SECTION 9.19
AEROSPACE

9.19.1
AIRCRAFT FUEL PUMPS

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The operating characteristics and reliability of aircraft fuel pumps are absolutely critical with respect to the performance and the safety of flight of today's gas turbine-powered commercial and military aircraft. With a large commercial airliner carrying upwards of 50,000 gallons (189,000 liters) of fuel on a long range flight, making fuel the single heaviest load the aircraft must handle, the importance of intelligent and safe processing of this fuel load is clearly evident.

The aircraft fuel pump system is divided into two separate but related systems: the airframe fuel pump system and the engine fuel pump system. Two systems are required because of the significantly different functional requirements of each system. The airframe system is a low pressure system that operates continuously at low values of inlet *NPSH* and utilizes booster pumps located throughout the airframe fuel system to supply pressurized vapor free fuel to the engine fuel system. The engine fuel system is a high-pressure system that further pressurizes the fuel for delivery to the engine combustor fuel nozzles and other engine systems. The requirements of these systems and the pumps in them are covered by a wide range of government and industry specifications. Minimally, these define the performance, fuel types, operating and ambient conditions, drive source, reliability, life, weight, installation, quality, materials, and test requirements to which the fuel pump must conform.

The detailed nature of these specifications further emphasizes the critical nature of aircraft fuel pumps. The fuel pump designer's task is to provide fuel pumps that meet these specifications with the lowest weight, best efficiency, and at a competitive cost. Both centrifugal and positive displacement types of pumps are used in performing the necessary fuel pumping functions on essentially all large gas turbine-powered aircraft.

Because of the specific installation and performance requirements for airframe and engine fuel pumps, each pump is an individual and custom design for each specific application. As such, there are no catalogue type standard pump configurations or designs for aircraft applications.

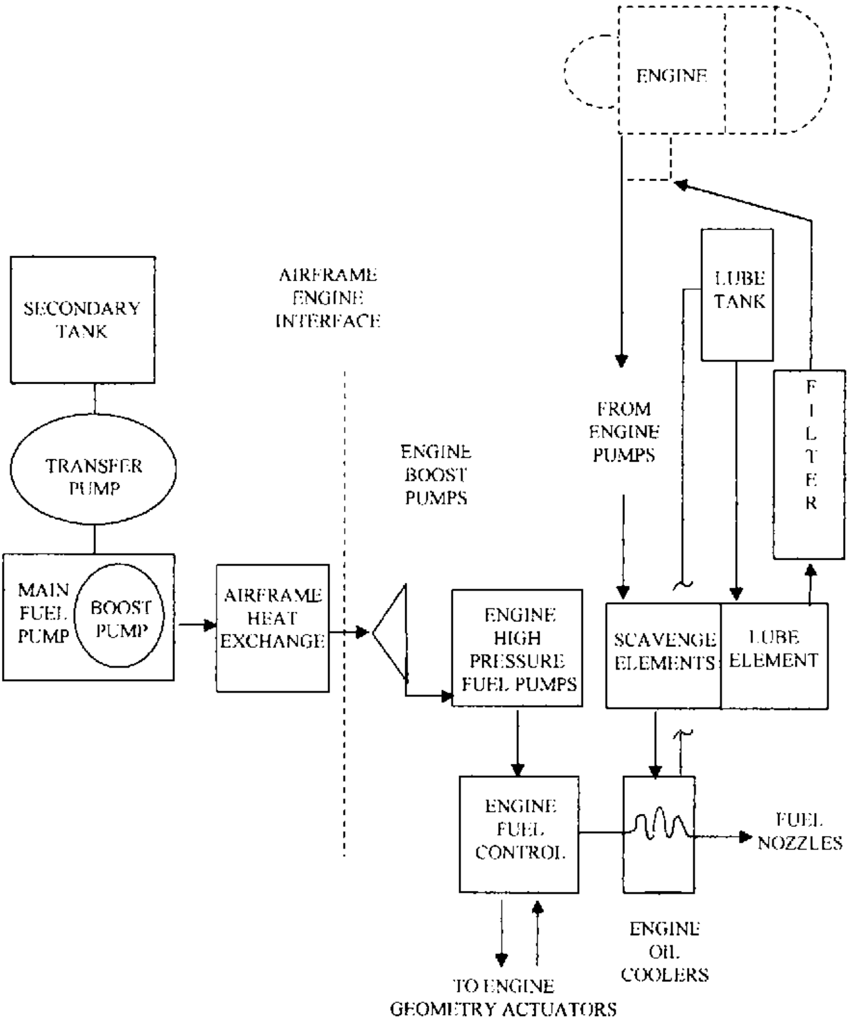

FIGURE 1 Basic schematic of fuel system

OVERALL AIRCRAFT FUEL SYSTEM

Figure 1 presents a basic schematic of the fuel pump components in the overall aircraft fuel system. The division between the airframe and engine systems is shown.

The primary function of the airframe fuel system is to provide a pressurized fuel feed to the engine fuel pump system under all operating conditions. In the event of the emergency conditions of non-operating or failed boost pumps, a bypass located either in the airframe plumbing or the boost pump allows the engine pump system to receive sufficient fuel to provide take-off and climb thrust. Other functions required of the airframe fuel pump system are as follows:

- Provides fuel transfer between various fuel tanks to maintain continuous engine feed and to adjust the center of gravity of the aircraft.
- Provides fuel jettison in flight in the event it is necessary to quickly reduce the aircraft weight.
- Assists in the defueling of the aircraft on the ground.

The primary function of the engine fuel system is to receive the fuel from the airframe fuel system, under normally pressurized conditions or emergency conditions, and provide pressurized fuel to the engine. This fuel is used for burning in the combustors and for powering actuators that control the engine's variable geometry.

Because fuel is the only consumable fluid carried by the aircraft, it represents the sole heat sink on board the aircraft. (For extreme conditions, some aircraft have carried an additional disposable heat sink fluid.) The on-board fuel and the air ingested by the engines or scoops provide all of the cooling necessary for the proper functioning of the various airframe and engine systems. The impact of this on the fuel pumps is a significant increase in the temperature of the fuel on which the pumps must operate.

GENERAL DISCUSSION OF AIRFRAME FUEL PUMPS

The primary type of pump used for providing the fuel boost and fuel transfer functions on an airframe is a centrifugal pump element driven by a fuel-flooded AC induction electric motor. Positive displacement elements are rarely used and alternate drive means such as hydraulic motors and air or fuel driven turbines have only been used on a selected few military aircraft. On small general aviation aircraft, jet pumps with the motive flow provided by the engine fuel pump are popular.

