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The 747 Fuel System

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National Air Transportation Meeting
New York, N.Y.
April 20-23, 1970

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THE PURPOSE OF THIS PAPER is to present a description of the fuel system installed in the Boeing Model 747 airplane. The complete system will be described in general. Following this, a detailed description of the pressure fueling system, including operating characteristics, will be given. Possible problems related to refueling large airplanes at high rates will be discussed.

DESCRIPTION

FUEL TANKS (See Fig. 1) - The Model 747-100 airplane has a total usable fuel capacity of 47,210 United States gal. Fuel is carried in seven tanks located between the front spar and the rear spar of the wings. Each tank is of integral construction and has several bays formed by the wind structure, that is, wing ribs and/or mid spars.

FUEL TANK VENTS (See Fig. 2) - Each fuel tank is vented individually to the surge tanks, one on each side of the airplane. Each surge tank, in turn, is vented to the atmosphere through a flush, round vent outlet on the under side of the wing near the wing tip. The outlet location provides the appropriate tank pressure during all flight maneuvers. Each wing tank is vented through a dive port, located at the outboard end of the tank, and a climb port, located at the inboard end of the tank, and two climb ports, located in the forward end of the tank. All dive ports are equipped with float valves to prevent fuel vent spillage during rotation and climb with full tanks. All climb ports are open ended. The No. 1 and No. 4 (outboard) main tanks have additional float valve-equipped vent ports, centrally located in each tank.

ENGINE FUEL FEED SYSTEM (See Fig. 3) - The main tank-to-engine fuel feed system supplies fuel directly from each main tank to its correspondingly numbered engine. This system consists of two electrically powered, centrifugal boost pumps, a boost pump bypass, and a butterfly type fuel shutoff valve for each main tank. These components are operated from the flight engineer's control panel shown in Fig. 4. Integral with the inlet port of each boost pump is a check valve to allow pump removal without draining the tank. The discharge lines from each of the two boost pumps are connected in parallel. If one pump becomes inoperative, the remaining pump will supply fuel at the required flow rate and pressure for all engine operating conditions. A boost pump low pressure warning light on the flight engineer's panel illuminates when there is low boost pump discharge pressure. The boost pump bypass is also connected in parallel with the boost pump discharge lines. For the emergency condition of both boost pumps inoperative, the boost pump bypass allows the engine driven fuel pump to withdraw fuel from the tank at a rate and pressure sufficient to develop takeoff thrust. The bypass is equipped with a check valve to prevent reverse flow through it during normal boost operation. The engine fuel shutoff valve is installed in the common line from the boost pumps and the boost pump bypass.

The crossfeed system interconnects the four main tank-to-engine fuel feed systems and allows fuel to be supplied from any main tank to any one or more engines. In addition to the necessary tubing, this system consists of four butterfly type fuel crossfeed valves. The two override/jettison pumps in the center wing tank discharge into the crossfeed manifold, thereby making it possible to supply fuel from this tank to any one or more engines. Discharge pressure from these pumps is sufficiently high to override the main tank boost pumps for all engine operating fuel flow conditions. The boost pumps in the

ABSTRACT

The fuel system installed in the Boeing Model 747 airplane is described in general, and the pressure fueling system treated in detail.

The general treatment includes description of fuel tanks, engine fuel feed system, fuel jettison system, defueling system, fuel quantity indicating system, and fueling system. The component parts of the pressure fueling system are described, and performance of the system is evaluated.

In the design of the 747 airplane, surge pressures and static electrification, possible problem areas associated with refueling large airplanes, have been minimized. The fuel system of the 747 meets applicable Federal Aviation Regulations and customer requirements.

