots to access the Flight Director (FD) and Instrument Landing System (ILS) [6]. To the side of both EFIS-Panels are identical Warning-Panels. The mirrored design of the glareshield enhances pilot comfort and increases efficiency and safety. Because of the mirrored design, both pilots can adjust the ND to their preferences which increases comfort and safety as it prevents distraction and being stressed [6]. Additionally, the mirrored design increases efficiency because it allows either pilot to access the functions of the EFIS-Panels. This means that any of the 2 pilots can quickly access the

EFIS-Panel or Warning-Panel functions instead of having one pilot finish their task and then pay attention to the EFIS-Panel or Panel and have the other pilot do nothing. Also, the design of the glareshield allows for easy access by both pilots [2].

The FCU on the glareshield is one of the most important systems on the A320. It serves the function of being the short-term interface between the pilots and the auto-flight system (AFS) [2], [5]. The programming of the flight parameters for the aircraft is conducted using this system. The height, heading and speed are all programmed in by the pilots themselves. In addition to flight parameters, it is also where the autopilot and auto-thrust functions are turned on or off. Furthermore, the FCU is where the required guidance mode is selected [5]. The EFIS-Panels also serve crucial functions. As mentioned before it allows both pilots to adjust their ND to their liking. It also serves the function of activating the FD and ILS systems. The EFIS-Panels are provided by Thales, which is an avionics company known for its EFIS-Panels and similar systems [7], [8]. The Warning-Panels are where the master warning and master caution buttons are located [6]. Other lights such as the auto-land and sidestick priority lights are also located here [5]. Below is figure 6, which shows the glareshield of the A320.

Figure 6: The glareshield for the A320 [2].

1.5 Main Instrument Panel

The main instrument panel (MIP) is the most important part of the cockpit in terms of controlling the aircraft. It contains many important components that are required for the safe and efficient operation of the aircraft. With that being said, it is not enough to just design a MIP. It needs to be designed such that it meets the requirements and needs of the pilots and regulators. The A320's MIP is designed to meet those requirements with many design features. Those design features are an evolution of design features developed earlier for the A300/A310 family of aircraft [5]. Many of those design features were discussed earlier in the Cockpit Design Requirements and Philosophy. However, one important design feature of the MIP is the principle of presentation or the need-to-know concept [5]. This design feature is really important especially for the MIP because the MIP provides a whole host of information that the pilots will need. The need-to-know concept is a philosophy that says that the information that is only required to be shown to the pilots will be shown and noncritical information will not be shown unless it requires urgent attention. The purpose of this philosophy is to ensure that pilots are not overloaded with information so that they do not become stressed or ‘paralyzed’ with too much data. This in turn increases safety because pilots are less likely to become panicked which reduces the chances of a mental error occurring. The MIP of the A320 is designed similarly to that of the glareshield in that it has a center column of instruments and mirrored components for both pilots. Not only is this required by law, but it also provides the same benefits that were discussed above for the glareshield. The MIP is broken up into 2 main sections, the center panel and CAPT and F/O panels [5]. The CAPT and F/O panels are mirrors of each other. Also, the MIP was designed such that the displays are in full view of both pilots [2]. The purpose of the MIP is to support the display units (DUs) which are required to fly, navigate, communicate, and monitor the A320 during the flight [2]. In total there are 6 DUs that use the newest screen technology for the time, LCD panels [6], [3]. The designers of the A320 used LCDs to replace the older and aging technology of CRT displays [3]. Furthermore, LCDs offer a variety of advantages over older CRTs such as being lighter, reduced power consumption and heat dissipation. LCDs also have better reliability and readability than CRTs. Figure 7 shows the layout of the MIP and figure 8 shows a detailed listing of all the components on the MIP and the glareshield.

Figure 7: The MIP of the A320 [2].

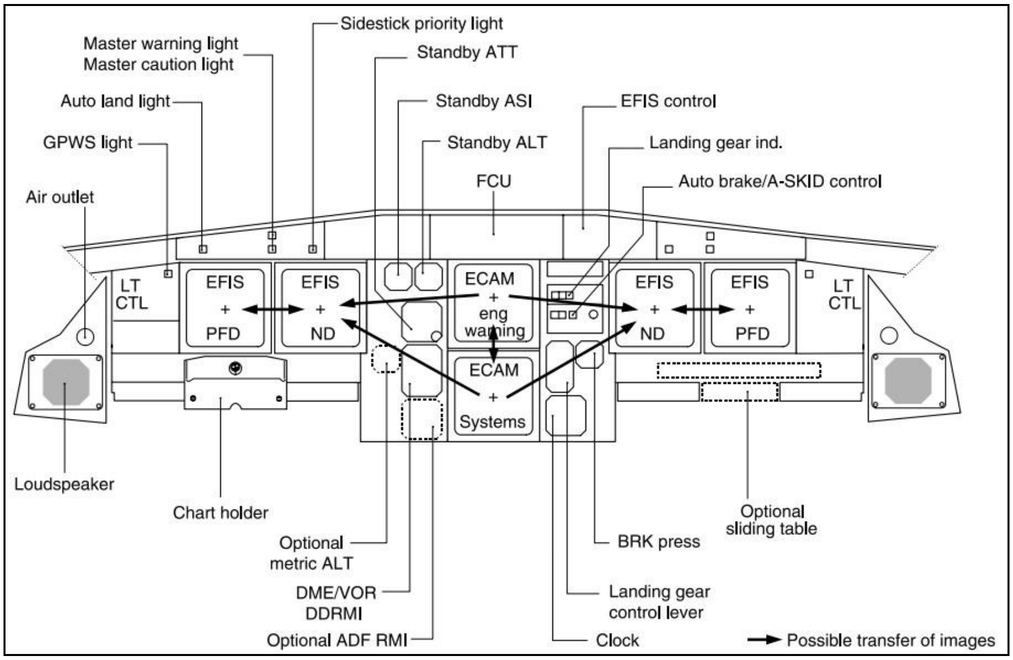


Figure 8: Schematic diagram of the MIP and Glareshield [6].

The CAPT and F/O panels, which stand for the captain and first officer panels, are to the left and right of the center panel. Looking at figure 7 they are the ones labelled with PFD and ND. The CAPT and F/O panels contain 2 DUs each for a total of 4 out of the 6. The DUs are fairly large, offering good resolution. They have a size of 7.25 in x 7.25 in or 18.42 cm by 18 .42 cm [5]. 1 DU is the primary flight display (PFD) while the other is the navigational display or ND. As stated before these DUs are mirrored for both pilots. The PFD is one of the most important DUs if not the most important [6]. It displays the basic T, which all aircraft must have as it is the law [5]. The PFD displays the artificial horizon, the attitude, the airspeed/Mach number with all upper and lower limits, the altitude with the vertical speed, heading, the AFS status, ILS deviation/marker and finally the radio altitude [5]. All of these pieces of information are crucial for flying the A320 (or any airplane for that matter of fact). Hence, why it is mirrored for both pilots. The NDs for the pilot and co-pilot displays the navigation route, airports, waypoints, and weather conditions from the weather radar [6]. Additionally, the ND can be set to 3 different modes to the liking of the pilots. These modes are ROSE, ARC and PLAN mode [5]. ROSE mode shows the heading, the aircraft symbol is centered on the screen and radar is available. ROSE mode also has some sub-modes, ROSE-ILS, -VOR or -NAV [5]. ARC mode, similar to ROSE mode, has the heading displayed and the radar is available too, but the horizon is limited to a 90-degree forward FOV. PLAN mode displays the north direction, and it is centered on the selected waypoint [5]. All 3 modes, specifically the ROSE-NAV mode, use map data from the flight management system (FMS). The layout of the CAPT and F/O panels is designed specifically to ensure enhanced visibility of all of the DUs in the normal configuration, shown in figure 8 above, or any other configuration [5]. Also, under the CAPT and F/O panels, there is the possibility of installing a sliding table and footrest to enhance crew comfort [6]. The location of the CAPT and F/O panels being front and center in the FOV of the pilots is key because it makes logical sense, and it enhances safety. The most essential information for flying a plane needs to be the center of attention for the pilots so having it feature predominantly in the pilot's FOV makes sense. Also, it ensures that the pilot does not miss any valuable information since it is in front of them.

The next section of the MIP is the center panel. The center panel has 2 DUs as well, which are also the same size and type as the ones used for the PFD and ND. They are also interchangeable with the CAPT and F/O DUs [5]. The DUs are stacked on top of each other. The upper DU is the engine display while the lower one is the system display [5], [6]. These displays are part of a larger system called the ECAM or Electronic Centralized Aircraft Monitor which does fault monitoring and corrective procedure checklist [6]. The engine display's main function is to display information related to the engine. It shows the main engine parameters, the thrust limit and command, total fuel, the position of the flaps/slats and lastly, memo and warning lights [5]. The system display shows the synoptic diagrams of the aircraft systems and the status of the aircraft. It shows a list of items that are operationally significant to the aircraft [5]. The center column also has more features important to the aircraft. The center column also has standby instruments, landing gear control and indicators with brakes and also a clock [5]. Since the center column contains some of the most vital information required by pilots it makes logical sense as to why it is centered for the pilots. This allows either pilot to easily view the information being displayed and react accordingly if there is an emergency. Additionally, since the center column is centered and on the MIP, it ensures that the information displayed on the 2 DUs is in the FOV of the pilots. This increases safety as the likelihood of a pilot not seeing critical information is low. Figure 9 below shows the schematic diagram of the center column for the MIP.

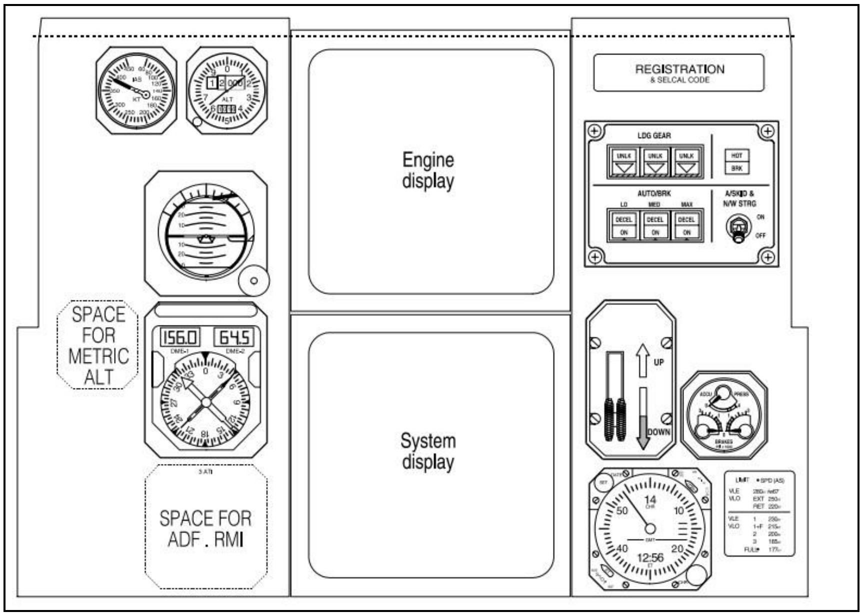


Figure 9: Schematic diagram of the MIP Center column [6].

While the most important aspects of the MIP have been discussed in the 2 paragraphs above, other features are included in the MIP. On the outer edges of the MIP are the brightness controls for the PFD and ND [6]. The loudspeaker and an air vent are also located on the outer edges of the MIP as seen in figure 8 [6]. These features are mirrored for the captain and the first officer. These features are important to the comfort and ergonomics of the pilots because they can adjust the brightness of the DUs to their liking, hear things clearly and be able to adjust the cabin temperature to be comfortable. While these are important, they are not as important as the information being shown by the DUs which is why they are off to the outer edges of the MIP.

1.6 Center Pedestal

The center pedestal (CP) is as equally important as the MIP as it contains many of the important controls for the aircraft. Therefore, the design of the CP must also be carefully considered. For the A320, the CP is designed to allow efficient and ergonomic access to the controls of the CP [3]. This enhances safety because the pilots can access these controls easily without any obstructions that could endanger the passengers and crew of the aircraft. Just like the overhead panel, the CP is divided into 2 sections, a forward and an after section [6]. The purpose of this, just like the overhead panel, is to provide an intuitive design so that pilots can reach for the desired control using their feel without necessarily looking at the CP or using thought. The front section contains the more vital controls, and the rear section contains the less vital controls. The purpose of the CP is to support the controls for engine and thrust, aircraft configuration, navigation, and communications [2]. In total there are 17 different controls/control panels on the CP, all crucial to the operation of the A320 [3]. Figure 10 below shows the schematic diagram of the CP for the A320.

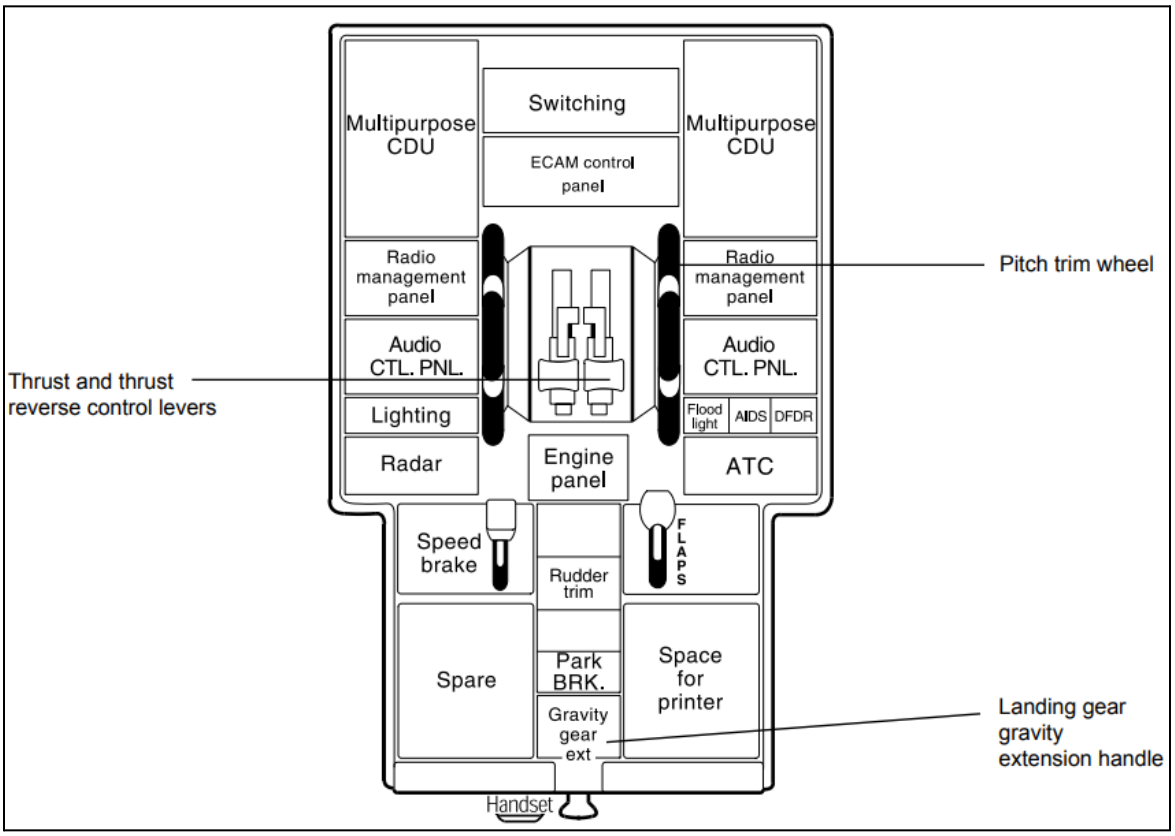


Figure 10: Schematic diagram of the CP [6].

Starting with the front section, the most important control of the front section is the throttle [3]. This is part of the engine controls, and it is where the thrust level of the engine is controlled. Given how important the throttle is, it being located in the front section and centered makes sense from an ergonomic standpoint and a safety standpoint. It allows the pilots to easily access the throttle controls without any obstructions that would occur if they were located anywhere else. Just next to the throttle, see figure 10 above, is the pitch trim wheel which is used to adjust the pitch trim of the aircraft during flight. This control is as important as the throttle which is why it is located next to them, for the same ergonomic and safety reasons. All around the throttle and pitch trim wheel are various controls and displays which are especially important. Controls such as the weather radar, air traffic communication (ATC), traffic alert and collision avoidance system (TCAS), ECAM control panel, multipurpose control, and display units (MCDU) and others are all located in the front section of the CP [5], [6]. Since these controls and others are the most important on the CP, it is why they are located in the front section. Also, these controls serve some of the most crucial functions and provide some of the key data that the pilots need. For instance, the ATC/TCAM, provide pilots with the means to communicate with air traffic controllers and ensure that they do not fly close to or collide with other aircraft or objects. The MCDU provides a whole host of functions from flight management to others like data link and maintenance [5]. The radio management panel (RMP) also located on the front section of the CP, provides the function of tuning all radio communications. It is also part of the redundancy system of the flight management and guidance system (FMCG) as it can be used as radio navigation if there is a failure in the FMCG [5]. The ECAM control panel, as the name suggests, allows the pilot to adjust what is being displayed on the system display DU discussed in the MIP section [6].

Moving on, the after section of the CP contains other important control functions. Looking at figure 10 the after section of the CP contains speed brake controls, rudder trim, flaps control, parking brake, gravity gear extension handle and a printer [5]. The speed brake, rudder trim, flaps, and parking brake controls, as the name suggests, are the controls for the respective systems. The gravity extension handle is part of the landing gear redundancy system. It ensures that the landing gear can extend through gravity if the electronic/hydraulic methods were to fail [6]. The printer is a feature part of the aircraft communications addressing and reporting system (ACARS). ACARS "is a digital communication system used on aircraft that allows messages to be sent and received in text format between aircraft and ground stations" [9]. This communication is facilitated by 3 different methods, VHS or Very High Frequency, HF or High Frequency and SATCOM or Satellite Communication. The messages usually sent via ACARS deal with communications related to ATC, Aeronautical Operational Control (AOC) and Airline Administrative Control (AAC) [9].

1.7 Sidestick Console

The last major part of the Instruments and Crew-plane Interface is the sidestick console. Due to the fly-by-wire method that the A320 uses, the traditional aircraft yoke seen in other aircraft is replaced by the sidestick console [3]. The sidestick console is the manual control interface for the pilots. Moving the sidestick changes the trajectory of the aircraft, similar to that of the traditional aircraft yoke or that of a joystick in other vehicles [5]. The manual input by the pilot moving the sidestick is sent to the Electronic Flight Control System (EFCS) where this input, called the trajectory order, is combined with the aerodynamic data to complete the maneuver. Furthermore, EFCS uses the aerodynamic data and the trajectory order to stabilize the aircraft and prevent prohibited attitudes [5]. The design of the sidestick console provides a host of benefits for pilots and has numerous safety and intuitive features. The sidestick was designed with human factors in mind, ergonomic and comfort based. Like with many of the instruments discussed already in this section, the sidestick is mirrored for both the captain and first officer. So, either pilot can control the sidestick. The design of the sidestick itself is meant to fit comfortably into the hands of the pilot [2]. It has an adjustable armrest so the pilot can comfortably control the sidestick [5]. The reason that the sidestick was chosen over a traditional yoke is that it would be mounted off to the side which would provide numerous benefits. Benefits such as non obstructed view of the MIP, easier access to the seat, and allowing the possibility of installing a sliding tray as discussed in the MIP section [5]. The intuitive design of the sidestick allows the pilot to disengage the autopilot or take priority control over another pilot with a single press of a button on the sidestick [2], [5]. There are also buttons to access the radio and disengage the neutral position of the sidestick [5]. Part of the safety features of the sidestick is that only one pilot can provide input to the sidestick, hence the need for the priority take-over button [3]. Another safety feature is that once the autopilot is on the sidestick is locked in the neutral position, meaning there is no input from 2 different sources [3]. Lastly, an intuitive and safe feature of the sidestick is that the autopilot can be disengaged in emergencies if the pilot puts sufficient force on the sidestick [3]. This makes sense because in emergencies pilots tend to grab and yank the yoke, so this feature facilitates that instinct in the sidestick. Figure 11 shows the sidestick control of the A320.

Figure 11: The Sidestick control of the A320 [10].

2. Electric Power System

2.1 System Overview

The Airbus A320 jetliner has an electrical and power system like any other competitor airliner on the market. The aircraft's electric power system is designed to supply power to all the components and other subsystems on the aircraft while in air and on ground. The electric power system on the A320 can be divided into four aspects for its analysis. The system is responsible for power generation, power conversion, power distribution and system protection. The aircraft uses two main generators known as Integrated Drive Generators (IDG) to generate the necessary AC power. If the normal operation of these generators fails, the aircraft uses a backup generator known as APU generator. The two engine driven generators through an integrated drive unit, each supply 90 KVA of three phase 115/200 V, 400 Hz power to the aircraft's electrical network. The power generated from each of the AC generators can power the entire electric network on the Airbus A320 aircraft. There is also an emergency generator which is driven by the blue hydraulic circuit. The emergency generator supplies 5KVA of three phase 115/200 V, 400 Hz power in case all three generators fail.

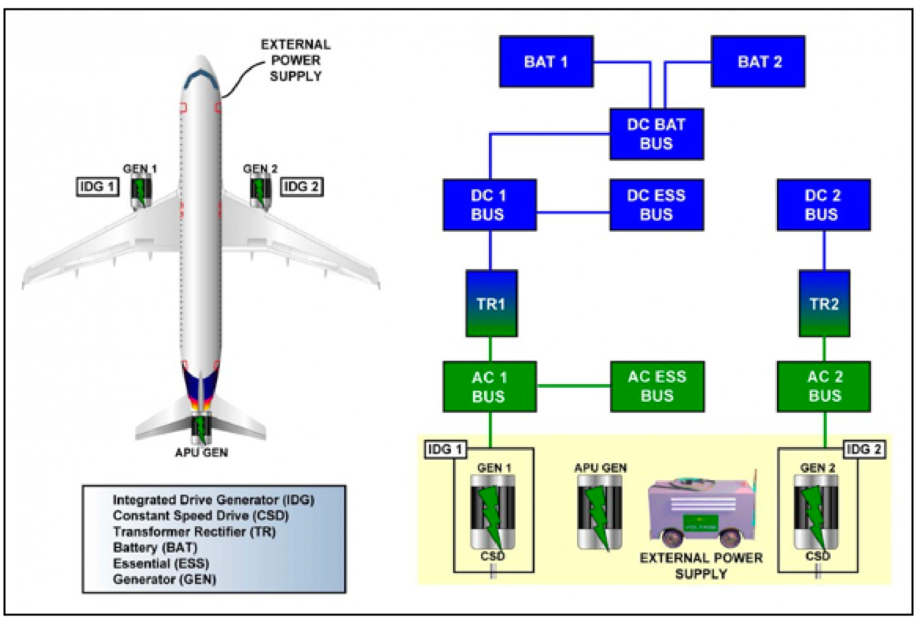


Figure 12: Airbus A320 Electric Power System [11].

The figure above illustrates the basic concept of the electric power system of Airbus A320. The aircraft consists of systems/components that either run on AC power or DC power. The power to each component is supplied by an AC Bus or DC Bus respectively. The electric system on the A320 generates AC power which is converted to DC power via a transformer rectifier unit. With the use of DC power from the batteries, they are charged and recharged throughout the flight from the AC power supply. These batteries are monitored through the current levels presented to the pilot on the Electronic Centralized Aircraft Monitor (ECAM). The DC power subsystem on the A320 consists of a 28-Volt DC power supply. The DC power system consists of two batteries that are responsible for maintaining DC power supply under transient conditions among other tasks discussed in the later section. In case of power failure of all AC power (from the two IDGs, APU and emergency) the DC power from the batteries is converted to AC power for AC essential components. The aircraft's electric system is designed such that it prioritizes the two engine driven generators over the APU and the external power source.

2.2 Components

The electric power system consists of many subsystems and components that are responsible for power generation, power conversion, power supply and system protection against short circuits. The electric power system on the Airbus A320 consists of two Engine Driven Generators or Integrated Drive Generator (IDGs), an APU generator, an external power connection, an emergency generator, a static inverter, a transformer rectifier, batteries, circuit breakers, AC Bus, AC essential Bus, DC Bus, DC essential Bus, etc. This section focuses on the operation of these components in relation to the four important aspects of the electric power system.

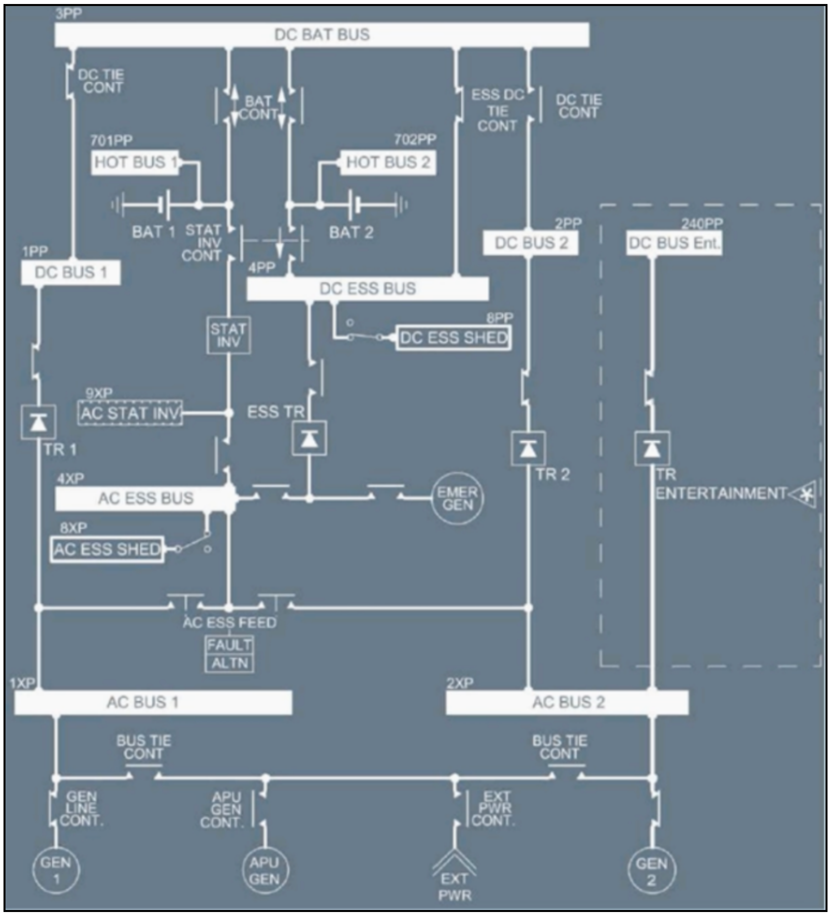


Figure 13: Electric Power System Diagram [12].

2.2.1 AC Components

The figure above illustrates a detailed circuit diagram of the power supply network of the A320's electric power system. As discussed in the previous section, the system consists of two three phase generators called 'GEN 1' and 'GEN 2' that generate AC power. The AC power is supplied to the AC buses 1 and 2, DC buses 1 and 2, AC essential bus via an AC essential feed switch, DC essential bus via a DC essential feed switch, the DC batteries for recharging, and the In-Flight Entertainment DC Bus. These generators are driven by an engine through an integrated drive unit. In addition to the two generators, there is an APU generator called 'APU GEN' which is capable of supplying power and replacing one or both engine driven generators in case they fail at any time. Each generator supplies the power to the respective AC bus via a Generator Line Contactor (GLC). The output for the generators is controlled by the Generator Control Unit (GCU). The GCU is responsible for controlling the voltage and frequency output from the generators. In addition, the GCU also controls the GLC for each generator to protect the network against any failures or short circuits. This is very essential as the power supply is the main objective of the system. Another source for power is the ground power. This is represented by 'EXT PWR' and is used when the aircraft is parked at the gate. The ground power connector is located near the nose wheel that allows the ground power to be supplied to all busbars. A Ground Power Control Unit (GPCU) protects the network by controlling the external power contactor. The connection of the external power and the APU generator to the AC bus 1 and AC bus 2 is controlled by a switchboard.

The emergency generator operated by the blue hydraulic circuit is represented by 'EMER GEN' on the diagram. The emergency generator is connected to the AC essential bus and DC essential bus via a switch in case all three generators fail. Like the DC power system, the AC power from the emergency generator is converted to DC power via a transformer rectifier (ESS TR). The function of the emergency power is controlled by the GCU. The GCU is responsible for maintaining the emergency generator at a constant speed. It controls the generator's output voltage and protects the network by controlling the GLC dedicated to the emergency generator. Another important AC component is the static inverter. This component is necessary to transform the DC power from the batteries into 1 KVA single phase 115 V 400 Hz AC power. This power is then supplied to the AC essential bus. The pilots can push the 'BAT 1' and 'BAT 2' buttons on the overhead panels to turn on the DC battery power supply in case of any AC power failures.

2.2.2 DC Components

As discussed previously, the power generated from the AC generators is also supplied to DC components and the batteries on the aircraft. The Airbus A320 also has an In-Flight Entertainment (IFE) service which requires the supply of DC power. The IFE receives power from the AC bus 2 under normal operation and is represented on the diagram with 'DC BUS Ent.'. The DC power is supplied to the remaining necessary components from the DC buses 1 and 2 which are connected to the AC buses 1 and 2 respectively. Two transformer rectifiers are used to convert the AC power into DC power. They are represented as 'TR 1' and 'TR 2' on the circuit diagram. The transformer rectifier unit for the entertainment system is called 'TR

ENTERTAINMENT'. The transformer rectifiers are responsible for supplying 200 A of DC current to the respective DC buses.

Figure 14: NCSP B 23060 LM - Nickel Cadmium Aircraft Battery [13].

The Airbus A320 uses two NCSP B 23060 LM - Nickel Cadmium Aircraft Battery with a nominal operating capacity of 23 ampere-hours at 1 hour rate. The two batteries are always connected to the hot buses called 'HOT Bus 1' and 'HOT Bus 2'. The hot buses for the batteries indicate the direct connection to the aircraft battery. The bus is always hot if there is a charged battery present on the aircraft. The hot bus powers the basic operations on the aircraft which always require a power source. These are entry doors, lighting, aircraft clock, etc. Another important feature of the hot bus is to supply power to components that are critical to flight safety. These include fire extinguishers, fuel shut off valves, and fuel pumps.

Each battery on the A320 has a Battery Charge Limiter (BCL). The BCL is responsible for monitoring battery charging along with controlling the connection/disconnection of the battery to the DC battery bus (DC BAT BUS). The DC battery bus serves in case of power failures. The batteries connect to the DC battery bus under the following circumstances:

- During APU start. The connection is limited until the APU is running and supplying the required output. The connection time is typically 3 minutes.
- Loss of AC Bus 1 and AC Bus 2.
- Battery charge below 26.5 Volt.

The Airbus A320 uses two types of circuit breakers. The use of circuit breakers is essential to cut off the power supply from the rest of the network in case of short circuits. The use of the circuit breakers is done to protect the network rather than to protect the sensor. This is because there are multiple redundant sensors connected to the network. The two types of circuit breakers are Monitored and Unmonitored. The monitored CBs are represented with green, and the non-monitored CBs are represented with black. The monitored CB shows a ECAM caution message called 'C/B TRIPPED' indicating the location of the tripped circuit breaker in case when the CB has been tripped for more than 1 minute.

2.3 System Configurations

2.3.1 Normal Configuration

In Flight

Under normal configuration, each engine driven generator supplies its associated AC BUS (1 and 2) via its generator line contactor (GLC 1 and GLC 2). The AC BUS 1 normally supplies the AC ESS BUS via a contactor. TR 1 normally supplies DC BUS 1, DC BAT BUS, and DC ESS BUS. TR2 normally supplies DC BUS 2. The batteries are connected to DC BAT BUS for charging, once fully charged, the battery charge limiter disconnects them. The figure below is a configuration for each electrical system in flight.

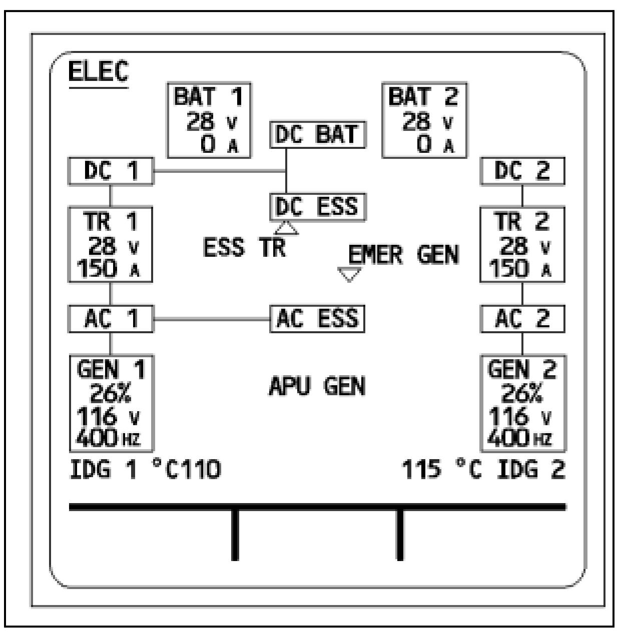


Figure 15: In Flight Electrical System Configuration

On Ground

On the ground, the APU generator or external power may supply the entire system. When only ground services are required, external power can supply the AC and DC GND/FLT directly. This configuration can be selected with the MAINT BUS switch in the forward entrance area.

