Florida State University Schools

2015 Student Technical Guide

State of Florida Student Astronaut Challenge

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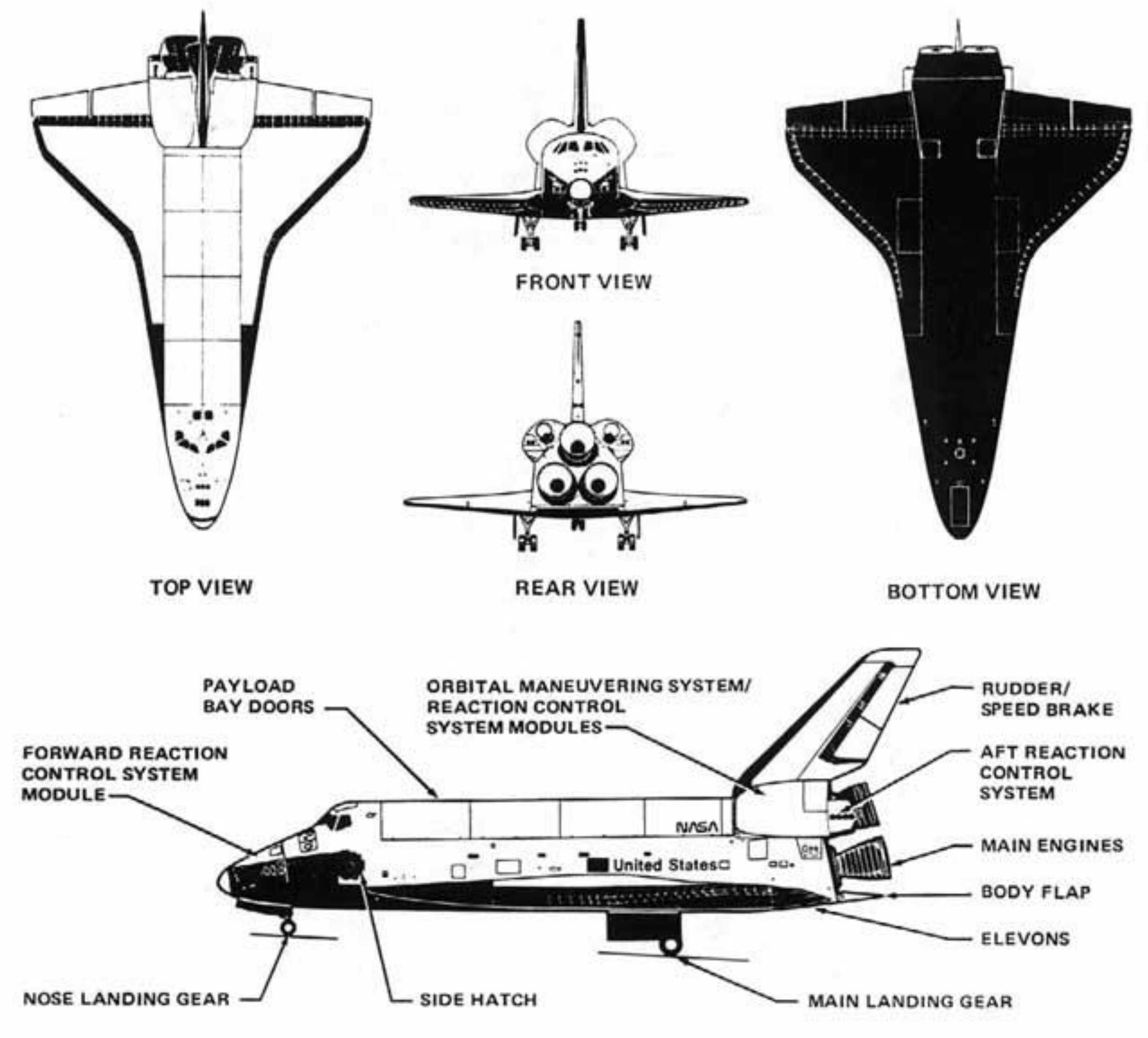
CHAPTER 1

The Space Shuttle



DIMENSIONS AND WEIGHT

WING SPAN	23.79 m	(78.06 FT)
LENGTH	37.24 m	(122.17 FT)
HEIGHT	17.25 m	(56.58 FT)
TREAD WIDTH	6.91 m	(22.67 FT)
GROSS TAKEOFF WEIGHT		VARIABLE
GROSS LANDING WEIGHT		VARIABLE
INERT WEIGHT (APPROX)	74 844 kg	(165 000 LB)

MINIMUM GROUND CLEARANCES

BODY FLAP (AFT END)	3.68 m	(12.07 FT)
MAIN GEAR (DOOR)	0.87 m	(2.85 FT)
NOSE GEAR (DOOR)	0.90 m	(2.95 FT)
WINGTIP	3.63 m	(11.92 FT)

Introduction

The space shuttle was the world's first reusable spacecraft, and the first spacecraft in history that could carry large satellites both to and from orbit. The shuttle launches like a rocket, maneuvers in Earth orbit like a spacecraft and lands like an airplane.

Because of these requirements the Shuttle was shaped to look like an aircraft but to operate as a spacecraft. The structure of the Shuttle Orbiter comprises nine separate sections, or elements: the forward fuselage, the forward reaction control system module, the mid-fuselage, the payload bay doors, the aft fuselage, the vertical tail, the two orbital maneuvering system/reaction control modules and the wing.

The demands are greater than is usually the case with a conventional aircraft because the stresses imposed upon the structure are unique to the Shuttle. Because of this, the design team at North American Aviation had no precedents on which to base their prototype. It was the first of its kind, without the advantage of any previous learning curve, and one of a kind without parallel.

Columbia was the first space shuttle orbiter to be delivered to NASA's Kennedy Space Center, Fla., in March 1979. Columbia and the STS-107 crew were lost Feb. 1, 2003, during re-entry. The orbiter Challenger was delivered to KSC in July 1982 and was destroyed in an explosion during ascent in January 1986. Discovery was delivered in November 1983. Atlantis was delivered in April 1985. Endeavour was built as a replacement following the Challenger accident and was delivered to Florida in May 1991. An early space shuttle orbiter, the Enterprise, never flew in space but was used for approach and landing tests at the Dryden Flight Research Center and several launch pad studies in the late 1970s.

A typical shuttle mission lasts seven to eight days, but can extend to as much as 14 days depending upon the objectives of the mission.

Launching the Space Shuttle

To lift the 4.5 million pound (2.05 million kg) shuttle from the pad to orbit (115 to 400 miles/185 to 643 km) above the Earth, the shuttle uses the following components:

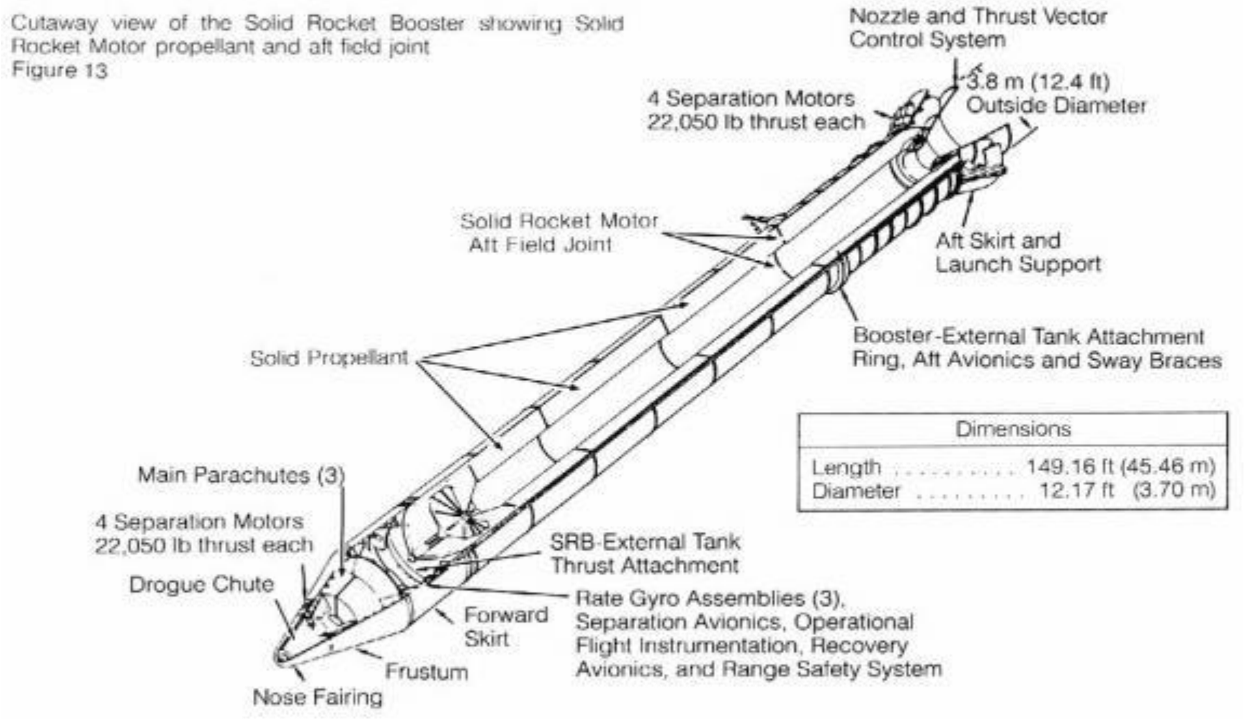
- two solid rocket boosters (SRB)
- three main engines of the orbiter
- the external fuel tank (ET)
- orbital maneuvering system (OMS) on the orbiter

Solid Rocket Boosters

The SRBs are solid rockets that provide most of the main force or thrust (71 percent) needed to lift the space shuttle off the launch pad. In addition, the SRBs support the entire weight of the space shuttle orbiter and fuel tank on the launch pad. Each SRB has the following parts:

- solid rocket motor - case, propellant, igniter, nozzle
- solid propellant fuel - atomized aluminum (16 percent) oxidizers - ammonium perchlorate (70 percent) catalyst - iron oxide powder (0.2 percent) binder - polybutadiene acrylic acid acrylonite (12 percent) curing agent - epoxy resin (2 percent)
- jointed structure
- synthetic rubber o-rings between joints
- flight instruments
- recovery systems parachutes (drogue, main) floatation devices signaling devices
- explosive charges for separating from the external tank
- thrust control systems
- self-destruct mechanism

Because the SRBs are solid rocket engines, once they are ignited, they cannot be shut down. Therefore, they are the last component to light at launch.

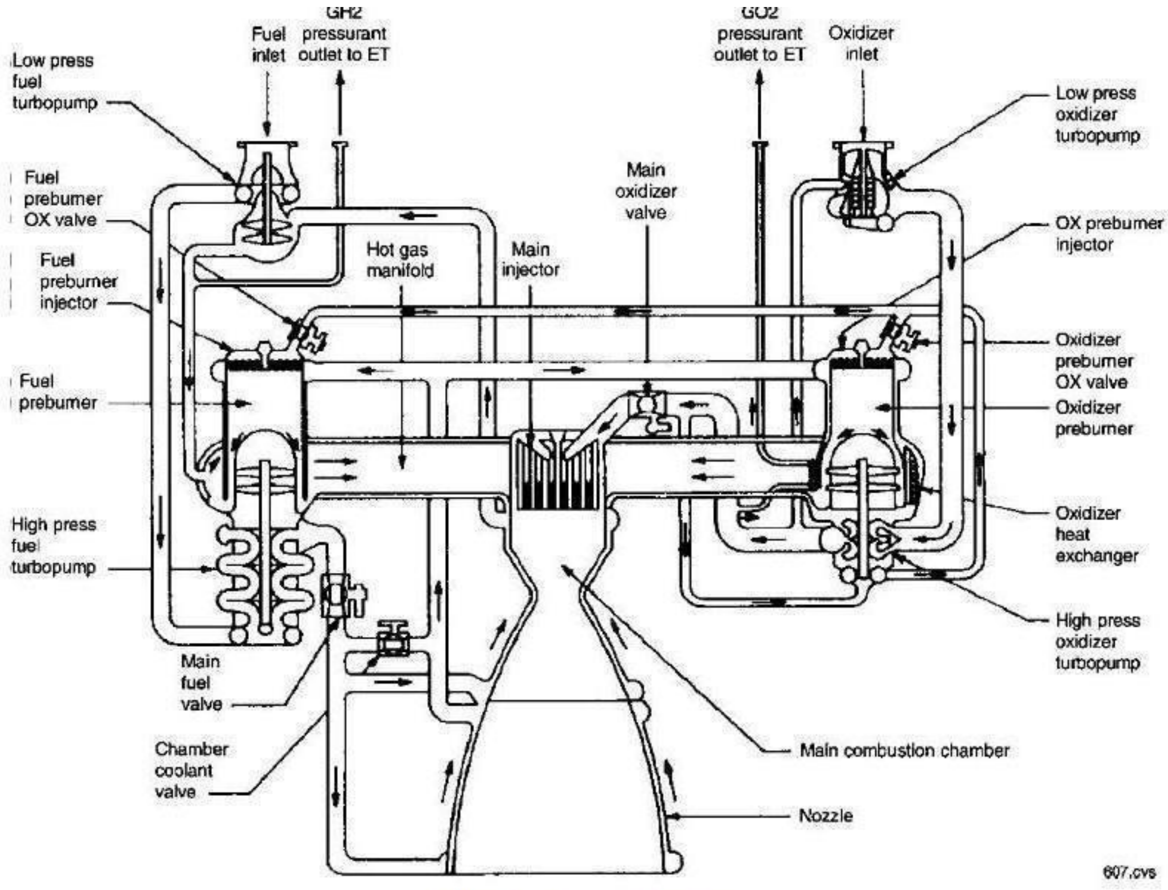


Cutaway view of the Solid Rocket Booster showing Solid Rocket Motor propellant and aft field joint
Figure 13

Main Engines

The orbiter has three main engines located in the aft (back) fuselage (body of the spacecraft). Each engine is 14 feet (4.3 m) long, 7.5 feet (2. 3 m) in diameter at its widest point (the nozzle) and weighs about 6,700 lb (3039 kg).

The main engines provide the remainder of the thrust (29 percent) to lift the shuttle off the pad and into orbit. The main engines burn liquid hydrogen and liquid oxygen as fuel which are stored in the external fuel tank (ET), at a ratio of 6:1. They draw liquid hydrogen and oxygen from the ET at an amazing rate, equivalent to emptying a family swimming pool every 10 seconds! The fuel is partially burned in a pre-chamber to produce high pressure, hot gases that drive the turbo-pumps (fuel pumps). The fuel is then fully burned in the main combustion chamber and the exhaust gases (water vapor) leave the nozzle at approximately 6,000 mph (10,000 km/h). Each engine can generate between 375,000 and 470,000 lb (1,668,083 to 2,090,664 N) of thrust; the rate of thrust can be controlled from 65 percent to 109 percent maximum thrust. The engines are mounted on gimbals (round bearings) that control the direction of the exhaust, which controls the forward direction of the rocket



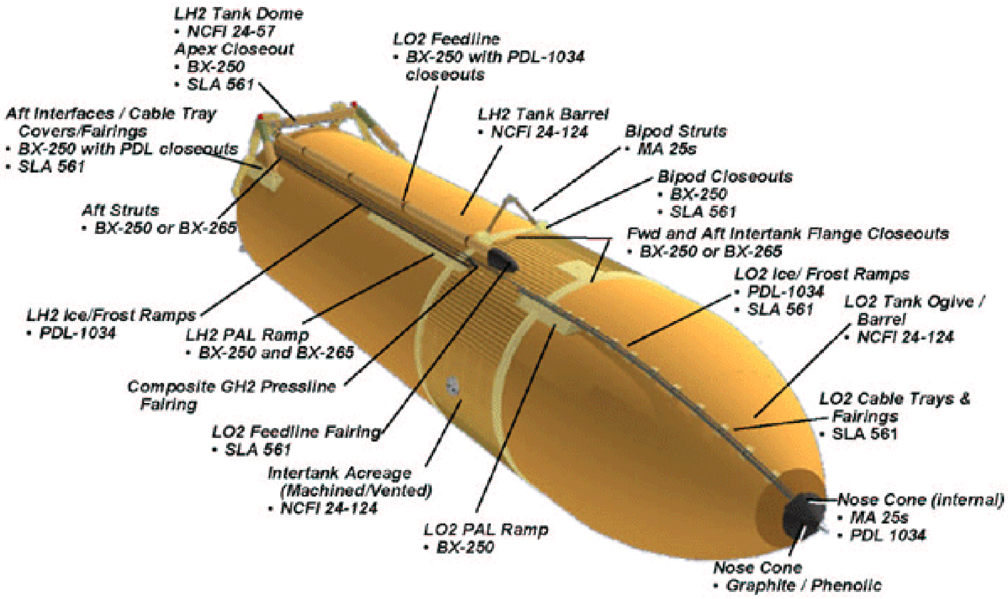
Main Engine Schematic

External Fuel Tank

As mentioned above, the fuel for the main engines is stored in the ET. The ET is 158 ft (48 m) long and has a diameter of 27.6 ft (8.4 m). When empty, the ET weighs 78,000 lb (35,455 kg). It holds about 1.6 million lb (719,000 kg) of propellant with a total volume of about 526,000 gallons (2 million liters).

The ET is made of aluminum and aluminum composite materials. It has two separate tanks inside, the forward tank for oxygen and the aft tank for hydrogen, separated by an inter-tank region. Each tank has baffles to dampen the motion of fluid inside. Fluid flows from each tank through a 17-inch (43 cm) diameter feed line out of the ET through an umbilical line into the shuttle's main engines. Through these lines, oxygen can flow at a maximum rate of 17,600 gallons/min (66,600 l/min) and hydrogen can flow at a maximum rate of 47,400 gallons/min (179,000 l/min).

The ET is covered with a 1-inch (2.5 cm) thick layer of spray-on, polyisocyanurate foam insulation. The insulation keeps the fuels cold, protects the fuel from heat that builds up on the ET skin in flight, and minimizes ice formation. When Columbia launched in 2003, pieces of the insulating foam broke off the ET and damaged the left wing of the orbiter, which ultimately caused Columbia to break up upon re-entry.

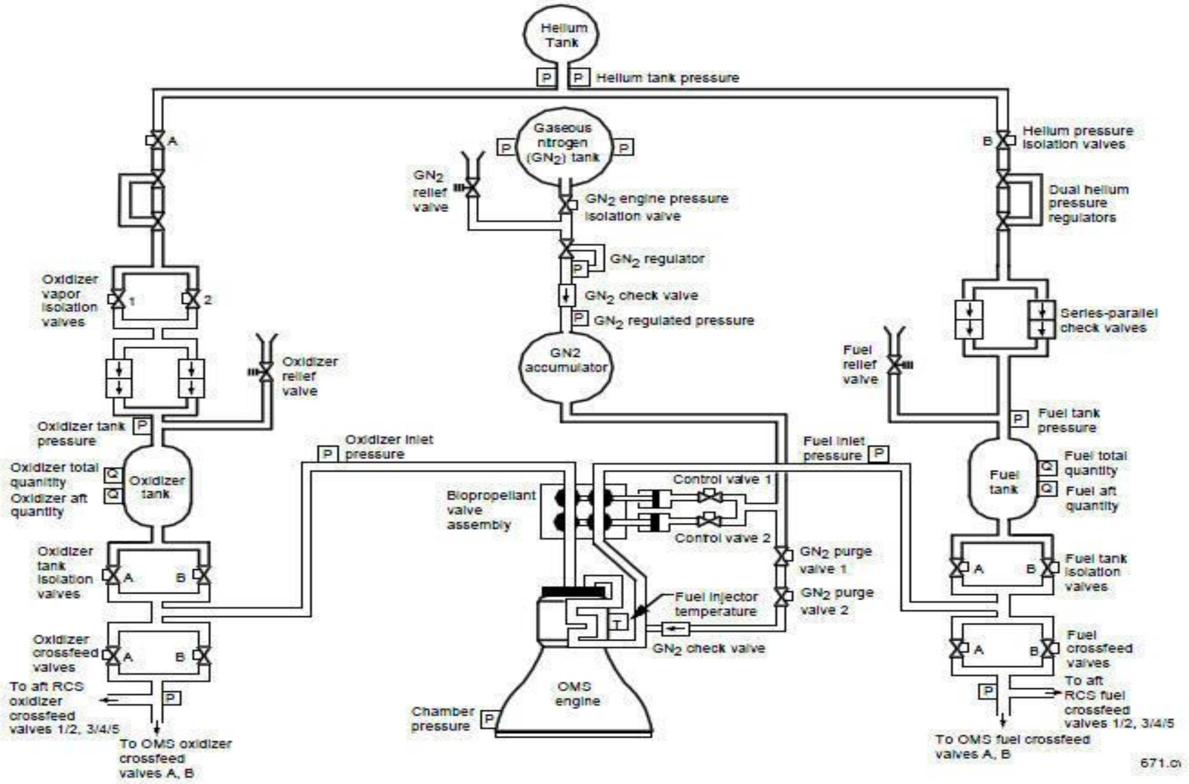


Space Shuttle Liftoff

The two orbital maneuvering systems' (OMS) engines are located in pods on the aft section of the orbiter, one on either side of the tail. These engines place the shuttle into final orbit, change the shuttle's position from one orbit to another, and slow the shuttle down for re-entry.

The OMS engines burn monomethyl hydrazine fuel (CH_3NHNH_2) and nitrogen tetroxide oxidizer (N_2O_4). Interestingly, when these two substances come in contact, they ignite and burn automatically (i.e., no spark required) in the absence of oxygen. The fuel and oxidizer are kept in separate tanks, each pressurized by helium. The helium pushes the fluids through the fuel lines (i.e., no mechanical pump required). In each fuel line, there are two spring-loaded solenoid valves that close the lines. Pressurized nitrogen gas, from a small tank located near the engine, opens the valves and allows the fuel and oxidizer to flow into the combustion chamber of the engine. When the engines shut off, the nitrogen goes from the valves into the fuel lines momentarily to flush the lines of any remaining fuel and oxidizer; this purge of the line prevents any unwanted explosions. During a single flight, there is enough nitrogen to open the valves and purge the lines 10 times!

Either one or both of the OMS engines can fire, depending upon the orbital maneuver. Each OMS engine can produce 6,000 lb (26,400 N) of thrust. The OMS engines together can accelerate the shuttle by 2 ft/s^2 (0.6 m/s^2). This acceleration can change the shuttle's velocity by as much as 1,000 ft/s (305 m/s). To place into orbit or to de-orbit takes about 100-500 ft/s (31-153 m/s) change in velocity. Orbital adjustments take about 2 ft/s (0.61 m/s) change in velocity. The engines can start and stop 1,000 times and have a total of 15 hours of burn time.



Orbital Maneuvering System Pressurization and Propellant Feed System for One Engine (other Engine Identical)

Profile of shuttle launch and ascent into orbit

As the shuttle rests on the pad fully fueled, it weighs about 4.5 million pounds or 2 million kg. The shuttle rests on the SRBs as pre-launch and final launch preparations are going on through T minus 31 seconds:

1. T minus 31 s - the on-board computers take over the launch sequence.

2. T minus 6.6 s - the shuttle's main engines ignite one at a time (0.12 s apart). The engines build up to more than 90 percent of their maximum thrust.

3. T minus 3 s - shuttle main engines are in lift-off position.

4. T minus 0 s -the SRBs are ignited and the shuttle lifts off the pad.

5. T plus 20 s - the shuttle rolls right (180 degree roll, 78 degree pitch).

6. T plus 60 s - shuttle engines are at maximum throttle.

7. T plus 2 min - SRBs separate from the orbiter and fuel tank at an altitude of 28 miles (45 km). Main engines continue firing. Parachutes deploy from the SRBs. SRBs will land in the ocean about 140 miles (225 km) off the coast of Florida. Ships will recover the SRBs and tow them back to Cape Canaveral for processing and re-use.

8. T plus 7.7 min - main engines throttled down to keep acceleration below 3g's so that the shuttle does not break apart.

9. T plus 8.5 min - main engine shut down.

10. T plus 9 min - ET separates from the orbiter. The ET will burn up upon re-entry.

11. T plus 10.5 min - OMS engines fire to place the shuttle in a low orbit.

12. T plus 45 min - OMS engines fire again to place the shuttle in a higher, circular orbit (about 250 miles/400 km).

Orbiter in Space

Once in space, the shuttle orbiter can be the home for astronauts for seven to 14 days. The orbiter can be oriented so that the cargo bay doors face toward the Earth or away from the Earth depending upon the mission objectives; in fact, the orientation can be changed throughout the mission. One of the first things that the commander will do is to open the cargo bay doors to cool the orbiter.