Helicopters commonly incorporate a special type of fuel system called a "suction feed" fuel system. Because a helicopter is altitude-limited, it is not necessary to provide a pressurized engine fuel inlet condition. In fact, for safety considerations, it is desirable not to pressurize the fuel lines between the fuel tanks, located in the lower sections of the airframe, and the engines, which are located in the upper sections of the airframe. For these applications, the engine fuel pumps are designed to continuously operate with a fuel inlet pressure lower than the fuel tank pressure by the height of the fuel lift between the fuel tank and the engine and the incurred fuel line pressure losses.

The standard electric power on aircraft is 400 Hertz, three-phase 115-volt line to neutral/200 volt line to line type. This type of power has been selected to minimize the weight and size of the total aircraft electrical system.

Various inlet configurations are used on airframe fuel boost pumps depending upon the configuration of the fuel tanks and the flight conditions under which the pump must operate. Figure 2 presents illustrations of some of the most common configurations.

The two configurations labeled "single attitude" are applicable to commercial airlines and transport-type aircraft. In these applications, only positive "G" loads are experienced; so the fuel location in the tank is always downward in the illustrations. Depending upon the fuel tank configuration and airframe structural requirements, either a tank bottom mount location or a snorkel-type fuel inlet is commonly employed. The bottom mount configuration results in the least complex pump configuration because when the pump inlet is covered with fuel, the pump is automatically primed.

With the snorkel-type inlet, some means must be provided within the fuel pump to evacuate the inlet line to prime the centrifugal element after the inlet to the snorkel is covered. This is most commonly provided by a liquid ring type-pumping element (see Reference 20 of Section 2.1) contained within the fuel pump.

For aircraft that will experience negative "G" and zero "G" conditions in flight operations, such as military tactical aircraft, the fuel may be located at the top, bottom, or anywhere in-between within the fuel tank. The configurations labeled negative "G"-capable in Figure 2 are applicable to these types of aircraft. Aircraft that are capable of the most extreme flight maneuvers generally use the dual impeller configuration. With this type of

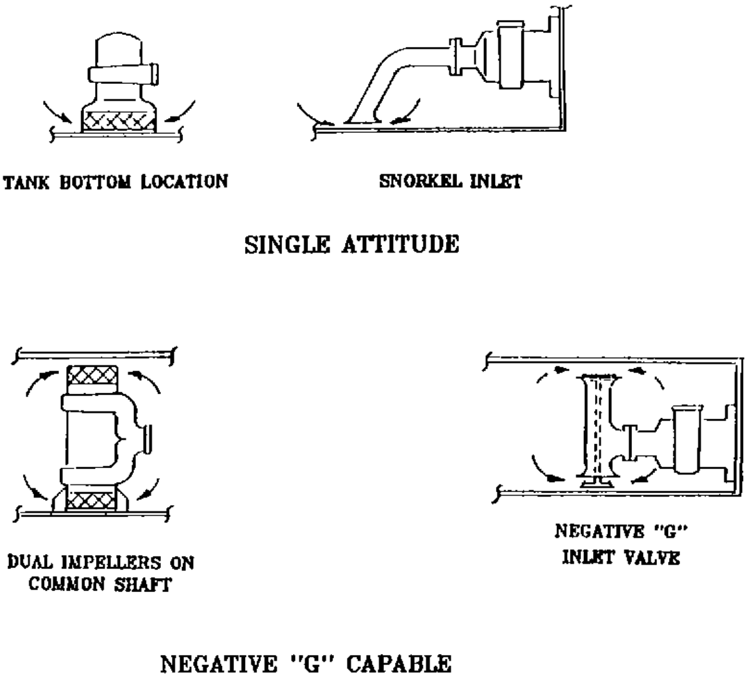

FIGURE 2 Airframe boost pumps—inlet types

pump, the response to negative “G” forces is essentially instantaneous, and full engine fuel flow is provided under all flight conditions. For aircraft with less demanding flight conditions, a pump with a single impeller and a negative “G” shuttle type inlet valve to ensure that only the primed inlet is connected to the impeller is commonly used. The number of pumps, the position of the pumps, and the configuration of the fuel tank are selected to ensure adequate fuel flow is delivered to the engines under all flight attitudes.

DESCRIPTION OF THE DESIGN OF AIRFRAME BOOST PUMPS

Figures 3 and 4 present a cross section view and a photograph of an electric motor-driven boost pump assembly that is used on a commercial airliner. This pump utilizes a snorkel inlet. The design of this pump incorporates cartridge type pump and discharge valve modules that greatly enhances the maintainability of these pumps. The elliptical shaped main housing is a semi-permanent assembly in the airframe fuel tank. The pump modules are easily removable from it without draining the fuel tank through an interlocking inlet valve mechanism that is actuated by the removal action of the pump modules. Except for a screwdriver to remove the cover plate, no tools are required for this maintenance function. The removal of the discharge valve modules are similarly enhanced by this type of design. The immense fuel loads carried by commercial airliners clearly emphasizes the desirability of these maintenance features.

In the interest of weight, all of the housing and structure of the pump assembly are made out of aluminum. Steel is used for high stress parts such as shafts and fasteners and the electric motor laminations. Fuel is circulated throughout the pump cartridge to lubri-

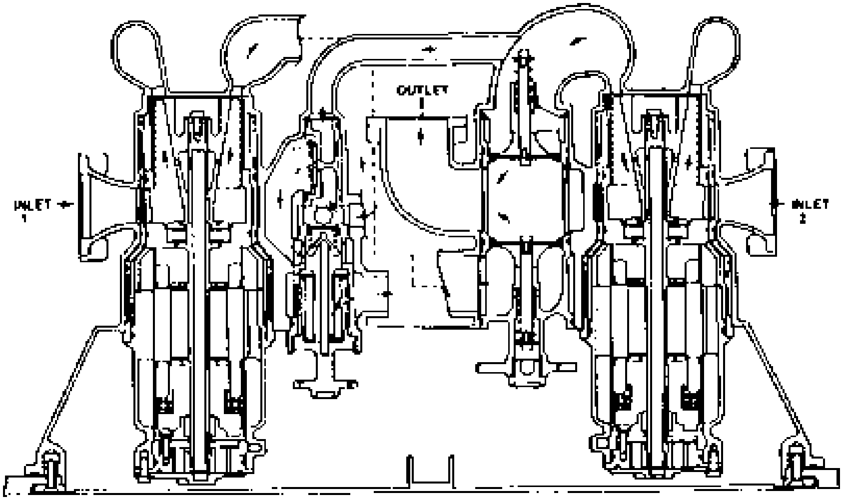

FIGURE 3 Main boost pump flow schematic (Courtesy Sundstrand Corporation)