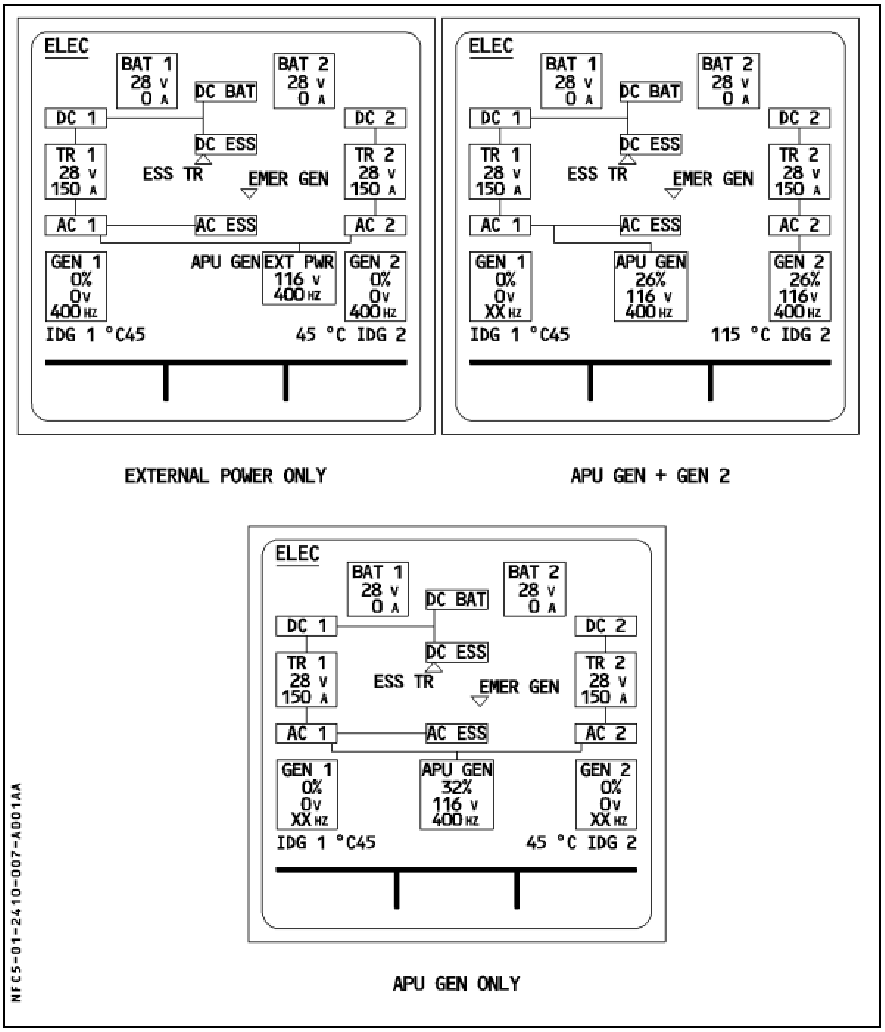


Figure 16: Possible On Ground Electrical System Configuration

2.3.2 Abnormal Configuration

Abnormal configurations can arise if one of the following events occurs: failure of one engine generator, failure of AC BUS 1, failure of one TR, or failure of TR 1 and TR 2. In the case of an engine generator failure the system automatically replaces the failed engine with the APU GEN if available or the other engine generator. The figure below shows the configuration after an engine generator failure.

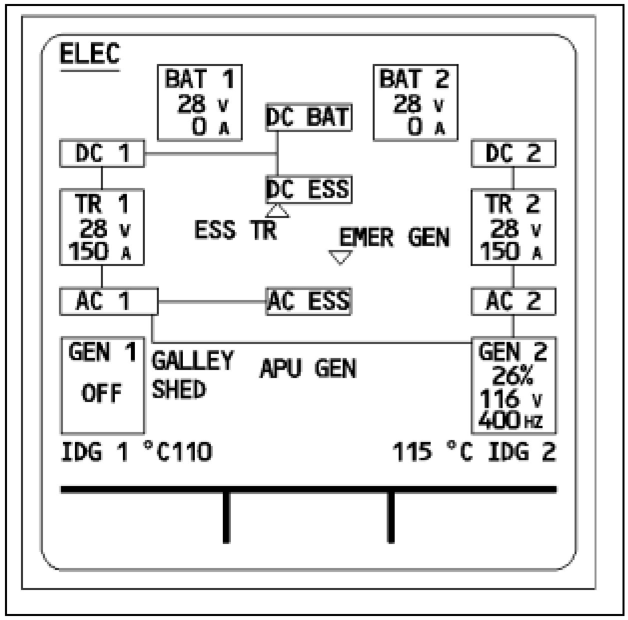


Figure 17: Failure of One Engine Generator.

In the case of AC BUS 1 failure, AC BUS 2 can supply the AC ESS BUS and the ESS TR can supply the DC ESS BUS, through the AC ESS FEED pushbutton switch. The DC BUS 2 supplies the DC BUS 1 and DC BAT BUS after 5 seconds. The figure below shows this configuration.

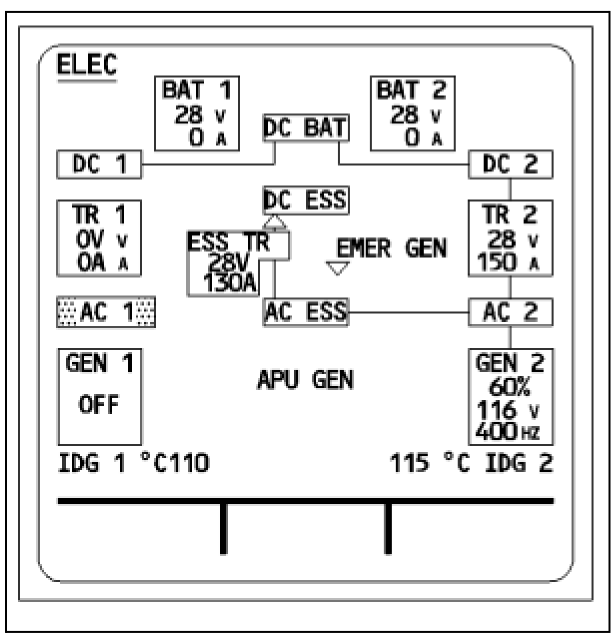


Figure 18: Failure of One AC BUS 1.

If one TR fails due to overheating or minimum current, then the contactor will open automatically and the other TR will have to replace the faulty one. The ESS TR will supply the DC ESS BUS as shown in the figure below.

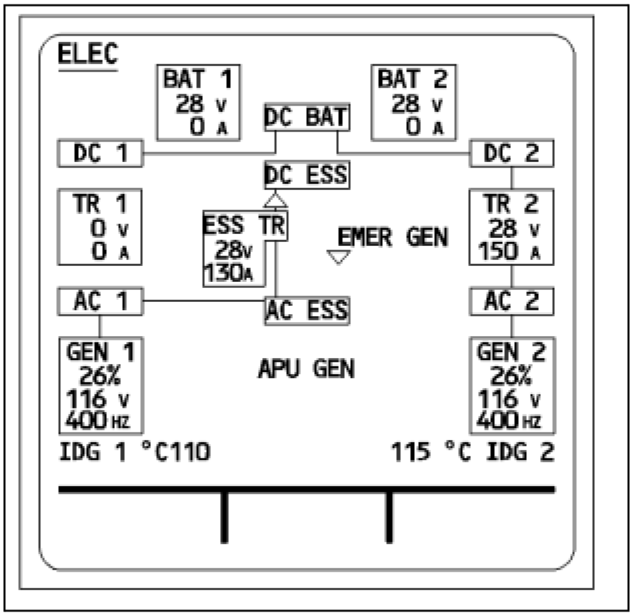


Figure 19: Failure of one TR.

If TR-1 and TR-2 are lost, then DC BUS 1, DC BUS 2, and DC BAT BUS are lost. DC ESS BUS is then supplied by the ESS TR, as shown in the figure below.

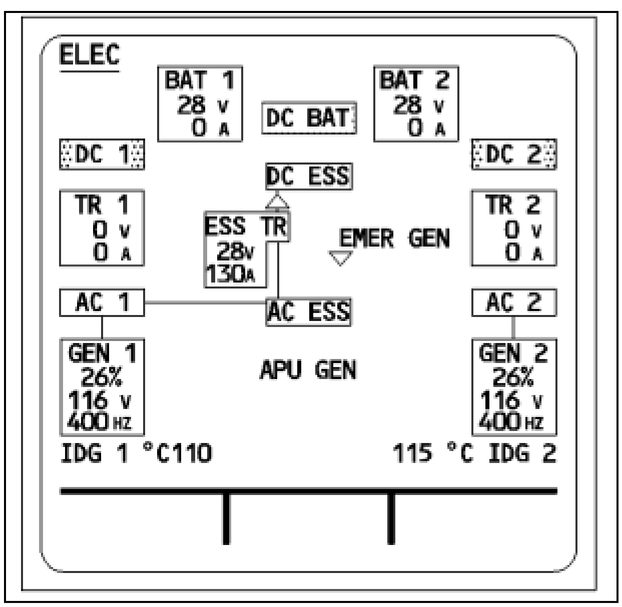


Figure 20: Failure of TR 1 and TR 2.

2.3.3 Emergency Configuration

If both AC BUS 1 and AC BUS 2 are lost and the aircraft speed is above 100 knots, then the Ram-Air Turbine (RAT) extends automatically. The RAT generator powers the blue hydraulic system, which drives the emergency generator by means of a hydraulic motor. The generator supplies the AC ESS BUS and the DC ESS BUS via the ESS TR. If the RAT stalls or if the aircraft is on the ground with speed less than 100 knots, the emergency generator has nothing to drive it. The emergency generation network transfers automatically to the batteries and static inverter and the buses AC SHED ESS and DC SHED ESS are shedded. When the aircraft is on the ground and below 100 knots, the DC BAT BUS is automatically connected to the batteries. When the aircraft is on the ground and below 50 knots, the AC ESS BUS is automatically shed, leading to the loss of all CRTs. The figure below shows the emergency generator running.

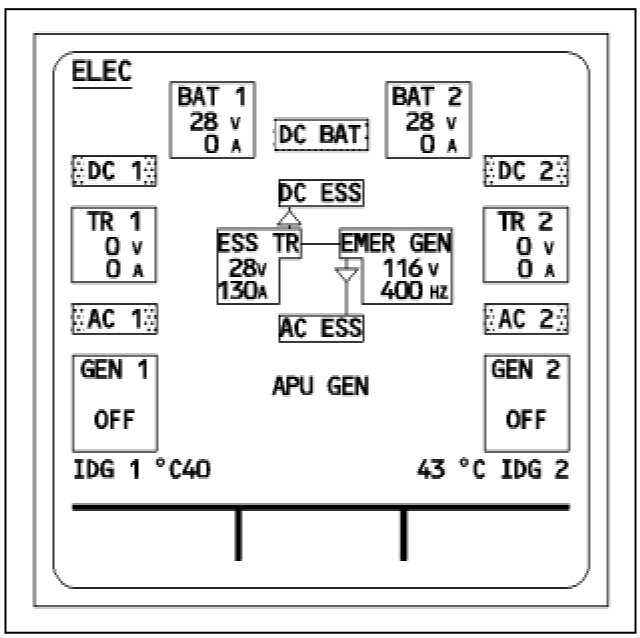


Figure 21: Electrical System with Emergency Generator Running.

2.3.4 Battery Configuration

In the case that the aircraft is flying with the only electrical source coming from the batteries, then the power is supplied to the units shown blacked out in the figure below on the left. The figure on the right shows the units powered when the power source is only from the batteries and the aircraft is on the ground with a speed less than 50 kt.

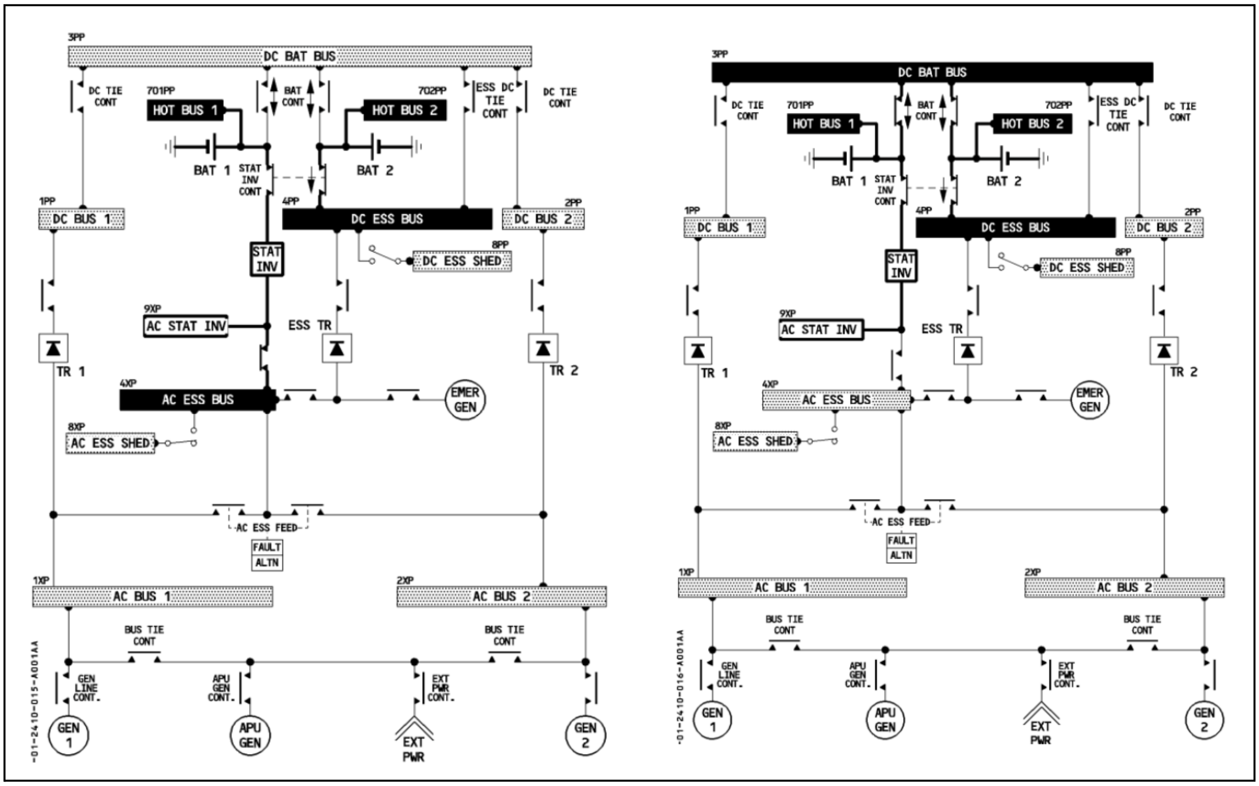


Figure 22: In Flight with Batteries Only and On Ground with Batteries Only.

2.3.5 Smoke Configuration

Smoke configuration occurs once the main bus bars are shedded, the electrical configuration is the same as the emergency configuration in that there is a loss of the main generators. The only exception is that the fuel pumps are connected upstream of the GEN 1 line connector. The result is that 75% of the entire electrical equipment becomes shedded and all remaining equipment is supplied through the circuit breakers located on the overhead panel.The figure below illustrates the overhead panel of the Airbus A320. The figure below shows the smoke configuration.

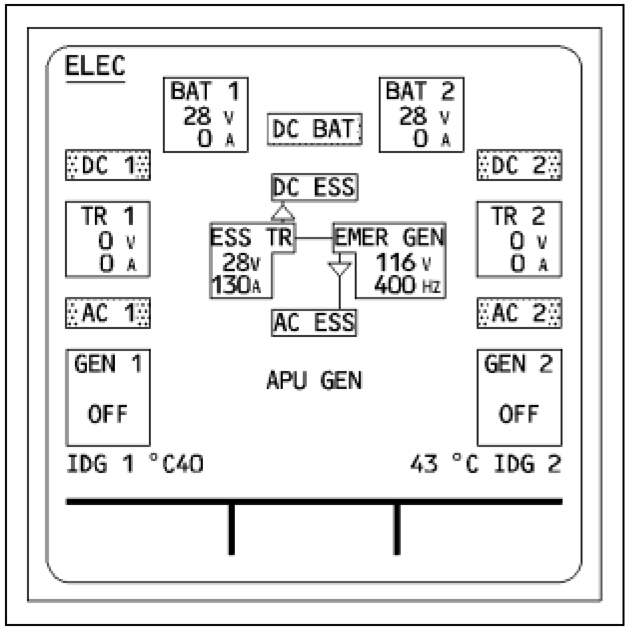


Figure 23: Smoke Configuration.

2.4 Controls and Indicators

The electrical indicators and controls are located on the overhead panel in the cockpit. The panel consists of the battery voltage display and various push buttons that control the battery, AC and DC buses, IDG, APU and emergency generator.

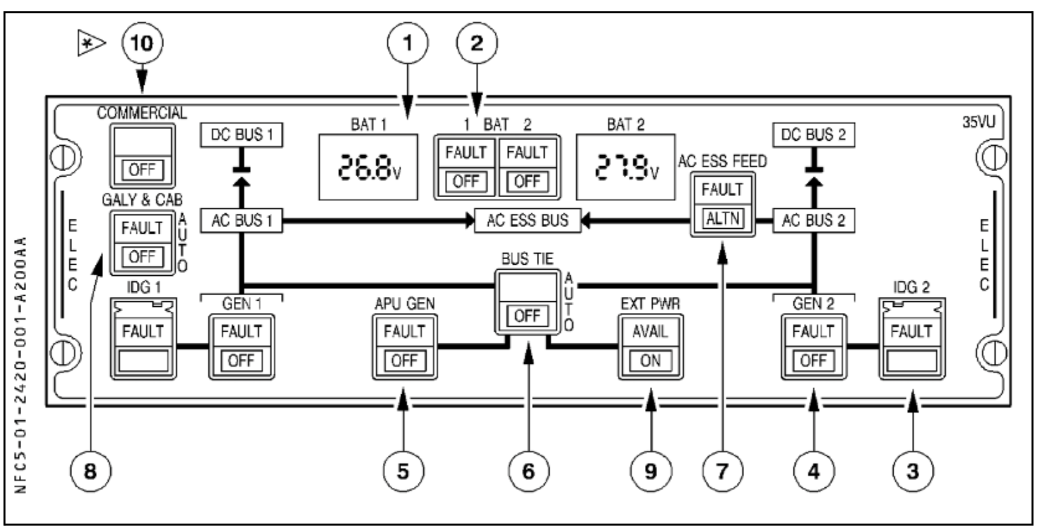


Figure 24: Overhead Electric Panel.

1. Indicates the voltage for battery 1 and 2.
2. Controls the connection/disconnection of battery 1 and 2 by controlling the battery charge limiter.
3. Controls the disconnection of the IDG 1 and 2 by disconnecting the respective IDG with its drive shaft.
4. Controls the energizing/de-energizing and the connection of the line contractor for the respective generator.
5. Controls the energizing/de-energizing and the connection of the line contractor for the APU generator.
6. The bus tie switch is on auto as a default and controls the bus tie contactors (BTC) to maintain power supply to AC buses 1 and 2.
7. Changes the AC essential power source from AC bus 1 to AC bus 2 under alternate configuration.
8. Controls the main galley, secondary galley and in seat power supply.
9. Controls the power supply from an external power source.
10. Controls the cabin and cargo lights, powers the toilet and water systems, and the passenger's entertainment.

3. Flight Control System

An aircraft's flight control system is made up of the flight control surfaces and corresponding linkages, as well as the pilot controls and mechanisms that control the aircraft's flightpath. In the Airbus A320, the flight control system is known as fly-by-wire (FBW). When the aircraft first entered into service, it was the first aircraft to operate with a digital fly-by-wire system. The basic principle of the fly-by-wire system is that the flight control surfaces are electrically controlled and are activated by hydraulics as opposed to a conventional control system which involves mechanical controls. The advantages of the fly-by-wire system is a weight reduction through reducing the number of mechanical linkages and replacing them with electrical ones, workload and training reduction, as well as an increase in stability and comfort which is a result of the more advanced autopilot. The FBW system works by taking pilot (and autopilot) control inputs into a series of seven flight control computers that process these inputs and calculate the necessary movements of the control surfaces that are needed to respond to the given input. All control surfaces displaced via hydraulic actuation. The figure below shows a simplified model of the way pilot and autopilot inputs are translated into movements of the control surfaces for the A320 [16] [17].

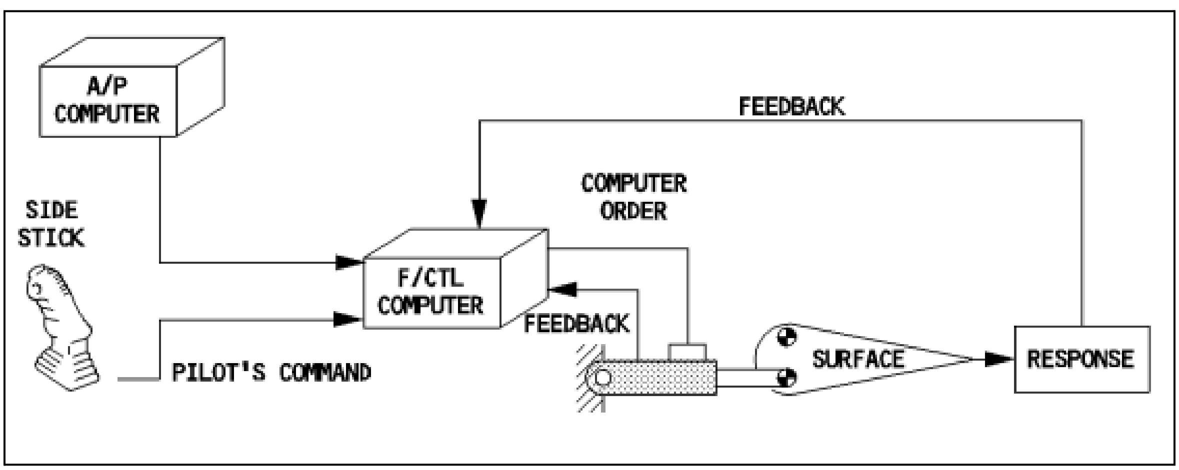


Figure 25: Flight Controls Model for Airbus A320. [16]

The captain and co-pilot each have a sidestick control that is used to regulate the pitch and roll of the aircraft, the two sidesticks are mechanically independent, and send two separate signals to the flight control computers. There are two sets of pedals which are rigidly interconnected that are used to mechanically control the rudder of the aircraft. A lever on the center pedestal is used to control the speed brakes, while a set of mechanically interconnected handwheels are used by the pilots to control the trimmable horizontal stabilizer. Lastly a single switch on the center pedestal regulates the rudder trim. [16]

3.1 Control Surfaces

The A320's flight control surfaces are made up of ailerons, flaps, spoilers, slats, speed brakes, horizontal stabilizers, elevators, and a rudder. All of these control surfaces are electrically controlled with the exception of the rudder which is controlled mechanically. The horizontal stabilizers are controlled electrically under normal and alternate control conditions, but can be controlled mechanically, when manual trim control becomes engaged. The figure below shows the configuration of the control surfaces on the A320. [16]

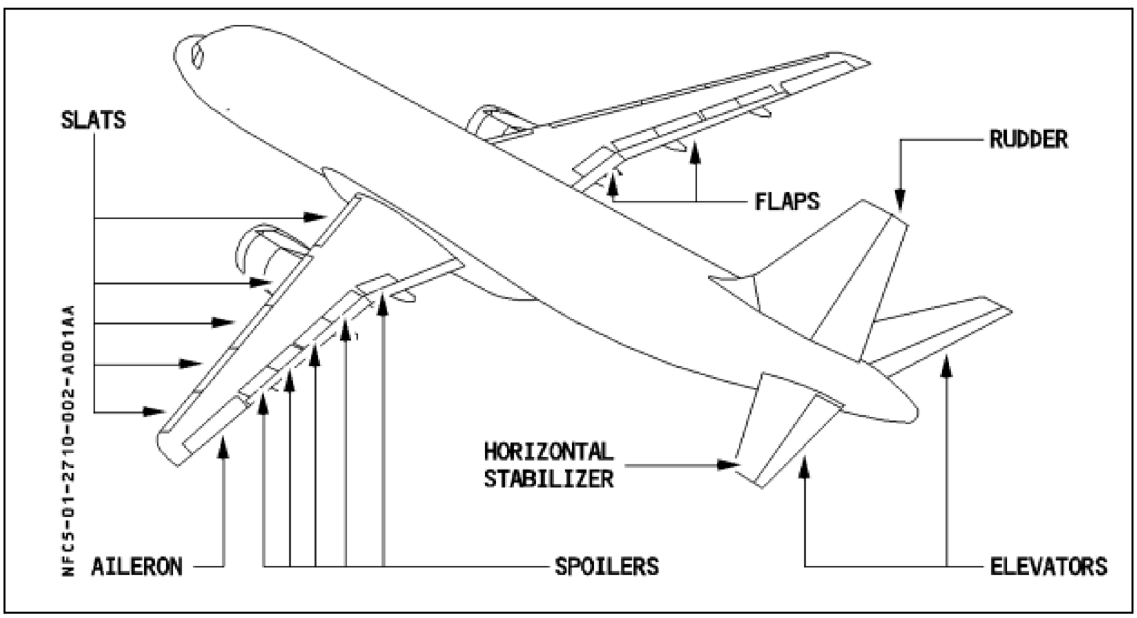


Figure 26: Flight Controls Surfaces for Airbus A320. [16]

3.2 Flight Control Computers

The entire FBW system is structured around control and monitoring computers, which have stringent safety requirements with two channels, one for control, and the other for monitoring. The control channel is used to control the control surface, while the monitoring channel ensures the control channel is performing properly. There are a total of 7 flight control computers that process the pilot or autopilot's inputs, of which 2 are Elevator Aileron Computers (ELAC), 3 are Spoiler Elevator Computers (SEC), and the last 2 are Flight Augmentation Computers (FAC). Each of these 7 computers has a control computer as well as a monitoring computer. The ELAC does most of the regular elevator and stabilizer control, while the SEC is on standby for the elevator and stabilizer control. There are 2 additional computers known as the Flight Control Data Concentrators (FCDC) which take data from the ELACs and SECs and transmit it to the Electronic Instrument System (EIS) and the Centralized Fault Display System (CFDS). These flight computers control the aircraft's movement in the three directional axes, pitch, yaw, and roll. The flaps and slats are lift augmentation devices, in that their primary goal is to increase the lift or drag of the aircraft, and are critical for takeoff and landing. There are 2 slat flap control computers (SFCC), each has a slat and flap channel. The aircraft is designed with redundancy in mind, in that each flight computer is able to control the aircraft in flight if the other computer(s) or its control surfaces of the same type become inoperable. The setup enhances safety as a single failure from the flight control system will not cause the pilot to lose control of the aircraft. The figure below shows the interactions between the pilot controls, data from sensors, the flight control computers, and the control surfaces [16].

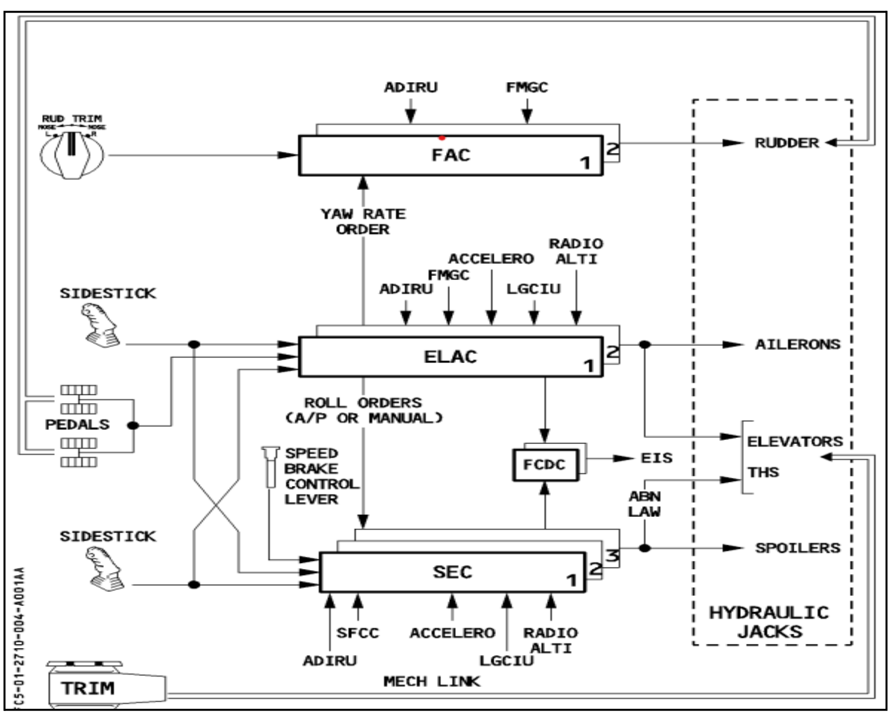


Figure 27: Flight Control System Network for Airbus A320. [16]

3.3 Computer Architecture

Each computer channel contains one or more processors, associated memories, input/output circuits, a power supply unit and software. Under normal operation, both channels operate in unison either and are either active simultaneously or waiting simultaneously to to an active state from standby. If the results of either channel diverge significantly, then the channel(s) cut any connection between the computer and the rest of the system. Failure detection is observed when the difference between the control and monitoring commands exceeds a certain threshold. This failure detection system prevents the error of one computer leaving and affecting the rest of the system. Flight control computers are designed to be protected against under and over voltages, electromagnetic forces, and the effects of lightning. They are designed to still operate if the ventilation system that provides cooling to the computers fails. The figure below shows the composition of the two channels that make up a flight control computer. [18]

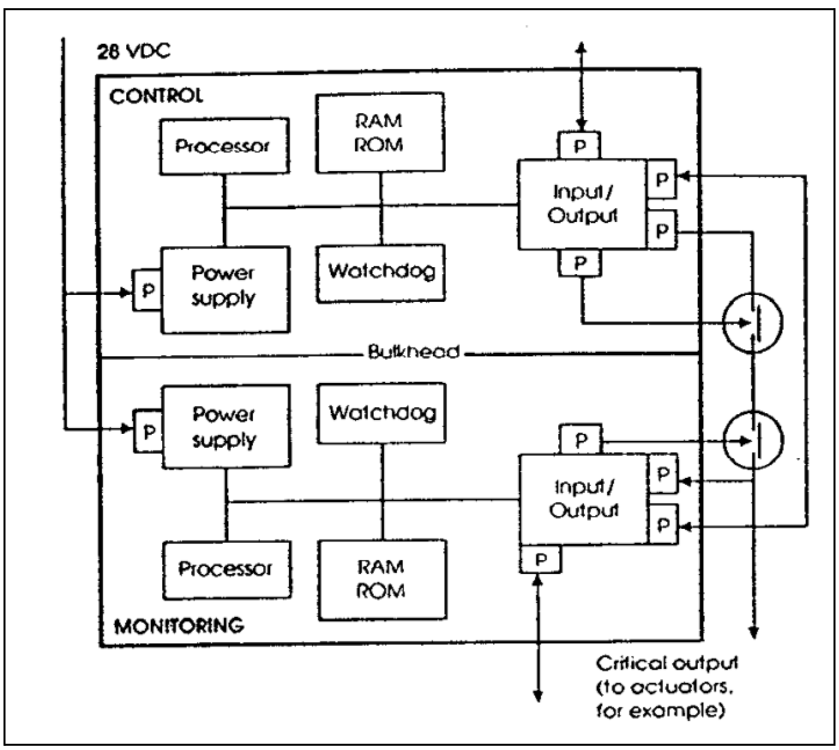


Figure 28: Control and monitoring computer architecture [18]

3.4 Failure Detection and Reconfiguration

The types of failures that can occur in flight control computers include latent failure and threshold failure. Latent failure is often very minute and can be hidden for a long time after they occur. An example is a monitoring channel that becomes passive only becomes detected when the monitored channel fails. To protect against latent failure, tests are conducted frequently so that the probability of failure in operation remains low. Typically self tests are conducted daily during the energization of the aircraft period. When the results between the control and monitoring channels exceed that of the allowable threshold, a failure becomes detected. There is a confirmation period that lasts approximately 0.05 seconds, which ensures that the detected failure is valid, before the computer is disconnected. The threshold is designed to be particularly wide to avoid unnecessary computer disconnections and particularly narrow so that errors do not go undetected. System tolerances are used to prevent incorrect failure detection, these tolerances include sensor inaccuracy, rigging tolerances and computer asynchronism. Errors that cannot be detected by the computers are assessed based on the impact they will have on the controls and structural loading. For any set of the flight control computers, one of the computers is active while the others are in standby. As soon as the operating computer fails and becomes inoperable, one of the standby computers almost instantly becomes active, without causing any changes to the control surfaces [18].