The orbiter consists of the following parts:

- crew compartment - where astronauts live and work
- forward fuselage (upper, lower parts) - contains support equipment (fuel cells, gas tanks) for crew compartment
- forward reaction control system (RCS) module - contains forward rocket jets for turning the orbiter in various directions
- movable airlock - used for spacewalks and can be placed inside the crew compartment or inside the cargo bay

•mid-fuselage: contains essential parts (gas tanks, wiring, etc.) to connect the crew compartment with the aft engines; forms the floor of the cargo bay

•cargo bay doors - roof of the cargo bay and essential for cooling the orbiter

•remote manipulator arm - located in the cargo bay: moves large pieces of equipment in and out of the cargo bay; platform for spacewalking astronauts

•aft fuselage - contains the main engines

•OMS/RCS pods (2) - contain the orbital maneuvering engines and the aft RCS module; turn the orbiter and change orbits

•airplane parts of the orbiter - fly the shuttle upon landing (wings, tail, body flap)

The crew compartment is located in the forward fuselage. The crew compartment has 2,325 cu.ft. of space with the airlock inside or 2,625 cu.ft with the airlock outside. The crew compartment has three decks:

Flight deck - uppermost deck

•forward deck - contains all of the controls and warning systems for the space shuttle (also known as the cockpit)
•seats - commander, pilot, specialist seats (two)

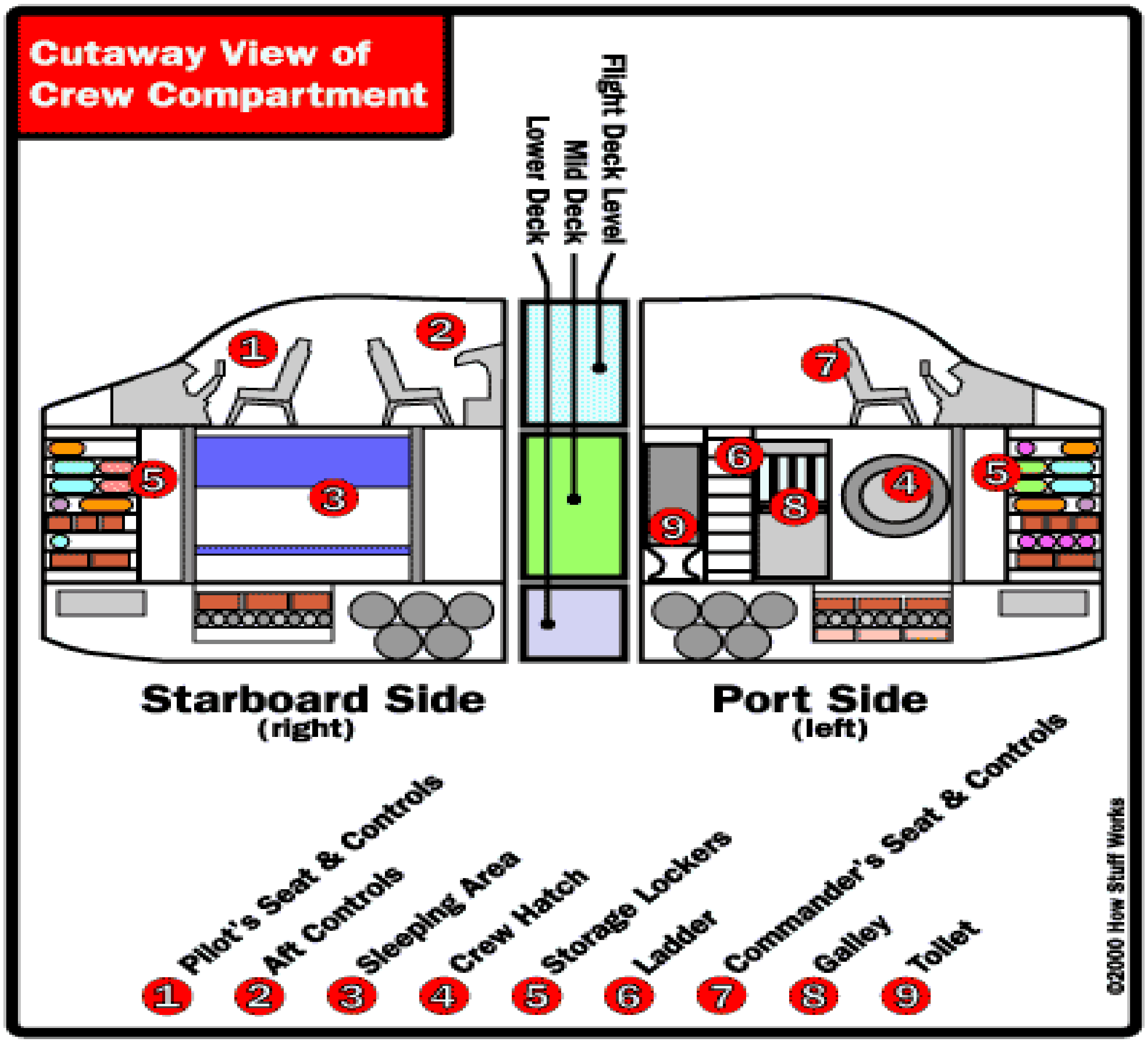
•aft deck - contains controls for orbital operations: maneuvering the orbiter while in orbit (rendezvous, docking, deploying payload, and working the remote manipulator arm

Mid-deck

•living quarters (galley, sleeping bunks, toilet)
•stowage compartments (personal gear, mission-essential equipment, experiments)
•exercise equipment
•airlock - on some flights
•entry hatch

lower deck (equipment bay)

•contains life support equipment, electrical systems, etc..



Living Environment

The shuttle orbiter provides an environment where astronauts can live and work in space. The shuttle provides the following:

- life support - atmosphere control, supply and recycling; water; temperature control; light; food supply; waste removal; fire protection
- ability to change position and change orbits
- capability to talk with ground-based flight controllers (communications and tracking)
- stellar navigation to find its way around in orbit
- make its own electrical power

•coordinate and handle information (computers)

•base from which to launch/retrieve satellites; construction - such as building the International Space Station and conduct experiments

The orbiter must provide astronauts with an environment similar to Earth. The shuttle must have air, food, water, and a comfortable temperature. The orbiter must also take away the wastes products produced by the astronauts (carbon dioxide, urine, feces) and protect them from fire

Our atmosphere is a mixture of gases (78 percent nitrogen, 21 percent oxygen, 1 percent other gases) at a pressure of 14 lbs/in^2 (1 atm) that we breathe in and out. The space shuttle must provide a similar atmosphere. To do this, the orbiter carries liquid oxygen and liquid nitrogen in two systems of pressurized tanks, which are located in the mid-fuselage (each system has two tanks for a total of four tanks). The cabin pressurization system combines the gases in the correct mixture at normal atmospheric pressure. While in orbit, only one oxygen-nitrogen system is used to pressurize the orbiter. During launch and landing, both systems of each gas are used.

•Five loops of fans circulate the atmosphere. The circulated air picks up carbon dioxide, heat and moisture:

•Chemical carbon dioxide canisters remove carbon dioxide by reacting it with lithium hydroxide. These canisters are located in the lower deck of the crew compartment and are changed every 11 hours.

•Filters and charcoal canisters remove trace odors, dust and volatile chemicals from leaks, spills and out gassing.

•A cabin heat exchanger in the lower deck cools the air and condenses the moisture, which collects in a slurper. Water from the slurper is moved with air to a fan separator, which uses centrifugal force to separate water from air. The air is re-circulated and the water goes to a wastewater tank.

Besides air, water is the most important quantity aboard the orbiter. Water is made from liquid oxygen and hydrogen in the space shuttle's fuel cells (the fuel cells can make 25 lb (11 kg) of water per hour). The water passes through a hydrogen separator to eliminate any trapped hydrogen gas (excess hydrogen gas is dumped overboard). The water is then stored in four water storage tanks located in the lower deck. Each tank can hold 165 lb (75 kg).

The water tanks are pressurized by nitrogen so that water can flow to the mid-deck for use by the crew. Drinkable water is then filtered to remove microbes and can be warmed or chilled through various heat exchangers depending upon the use (food preparation, consumption, personal hygiene). Excess water produced by the fuel cells gets routed to a wastewater tank and subsequently dumped overboard.

Outer space is an extremely cold environment and temperatures will vary drastically in different parts of the orbiter. You might think that heating the orbiter would be a problem. However, the electronic equipment generates more than enough heat for the ship. The problem is getting rid of the excess heat. So the temperature control system has to carry out two major functions:

- Distribute heat where it is needed on the orbiter (mid-fuselage and aft sections) so that vital systems do not freeze in the cold of space.

- Get rid of the excess heat.

To do this, the shuttle has two methods to handle temperature control:

- Passive methods - generally simple methods that handle small heat loads and require little maintenance; insulating materials (blankets), surface coatings, paints, all reduce heat loss through the walls of the various components just like home insulation. Electrical heaters - use electrically-heated wires like a toaster to heat various areas.

- Active methods – generally more complex, these systems use fluid to handle large heat loads and require maintenance. Cold plates are metal plates that collect heat by direct contact with equipment or conduction. Heat exchangers are used to collect heat from equipment using fluid. The equipment radiates heat to a fluid (water, ammonia) which in turn passes heat on to Freon. Both fluids are pumped and re-circulated to remove heat. Pumps, lines, valves - transport the collected heat from one area to another. Radiators - located on the inside surfaces of the cargo bay doors that radiate the collected heat to outer space Flash evaporator/ammonia boilers - these devices are located in the aft fuselage and transfer heat from Freon coolant loops overboard when cargo bay doors are closed or when cargo bay radiators are overloaded. Flash evaporator Freon coolant loops wrap around an inner core. The evaporator sprays water on the heated core. The water evaporates removing heat. The water vapor is vented overboard. Ammonia boiler Freon coolant loops pass through a tank of pressurized ammonia. Heat released from the Freon causes the ammonia to boil. Ammonia vapor is dumped overboard.

The cabin heat exchanger also controls the cabin temperature. It circulates cool water to remove excess heat (cabin air is also used to cool electronic equipment) and transfers this heat to a Freon exchanger. The Freon then transfers the heat to other orbiter systems (e.g., cryogenic gas tanks, hydraulic systems) and radiates excess heat to outer space.

The orbiter has internal fluorescent floodlights that illuminate the crew compartment. The orbiter has external floodlights to illuminate the cargo bay. Finally, the control panels are lighted internally for easy viewing.

Food is stored on the mid-deck of the crew compartment. Food comes in several forms (dehydrated, low moisture, heat-stabilized, irradiated, natural and fresh). The orbiter has a galley-style kitchen module along the wall next to the entry hatch, which is equipped with the following:

- food storage compartments
- food warmers
- a food preparation area with warm and cold water outlets
- metal trays so the food packages and utensils do not float away

Like any home, the orbiter must be kept clean, especially in space when floating dirt and debris could present a hazard. Wastes are made from cleaning, eating, work and personal hygiene. To maintain general housecleaning, the astronauts use various wipes (wet, dry, fabric, detergent and disinfectant), detergents, and wet/dry vacuum cleaners are used to clean surfaces, filters and the astronauts themselves. Trash is separated into wet trash bags and dry trash bags, and the wet trash is placed in an evaporator that will remove the water. All trash bags are stowed in the lower deck to be returned to Earth for disposal. Solid waste from the toilet is compacted, dried and stored in bags where it is returned to Earth for disposal (burning). Liquid waste from the toilet goes to the wastewater tank where it is dumped overboard.

Fire is one of the most dangerous hazards in space. The orbiter has a Fire Detection and Suppression Subsystem that consists of the following:

- area smoke detectors on each deck
- smoke detectors in each rack of electrical equipment
- alarms and warning lights in each module
- non-toxic portable fire extinguishers (carbon dioxide-based)
- personal breathing apparatus - mask and oxygen bottle for each crew member

After a fire is extinguished, the atmosphere control system will filter the air to remove particulates and toxic substances.

Work aboard the Shuttle

The shuttle was designed to deploy and retrieve satellites as well as deliver payloads to Earth orbit. To do this, the shuttle uses the Remote Manipulator System (RMS). The RMS was built by Canada and is a long arm with an elbow and wrist joint. The RMS can be controlled from the aft flight deck. The RMS can grab payloads (satellites) from the cargo bay and deploy them, or grab on to payloads and place them into the bay.

In the past, the shuttle was used for delivering satellites and conducting experiments in space. Within the mid-deck, there are racks of experiments to be conducted during each mission. When more space was needed, the mission used the Spacelab module, which was built by the European Space Agency (ESA). It fit into the cargo bay and was accessed by a tunnel from the mid-deck of the crew compartment. It provided a "shirt-sleeve" environment in which you could work. The Spacelab was lost along with Columbia in 2003. Now, most experiments are conducted aboard the International Space Station.

The shuttle's major role was to build and re-supply the International Space Station. The shuttle delivers components built on Earth. Astronauts use the RMS to remove components from the cargo bay and to help attach them to existing modules in space station.

Space Shuttle Positioning, Communication and Navigation

To change the direction that the orbiter is pointed (attitude), the reaction control system (RCS) located on the nose and OMS pods of the aft fuselage is used.

The RCS has 14 jets that can move the orbiter along each axis of rotation (pitch, roll, yaw). The RCS thruster’s burn monomethyl hydrazine fuel and nitrogen tetroxide oxidizer just like the OMS engines described previously. Attitude changes are required for deploying satellites or for pointing (mapping instruments, telescopes) at the Earth or stars. To change orbits (e.g., rendezvous, docking maneuvers), you must fire the OMS engines. As described above, these engines change the velocity of the orbiter to place it in a higher or lower orbit.

Tracking and Communication

The astronauts talk with flight controllers on the ground daily for the routine operation of the mission. In addition, they must be able to communicate with each other inside the orbiter or its payload modules and when conducting spacewalks outside.

NASA's Mission Control in Houston will send signals to a 60 ft. radio antenna at White Sands Test Facility in New Mexico. White Sands will relay the signals to a pair of

Tracking and Data Relay satellites in orbit 22,300 miles above the Earth. The satellites will relay the signals to the space shuttle. The system works in reverse as well.

The orbiter has two systems for communicating with the ground:

- S-band - voice, commands, telemetry and data files
- Ku-band (high bandwidth) - video and transferring two-way data files

The orbiter has several intercom plug-in audio terminal units located throughout the crew compartment. Each astronaut wears a personal communications control with a headset. The communications control is battery-powered and can be switched from intercom to transmit functions. They can either push to talk and release to listen or have a continuously open communication line. To talk with spacewalkers, the system uses a UHF frequency, which is picked up in the astronaut's space suit. The orbiter also has a series of internal and external video cameras to see inside and outside.

Navigation, Power and Computers

The orbiter must be able to know precisely where it is in space, where other objects are and how to change orbit. To know where it is and how fast it is moving, the orbiter uses global positioning systems (GPS). To know which way it is pointing (attitude), the orbiter has several gyroscopes. All of this information is fed into the flight computers for rendezvous and docking maneuvers, which are controlled in the aft station of the flight deck.

All of the on-board systems of the orbiter require electrical power. Three fuel cells make electricity; they are located in the mid fuselage under the payload bay. These fuel cells combine oxygen and hydrogen from pressurized tanks in the mid fuselage to make electricity and water. Like a power grid on Earth, the orbiter has a distribution system to supply electrical power to various instrument bays and areas of the ship. The water is used by the crew and for cooling.

The orbiter has five on-board computers that handle data processing and control critical flight systems. The computers monitor equipment and talk to each other and vote to settle arguments. Computers control critical adjustments especially during launch and landing:

- operations of the orbiter (housekeeping functions, payload operations, rendezvous/docking)
- interface with the crew
- caution and warning systems

- data acquisition and processing from experiments
- flight maneuvers

Pilots essentially fly the computers, which fly the shuttle. To make this easier, the shuttles have a Multifunctional Electronic Display Subsystem (MEDS), which is a full color, flat, 11-panel display system. The MEDS, also known as the "glass cockpit", provides graphic portrayals of key light indicators (attitude, altitude, speed). The MEDS panels are easy to read and make it easier for shuttle pilots to interact with the orbiter.

The Shuttle's Return to Earth

For a successful return to Earth and landing, dozens of things have to go just right. First, the orbiter must be maneuvered into the proper position. This is crucial to a safe landing. When a mission is finished and the shuttle is halfway around the world from the landing site (Kennedy Space Center, Edwards Air Force Base), mission control gives the command to come home, which prompts the crew to:

1. Close the cargo bay doors. In most cases, they have been flying nose-first and upside down, so they then fire the RCS thrusters to turn the orbiter tail first.
2. Once the orbiter is tail first, the crew fires the OMS engines to slow the orbiter down and fall back to Earth; it will take about 25 minutes before the shuttle reaches the upper atmosphere.
3. During that time, the crew fires the RCS thrusters to pitch the orbiter over so that the bottom of the orbiter faces the atmosphere (about 40 degrees) and they are moving nose first again.
4. Finally, they burn leftover fuel from the forward RCS as a safety precaution because this area encounters the highest heat of re-entry.

Because it is moving at about 17,000 mph (28,000 km/h), the orbiter hits air molecules and builds up heat from friction (approximately 3000 degrees F, or 1650 degrees C). The orbiter is covered with ceramic insulating materials designed to protect it from this heat. The materials include:

- Reinforced carbon-carbon (RCC) on the wing surfaces and underside
- High-temperature black surface insulation tiles on the upper forward fuselage and around the windows
- White Nomex blankets on the upper payload bay doors, portions of the upper wing and mid/aft fuselage

- Low-temperature white surface tiles on the remaining areas

Maneuvering of the orbiter for re-entry

These materials are designed to absorb large quantities of heat without increasing their temperature very much. In other words, they have a high heat capacity. During re-entry, the aft steering jets help to keep the orbiter at its 40 degree attitude. The hot ionized gases of the atmosphere that surround the orbiter prevent radio communication with the ground for about 12 minutes (i.e., ionization blackout).

When re-entry is successful, the orbiter encounters the main air of the atmosphere and is able to fly like an airplane. The orbiter is designed from a lifting body design with swept back "delta" wings. With this design, the orbiter can generate lift with a small wing area. At this point, flight computers fly the orbiter. The orbiter makes a series of S-shaped, banking turns to slow its descent speed as it begins its final approach to the runway. The commander picks up a radio beacon from the runway (Tactical Air Navigation System) when the orbiter is about 140 miles (225 km) away from the landing site and 150,000 feet (45,700 m) high. At 25 miles (40 km) out, the shuttle's landing computers give up control to the commander. The commander flies the shuttle around an imaginary cylinder (18,000 feet or 5,500 m in diameter) to line the orbiter up with the runway and drop the altitude. During the final approach, the commander steepens the angle of descent to minus 20 degrees (almost seven times steeper than the descent of a commercial airliner).

Shuttle flight path for landing

When the orbiter is 2,000 ft. (610 m) above the ground, the commander pulls up the nose to slow the rate of descent. The pilot deploys the landing gear and the orbiter touches down. As the commander applies the wheel brakes, the speed brake on the vertical tail is opened to help slow down the shuttle. A parachute is deployed from the back to help stop the orbiter. The parachute and the speed brake on the tail increase the drag on the orbiter. The orbiter stops about midway to three-quarters of the way down the runway.

After landing, the crew goes through the shutdown procedures to power down the spacecraft. This process takes about 20 minutes. During this time, the orbiter is cooling and noxious gases, which were made during the heat of re-entry, blow away. Once the orbiter is powered down, the crew exits the vehicle. Ground crews are on-hand to begin servicing the orbiter.

Space Shuttle Emergency Management

When an emergency occurs it is Mission Controls responsibility to evaluate the event, triage the process, and evaluate the most important jobs that need to be accomplished. The safety of the flight crew is the primary focus of an emergency as Mission Control takes on a new series of responsibilities.

Understandably the flight crew gets very engaged after an anomaly. They want to help ensure the mission is a success and failure is a big concern. They need to be provided frequent updates on findings and progress and participate in the evaluation of the emergency and its mitigation. This mission is very important to the flight crew but reason and balance needed to prevail.

The first concern is to "stop the bleeding", questions naturally begin to surface about why the anomaly occurred. These queries, while important to understanding your continuing risk, should not distract the team from focusing their attention on continuing the mission and managing the problem.

Watch for Things Getting Complicated

After the anomaly, Mission Control needs to work through the data, consider responses, and to solve the problem. Teams have a tendency to create complex, multilayer solutions to mitigate the problem. Sometimes discussions work their way from one incremental fix to another, arriving at complex fixes and patches that would move the team far from its operations training and might not address the real problem. This complexity growth actually grows risk that the system will become so sophisticated it will be prone to operator error or create unforeseen interactions. In the heat of battle, there needs to be someone who keeps an eye on the risk of the solution. This is the responsibility of Mission Control, someone needs to ask, "Do we need to go that far, or can we live with just the first corrective measure?" Sometimes you need to agree that you can accept residual risk after addressing the principal problem. Missions have been lost because smart people did well-intended things that made problems worse.

Meeting the Challenge of the Emergency

The triage process must be a mix of urgency and focus, which comes from many, many operational rehearsals where the team trains for what is supposed to happen and even what is not supposed to happen. You need to focus not just on the specifics of what could go wrong, but on your behavior and process when something goes wrong.

Mission Control has many responsibilities when an emergency happens. You will have to depend on individual and team capabilities, training, and roles in ways that are hard to describe. You know that you must trust the team's abilities and judgment, but also watch for signs, both within the team and outside, of good intentions yielding problematic results. You must be reasonable and evenhanded, understanding that you cannot eliminate risk. The emergency is a time when a mission team shows what it is really made of.

Space Shuttle Abort Modes

The worst possible outcome of an Emergency is the “Mission Abort”. To meet this need NASA developed multiple procedures to mitigate this specific possibility. A Space Shuttle abort procedure is an emergency procedure that is needed due to equipment failure on NASA's Space Shuttle, most commonly during ascent. A main engine failure was a typical abort scenario. There were fewer abort options during reentry and descent. For example, the Columbia disaster happened during reentry, and there were no alternatives in that portion of flight.

Later in descent, certain failures were survivable, although not usually classified as an abort. For example, a flight control system problem or multiple auxiliary power unit failure would make reaching a landing site impossible, thus requiring the astronauts to bail out.

There were five abort modes available during ascent, in addition to pad (RSLS) aborts. These were divided into the categories of intact aborts and contingency aborts. The choice of abort mode depended on how urgent the situation was, and what emergency landing site could be reached. The abort modes covered a wide range of potential problems, but the most commonly expected problem was Space Shuttle Main Engine (SSME) failure, causing inability either to cross the Atlantic or to achieve orbit, depending on timing and number of failed engines. Other possible non-engine failures necessitating an abort included multiple auxiliary power unit (APU) failure, cabin leak, and external tank leak (ullage leak).

Redundant Set Launch Sequencer (RSLS) Abort

The main engines were ignited roughly 6.6 seconds before liftoff. From that point to ignition of the Solid Rocket Boosters at T - 0 seconds, the main engines could be shut down. This was called a "Redundant Set Launch Sequencer Abort", and happened five times, on STS-41-D, STS-51-F, STS-51, STS-55, and STS-68. It always happened under computer (not human) control, caused by computers sensing a problem with the main engines after starting but before the SRBs ignited. The SRBs could not be turned off once ignited, and afterwards the shuttle was committed to take off. If an event such as an SSME failure requiring an abort happened after SRB ignition, acting on the abort would have to wait until SRB burnout 123 seconds after launch. No abort options existed if that wait was not possible.

Intact abort modes

There were four intact abort modes for the Space Shuttle. Intact aborts were designed to provide a safe return of the orbiter to a planned landing site or to a lower orbit than planned for the mission.

Return To Launch Site (RTLS)

In a Return To Launch Site (RTLS) abort, the Shuttle would have continued downrange until the solid rocket boosters were jettisoned. It would then pitch around, so the SSMEs fired retrograde. This maneuver would have occurred in a near-vacuum above the appreciable atmosphere and was conceptually no different from the OMS engines firing retrograde to de-orbit. The main engines continued burning until downrange velocity was killed and the vehicle began heading back toward the launch site at sufficient velocity to reach a runway. Afterwards the SSMEs were stopped, the external tank was jettisoned, and the orbiter made a normal gliding landing on the runway at Kennedy Space Center about 25 minutes after lift-off. The CAPCOM would call out the point in the ascent at which an RTLS was no longer possible as "negative return", approximately four minutes after lift-off.

Should all three SSMEs have failed, the shuttle would not have been able to make it back to the runway at KSC, forcing the crew to bail out. While this would have resulted in the loss of the Shuttle, the crew could escape safely and then be recovered by the SRB recovery ships.
This abort mode was never needed in the history of the Shuttle program. Astronaut Mike Mullane referred to the RTLS abort as an "unnatural act of physics," and many pilot astronauts hoped that they would not have to perform such an abort due to its difficulty.

Transoceanic Abort Landing (TAL)

A Transoceanic Abort Landing (TAL) involved landing at a predetermined location in Africa or western Europe about 25 to 30 minutes after lift-off. It was used when velocity, altitude, and distance downrange did not allow return to the launch point via RTLS. It was also used when a less time-critical failure did not require the faster but possibly more stressful RTLS abort.

A TAL abort would be declared between roughly T+2:30 minutes (2 minutes and 30 seconds after liftoff) and Main Engine Cutoff (MECO), about T+8:30 minutes. The Shuttle would then land at a pre-designated friendly airstrip in Europe. The last four TAL sites until the Shuttle's retirement were Istres Air Base in France, Zaragoza and Morón air bases in Spain, and RAF Fairford in England. Prior to a Shuttle launch, two of them were selected depending on the flight plan, and staffed with standby personnel in case they were used. The list of TAL sites changed over time; most recently Ben Guerir Air Base in Morocco (TAL site from July 1988–June 2002) was eliminated due to terrorist attack concerns. Other previous TAL sites included Lajes Air Base, Terceira, Azores, Mallam Aminu Kano International Airport, Kano, Nigeria; Mataveri International Airport, Easter Island, Chile (for Vandenberg launches); Rota, Spain; Casablanca, Morocco; Banjul, Gambia; and Dakar, Senegal.

Preparations of TAL sites took 4 to 5 days and began a week before a launch with the majority of personnel from NASA, the Department of Defense, and contractors arriving

48 hours before launch. Additionally, two C-130 aircraft from the Manned Space Flight support office from the adjacent Patrick Air Force Base including eight crew members, nine para-rescue men, two flight surgeons, a nurse and medical technician, along with 2,500 pounds of medical equipment were deployed to either Zaragoza, Istres, or both. One or more C-21 or a C-12 aircraft were also deployed to provide weather reconnaissance in the event of an abort with a TALCOM, or astronaut flight controller aboard for communications with the shuttle pilot and commander. This abort mode was never needed during the entire history of the space shuttle program.

Abort Once Around (AOA)

An Abort Once Around (AOA) was available when the shuttle could not reach a stable orbit but had sufficient velocity to circle the earth once and land, about 90 minutes after lift-off. The time window for using the AOA abort was very short – just a few seconds between the TAL and ATO abort opportunities. Therefore, taking this option was very unlikely.This abort mode was never needed during the entire history of the space shuttle program.

Abort to Orbit (ATO)

An Abort to Orbit (ATO) was available when the intended orbit could not be reached but a lower stable orbit was possible. This occurred on mission STS-51-F, which continued despite the abort to a lower orbit. The Mission Control Center in Houston (located at Lyndon B. Johnson Space Center) observed an SSME failure and called "Challenger--Houston, Abort ATO. Abort ATO".

The moment at which an ATO became possible was referred to as the "press to ATO" moment. In an ATO situation, the spacecraft commander rotated the cockpit abort mode switch to the ATO position and depressed the abort push button. This initiated the flight control software routines which handled the abort. In the event of lost communications, the spacecraft commander could have made the abort decision and taken action independently.