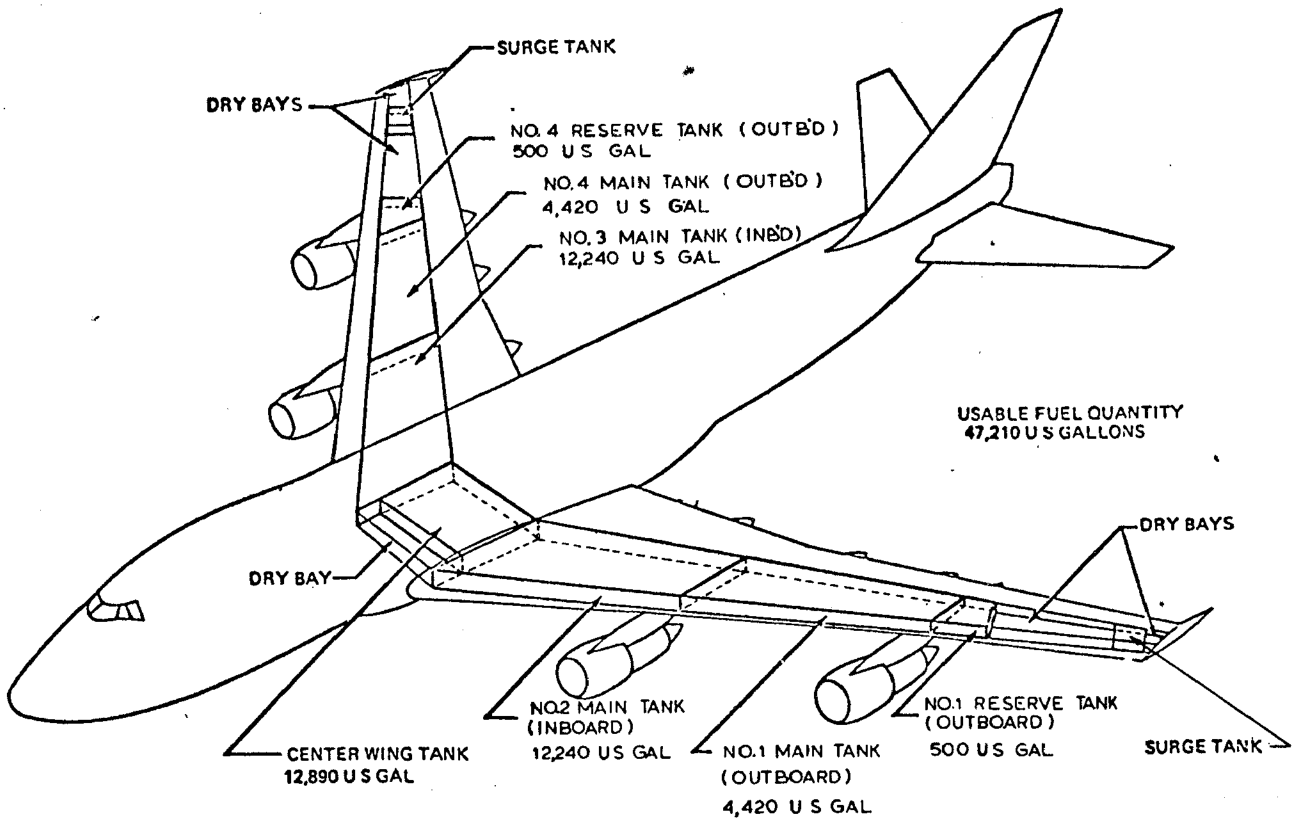

Fig. 1 - Fuel tanks

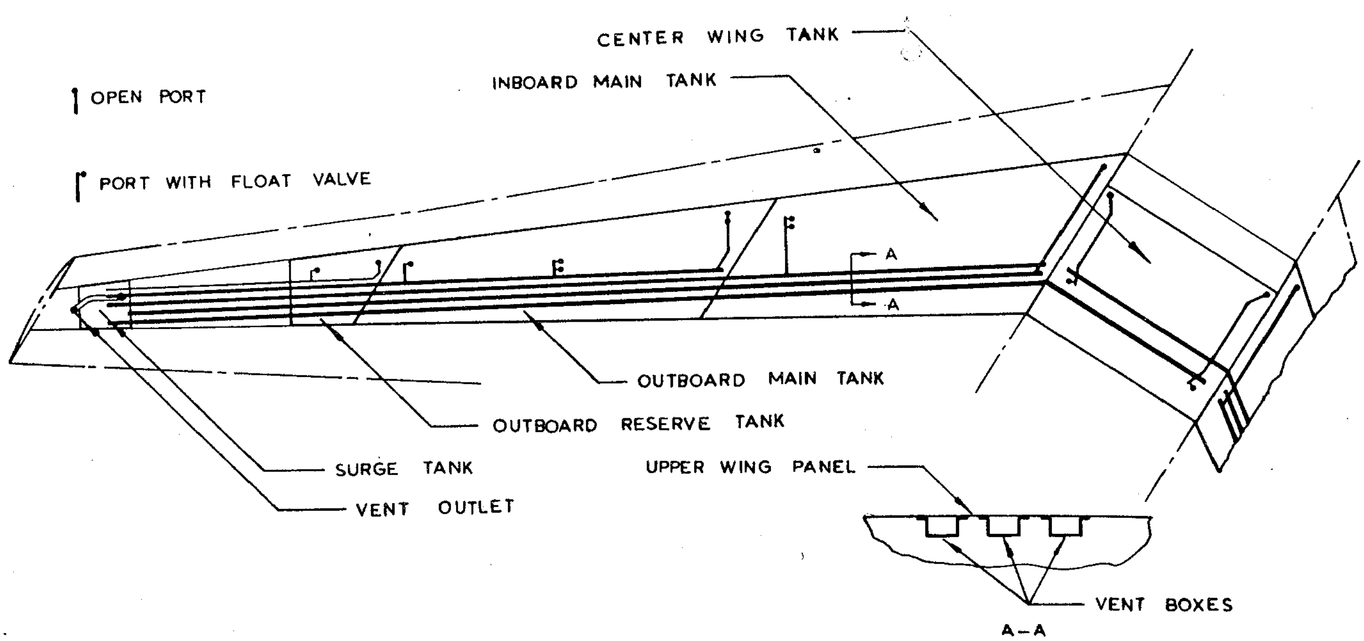

Fig. 2 - Vent system schematic .