3.5 General Architecture

The figure below shows the framework for all of the control surfaces on the aircraft and the computers that control them. The letters G, B, and Y indicate the hydraulic power source for each servo control. The system is designed with multiple power sources so that the aircraft can still be controllable in the event that hydraulic power were to be lost from one of these power sources [16].

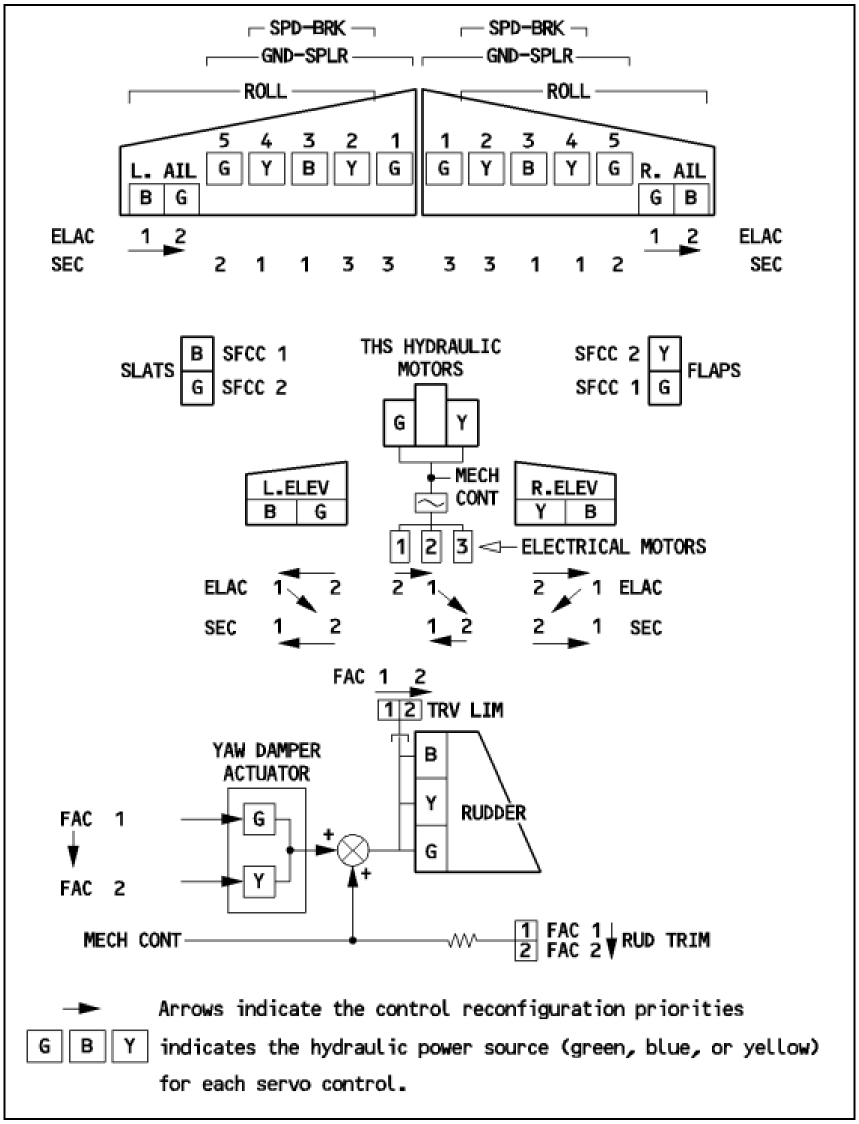


Figure 29: General architecture [16]

3.6 Pitch Control

Two elevators and the trimmable horizontal stabilizer (THS) are used to control the pitch of the aircraft. The elevator has a maximum deflection angle of 30° nose up and 17° nose down. The maximum horizontal stabilizer deflection angle is 13.5° nose up and 4° nose down. During normal flight operations, the ELAC2 computer controls the elevators and horizontal stabilizer, with the green and yellow hydraulics driving the left and right elevators respectively. The THS is driven by the first of three electric motors. If a failure were to occur with either the ELAC2 computer or the hydraulic system/ hydraulic jack, then the pitch control system shifts to the ELAC1. ELAC1 controls the elevators via the blue hydraulic jack and the THS via the second electric motor. If both ELAC computers are unusable, then the system shifts the pitch control over to SEC1 or SEC2 and the THS to motor 2 or 3. Typically, SEC2 and motor 3 will be selected first if the ELAC computers are unavailable. Mechanical control of the THS is available via the pitch trim wheel assuming that the green or yellow hydraulics are functioning. The mechanical control input takes priority over the electrical control and is like a manual override.

Two electrically-controlled hydraulic servo jacks drive each elevator. Each servojack has an active mode where the position of the jack is controlled electrically, a damping mode whereby the jack follows the movement of the control surface, and a centering mode whereby the jack is retained in the neutral position. Under normal conditions one jack is active while the other is damping unless a maneuver were to necessitate the use of the second jack. If the active servojack fails then the active and damping servojacks swap roles. If neither jack is being controlled electrically or hydraulically then both are automatically switched to centering or damping mode respectively. In the case of a single elevator failure, a limitation is put on the deflection of the remaining elevator, to avoid excessive loads on the tail or rear fuselage. A screwjack driven by two hydraulic motors drives the trimmable horizontal stabilizer. The two hydraulic motors are controlled by one of three electric motors or the mechanical trim wheel. The figure below shows the schematic for the pitch control, including the servo loop priorities for the ELAC and SEC computers including inputs from the pitch transducer, accelerometer, flight management computers (FMGC), air data inertial reference unit (ADIRU), resolution advisory (RA), slat flap control computer (SFCC), landing gear control interface unit (LGCIU), and hydraulic pressure [16].

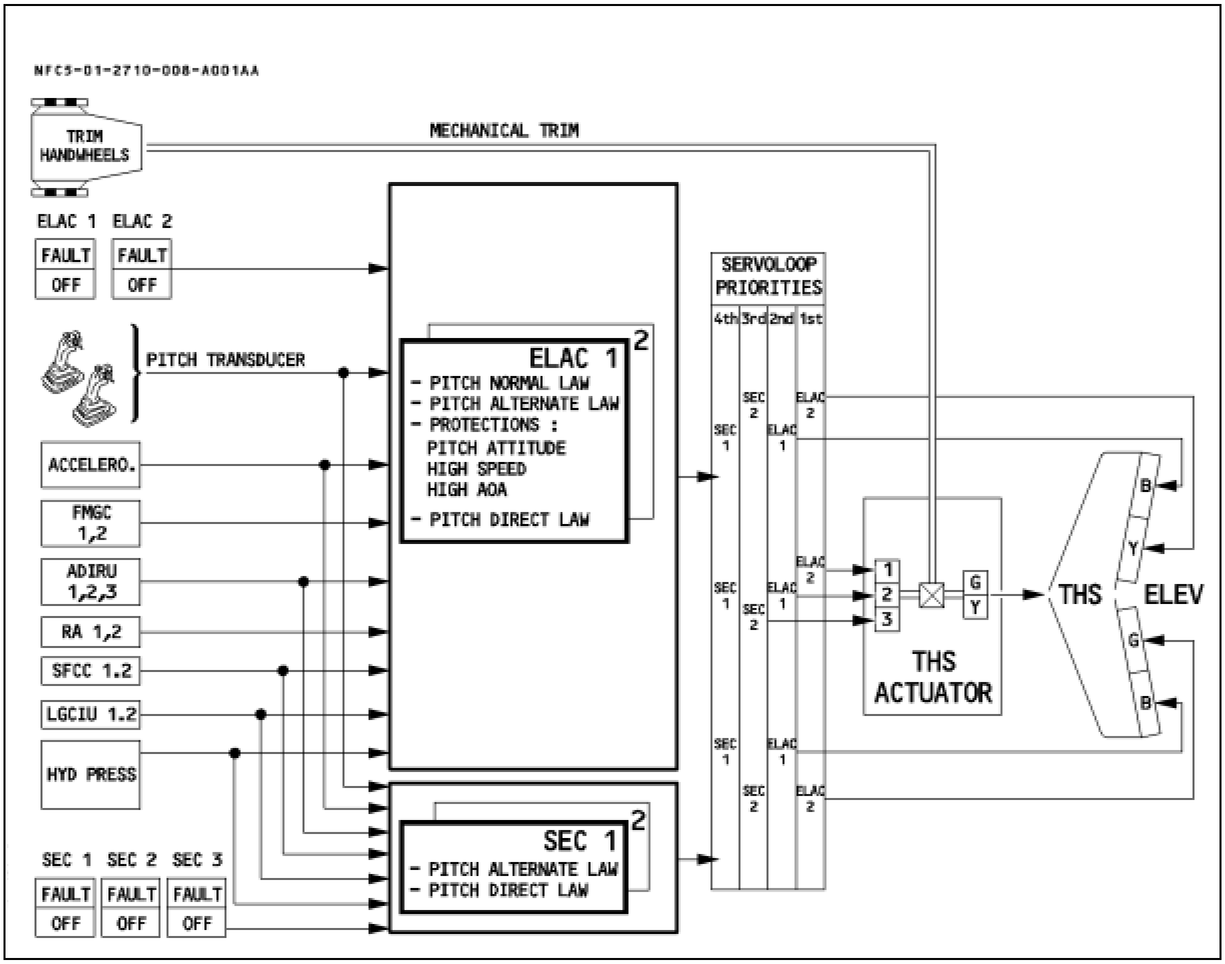


Figure 30: Pitch Control Schematic [16]

3.7 Roll Control

Each wing contains one aileron and four spoilers that control movement about the roll axis. The ailerons and spoilers have a maximum deflection angle of 25° and 35° respectively. The ailerons droop 5° downward when the flaps are extended. During normal flight conditions, ELAC1 controls the ailerons. If ELAC fails, then aileron control is transferred to ELAC2, however if both fail the ailerons are reverted to damping mode. Sec3 controls the N° 2 spoilers, SEC1 controls N° 3 and 4 spoilers and SEC2 controls the N° spoilers. If a SEC fails, the spoilers it controls are retracted. Each aileron has two electrically controlled hydraulic servo jacks, with one operating per aileron at a time. Each servojack has two control modes, active where the jack position is electrically controlled and damping, where the jack follows the control surface movement. Damping mode is automatic if both ELACs fail or if there is low blue and green hydraulic pressure. Each spoiler is positioned by a servojack and receives hydraulic power by either the green, yellow, or blue hydraulic system, depending on if it is controlled by SEC1, 2, or 3. If electric control is lost the spoiler fully retracts, a loss of hydraulic pressure causes the spoiler to retain the deflection at loss or a lesser deflection, if aerodynamic forces push it down. If a spoiler fails on one wing, the corresponding spoiler on the other wing is inhibited. The pilot is able to control the speed brakes with the speed brake lever, the speed brakes are spoilers 2, 3, and 4. Extension of speedbrakes is inhibited if SEC1 and SEC3 have faults, either elevator has a fault, angle of attack protection is active, flaps are fully extended, thrust levers are above MCT position or if alpha floor is activated (low speed protection to avoid stalls). If an inhibition condition occurs, speedbrakes are automatically retracted and stay retracted until the condition disappears and the lever is reset by the pilot. If a speedbrake fails on one wing, the corresponding spoiler on the other wing is inhibited. In manual flight speed brakes can deflect up to 40^o for spoilers 3 and 4 and 20^o for spoiler 2. When autopilot is engaged the maximum deflection angle is 25^o for spoilers 3 and 4 and 12.5^o for spoiler 2. Spoilers 1 to 5 act as ground spoilers. Ground spoilers are activated by the pilot when the speedbrake control lever is pulled up into the armed position. Ground spoilers are automatically extended during rejected takeoff if the speed of the aircraft is greater than 72 knots, or at landing when both main landing gears have touched down and the ground spoilers are armed with the thrust levers at or near idle, or if reverse is selected on at least one engine and the ground spoilers are not armed. The spoiler roll function is inhibited when the spoilers are used for their ground spoiler function. The ground spoilers partially extend to 10^o when reverse is selected on at least one engine (the other at idle) and one main landing gear strut is compressed. The partial extension decreases lift and eases compression of the second landing gear strut, leading to full ground spoiler extension. The ground spoilers retract after landing, or after a rejected takeoff when the ground spoilers are disarmed, or during a touch and go when at least one thrust lever is pushed beyond 20^o. The figure below shows the conditions that necessitate spoiler extension and partial spoiler extension [16].

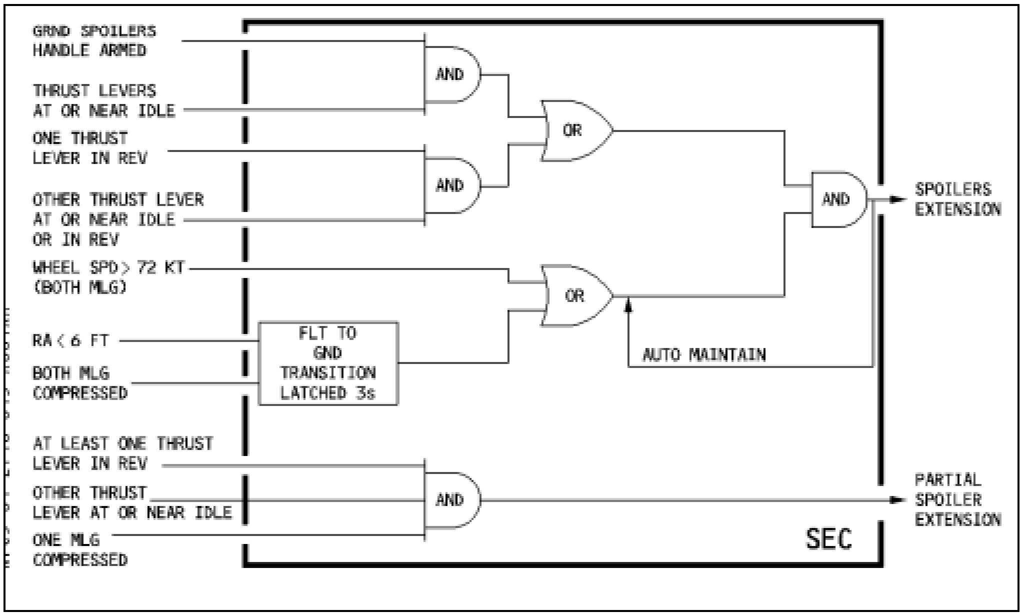


Figure 31: Ground Spoiler Logic [16]

The figure below shows the schematic for the roll control, including the servo loop priorities for the ELAC and SEC computers including inputs from the stick transducer, flight management computers (FMGC), air data inertial reference unit (ADIRU), resolution advisory (RA), slat flap control computer (SFCC), landing gear control interface unit (LGCIU), hydraulic pressure, wheel speed, as well as inputs from the rudder pedals and speed brakes lever [16].

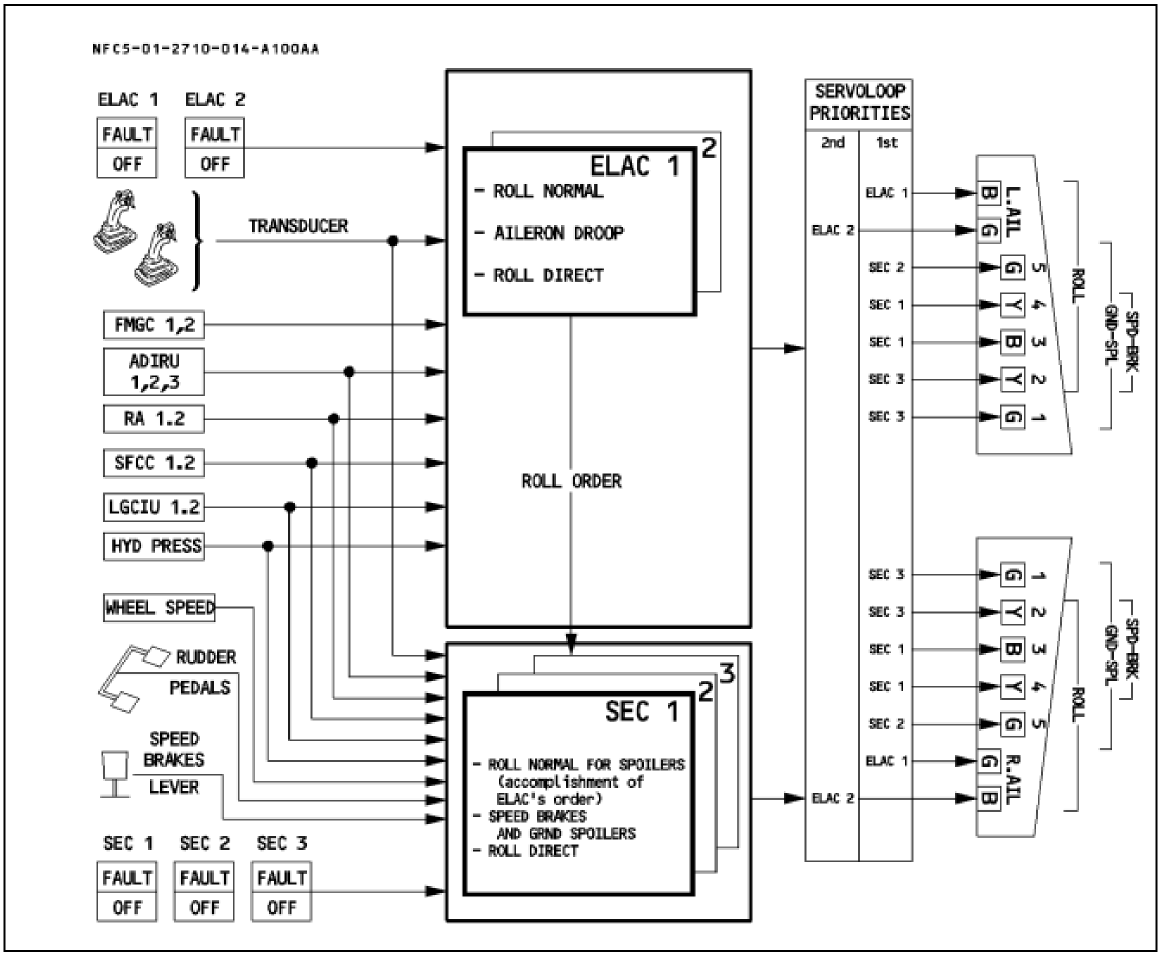


Figure 32: Roll Control Schematic [16]

3.8 Yaw Control

Yaw damping and turning coordination functions are automatic and are performed using electrical rudder control. The ELACs compute yaw orders for coordination turns and yaw damping oscillations and transmit the yaw orders to the FACs. The pilot can use the rudder pedals to control the rudder mechanically. There are three independent hydraulic servo jacks that operate in parallel to actuate the rudder. Under normal operation, a green servo drives all three servojacks, the yellow is synchronized and takes over in the event of failure. The maximum deflection of the rudder is a function of the aircraft's speed. Under 160 knots, the maximum deflection is 25°, at 380 knots and above the lowest maximum deflection is achieved at 3.4°. There are two electric motors that are used for the positioning of the artificial feel unit and also trim the rudder. Under normal operation computer FAC1 controls motor 1 and drives the trim, and FAC2 and motor 2 remain synchronized on standby. In manual flight, the pilot can deflect the rudder up to 20º in either direction. The figure below shows the schematic for the roll control, including the servo loop priorities for the FAC computers including inputs from the stick and pedal transducers, flight management computers (FMGC), air data inertial reference unit (ADIRU), slat flap control computer (SFCC), landing gear control interface unit (LGCIU), hydraulic pressure, and the rudder trim [16].

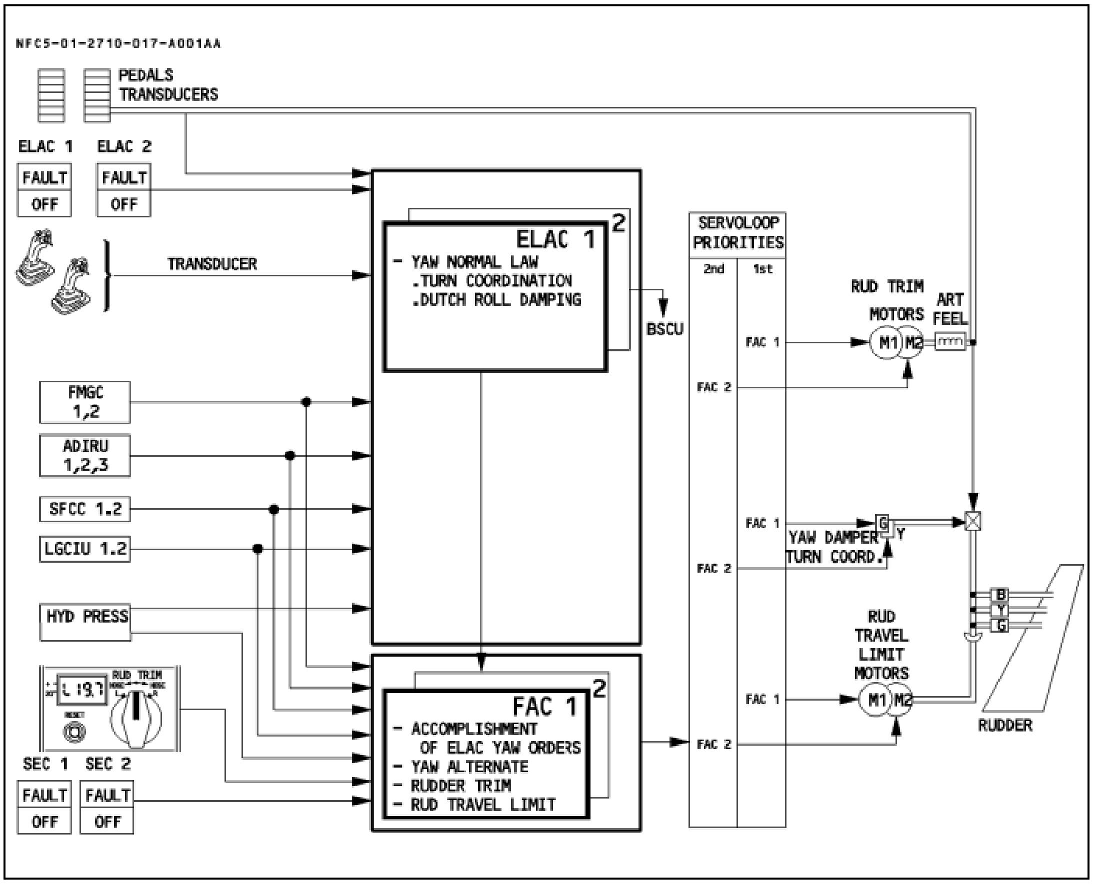


Figure 33: Yaw Control Schematic [16]

3.9 Flaps and Slats

Each wing contains two flap surfaces and five slat surfaces, each of these surfaces are electrically controlled and operate under hydraulics. The pilot extends the slats and flaps by pulling the FLAPS lever, to one of five positions on the center pedestal. There are two slat flap control computers SFCC, each containing one slat and one flap channel. A power control unit (PCU) is used to power two independent hydraulic motors, with green and blue hydraulic power used for the slats and yellow and green power for the flaps. The figure below shows the architecture for the flaps and slats [16].

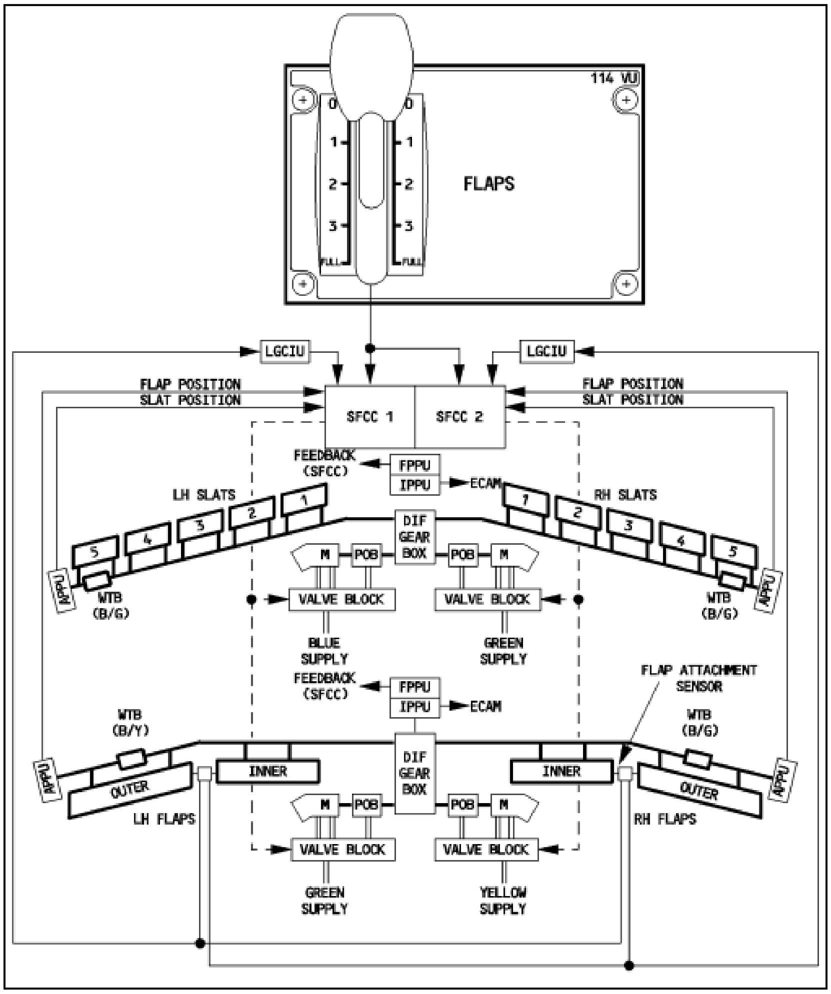


Figure 34: Yaw Control Schematic [16]

The FLAPS lever has five positions: 0, 1, 2, 3, and FULL. There are two flap configurations that correspond to position 1, configuration 1 and configuration 1+F. Configuration 1 occurs when the FLAPS lever is moved from 0 to 1 and the airspeed is greater than 100 knots or when the FLAPS lever is moved from 2 to 1 and/or the airspeed is greater than 210 knots. In all other cases, the configuration becomes 1+F. The table below shows the operation of the FLAPS lever and the corresponding positioning of the control surfaces as well as the scenario they are used in [16].

Table 2: Slat and Flap Positioning [16]

<table>
<tr><th>Position</th><th>Slats</th><th>Flaps</th><th>Indications on ECAM</th><th colspan="3">Flight Condition Used</th></tr>
<tr><td>0</td><td>0</td><td>0</td><td></td><td></td><td>Cruise</td><td rowspan="2">Hold</td></tr>
<tr><td rowspan="2">1</td><td rowspan="2">18</td><td>0</td><td>1</td><td></td><td></td></tr>
<tr><td>10</td><td>1+F</td><td rowspan="3">Takeoff</td><td></td><td></td></tr>
<tr><td>2</td><td>22</td><td>15</td><td>2</td><td></td><td rowspan="2">Approach</td></tr>
<tr><td>3</td><td>22</td><td>20</td><td>3</td><td rowspan="2">Landing</td></tr>
<tr><td>FULL</td><td>27</td><td>35</td><td>FULL</td><td></td><td></td></tr>
</table>

3.10 Normal Law

Flight control normal law covers three-axis control, flight envelope protection, and alleviation of maneuver loads. Normal law contains three modes that correspond to the current phase of the flight. Failure of a single computer does not impact the capability of normal law. The first mode, ground mode, is active when the aircraft is on the ground and becomes inactive shortly after takeoff. While active, there is a direct proportional relationship between sidestick deflection and the deflection of the flight controls. Ground mode is reactivated shortly after touchdown and stabilizer trim is reset to zero. Flight mode is the second mode and is activated after liftoff and remains activated until flare mode is activated before touchdown. In this mode, sidestick deflection and loads imposed on the aircraft are directly proportional and if the sidestick is in neutral position and the wings are level the system maintains a 1 g load in pitch. Additionally, a given side stick deflection results in the same roll rate response and roll rate is independent of airspeed. Lastly there is no rudder pedal feedback for yaw damping and turn coordination functions. Flare mode takes over when the aircraft is 50’ RA as the plane descends to land. The system memorizes the pitch attitude at 50’ and forces the pilot to flare the aircraft [16] [19].

Normal law protects the aircraft as follows: load factor limitation, attitude protection, high angle of attack protection, high speed protection, and low energy warning. Load factor limitation prevents the pilot from overstressing the aircraft even if full force is applied to the sidestick. Attitude protection limits the pitch from being greater than 30^{o} up, 15^{o} down, and 67^{o}

of bank. The limits are indicated on the primary flight display. Additionally bank angles greater than 33° require constant input from the pilot on the side stick to maintain the angle. High angle of attack protection occurs when alpha exceeds a threshold called alpha prot, the angle of attack becomes proportional to side stick deflection and does not allow the pilot to exceed alpha max. High speed protection prevents exceeding V_{MO} or M_{MO} by introducing a pitch up load factor that cannot be overridden by the pilot. Low energy warning occurs when a change in flight path alone is insufficient to regain a positive flight path, an audible sound of the words "SPEED SPEED SPEED" is emitted [19].

3.11 Alternate Law

Flight controls are reconfigured to alternate law if multiple failures of redundant systems occur. The ECAM will display the message: "ALTN LAW: PROT LOST". In alternate law, the ground mode is identical to Normal law, flight mode is similar to normal law but with reduced protections. Pitch alternate law becomes pitch direct law when the landing gear is deployed, since there is now flare mode when pitch normal law is lost. Additionally, alternate law loses turn coordination and roll degrades to direct law, whereby the roll rate is dependent on airspeed.

All protections with the exception of load factor maneuvering protection are lost. A low speed stability function replaces the normal angle of attack protection. The system creates a nose down command to prevent the speed from decreasing further, but it can be overridden by sidestick input meaning the airplane can be stalled. The alpha floor function is inoperative and an audible sound consisting of crickets and "STALL" is activated. The primary flight display maintains V_{LS}, however, $V_{ALPHA\ PROT}$ and $V_{ALPHA\ MAX}$ are removed. A nose up command is introduced when the plane exceeds the V_{MO}/M_{MO} ratio to prevent the speed from increasing further, but it can be overridden by the sidestick. Furthermore bank angle protection is lost and yaw damping may be lost if the cause of failure is a triple ADR failure [19].

3.12 Abnormal Alternate Law

Abnormal alternate law becomes activated when the airplane is flying in alternate law and enters an unusual attitude, it is designed to help facilitate recovery to a more appropriate attitude. Under abnormal alternate law, pitch law follows Alternate Law albeit without autotrim or protection other than load factor protection. Additionally, roll law becomes direct law with mechanical yaw control. After recovery from unusual attitude, the following laws remain active for the rest of the flight: pitch follows alternate law without protections and with autotrim, roll follows direct law, and yaw follows alternate law. Under abnormal alternate law, no reversion to direct law occurs when the landing gear is extended [19].

3.13 Direct Law

Direct law is the lowest level of computer flight control and occurs after certain multiple failures have taken place. With direct law, pilot input controls are transmitted unmodified to the control surfaces, providing a direct relationship between sidestick and control surface. In direct lawn control sensitivity is dependent on the airspeed and auto trimming is unavailable. An amber message saying “USE MAN PITCH TRIM” appears on the PFD. No protections are provided under direct law, but overspeed and stall audible warnings are still provided. Lastly, the PFD airspeed scale remains the same as in alternate law [19].

3.14 Mechanical Backup

Mechanical backup mode occurs in the case of a complete loss of electrical flight control signals, allowing temporary control over the aircraft. Under mechanical backup, pitch control can be achieved via the horizontal stabilizer using the manual trim wheel and lateral control is established via the rudder pedals. Neither of these controls will be usable if hydraulic power is lost. A red MAN PITCH TRIM ONLY warning appears on the PFD [19].