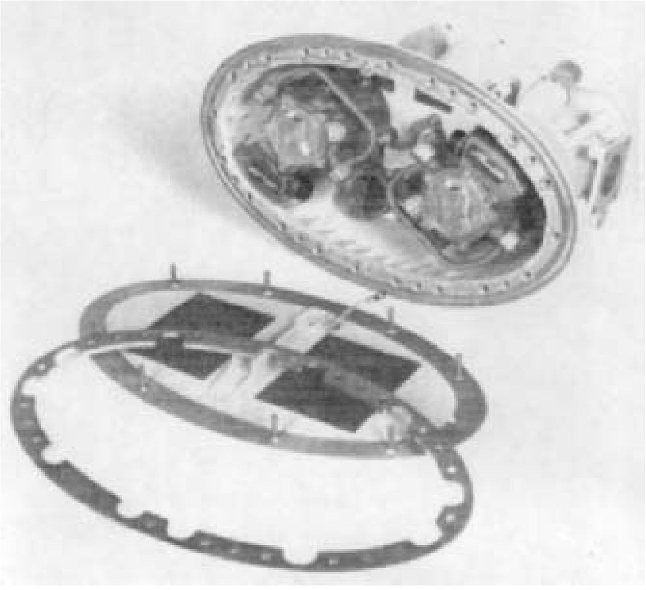

FIGURE 4 Main boost pump assembly (Courtesy Hamilton Sundstrand)

cate the bearings and cool the motor. This fuel is returned to the tank through a port that incorporates a flame arrestor.

In the normal operation of the aircraft, fuel tanks will be run dry by the selective usage of fuel from the various fuel tanks to maintain aircraft balance. Under these conditions, the fuel pumps in these tanks will run dry. To simplify the management of the fuel system, it is normal practice to let the pumps run dry for the remainder of the flight. It is therefore necessary to provide a bearing system for the pump, which will accept continuous dry running without detrimental results to the pumps. This is generally accomplished through special configurations of carbon journal and thrust bearings with chrome plated journal and thrust running surfaces.

Because these pumps are located in the aircraft fuel tanks and are totally immersed in fuel, their safety and explosion-proof features are of utmost importance. All openings that communicate the pump electric motor cavity with the interior of the fuel tank must incorporate flame-arresting features. This includes communication through the pumping elements to the pump inlet. Also non-resetable thermal fuses are incorporated in the motor end turns to ensure the motor is disconnected before it can reach the minimum auto-ignition temperature of jet fuel (approximately 390°F/199°C) through various failure modes. It is general practice to provide two electrical insulation barriers between all points of different electrical potential.

Electric motor driven boost pumps are in use in sizes up to 200 gpm (45.42 m^3/h) flow and at pressure rises ranging from 10 to 50 lb/in^2 (.69 to 3.45 bar) with a motor out power of up to 6.5 hp (4.85 kw).

Electric motors of 8, 6, and 4 poles designs are in general use. The synchronous speeds of the motors with 400 Hertz power are 6000, 8000, and 12000 rpm respectively. The constant demand for smaller and lighter components has seen the increased application of 6- and 4-pole motors in recent years.

The overall weight per pump element (impeller, motor and housings) ranges from 7 to 25 pounds (3.17 to 11.34 kg). The number of pump elements used on large commercial aircraft in service today ranges from four to sixteen.

PERFORMANCE CRITERIA OF AIRFRAME BOOST PUMPS

The fact that aircraft boost pumps operate at very low net positive suction heads is evident in their operating environment. Fuel tanks are vented to ambient pressure and commercial airlines fly up to 45,000 foot altitudes where the standard atmospheric pressure is 2.14 lb/in^2 (.148 bar). Altitudes are even greater for supersonic aircraft. Tank pressurization above the ambient pressure is employed only on some specialized military aircraft.

The performance criteria that specifically define the design of the centrifugal pumping element in an airframe boost pump are presented in the following discussions.

MAXIMUM/MINIMUM PRESSURE RISE AND MOTOR SPEED

The pressure rise limits of the pump are defined by the pump specification and are determined by airframe and engine system needs.

The motor speed (that is, the number of poles) is selected by the pump designer to be compatible with the overall requirements of the pump, in particular the altitude requirements. Because of the need to minimize size and weight, the maximum possible speed is employed. This has, in recent years, resulted in the almost exclusive use of axial inducers in airframe boost pumps. They are used either alone, as purely axial pumping elements, or in conjunction with mixed-flow sections depending upon the flow and pressure requirements. Axial inducers are a pumping element that have proven to provide the best suction performance because of their low blade loading and gradual pressure rise characteristic. The inducers on airframe boost pumps incorporate features such as blade sweep back, blended suction surfaces, and thin blade inlet edges. The inlet blade angle at the tip usually ranges from eight to ten degrees measured from a plane perpendicular to the axis of rotation. These pump elements have demonstrated the capability of operating at suction-specific speeds in excess of 40,000 measured in units of gpm, feet of fluid, and rpm (that is, the universal suction specific speed Ω_{ss} exceeds 14.6).

FUEL TYPE

Two types of fuels are in general use worldwide in aircraft gas turbine engines. They are referred to as "wide cut fuels" and "kerosene-based fuels."

Both types of fuel are composed of a complex mixture of a range of individual hydrocarbon compounds. As the name suggests, the wide cut fuels have a wider range of hydrocarbons than kerosene-based fuels. The composition of the fuel is controlled, rather loosely, by the fuel specifications through defining limits on such factors as distillation range, density, flash temperature, heat of combustion, vapor pressure, freezing point, additives, and limits on certain compounds. Wide cut fuels are characterized by relatively low density, low freezing point (−65°F/−53.9°C), high vapor pressure and low flash point (−45°F/−42.8°C). Kerosene-based fuels on the other hand are characterized by a relatively high density, higher freezing point (−40°F/−40°C), low vapor pressure, and high flash point (140°F/60°C). The United States designations for wide cut fuels for commercial and military uses are Jet B and JP-4 respectively. The designations for kerosene-based fuels are Jet A1 for commercial uses and JP-5 and JP-8 for military uses. Jet A1 predominates in production because of the huge demands of the airlines. Jet A1 is used in commercial service worldwide primarily for safety reasons because of its high flash point. Jet B is only used when its low freezing point is required; for example, in northern Canada in the winter. The U.S. Air Force previously used JP-4 as their standard fuel, but for availability and safety reasons have switched to JP-8, which is a military version of Jet A1. The navy uses JP-5 because of its high flash point for safety considerations on board aircraft carriers.

The knowledge of the true vapor pressure of the fuel used is necessary in the design and test evaluation of the centrifugal pump element. Because the fuels are a mixture of a range of hydrocarbons, the direct determination of the true vapor pressure is difficult. It is determined indirectly, for a desired temperature, through the Reid Vapor Pressure (RVP). The RVP is an average vapor pressure determined under a defined set of conditions, established by test at 100°F (38°C). The True Vapor Pressure (TVP) at this temperature is slightly higher than the RVP. Moreover, the TVP-versus-temperature relationship is determined by the RVP (see Reference 1).