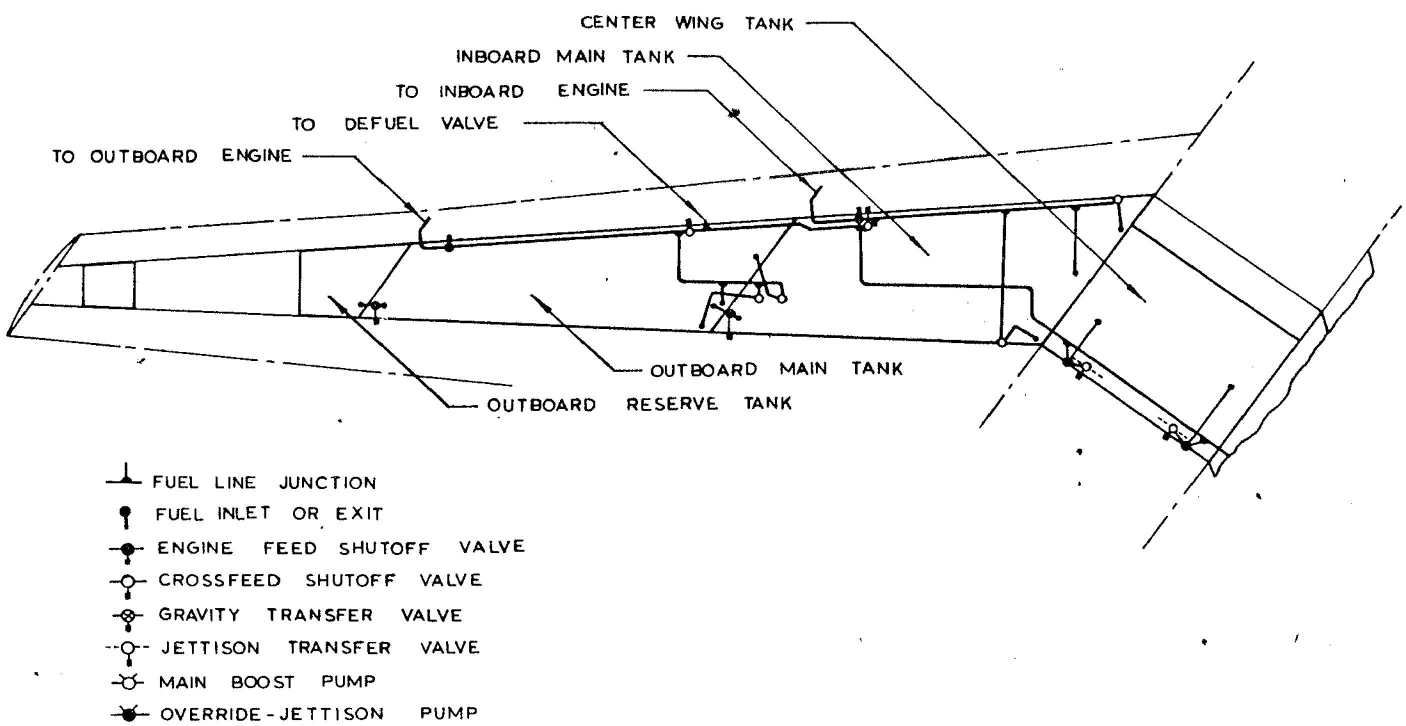

Fig. 3 - Fuel feed system schematic

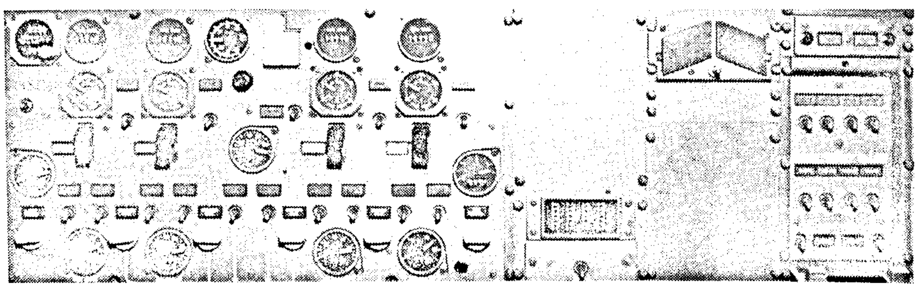

Fig. 4 - Flight engineer's fuel control panel

four main tanks are equipped with check valves to prevent reverse flow through them during fuel feed from the center wing tank.

Fuel in the No. 1 and No. 4 (outboard) reserve tanks is supplied to the engines indirectly by allowing it to flow by gravity into the adjacent outboard main tanks. Control of this flow is obtained with a butterfly type shutoff valve installed between adjacent tanks.

FUEL JETTISON SYSTEM (See Fig. 5) - The airplane is equipped with a fuel jettison system for rapidly off-loading fuel if required during flight emergencies. The system consists of six jettison pumps (two in each inboard main and two override/jettison pumps, mentioned above, in the center wing tank), the jettison manifold, nozzles, and shutoff valves. The components are operated from the flight engineer's control panel shown in Fig. 4. All jettison pumps, including the override/jettison pumps, may be removed without draining the tank. The four pumps in the inboard main tanks discharge directly into the manifold. The two override/jettison pumps in the center wing tank also discharge into the jettison manifold. However, when it is desired to supply fuel to the engines from the center wing tank, the override/jettison pumps may be isolated from the jettison manifold with the two center wing tank jettison valves. The jettison manifold, part of which is also the pressure fueling manifold, extends from one wing-tip to the other. It terminates with the jettison nozzles which extend aft of the training edge of the wing to prevent fuel impingement on any part of the airplane during jettisoning. A valve at each nozzle allows the termination of jettisoning at any desired time. Outboard main tank fuel is jettisoned indirectly by opening the main tank transfer valve, installed between each outboard main tank and its adjacent inboard main tank. Likewise, outboard reserve tank fuel is jettisoned indirectly by opening the reserve tank gravity transfer valve, installed between each outboard reserve tank and its adjacent outboard main tank, thereby allowing the fuel to flow by gravity from the outboard reserve tank into the outboard main tank. It is impossible to jettison fuel below the minimum reserve fuel level.