4. Environmental Control System

The Environmental Control System (ECS) is the quintessential system in charge of maintaining the temperature, pressure and ventilation within an aircraft [20]. The following section will break the environmental control system of the *Airbus A320* aircraft down into its subsystems, describe their corresponding responsibilities, and illustrate their function using informative diagrams and schematics. The subsystems that will be evaluated include: The bleed air, air conditioning, temperature, ventilation, pressurization, cargo control, fire and smoke, and anti-ice systems.

4.1 Bleed Air System

Nearly all commercial passenger aircrafts use environmental control systems (ECSs) based on an engine bleed air system [21]. The bleed air from the engines (as well as the auxiliary power unit 'APU' or a ground source in special cases) is used by the ECS to heat, cool, pressurize and ventilate the aircraft cabin [21]. The bleed air system works by intaking air through the engines and dividing it into two flow paths. One flow, known as the 'inner' flow, passes through a multi-stage compressor that compresses it to a very high pressure. The air then flows into a combustion chamber, where it is heated and expanded. This very high-pressure and high-temperature air then leaves the turbine with intense velocity, powering the engines and providing extra thrust for propulsion [21].

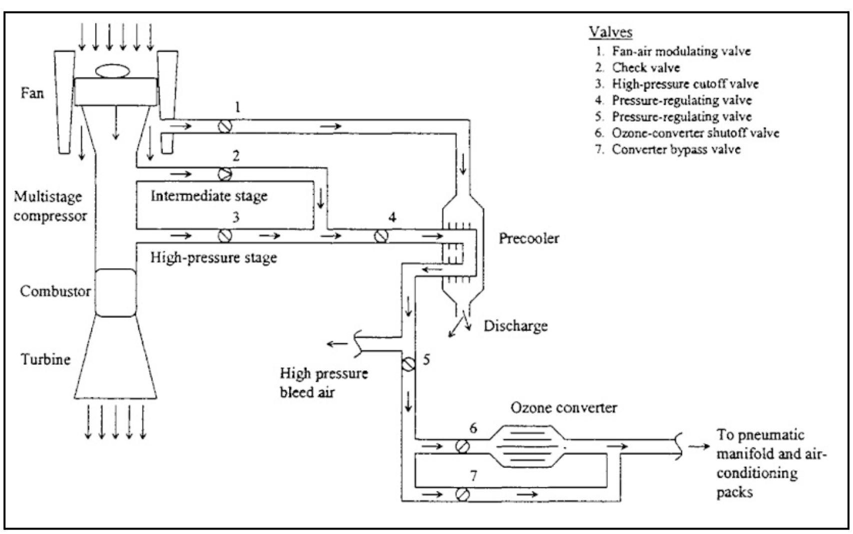


Figure 35: Standard Bleed Air System from Engine [21].

The air used by the ECS is from the second flow, which also passes through the multi-stage compressor to compress it to a high pressure. Instead of passing into the compressor as seen in Figure 35, it passes instead into a precooler that uses cool air from the engines fan to cool the bleed air. Any bleed air still too high-pressure to enter the ECS is tapped off using a pressure-regulating valve. For the Airbus A320, the bleed air is then supplied to the anti-ice, air continuing packs and heating systems as seen in Figure 36.

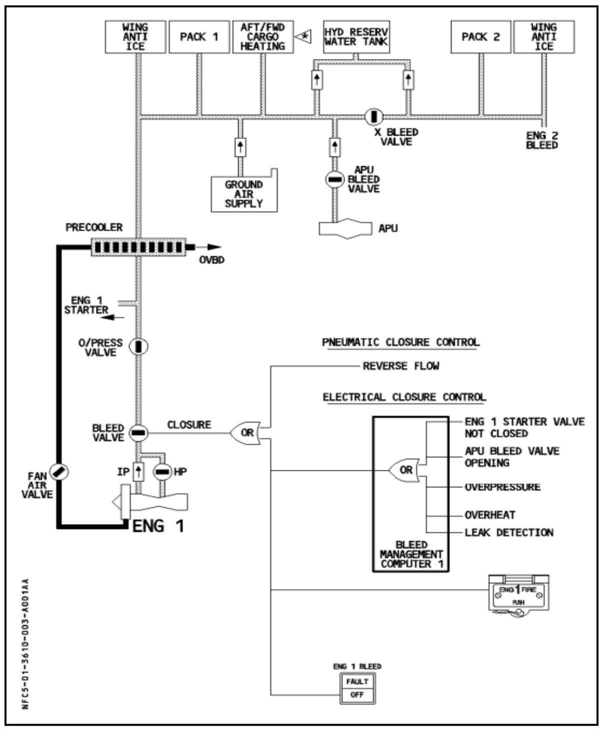


Figure 36: The Engine Bleed Air System of the Airbus A320 Aircraft [22].

The Airbus A320 has two engine bleed air systems: Eng 1 Bleed and Eng 2 Bleed [22]. Each system is monitored and controlled by a Bleed Monitoring Computer (BMC) that selects the compressor stage, regulates the bleed air temperature, and regulates the bleed air pressure [22].

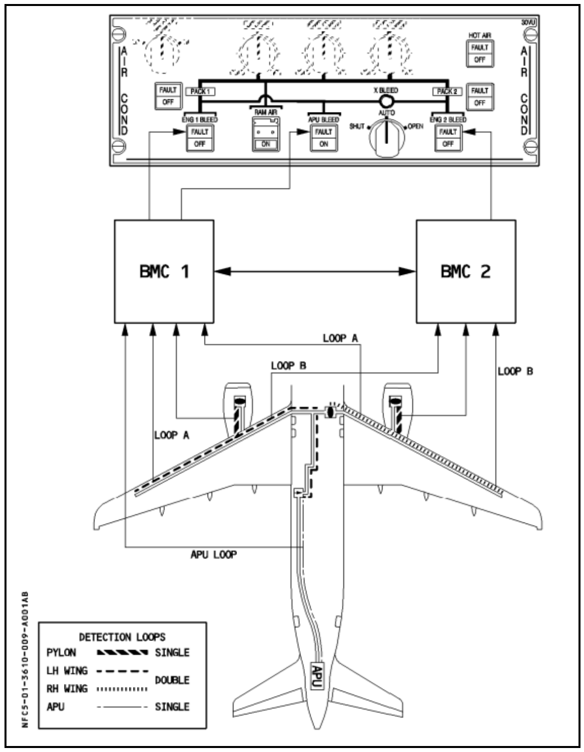


Figure 37: The BMCs of the Airbus A320 Aircraft [22].

As seen in Figure 37, Loop A and Loop B are leak detection loops that monitor for any overheating near the fuselage and wings. If a leak is detected in either loop, the corresponding bleed valve will automatically close and the fault light on the air conditioning panel will turn on. In the case of one BMC failure, the adjacent BMC can take over and monitor the other bleed system for leaks. However, the substitute BMC cannot close the other bleed valve nor turn on the AC failure light [22].

4.2 Air Conditioning System

The air conditioning system onboard the Airbus A320 aircraft is fully automatic [23]. Its primary function is the continual renewal of the air and maintenance of the temperature of the air in the cockpit, fwd cabin and aft cabin.

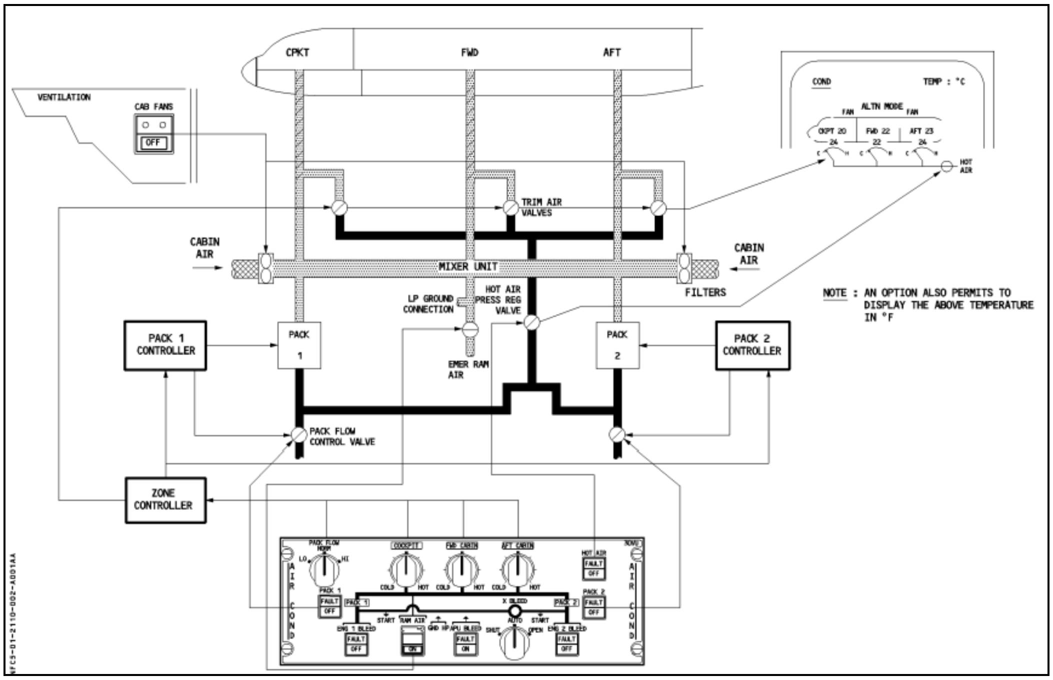


Figure 38: The Air Conditioning System of the Airbus A320 Aircraft [23].

As illustrated above in Figure 38, the air conditioning system works by supplying bleed air to the two pack flow control valves, which control the air flow to the two air conditioning packs [23]. Each air conditioning pack consists of two heat exchangers cooled by ram air, a compressor and a turbine [21]. They are also fully automatic and are controlled by their respective pack controllers [23]. Bleed air enters the pack and passes through the primary heat exchanger to cool it. The then cooled air enters the compressor compressing it to a higher pressure and temperature. It is cooled again in the main heat exchanger before passing through the turbine. The expansion of the air generates power to the compressor and reduces the temperature of the air, making it cool enough to distribute in the cabin [23]. This air passes out of the pack and into the systems mixing unit, which mixes the air coming from the cabin and the fresh air coming from the packs. It then distributes it into the three zones: cockpit, fwd cabin and aft cabin.

4.3 Temperature control system

The temperature onboard the Airbus A320 aircraft is regulated by the zone controller [23]. The temperature selection range on the air conditioning panel ranges from 18 degrees celsius to 30 degrees celsius. This temperature can be manually adjusted by the flight crew. The average cabin temperature sits around 24 degrees celsius [23]. This is also the temperature that the system will automatically maintain if there are any trim air system failures. The actual temperature in the cockpit and in the cabin are measured by sensors in the air ducts, which send signals to the pack controllers. The pack controllers then instruct the packs to produce the desired output temperature [23].

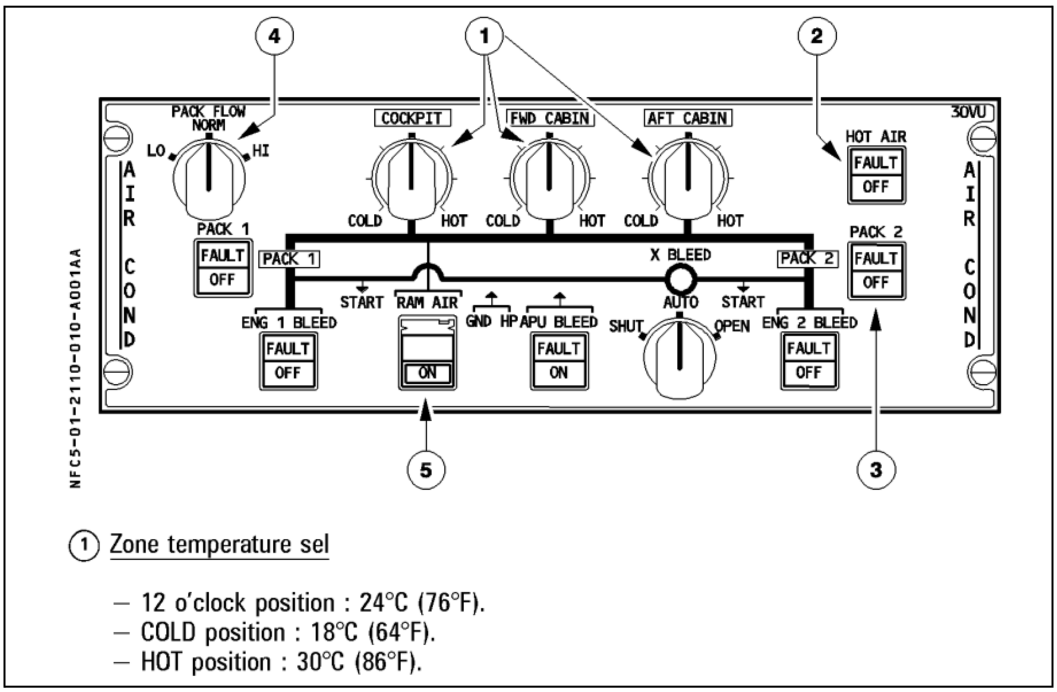


Figure 39: The Overhead Temperature Controls of the Airbus A320 Aircraft [23].

It can be seen in Figure 39, that at the 12 o'clock position, the temperature controllers for the cockpit, fwd cabin and aft cabin are set to 24 degrees celsius. When turned to the HOT position, the temperature is set to its maximum temperature of 30 degrees celsius. In contrast, when turned to the COLD position, the temperature is set to its minimum temperature of 18 degree celsius [23].

4.4 Ventilation System

The ventilation system onboard the Airbus A320 aircraft includes ventilation for the avionics equipment, the battery, the lavatories and the galleys [23]. The avionics system specially is fully automatic and consists of 6 main components:

1. Two Fans
2. Skin Air Inlet and Extract Valves
3. Skin Exchange Inlet and Outlet Bypass Valves
4. Air Conditioning Inlet Valve
5. Skin Exchange Isolation Valve
6. Avionics Equipment Ventilation Computer (AEVC)

In brief, it uses two electric fans to circulate cool air over all the avionic electronics, instruments and circuit breaker panels. The skin air inlet and extract valves intake air from outside the aircraft and taps out hot air from inside the aircraft. The skin exchange valves allow air to circulate between the avionics bay and the underside of the cargo floor. The air conditioning valve opens to bring in the air conditioned air to the avionics bay. The skin isolation valve controls the access to the skin heat exchanger. Finally, the AEVC controls the operation of the entire avionics ventilation system as seen in Figure 40.

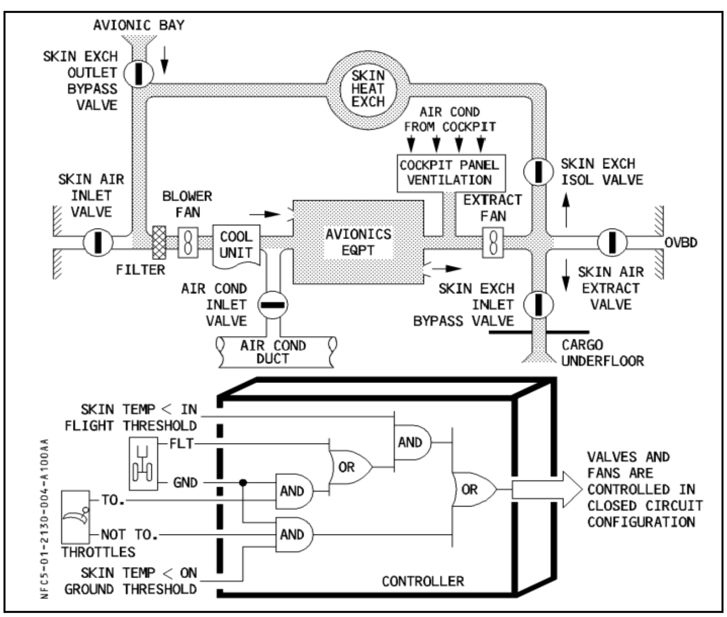


Figure 40: The Avionics Ventilation System of the Airbus A320 Aircraft [23].

Furthermore, a venturi tube, similar to a vacuum pump, draws in the air surrounding the batteries and vents it out to ventilate the batteries [23]. Likewise, an extraction fan draws in the air from the cabin, lavatories and galley, and exhausts it near the outflow valve [23]. This is illustrated in Figure 41 below.

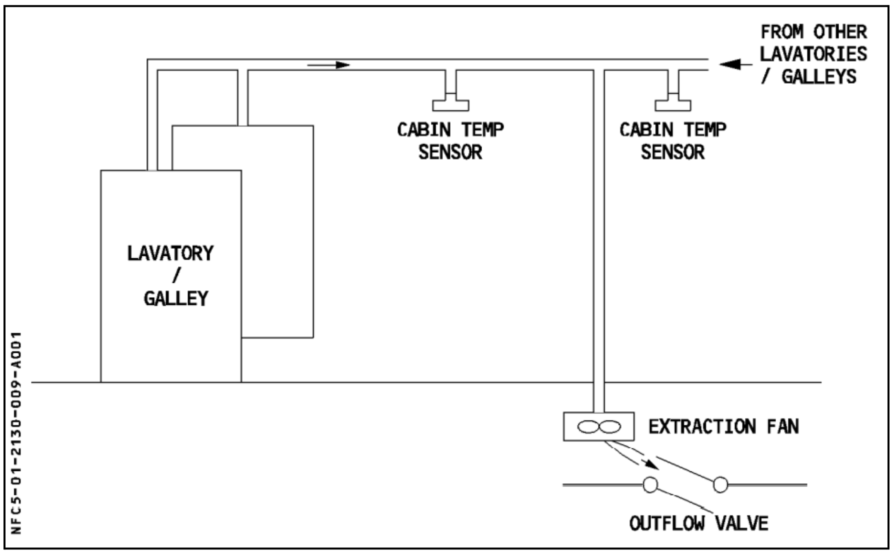


Figure 41: The Lavatory / Cabin Ventilation System of the Airbus A320 Aircraft [23]

4.5 Pressurization System

The pressurization system onboard the Airbus A320 consists of two cabin pressure controllers (CPC), an outflow valve, a control panel and two safety valves. The system is fully automatic, but the flight crew can set it to operate semi-automatically or manually if desired [23].

When operated automatically, the cabin pressure controllers (CPCs) use the signals from the Air Data Reference System (ADIRS), the Flight Management and Guidance System (FMGS), the Engine Interface Unit (EIU), and the Landing Gear Control Interface Unit (LGCIU) to maintain the pressure cabin [23]. The CPCs also control the outflow valve, which is powered by one of the electric motors. There are also two independent safety valves to prevent the cabin's pressure from getting too high [23].

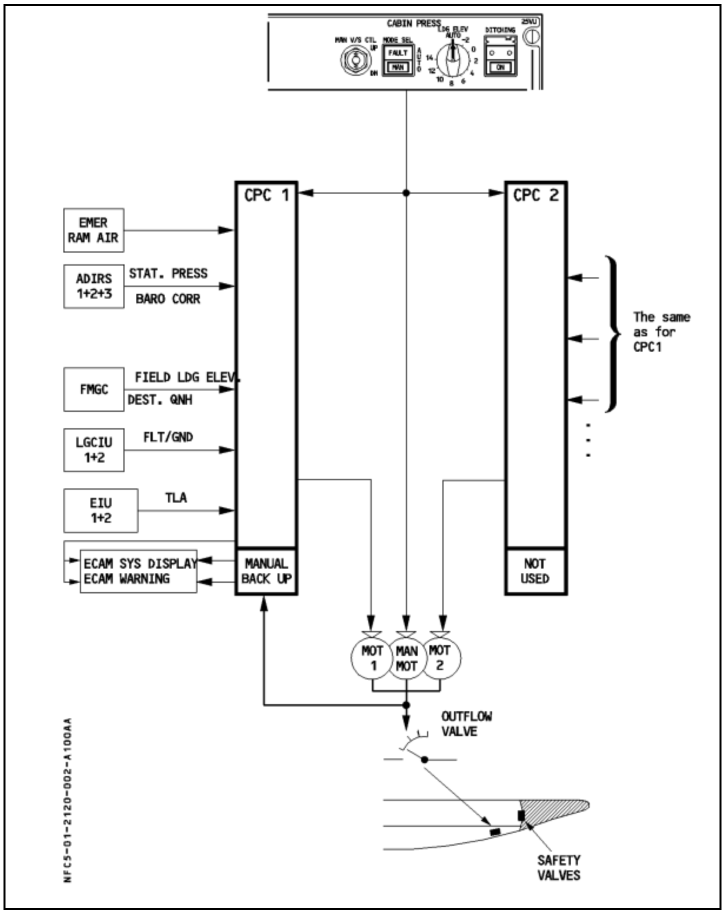


Figure 42: The Pressurization System of the Airbus A320 Aircraft [23].

The pressurization system is responsible for four main functions:

1. Ground function
2. Pre-Pressurization
3. Pressurization in Flight
4. Depressurization

In brief, the ground function opens the outflow valve while still on the ground to release any extra pressure in the cabin. Pre-pressurization then occurs during takeoff. During this stage the cabin pressure is increased to avoid a surge in the cabin pressure. Pressurization in flight adjusts the pressure with the change in altitude. This step is pivotal in providing a comfortable experience for the passengers. Similar to the ground function, depressurization occurs on the ground after touchdown wherein the outflow valve is opened to gradually release any residual pressure in the cabin [23].

4.6 Cargo Control Systems

In addition to maintaining the temperature, pressure and ventilation within the cockpit and cabin, the ECS is also responsible for cooling the cargo compartments [23]. The system works by way of using extraction fans located in the cargo compartment to draw the air out and extract it overboard. The air from the cabin then replaces the exhausted air, which in turn ventilates the cargo compartment. The flight crew can also control the temperature of the cargo compartment by adding in hot bleed air [23]. However, unlike the temperature controllers for the cockpit and cabin, the average (middle) temperature in the cargo is set to 15 degrees celsius. When turned to the HOT position, the temperature is set to its maximum temperature of 26 degrees celsius, and when turned to the COLD position, the temperature is set to its minimum temperature of 5 degree celsius [23]. Due to external factors such as the weather conditions, the temperature in the cargo varies and may be colder than the selected temperature.

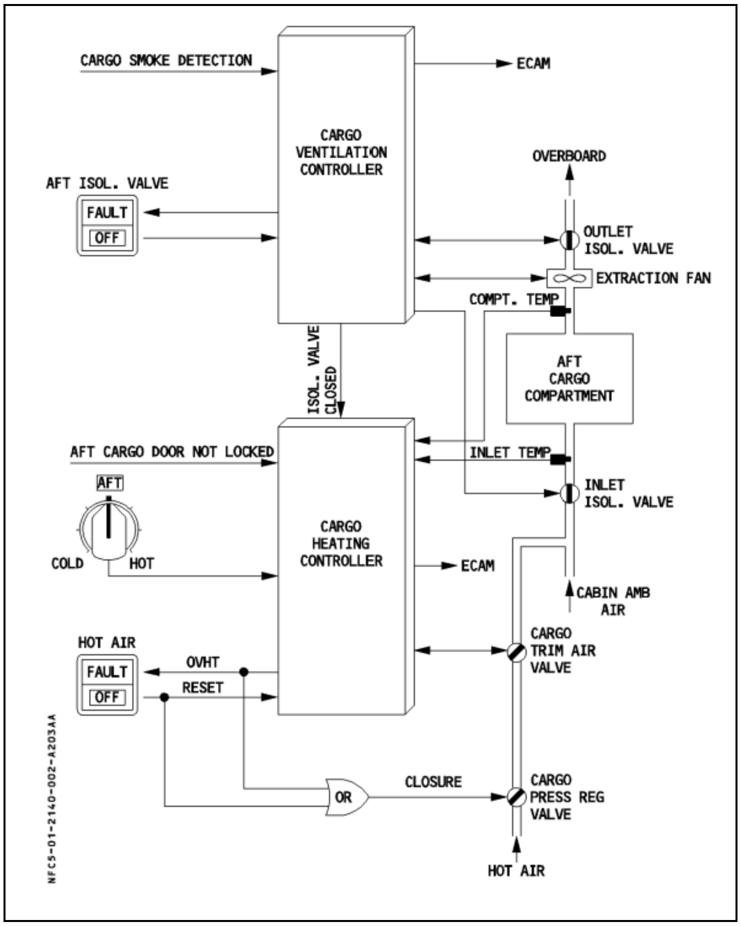


Figure 43: The Cargo Control Systems of the Airbus A320 Aircraft [23].

4.7 Fire and Smoke System

The Environmental Control System is also responsible for the fire and smoke detector systems onboard the aircraft. The Airbus A320 specifically has Smoke Detection Control Units (SDCU) in the cargo compartments, lavatories, galley, cabin and cockpit that detect the presence of smoke. The SDCU will forward the warning to the Flight Control Computer (FWC) and Cabin Intercommunication Data System (CIDS). In the cargo, if smoke is detected, the inlet and exhaust valves will be automatically closed and a fire bottle will be emptied if manually designated to extinguish the fire [24].

4.8 Anti-Ice System

The Environmental Control System onboard the Airbus A320 is responsible for the anti-ice system for the wings and the engines. The anti-ice system for the wings specifically only uses hot bleed air from the pneumatics system, never the APU. Each wing has a special electrically controlled valve that controls the air flow to the three outboard slats of each wing. This valve will automatically close if any hot air leaks are detected [24]. Figure 44 below shows the anti-ice system for one of the aircraft wings.

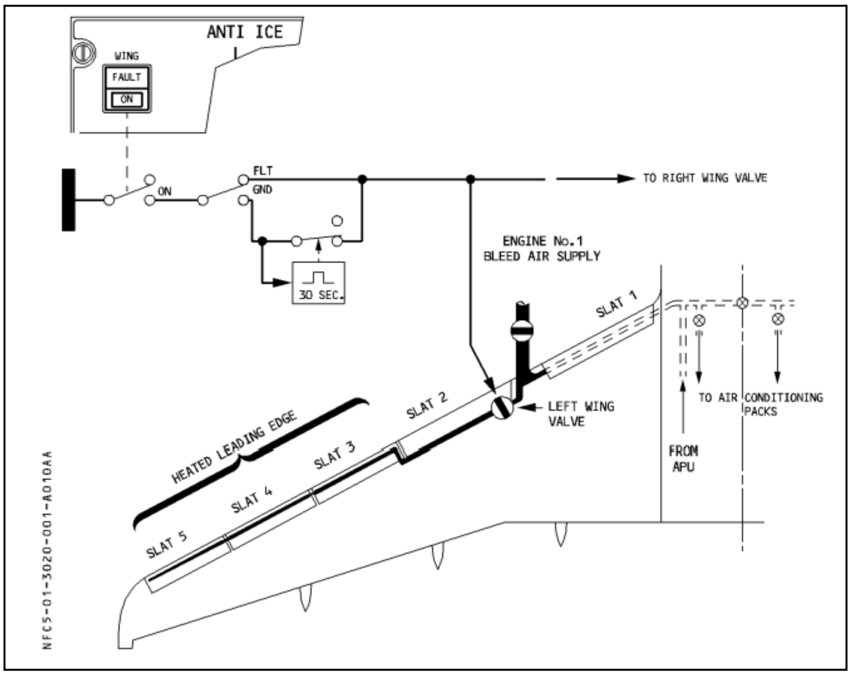


Figure 44: The Wing Anti-Ice System of the Airbus A320 Aircraft [25].

In contrast, the engine's anti-ice system uses an independent hot air bleed from the HP compressor. Each engine has an electrically controlled valve that controls the hot air flow [25]. This is controlled manually by the flight crew for each engine as demonstrated in Figure 45.

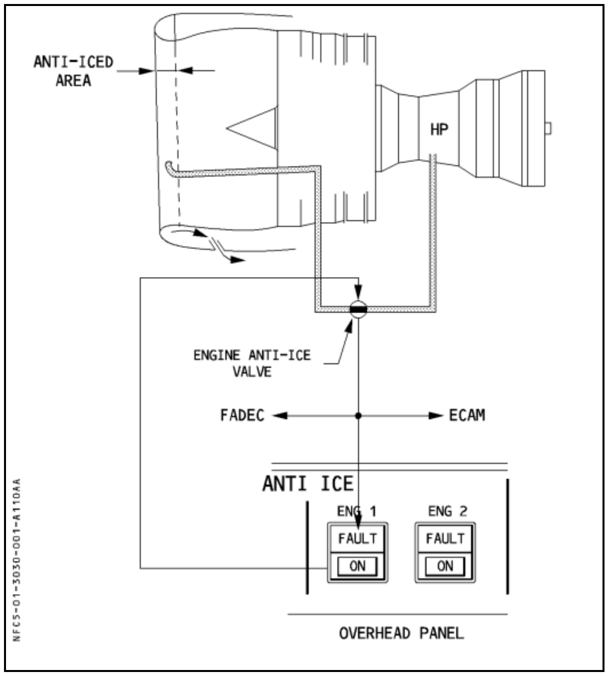


Figure 45: The Engine Anti-Ice System of the Airbus A320 Aircraft [25].

5. Engine Control System

The Airbus A320 jetliner offers two engine type configurations: a pair of IAE V2500 engines or a pair of CFM 56-5 engines. The engines produce approximately 111KN to 120 KN of thrust and with a fuel capacity of approximately 24,000 liters, the aircraft has a range of 5000 Km at full capacity. Currently, the CFM 56-5 engines power 65% of the Airbus A320 aircraft, and the remaining are powered by the IAE V2500 engines. This is due to the higher reliability of the CFM 56-5 engines over the IAE V2500 engines. Moreover, the CFM 56-5 engine operates on lower idle thrust levels making them more fuel efficient. The CFM 56-5 engines are also faster during their start-up and ignition procedures since it takes only 30 seconds for CFM engines vs the 1-minute start-up for the IAE engines. This section of the report does a detailed analysis of the Airbus A320's engine control system considering the popularity of the two engines. Furthermore, the analysis explores all the subsystems for the engine control used in combination with the CFM 56-5 engines.

5.1 System Overview

The Airbus A320 engine control system comprises a main control unit called Full Authority Digital Engine Control (FADEC) system, fuel and oil systems, a thrust control system, an air system, a thrust reversal system, and an ignition and start-up system. The CFM 56-5 engine is a high bypass ratio turbofan engine consisting of a low-pressure compressor/turbine, a high-pressure compressor/turbine, a combustion chamber, and an accessory gearbox. The following figure illustrates a cut-across section of the engine detailing all the important components.

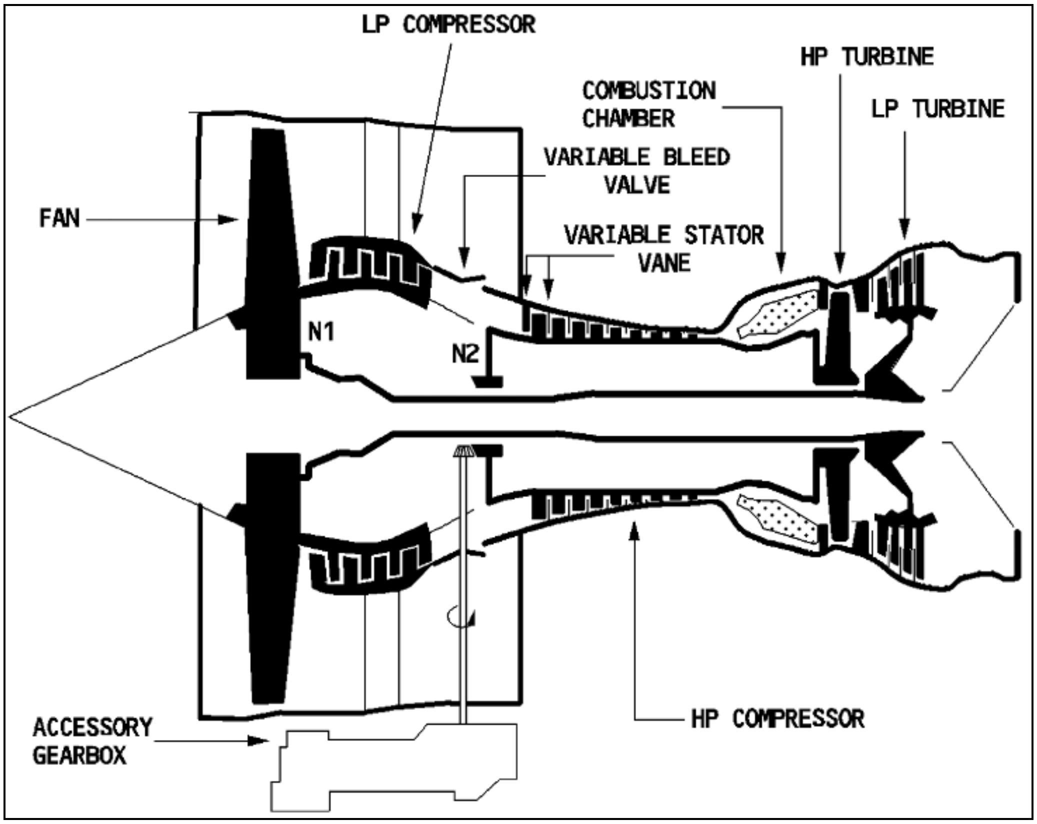


Figure 46: Sectional Schematic of CFM 56-5 Engine [26].