Another key property of the fuel that directly influences the design and performance of airframe boost pumps is the solubility of air in the fuel. This is defined by Henry's law through a solubility coefficient. The ullage volume above the fuel in the aircraft tanks is generally vented to the ambient pressure. The maximum amount of dissolved air in the fuel will occur on the ground. The fuel will be in an air-saturated condition.

Any reduction in the pressure of the fuel will result in the release of this air in accordance with Henry's law and expansion of this air to a volume in accordance with Dalton's law of partial pressures. In addition, as the pressure is reduced, the vapor pressure of the light end hydrocarbon constituents of the fuel is reached. They too will vaporize, adding to the volume of vapor evolved. Reference 1 provides a detailed review of all of the properties of aircraft gas turbine engine fuels.

ALTITUDE CLIMB PERFORMANCE

The altitude climb performance required of an airframe boost pump is specified in terms of altitude achieved versus time in minutes, flow required with respect to altitude, the fuel tank temperature with respect to altitude, and the minimum pump pressure rise required versus altitude. The temperature versus altitude represents the cooling of the fuel through heat transfer to the cold ambient atmosphere and boiling of the fuel that is experienced in a climb event.

Immediately upon take-off, as the aircraft gains altitude, the dissolved air in the fuel will begin to evolve. The rate of this air evolution will depend upon the climb rate of the aircraft. Presently, there is no accurate way to determine this rate of air evolution. This volume of evolved air is handled in the design of the pump by judicious oversizing of the inlet based upon experience and empirical design parameters. Further assistance in handling the volume of vapor is provided in tank bottom mount pumps through pump element inlet tip vapor vents and discharge hub vapor vents. Snorkel inlet pumps can receive vapor handling assistance through the liquid ring reprime element. Any remaining air and fuel vapor mixture is compressed as it passes through the increasing pressure within the inducer and is redissolved into the fuel. Therefore, the pressurized fuel delivered to the engine is free of vapor.

As the altitude increases, a tank pressure will be reached that will equal the vapor pressure of the fuel. At this point, especially with wide cut fuels, the vapor release will become quite violent (boiling). Here, the rate of vapor evolution will be determined by the capacity of the tank vent system. As the light ends leave the fuel, the vapor pressure of the fuel will decrease. This is referred to as "weathering" of the fuel. After the maximum cruise altitude is reached, the vapor pressure of the fuel will reach equilibrium with the altitude pressure.

The altitude climb test is the most difficult test to perform on airframe boost pumps because it must be a single fuel pass test without recirculation to accurately reproduce an actual climb condition. This requires approximately 1500 gallons (5,680 liters) of fuel for one test on an average commercial airliner fuel boost pump element. Figure 5 presents the results of an altitude climb test on the fuel boost pump depicted in Figures 3 and 4.

CONSTANT ALTITUDE PERFORMANCE

This requirement for an airframe boost pump is specified in terms of a required fuel flow range at a given temperature and at a constant altitude. The minimum required pressure rise is also specified. The submergence of the inlet of the pump (for bottom mount types) or the snorkel inlet (for snorkel inlet types) is also defined and is measured in the range of a few inches. For altitude pressures lower than the initial fuel vapor pressure, the fuel is weathered to achieve equilibrium with the altitude pressure. The fuel is recirculated in this test. Figure 6 presents the constant altitude performance of the fuel boost pump depicted in Figures 3 and 4.

GENERAL DISCUSSION OF ENGINE FUEL PUMPS

The primary fuel pump used for providing the boost and high-pressure fuel pumping function for an engine is called the "main fuel pump." It is engine gearbox-mounted and driven. In its most common form, it includes a positive displacement external spur gear high-pressure stage and an integral centrifugal boost stage. This type of pump is exclusively used on all modern commercial airliner engines and supplies all of the fuel flow requirements of the engine combustors. On commercial airliner engines, the main fuel pump is the sole engine fuel pump and therefore is a prime reliability piece of equipment. All engines, commercial and military, have a main fuel pump.

Positive displacement pumps have certain operating characteristics that make them very adaptable to aircraft gas turbine engine fuel systems. These characteristics include the ability to reprime from a completely dry condition and the ability to deliver useful fuel pressure over a wide speed range. Engine control systems utilize a portion of the main fuel pump discharge flow to power the actuation systems for fuel burn flow metering and engine variable geometry control for all operating conditions. Corner point operating conditions, such as altitude re-light and ground starting, occur at 8 to 10 percent of rated operating speed. The pressure required for actuator muscle and response characteristics at these conditions is generally a 250 lb/in^2 (17.2 bar) pressure rise. At the maximum power take off condition at 100 percent speed, the pressure rise requirement ranges up to 1500 lb/in^2 (103 bar). Positive displacement pumps have proven capable of meeting these needs and the external spur gear pump type has received the widest acceptance from the industry.

The key attribute of the external spur gear main fuel pumps relates to the safety of flight and prime reliability requirements. In over fifty years of experience, this type of

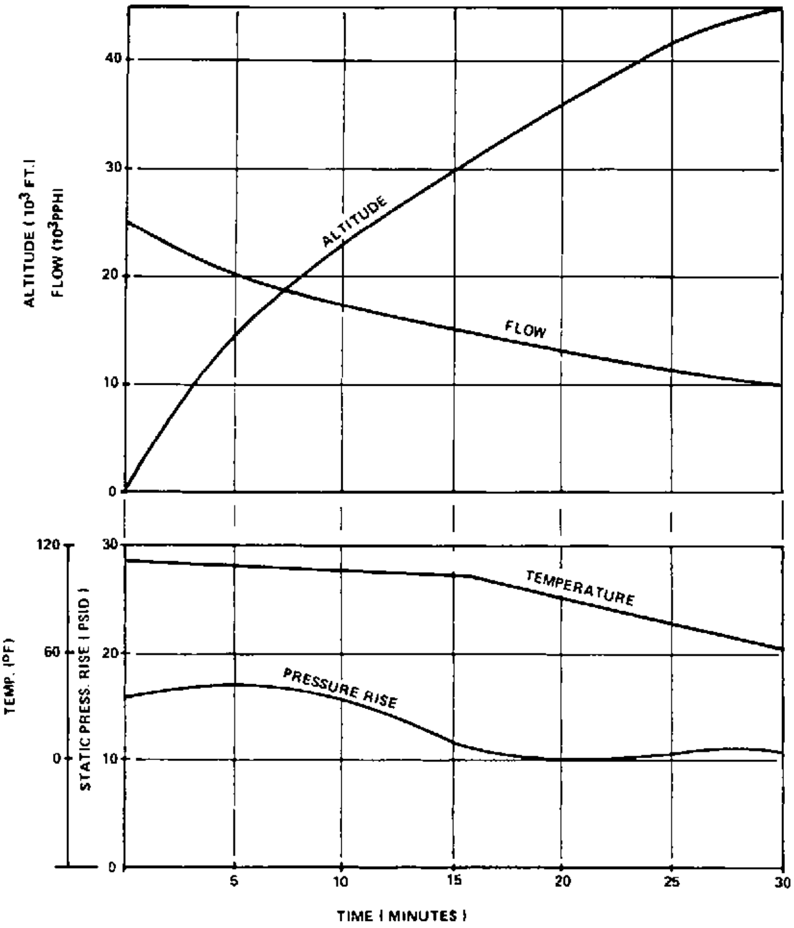

FIGURE 5 Main boost pump altitude climb (kg/h = PPH × 0.4536; m = ft × 0.3048; bar = psi × 0.06895; °C = (°F − 32) × 0.556).