DEFUELING SYSTEM (See Figs. 3 and 5) - The airplane

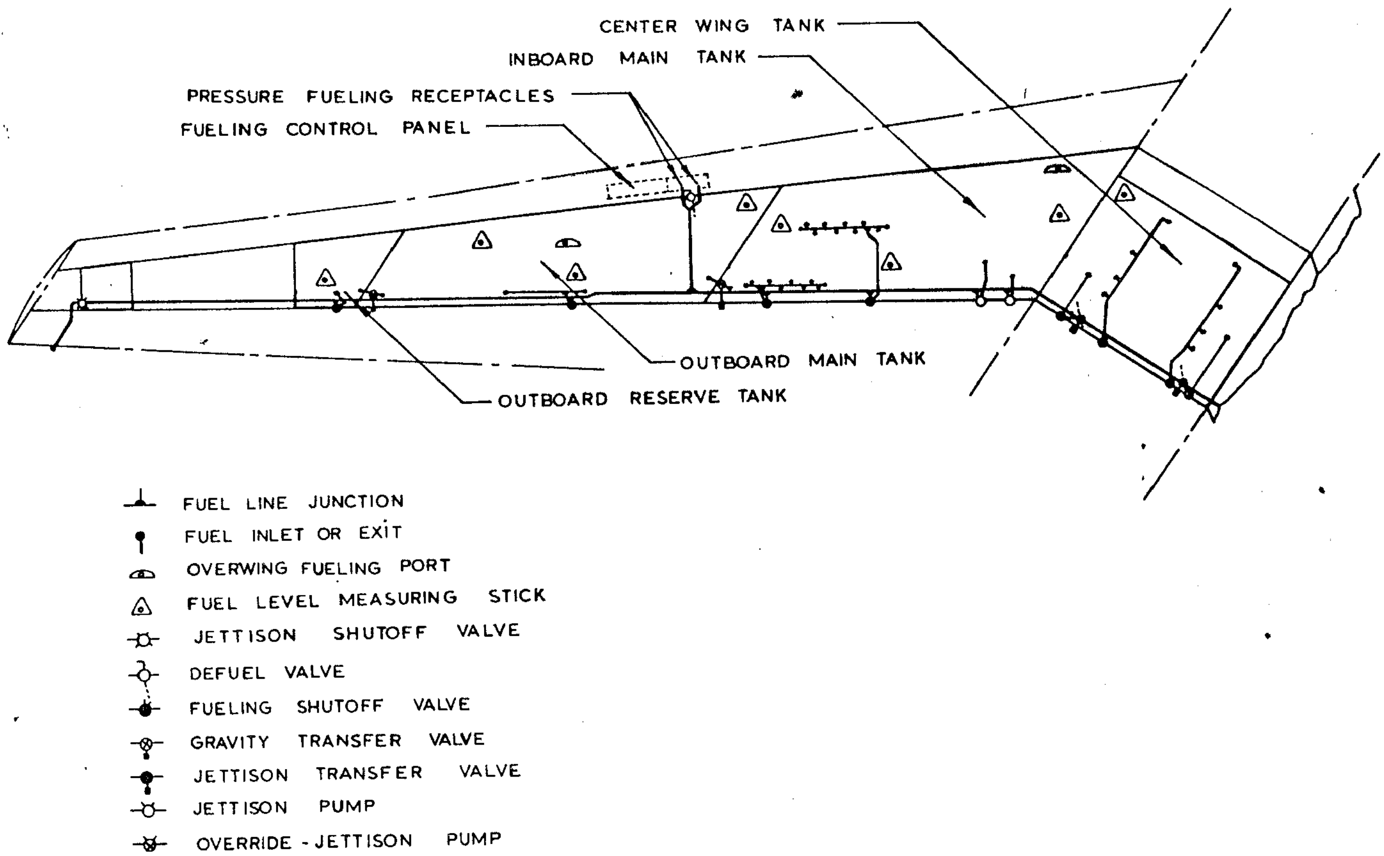

Fig. 5 - Pressure fueling and jettison system schematic

can be defueled through the pressure fueling receptacles. This requires a refueling tanker or hydrant cart and tank farm to serve as a receiving reservoir. Defueling to the reserve fuel level may be accomplished with the jettison system described above. This requires that the gravity transfer valves between the inboard and outboard main tanks and the outboard main and outboard reserve tanks be opened. It also requires that the jettison nozzle valves remain closed to prevent spilling fuel through the jettison nozzles. The fuel feed system can be used to defuel to the sump level. This is accomplished through the crossfeed manifold and interconnecting lines by opening the defuel valves at the pressure fueling adapters. The fuel feed system can also be used to suction-defuel to the sump level. See Table 1 for defueling system performance.

FUEL QUANTITY INDICATING SYSTEM - The usable fuel quantity in the tanks is continuously indicated on individual gages on the flight engineer's panel, shown in Fig. 4, whenever electrical power is on the airplane. In addition, a totalizer gage sums the individual gage readings to give the total quantity of usable fuel in all tanks. Tank units, which sense fuel quantity, and compensator units in each tank provide input signals to the corresponding fuel quantity indicators. The number and location of the tank units are chosen so that minimum errors in the quantity indication result from change in airplane attitude. The tank units are variable capacitors, their capacitance varying with the level of fuel in the tank. The compensator

Table 1 - Defueling Performance

1. Defueling with jettison system pumps or fuel feed system pumps.

The single tank defueling rates are: [1]

Pump Used	No. 1 or 4 Main Tank, gpm	No. 2 or 3 Main Tank, gpm	Center Wing Tank, gpm
Jettison [2]			
1 pump	–	186	–
2 pumps	–	362	–
Main Boost [3]			
1 pump	60	46	–
2 pumps	117	90	–
Override-Jettison [2]			
1 pump	–	–	183
2 pumps	–	–	356

[1] For 0 psig nozzle pressure

[2] To reserve fuel level

[3] To sump fuel level

2. Suction defueling
Defueling of the tanks to sump fuel level is possible through the fueling adapters using ground suction facilities.