The engine consists of two compressor/turbine assemblies, a low-pressure assembly, and a high-pressure assembly. The low-pressure assembly has a four-stage low-pressure compressor which is connected to a four-stage low-pressure turbine. The assembly also has a low-speed rotor (N1). On the other hand, the high-pressure assembly consists of a nine-stage high-pressure compressor connected to a single-stage turbine along with a high-speed rotor (N2). The combustion chamber illustrated in figure 46 is the area where the fuel is mixed with air. The mixture ratio of air and fuel depends on the aircraft's flight envelope and is controlled by the FADEC system. The combustion chamber is fitted with 20 fuel nozzles and 2 igniters.

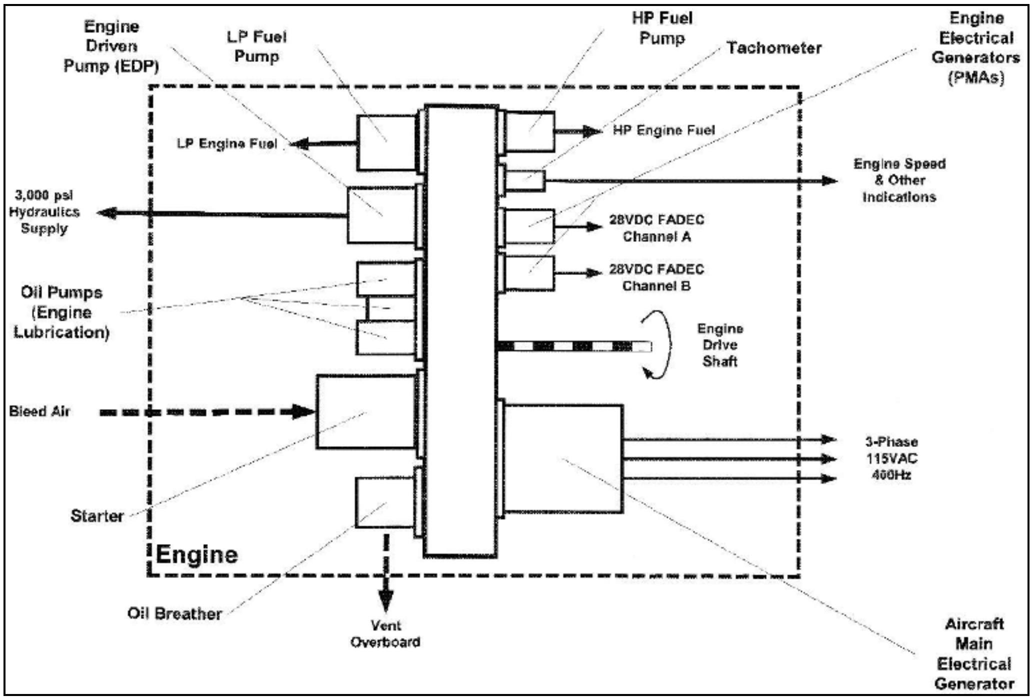


Figure 47: Accessory Gearbox Schematic [27].

An accessory gearbox is a place that consists of the oil feed pump, the FADEC alternator, the engine-driven main generator, the hydraulic pump, the integrated drive generator (IDG), the pneumatic starter, and the main engine fuel pumps. These accessories are powered by a mechanical linkage that transmits torque from the horizontal high-pressure rotor shaft. The variable bleed valve is a valve that controls the engine air bleed based on the aircraft's flight envelope. The variable bleed valve is located upstream of the high-pressure compressor as seen in figure 46. The bleed valve is variably open or closed based on the compressor inlet temperature and N2. The valve is fully open during start-ups, low thrust, and fast deceleration. The valves are fully closed during high-thrust conditions like take-off and cruise. On the opposite, the variable stator vane is fully shut off during the start-ups and open during high-thrust situations. These stator vanes are used to optimize the compressor efficiency of the high-pressure compressors at a steady state.

5.2 FADEC

The FADEC system or Full Authority Digital Engine Control system is an electronic engine control unit responsible for managing all engine operations. The Airbus A320 engine control system consists of a two-channel redundancy with one active channel and one standby channel. The FADEC system is separate from the accessory gearbox and is located at the foot of the engine rotor. The internal power source for the system is a magnetic alternator that supplies power to both channels. The power supply for the FADEC doesn’t depend on the aircraft's power and is variable depending on the flight conditions. The system is also equipped with an engine interface (EIU) unit that records and transmits the necessary data that is used to manage engine operations. The EIU consists of the engine master switch connection, the engine mode switch connection, the engine anti-ice connection, the air conditioning system controller, and the LGCIU. The EIU gathers information and requirements from these subsystems and transmits that data to the FADEC for the necessary actions. Another important function of the FADEC system is to display any warnings related to engine malfunction. As depicted in the FADEC architecture in figure 48, the system is responsible for managing the engine and engine-related tasks and is very critical for the engine's safe functional operation. The redundancy used by the FADEC is adopted by the N-version programming. If channel ‘A’ fails, then the second channel (channel ‘B’) is provoked to perform engine operations.

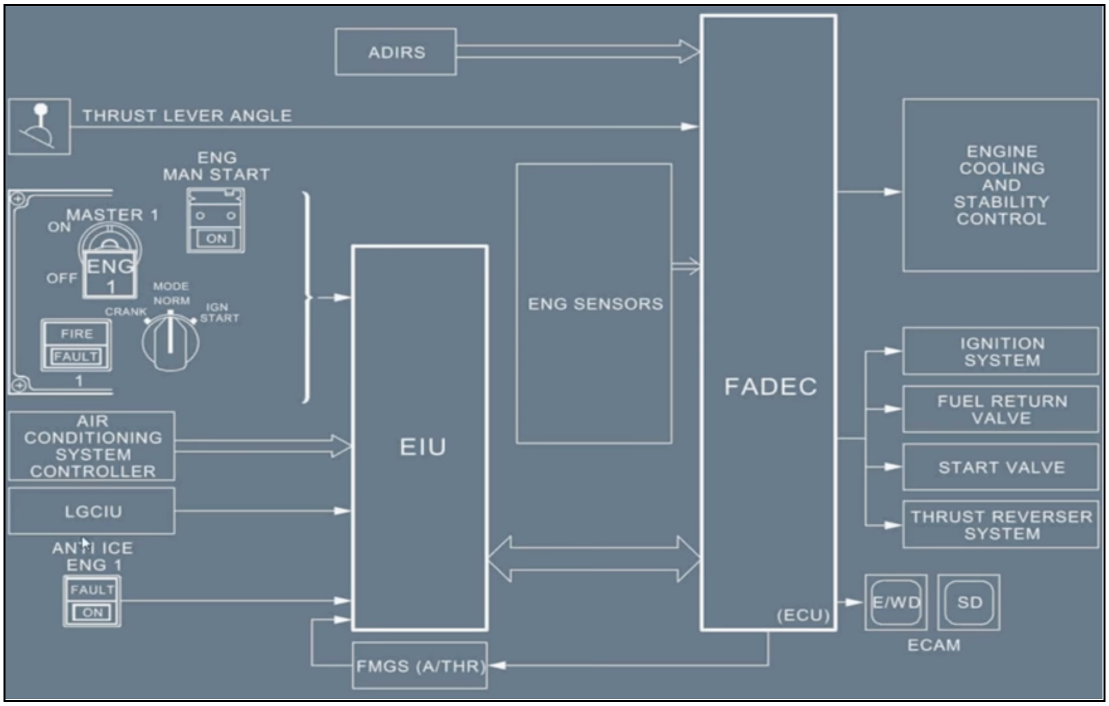


Figure 48: FADEC Schematic Diagram [26].

The FADEC system controls the gas generator that is responsible for the fuel flow rate to the combustion chamber and the engine idle settings. The system gathers information from the EIU and monitors acceleration and deceleration schedules. The system also controls the variable air bleed valves and variable stator vanes depending on the flight envelope. The FADEC system performs checks that protect against engine exceeding limits. These include protection against exceeding N1 and N2 speeds and monitoring Exhaust Gas Temperature (EGT) during engine start-ups. The FADEC will automatically shut down the engine if it records data that exceeds the preset limit. The FADEC oversees and controls engine power management. The engine power management includes the automatic control of engine thrust rating, computation of thrust limits for the given ambient conditions, manual power management (from the pilot's inputs on the thrust lever), and automatic power management during specific flight conditions. One of the most important responsibilities of the FADEC system is to control the automatic start-up sequence. The sequence includes the control of the start valve, high-pressure fuel flow, and fuel flow. Throughout the sequence, the system monitors the ratings of N1, N2, fuel flow, and EGT. In cases of any system or sensor failure, the system initiates the abort and recycles the sequence (only on the ground). On the other hand, during a manual start-up sequence, the system passively monitors the sequence and controls the fuel start valve and high-pressure fuel valve. During manual start-ups, the pilot has all the authority to abort, and sequence recycle.

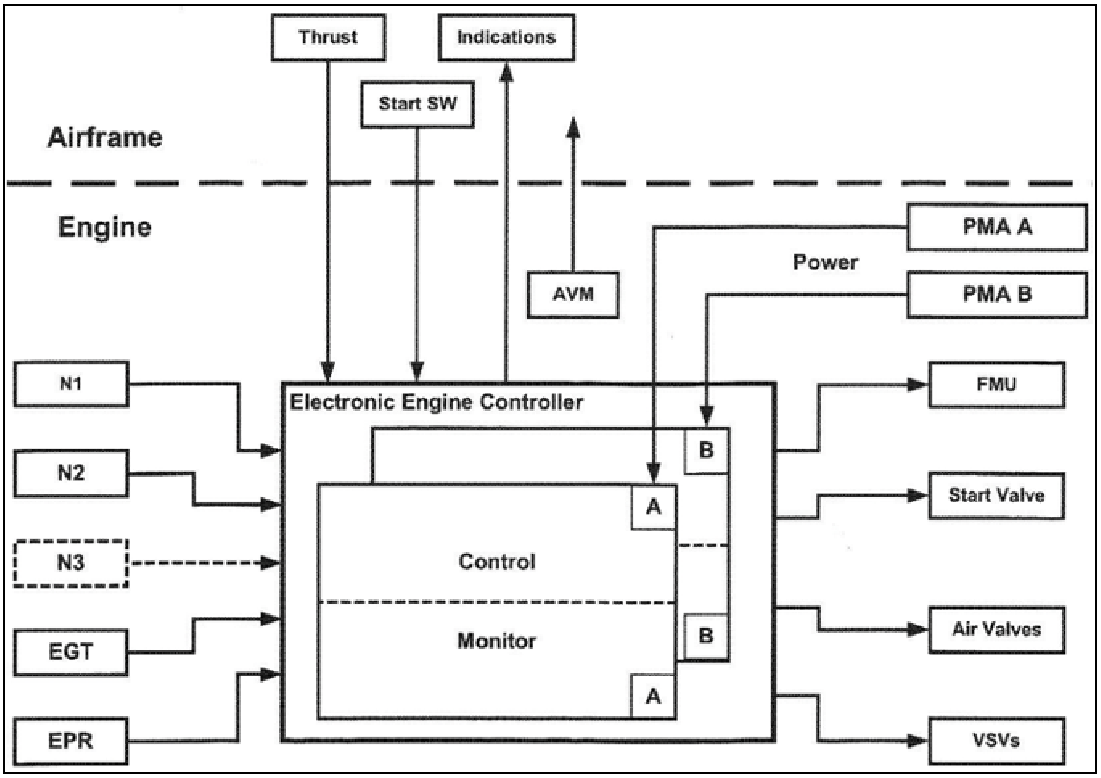


Figure 49: FADEC Sub-System on Airbus A320 [27].

The Airbus A320 airliner is equipped with a thrust reversal system that is used to slow down the aircraft speeds during landings on short runways. The thrust reversal system on the CFM 56-5 engines is controlled by the FADEC system. The system controls the actuators that move the blocker doors of the thrust reversal. The system also controls the fuel and engine setup during thrust reversal conditions. The system is responsible for fuel and oil circulation and recirculation depending on their temperature and flight phase. The FADEC system records the data and communicates it to the EIC. Specifically, the system transmits engine parameters packages to the cockpit indicators. These information packages include the general engine parameters, start-up status, thrust reversal system status, and FADEC system status. The performance of the system is very essential to the safe operation of the engine and thus requires cooling. Cooling is mainly achieved by circulating cold fuel or oil around the system in a coiled manner. Lastly, the FADEC is responsible for the safety partitioning of any failures that occur within the engine control system. The failures are detected and isolated within the sub-system and the data is recorded for future failure analysis.

The table below tabulates the idle modes of the FADEC system. The system has three modes: Modulated, Approach, and Reverse. The Modulated mode is activated depending on the ambient conditions and the requirements of the bleed system. This mode is selected in flight when the flaps are at zero and on the ground when the flaps are set at NO REV. For instance, if the bleed system demands more pneumatic then the modulated mode will be increased to provide more engine bleed. The Approach mode depends on the aircraft's cruise altitude. The mode helps the engine accelerate rapidly, for example, from idle to go-around thrust. This feature is important during go-around landing and takeoff as the aircraft demands rapid acceleration. The reverse mode is selected on the ground when the REV IDLE is selected. The most important feature of this mode is that the thrust generated by it is slightly higher than the forward thrust to slow down the aircraft.

Table 2: Idle Modes of FADEC

Modulated	Approach	Reverse
Depends on the bleed system demand and the ambient conditions.	Depends on the aircraft's altitude during the approach.	Activates when REV IDLE is selected.
Selected when flaps are at zero during flight.	Selected when the flaps are not at zero during flight.	The reverse thrust is higher than the forward thrust.
	This mode helps the engine accelerate rapidly.	

The FADEC system is powered by a magnetic alternator. The power supply diagram for the FADEC system is illustrated in the figure below. When the aircraft is supplied with A/C ground power, the FADEC system turns itself on for five minutes to perform system checks and tests and then shuts itself off. When the ignition and start are selected to turn on the engine, the FADEC system power also turns on. As the N2 rev increases above 12%, the FADEC system is self-powered with the engine power/torque. When the master switch is turned off to power down the engine, the FADEC system self-powers itself until the N2 drops below 12% and then switches to its internal power from the alternator. The system runs for five minutes from the time the master switch is turned off to perform and record system tests. During ignition and engine start and before the master switch is on, if the engine mode is selected as NORM, the FADEC system has the authority to shut itself off.

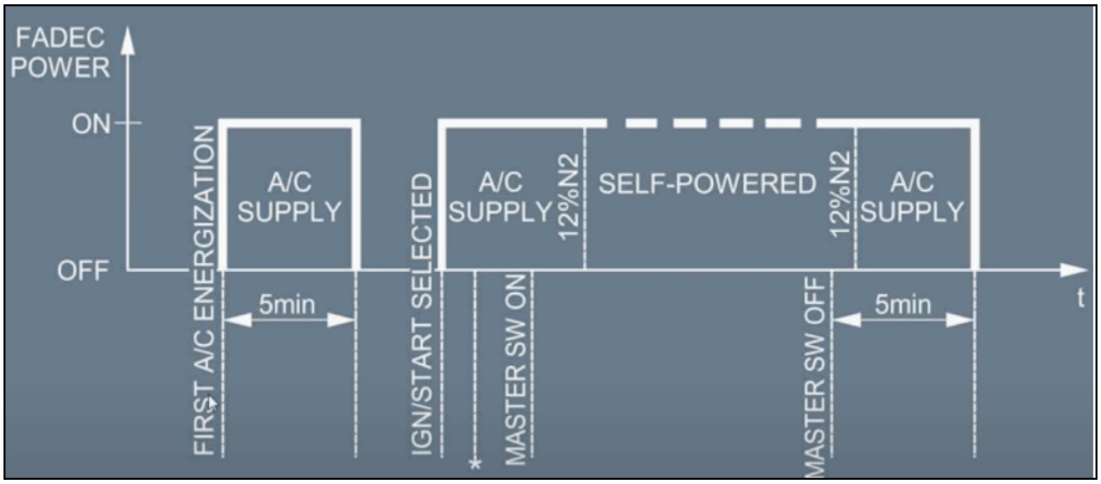


Figure 50: FADEC Power Supply Diagram [26].

5.3 Control System

At a given flight envelope, several variables affect the engine performance which the pilot cannot control constantly with the throttle lever. As discussed in the previous section, the movement of the throttle position determines the amount of fuel and air input to the combustion chamber. This, therefore, changes the turbine speed and the exhaust gas temperature. Therefore, the engine control system can be viewed as a control system problem where the inputs and outputs are divided with sensors that can compute the engine conditions for appropriate engine control requirements. As illustrated in the figure below, the inputs for the control system include the throttle position from the pilot or the FADEC system, the air data computed by the flight computer, the engine turbine and rotor speeds, and the engine temperatures from the necessary sections. Based on the throttle position, the control system also receives the fuel flow rate and turbine pressure ratios. These inputs are managed and monitored by the FADEC system and the EIU. The outputs for the control system would be the thrust, heat, and noise generated.

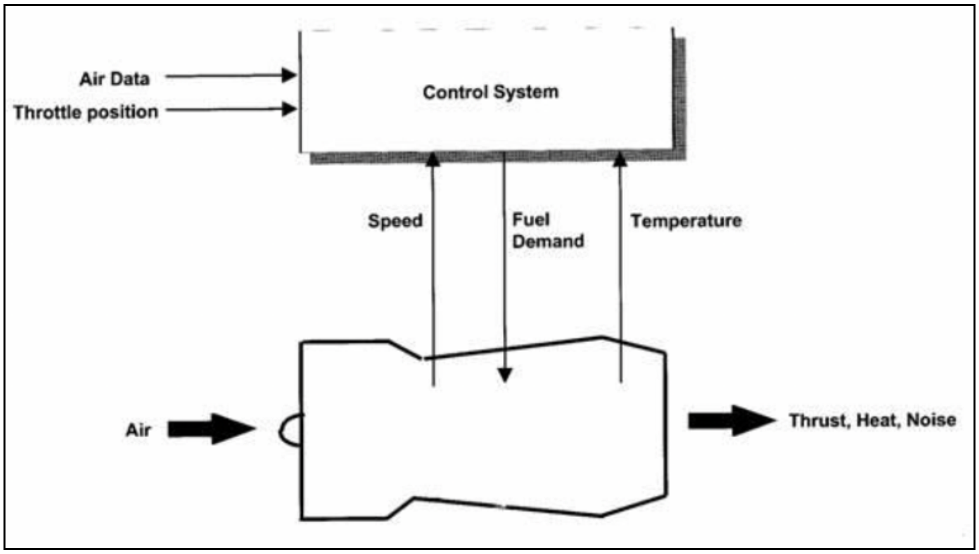


Figure 51: Engine Control System [27].

5.4 Thrust Control System

The thrust control system is a system dedicated to controlling the amount of thrust produced by the engine depending on the thrust lever position set by the pilot. The FADEC system dedicated to each engine controls the thrust from the respective engine. If the pilot adjusts the thrust lever, the FADEC thrust control system automatically sets itself into manual mode. When the Flight Management and Guidance System (FMGS) sets the thrust, the system is automatically set into automatic mode. As discussed in the previous section, the FADEC system is responsible for making sure that the thrust limits are maintained under manual and automatic modes. The following figure illustrates the thrust lever used by the pilot for manual thrust control.

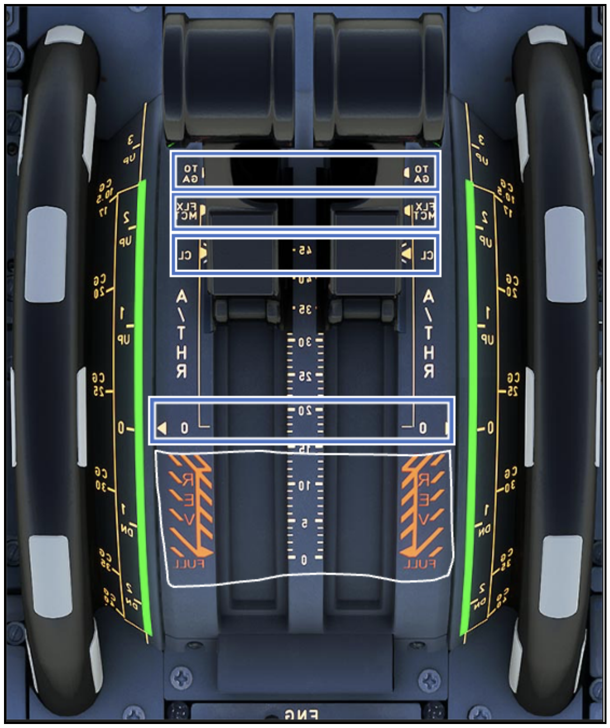


Figure 52: Thrust Levers on Airbus A320 [28].

The thrust levers on the Airbus A320 are located on the center pedestal consisting of five detents or stops. The pilots can set between these five predefined positions based on the flight envelope. Then based on the position, the thrust control system and the FADEC system determine the air-to-fuel ratio and the engine air-bleed ratio. The first position is “TO/GA” which means take off and go around scenarios. The second position is “FLX/MCT” which means flex take-off and maximum continuous thrust. The position marked “CL” provides the thrust for maximum climb. The position “0” represents the engine idle setting. The last detent is thrust reversal with a reverse idle and a maximum reversal position.

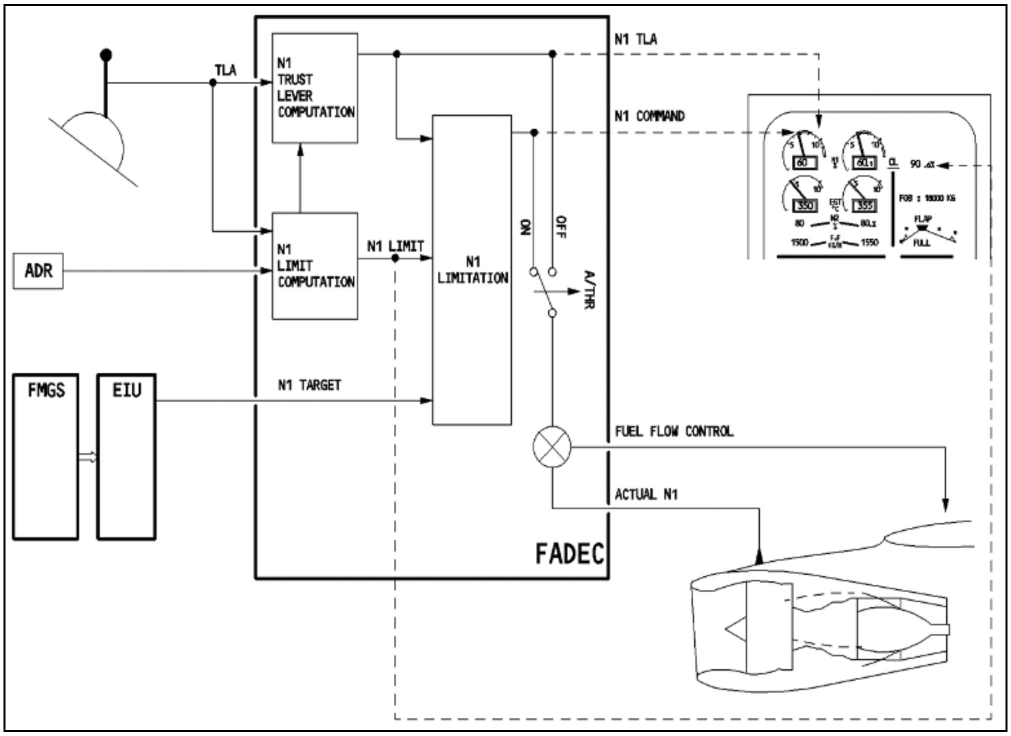


Figure 53: Thrust Control System [26].

When the aircraft is operating with two healthy engines the auto thrust range for the lever is from the idle position to the maximum climb position. Whereas, in case of a single engine failure, the auto thrust range for the lever increases from the idle position to the maximum continuous thrust position. During the flight and on the ground, the thrust lever position is transmitted to the FADEC system which then calculates the thrust limits for that position. This information is then displayed to the pilot along with the N1 for the selected thrust lever angle. If the thrust lever position is set between two detents the FADEC system calculates the rating limit for the higher detent.

During the manual mode, the pilot sets the thrust position by moving the lever between the IDLE and TOGA positions. The FADEC system calculates each detent's limit ratings and displays them to the pilot. The schematic diagram of the thrust control system illustrates the functionality of the system for manual and automatic modes. During the automatic mode, the FMGS transmits the thrust requirements to the EIU which is forwarded to the FADEC system for limit rating computation. The FADEC then controls the engine air-to-fuel mixture ratio and N1 revs for the desired thrust. The limits for the required thrust are transmitted back to the FMGS and are also displayed to the pilots.

5.5 Engine Fuel System

The fuel system is responsible for supplying the fuel to the combustion chamber at the desired flow rate, temperature, and pressure. The desired requirements depend on various factors such as flight envelope, ambient conditions, thrust lever position, etc. The fuel is pumped from the fuel tanks (located on the wings) via the fuel pumps (located in the accessory gearbox) and the fuel/oil heat exchanger unit (located on the outer engine) to the Hydromechanical Unit (HMU) and the fuel nozzles in the combustion chambers. The FADEC system controls the HMU system which is responsible for regulating the fuel flow to the combustion chamber, and fuel hydraulic signals to the engine actuators.

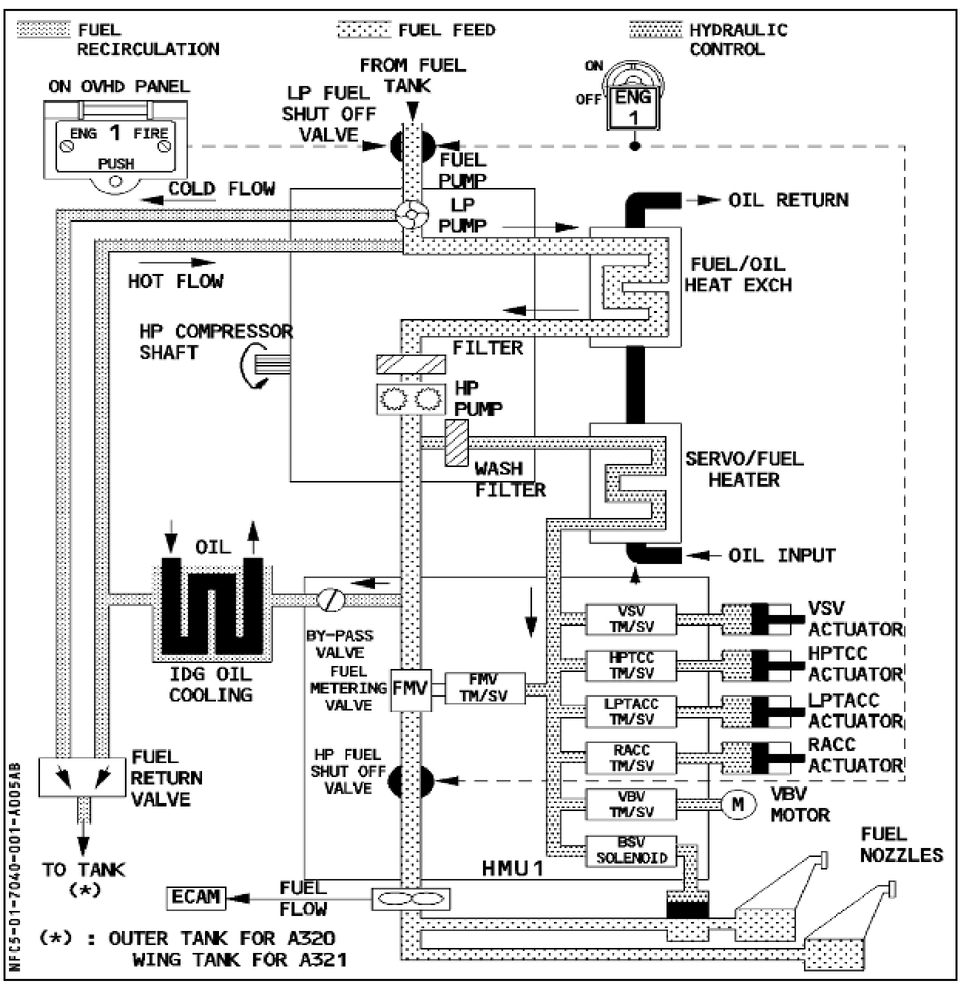


Figure 54: Fuel Control System [26].

The figure presented above illustrates the fuel flow from the tank to the fuel nozzles. The cold fuel travels from the tanks to the fuel/oil heat exchanger to the HMU and then to the fuel nozzles. After the fuel is heated, it goes through a filter to remove any contamination and then to a servo fuel heater to eliminate any ice particles that might damage the HMU actuators. The HMU system also monitors and protects the rotors from over-speeding. The HMU is also called a speed governor which refines to provide automatic speed adjustments. The HMU system consists of four actuator valves and a motor valve known as hydraulic signals. The four valves connect to the following actuators: Variable Stator Vane (VSV) actuator, High-Pressure Turbine Clearance Control (HPTCC) actuator, Low-Pressure Turbine Active Clearance Control (LPTACC) actuator, and Rotor Active Clearance Control (RACC) actuator. The motor valve connects to the Variable Bleed Valve (VBV) motor. The VSV actuator controls the variable stator vanes to optimize the compressor efficiency of the high-pressure compressors at a steady state. The HPTCC actuator gives clearance to the turbine to optimize its performance and reduce the exhaust gas temperature. The LPTACC actuator modulates the fan bleed airflow for cooling the low-pressure turbine. In summation, the HMU controls the actuators that regulate the turbine and compressor cooling so that the expansion of the turbine blades due to the heat does not harm the engine efficiency. The figure below illustrates the signal loop for the VSV actuators. The signal from the FADEC system is relayed to the HMU, which then supplies the fuel to the VSV actuators. Based on the requirements, the actuator sends a feedback signal back to the FADEC.

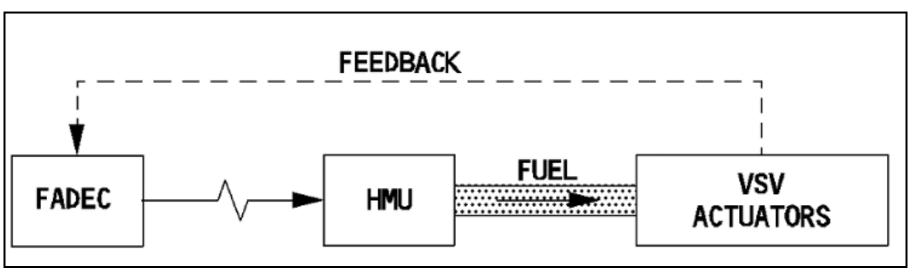


Figure 55: Hydraulic Signal Loop on the HMU [27].

The fuel flow to the fuel nozzles passes through the Fuel Metering Valve (FMV) and is monitored by the Electronic Centralized Aircraft Monitor (ECAM). The FMV is responsible for supplying the required amount of fuel to the nozzles as directed by the FADEC system. The FMV also generates a feedback signal proportional to the FMV position. The bypass valve ensures that the pressure across the FMV is maintained. In the case of engine over-speeding, the by-pass valve opens to draw out the extra fuel. The fuel travels back to the fuel tanks through an IDG oil cooling unit. The extra fuel that is en route back to the tank is mixed with the cold fuel to maintain the fuel temperatures in the tank. During fire hazards, when the pilot presses the Engine one/two fire switch on the overhead panel, the fuel control system only shuts off the Low-Pressure Fuel valve. Whereas when the pilot turns off the fuel master switch, the system shuts off both the Low-Pressure Fuel valve and the High-Pressure Fuel valve. The figure below illustrates a block diagram highlighting the flow of information and the appropriate functionality of each system that is required by the FADEC system to compute the thrust limit ratings.