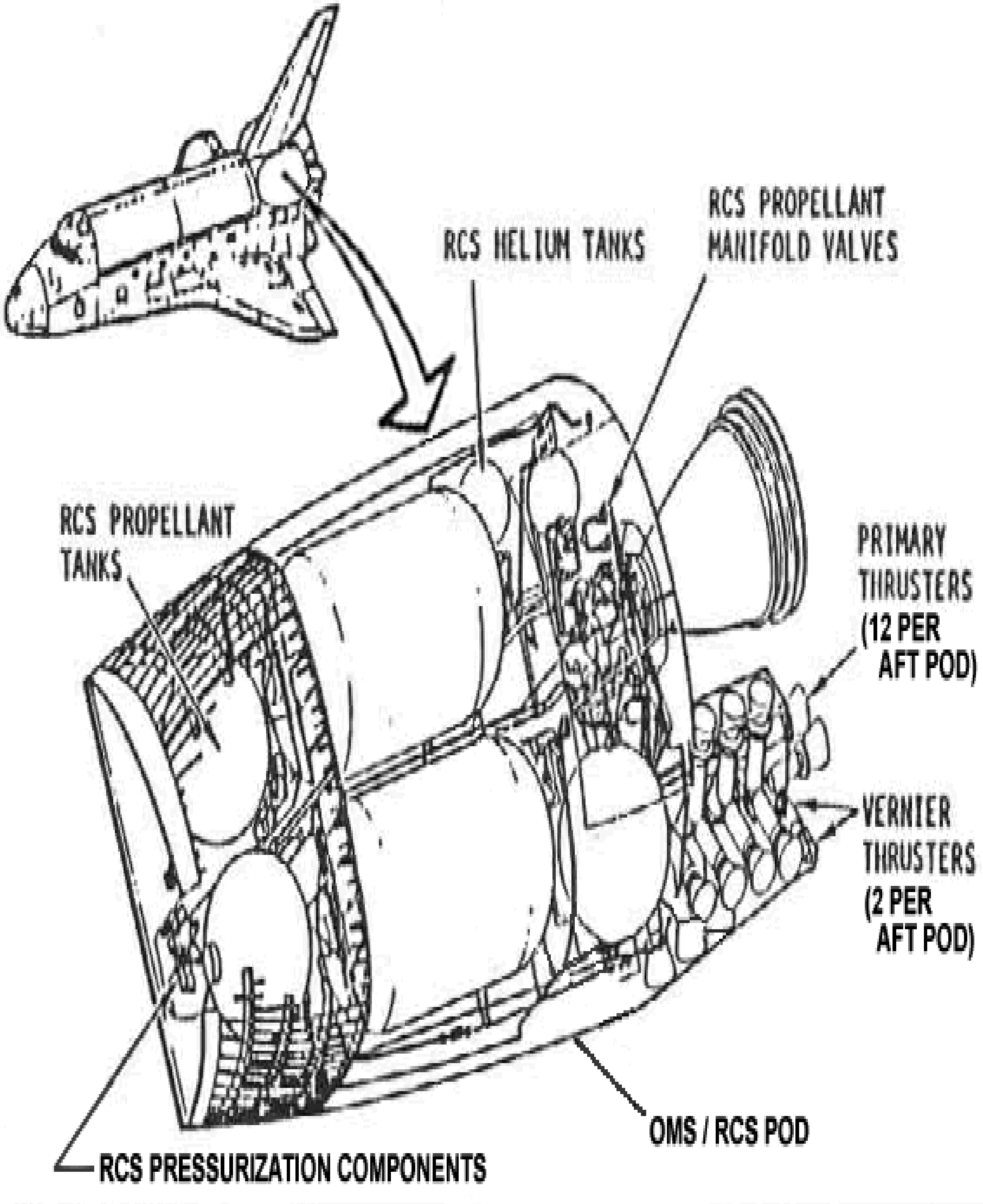
A hydrogen fuel leak in one of the SSMEs on STS-93 resulted in a slightly lower orbit than anticipated, but was not an ATO; if the leak had been more severe, it might have necessitated an ATO, RTLS, or TAL abort.

Emergency landing sites

Pre-determined emergency landing sites for the Orbiter were determined on a mission-by-mission basis according to the mission profile, weather and regional political situations.

Chapter 2

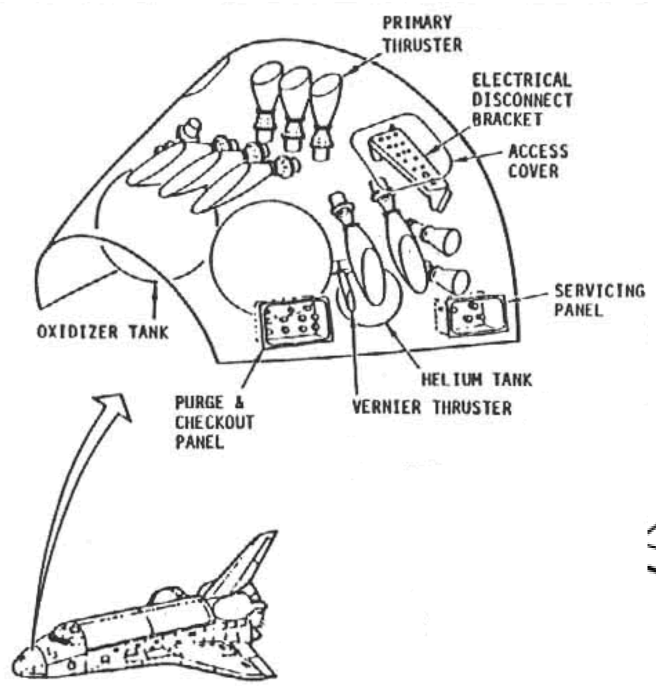
Reaction Control System

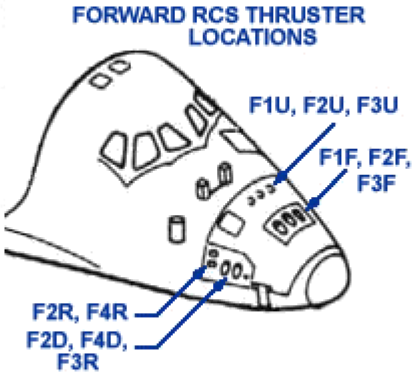


Introduction

The Reaction Control System (RCS) is a set of maneuvering thrusters used primarily to make attitude adjustments to the space shuttle orbiter. Key tasks include the separation of the shuttle from the external fuel tank after launch and repositioning the shuttle for reentry. It also can serve as a replacement for one of the main engines in the event of main engine failure and can serve as a fuel dump under emergency conditions. Valves in an RCS module are controlled from a panel of switches that can be set to OPEN, CLOSE, or GPC for computer control. Talkbacks on the panel provide sensory feedback on the position of the valves

Forward RCS structures and components:





Construction

The RCS is composed of three subsystems which are the forward, left, and right RCS located in the nose and aft sections of the shuttle. Each subsystem consists of a fuel tank, an oxidizer tank, and a set of 14 jets (16 jets for the Forward RCS).

Jet usage and firing can be monitored and controlled from the ground, by the on-board computers, or by manually reading gauges and operating valves. Normally, jet firing is controlled by a computer that makes decisions on what jets to fire based on the type of attitude adjustment and the jets currently available.

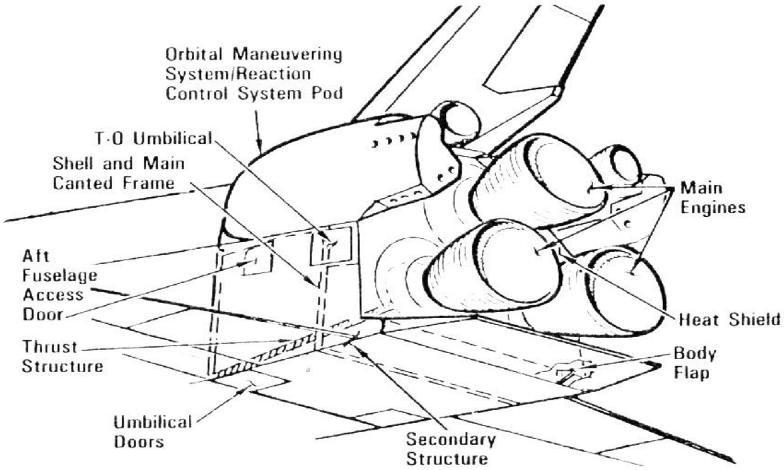
All three subsystems have a similar structure. A subsystem is composed of two pressurization and propellant feed systems one for oxidizer and one for fuel. These two systems are independent and connect at the thruster chambers at the ends of each manifold. Each feed system consists of a helium tank (which pressurizes the propellant), a propellant tank, a set of manifolds and thrusters, and a set of regulators and valves that distribute the propellant and deliver it to one or more of the manifolds.

Additionally, the left and right subsystems can be cross-connected so that they can share the same fuel and/or oxidizer tanks. They may also be connected to the main engine fuel and/or oxidizer tanks as well. Each pressurization system contains sensors used to monitor the RCS and assist in fault isolation as well as to calculate the quantity of propellant remaining.

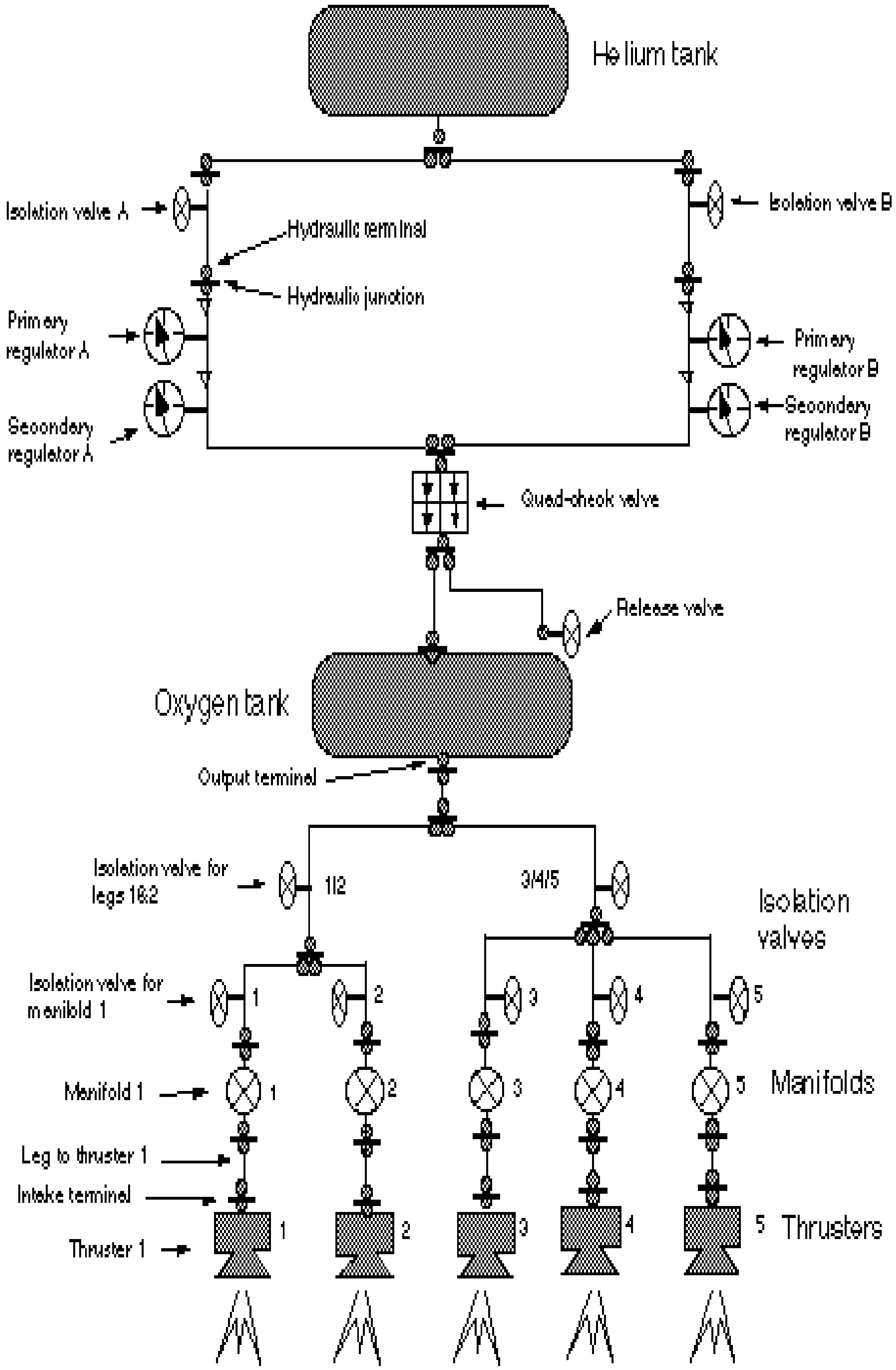
The helium tank passes through a series of regulators that reduce the pressure to the desired working pressure (242 to 248 psig). This pressure is transferred to the propellant tank which in turn forces the propellant into the tank lines, past any open isolation valves, and into any open manifolds. Finally, if the jet corresponding to a manifold is on, the fuel and oxidizer from the pair of feed systems is pushed into the thrust chamber where they explode on contact and produce thrust.

The system is designed for maximum re-configurability, normally only one of the paths from the helium tank to the propellant tank is open with the second one kept as a spare. Each of these paths has two pressure regulators in series to guard against a single regulator failure. The isolation and manifold valves below the propellant tanks are used to reconfigure around a variety of leaks. Finally, the cross feed valves permit operation of the system even when there is a catastrophic failure above the tank isolation valves.

To prevent under and over pressures in the propellant tank, a check valve (which prevents back flow into the helium tank) and a relief valve (which prevents the propellant tank pressure from becoming too high) are placed between the regulators and the propellant tank.



Aft Fuselage Structure



Helium tank
Isolation valve A
Isolation valve B
Hydraulic terminal
Hydraulic junction
Primary regulator A
Primary regulator B
Secondary regulator A
Secondary regulator B
Quad-check valve
Release valve
Oxygen tank
Output terminal
Isolation valve for legs 1&2
1/2
3/4/5
Isolation valves
Isolation valve for manifold 1
1
2
3
4
5
Manifold 1
Manifolds
Leg to thruster 1
Intake terminal
Thruster 1
Thrusters

System failures

Jets may be unavailable due to failures of the RCS. The following are possible conditions which would cause RCS failure.

Leaks - The locations of leaks are determined by the location of flow inhibition valves. Important leak locations are at:

1. The helium tank. A leak here will force the check valve to close. This cause a situation called “blowdown" to occur where the amount of usable propellant in the propellant tank is determined by the remaining pressure in the propellant tank (called “ullage"). If ullage pressure is low, then a potentially large amount of propellant will be trapped in the tank, unable to flow to the thrusters because there will not be enough pressure to push it out.

2. The helium line. A leak here has similar consequences to a helium tank leak. If the leak is in one of the helium legs (between the primary regulator and the helium tank isolation valve), then that leg can be isolated and helium flow will pass through the other helium leg. If the leak cannot be isolated, then both helium isolation valves can be closed to maintain helium tank pressure. This places the system in a blowdown situation.

3. The propellant tank. A leak here requires closing the tank isolation valves. Cross-feed from the other RCS is needed to operate the jets within the subsystem.

4. The tank leg. This failure can be configured around, with the loss of fuel to some jets.

5. The manifolds. A leak here can be isolated with the loss of only the affected manifold.

6. The cross-feed line. A leak here reduces the reconfigurability of the system as cross-feeds cannot be performed.

Regulator failures - Regulators can fail open or closed. Because of the series design of the helium line regulators and the fact that the regulators regulate at different pressures, there are three possible series regulator failures: failed closed (either regulator), primary failed open but secondary working, and both primary and secondary failed open.

The thrusters require a minimum pressure differential across them to function. When the manifold pressure is to low (below 180 psig) the jets will no longer operate, even if the manifold is re-pressurized. This failure is known as “jet starvation”. Once the jet has “starved”, it is unusable for the remainder of the mission.

Other failures - These include electrical and computer failures as well as individual valve failures.

Managing System Failures

Monitoring and diagnosing problems can be broken down into three phases typically described by the acronym “DIR”.

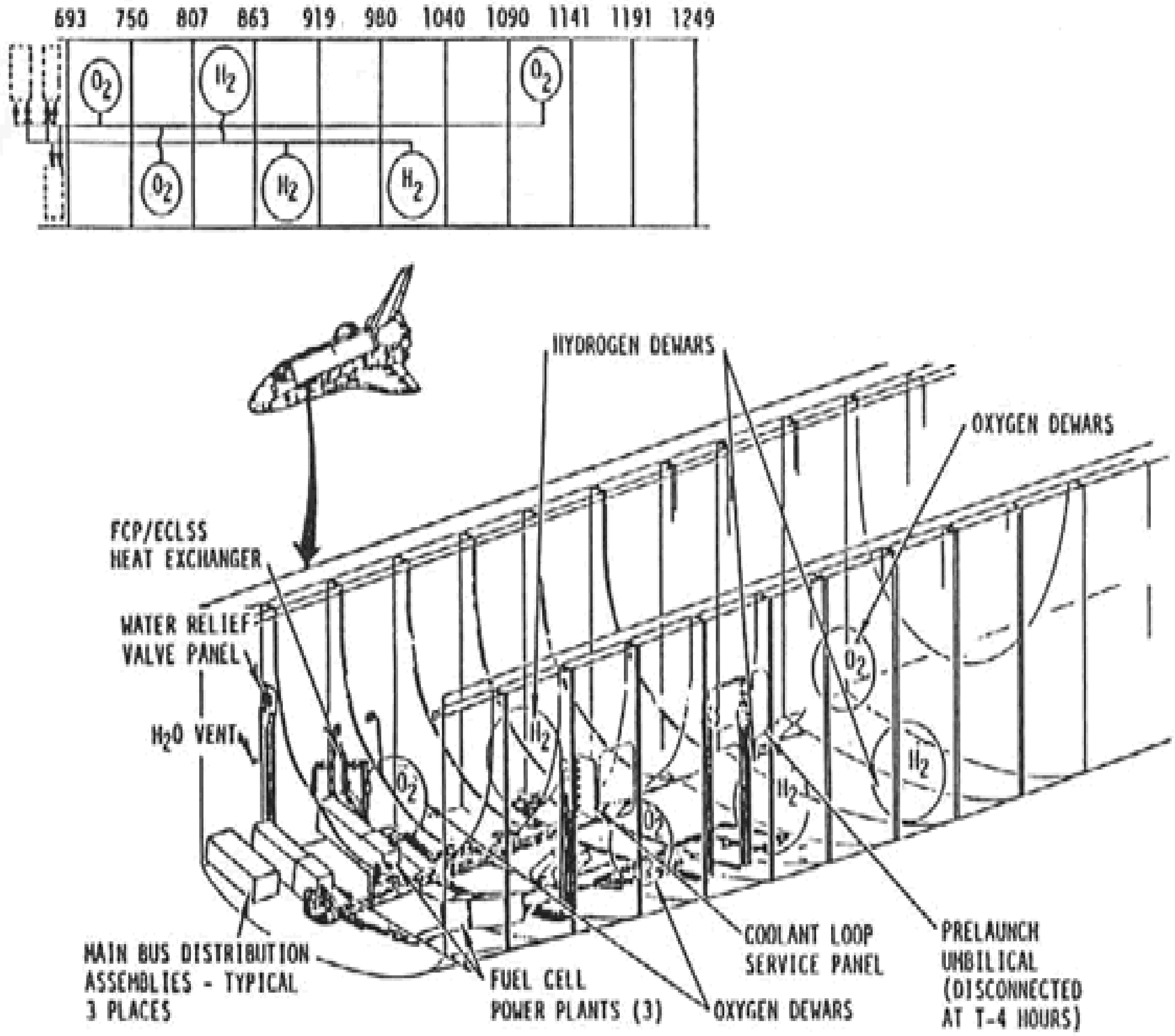
> D- Detection. Failures are detected by the mission controllers on the ground, the astronauts or the on board computer.
>
> I – Isolation. If the fault is plumbing related (either a leak or regulatory failure) the following two steps are performed.
>
> > 1. “Safe” the system. This involves closing valves starting at the thrusters and working back to the helium tank. This prevents venting any section of the system unnecessarily.
> >
> > 2. Diagnose the problem. By reopening valves pressure differences can be calculated to isolate the leak.
>
> R – Reconfiguration. Based on the source of the problem and remaining mission objectives certain portions of the system are cut off from the propellant flow.

Once the system has been reconfigured the system can be tested and made operational to restore RCS control and complete the mission.

CHAPTER 3

Electrical and Power Systems

ELECTRICAL POWER SUBSYSTEM



Introduction

All major systems within the space shuttle require electricity to operate. In order to meet this need the shuttle uses fuel cells. Fuel cells are energy conversion devices that continuously transform the chemical energy of a fuel and an oxidant into electrical energy. This energy conversion process is accomplished by an electrochemical reaction whereby the reactants are consumed, by-product(s) are expelled, and heat may be released or consumed. Fuel cells will continue to generate electricity as long as both fuel and oxidant are available. Pure hydrogen, hydrocarbons, alcohols, and hydrazine are common fuels while pure oxygen and air are conventional oxidants.

Understanding Electrical Circuits

The three most basic units in electricity are voltage **(V),** current **(I**) and resistance **(r).** Voltage is measured in volts, current is measured in amps and resistance is measured in ohms. To understand these terms it is best to compare the flow of electricity to a system of plumbing pipes. The voltage is equivalent to the water pressure, the current is equivalent to the flow rate, and the resistance is like the pipe size.

An Electric charge is nothing but the flow of electrons from one object to another. An electrical circuit or power circuit is the arrangement of an electrically conductive path for the flow and movement of electric charge or electricity. To make an electrical circuit, we need a path for the electrons to flow, and a power-source to push them along. Electrons travel well through metals. Therefore, in an electrical circuit, a path is made out of thin metal in the form of wire. Power source for the circuit could be an electrical generator or a battery.

For example a light-bulb connected to a battery. In order to glow the bulb, electrons have to be pushed out of the battery, this is done through an electric field. The electrons then pass through the light-bulb, and back to the other end of the battery. During this process, the wire (normally tungsten) in the light-bulb gets so hot that it glows and emits bright light. Similarly, electricity travels across wiring in a plane allows the equipment to work.

Resistance

An electron traveling through the wires and loads of the external circuit encounters resistance. Resistance is the hindrance to the flow of charge. For an electron, the journey from terminal to terminal is not a direct route. Rather, it is a zigzag path that results from countless collisions with fixed atoms within the conducting material. The electrons encounter resistance, a hindrance to their movement. While the electric potential difference established between the two terminals encourages the movement of charge, it is resistance that *discourages* it. The rate at which charge flows from terminal to terminal is the result of the combined effect of these two quantities.

Variables Affecting Electrical Resistance

The flow of charge through wires is often compared to the flow of water through pipes. The resistance to the flow of charge in an electric circuit is analogous to the frictional affects between water and the pipe surfaces as well as the resistance offered by obstacles that are present in its path. It is this resistance that hinders the water flow and reduces both its flow rate and its *drift* speed. Like the resistance to water flow, the total amount of resistance to charge flow within a wire of an electric circuit is affected by some clearly identifiable variables.

First, the total length of the wires will affect the amount of resistance therefore the longer the wire, the more resistance that there will be. There is a direct relationship between the amount of resistance encountered by charge and the length of wire it must traverse. After all, if resistance occurs as the result of collisions between charge carriers and the atoms of the wire, then there is likely to be more collisions in a longer wire. More collisions mean more resistance.

Second, the cross-sectional area of the wires will affect the amount of resistance. Wider wires have a greater cross-sectional area. Water will flow through a wider pipe at a higher rate than it will flow through a narrow pipe. This can be attributed to the lower amount of resistance that is present in the wider pipe. Just like the pipe, the wider the wire is the less resistance there will be to the flow of electric charge. When all other variables are the same, charge will flow at higher rates through wider wires with greater cross-sectional areas than through thinner wires.

A third variable that is known to affect the resistance to charge flow is the material that a wire is made of. Not all materials are created equal in terms of their conductive ability. Some materials are better conductors than others and offer less resistance to the flow of charge. Silver is one of the best conductors but is never used in wires of household circuits due to its cost. Copper and aluminum are among the least expensive materials with suitable conducting ability to permit their use in wires of household circuits.

Mathematical Nature of Electricity

Resistance

Resistance is a numerical quantity that can be measured and expressed mathematically. The standard metric unit for resistance is the ohm, represented by the Greek letter omega - Ω. An electrical device having a resistance of 5 ohms would be represented as $\mathbf{R = 5}\ \Omega$. The equation representing the dependency of the resistance (**R**) of a cylindrically shaped conductor (e.g., a wire) upon the variables that affect it is

$$\mathbf{R = (P)\ x\ (L/A)}$$

where **L** represents the length of the wire (in meters), **A** represents the cross-sectional area of the wire (in meters^2), and **P** represents the resistivity of the material (in ohm•meter). Consistent with the discussion above, this equation shows that the resistance of a wire is directly proportional to the length of the wire and inversely proportional to the cross-sectional area of the wire. As shown by the equation, knowing the length, cross-sectional area and the material that a wire is made of (and thus, its resistivity) allows one to determine the resistance of the wire.

Example: A copper wire has a length of 160 m and a diameter of 1.00 mm. If the wire is connected to a 1.5-volt battery, what is the resistance of the wire?

L is the length, 160 m. The resistivity for copper is:

$$\text{For copper, } \rho = 1.72 \times 10^{-8}\ \Omega\ \text{m}$$

The area is the cross-sectional area of the wire. This can be calculated using:

$$A = \pi r^2 = \pi\,(0.0005)^2 = 7.85 \times 10^{-7}\ \text{m}^2$$

The resistance of the wire is then:

$$R = \rho\ L\ /\ A = (1.72 \times 10^{-8})\ (160)\ /\ (7.85 \times 10^{-7}) = 3.50\ \Omega$$

<u>Ohm's Law</u>

Ohm’s law states that in an electrical conductor the ratio of potential difference (voltage) to current is constant. For example, if the terminals of an electric battery are connected to an electric lamp and the voltage output of the battery is then decreased by 20 per cent, the amount of current flowing through the lamp will also be reduced by 20 per cent.

Ohm's Law was derived experimentally by the German physicist Georg Simon Ohm in 1826. It is expressed by the following equation:

$$\mathbf{V = I \times R}$$

In this equation **V** represents the potential difference between one end of the conductor and the other (that is, the voltage applied to the conductor); **I** is the current flowing through the conductor; and R is called the resistance of the conductor. If **V** is given in volts and **I** is given in amperes, **R** will be in ohms. The law offers a simple method of calculating the voltage, current, or resistance in a conductor when two of these three quantities are known.

For example, if the direct-current voltage applied to an electric light bulb is 120 volts and the filament in the bulb has a resistance of 240 ohms, the current flowing through the filament is: I = V/R = 120 volts/240 ohms = 0.5 ampere.

The Space Shuttles Electrical Power system

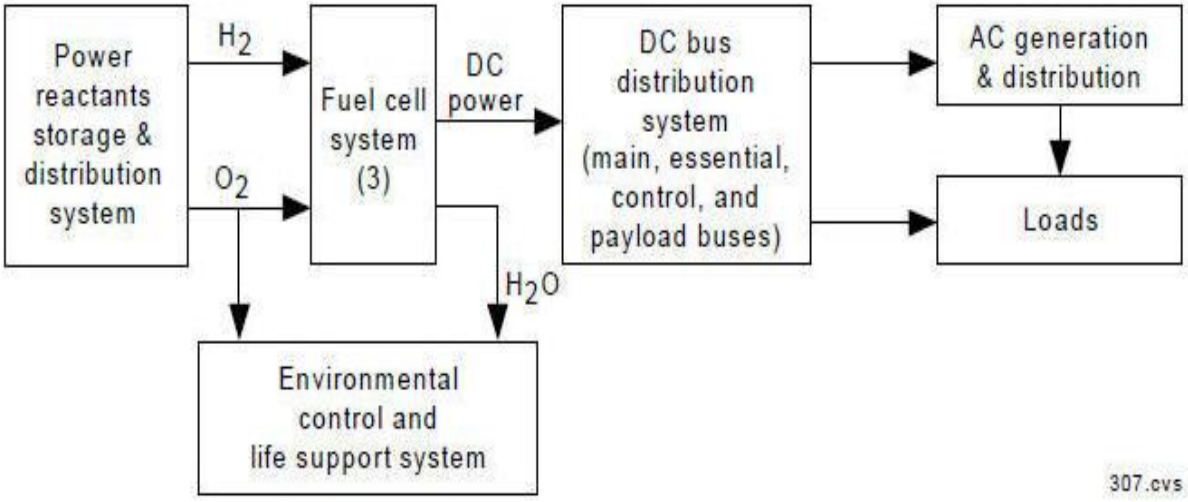
The electrical power system (EPS) consists of the equipment and reactants that produce electrical power for distribution throughout the orbiter vehicle, and fulfill all the orbiter external tank, solid rocket booster, and payload power requirements, when not connected to ground support equipment.