pump has demonstrated a graceful type of failure mode. It does not fail in a catastrophic manner in which it suddenly ceases to function. It slowly, over an extended period of time, degrades in performance until it no longer meets minimum requirements, but continues to function. In commercial service, these pumps routinely operate for over 10,000 flight hours without service or repair.

Table 1 presents the pertinent characteristics of representative external spur gear main fuel pumps.

Other types of positive displacement pumps, such as axial piston and sliding vane pumps, have been applied to engine main fuel pumps. These have not achieved the level of acceptance of external tooth gear pumps.

On highly specialized engines, such as military fighter aircraft engines, additional high-pressure fuel pump functions may be required. These include fuel pumps for supplying the thrust augmentation systems (afterburners) and, in some applications, fuel pressure for the actuation system for the engine's exhaust nozzle. Because augmentation fuel

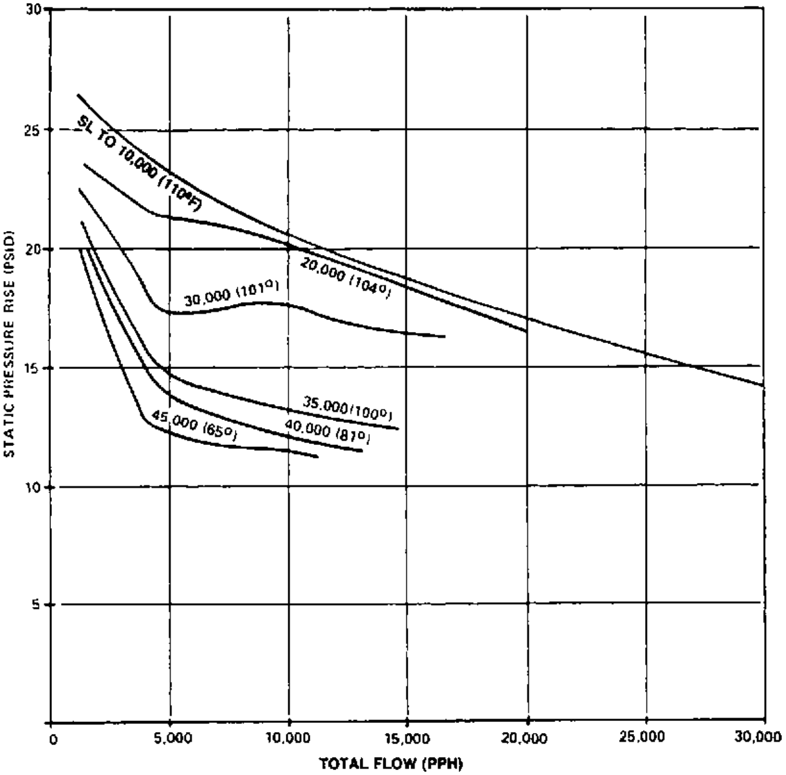

FIGURE 6 Main boost pump altitude performance (Altitudes are shown on the curves in ft; m = ft × 0.3048; kg/h = PPH × 0.4536; bar = psi × 0.06895; °C = (°F − 32) × 0.556).

flows are very high and the systems are operational for only a small percentage of the mission time, high-speed centrifugal pumps are used in these situations. Centrifugal pumps offer a low unit weight and the ability to be run dry when the system is not operating, thereby conserving power. These centrifugal pumps operate at speeds up to 25,000 rpm and deliver up to 200 gpm (45.42 m^3/h at 1000 lb/in^2 (69 bar) pressure rise. The fuel actuation function has been provided by variable displacement piston pumps. The fuel boost function for the multiple high-pressure fuel pump engines is usually provided by a single centrifugal boost element either separately mounted on the gearbox or integrated with the main fuel pump.

An alternative drive means has been used for the centrifugal augmentor fuel pump in some applications. An air turbine utilizing engine compressor bleed has been used as a drive source. When the system is non-operational, the pump may be stopped or idled by throttling the turbine inlet air supply, thereby conserving power.

For large engines, such as those used on commercial airlines, the boost stage is a conventional centrifugal element that generally incorporates an axial inducer. For smaller engines used on general aviation and helicopter applications, various specialized centrifugal elements and jet pumps have been used and have shown the capability of meeting the needs of suction feed fuel systems.

As discussed the engine boost pump must function with the airframe boost pump in both the operating and failed, or not operating, conditions. The engine fuel inlet pressure with the airframe boost pumps operational is generally specified over a range from

TABLE 1 Main fuel pump parameter chart

Engine Application and Engine Power	Gear Stage Displacement in^3/rev (cm^3/rev)	Rated Input Speed RPM	Rated Output Flow GPM (m^3/h)	Rated Pressure Rise lb/in^2 (bar)	Unit Weight Pounds (kg)
• Commercial Airliner • 68,000 Pounds (302 kN) Of Thrust	3.487 (57.142)	6270	86 (19.53)	1250 (86.2)	34 (15.42)
• Fighter Aircraft • 28,000 Pounds (124 kN) Of Thrust	2.341 (38.36)	6075	55.2 (12.54)	1390 (95.8)	24.5 (11.11)
• Executive Jet • 5,000 Pounds (22 kN) Of Thrust	.631 (10.34)	6300	15.5 (3.52)	1200 (82.7)	12 (5.44)
• Helicopter • 650 H.P. (485 kW)	.233 (3.818)	4205	4 (.91)	1000 (69)	4.6 (2.09)

50 lb/in^2 (3.45 bar) to 5 lb/in^2 (.345 bar) plus TVP for all engine operating conditions. There are to be no vapor or air bubbles present in the fuel. For the condition of failed, or non-operating, air frame boost pumps, the engine boost pump is required to operate with an inlet vapor-to-liquid volume ratio (V/L) of .45 at the maximum fuel tank temperature for takeoff conditions to at least a 10,000 ft (3048m) altitude (to cover high altitude airports) and appropriate V/L and fuel temperature conditions for maximum continuous thrust conditions up to 45,000 ft (13,716m). The V/L condition occurs because of the line pressure drop that occurs between the fuel tank and the engine boost pump inlet. This is depicted in Figure 7. The value of the V/L ratio is defined as the volume of vapor divided by the volume of fuel. A V/L of .45 represents a void volume ratio of approximately 30 percent.