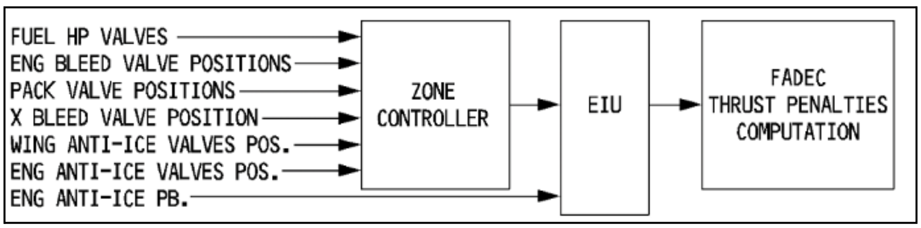


Figure 56: Fuel Control System and FADEC limit Computation.[27]

5.6 Engine Oil System

The oil system on the CFM 56-5 engine is responsible for lubricating the engine components and supplying oil for the fuel/oil heat exchanger unit. The oil supply system consists of an oil tank, lube and scavenging pump modules, a fuel/oil heat exchanger unit, filters, chip detectors, pressure relief, and bypass valves.

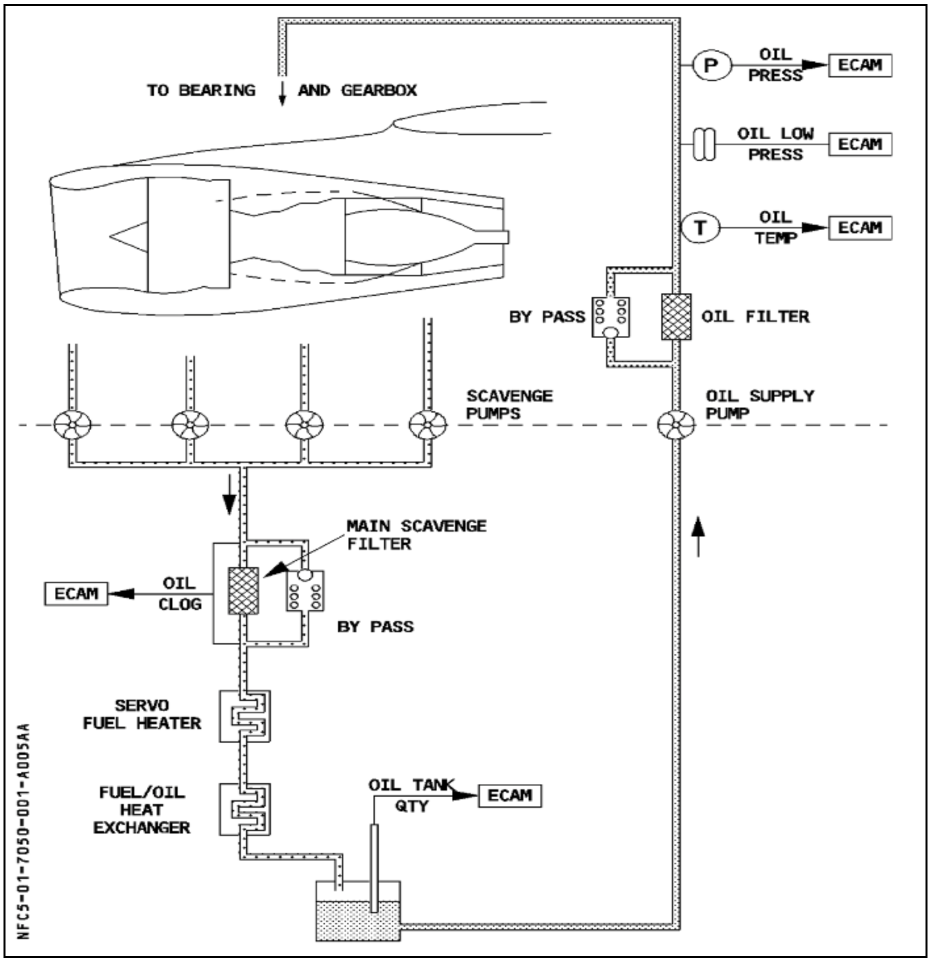


Figure 57: Oil Supply System Schematic [26].

The oil is extracted from the oil reservoir by an oil supply pump. The figure above illustrates the schematic diagram of the oil flow system. The fuel then passes through an oil filter. If the filter is clogged a bypass system is used. Then the fuel temperature and pressure are recorded and displayed on the ECAM for the pilot's information. If the pressure recorded is low a warning is displayed on the ECAM. The fuel is then supplied to the engine bearing and the gearbox. As seen in the figure, four scavenge pumps are used to extract the oil which then passes through an oil filter. If the filter is clogged a warning is displayed and a bypass is used. The oil then passes through the servo fuel heater and the fuel/oil heat exchanger. The cold oil that exits from the fuel/oil exchanger flows back to the reservoir.

5.7 Engine Air bleed System

The air bleed system on the Airbus A320 provides the aircraft with compressed air. The system uses a network of ducts, valves, and regulators to transfer medium to high-pressure air from the engine's compressor section to various parts of the aircraft. The bleed air system is mainly used for environmental control of the cabin. This section will discuss using engine bleed air to cool the engine compartments and the turbines. Cooling of the engine is an important aspect to prevent the rotor and turbine blades from expanding too much to maintain engine efficiency. The bleed air system also helps during engine start-up by providing the engine with the pneumatic energy that is required to start the blade rotation in the main engine. The pneumatic energy is supplied from the air bleed system located in the Auxiliary Power Unit (APU). The air bleed system is also used to protect the wing against icing problems by routing the high-temperature bleed air to the wing's leading edge.

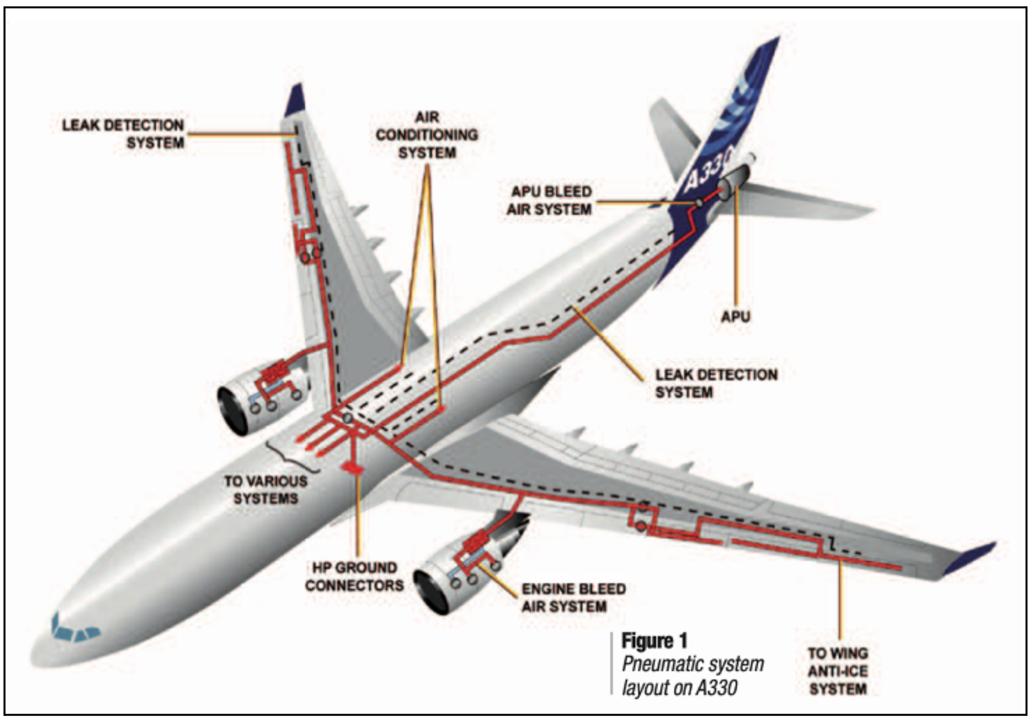


Figure 58: Air-Bleed System [29].

As discussed in the previous sections, the air bleed is extracted from the variable bleed valves located between the N2 rotor and the low-pressure compressor. The engine cooling on the CFM 56-5 is done using three actuators controlled by the Hydromechanical Unit (HMU). The three actuators include – RACC, HPTCC, and LPTCC and are discussed in the fuel system section. The FADEC controls these actuators through the HMU. The RACC, also known as Rotor Active Clearance Control, uses fifth-stage compressor bleed air that has been modulated according to the flight parameters and passed through the N2 rotor. The HPTCC, also known as High-Pressure Turbine Clearance Control, uses the high-pressure compressor bleed to cool down the high-pressure turbine case. Lastly, the LPTCC (Low-Pressure Turbine Clearance Control) uses the fan bleed airflow to cool down the low-pressure turbine case.

5.8 Thrust Reverser System

The Airbus A320's reverse thrust is a system that helps in reducing the aircraft speed during landing. The reduced speeds help in landing the aircraft on short or medium runways making the aircraft more accessible to more airports. The system reverses the engine thrust by using four pivoting blocker doors to deflect the incoming airstream. The A320's thrust reverser system improves the aircraft's and propulsion system's performance. The blockers are designed to be aerodynamic and robust as they undergo additional forces when deployed. The thrust reversers are controlled by the aircraft's hydraulic system under the control command from the engine's FADEC system. The green circuit in the hydraulic system operates the reverser doors on engine one, whereas the yellow circuit operates the reverser doors on engine two. Along with the reverser control, FADEC is also responsible for monitoring the system.

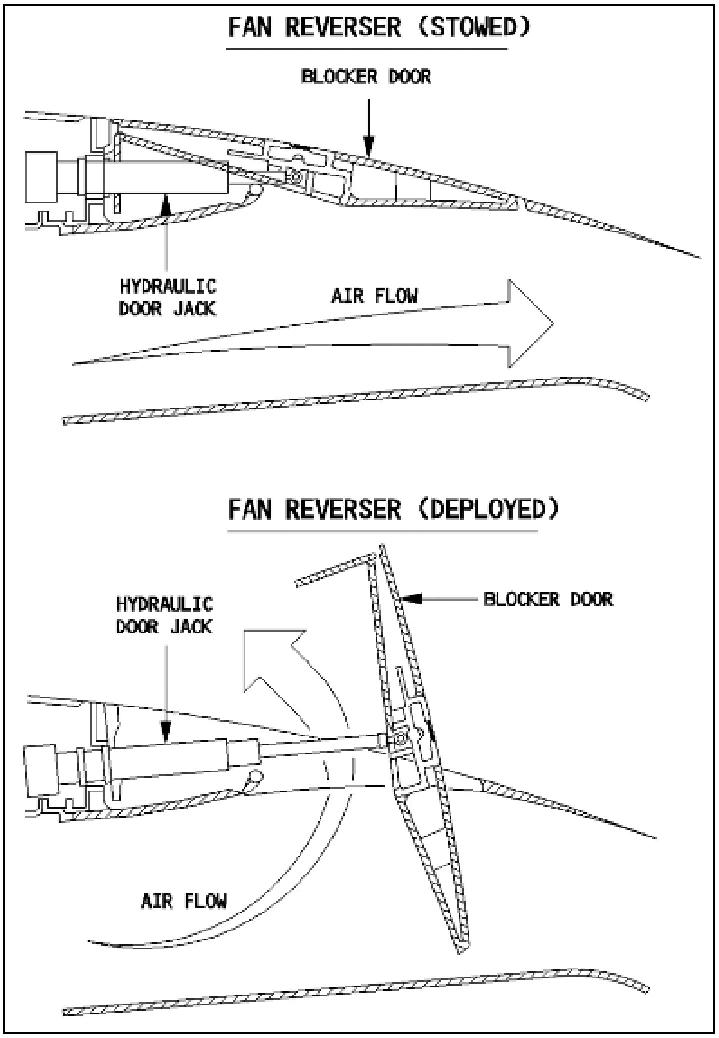


Figure 59: Thrust Reversers on A320 [26].

The figure above illustrates the reverser blocker doors position in stowed and deployed positions. On each of the two engines, there are four actuators, 4 blocker doors, a Hydraulic Control Unit (HCU), and a hydraulic shutoff valve. The HCU is responsible for pressurizing the thrust reverser hydraulic actuator, which helps to regulate the speed of the blocker doors. In cases of hydraulic system failure, the thrust reverser goes to idle reverse positions.

5.9 Controls and Indicators

The engine controls and indicators are a piece of important display information to the pilot. The instruments and indicators are placed in the pilot's close and direct proximity due to the level of the criticalness of the engine control. In the Airbus A320, the engine controls and indicators are divided into the main instrument panel, the central pedestal, the overhead panel, and the maintenance panel. The main instrument panel consists of instruments that indicate primary engine parameters and secondary engine parameters. These primary parameters include N1 speeds, thrust limit mode, N1 rating limit, FLEX temperature, exhaust gas temperature (EGT), N2 speeds, fuel flow, and engine idle indication. The secondary parameters include fuel used, oil quantity, oil pressure, oil temperature, N1 and N2 vibrations (VIB), oil filter clog, fuel filter clog, ignition, start valve position, engine bleed pressure, and nacelle temperature. The main engine switches are located on the central pedestal below the thrust lever. These include the engine mode selector knob in the middle, engine 1 and 2 master switches on the top, and fault switches in case of engine fire dedicated for each engine.

Figure 60: Engine Primary Parameter Indicator.

6. Fuel System

The storage of enough fuel in tanks and supplying the engine with an optimum amount of fuel are the main goals of the fuel system. According to the FADEC system's specifications, the fuel supply unit must circulate enough fuel into the combustion chamber at the proper flow rate, pressure, and temperature. This function also serves in the cooling of the Integrated Drive Generator (IDG). Fuel would also be stored in the outer wings for minimizing the effects of flutter and wing bending. Furthermore, supplying fuel to the engines and Auxiliary Power Unit (APU) is also a crucial aspect. An ideal fuel system's key objectives all revolve around the primary goals of storage and circulation. Thus, depending on the aircraft, most functions of the fuel system are derived from storage and circulation [33].

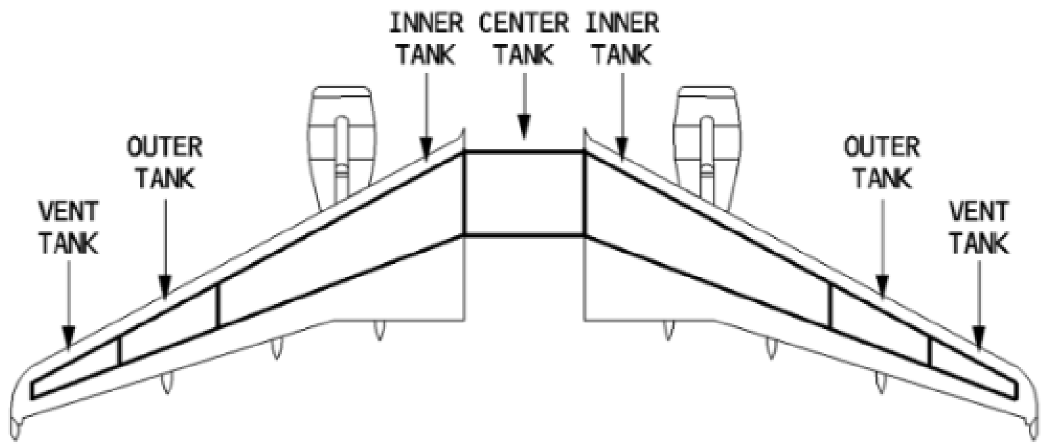
6.1 Storage

In general, fuel consumption is calculated based on mass. Fuel for jet aircrafts is measured in pounds since the fuel's volume varies with temperature[35]. This is crucial when an airplane is flying at a high altitude when it will be between -40 to -50 degrees Fahrenheit. The total fuel capacity of the Airbus A320 is roughly 42,000 pounds for a full range flight[F1]. This is distributed throughout the aircraft among 5 tanks according to the table provided below.

Table 3: Fuel Distribution [33].

Cell Location	Fuel Amount (lbs)
Wing Inner Tank (Each)	12200
Wing Outer Tank (Each)	1500
Center Tank	14500

Since there are 2 inner and outer tanks each, this adds up to the approximate total fuel amount (42 thousand pounds) mentioned earlier. A more detailed breakdown of the fuel distribution can be found in the figure below which is taken from the 'Flight Crew Operating Manual'. From that it's clearly visible how the tanks compare in size and how they are spaced out. As evident from this very image, all the fuel is stored at the middle of the aircraft spanning from one wing to the other. Additionally, a more detailed table is also provided within the figure regarding the amount of fuel in each tank for operation. Different types of units are displayed for a better understanding of the total fuel distribution which aligns with the simple above mentioned table [34].



USABLE FUEL					
		OUTER TANKS	INNER TANKS	CENTER TANK	TOTAL
VOLUME	(liters)	880 x 2	6924 x 2	8250	23858
	(US gallons)	232 x 2	1829 x 2	2180	6302
WEIGHT *	(KG)	691 x 2	5435 x 2	6476	18728
	(LB)	1520 x 2	11982 x 2	14281	41285

Figure 61: Tank Locations and Fuel Specifications [34].

The amounts indicated above are based on a fuel density of 0.785 Kg/L or 6.551 lb/US Gallons. When fully refueled, fuel can expand by about 2% without spillage (@20°C temperature rise). For this reason, there is a vent surge tank beyond the outer tank in each wing. There also lies an overpressure protector between them.

6.2 Transfer

Fuel lines and valves connect each fuel tank to its corresponding pump. The display is also used to show the temperatures that each wing tank is subjected to while in flight. When the amount of fuel in the inner wing fuel tanks reaches about 750 kg, a transfer takes place utilizing gravity, and the fuel in the outer wing tanks is used. This is done to prevent catastrophic events from occurring due to wing flutter and wing bending. The two sides of the fuel systems are typically maintained apart from one another, but in the event of any abnormality, the isolation can be lifted to allow gasoline to flow from denser to lighter areas. Six gasoline pumps are included in all, two in each of the wing tanks and two in the center tank. Each engine receives a predetermined amount of fuel that is delivered from the high-pressure fuel lime through the IDG heat exchanger, where it absorbs heat, to the fuel return valve, and finally to the external fuel tank. When the oil temperature is high or the engine is running at a low power level, this procedure causes the IDG cooling. Warm fuel from the IDG cooling system is sent back to the associated wing tank by the fuel recirculation system [34].

6.3 Engine Feed

The system primarily has 6 fuel pumps. The main fuel pump supplies the fuel from the tanks to the engines. During casual operation cases, each engine is supplied by one pump in the center tank or two in the inner and outer tanks during. Throughout the duration of the entire flight, all wing tank pumps stay turned on. They are accommodated with pressure relief sequence valves. These valves guarantee that when every pump is running, the center tank pumps shall deliver fuel more appropriately. Additionally, each wing has two electrical transfer valves mounted on them. Their implementation is meant for allowing fuel transfer between the outer and inner tanks. On the other hand, there exists a cross feed valve which ensures more flexibility in fuel transfer. This particular valve is controllable by a double motor and it thus allows either both engines to be fed from one side, or one engine to be fed from both sides. This gives the flight crew options to choose from based on the situation at hand. Priority can be given to transferring to both engines from one side if there are any issues on the other side. Furthermore, the fuel flow to engines can be discontinued if needed by the LP (low pressure) valves. This is initiated by either the engine master switch or by pressing the 'ENG FIRE PUSH' button. These low pressure valves exist to take immediate action in case of overfueling. Finally, the suction valves come into play to let engines be fed with the aid of gravity [34]. If the inner tank pumps fail amidst general operation, the suction valves are closed by pressure. Utilizing gravity here minimizes the need for any mechanism, additional equipment or labor. It's noteworthy that the central tank pumps do not have suction valves fitted. Hence, it would be impossible to perform engine feed via gravity from the tank within the center. A figuring is shown below illustrating the engine feed processes:

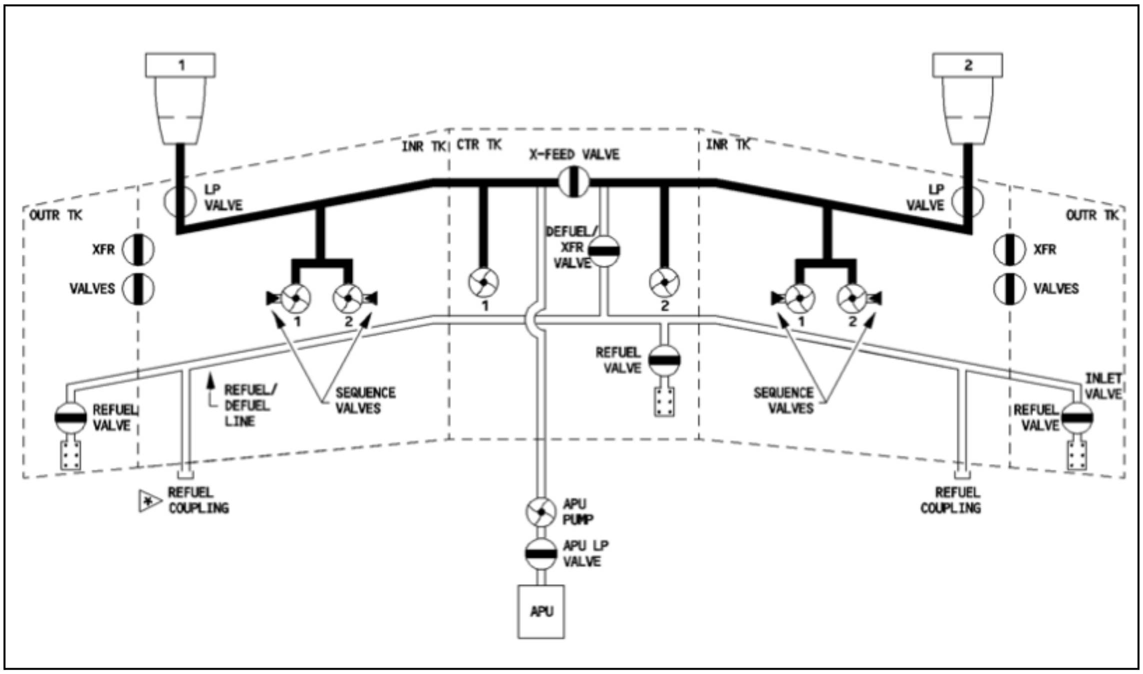


Figure 62: Valve locations and functions [34].

6.4 Fuel Feed Sequence

Airplanes require modes of sequence for fuel feed. Fortunately the Airbus 320 keeps things simple by having only one sequence for that function. The tanks are emptied in a specific order everytime. First is the center tank, then inner tanks (down to 750 Kg) and finally outer tanks (transferring to inner tanks).

When about 500 Kgs or 1100 lbs of inner tank fuel has been used, the center tank pumps are halted. This is due to the fuel level reaching the underfull sensors. The center tank pumps will always run smoothly (unless technical issues arise) when the 'MODE SEL' is set to 'MAN'. This stands for manual and in this mode, the 'CTR TK PUMP' button must be pressed to 'OFF' whenever the center tank is fully emptied. An image is attached below showcasing the center tank pumps control logic:

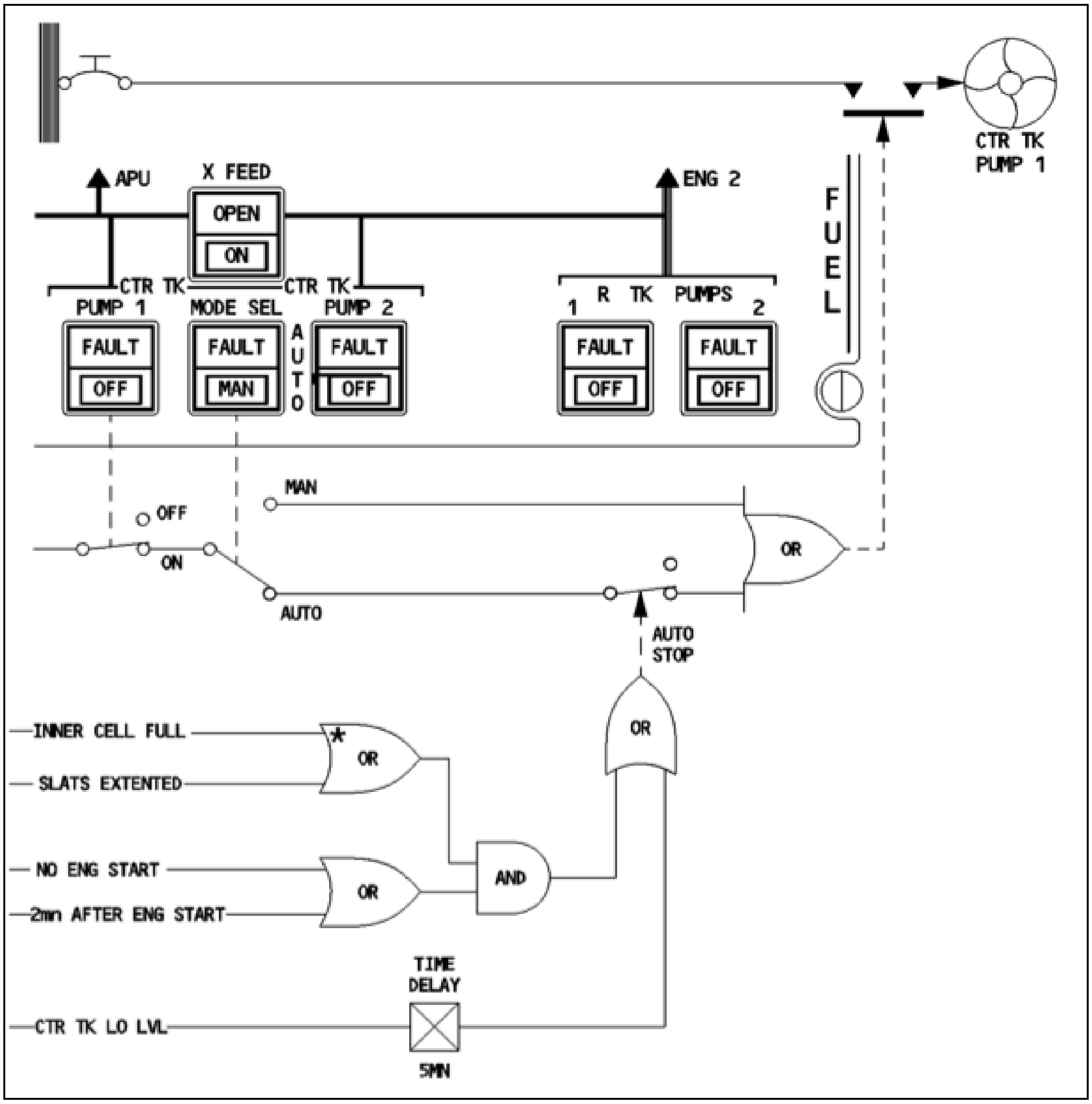


Figure 63: Pump Control Logic of Center Tank [34].

This diagram complements the description of manual mode for fuel feeding sequence of the center tank. Note that both pump 1 and 2 buttons are set to 'off'. The auto stop feature only occurs when the mode is in automatic instead of manual.

6.5 Recirculation

When the inner tank fuel diminishes to around 750 Kg, the transfer valves automatically open. This allows for the fuel to be drained from the outer tanks and be poured into the inner ones. These valves are latched when open and will close by themselves at the next refueling session. However, 'MODE SEL' should be set to 'REFUEL' for that to occur. It's an easy and automated process if the functionality is well understood.

Within each inner tank, there are two level sensors. These sensors control the transfer valves in the wings mentioned earlier. It is important to make sure that fuel transfer is seamless and simultaneous. The sensors aid in that purpose by a great margin since they affect the operation of the valves by default. The 750 Kg value also mentioned earlier is based on the aircraft level attitude with zero (0) acceleration. A 'low level warning' may be triggered by the sensors during nose dives, given that the opening of the transfer valves occurs with inner tank fuel reaching that value. A figure is provided below showing this indication:

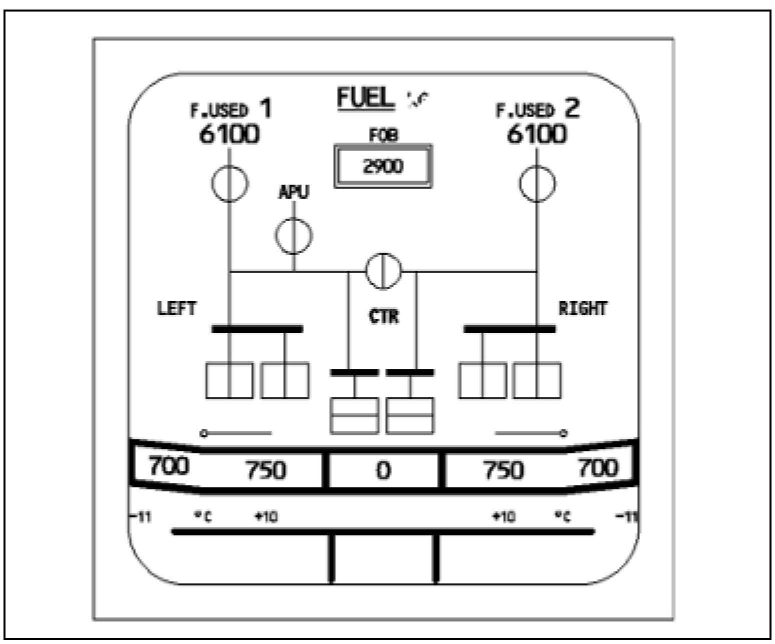


Figure 64: ECAM Indication [34].

The above figure shows an indication that illustrates both the transfer from outer to inner tanks and the inner tank feeding. The sensors and transfer valves working properly contribute to whatever parameters are displayed here.

Loss within the tank pumps or AC electrical supply may lead to low fuel feed pressure. In such a case, a special fuel pump supplies fuel for the APU startup. Each engine receives fuel through a high-pressure fuel line within the engine to the integrated drive generator (IDG) heat exchanger. There it absorbs heat, carries to the fuel return valve, and finally to the outer fuel tank. When the oil temperature is high or the engine is running at low power, this function ensures IDG cooling. The fuel return valve is managed by the FADEC. Fuel spills into the inner tank through a spill pipe if the outer tank is already full. The wing tank tends to overfill when the center tank is feeding, and the mechanism automatically turns off the 'CTR TK PUMP' when the inner tank is full. When the fuel level hits the underfull sensors, the wing tank pumps will continue to operate until the engine has utilized about 500 kg (1100 lb) of fuel [34]. The center tank pumps are then restarted by the logic circuits. This is shown in the figure provided below:

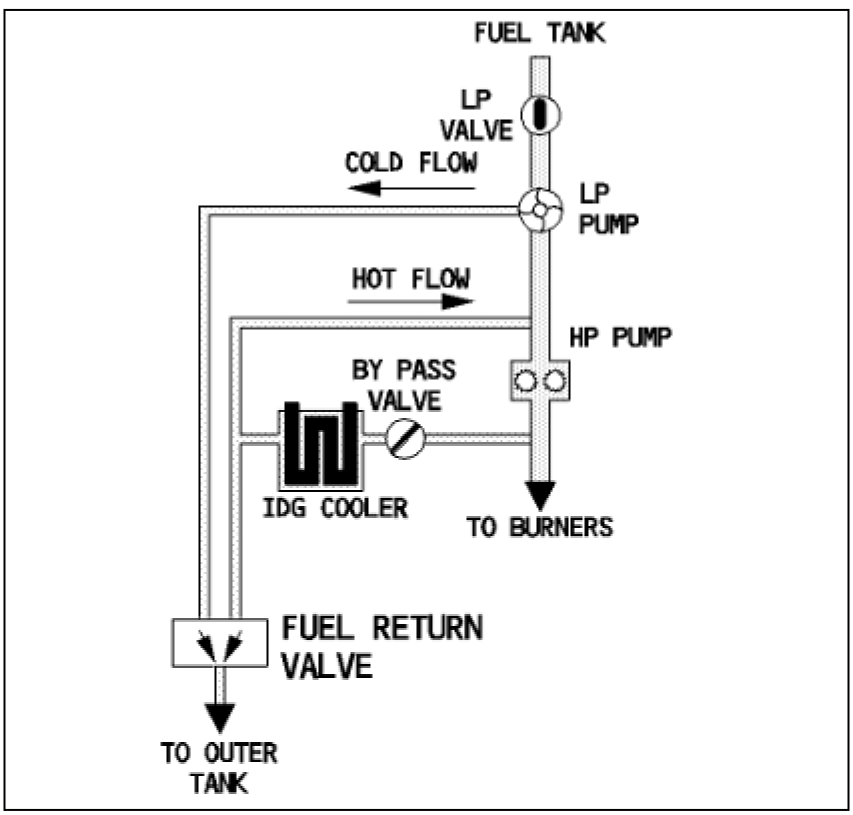


Figure 65: Logic Circuit [34].

As clearly evident from the above image, fuel is carried to the return valve after the IDG cooler extracts the heat energy from it. Only after that, the fuel is successfully carried to the outer tank. This mechanism exists to ensure that fuel temperature and pressure are ideally maintained.