The fuel cell picks up full power load support after ground equipment is turned off at T minus 3 minutes 30 seconds, supporting power requirements for the solid rocket booster, orbiter, and some payloads. The EPS operates during all flight phases. For nominal operations, very little flight crew interaction is required by the EPS. The EPS is functionally divided into three subsystems:

- power reactants storage and distribution (PRSD)
- three fuel cell power plants (fuel cells)
- electrical power distribution and control (EPDC).

Through a chemical reaction, the three fuel cells generate all 28-volt direct-current electrical power for the vehicle from launch minus 3minutes and 30 seconds through landing rollout. Prior to that, electrical power is provided by ground power supplies and the on board fuel cells.

Power is controlled and distributed by assemblies located in the forward, mid, and aft sections of the orbiter. Each assembly is housing for electrical components such as remote switching devices, buses, resistors, diodes, and fuses. Each assembly usually contains a power bus or buses and remote switching devices for distributing bus power to subsystems located in its area.



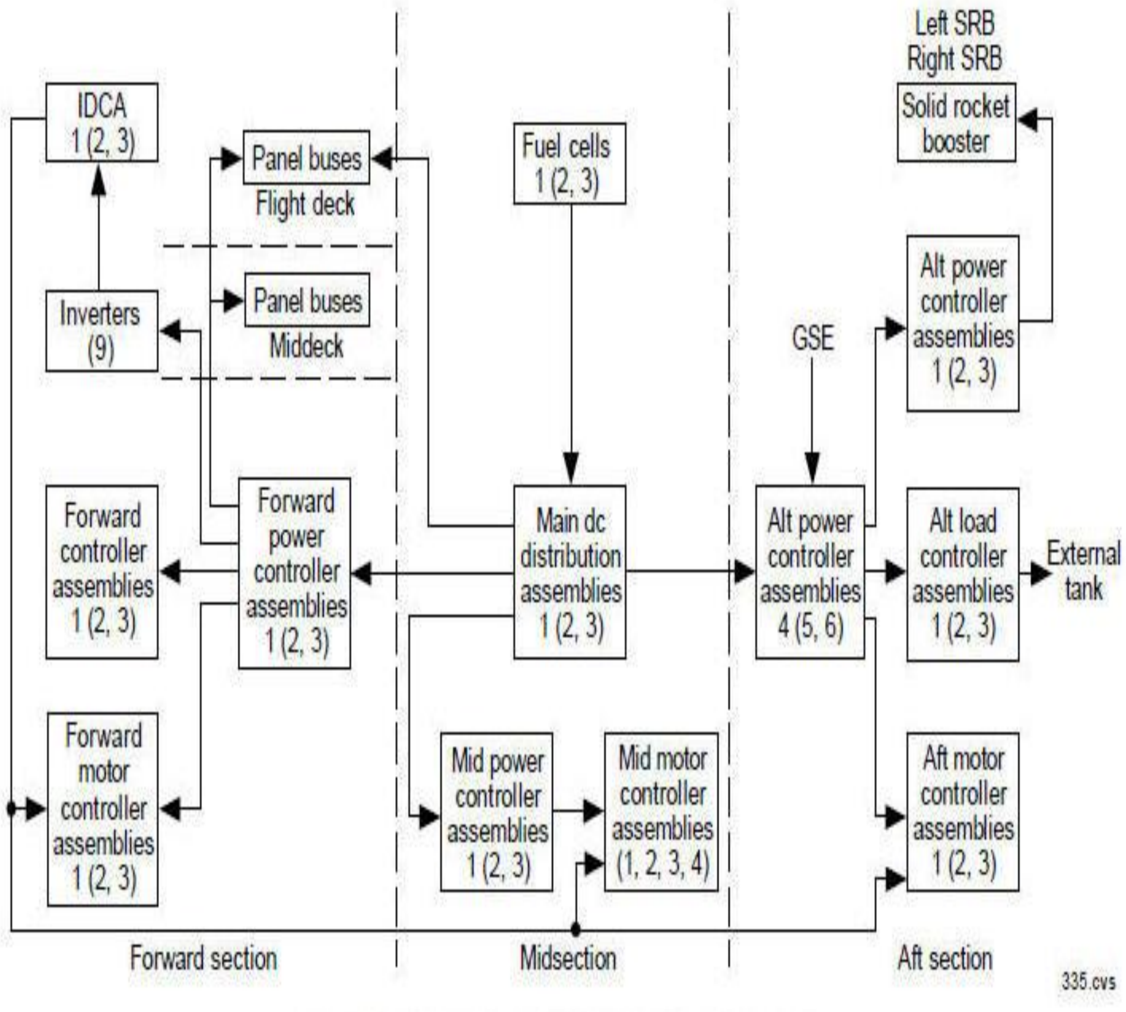
The Electrical Power System

Power Reactants Storage and Distribution System

The power reactants storage and distribution system stores the reactants (cryogenic hydrogen and oxygen) and supplies them to the three fuel cells that generate all the electrical power for the vehicle during all mission phases.

In addition, the subsystem supplies cryogenic oxygen to the environmental control and life support system (ECLSS) for crew cabin pressurization. The hydrogen and oxygen are stored in tanks at cryogenic temperatures (-285°F for liquid oxygen and -420° F for liquid hydrogen) and supercritical pressures (above 731 psi for oxygen and above 188 psi for hydrogen).

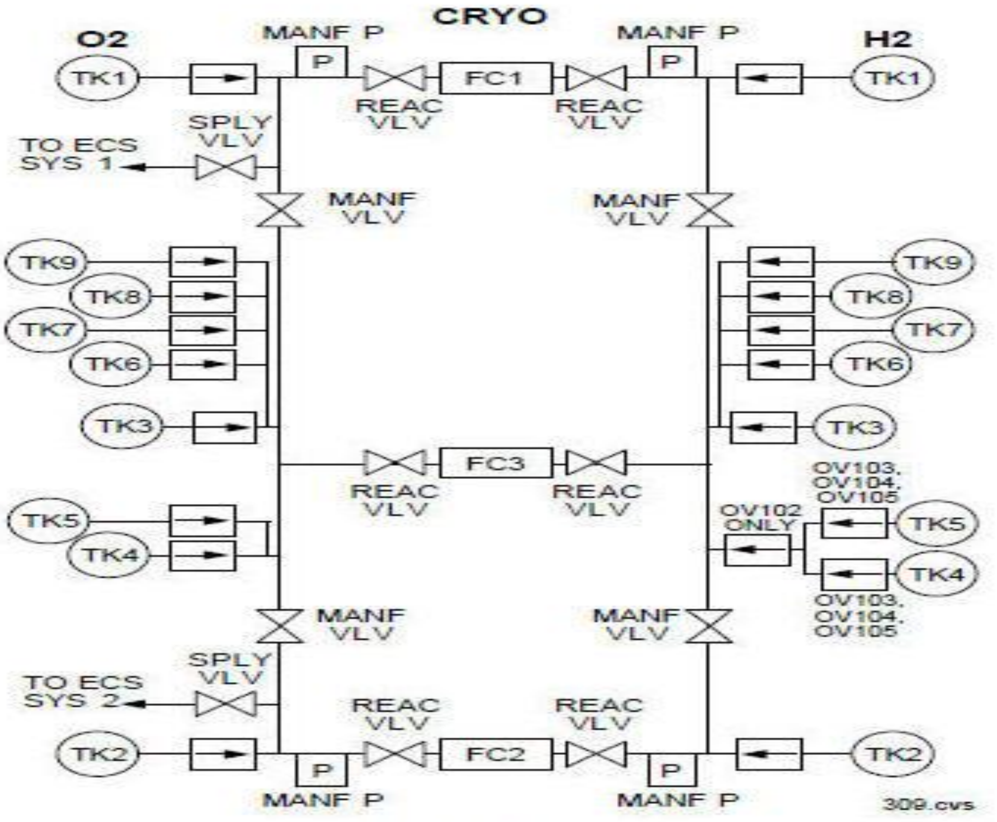
The system stores the reactants hydrogen and oxygen in double-walled, thermally insulated spherical tanks with a vacuum annulus between the inner pressure vessel and outer tank shell. Each tank has heaters to add energy to the reactants during depletion to control pressure.



Electrical Power Distribution Block Diagram

Fuel Cell System

The three fuel cells are located under the payload bay area in the forward portion of the orbiter’s mid-fuselage. Each fuel cell is 14 inches high, 15 inches wide, 40 inches long, and weighs 255 pounds. Each fuel cell is reusable and re-startable. The three fuel cells are individually coupled to the PDRS subsystem, the active thermal control system (ATCS), the supply water storage subsystem, and the electrical power distribution and control (EPDC) subsystem.



The PDRS System

The fuel cells generate heat and water as by-products of electrical power generation. The excess heat is directed to fuel cell heat exchanger, where it is rejected to the Freon coolant loops. The water is directed to the supply water storage subsystem for the environmental control and life support system.

The fuel cell generates power through an electrochemical reaction of hydrogen and oxygen. At the hydrogen electrode (anode), hydrogen is oxidized according to the following reaction:

$$2H_2 + 4OH \rightarrow 4H_2O + 4e$$

forming water and releasing electrons. At the oxygen electrode (cathode), oxygen is reduced in the presence of water. It forms hydroxyl ions according to the following relationship:

$$O_2 + 2H_2O + 4e \rightarrow 4OH$$

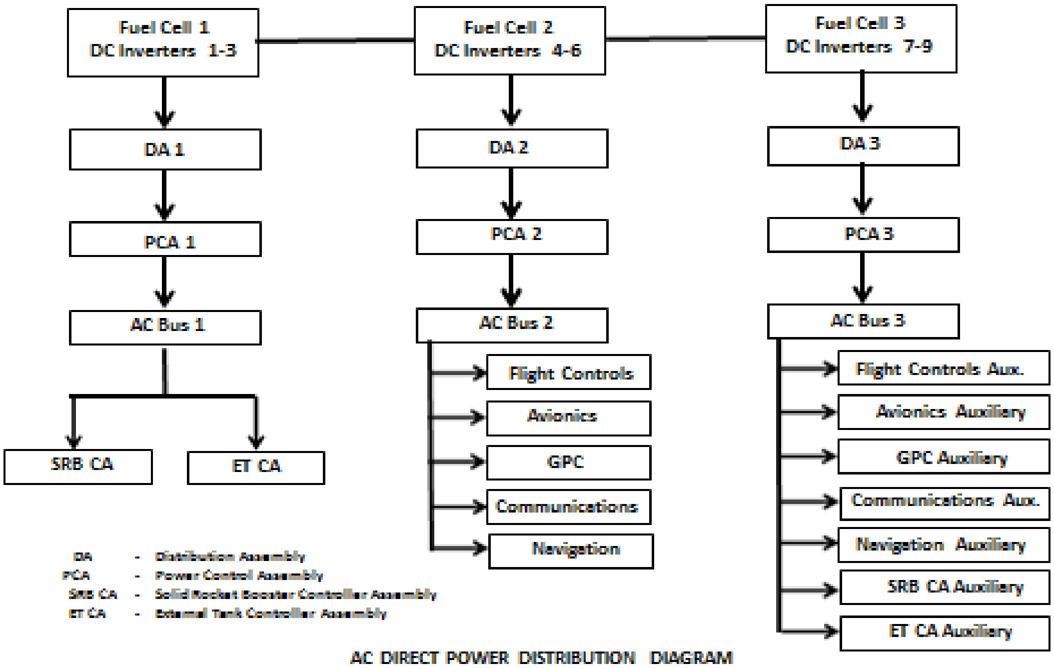
The net reaction consumes one oxygen molecule and two hydrogen atoms in the production of two water molecules, with electricity and heat formed as by-products of the reaction.

Electrical Power Distribution and Control

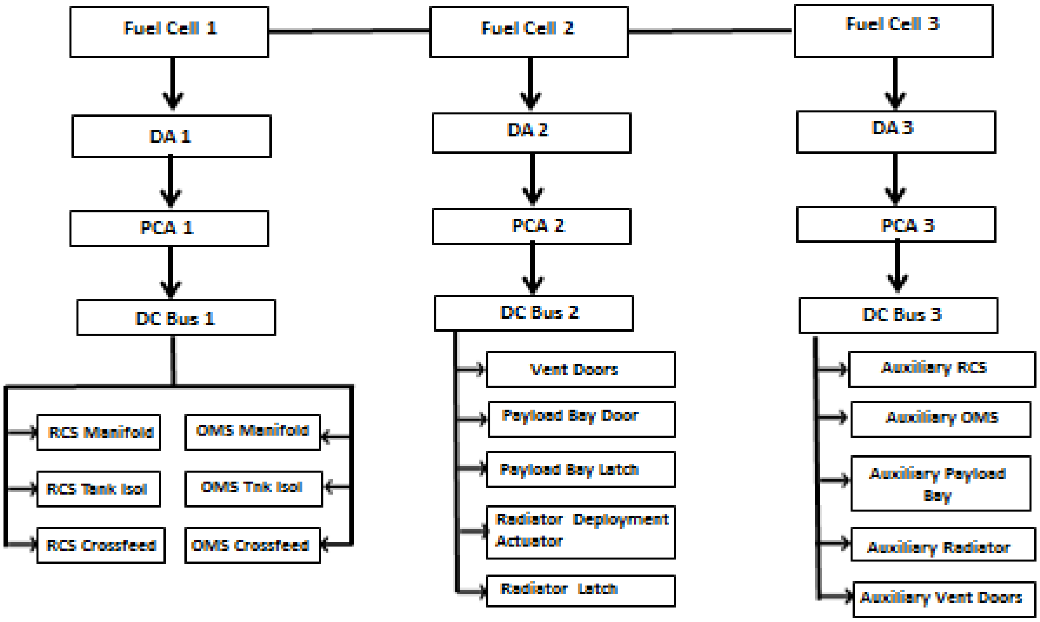
The electrical power distribution and control system distributes electrical power throughout the orbiter. It has five types of assemblies: power control, load control, motor control, main dc distribution, and ac distribution and control.

The 28 volts dc generated by each of the three fuel cells is distributed to a main dc bus. A bus is a distribution point in an aircraft electrical system to which the battery and the generator(s) are connected and from which the electrical loads derive their power.

The three main dc buses (MN A, MN B, and MN C) are the prime sources of power for the vehicle's dc loads. Each of the three dc main buses supplies power to three solid-state (static), single-phase inverters, each of which powers one three-phase alternating-current bus; thus, the nine inverters convert dc power to ac power for distribution to three ac buses (AC 1, AC 2, and AC 3) for the vehicle's ac loads.



AC DIRECT POWER DISTRIBUTION DIAGRAM



DA - Distribution Assembly
PCA - Power Control Assembly

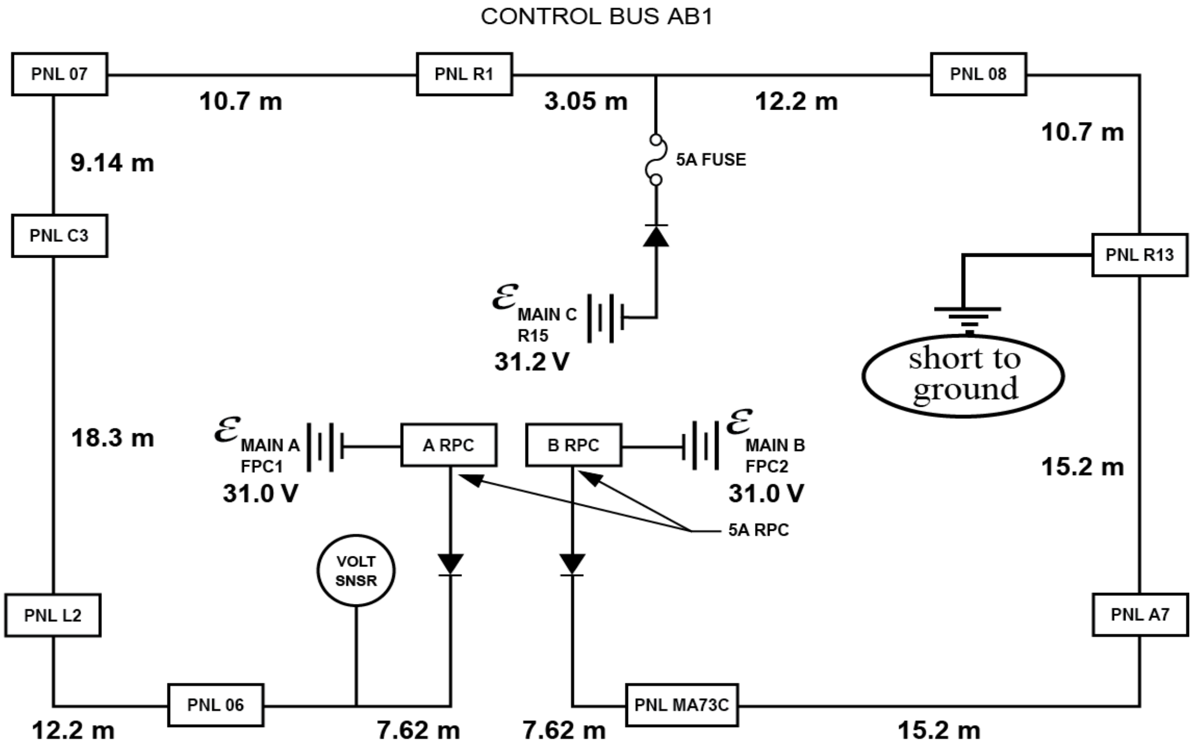
DC DIRECT POWER DISTRIBUTION DIAGRAM

Bus System

A Bus system is a distribution point in an aircraft electrical system to which the battery and the generator(s) are connected and from which the electrical loads derive their power.

The three main dc buses are main A (MN A), main B (MN B), and main C (MN C). Three ac buses, AC 1, AC 2, and AC 3, supply ac power to the ac loads. Three essential buses, ESS1BC, ESS2CA, and ESS3AB, supply dc power to selected flight crew controls and electrical loads that are deemed essential. Nine control buses - CNTL AB 1, 2, 3; CNTL BC 1, 2, 3; and CNTL CA 1, 2, 3 - are used to supply control power to flight crew controls. Two preflight buses, PREFLT 1 and PREFLT 2, are used only during ground operations.

Depending on the criticality of orbiter electrical equipment, some electrical loads may receive redundant power from two or three main buses. If an electrical load receives power from two or three sources, it is for redundancy only and not for total power consumption.



PNL=Panel RPC =Remote Power Controller SNSR = Sensor

The figure above is a simplified layout of a control bus for the space shuttle. At each end of the bus there is a 31 V power source and a 5 A circuit protection device called a remote power controller (RPC). This is a closed loop because the return path is through vehicle ground (not shown in diagram).

The RPCs will break the circuit (trip) after exceeding the rated current for a specified duration and can be reset after a trip. There is also a 31.2V power source connected at the center of the electrical bus through a 5A fuse as shown above.

Over Current Protective Devices

Over current protective devices (fuses and circuit breakers) are used to protect circuits and equipment against overloads and short circuits (faults). These devices vary in characteristic, design and function. Fuses and circuit breakers are designed to sense abnormal overloads and short circuits and open the circuit before catastrophic events occur.

Fuses - A fuse is an intentional weak link in a circuit. It is a thermally responsive device designed to provide over current protection. The main function of a fuse is to protect conductors and equipment from damaging over currents and quickly de-energize faulted circuits minimizing hazards to personnel.

Fuses may be classified as fast-acting or time delay and as current-limiting or non-current limiting. Fast-acting fuses are designed to respond quickly to overload currents, while time delay fuses are required to carry an overload current for a predetermined amount of time. This permits time-delay fuses to carry starting current and other temporary overloads. Fuses that limit the maximum peak current that could flow during a short circuit are classified as current limiting fuses. Whether the fuse is classified as fast-acting or time-delay, current-limiting fuses will open quickly during short-circuit conditions.

Circuit breakers - circuit breakers are designed to protect circuits from overload and short circuit conditions when applied within their ratings. Most circuit breakers utilize a mechanical latching, spring assisted switching mechanism and a thermal, thermal-magnetic, hydraulic-magnetic, or electronic current sensing circuit that causes the switching mechanism to unlatch and open the circuit.

Space Shuttle Basic Electrical System

The majority of the control panels on the space shuttle are connected and powered by long, low amperage wires strung together to form what is called a “control bus”. A potential electrical problem is a short to ground (a low resistance current return path) somewhere on the wire. In the space shuttle, the negative poles of the fuel cells are tied to the airframe just like the negative battery pole in a car is tied to the frame. If a wire from a positive terminal touches the frame it will result in a large spark as a significant amount of current will take the path of least resistance.

A circuit is a closed loop because the return path is through vehicle ground. Each switch function in each control panel takes the powered control bus input, feeds it through the switch out to electronic devices in the circuit, and then returns it to ground. The control bus in normally uses 24-gauge wires, wire gauge is a measurement of how large a wire is.

As the diameter of the wire decreases, the gauge number increases as does the resistance in the wire. Because the wire gauge is small and the line length is long, the resistance in the wire is significant.

The 24-gauge wire used in the shuttle has a resistance of 0.0846 Ω/m. In the event of a short to ground somewhere on the wire, one source may draw enough current to trip the circuit protection. However, the resistance in the line may prevent a high enough current draw at the other sources to trip the circuit protection. This means that the short continues to be powered and could cause a fire.

Fuses and circuit breakers have characteristic trip curves that level off at somewhere above the rated trip current. This allows the user to safely operate a load at the rated current without fear of tripping the circuit. These thermal devices rely on heat buildup, so it takes some finite period of time to trip. The resistance (Ω Ohms) can be calculated by using the formula R= (resistance of the wire) (Length of the wire)

Electrical problems

Overload - An Overload is defined as an over current that is confined to the normal current path. Excessive connected loads, stalled motors, overloaded machine tools, etc. can overload a circuit. Most conductors can carry a moderate overload for a short duration without damage. In fact, transient moderate overloads are part of normal operation.

Startup or temporary surge currents for motors, pumps, or transformers are common examples. Over current protection must be selected that will carry these currents. However, if the overload persists for too long, excessive heat will be generated ultimately causing insulation failure. This may result in fires or lead to a short circuit.

Short Circuit - A Short Circuit is any current not confined to the normal path. The term comes from the fact that such currents bypass the normal load (i.e., it finds a “short” path around the load). Usually, when a current is greater than 6 times (600%) the normal current, it should be removed as quickly as possible from the circuit. Short Circuits are usually caused by accidental contact or worn insulation and are more serious than overloads. Damage occurs almost instantly.

Examples of Short Circuits include two or more conductors accidentally touching, someone touching or dropping tools across energized conductors or accidental connection between energized conductors and ground. Such ground faults may vary from a few amperes to the maximum available short circuit fault current.

Managing System failures

Some general rules for managing problems within electrical power system:

1. Never close a circuit breaker or reset an RPC found out of configuration without Mission Control coordination.

2. Never connect or reconnect power to a known shorted or failed component; this includes switch throws, circuit protection device resets, or bus ties.

3. If a system fault is discovered a circuit breaker or RPC may have to be bypassed to ensure adequate power supply to the systems that are served. This must be done under Mission Control Coordination.

4. Loss of cooling to a fuel cell requires crew action within 9 minutes to prevent a catastrophic loss of crew/vehicle due to possible fuel cell fire and explosion.

5. Fuel cell run limit prior to shut-down for loss of cooling is 9 minutes at a 7 kW nominal load. Run time is inversely proportional to fuel cell load.

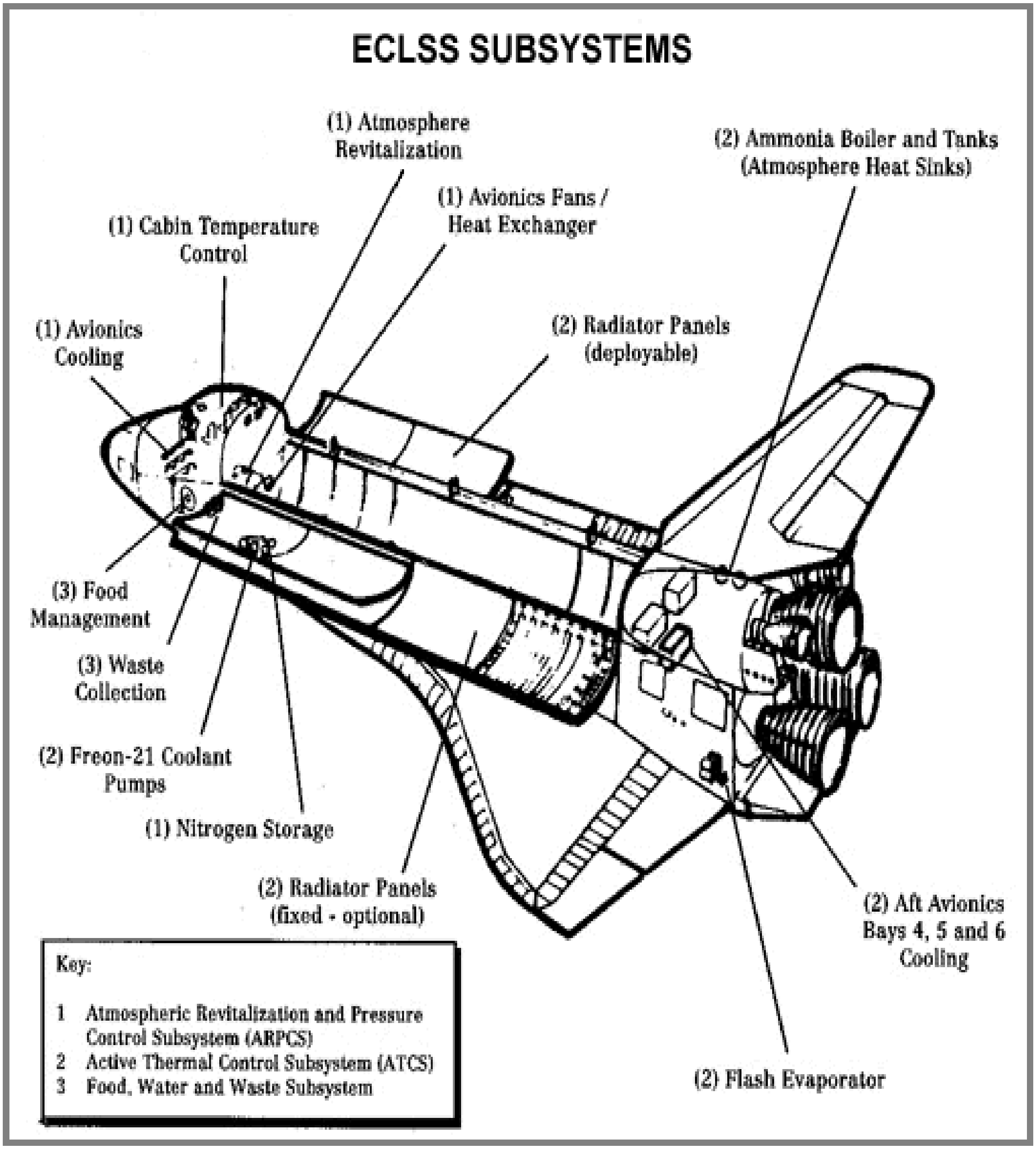
6. Any interruption of continuous ac power during ascent may result in the loss of main engine controller redundancy. Reconfiguration of ac powered equipment prior to Main engine cutoff (MECO) should be avoided.