Because the engine mounted boost pump is line-mounted and is external to the airframe fuel tank, the vapor entrained by the fuel cannot be ejected back to the tank as it is with the tank-mounted airframe pumps. All the vapor must be ingested by the boost pump and be compressed and re-dissolved back into the fuel. If the boost stage becomes overwhelmed by vapor, the vapor will build up at the pump inlet and the system will become vapor locked. This must be absolutely avoided.

The value of .45 for the take-off V/L ratio has been established over the years as a value that will provide adequate vapor lock margin. See Reference 2 for a history of the V/L parameter. Airframe systems are analyzed to ensure the margin is maintained. The reduced usage of wide cut fuels in the future will somewhat relieve this requirement. Figure 8 presents the relationship between V/L and tank altitude. Note that for a constant value of V/L, as the tank altitude level increases, the pump inlet pressure, and therefore its *NPSH,* decreases.

In addition to the magnitude of the V/L ratio and the boost pump *NPSH,* the condition of the multiphase flow is important. To ensure continuous and stable operation of the system, the phases must be well mixed and have equal transport velocities. An operating limit is reached when the phases separate and transport velocities of the vapor phases are less than that of the liquid phase. Under these conditions, vapor will collect at a high point in the system. In time, the system will become unstable if some means of removing this collecting vapor is not provided. A rule of thumb for roughly estimating this transition point is a minimum velocity of 3 ft/sec (1 m/s) for the liquid phase occupying the full diameter of the pipe. For velocities below this level, the probability that phase separation will occur increases. In practice, an adequate mixing of the phases is maintained in pump tests that are run to prove the pump will meet the emergency conditions as previously defined.

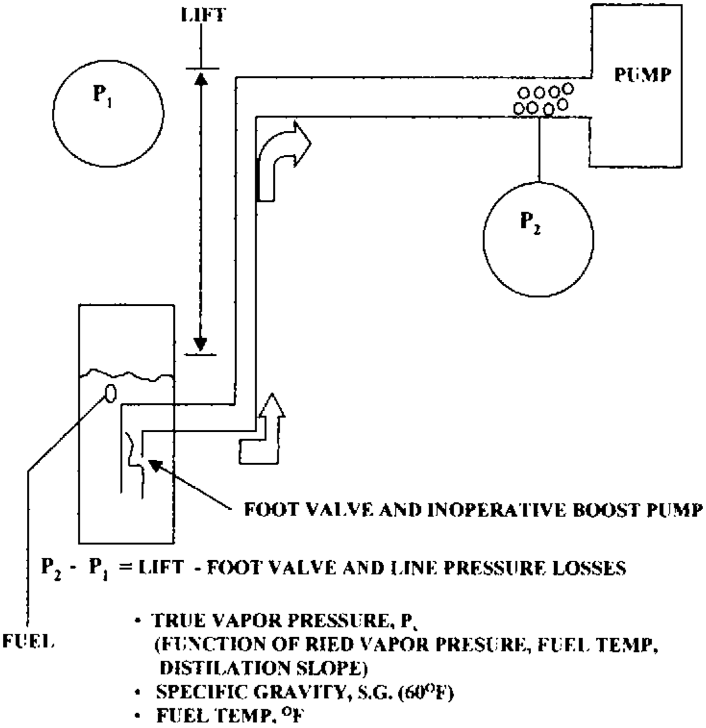

FIGURE 7 Factors that determine V/L ratio. $V/L = O \times (P_1 - P_2)/(P_2 - P_v)$, where the Ostwald coefficient O for typical fuels is in the range 0.1 to 0.2, depending upon these factors. Pressures P are absolute. [°C = (°F − 32) × 0.556]

For the suction-feed fuel systems employed on some helicopters, the uniform mixing of the vapor and liquid phases may not be maintained for all operating conditions. As previously discussed, these systems operate continuously under fuel-vapor-forming pump inlet conditions for all engine operating conditions; that is, from flight idle to maximum contingency power at all altitudes. Depending upon the engine fuel flow requirements, the fuel temperature and type and the fuel line configuration, separation of the liquid and vapor phases may occur. Because of the significant vertical pipe runs in these systems, this separated flow may exist in the form of alternating "slugs" of vapor and liquid flow in the line. When flow conditions of this type occur at the inlet to the engine fuel boost pump, a reserve volume of fuel must be provided within the pump. It is necessary to maintain a continuous flow of liquid fuel to the engine combustors for the time period when the vapor slug is being ingested by the pump and being compressed and redissolved into the fuel. Figure 9 is a pictorial presentation of the potential vapor and liquid flow conditions at the pump inlet. References 3 and 4 present a detailed review of these flow conditions.

DESCRIPTION OF THE DESIGN OF MAIN FUEL PUMPS

In this subsection, the design of a main fuel pump utilizing an external spur gear high-pressure element for application on engines powering modern airliners will be discussed. The designs of main fuel pumps for engines powering other classes of aircraft such as military fighters, executive aircraft, and helicopters are similar and differ mainly in the

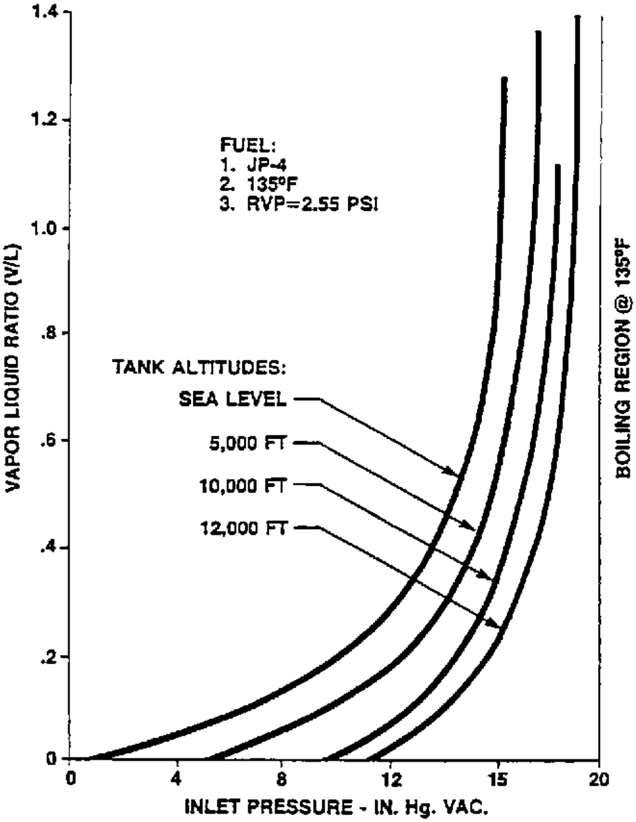

FIGURE 8 Vapor/liquid ratio versus inlet pressure (m = ft × 0.3048; bar = psi × 0.06895; °C = (°F − 32) × 0.556; mm Hg = in Hg × 25.4)