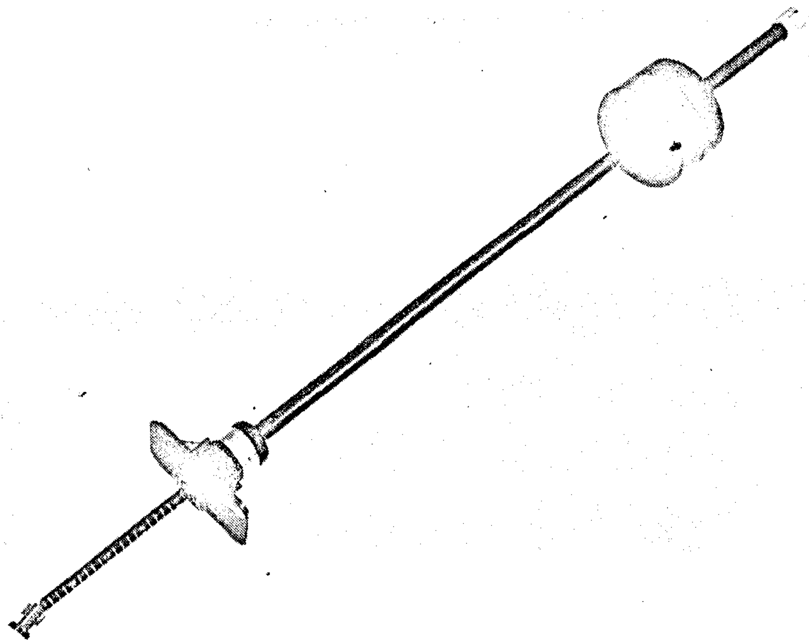

Fig. 6 - Fuel level measuring stick

units, similar in construction to the tank units, provide a correction for variation in dielectric constant with the fuel density. Compensators are installed in the tanks so that they are always immersed in fuel.

The fuel quantity in each tank may also be determined, when the airplane is on the ground, with a set of fuel level measuring sticks. A typical measuring stick is shown in Fig. 6. These sticks are installed in the lower wing surface. Each stick measures fuel depth at the stick location. The airplane is equipped with a set of tables from which this depth may be converted into fuel volume (or weight) for various ground attitudes.

FUELING SYSTEM (See Fig. 5) - All fuel tanks may be filled through the pressure fueling system or through overwing fueling ports.

Each main tank has an overwing fueling port which is located so that the tank cannot be filled in excess of its usable fuel quantity. The No. 1 and No. 4 (outboard) reserve tanks and the center wing tanks can be filled indirectly through No. 2 and No. 3 (inboard) main tank filler ports. This is accomplished by transferring fuel to the desired tanks from the inboard main tanks using the inboard main tank jettison pumps and the pressure fueling/jettison manifold.

The pressure fueling system, which is the primary subject of this paper, will now be described in detail. (See Fig. 5.)

PRESSURE FUELING SYSTEM DESCRIPTION

FUELING STATIONS - Both the left wing and the right wing fueling stations are located in the leading edge forward of the front spar of the respective wing in the area between the engine nacelles. The pressure fueling control panel, shown in Fig. 7, is located outboard of, and adjacent to the left wing fueling station.

RECEPTACLES - Two receptacles at each fueling station, shown in Fig. 8, are mounted on the forward face of the front spar. Each receptacle consists of a fueling nozzle adapter, a cast aluminum elbow, a cap, a spring-loaded check valve, and a manual shutoff valve that attaches to the spar and connects to the receptacle manifold. The spring-loaded check valve is designed to open when a positive fuel pressure differential is applied to the nozzle side of the valve and to close when the differential is removed. Its design also includes a means to open the valve manually for defueling the airplane. A defueling line with a manually operated defuel valve is installed in the casting of the outboard fueling receptacles at each fueling station. This plumbing and valve interconnects the crossfeed and pressure fueling lines for the defueling operation. The manual shutoff valve is installed to satisfy an FAA requirement.

MANIFOLDS - The fueling manifold distributes fuel to all tanks during the pressure fueling operations. The manifold consists of two receptacle manifolds and a main distribution manifold, used also as the jettison manifold. The receptacle manifolds extend from the fueling receptacles at the front spar into the outboard main tanks to the main distribution manifold which runs along the rear spar, all of which are routed inside the fuel tank area.

SHUTOFF VALVES - The fueling shutoff valves, electrically actuated and hydraulically operated, are used to terminate the fuel at any time the operator selects or to terminate automatically the fuel flow at the shutoff level for each tank. The shutoff valves in each tank are installed in the plumbing emanating from the main distribution manifold. There are two shutoff valves in the center wing and each inboard main tank, whereas the outboard main and reserve tanks each have one shutoff valve. The valves are operated by individual switches in the fueling station control panel or automatically by the volumetric shutoff system when a full tank is sensed. The shutoff valves have fail safe characteristics. They will close