7. Three oxygen and hydrogen tanks are good for up to 8 days on orbit; five oxygen and hydrogen tanks are good for up to 12 days on orbit; eight oxygen and hydrogen tanks are good for up to 18 days on orbit. Exact duration varies with crew complement and power load.

8. A fuel cell hydrogen pump uses 0.3 amps/AC phase; a coolant pump uses 0.5 amps/AC phase.

CHAPTER 4

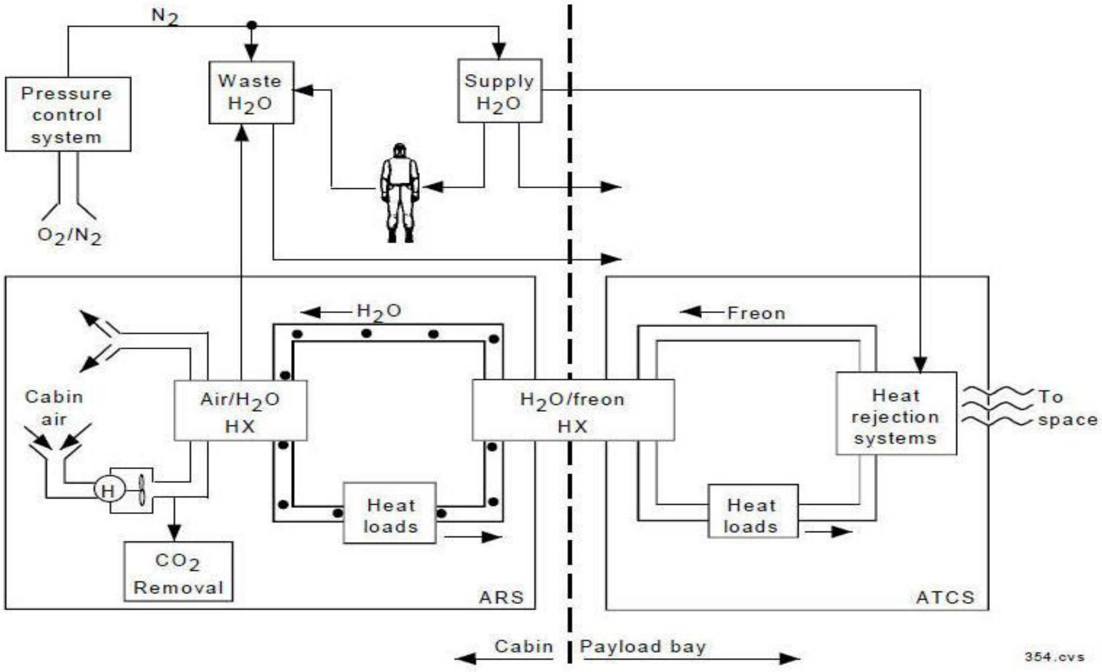
Environmental Control and Life Support System



Overview

Introduction

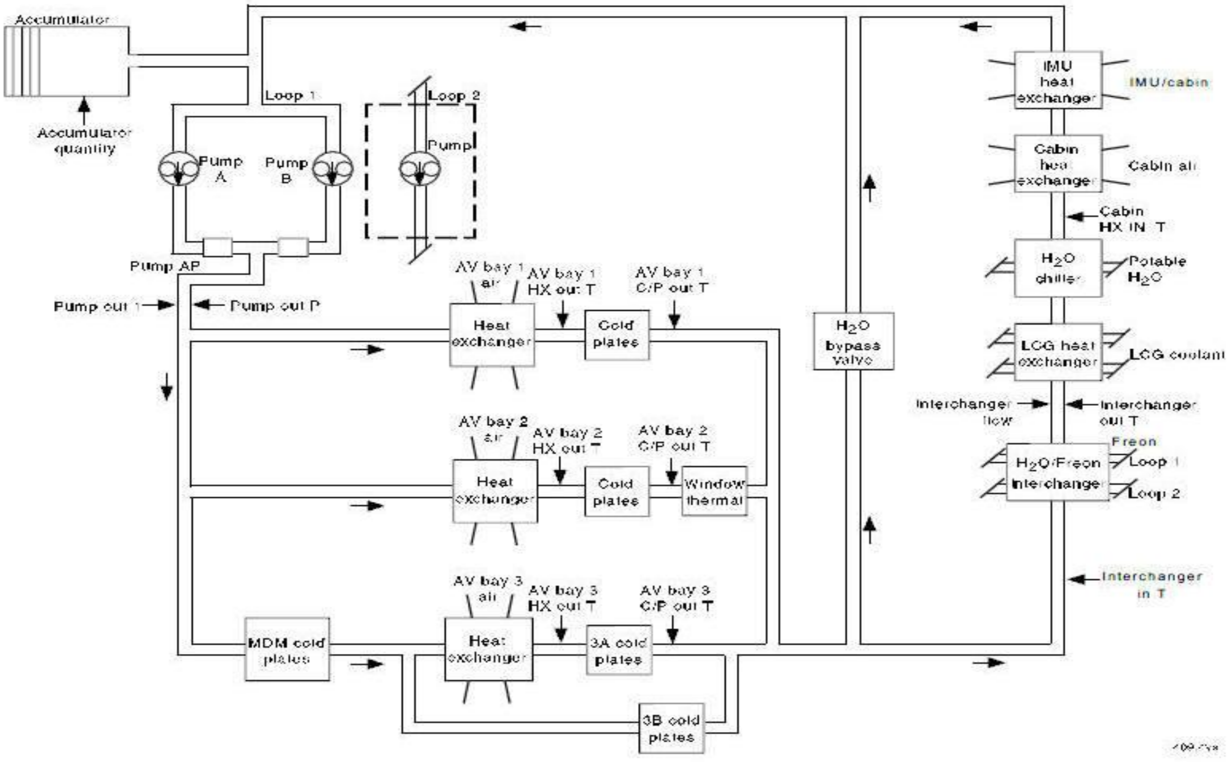
The Environmental Control and Life Support System (ECLSS) consists of an air revitalization system, water coolant loop systems, atmosphere revitalization pressure control system, active thermal control system, supply water and waste water system, waste collection system and airlock support system. These systems interact to provide a habitable environment for the flight crew in the crew compartment in addition to cooling or heating various orbiter systems or components.



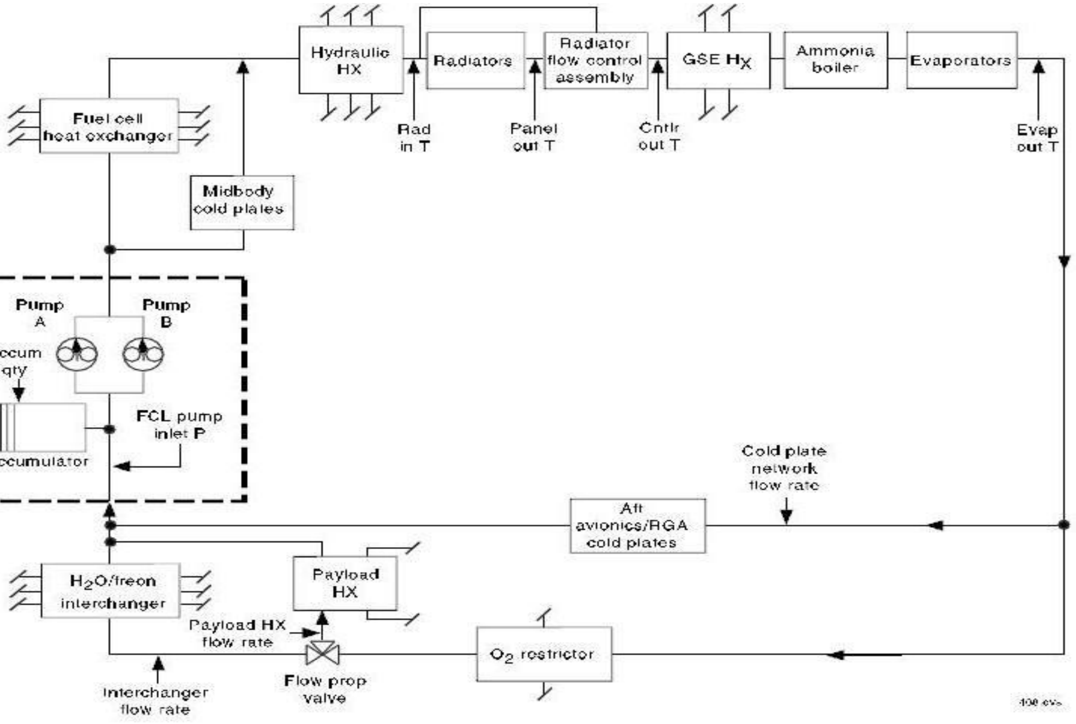
Environmental Control and Life Support System Overview

The Atmosphere Revitalization Pressure Control System (ARPCS) controls relative humidity between 30 and 75 percent, maintains carbon dioxide and carbon monoxide at non-toxic levels, controls temperature and ventilation in the crew compartment, and provides cooling to various flight deck and mid-deck electronic avionics and the crew compartment.

The ARPCS consists of water coolant loops, cabin air loops and pressure control. Cabin air is ducted to the crew compartment cabin heat exchanger, where the cabin air is cooled by the Water Coolant Loop System (WCLS) therefore; cabin air cools the crew cabin, flight crew and crew compartment electronic avionics. The water coolant loop system collects heat from the crew compartment cabin heat exchanger and heat from some of the electronic units in the crew compartment and transfers it to the water coolant/Freon-21 coolant loop heat exchanger of the Active Thermal Control System (ATCS).



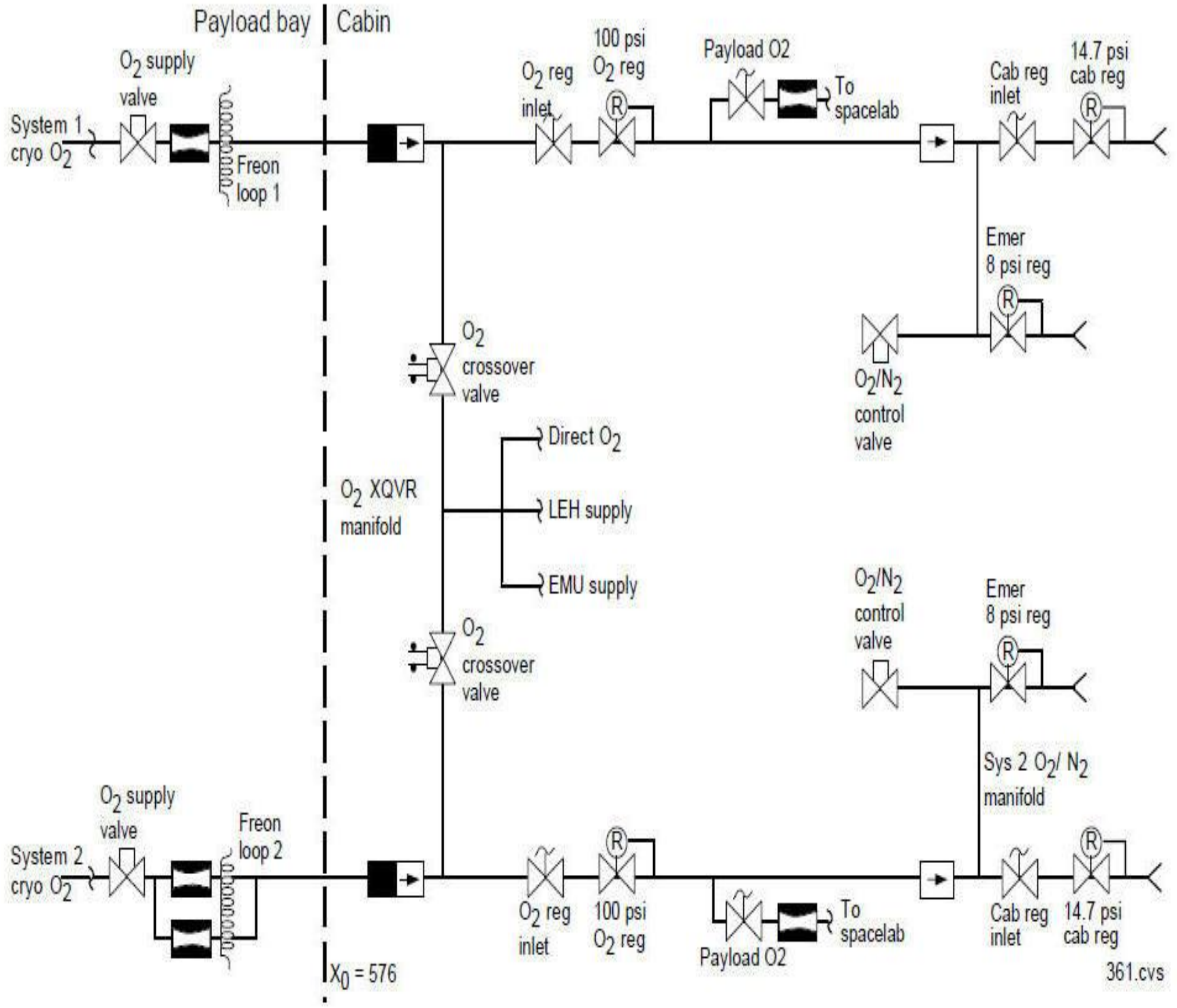
Water Loops



Freon Flow

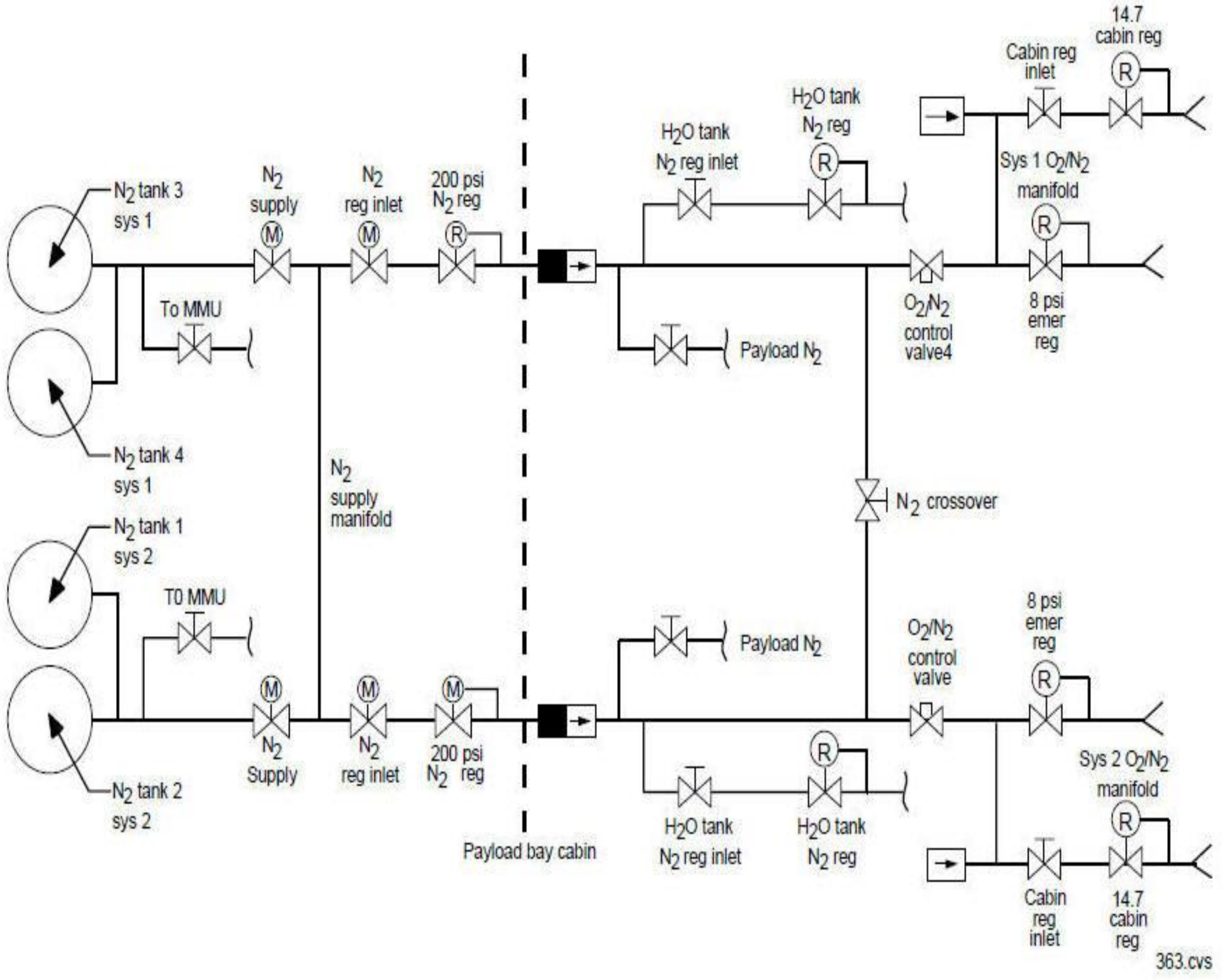
Cabin Oxygen and Nitrogen System

The ARPCS controls crew compartment cabin pressure at 14.7 psi, plus or minus 0.2 psi, with an average of 80-percent nitrogen and 20-percent oxygen mixture. Oxygen partial pressure is maintained between 2.95 psi and 3.45 psi, with sufficient nitrogen pressure of 11.5 psi added to achieve the cabin total pressure of 14.7 psi, plus or minus 0.2 psi. The pressurization control system receives oxygen from two power reactant storage and distribution cryogenic oxygen systems in the mid-fuselage of the orbiter.



Oxygen System

Gaseous nitrogen is supplied from two nitrogen systems consisting of two nitrogen tanks for each system located in the mid-fuselage of the orbiter. An optional mission kit consists of an emergency gaseous oxygen tank, and the system can be located in the mid-fuselage of the orbiter. The gaseous nitrogen system is also used to pressurize the potable and waste water tanks located below the crew compartment middeck floor.



Nitrogen System for Nominal Mission OV-104

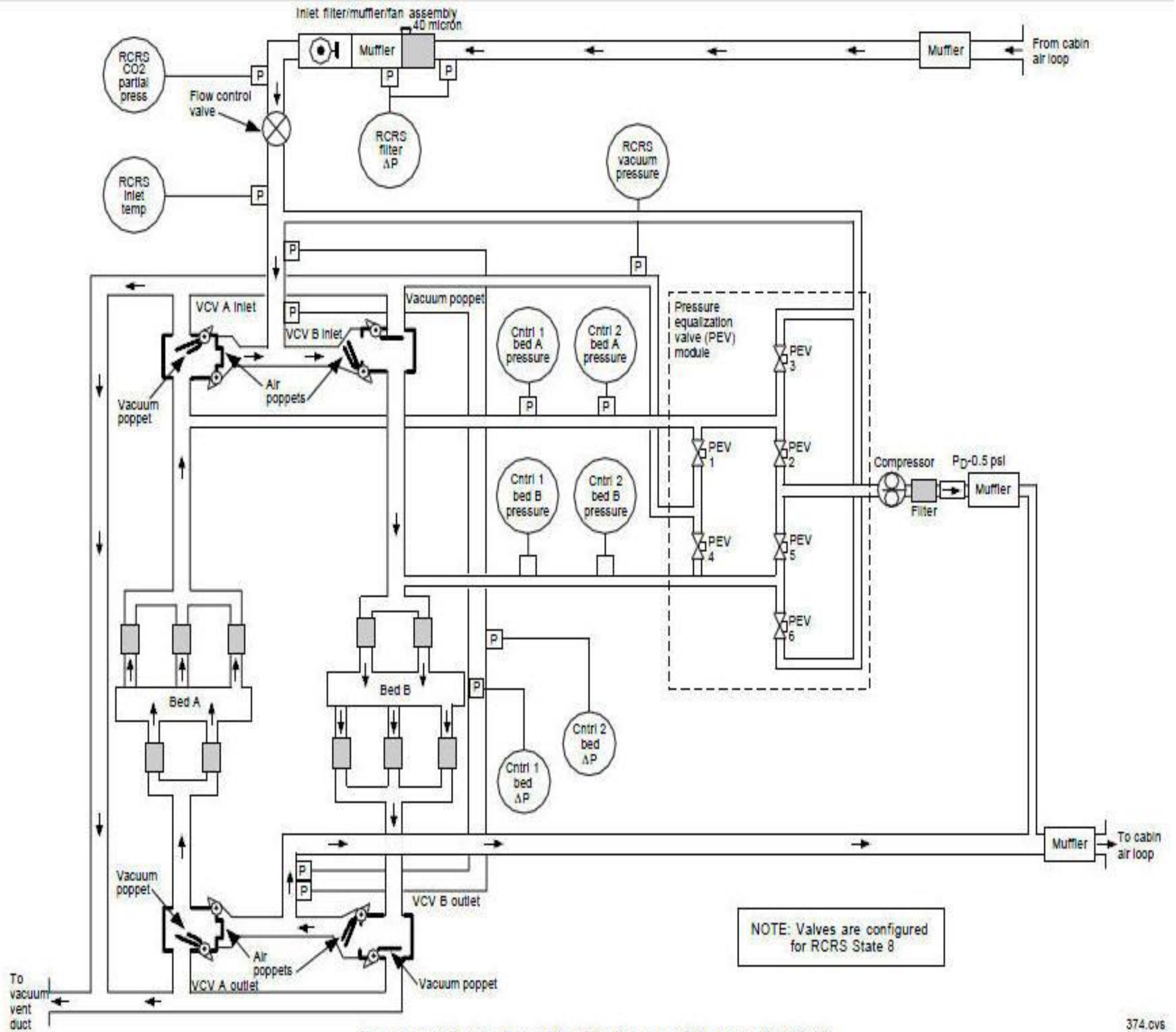
Potable water produced by the three fuel cell power plants is directed and stored in potable water tanks for flight crew consumption and personal hygiene. The potable water system is the supply to the flash evaporator system when it is used to cool the Freon-21 coolant loops. A waste water tank is also located below the crew compartment mid-deck floor to collect waste water from the crew cabin heat exchanger and flight crew waste water. Solid waste remains in the waste management system in the crew compartment mid-deck until the orbiter is serviced during ground turnaround operations.

The orbiter crew compartment provides a life-sustaining environment for a flight crew of eight. The crew cabin volume with the airlock inside the mid-deck is 2,325 cubic feet. For extravehicular activity requirements, only the airlock is depressurized and re-pressurized. If the airlock is located outside of the mid-deck in the payload bay, the crew cabin volume would be 2,625 cubic feet.

The oxygen and nitrogen supply systems provide the makeup cabin oxygen gas consumed by the flight crew and nitrogen for pressurizing the potable and waste water tanks and re-pressurizing the airlock. An average of 1.76 pounds of oxygen is used per flight crew member per day. Up to 7.7 pounds of nitrogen and 9 pounds of oxygen are expected to be used per day for normal loss of crew cabin gas to space and metabolic usage. The potable and waste water tanks are pressurized to 17 psi.

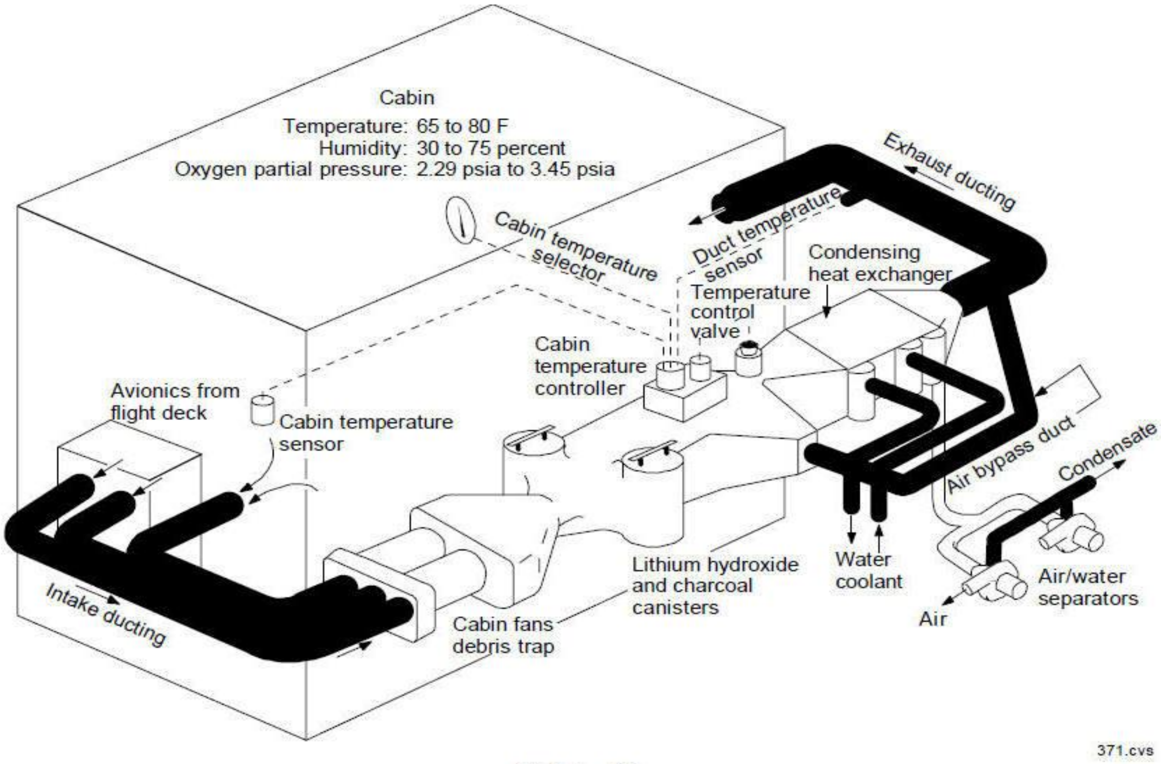
Cabin Air Revitalization

There are five independent air loops in the cabin: the cabin itself, three avionics bays and inertial measurement units. The cabin pressure atmosphere is circulated by the air revitalization system. The air circulated through the flight crew cabin picks up heat, moisture, odor, carbon dioxide and debris with additional heat from electronic units in the crew cabin. The cabin air is drawn through the cabin loop and through a 300-micron filter by one of two cabin fans located downstream of the filter.