details of size and specific operating requirements. The flow and component schematic of a typical commercial engine main fuel pump is presented by Figure 10. The components encompassed by the dotted square are contained within the pump. As shown, the fuel from the airframe system enters the boost stage inlet. It then passes through the engine oil-to-fuel cooler where the fuel absorbs rejected engine heat, thereby fulfilling its function as a heat sink. This positioning of the oil-to-fuel cooler also provides the de-icing function for the next component in the system, the engine fuel filter. Using the engine oil-rejected heat for the de-icing function eliminates the need for fuel heaters using engine compressor bleed air as the heat source. These types of systems were used on previous generations of engines incurring weight and engine efficiency penalties.

Fuel filters are usually rated at 10 microns nominal and 40 microns absolute. The minimum filter surface area is usually determined by the worst icing condition. A filter bypass valve is provided to ensure continuous engine fuel flow in the event the filter becomes blocked. An indicator is provided to indicate impending filter bypass so maintenance actions can be initiated.

The fuel then enters the high-pressure gear stage element and is delivered to the engine fuel control unit at a pressure determined by the downstream resistance characteristics. A high-pressure relief valve is utilized for burst protection for the high-pressure components of the fuel system in the event of a downstream blockage.

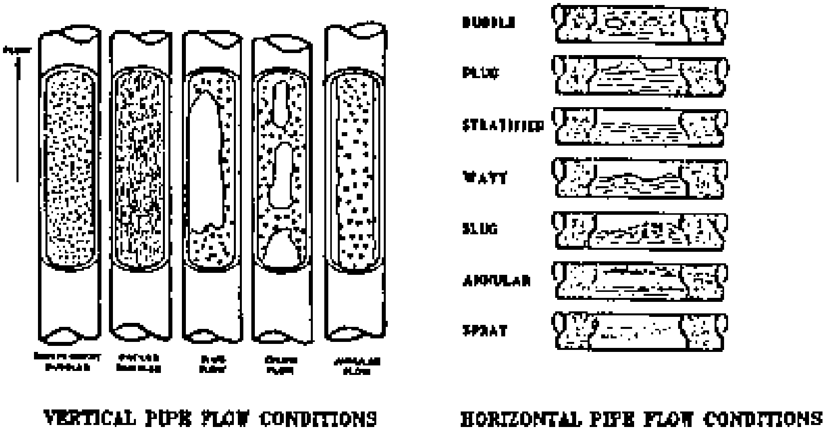

FIGURE 9 Possible multiphase flow conditions at pump inlet

The control of the engine fuel flow is achieved in the fuel control system by bypassing the excess fuel back to the fuel pump upstream of the fuel oil cooler. This returned flow represents waste heat that is proportional to the quantity of the bypassed flow and the pressure differential between the gear stage and boost stage discharge pressures. This waste heat further increases the gear stage fuel inlet temperature.

The volumetric flow characteristics of positive displacement pumps closely match the fuel flow requirements of aircraft gas turbine engines. The ideal volumetric flow rate of a positive displacement pump is directly proportional to its rotational input speed. In actual practice, this is somewhat modified by the internal leakage flows that occur from the high-pressure discharge to the low-pressure inlet. These leakage flows are a combination of flow through the clearances between the pump parts and the necessary bearing lubrication and cooling flows. Also, leakage flows are proportional to the pressure rise across the pump and essentially constant over the operating speed range of the pump. Therefore, the leakage flows are a higher percentage of the ideal flow for lower percentages of rated pump speed. The percentage of the ideal flow that the delivered flow represents is the volumetric efficiency of the pump. Figure 11 depicts the basic relationship between the output characteristics of a positive displacement pump and the engine fuel flow requirements.

As previously discussed, the main fuel pump is required to provide both the engine burn flow requirements and the engine geometry actuation flow requirements. For a given class and type of engine (for example, commercial airline turbo fan engines), the engine geometry actuation flows are usually an essentially constant value for all engine speeds for a given number of actuator servos. Therefore, because of the volumetric characteristics of positive displacement pumps, the displacement sizing point of the high-pressure element for larger engines will tend to be the rated take-off power high pump rotational speed condition. For smaller engines, it will tend to be the starting low pump rotational speed condition. The example in Figure 11 is sized at the starting condition. The disadvantage of this type of pump concept, clearly shown in Figure 11, is the significant over-capacity of the high-pressure element for low engine power conditions such as the idle condition. This over-capacity represents the quantity of waste heat in the form of throttling loss in the bypass control loop that complicates the engine heat management system. The task is to avoid reaching the fuel thermal stability temperature limit (about 325°F/163°C) in the combustor fuel nozzles. Exceeding this limit will result in clogging the nozzles with fuel "coking" deposits. Significant effort has been expended on alleviating this problem through the application of variable displacement pumps. These efforts have not achieved general acceptance because of reliability, safety, and cost disadvantages.