6.6 Refueling/Defueling

The core refueling points exist underneath each wing. The design allows for flexible refueling from either side of the aircraft. An additional refueling panel exists on the side of the fuselage either below the right wing or left wing adjacent to the refuel coupling. A figure is shown below for an visual understanding:

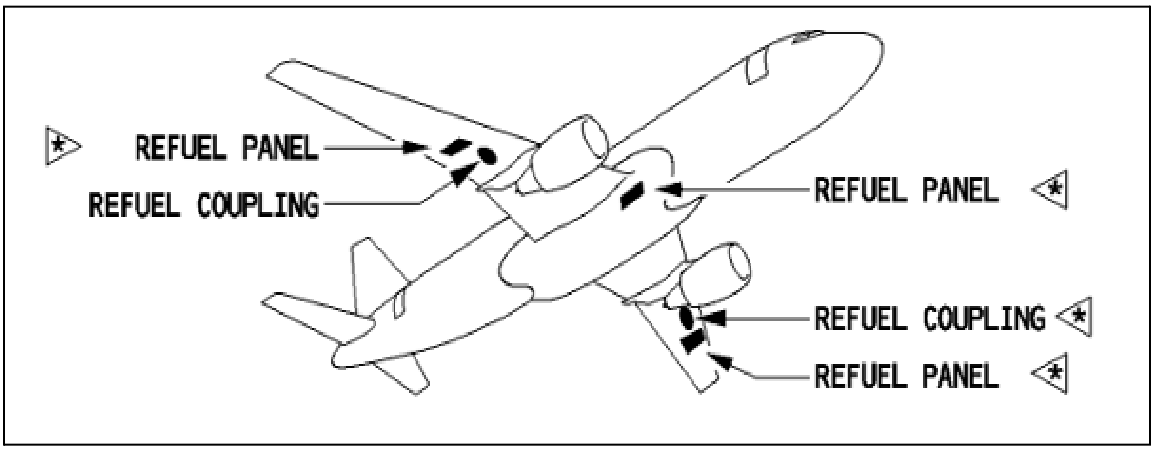


Figure 66: Refuel Panel Locations [34].

The refuel coupling is linked to each tank's refuel valve by a gallery. Refueling is often automatic with the preselector set to the desired fuel load. There is also manual control accessible. The outer cells start the automatic refueling process. The center tank is refueled concurrently if the chosen fuel load is more than the capacity of the wing tanks. Fuel spills into the inner cell through a spill pipe when an outer cell is full. When the tanks are filled with the desired load or when sensors detect a high fuel level, refuel valves automatically close. When battery power is the only source of power, the aircraft can be refueled. Through refueling points on the top of the wings, the wing tanks may be refilled by gravity. Note that the refueling time taken at nominal pressure is 17 minutes for the wing tanks and 20 minutes for other tanks. The ideal pressure falls within 40 to 45 psi [35]. Between the refueling gallery permits and engine feed system, the transfer valve allow for the following:

- Defueling via the refuel coupling.
- Transfer of fuel from one tank to another via the tank pumps

Note that the highly sensitive sensor is right next to the engine feed. The spill pipe lies directly under the refuel coupling. An additional figure is provided below to show the different components between the refuel coupling and engine feed:

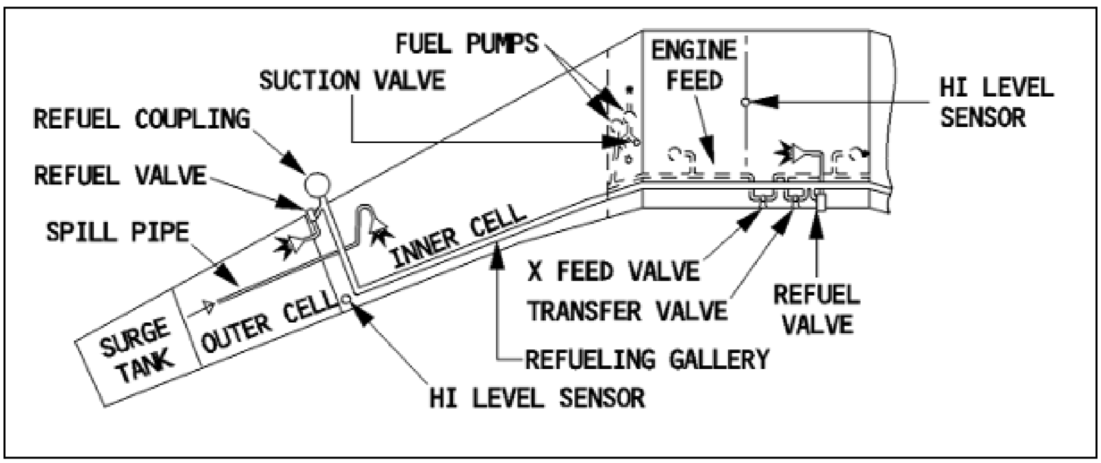


Figure 67: Detailed view of fuel components under wing [34].

Note that the structure shown above is symmetrical and mirrored on the other wing.

6.7 FQI System & FLSCU

The fuel quantity indication system (FQI) and fuel level sensing control unit (FLSCU) are key highlights of this aircraft. FQI depends directly on the accuracy of FLSCU [34]. The FQI is an electronic device that:

- Communicates to the ECAM the real total fuel mass as well as the amount and temperature of fuel in the tanks.
- Manages fueling by automatic means.

Fuel calculations are done by two channels, with channel 2 immediately activating if channel 1 fails. The FQI system is made up of:

- A computer called FQI.
- A set of capacitance probes to measure the temperature and fuel level in each tank. Each wing inner tank contains a densitometer (cadensicon) sensor that allows the amount of fuel to be calculated.
- One Capacitance Index Compensator (CIC) in each inner tank, which, in the event of a Cadensicon failure, provides the fuel's dielectric constant.
- A preselector that displays the preselected and real total fuel amounts on the refuel/defuel screen.

In order to operate the proper switching functions for refueling and defueling, as well as to manage the IDG cooling recirculation system and the center-tank-to-wing-tank fuel transfer system, the fuel level system generates fuel-level and fuel-temperature signals. Fuel level sensors that detect high, low, and overflow levels are part of the FLSCU [34].

- A fuel temperature sensor to regulate the IDG cooling recirculation
- The low-level sensor activates the LO LVL warning on the ECAM when the fuel level in one wing tank drops to less than 750 kg (1650 lb).

6.8 System Architecture

The FQI computer is the core of the system by playing the most vital role in understanding the current fuel conditions of the airplane. The fuel system process is depicted in the figure below:

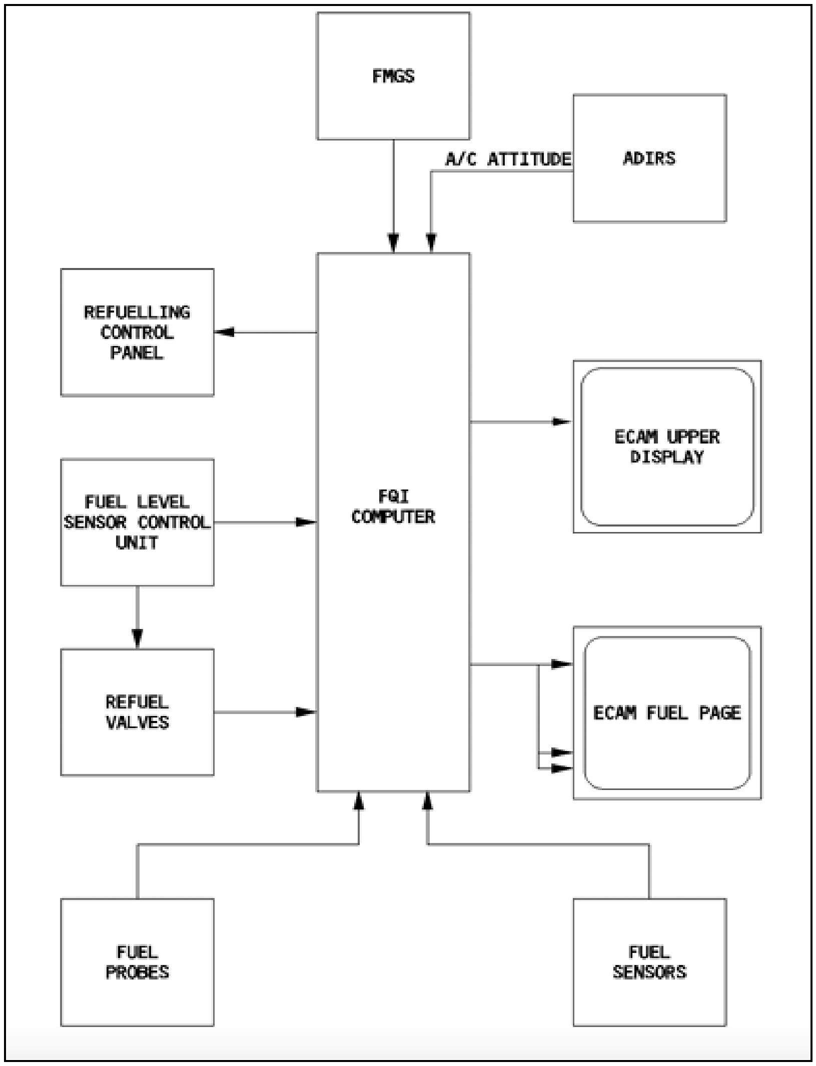


Figure 68: Fuel Architecture [34].

The overall fuel system of this particular aircraft gives reassurance to the longevity of fuel supply, system maintenance and control.

7. Hydraulic System

Hydraulic systems are some of the most common modern day systems found in machines. They are considered to be effective and are adjourned to be an industrial standard way to create movement and repetition. The basic concept behind the workings of a hydraulic system is simple and straightforward. Hydraulic systems function and perform tasks through using a fluid that is pressurized. Another way to put this is the pressurized fluid makes things work [36]. In the following few paragraphs the hydraulic systems associated with the Airbus A320 will be discussed and thoroughly dissected.

7.1 A320 Hydraulic System Overview

On the Airbus A320 the hydraulic systems have been worked in a way that they can be represented by 3 colors which indicate 3 separate hydraulic systems. These 3 colors are green, blue, and yellow. These colors and their corresponding functionalities through the hydraulic system can be seen in figure 69 below. The fluid and reservoir exists for each of these systems independently therefore it cannot be moved from one to another [37].

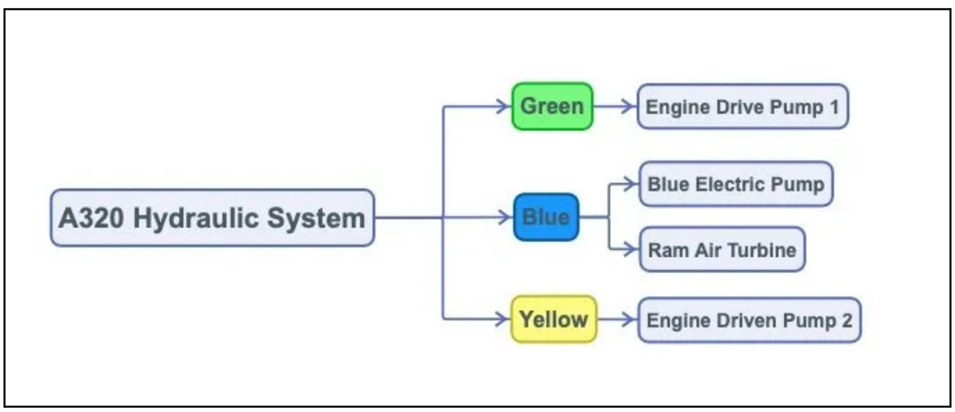


Figure 69: The Hydraulic Systems Colour Division for Airbus A320 [37].

A more descriptive image of the following hydraulic systems can be found on figure 70. This figure showcases the 2 engine systems as well as the 3 separate hydraulic systems along with their functionality. The green and yellow hydraulic systems are pressurized by an EDP (engine driven pump) labeled 1 & 2 respectively. EDPs are responsible for ensuring the system is pressurized to 3000 psi. In addition to that, it is to be noted that both the yellow and the green system maintain a pressure of 3000 psi. The blue hydraulic system is normally pressurized by the electric pump, however, it can be pressurized by the A320 Ram Air Turbine (RAT) as well, although the pressure is reduced by 2500 psi when done by the RAT [37].

Observing figure 70 carefully it can also be noted that the yellow hydraulic system allows for pressurization to be done through a hand pump operated by a ground crew when there is no electrical power available to the aircraft. This would operate the cargo door [37]. The ability for the yellow hydraulic system to be powered through an electric pump is also to be noted- this is useful on the ground when engine 2 is shut down.

The concept of redundancy is thoroughly observed throughout the hydraulic systems in the Airbus A320. The addition of the RAT as a backup in the blue system, plus, the addition of the hand pump as well as the electrical pump as a backup in the yellow system are all examples of this. Considering the emergency and backup options available in the systems of an aircraft is paramount.

The RAT is *utilized in the event of a dual engine failure or a serious electrical problem to supply power [37].* On the Airbus A320 in particular, a small-scale propeller can be deployed into the airstream to supply the blue system with power (using RAT). The RAT has been credited to saving lives which once again enhances its importance in the emergency response attributes for the A320 [39]. The RAT can be deployed both automatically and manually when specific conditions are met. For automatic deployment there should be a loss of both engines (AC BUS 1 & 2) and an airspeed which exceeds 100 knots. Manually it can be deployed through a guarded button on the overhead panel. This may be done in response to an ECAM (Electronic Centralized Aircraft Monitor) whilst following a QRH (Quick Reference Handbook) procedure [39].

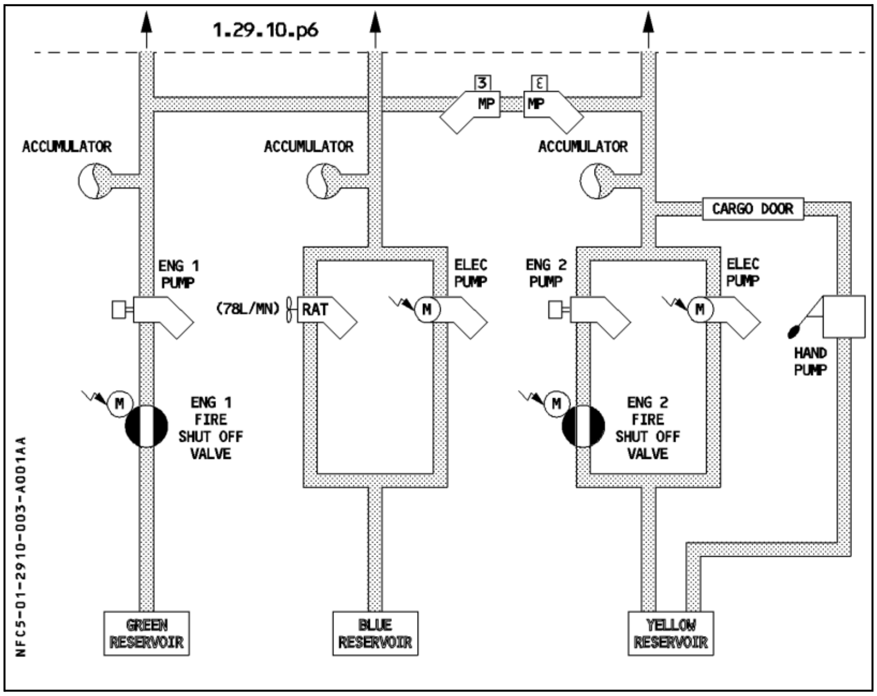


Figure 70: A detailed diagram of the hydraulic systems for Airbus A320 [38].

A comprehensive look at the hydraulic systems and its physical effects on the airplane can be observed on figure 71 & 72. Here, each coloured system as well as their flight controls are aptly listed.

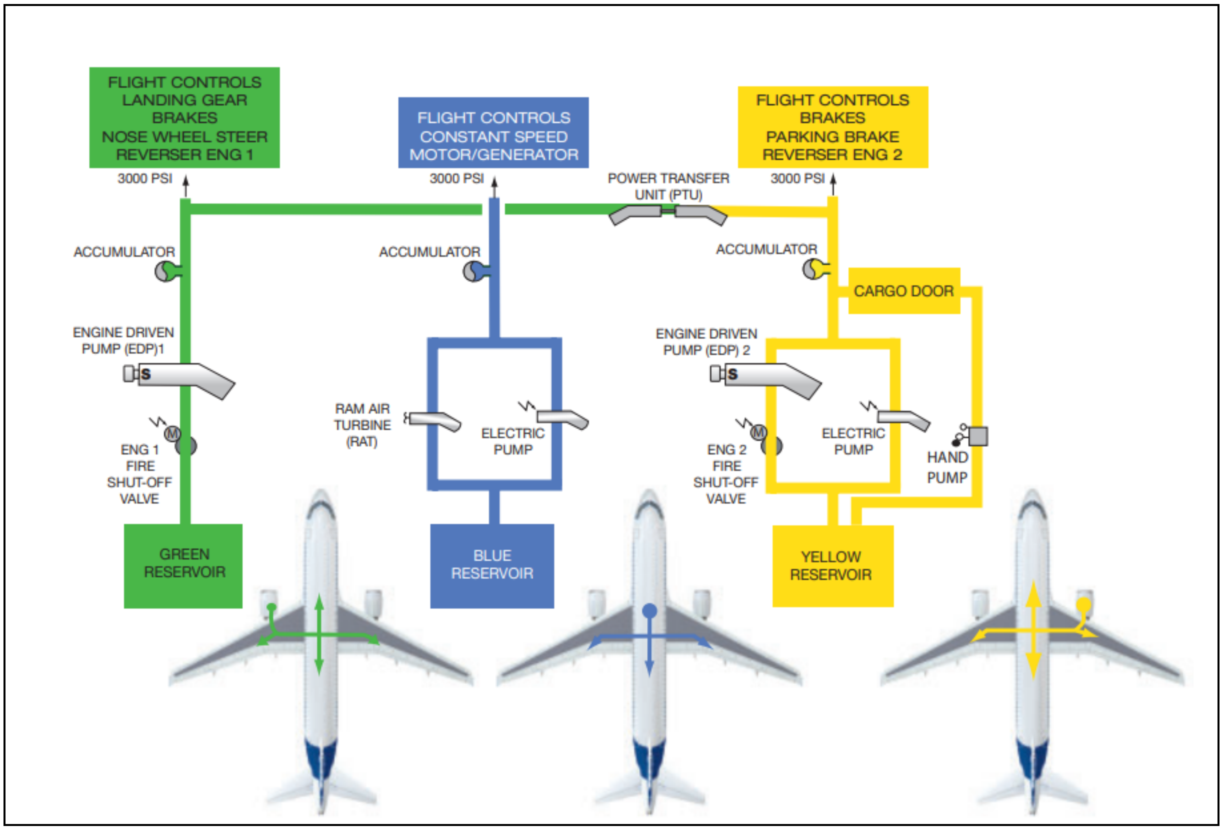


Figure 71: A Visual of the Hydraulics Systems on the Airbus A320 [38].

Through the above diagram an interesting detail that can be seen is the fire shut-off valves on the yellow and green systems. These are vital components of the hydraulic system to mitigate the risks associated with a fire occurring. Both are positioned near and after the reservoir's location and this is to address the issue in an isolated manner which further adds to the safety of the system. A leak measurement valve also exists in the hydraulic system of the Airbus A320. This valve is located forward of the primary flight controls. This is there to keep in accordance with the leakage measurement of each circuit [40]. “Priority valves” are also present in the system in the event of “low hydraulic pressure” to maintain the essential system and cut off hydraulic power to heavy load users. These valves in addition to an in depth overview of the components associated with the hydraulic systems can be found in figure d below.

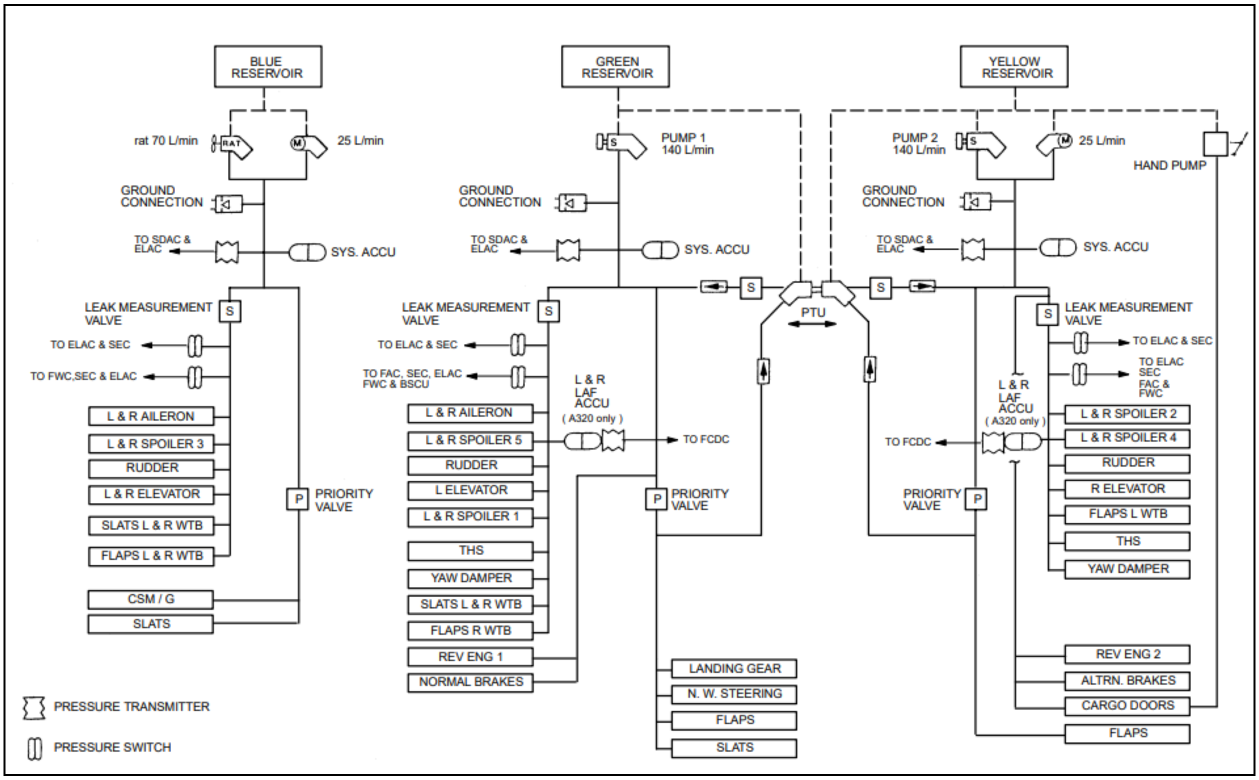


Figure 72: Hydraulics Systems & Associated Components [40].

The above diagram also gives a descriptive look at every individual control surface which can be controlled through the means of the hydraulic systems. The yellow channel is responsible for controlling the brakes (including parking), reversal engine 2, as well as other flight controls such as rudder, stabilizers, elevator (right), spoiler 2 (left and right), and spoiler 4 (left and right), yaw damper 2, and flap (left WTB). The blue channel is responsible for motors and generators, on top of flight controls such as the rudder, the ailerons (left and right), elevators (left and right), spoiler 3 (left and right), slats (left and right), and flaps (left and right). Finally, the green hydraulic channel is in charge of the landing gear, brakes, nose wheel steering, and thrust reversal as well. On top of this, the various control surfaces maneuvered through the green hydraulic system include the elevator (left), flap (right WTB), the stabilizer, the rudder, yaw damper 1, ailerons (left and right), spoiler 5 &1 (left and right), and other flaps and slats as well. The combination of these hydraulic systems help in assisting the pilot & other avionic systems to have a smooth control over the airplane.

7.2 A320 Pressure Transfer Unit

A component which is vital to the hydraulic systems onboard the Airbus A320 is the Pressure Transfer Unit (PTU). The PTU is a feature component of the Airbus A320 that can let the aircraft transfer pressure between the green and yellow hydraulic systems. It is essentially a bidirectional unit which can be activated when there is a psi difference of 500 (32 bar) or greater between the green and yellow systems [1]. As it was aforementioned, this process does not involve any fluid transfer whatsoever - rather it is done through a mechanical means. A visual of the system which is provided in the operating manual can be seen on figure 73.

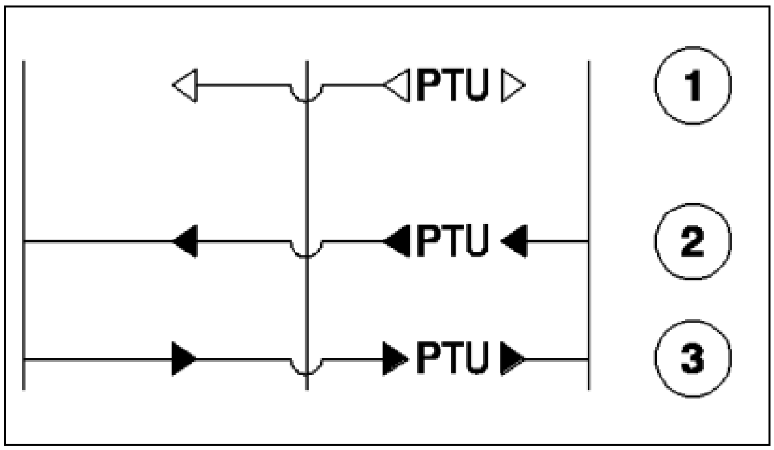


Figure 73: Control System of the PTU for Airbus A320.

In the above figure (figure 73), it is shown that the network labeled 2 is supplying the green hydraulic system, meanwhile the one labeled 3 is supplying the yellow one. The PTU is labeled by the number '1' and it is in AUTO mode. On the diagram it is switched off [38]. In order to mitigate the unwanted usage of the PTU (on ground), other switches and relays are installed on the A320. These would help provide power through the 2 solenoid valves when certain conditions are met. The PTU will not operate when:

- (1) The electric pump (yellow channel) is operating close to the cargo doors.
- (2) The aircraft is on ground plus only one engine is in operation and the parking brakes are "ON"
- (3) The aircraft is on ground plus only one engine is in operation and the parking brakes are "OFF", also the NWS (nose wheel steering) is deactivated.
- The PTU on the panel 40VU is set to "OFF"

In addition to that, on ground, with the engines shut off, the yellow electric pump can pressurize the green system [40].

7.3 Control Panels for Hydraulic Systems

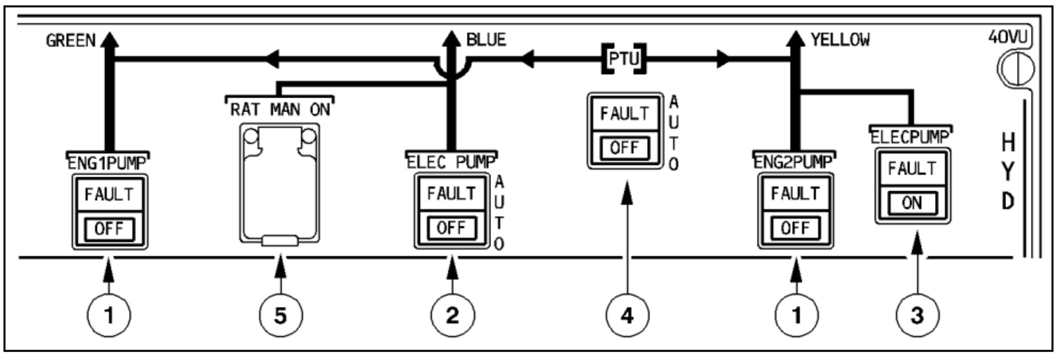


Figure 74: Overhead Panel to control Hydraulic Systems for Airbus A320.

The figure above (figure 74) shows the overhead panel which is responsible for the control of the hydraulic systems. The positioning of this panel is critical as this is the way the pilot can access and control the various hydraulic systems and their subsequent functionalities. The clarity of thought in the placement of each control panel can be examined. The avionics engineer pays crucial attention to this detail. In the following panel the color based hydraulic systems as well as the RAT can be noticed. In the images (figure 75 & 76*)* below the positioning of these overhead panels in the cockpit can be clearly noticed. It is marked (A), (B), and (C), and these letters refer to the hydraulic panel 40VU, emergency electric panel 21VU, and finally, maintenance panel 50VU respectively.

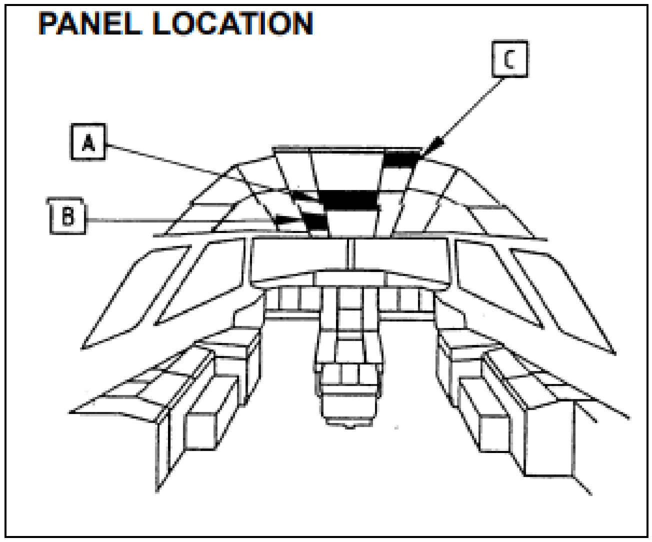


Figure 75: Overhead Panel Locations.

Figure 76: Hydraulic Panel in Cockpit.

On figure 76 & 74 above, the control panel for the hydraulic systems can be seen in the Airbus A320 cockpit. Further breaking down the main control panel and the various functions associated with it; firstly the different hydraulic system channels are clearly named on the panels. When flying the airplane such clarity is essential for the pilot as it enhances the ease of use. For all 3 channels there is an indicator which showcases the pressurization to be “OFF”, this means that there is depressurization in the respective channels. When it is “ON” the system is pressurized and power generation in correspondence is on as the engine is running. By the blue channel in particular there is a control for the RAT (ram air turbine) - when “RAT MAN ON” switch is enabled the pilot can operate the ram air turbine. This button is known as a “guarded switch”, this indicates that the button is covered by a red coloured tab that needs to be pushed aside before pressing the main button. A vital thing to note about the guarded switches is that both pilots would need to approve the use of them due to their criticality [37]. The electric pump switch can also be noticed associated with the blue hydraulic system channel. The electric pump would perform operation if the AC power is available in the flight or on the ground if one engine is running. It is to be noted, if the crew has pushed the BLUE PUMP OVRD pushbutton on the maintenance panel the electric pump can still operate [38]. Besides the blue hydraulic systemc channel the operator for the PTU switch can be noticed. The PTU can be enabled automatically whenever the pressure differential between the yellow and green system is above 500 psi. However, the PTU can be turned “OFF”, this is done through closing the electrohydraulic valves of the green and yellow channels. On the yellow hydraulic system switches there is an indicator for the electric pump which is “ON”. The pump for the yellow channel can automatically become active and turn on when a crew member sets the lever associated with the ‘cargo door manual selector valve' to "OPEN” or "CLOSE”.

On any avionics system there needs to be measures put in place to detect faults or issues. Safety is a paramount metric for systems on an airplane and this applies to hydraulic systems as well. Fault tolerance and fault detection (which is a central element to all fault tolerance systems [42]) is a concept considered in the design of the hydraulic system of the Airbus A320. There are redundancy elements found in all 3 of the channels and this ensures safe operation of the plane. Whenever there is a fault detected, an amber light displays on the overhead hydraulic panel. Below is an image highlighting the location where the fault detection can be seen in the overhead panel itself.

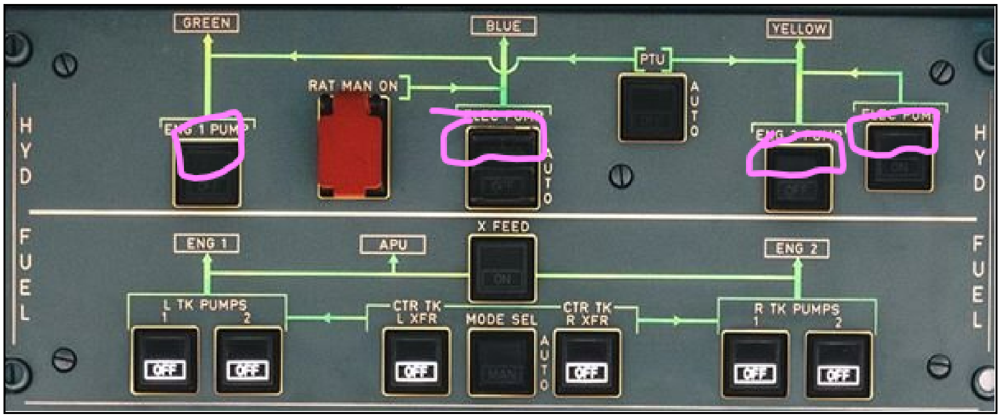


Figure 77: Fault Detection in Hydraulic Panel.