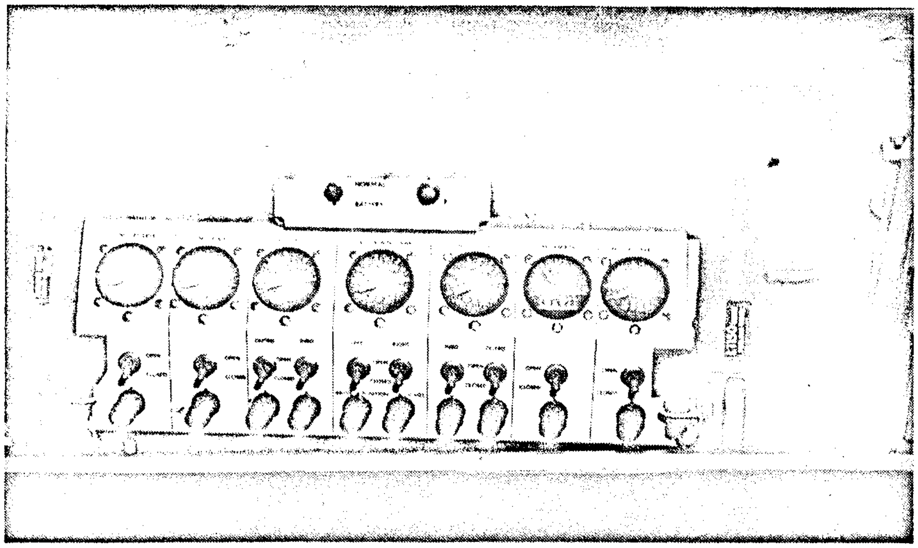

Fig. 7 - Pressure fueling system control panel

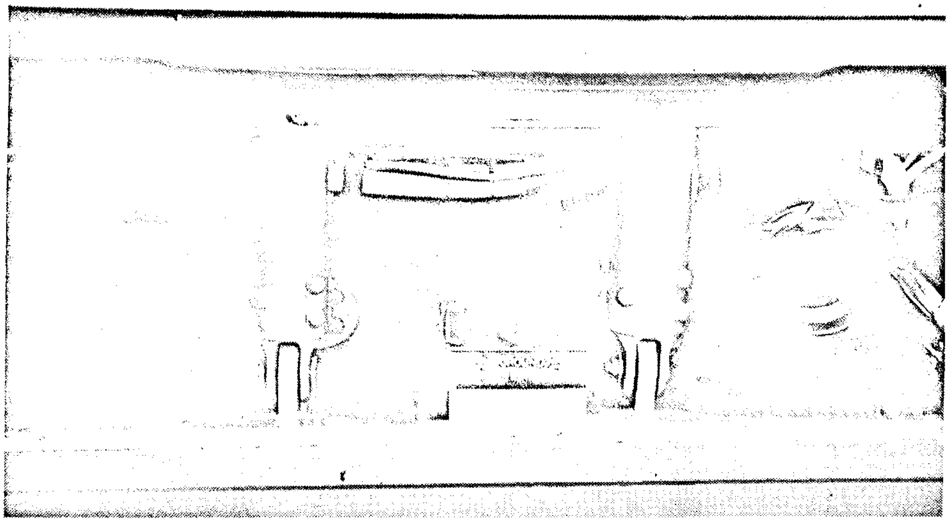

Fig. 8 - Pressure fueling receptacles

automatically if the diaphragm is ruptured or if a power failure is experienced during pressure fueling. Manual override of the shutoff valve is also provided to permit fueling without electrical power or if the valve fails to open after electrical actuation.

ORIFICES - Orifices are installed downstream of each shutoff valve to achieve the design simultaneous refueling rate of 2000 gpm with 50 psig at each fueling nozzle. In the center wing tank, the orifices are located on the end of each distribution tube. The design fueling rate is such that in the event of a tank overfill resulting from a malfunction of the automatic shutoff device, the fuel tank vent system will carry fuel overboard without over-pressurizing the tanks.

FUEL DISTRIBUTION TUBES - In the center wing tank, the distribution tube downstream of each of the two shutoff valves has four outlets. Each inboard main tank has a fuel distribution system such that the outboard shutoff valve distributes fuel behind the mid spar through ten outlets and the inboard shutoff valve distributes fuel forward of the mid spar also through ten outlets. In each outboard main tank, the distribution system downstream of the shutoff valve has two outlets behind the mid spar. Each outboard reserve tank has a single outlet downstream of the shutoff valve. Multiple outlet flow distribution tubes, referred to generally as piccolo tubes, minimize the effects of static electrification by distributing the incoming charged fuel throughout the tanks.

FUELING CONTROL PANEL - The fueling control panel, shown in Fig. 7, contains all the controls required for operation of the pressure fueling system. Components mounted on the panel include seven fuel tank quantity indicators, one indicator test switch, one refuel power-selector switch, ten pressure fueling shutoff valve switches, and ten fueling shutoff valve position indicator lights. The quantity indicators at the control panel are repeaters and receive their electrical signal from the corresponding fuel quantity gages on the flight engineer's panel. These repeater gages are interchangeable with a set of preselect units which make it possible to terminate automatically pressure fueling of each tank at any desired fuel quanity. The indicator test switch provides a means of checking the quantity indicators at the pressure fueling control panel for operation.