Regenerable Carbon Dioxide Removal System (RCRS)

The cabin air from the cabin fan is ducted to the two lithium hydroxide canisters, where carbon dioxide is removed and activated charcoal removes odors and trace contaminants. An orifice in the duct directs a specific amount of cabin air through each lithium hydroxide canister. The canisters are also located under the mid-deck floor. They are changed alternately every 12 hours through an access door in the floor. For a flight crew of seven, the lithium hydroxide canisters are changed alternately every 11 hours. Replacement canisters are stored under the mid-deck floor between the cabin heat exchanger and water tanks.



Cabin Air

Cabin air is then directed to the crew cabin heat exchanger located under the mid-deck floor and cooled by the water coolant loops. Humidity condensation that forms in the slurper of the cabin heat exchanger is removed by a fan separator that draws air and water from the cabin heat exchanger. The moist air is drawn from the slurper into the humidity separator fan, where centrifugal force separates the water from the air. The fan separator removes up to approximately 4 pounds of water per hour. The water is routed to the waste water tank, and the air is ducted through the exhaust for return to the cabin. The relative humidity in the crew cabin is maintained between 30 and 65 percent in this manner. A small portion of the revitalized and conditioned air from the cabin heat exchanger is ducted to the carbon monoxide removal unit, which converts carbon monoxide to carbon dioxide.

Based on the crew cabin volume of 2,300 cubic feet and 330 cubic feet of air per minute, one volume crew cabin air change occurs in approximately seven minutes, and approximately 8.5 air changes occur in one hour.

Environmental Control and Life Support System Malfunctions

The red cabin atm. caution and warning light is illuminated for any of the following monitored parameters:

- Cabin pressure below 14.0 psi or above 15.4 psi.
- PPO2 below 2.8 psi or above 3.6 psi.
- Oxygen flow rate above 5 pounds per hour.
- Nitrogen flow rate above 5 pounds per hour.

A klaxon will sound in the crew cabin and the master alarm push button light indicators will be illuminated if the change in pressure versus change in time decreases at a rate of 0.05 psi per minute or greater. The normal cabin depressurization is zero psi per minute, plus or minus 0.01 psi, for all normal operations.

The temperature and pressure of the primary and secondary nitrogen and emergency oxygen tanks are monitored and transmitted to the systems management computer. This information is used to compute oxygen and nitrogen quantities.

The two cabin relief valves are in parallel to provide over pressurization protection of the crew module cabin above 16 psi. Each cabin relief valve is controlled by its corresponding switch. The cabin relief A switch controls cabin relief A, and the cabin relief B switch controls cabin relief B. When the switch is positioned to enable, the corresponding motor-operated valve allows the cabin pressure to a corresponding positive pressure relief valve that relieves at 16 psi and reseats at 15.5 psi. The relief valve maximum flow capability is 150 pounds per hour.

Waste Control System

The waste collection system (WCS) is an integrated, multifunctional system used primarily to collect and process biological wastes from crew members in a zero-gravity environment. The WCS is located in the middeck of the orbiter crew compartment in a 29-inch -wide area immediately aft of the crew ingress and egress side hatch. The commode is 27 by 27 by 29 inches and is used like a standard toilet.

The system collects, stores and dries fecal wastes and associated tissues; processes urine and transfers it to the waste water tank; processes extravehicular mobility unit (EMU) condensate water from the airlock and transfers it to the waste water tank if an extravehicular activity is required on a mission; provides an interface for venting trash container gases overboard; provides an interface for dumping air revitalization system (ARS) waste water overboard in a contingency situation; and transfers ARS waste water to the waste water tank.

The WCS consists of a commode, urinal, fan separators, odor and bacteria filter, vacuum vent quick disconnect and waste collection system controls. The commode contains a single multilayer hydrophobic porous bag liner for collecting and storing solid waste. When the commode is in use, it is pressurized, and transport air flow is provided by the fan separator. When the commode is not in use, it is depressurized for solid waste drying and deactivation. The urinal is essentially a funnel attached to a hose and provides the capability to collect and transport liquid waste to the waste water tank. The fan separator provides transport air flow for the liquid. The fan separators separate the waste liquid from the air flow. The liquid is drawn off to the waste water tank, and the air returns to the crew cabin through the odor and bacteria filter. The filter removes odors and bacteria from the air that returns to the cabin. The vacuum quick disconnect is used to vent liquid directly overboard from equipment connected to the quick disconnect through the vacuum line.

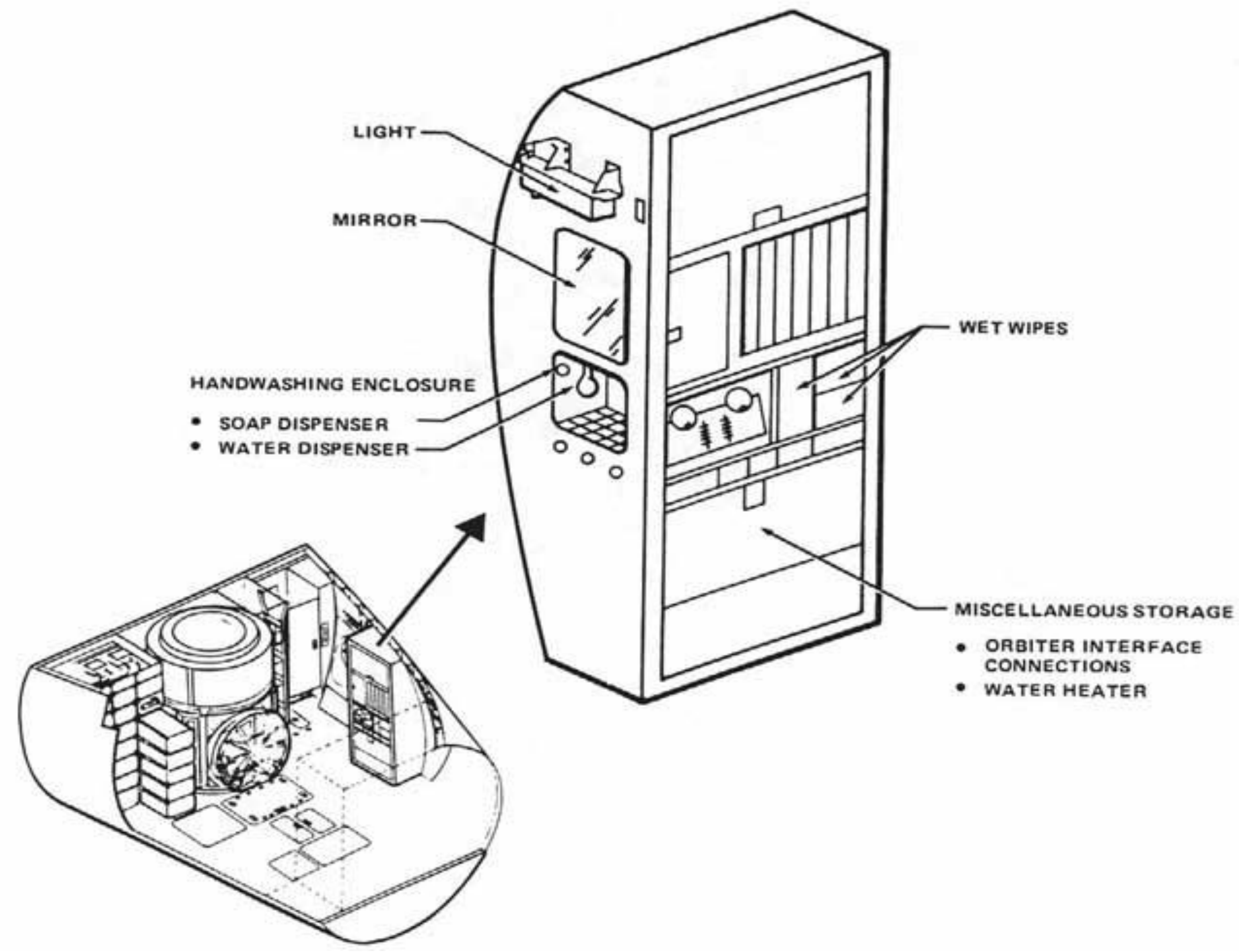
The urinal can accommodate both males and females. The urinal assembly is a flexible hose with attachable funnels for males or females. It can be used in a standing position or can be attached to the commode by a pivoting mounting bracket for use in a sitting position.

All waste collection system gases are ducted from the fan separator into the odor and bacteria filter and then mixed with cabin air. The filter can be removed for in-flight replacement.

The system employs various restraints and adjustments to enable the user to achieve the proper body positioning to urinate or defecate in a zero-gravity environment. Two foot restraints are provided. A toe bar is located at the commode base and is used to urinate standing. It consists of two flexible cylindrical pads on a shaft that can be adjusted to various heights by releasing two locking levers that are turned 90 degrees counterclockwise. The crew member is restrained by slipping the feet under the toe bar restraint. A footrest restrains the feet of a crew member sitting on the commode. It consists of an adjustable platform with detachable Velcro straps for securing the feet. The Velcro straps are wrapped crosswise over each foot and secured around the back. The footrest can be adjusted to various angles and heights. Two locking handles pulled outward adjust the angle; two other locking levers adjust the height of the footrest.

Two body restraints are provided for use when crew members are seated on the commode. The primary restraint is a thigh bar that the crew member lifts up out of the detent position, rotates over the thigh and releases. It exerts a preloaded force on each thigh of approximately 10 pounds. The second restraint is a backup method. It consists of four Velcro fabric thigh straps with a spring hook on one end. Two of the straps are attached to the top front commode surface mating attach points, and the other two are installed on a bracket with five holes on the upper sides of the commode, below and outboard of the thigh bars. The crew member is secured in position by wrapping two straps over each thigh and attaching the mating Velcro surfaces.

Handholds are used for positioning or stabilizing the crew member while using the WCS and form an integral part of the top cover of the waste management collection system assembly.



Personal Hygiene Equipment on Orbit Locations (with galley)

Waste System Malfunctions

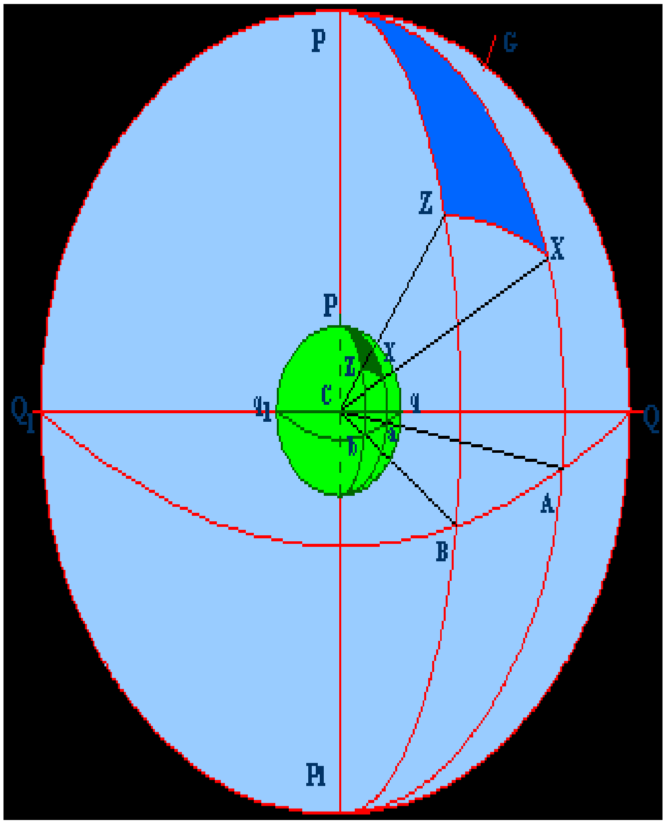
If fan separator 1 is inoperative or fails to achieve proper operational speed (which can be verified by a reduced noise level or lack of air flow), the fan step switch is positioned from 1 to 2, and fan separator 2 will operate in the same manner as 1.

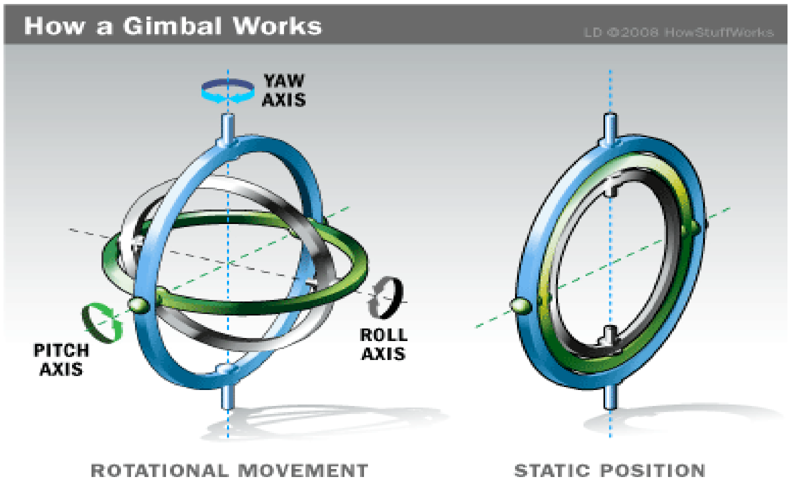
If both fan separators in the waste collection system fail, feces are collected by the Apollo fecal bag. To dispose of the Apollo fecal bag, the waste collection system is configured as in the urine and feces collection mode and the bag is stowed in the commode.

If both fan separators in the waste collection system fail and it is not possible to dump urine overboard, urine may be collected using a contingency urine collection device.

Chapter 5

Guidance and Navigation





Introduction

The navigation system maintains an accurate estimate of vehicle position and velocity, referred to as a state vector. From position, attitude and velocity, other parameters (acceleration, angle of attack) are calculated for use in guidance and for display to the crew. The current state vector is mathematically determined from the previous state vector by integrating the equations of motion using vehicle acceleration as sensed by the IMUs and/or computed from gravity and drag models.

The alignment of the IMU and, hence, the accuracy of the resulting state vector deteriorate as a function of time. Celestial navigation instruments (star trackers and crewman optical alignment sight) are used to maintain IMU alignment in orbit. For entry, the accuracy of the IMU-derived state vector is, however, insufficient for either guidance or the flight crew to bring the spacecraft to a pinpoint landing. Therefore, data from other navigation sensors-air data system, tactical air navigation, microwave scan beam landing system and radar altimeter-is blended into the state vector at different phases of entry to provide the necessary accuracy.

The three IMUs maintain an inertial reference and provide velocity changes until the microwave scan beam landing system is acquired. Navigation-derived air data are needed during entry as inputs to guidance, flight control and flight crew dedicated displays. Such data are provided by tactical air navigation, which supplies range and bearing measurements beginning at 160,000 feet; the air data system provides information at about Mach 3. Tactical air navigation is used until the microwave scan beam landing system is acquired or an altitude of 1,500 feet is reached if MSBLS is not available.

During rendezvous and proximity operations, the onboard navigation system maintains the state vectors of both the orbiter and target vehicle. During close operations (separation of less than 15 miles), these two state vectors must be very accurate in order to maintain an accurate relative state vector. Rendezvous radar measurements (range and range rate) are used for a separation of about 15 miles to 100 feet to provide the necessary relative state vector accuracy. When two vehicles are separated by less than 100 feet, the flight crew relies primarily on visual monitoring (aft and overhead windows and closed-circuit television).

Inertial Measurement Units

The IMUs consist of an all-attitude, four-gimbal, inertially stabilized platform. They provide inertial attitude and velocity data to the GN&C software functions. Navigation software uses the processed IMU velocity and attitude data to propagate the orbiter state vector. Guidance uses the attitude data, along with state vector from the navigation software, to develop steering commands for flight control. Flight control uses the IMU attitude data to convert the steering commands into control surface, engine gimbal (thrust vector control) and reaction control system thruster fire commands.

Although flight could be accomplished with only one, three IMUs are installed on the orbiter for redundancy. The IMUs are mounted on the navigation base, which is located inside the crew compartment flight deck forward of the flight deck control and display panels

Very precise thermal control must be maintained in order to meet IMU performance requirements. The IMU thermal control system consists of an internal heater system and a forced-air cooling system. The internal heater system is completely automatic and is powered on when power is initially applied to the IMU. It continues to operate until the IMU is powered down. The forced-air cooling consists of three fans that serve all three IMUs. Only one fan is necessary to provide adequate air flow. The IMU fan pulls cabin air through the casing of each IMU and cools it in an IMU heat exchanger before returning it to the cabin. Each IMU fan is controlled by an individual on/off switch.

Each IMU is supplied with redundant 28-volt dc power through separate remote power controllers when control bus power is applied to the RPCs by the IMU power switch. Loss of one control bus or one main bus will not cause the loss of an IMU.

Each IMU has two modes of operation: a warm-up/standby mode and an operate mode. When the respective IMU switch is positioned to on that IMU is powered and enters the warm-up/standby mode, which applies power only to the heater circuits. It takes approximately 30 minutes for the IMU to reach its operating range, at which time the IMU enters a standby mode, when it can be moded to the operate mode by flight crew command.

During ascent, the IMUs provide accelerometer and resolver data to the GN&C software to propagate the state vector, determine attitude and display flight parameters. During the orbital flight phase, the IMUs provide GN&C software with attitude and accelerometer data. On-orbit alignments are necessary to correct platform misalignment caused by uncompensated gyro drift.

During entry, IMU operation differs only in the manner in which accelerometer data are used by navigation. The IMU software scheme is designed to select the best data for GPC use and to detect system failures. This scheme is referred to as redundancy management.

In the event of an IMU failure, the IMU red caution and warning light will be illuminated. If temperatures are out of limits or if built-in test equipment detects a failure, a fault message and SM alert will be annunciated.

The accuracy of the IMU deteriorates with time. If the errors are known, they can be physically or mathematically corrected. Software based on preflight calibrations is used to compensate for most of the inaccuracy. The star trackers and crewman optical alignment sight are used to determine additional inaccuracies.

Star Tracker

The star tracker system is part of the orbiter's navigation system. Its two units are located just forward and to the left of the commander's plus X window in a well outside the pressurized crew compartment-an extension of the navigation base on which the IMUs are mounted. The star trackers are slightly inclined off the vehicle's negative Y and negative Z axes, for which they are named. The star trackers are used to align the IMUs on board the orbiter as well as to track targets and provide line-of-sight vectors for rendezvous calculations.

Alignment of the IMUs is required approximately every 12 hours to correct IMU drift, within one to two hours before major on-orbit thrusting duration or after a crewman optical alignment sight IMU alignment. IMU alignment is accomplished by using the star trackers to measure the line-of-sight vector to at least two stars. With this information, the GPC calculates the orientation between these stars and the orbiter to define the orbiter's attitude. A comparison of this attitude with the attitude measured by the IMU provides the correction factor necessary to null the IMU error.

The GPC memory contains inertial information for 50 stars chosen for their brightness and their ability to provide complete sky coverage.

The star trackers are oriented so that the optical axis of the negative Z star tracker is pointed approximately along the negative Z axis of the orbiter and the optical axis of the negative Y star tracker is pointed approximately along the negative Y axis of the orbiter. Since the navigation base provides the mount for the IMUs and star trackers, the star tracker line of sight is referenced to the navigation base and the orbiter coordinate system; thus, the GPC knows where the star tracker is pointed and its orientation with respect to the IMUs.

Each star tracker has a door to protect it during ascent and entry. The doors are opened on orbit to permit use of the star trackers. In addition to aligning the IMUs, the star trackers can be used to provide angular data from the orbiter to a target. This capability can be used during rendezvous or proximity operations with a target satellite.

There is no redundancy management for the star tracker assemblies; they operate independently, and either can do the whole task. They can be operated either separately or concurrently. In addition, the star tracker SOP maintains the star table. When a star tracker has acquired and tracked a star and the data has passed software checks, the star identification, time tag and line-of-sight vector are stored. The identification and time elapsed since time tag are displayed in the star table. When two or three stars are in the table, the angular difference between their line-of-sight vectors is displayed. The difference between the star tracker and star catalog angular differences is displayed as an error. The star tracker SOP selects line-of-sight vectors of two stars in the star table for IMU alignment and outputs an align ena discrete. The software selects the star pair whose angular difference is closest to 90 degrees or the pair whose elapsed time of entry into the table is less than 60 minutes. The flight crew may manually override the SOP selection or clear the table if desired. The SOP also determines and displays star tracker status.

Crewman Optical Alignment Sight

The crewman optical alignment sight is used if inertial measurement unit alignment is in error by more than 1.4 degrees, rendering the star tracker unable to acquire and track stars. The COAS must be used to realign the IMUs to within 1.4 degrees. The star trackers can then be used to realign the IMUs more precisely.

The COAS is mounted at the commander's station so the crew can check for proper attitude orientation during ascent and deorbit thrusting periods. For on-orbit operations, the COAS at the commander's station is removed and installed next to the aft flight deck overhead right minus Z window.

By knowing the star being sighted and the COAS's location and mounting relationship in the orbiter, software can determine a line-of-sight vector from the COAS to the star in an inertial coordinate system. Line-of-sight vectors to two stars define the attitude of the orbiter in inertial space. This attitude can be compared to the attitude defined by the IMUs and can be realigned to the more correct orientation by the COAS sightings if the IMUs are in error.

COAS can also be used to visually track targets during proximity operations or to visually verify tracking of the correct star by the minus Z star tracker. COAS data processing is accomplished in the star tracker SOP. This SOP accepts and stores crew inputs on COAS location, star identification or calibration mode; accepts marks; computes and stores the line-of-sight vectors; enables IMU alignment when two marks have been accepted; and computes, updates and provides display data.

Orbiter Rate Gyro Assemblies

The orbiter rate gyro assemblies are used by the flight control system during ascent, entry and aborts as feedbacks to final rate errors that are used to augment stability and for display on the commander's and pilot's attitude director indicator rate needles on panels F6 and F8. The four orbiter RGAs are referred to as RGAs 1, 2, 3 and 4.

The RGAs sense roll rates (about the X axis), pitch rates (about the Y axis) and yaw rates (about the Z axis). These rates are used by the flight control system to augment stability during both ascent and entry.

Each RGA contains three identical single-degree-of-freedom rate gyros so that each gyro senses rotation about one of the vehicle axes. Thus, each RGA contains one gyro-sensing roll rate (about the X axis), one gyro-sensing pitch rate (about the Y axis) and one gyro-sensing yaw rate (about the Z axis).

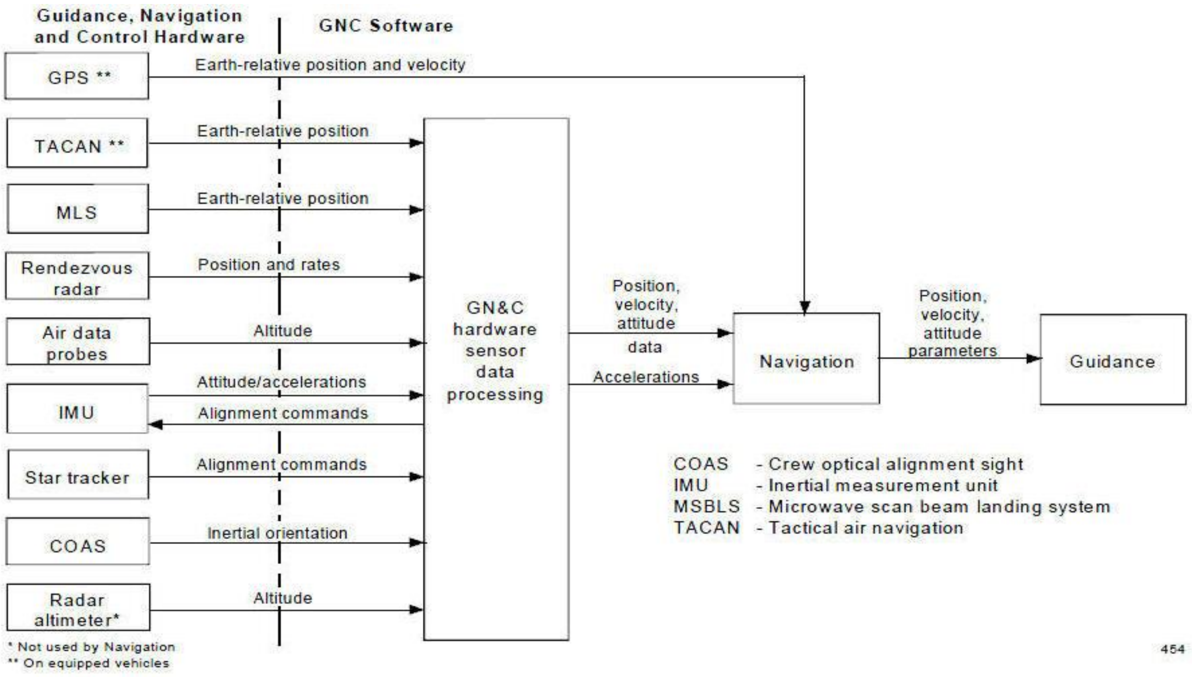
Each gyro has three axes. A motor forces the gyro to rotate about its spin axis. When the vehicle rotates about the gyro input axis, a torque results in a rotation about the output axis. An electrical voltage proportional to the angular deflection about the output axis-representing vehicle rate about the input axis-is generated and transmitted through the flight aft MDMs to the GPCs and RGA SOP. This same voltage is used within the RGA to generate a counteracting torque that prevents excessive gimbal movement about the output axis. The maximum output for roll rate gyros is plus or minus 40 degrees per second; for the pitch and yaw gyros, the maximum output is plus or minus 20 degrees per second.

The RGA SOP converts the voltage rate into units of degrees per second.