The ECAM caution appears and the amber fault detection light gets turned on if the following occurs:

1) The reservoir level is low (green, blue, & yellow channel)
2) The reservoir overheats (green, blue, & yellow channel)
3) The reservoir air pressure is not at the required level (green & blue Channel)
4) The pump pressure is low on the ground when the engine is stopped (green, blue, & yellow channel)
5) Pump overheats (yellow channel)

The light illuminating which displays the fault occurring can go out when the crew selects "OFF" with the only exception being during an overheat incident. The PTU also has its fault detection in which an amber light comes on if the following occurs:

1) Overheating of the green or yellow reservoir
2) Low air pressure of the green or yellow reservoir
3) Low fluid level of the green or the yellow reservoir

7.4 Electronic Centralized Aircraft Monitor (ECAM)

The Electronic Centralized Aircraft Monitor is a crucial component of an aircraft system. This is an electronic system tool that is employed in airplanes to monitor and observe the vast aircraft systems such as the hydraulic system, electric system, fuel system, etc. The ECAM plays a pivotal role in alerting the pilot whenever there is a problem detected and the necessary checklist to assist in mitigating the detected malfunction [37]. In figure 78 below the ECAM HYD (ECAM Hydraulics) display can be seen. On the display, the 3 channels along with their associated reservoirs. Valves, pumps, and pressure indicators are showcased.

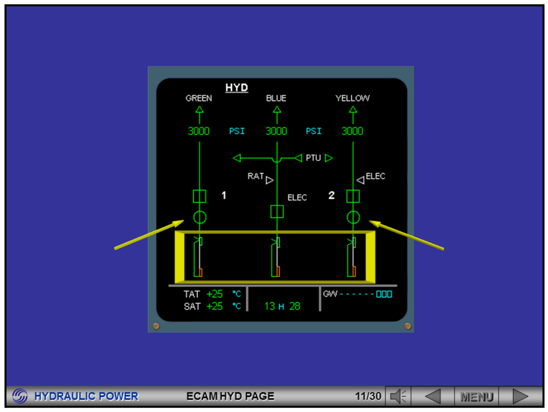


Figure 78: ECAM Hydraulic System [43].

In the figure above, the fire shut-off valves (red-green rectangle) and the reservoirs (circle icons) are highlighted for each of the channels. Above it, the engine pumps can be noticed (square icons). The electrical variant is marked for the blue channel. The pressure as well as the pressure transfer unit (PTU) is indicated on the ECAM. The clarity of the ECAM is essential to providing the crew and the pilot with effective information quickly. The layout of the ECAM resembles the layout of the overhead panel to add clarity. Figure 79 below showcases this:

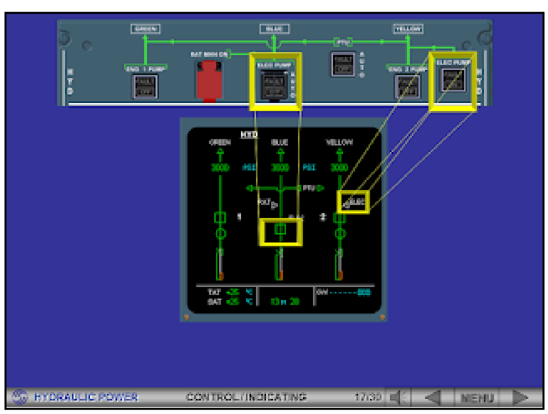


Figure 79: ECAM vs Overhead Panel Comparison [43].

7.5 Hydraulic Piping

The hydraulic piping of the aircraft (pipe layout) needs to be taken into consideration to mitigate against common mode failures due to accidental damage. Having this layout determined can assist in the calculation of the flow rates, pipe diameters, etc [44]. All the piping for the Airbus A320 is along the aircraft itself. The figures below (figure 80 & 81*)* showcases how the different channels are responsible for the various controls. The distribution of the piping can be seen as well in figure 83 on the next page.

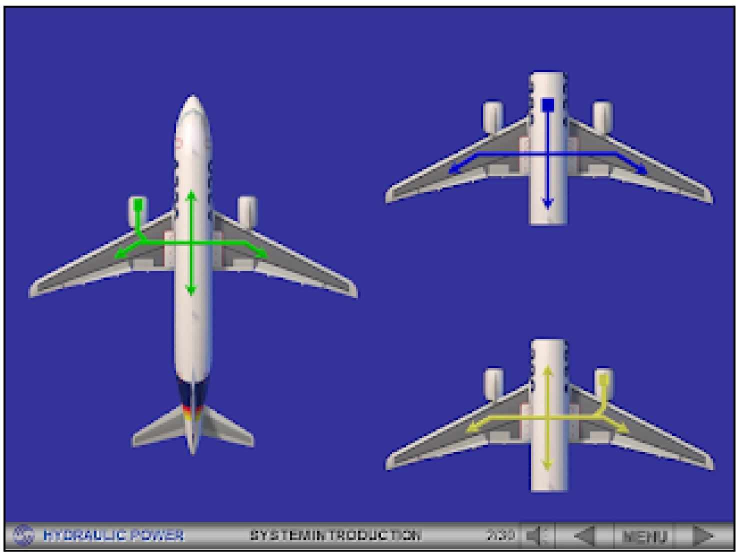


Figure 80: Distribution of Hydraulic Channels.

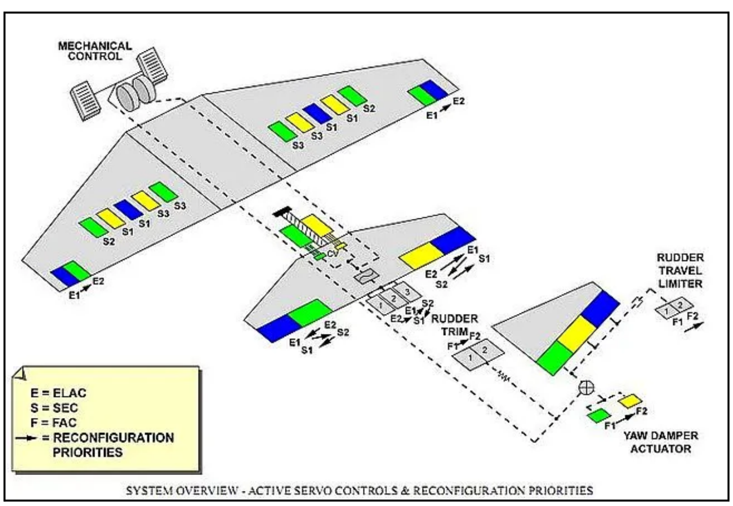


Figure 81: Controls by Each Channel [45].

Each of the hydraulic pipelines are tagged with a color code as well as a number which corresponds to the system identification. The components are marked as well. This helps with the maintenance of the system. The color code for components (green, blue, and yellow) matches with the channel. On figure 82 below the pipeline identification can be showcased:

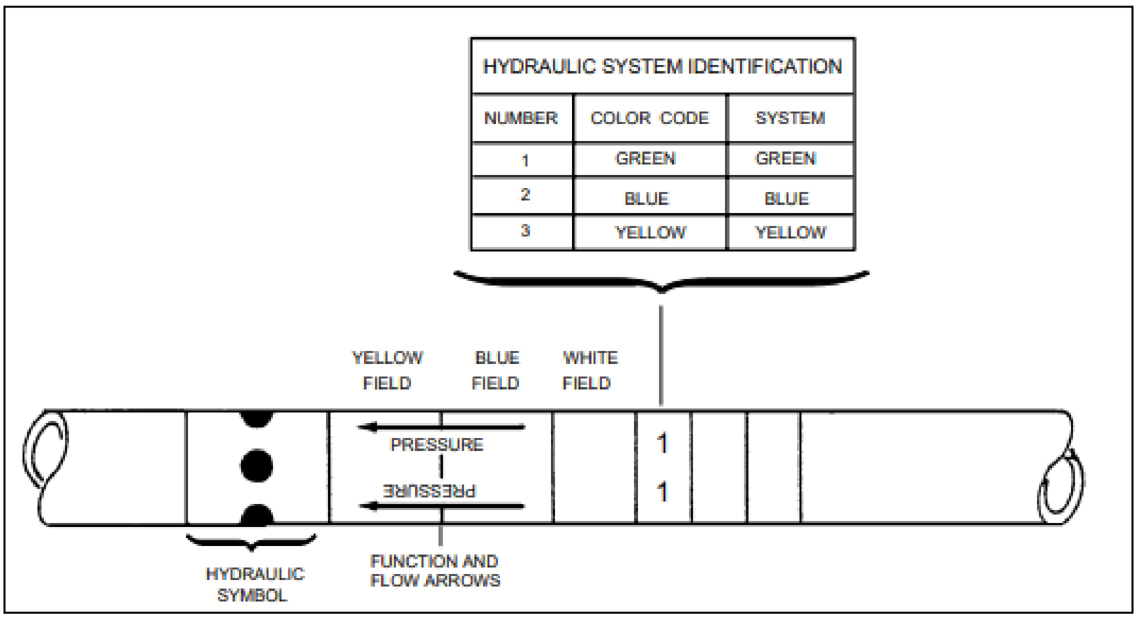


Figure 82: Pipeline Identification.

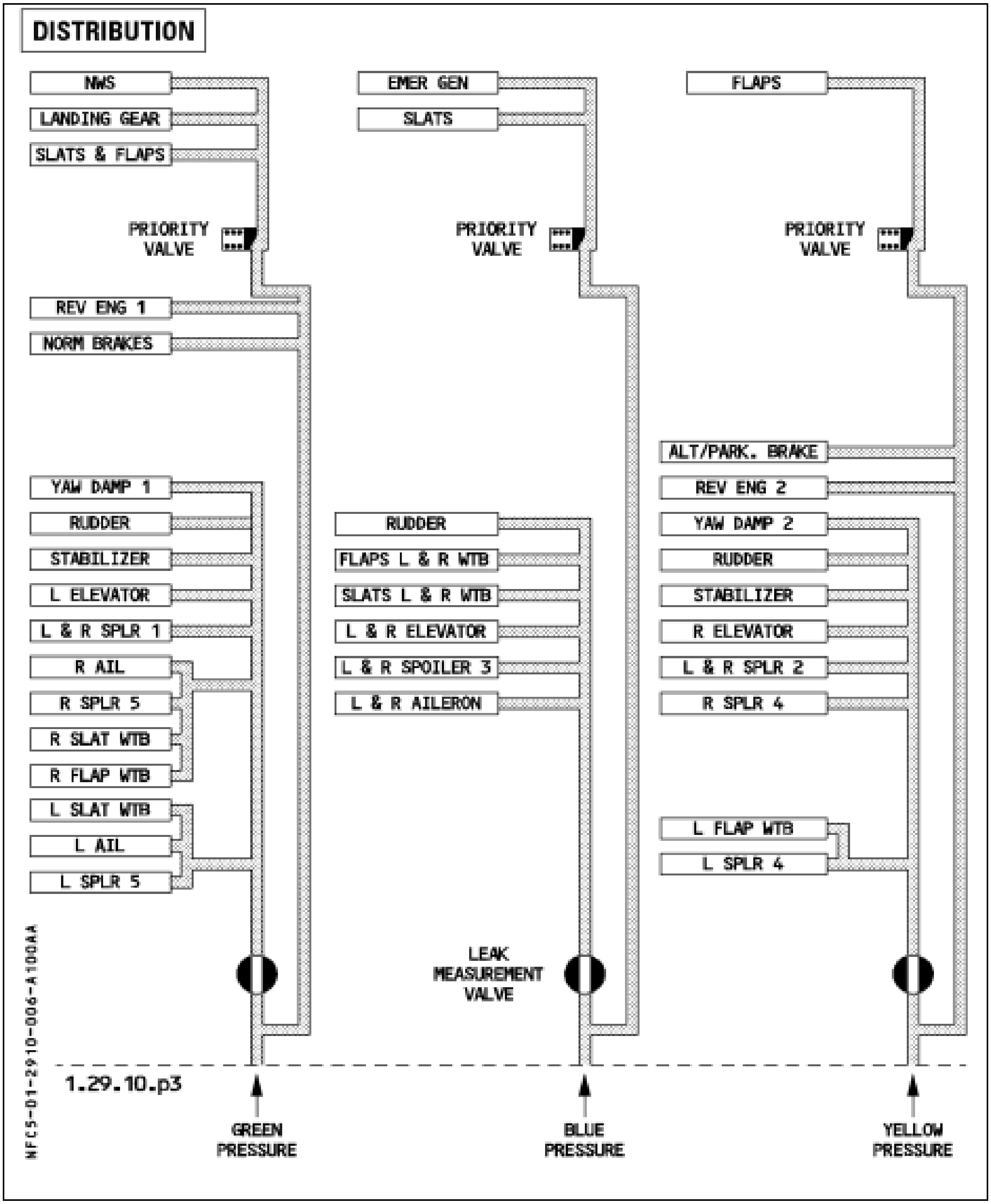


Figure 83: Distribution of Hydraulics with Controls.

7.6 Hydraulic Pumps

Hydraulic pumps are generally designed to sense the outlet pressure and feed that signal back to the plate carrying the reciprocating pistons. Generally the pump is mounted on the engine gearbox [45]. For the Airbus A320 the engine driven pump for the green channel can be noticed on the gearbox. Reiterating previous information, the A320 aircraft consists of EDPs (engine driven pumps) for the green as well as yellow hydraulic channels, in addition to that there are electric pumps as well for the yellow and blue channel. An additional component found in the hydraulic systems is a hand pump associated with the yellow channel and the critically important Ram Air Turbine (RAT) for the blue channel. Some of the aforementioned pumps & components can be visually seen in figure 84 below.

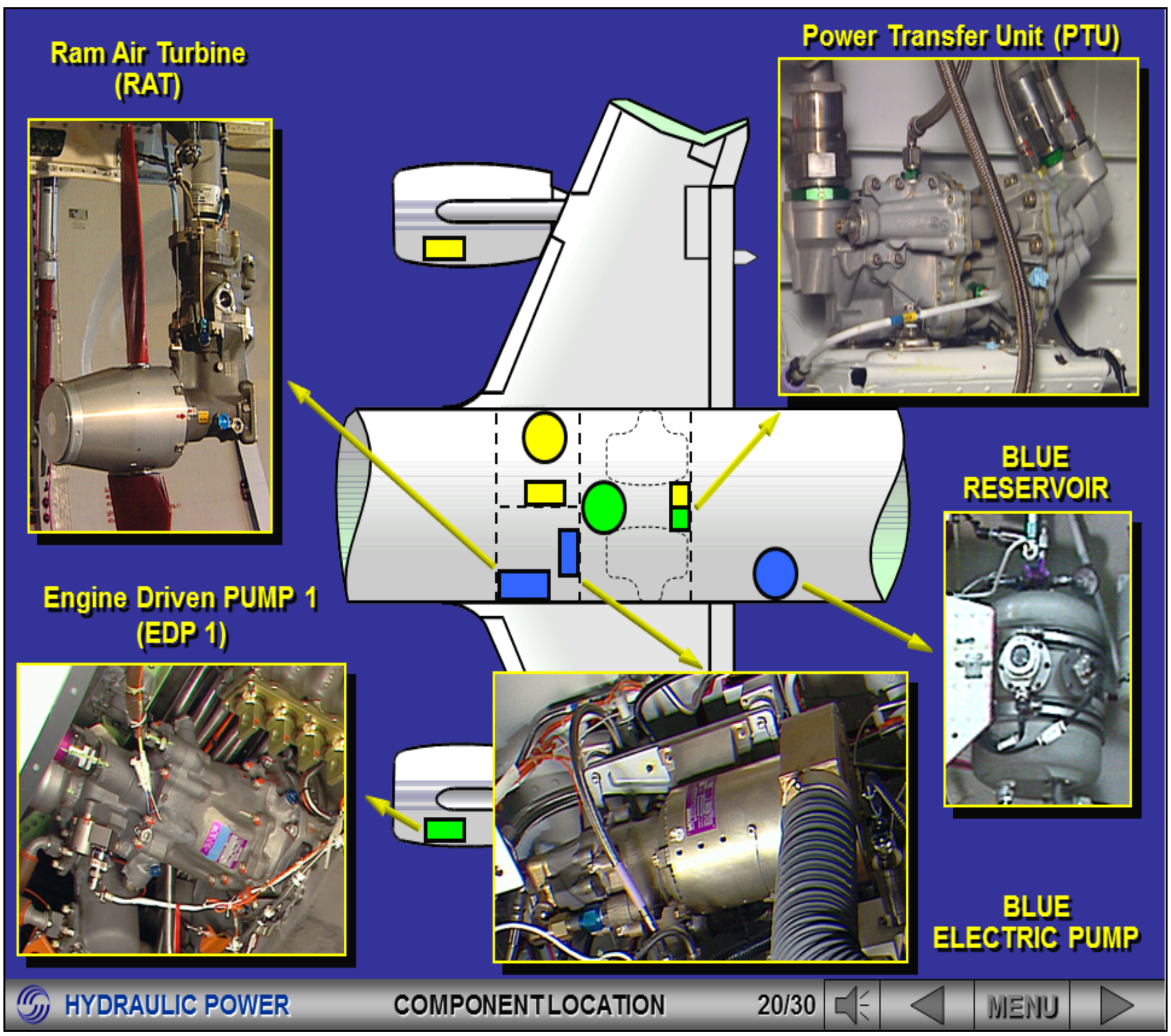


Figure 84: Visual of the RAT, EDP, & PTU.

As it can be seen in the figure above (figure 84*)* the Pressure Transfer Unit is located by the main landing gear bay area, while the blue electric pump and the Ram Air Turbine is located by the blue hydraulic bay area. Near the rear of the main landing gear the blue reservoir can be found. Meanwhile, the green reservoir is located in the main landing gear bay. The yellow electric pump and reservoir can be found in the yellow hydraulic bay area.

As for the engine driven pump itself there can be a couple different types of EDP which are permitted for use, one of them is the *ABEX* and the other is *VICKERS*. Both can be changed with one another as they give an equivalent supply of hydraulic power in addition to maintaining the same mechanical and electrical connections. A few schematics of the engine driven pump and its corresponding location can be found in the figures below (figure 85 and 86).

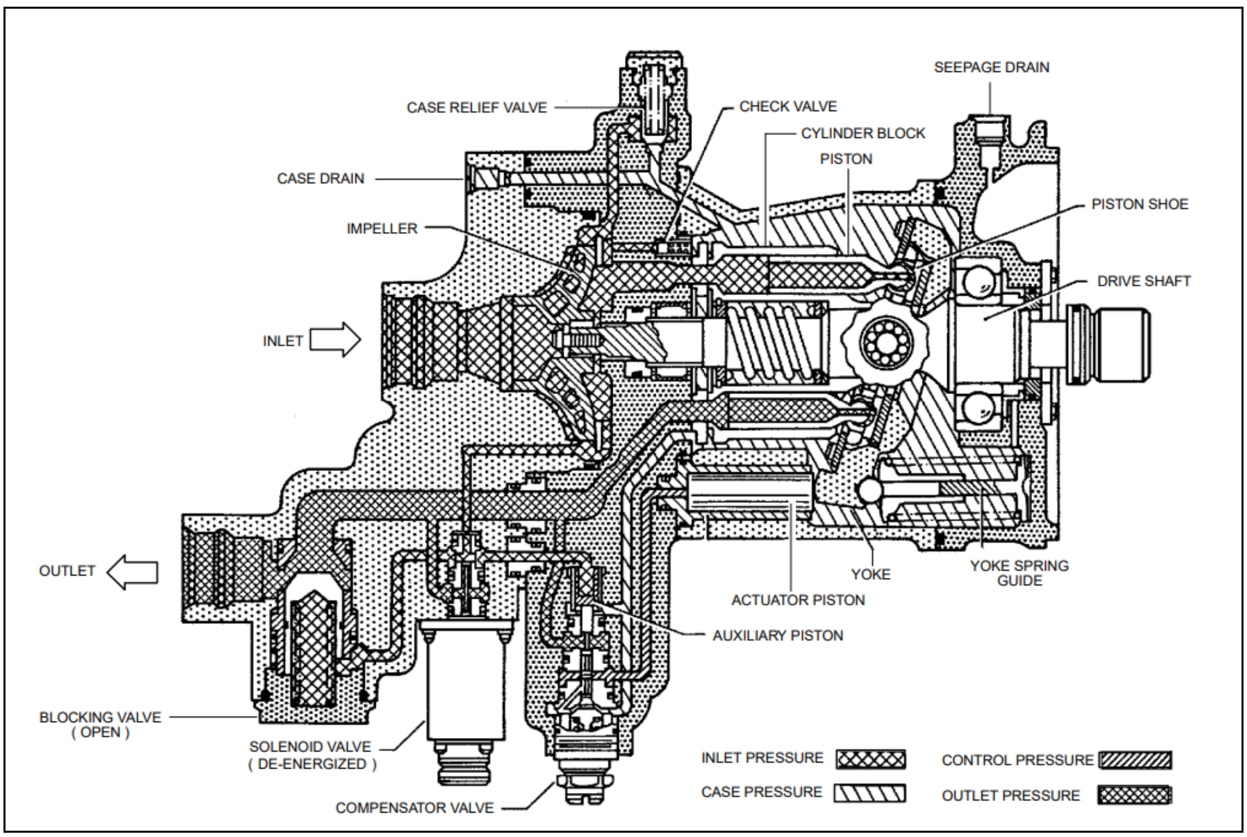


Figure 85: Schematic of the Engine Driven Pump [40].

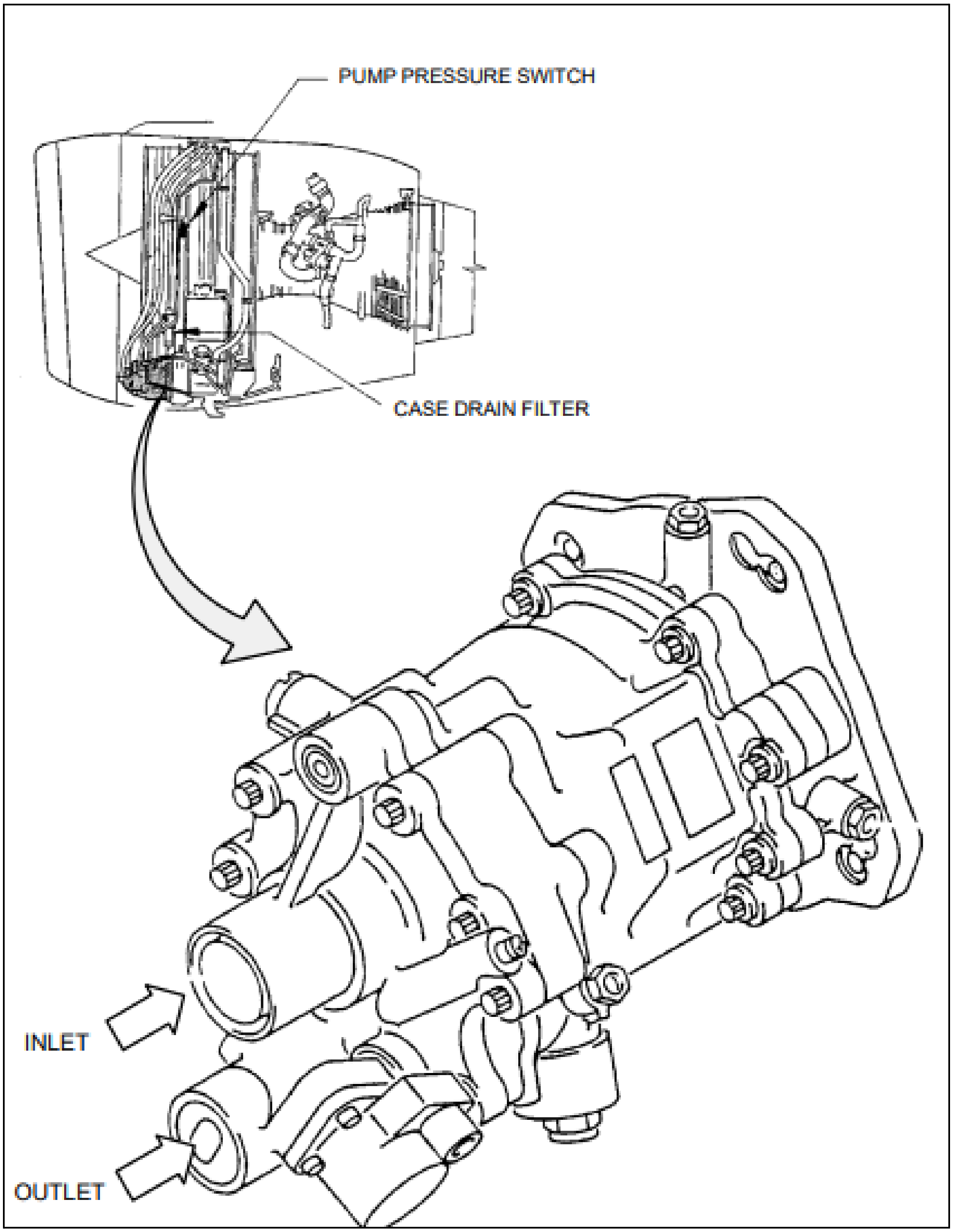


Figure 86: Location of the EDP [40].

7.7 Fluid Conditioning & Servicing

Any hydraulic system, especially on an airline would need conditioning; this means the fluid would need to be cooled and cleaned [8] and the Airbus A320 is no different. There are detection measures which can be displayed on the ECAM for the reservoir overheating or low air pressure. The ECAM display also shows the reservoir quantity. In the figure below the indication of these warnings can be seen (figure 87). The pressurization of the hydraulic reservoirs can be done through the engine bleed air, this prevents cavitation which in turn helps in conditioning of the system. As for the fluid itself, there are temperature indicators which can assist in knowing if the fluid is overheating to which a heat exchanger can be utilized to control the temperature.

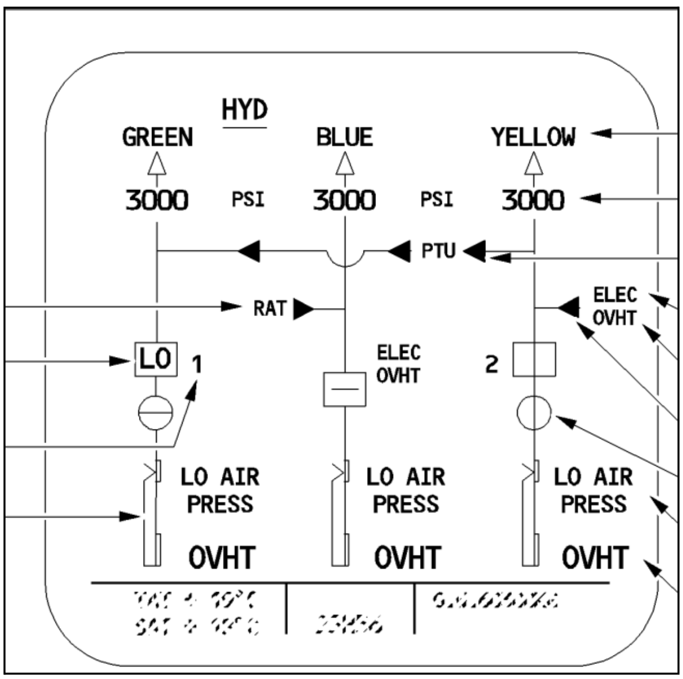


Figure 87: Indications for Fluid Conditioning on ECAM [40].

There are filters in the hydraulic system which assist in the cleaning of the fluid. High pressure filters exist on each system, the reservoir filling system, and on the normal braking system. There are also return filters on each of the lines. Through the usage of case drain filters on the engine and the blue channel electric pump, monitoring of the filters can be done through detecting the metallic particles on them.

All 3 of the channel reservoirs can be filled from one location as most of the components in correspondence to the filing system are installed on the green channel's ground service panel. There are also several conditions that need to be met prior to servicing and filling (which can be done through a ground hydraulic supply or a container). Below is a list of conditions that should be met:

1) Hydraulic systems should be depressurized
2) Speed brakes & spoilers should be retracted with the thrust reversers closed.
3) Landing gear doors should also be closed along with the cargo compartment doors
4) The indicated pressures on the brakes and systems should be correct
5) Reservoir air pressure should be at 50 psi

In the below figure the reservoir filling system can be seen. This includes the quantity indicator, the system return, the fill filter (used for conditioning), the fill valve, and finally the hand pump can also be noticed.

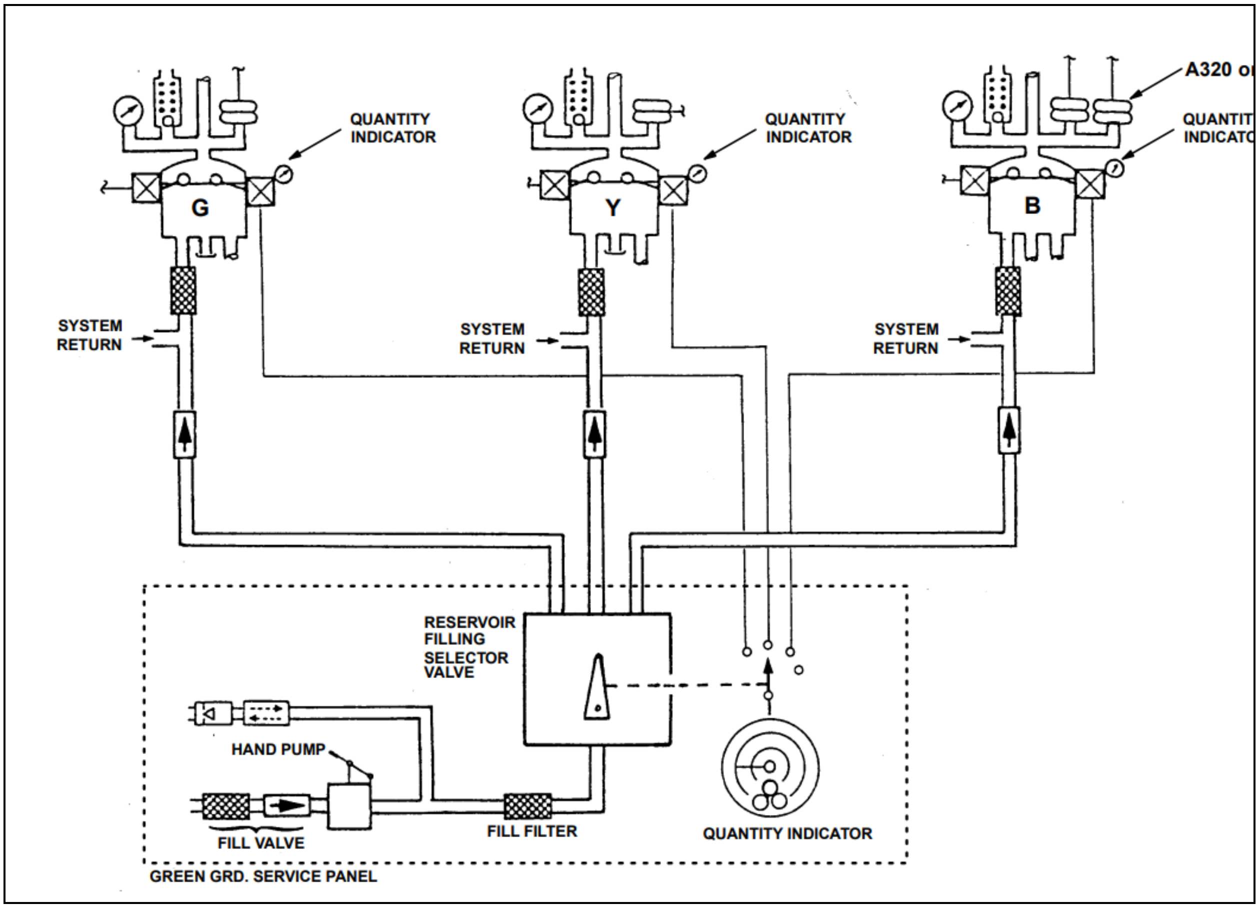


Figure 88: Reservoir Filling System.

Conclusion

In summary, the Airbus A320 was thoroughly analyzed to further our systemic understanding of the systems, subsystems and avionics of the aircraft. This paper outlined the project plan, as well as the details for the instruments and crew-plane interfaces, electric power systems, flight control systems, environmental control systems, engine control systems, fuel systems and hydraulic systems. Each section used diagrams, schematics and data tables to illustrate the systems in further detail.

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