VOLUMETRIC SHUTOFF SYSTEM - The volumetric shutoff system uses the fuel quantity tanks units sensor signals to close the fueling shutoff valve and thus terminate the fueling operation automatically when a fuel tank has been filled. The volumetric shutoff system consists of the tank units of the fuel quantity indicating system, volumetric shutoff system compensator units, and volumetric shutoff control units. The volumetric shutoff system compensator units are the same as the compensator units used in the fuel quantity indicating system. They are installed in the No. 1 (outboard) reserve tank, the No. 1 and No. 4 (outboard) main tanks and the No. 2 (inboard) main tank. Additional units similar to the compensators are installed in the surge tanks to provide overfill protection. The shutoff control unit for each tank is on an electronic circuitry card. All cards are mounted in a box installed in the main electronics equipment bay located under the main passenger deck forward of the forward cargo compartment. During the pressure fueling operation, the volumetric shutoff control unit energizes the fueling shutoff valve solenoid to the open position; when a full fuel tank is sensed, electrical power is discontinued to the solenoid and the valve(s) closes. The volumetric shutoff system is adjusted to provide a fuel tank expansion space of at least 2% of the fuel capacity of the tank when in the normal ground attitude. The volumetric shutoff control units are checked during the fueling operation by activation of the "test gage" press-to-test switch at the fueling station control panel. This removes electrical power to the shutoff valves. Then, the valve closes, the valve position indicator light goes off, and fuel quantity indicators all move down scale. Release of the press-to-test switch returns the system to a normal condition and fueling resumes.

PRESSURE FUELING OPERATION - For normal fueling operation, the ground fueling facility is connected to the fuel receptacles, then the valve switches for the particular tanks requiring fuel are opened. The manually operated valves at the fueling receptacles are then opened and fueling is begun. The pressure in the manifold tubing causes the pressure fueling shutoff valves to open, and the valve position indication light comes on when fuel begins to flow into the tanks. Automatic shutoff will occur when the tank is full. At this time, the valve position indication light goes off indicating that the valve is closed. The fuel quantity indicator will reflect the quantity corresponding to a full tank as a further check of the system.

PRESSURE FUELING SYSTEM PERFORMANCE

The Model 747 airplane fuel system is designed to meet all the applicable requirements prescribed in Part 25 of the Federal Aviation Regulations. Tests were conducted to demonstrate compliance of the fuel system with these requirements. An Airworthiness Certificate was awarded on December 30, 1969.

In addition to the requirements of Part 25 of the Federal Aviation Regulations, the pressure fueling system is designed for refueling with ground facilities equipped with standard, 2-1/2 in. diameter MS29520 nozzles. The design refueling rate, for filling all tanks simultaneously through all four nozzles, is approximately 2000 gpm with a pressure of 50 psig at each nozzle. This rate allows a normal refueling within the design turn around time of 1/2 hr for the airplane. A normal refueling is defined as filling the fuel tanks from the normal reserve level (1050 gal in each main tank and empty reserve and center wing tanks) to full mains and reserves and to 6000 gal in the center wing tank.

Single tank refueling rates and system pressures were measured during fuel system performance tests made on the airplane. Pressure loss coefficients for the pressure fueling system, determined from this experimental data, were then used to calculate the refueling rate with all tanks filling simultaneously. This rate is 1960 gpm (789,880 lb/hr with a fuel density of 6.72 lb/gal when filling through four nozzles and with a pressure of 50 psig at each nozzle. Pressure fueling system performance is shown in Fig. 9. The time required for a normal refueling at 50 psig nozzle pressure is shown in Fig. 10.

Two possible problems related to the higher fueling rates associated with the large jets of today and tomorrow are higher surge pressures resulting from closure of the pressure fueling shutoff valve and higher electrostatic energy density on the surface of the fuel in the tanks.

The 747 pressure fueling shutoff valves are equipped with a surge relief mechanism which allows valve closure time to vary directly with fuel pressure at the valve, thereby preventing excessive surge pressure. Surge pressure tests were conducted at the Boeing Flight Test Center at Boeing Field in Seattle using two tank trucks and at the Grant County Airport at Moses Lake, Wash., using a hydrant system. For both fueling facilities, the maximum surge pressure in the airplane occurred with the simultaneous closure of all valves. Although all tanks in the airplane will not normally become full at the same instant, causing simultaneous closure of all valves, this case is simulated when the press-to-test button on the pressure fueling control panel is pushed. This is a standard operating procedure to check the operation of the volumetric shutoff control unit and is performed shortly after the start of fueling.

The maximum surge pressure recorded during refueling from the tank trucks was 87 psig and occurred at the No. 1 reserve tank valve with the maximum output from the two tank trucks of 1748 gpm. Maximum surge pressure at the fueling nozzles was 85 psig and occurred at both left wing nozzles. Output from each tank truck was reduced from its design value because of the flowmeter installation between the nozzles on the truck and the receptacles on the airplane. It is expected that the surge pressure corresponding to the fuel flow rate of 1960 gpm from the two tank trucks would be well below the maximum allowable static pressure of 195 psig.

The maximum surge pressure recorded during refueling from the hydrant system at Grant County Airport was 136 psig and occurred at the No. 4 reserve tank valve with the maximum output from the system of 1565 gpm. Maximum surge pressure at the fueling nozzles was 139 psig and occurred at both right wing nozzles. The same fuel flowmeter installation used with the tank trucks was also used with this hydrant system. Consequently, the fuel flow rate was below the design rate for