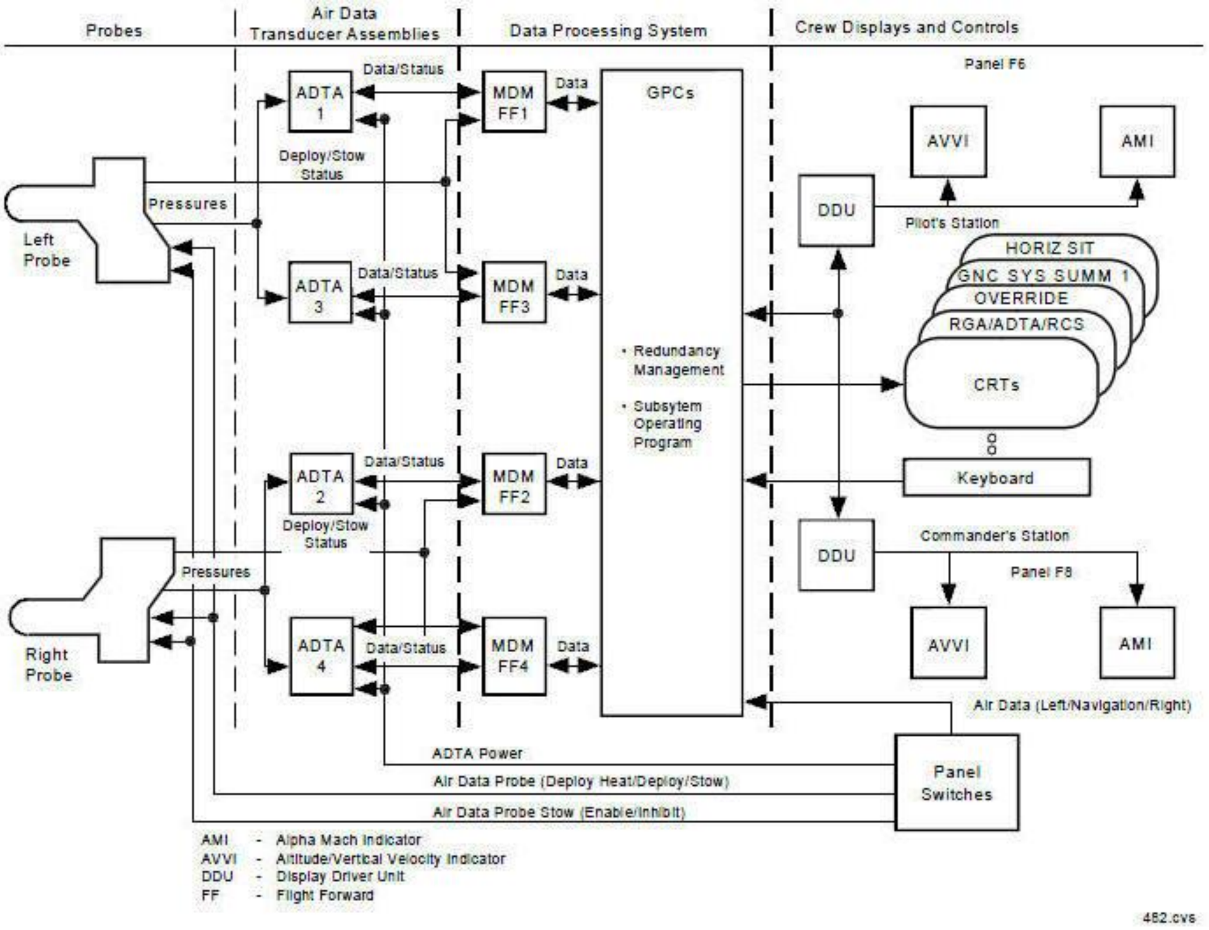
The RGAs remain off on orbit except during flight control system checkout to conserve power. The RGAs afford fail-operational redundancy during both ascent and entry. A quad mid value software scheme selects the best data for use in redundancy management and failure detection.

The RGAs are located on the aft bulkhead below the floor of the payload bay. They are mounted on cold plates for cooling by the Freon-21 coolant loops. The RGAs require a five-minute warm-up time.

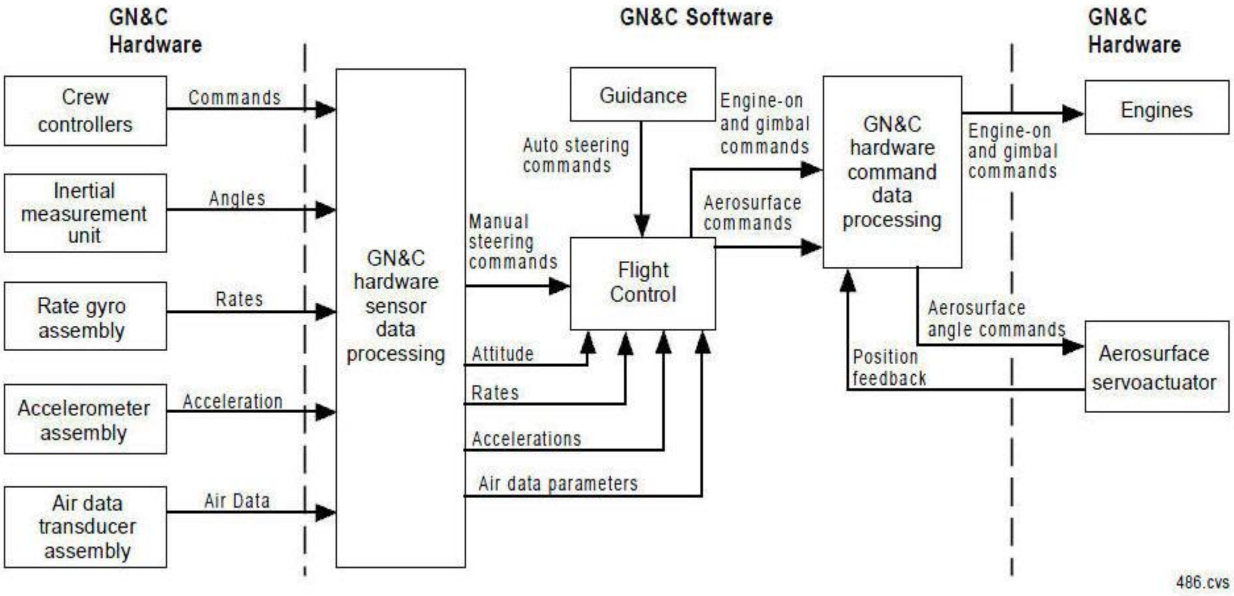
Navigational Control System Schematics



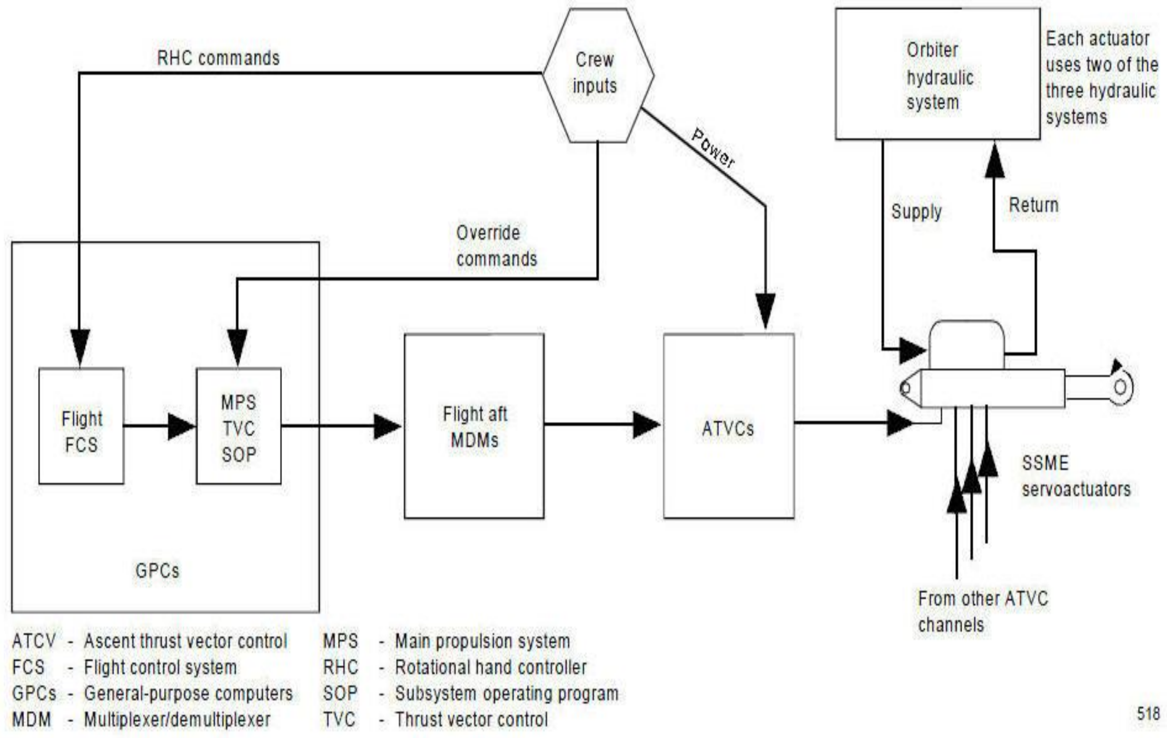
Navigation Interfaces



Air Data System Functional Block Diagram



Flight Control Interfaces



SSME Thrust Vector Control Interface Flow

Orbital Management

Mission control is responsible to monitor the orbital path of the shuttle. The key position that is responsible for this is “FDO" (pronounced 'fido'), the flight dynamics officer. FDO is responsible for the space shuttle's motion - predicting the shuttle's path. While the shuttle's on orbit the FDO is responsible for calculating the shuttle's orbit, maneuvers from the shuttle's maneuvering engines. During the shuttle's entry the FDO is responsible for calculating whether the shuttle should land from north to south or south to north based on the winds and the sun angles, where the shuttle should touchdown on the runway, and coordinating with emergency landing facilities among other tasks.

To successfully manage these responsibilities it is extremely important to understand the math behind orbital determination. To determine orbit parameters of an object (e.g. spacecraft) one needs to understand some basic math and definitions of an elliptical orbit. Let’s assume for reference that our spacecraft is orbiting the Moon. The distance between the perilune and apolune is called the major axis and half of this distance is known as the semi-major axis.

If we define the semi-major axis to be equal to a then the major axis equals $2a$. Each point of the orbit has a distance r to the center of the attracting body (e.g. Moon). The distance where the spacecraft is closest to the center of the attracting body will be referred to as r_p (i.e. in perilune) and the furthest distance (i.e. in apolune) r_a and so:

$r_a + r_p = 2a$.

The measure of how elliptical an orbit is expressed with eccentricity e. If e = 0 we have a perfect circular orbit. For e < 1 we have an eliptical orbit and when e = 1 we have reached escape velocity and e > 1 means we are no longer in orbit; the spacecraft will never return. The eccentricity has the following relation with r_a and r_p

$r_a = a(1 - e)$

$r_p = a(1 + e)$

Now we have enough to calculate the velocity v at perilune and apolune if we desire an orbit that has a closest approach of 100km above the surface of the Moon and a farthest point of 500km above the surface. Since the Moon has an average radius of 1738 km (i.e. 1738000 m) we can now determine r_a and r_p. and a

$r_a = 2238000$ m

$r_p = 1838000$ m

$a = (r_a + r_p) / 2 = (2238000 \text{ m} + 1838000 \text{ m}) / 2 = 2038000 \text{ m}$

Now we can determine if this orbit is actually stable with regards to these parameters

$e = r_a / a - 1$

$e = -r_p / a + 1$

$e = 0.098135$

Since the eccentricity is less than 1 the orbit is stable and achievable.

To calculate the velocity in at either apolune or perilune we need the gravitational parameter u for the body we are orbiting (i.e. $4.9 \cdot 10^{12}$ m^3/s^2) and the following formula:

$v =$ **SQRT**$(u (2 / r_x - 1 / a))$

where:

- r_x is is the distance to the center of the orbiting body.
- SQRT is the Square root

So the velocity at perilune (i.e. 100km above the lunar surface) is:

$v =$ **SQRT**$(4.9 \cdot 10^{12} \text{ m}^3/\text{s}^2 (2 / 1838000 \text{ m} - 1 / 2038000 \text{ m})) = 1711.013 \text{ m/s}$

Changing Orbit Altitude

To change orbits (i.e. its altitude) is quite easy as long as you know when to start a burn and how much change in velocity is required to end up in the new orbit. When you know your current orbit and the new desired orbit then all you have to do is wait until both orbits intersect. Typically maneuvers are executed in either periapsis or apoapsis. Especially if you want to circularize your orbit.

Lets assume for the following example that we are in lunar orbit once again but this time in a circular orbit at 100 km above the surface and we want to lower our orbit to a circular 50 km orbit. This will require 2 burns to accomplish. The first burn will change the orbit from a cirular to an eliptical orbit with its perilune at 50 km and its apolune at 100 km. The second burn would lower the apolune so that both apolune and perilune are 50 km. The previous section has shown how to calculate the velocity of the spacecraft in both apolune and perilune. We use the same methods in this section to determine the velocities of both perilune and apolune for all three orbits and from there we can derive the change in velocity commonly known as *Delta-V*.

Since the first orbit is circular we know that $e = 0$ and that that the velocity in both the perilune and apolune are equal:

$a = r_a = r_p = 100 \text{ km} + 1738 \text{ km} = 1838 \text{ km}$

$v = \textbf{SQRT} (4.9*10^{12} \text{ m}^3/\text{s}^2 (2 / 1838000 \text{ m} - 1 / 1838000)) = 1632.771 \text{ m/s}$

This velocity is also the apolune of our intermediate orbit (i.e. 100 km by 50 km). Since it is the apolune of our new orbit it means that we have to reduce our velocity to a value that will have the apolune of 100 km and a perilune of 50 km. Since we are lowering our orbit we must fire against are path of travel (retrograde). To determine the change in velocity we just calculate the velocity for the apolune of this new orbit.

$r_a = 1838000 \text{ m}$

$r_p = 1788000 \text{ m}$

$a = (r_a + r_p) / 2 = 1813000 \text{ m}$

$v_a = \textbf{SQRT} (4.9*10^{12} \text{ m}^3/\text{s}^2 (2 / 1838000 \text{ m} - 1 / 1813000) = 1621.475 \text{ m/s}$

$v_p = \textbf{SQRT} (4.9*10^{12} \text{ m}^3/\text{s}^2 (2 / 1788000 \text{ m} - 1 / 1813000) = 1666.818 \text{ m/s}$

Now that we have the new velocities we determine *Delta-V*$_a$:

Delta-V$_a$ = 1621.475 m/s - 1632.771 m/s = -11.296 m/s

To accomplish this change in velocity we must ignite the engine at the right moment at burn for a certain amount of time (see next section) based on the performance of the rocket engine. Since we wanted to get into a lower circular orbit (50km above the surface) it is necessary to once again execute a burn but now at the new perilune. This burn must be again retrograde since we are lowering the orbit. Again we use the same method to determine the velocities for the new orbit:

$a = r_a = r_p$ = 1788000 m (The orbit is circular)

v = **SQRT** ($4.9*10^{12}$ m^3/s^2 (2 / 1788000 m - 1 / 1788000) = 1655.443 m/s

$Delta\text{-}V_p$ = 1655.443 m/s - 1666.818 m/s = -11.375 m/s

The Delta-V can be used to determine for how long we must fire the rocket engine and how much propellant will be consumed (see respective section below)

Changing Orbit Plane

Changing the plane of the orbit is also not difficult as long as we stick with some basic assumptions that must hold for the math in this section: The orbit must be circular (so if it is not first circularize your orbit) and we only change the plane of the orbit and not its altitude at the same time. This is known as a pure plane change maneuver. This maneuver is executed when you want to change the declanation of your orbit or when you want to align the orbit of the spacecraft with a target body to reach (e.g. change to the same plane as the Moon before executing the Translunar Injection (TLI)). The burn is typically executed over the equator of the orbiting body but isn't mandatory. However the burn must be executed in the node where both the old and new orbit intersect. Since the orbits are circular there are two points in the current orbit where this can occur. The attitude of the spacecraft must be such that the thrust vector is perpendicular to the direction of travel. The *Delta-V* required for this burn:

$Delta\text{-}V = 2 \cdot v_{cir} \cdot \sin(½ \cdot i_{change})$

where:

- v_{cir} is the orbital velocity (both orbits are circular and both have the same speed)
- i_{change} is the change in inclination between the old and new orbit.

So if we are in the 50 km orbit around the moon with an orbital velocity of 1655.443 m/s we would need the following Delta-V perpendicular to our direction of travel to reach a 4° change in inclination:

$Delta\text{-}V = 2 \cdot 1655.443\ m/s \cdot \sin(2°) = 115.548\ m/s$

From the formula you can also find that any plane equal or larger than 60° (i.e. sin(30°) = 0.5) requires as much Delta-V as the current orbital velocity and you may have just as well re-launched with a new rocket in the desired plane. The *Delta-V* determined here can now be used to calculate fuel consumption and burn time.

Propellant and Burn time

A rocket engine can be characterized by two major parameters: thrust and specific impulse. You might think that if you give the spacecraft a bigger engine (more thrust) that it is then easier to make the change in velocity. That is true, it will take less time. But the real interest of the engineers is the amount of propellant you use for a certain change in velocity and that is what the specific impulse tells you. Specific impulse of a rocket engine conveys its performance just like miles per gallon does for a combustion engine in a vehicle. The higher the specific impulse the more effective the thrust is. The LM has a descent engine with a specific impulse of about 311 seconds and a thrust of 45.04 kN. With the engine performance and the Delta-V values we can determine the burn time and amount of propellant that is needed using Konstantin Tsiolkovsky's formula.

Tsiolkovsky's formula indicates how much propellant is needed to perform the Delta-V burn with a given engine for a given spacecraft mass:

$Delta\text{-}V = I_{sp}\, g\, \mathbf{ln}(M_{initial} / M_{end})$

In this formula g = $9.81\ \text{m/s}^2$ is the acceleration at Earth and I_{sp} the specific impulse of the rocket engine. Since we know Delta-V (use the absolute value) we can determine M_{end}.

$M_{end} = M_{initial} / \mathbf{e}^{\text{Delta-V / (Isp} \cdot \text{g)}}$

where:

- **e** = the natural number i.e. 2.71828 and not eccentricity.

Lets assume we have a Lunar Module in landing configuration, which means a mass of 15004 kg and we use the DPS (Descent Propulsion System) engine to change our orbits.

$M_{end} = 15004\ \text{kg} / e^{11.296\ \text{m/s} / (311\ \text{s} \cdot 9.81\ \text{m/s}^2)} = 14948.55\ \text{kg}$

So the change in mass is 15004 kg - 14948.55 kg = 55.45 kg for our first burn. To calculate fuel consumption per second we need to know the thrust and specific impulse I_{sp}:

fuel consumption per second = thrust / ($I_{sp} \cdot$ g)

fuel consumption per second = 45040 / (311 · 9.81) = 14.763 kg/s

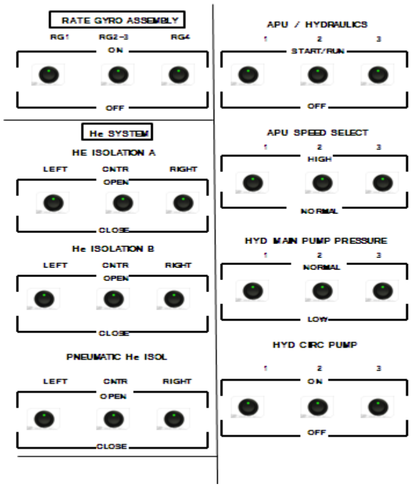
Now we can just take the amount of fuel consumed for the Delta-V and divide that by the rate of consumption and we find that this burn would take 3.76 seconds:

burn time = 55.45 kg / 14.763 kg/s = 3.76 s

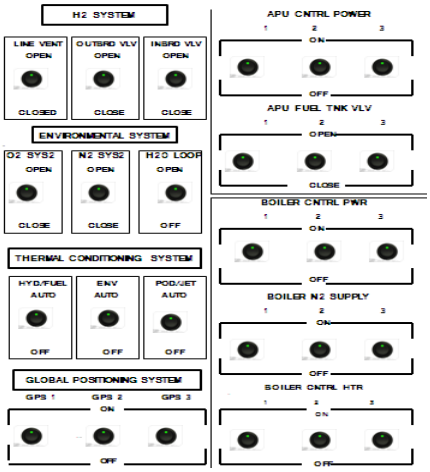
Now for the next burn you must take the new mass of the Lunar Module 14948.55 Kg and the Delta-V for the next burn and follow the same steps as the first burn to determine the second burn time for the DPS engine. With the above knowledge you should be able to not only change orbits around a body but also have the tool set for some very simplistic Homann transfers to leave one orbiting body for another (e.g. leave the Earth to go to the moon).

COCKPIT CONTROL SWITCHES

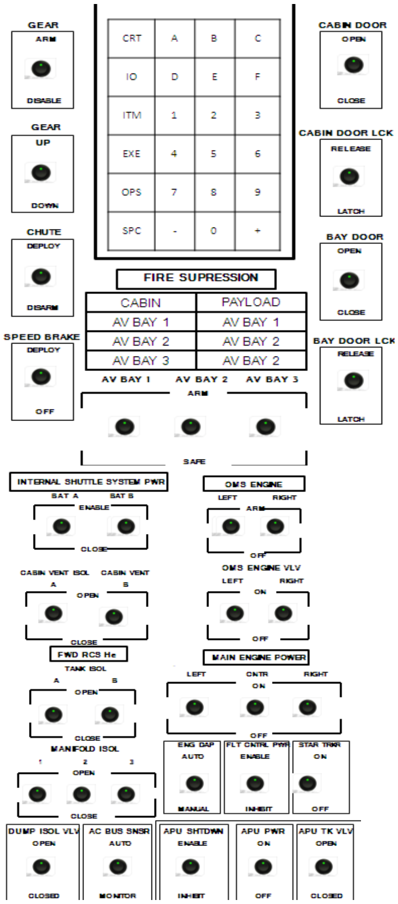
Pilot Seat Left



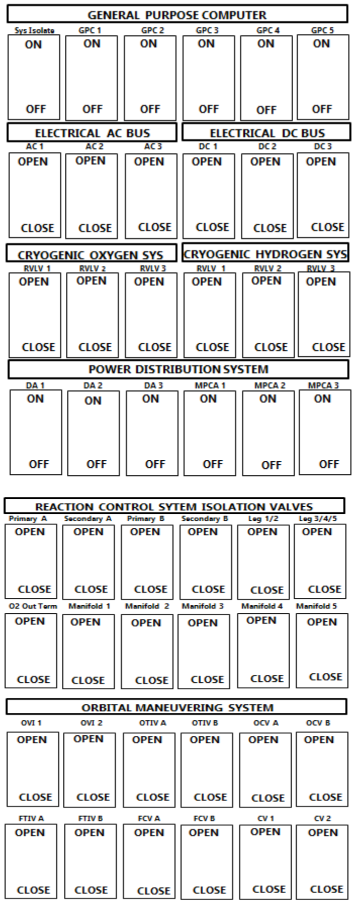
Co-Pilot seat Right

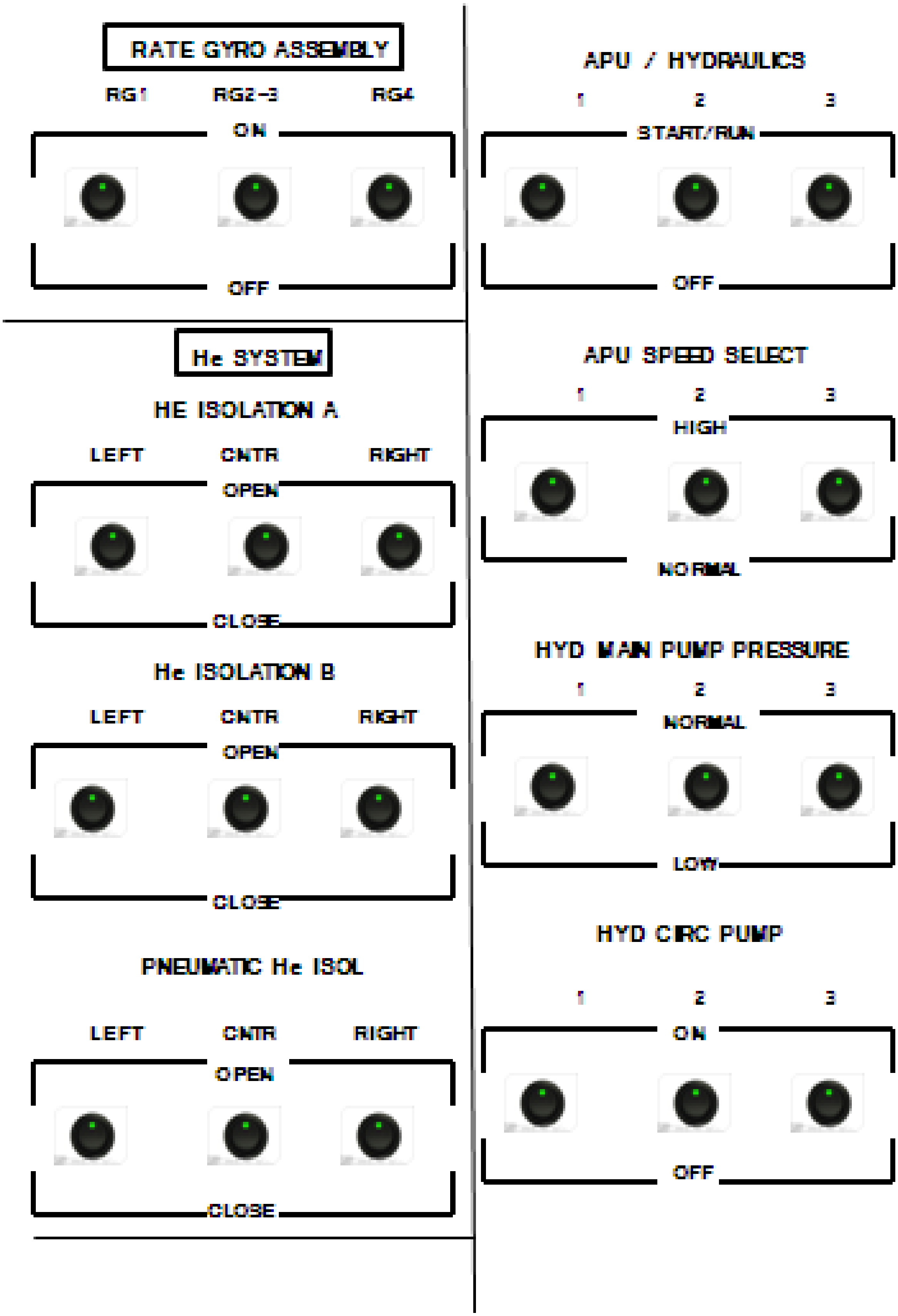


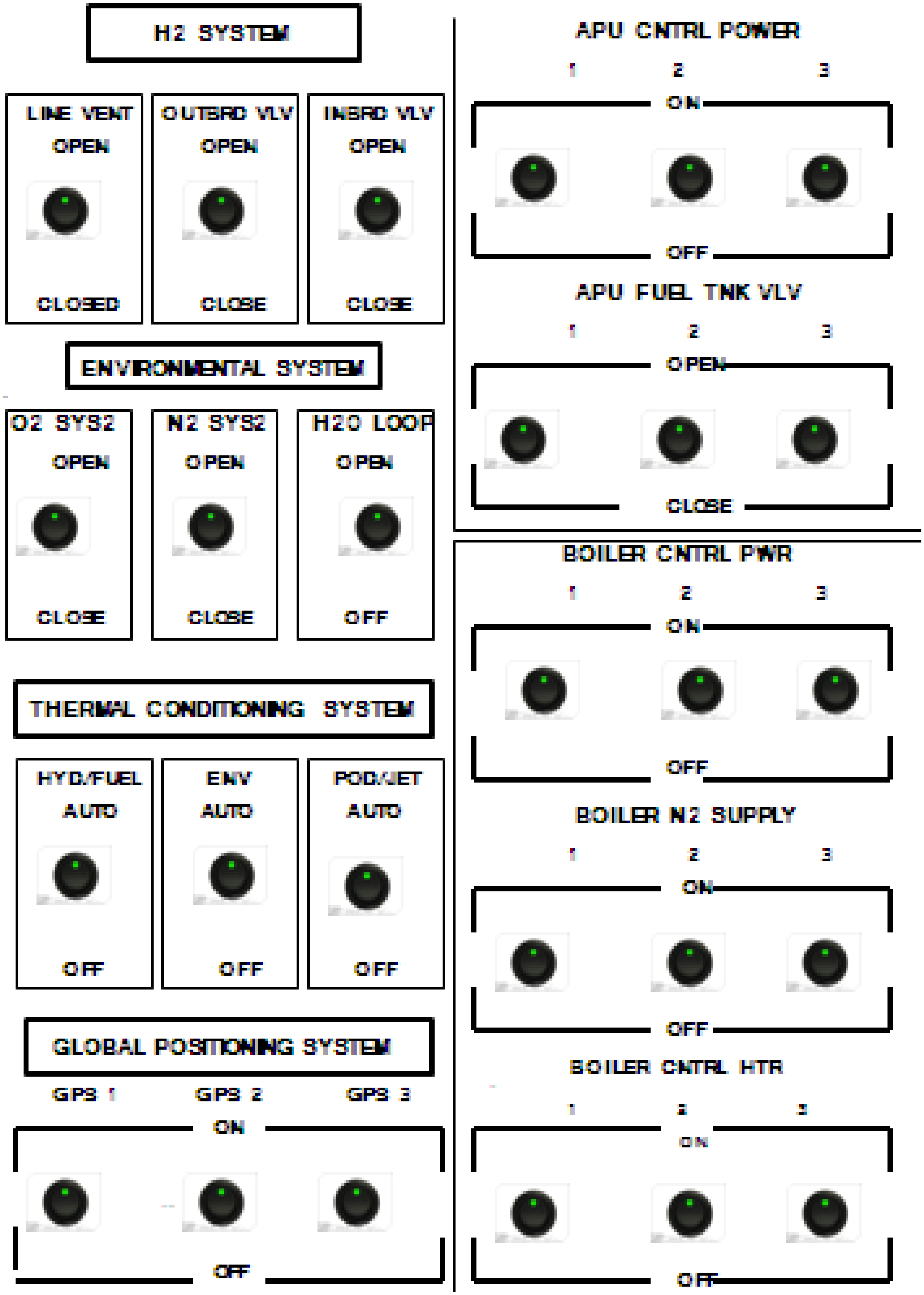
Center Console

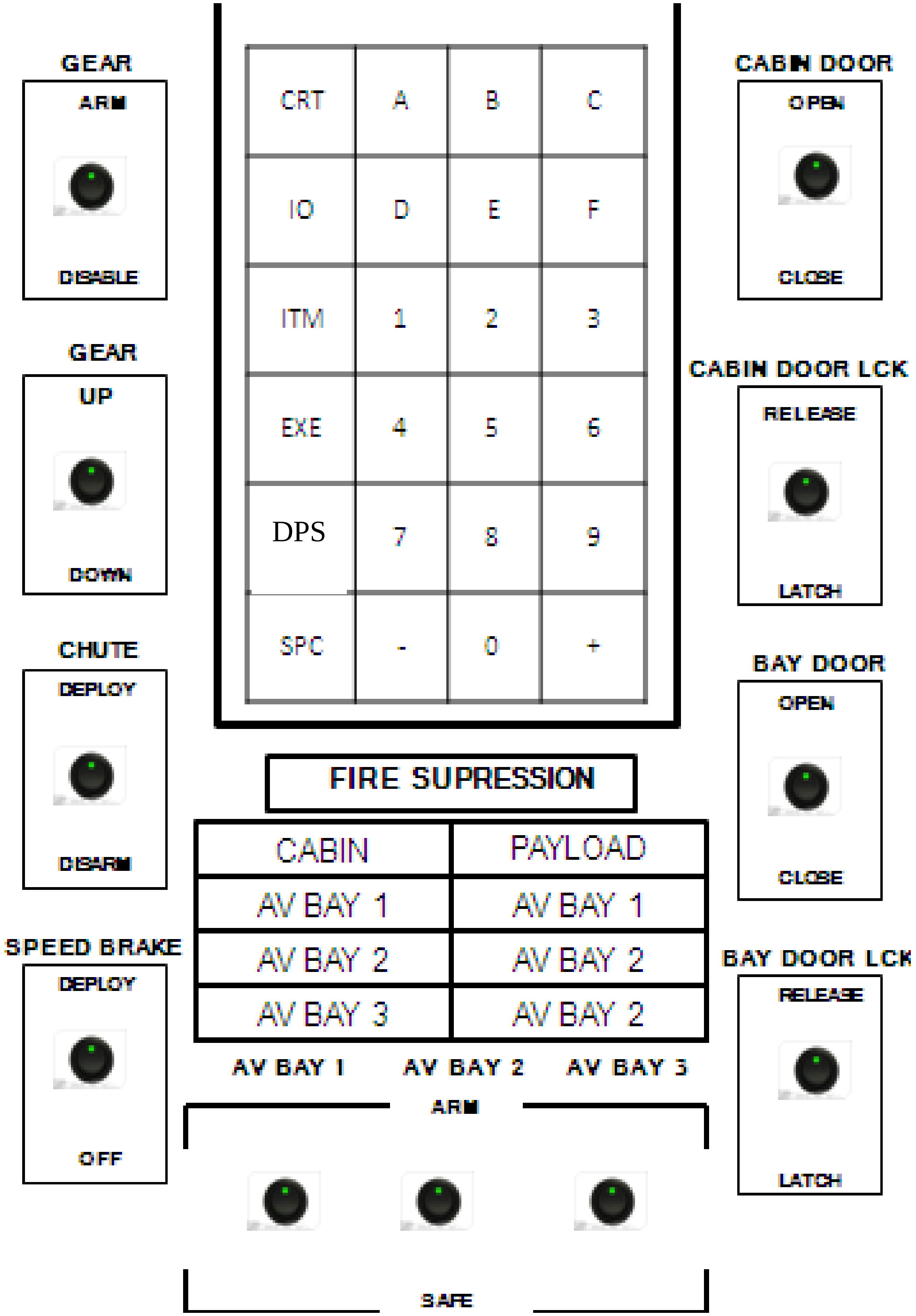


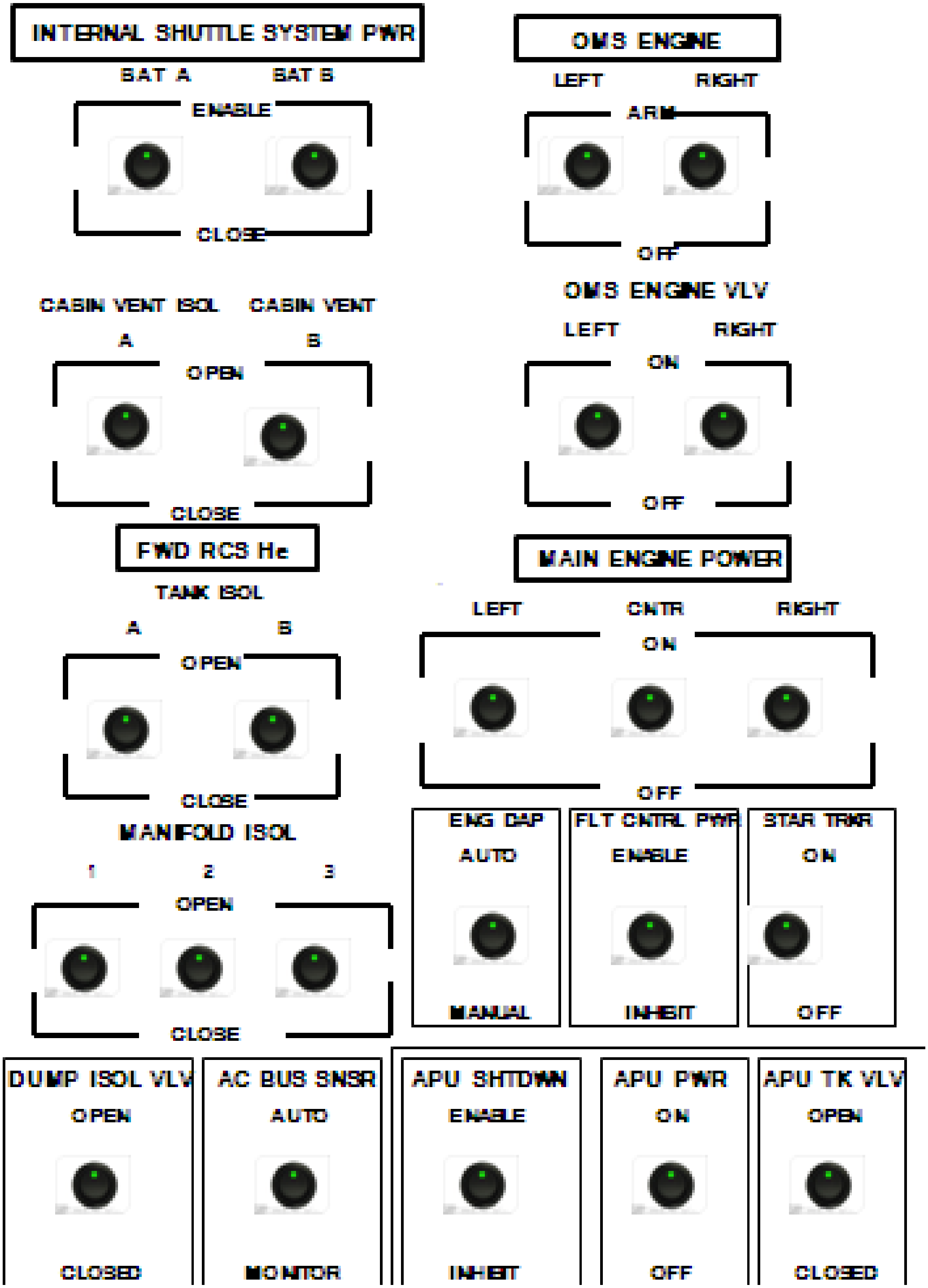
Flight Engineers Console

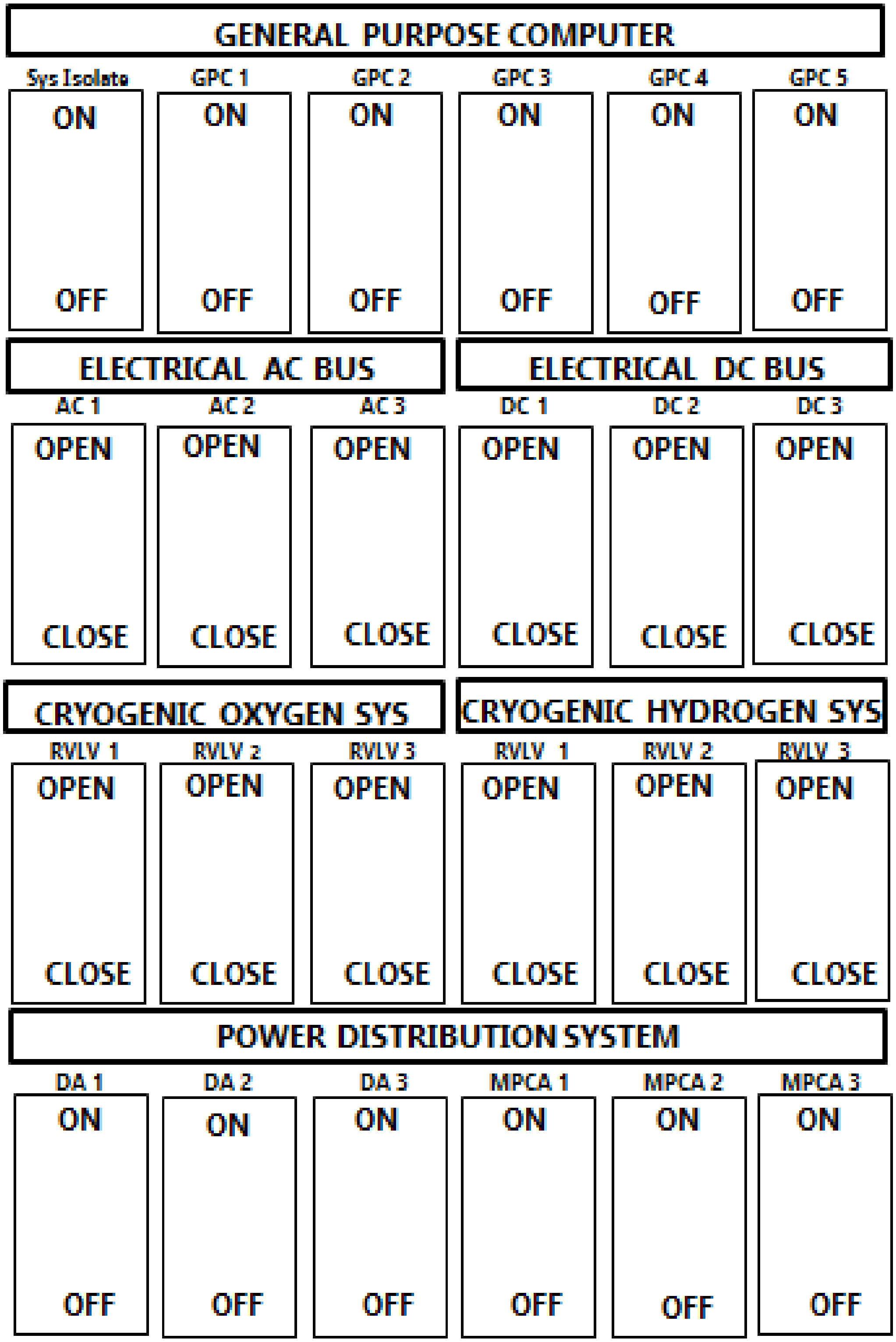


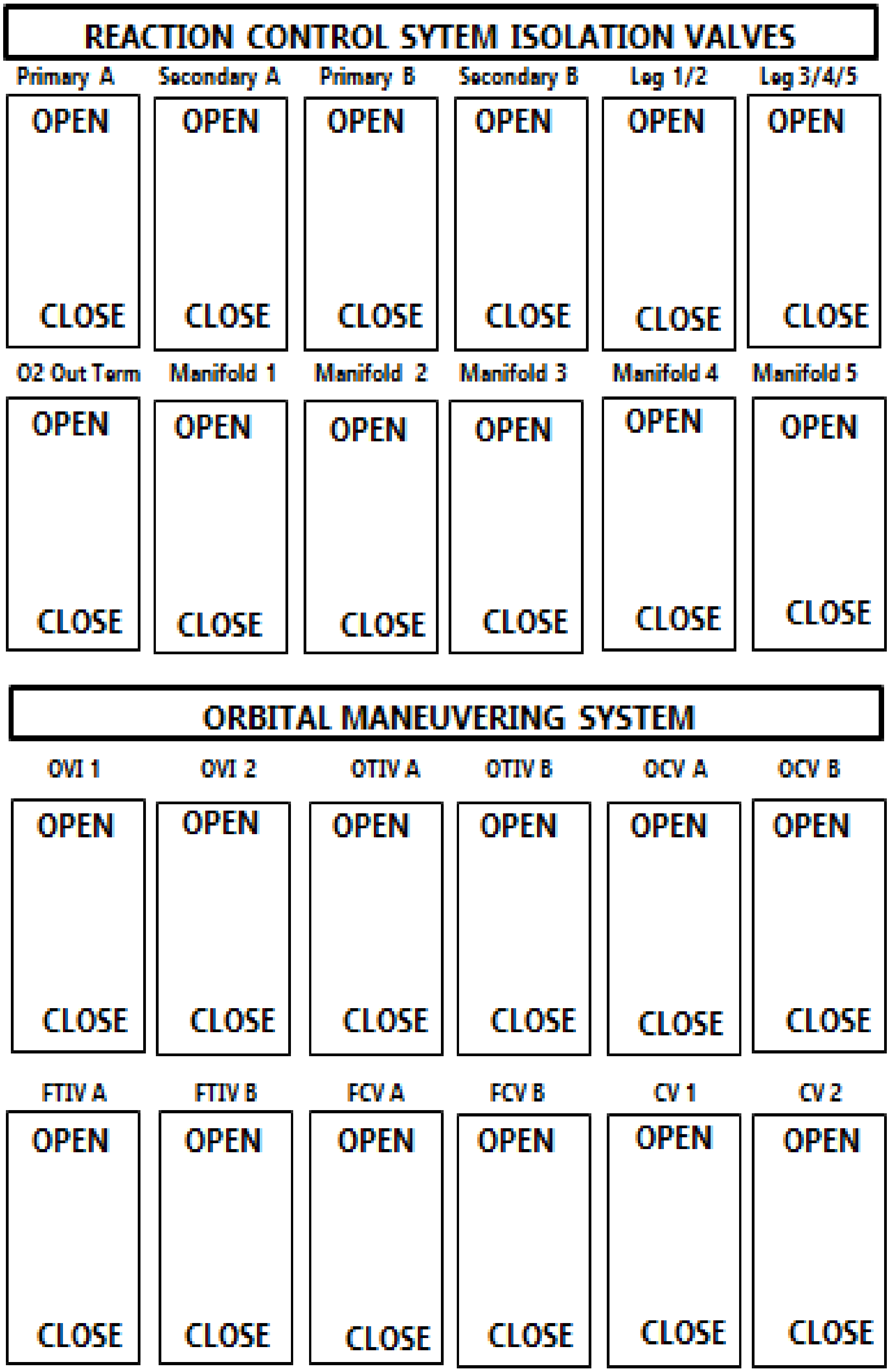

RATE GYRO ASSEMBLY
RG1
RG2-3
RG4
ON
OFF
He SYSTEM
HE ISOLATION A
LEFT
CNTR
RIGHT
OPEN
CLOSE
He ISOLATION B
LEFT
CNTR
RIGHT
OPEN
CLOSE
PNEUMATIC He ISOL
LEFT
CNTR
RIGHT
OPEN
CLOSE
APU / HYDRAULICS
1
2
3
START/RUN
OFF
APU SPEED SELECT
1
2
3
HIGH
NORMAL
HYD MAIN PUMP PRESSURE
1
2
3
NORMAL
LOW
HYD CIRC PUMP
1
2
3
ON
OFF


H2 SYSTEM
LINE VENT
OPEN
CLOSED
OUTBRD VLV
OPEN
CLOSE
INBRD VLV
OPEN
CLOSE
ENVIRONMENTAL SYSTEM
O2 SYS2
OPEN
CLOSE
N2 SYS2
OPEN
CLOSE
H2O LOOP
OPEN
OFF
THERMAL CONDITIONING SYSTEM
HYD/FUEL
AUTO
OFF
ENV
AUTO
OFF
POD/JET
AUTO
OFF
GLOBAL POSITIONING SYSTEM
GPS 1
GPS 2
GPS 3
ON
OFF
APU CNTRL POWER
1
2
3
ON
OFF
APU FUEL TNK VLV
1
2
3
OPEN
CLOSE
BOILER CNTRL PWR
1
2
3
ON
OFF
BOILER N2 SUPPLY
1
2
3
ON
OFF
BOILER CNTRL HTR
1
2
3
ON
OFF


GEAR
ARM
DISABLE
GEAR
UP
DOWN
CHUTE
DEPLOY
DISARM
SPEED BRAKE
DEPLOY
OFF
CRT
A
B
C
IO
D
E
F
ITM
1
2
3
EXE
4
5
6
DPS
7
8
9
SPC
-
0
+
CABIN DOOR
OPEN
CLOSE
CABIN DOOR LCK
RELEASE
LATCH
BAY DOOR
OPEN
CLOSE
BAY DOOR LCK
RELEASE
LATCH
FIRE SUPRESSION
CABIN
PAYLOAD
AV BAY 1
AV BAY 1
AV BAY 2
AV BAY 2
AV BAY 3
AV BAY 2
AV BAY 1
AV BAY 2
AV BAY 3
ARM
SAFE


INTERNAL SHUTTLE SYSTEM PWR
BAT A
BAT B
ENABLE
CLOSE
OMS ENGINE
LEFT
RIGHT
ARM
OFF
CABIN VENT ISOL
CABIN VENT
A
B
OPEN
CLOSE
OMS ENGINE VLV
LEFT
RIGHT
ON
OFF
FWD RCS He
TANK ISOL
A
B
OPEN
CLOSE
MAIN ENGINE POWER
LEFT
CNTR
RIGHT
ON
OFF
MANIFOLD ISOL
1
2
3
OPEN
CLOSE
ENG DAP
AUTO
MANUAL
FLT CNTRL PWR
ENABLE
INHIBIT
STAR TRKR
ON
OFF
DUMP ISOL VLV
OPEN
CLOSED
AC BUS SNSR
AUTO
MONITOR
APU SHTDWN
ENABLE
INHIBIT
APU PWR
ON
OFF
APU TK VLV
OPEN
CLOSED


GENERAL PURPOSE COMPUTER
Sys Isolate
GPC 1
GPC 2
GPC 3
GPC 4
GPC 5
ON
OFF
ELECTRICAL AC BUS
ELECTRICAL DC BUS
AC 1
AC 2
AC 3
DC 1
DC 2
DC 3
OPEN
CLOSE
CRYOGENIC OXYGEN SYS
CRYOGENIC HYDROGEN SYS
RVLV 1
RVLV 2
RVLV 3
RVLV 1
RVLV 2
RVLV 3
OPEN
CLOSE
POWER DISTRIBUTION SYSTEM
DA 1
DA 2
DA 3
MPCA 1
MPCA 2
MPCA 3
ON
OFF


REACTION CONTROL SYTEM ISOLATION VALVES
Primary A
Secondary A
Primary B
Secondary B
Leg 1/2
Leg 3/4/5
OPEN
CLOSE
O2 Out Term
Manifold 1
Manifold 2
Manifold 3
Manifold 4
Manifold 5
OPEN
CLOSE
ORBITAL MANEUVERING SYSTEM
OVI 1
OVI 2
OTIV A
OTIV B
OCV A
OCV B
OPEN
CLOSE
FTIV A
FTIV B
FCV A
FCV B
CV 1
CV 2
OPEN
CLOSE

Glossary of Essential Terms

AC Bus Sensor - A three-bus system that distributes electrical power to the forward, mid, and aft sections of the orbiter for equipment used in those areas.

Apoapsis - the farthest point in an orbit from the body being orbited.

APU - The Space Shuttle APUs provides hydraulic pressure. The Space Shuttle has three redundant APUs, powered by hydrazine fuel. They function during powered ascent, re-entry, and landing. During ascent, the APUs provides hydraulic power for gimballing of Shuttle's engines and control surfaces. During landing, they power the control surfaces and brakes.

Boiler System – this water system cools the Auxiliary Power Unit (APU) lubrication oil and hydraulic fluid. Three independent Water Spray Boilers each serve a corresponding APU. The Water Spray Boiler System sprays water onto the APU lubrication oil and hydraulic fluid lines, thus cooling the fluids within them.

COMM – communication system

CRT - Display System that allows onboard monitoring of orbiter systems, computer software processing and manual control for flight crew data and software manipulation.

DAP – The Digital Auto Pilot controls the RCS thrusters while in orbit.

GPC – General Purpose Computer Control. When the toggle switch is in the straight up or middle position (not on or off) it allows the valve to be controlled by the flight software loaded in the general purpose computer.

Helium System - During prelaunch, the pneumatic helium supply provides pressure to operate the liquid oxygen and hydrogen pre-valves and outboard and inboard fill and drain valves. The three engine helium supply systems are used to provide anti-icing purges.

Hydraulic System - this system distributes the hydraulic pressure produced by the Auxiliary Power Unit (APU) System. The Hydraulic System is made up of three independent hydraulic systems, each of which is mated to a corresponding APU.

H_2 Main propulsion System - Within the orbiter aft fuselage, liquid hydrogen and liquid oxygen pass through the manifolds, distribution lines and valves of the propellant management subsystem. During prelaunch activities, this subsystem is used to control the loading of liquid oxygen and liquid hydrogen in the external tank. During SSME thrusting periods, propellants from the external tank flow into this subsystem and to the three SSMEs. The subsystem also provides a path that allows gases tapped from the three SSMEs to flow back to the external tank through two gas umbilical’s to maintain pressure in the external tank's liquid oxygen and liquid hydrogen tanks. After MECO, this subsystem controls MPS dumps, vacuum inerting and MPS re-pressurization for entry.

IMU – The Inertial Measurement Units consist of an all-attitude, four-gimbal, inertially stabilized platform. They provide inertial attitude and velocity data to the Navigation software. Guidance uses the attitude data, along with state vector from the navigation software, to develop steering commands for flight control.

Isolation valves - The propellant tank isolation valves are located between the propellant tanks and the manifold isolation valves and are used to isolate the propellant tanks from the remainder of the propellant distribution system

MECO - Main Engine Cut Off point is where the engines shutdown at about 8 minutes and 30 seconds into the flight.

MFD - Multi-function display is a small screen in an aircraft that can be used to display information to the pilot in numerous configurable ways.

OMS - The Space Shuttle Orbital Maneuvering System, is a system of rocket engines for use on the space shuttle orbiter for orbital injection and modifying its orbit

Periapsis - The point in the orbit closest to the body being orbited.

Prograde - Orbital motion in the usual direction of celestial bodies within a given system, i.e. in the direction of the planets rotation.

RCS – The reaction control system is a subsystem of a spacecraft whose purpose is attitude control and steering by the use of thrusters. An RCS system is capable of providing small amounts of thrust in any desired direction or combination of directions The RCS engines use a Hypergolic Fuel which lights up when its two components (Fuel and Oxidizer) come into contact. This allows the system to be almost fail-safe due to the simple nature of the system.

Retrograde - Motion in an orbit opposite to the usual orbital direction of celestial bodies within a given system, i.e. in the opposite direction of the planets rotation

RGA - The orbiter rate gyro assemblies are used by the flight control system during ascent, entry and aborts as feedbacks to final rate errors that are used to augment stability and for display on the commander's and pilot's attitude director indicator.

SSME - Space Shuttle Main Engines are reusable liquid-fuel rocket engines, each Space Shuttle ascent to orbit is propelled by three engines

Star tracker - The star tracker system is part of the orbiter's navigation system which works to help maintain the IMU during flight.

TCS - Thermal Conditioning system consists of an air revitalization system, water coolant loop systems, atmosphere revitalization pressure control system, active thermal control system, supply water and waste water system, waste collection system and airlock support system. These systems interact to provide a habitable environment for the flight crew in the crew compartment in addition to cooling or heating various orbiter systems or components.

References

"How Space Shuttles Works" by Craig Freudenrich, Ph.D.
http://science.howstuffworks.com/space-shuttle1.htm

"NSTS 1988 Reference Manual" National Aeronautics and Space Administration
http://science.ksc.nasa.gov/shuttle/technology/sts-newsref/stsref-toc.html

"Orbiter" by Martin Schweiger, Ph.D.
http://orbit.medphys.ucl.ac.uk

"Space Shuttle Operating Systems" by National Aeronautics and Space Administration"
http://science.ksc.nasa.gov/shuttle

"Space Technology and Engineering project" by Peter Carafano, RN, M.Ed.
http://stem21id.wikispaces.com/file/.../Project+Abstract+and+Summary2.do

"The Basics of Flight" by Jet Propulsion Laboratory, California Institute of Technology
http://www2.jpl.nasa.gov/basics/index.php