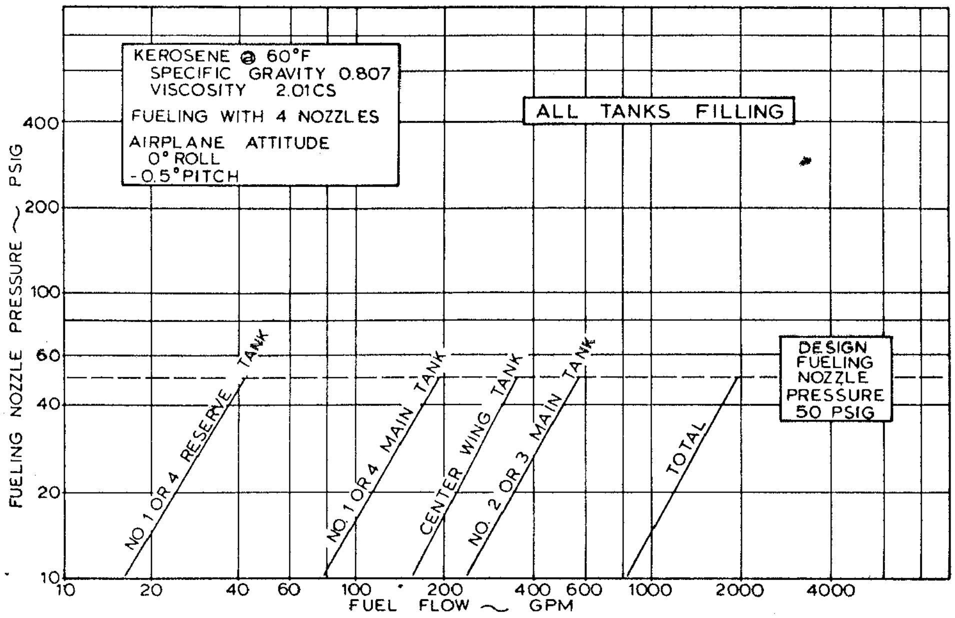

Fig. 9 - Pressure fueling system performance

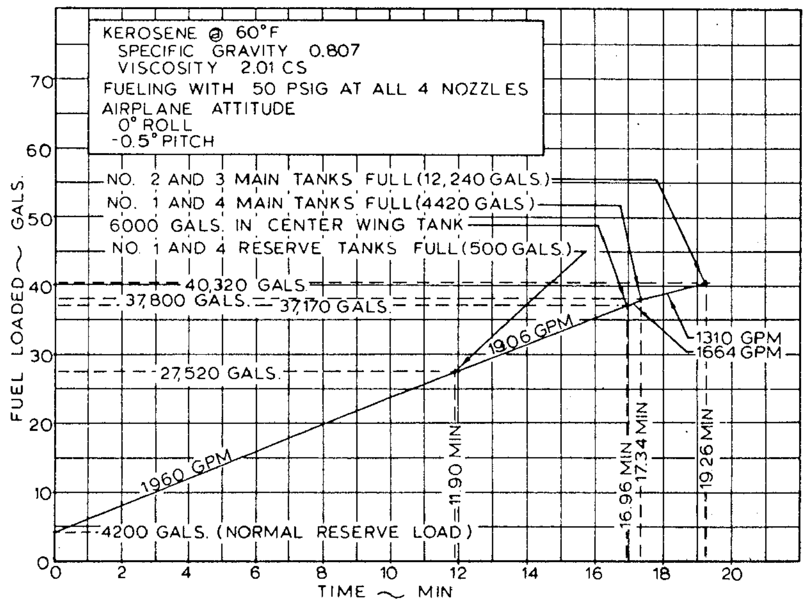

Fig. 10 - Fuel loading characteristics

the system. The surge pressure corresponding to a fuel flow rate of 1960 gpm from this hydrant system might approach 195 psig. Results of these two tests show that the surge pressure experienced in an airplane is significantly affected by the surge suppression characteristics of the fueling facility. Therefore, surge suppression should be an important facet for designing future fueling facilities with the higher flow capacities.

Electrostatic energy density while fueling the 747 airplane has been minimized. As previously described, the 747 fuel tanks are subdivided by the mid-spar and the wing ribs into a multitude of small bays. Use of multiple outlet tubes (called piccolo tubes) thus allows simultaneous fuel distribution into several of the small bays. This design converts the large tanks–high flow rate concept to a small tank–low flow rate condition. From the piccolo tubes, installed near the bottom of the tanks, fuel is directed downward into the fuel tank bays. Maximum manifold fuel velocity in the 747 airplane is 26 fps with the design nozzle pressure of 50 psig. This manifold velocity is less than the maximum manifold velocities in other Boeing commercial jet airplanes. The lower velocity in conjunction with longer fuel lines relative to other United States commercial jet airplanes assures charge relaxation of an equal or greater magnitude than in present United States commercial jet transports. Therefore, the 747 is designed to be as safe as or safer than any of the airplanes in the present United States commercial jet fleet, for which there are no recorded incidents of fire or explosion caused by electrostatic discharge during fueling. A significant part of the electrostatic charge density is generated in the fuel as it flows through the filter units in the fueling facility. This charge density increases with increasing fuel flow rate. Therefore, minimizing electrostatic charge generation becomes an important aspect of designing future fueling facilities with higher flow capacities.

No problems due to electrostatic charge or surge pressure have been reported during the extensive Boeing flight test program or during the airline use of the Boeing 747 airplane.

CONCLUSIONS

The fuel system of the Boeing Model 747 airplane has been described in general and the pressure fueling system has been described in detail. Possible pressure fueling problems are discussed. It is concluded that:

1. Electrostatic charge accumulation in the fuel tanks and high surge pressures are two items that require special consideration in the design of refueling systems for the large airplanes. Both of these are influenced by the refueling equipment used.

2. The Boeing 747 has been designed to minimize fuel static electrification and surge pressures.

3. Surge suppression and low electrostatic charge generation should be considered when designing fueling facilities with high flow capacities.

4. The Boeing 747 fuel system meets all applicable requirements of Part 25 of the Federal Aviation Regulations.

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12 page booklet. Printed in U.S.A.