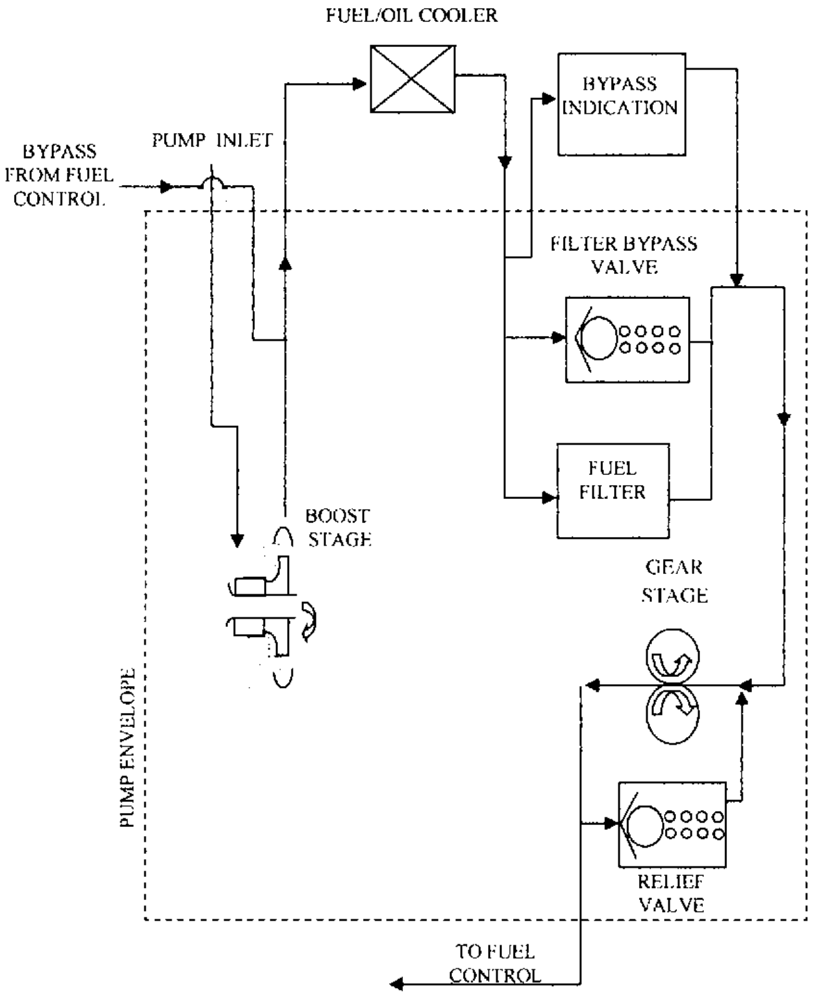

FIGURE 10 Main fuel pump system schematic

Figures 12 and 13 present a photograph and a cross-section of a main fuel pump incorporating an external spur gear high-pressure stage and centrifugal boost stage. The pump is mounted directly to the engine gearbox and the rotational input power is transmitted directly to the spur gear stage by a spline coupling. The boost stage is driven by a secondary splined coupling. The drive priority is selected to reflect the power input order of the elements and that the high-pressure element is the primary pumping element. The housings are aluminum castings that provide the minimum weight and also provide the necessary structural integrity and stiffness for all specified conditions.

A face-type dynamic mechanical shaft seal is provided at the drive end of the pump. A wide range of design configurations have been employed, but all modern pumps utilize the sealing faces as the primary seal and "O" rings for the secondary seal. These seals are required to operate with pressure differentials in both directions. Special design features must be employed to accommodate this requirement. The drive shaft seal is vented to a

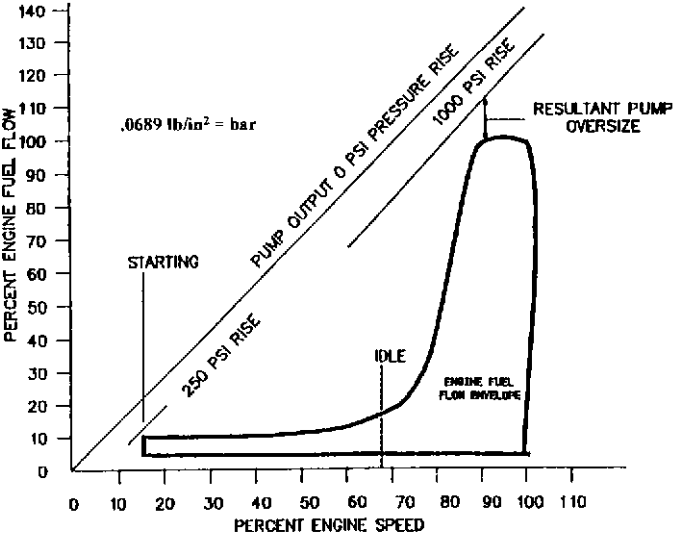

FIGURE 11 Positive displacement pump output characteristic versus engine flow requirements

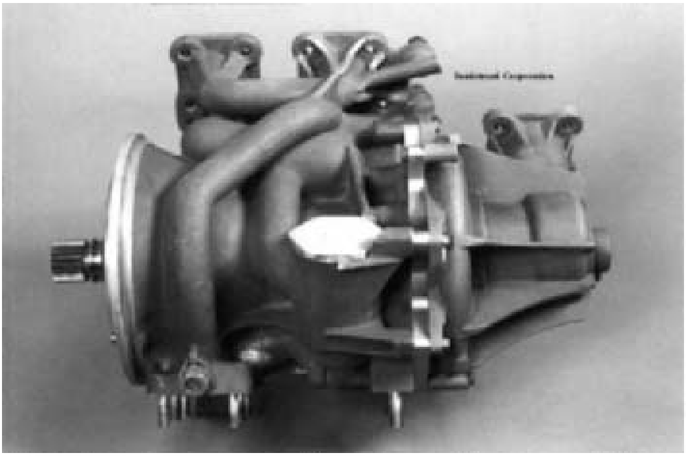

FIGURE 12 Main fuel pump assembly (Courtesy Hamilton Sundstrand)

dry cavity that is connected to the engine overboard drain system. For reasons of safety, all fuel and oil passages separated by seals, static or dynamic, must have double seals with a drain port between them.

The type of external spur gear pump element used in main fuel pumps is the fully pressure-loaded type. Figure 14 depicts the basic details of the configuration used. The six parts shown in Figure 14 are assembled into a figure-eight bore arrangement in the pump housing. The four bearing blocks, which are a slip fit, are pressure-loaded towards the faces of the spur gears, and the assembly as a whole is pressure-loaded towards the inlet side of the housing bores. An initial axial sealing force is provided by springs. The axial

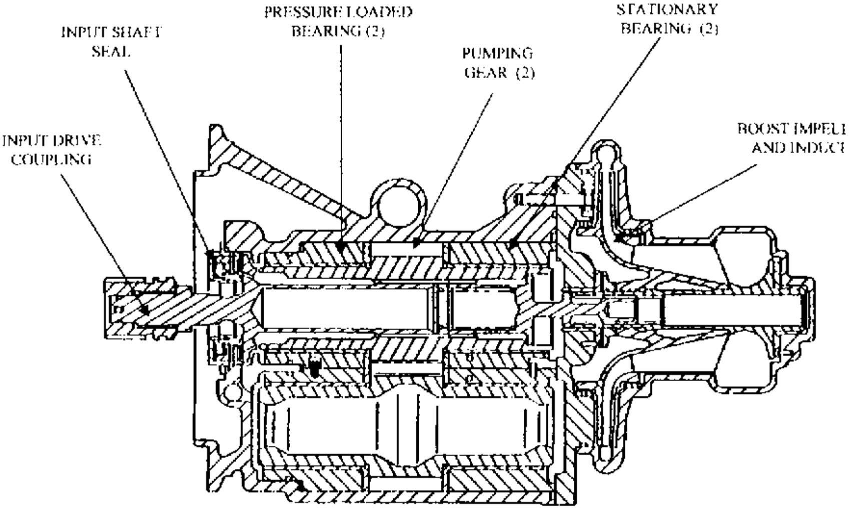

FIGURE 13 Main engine fuel pump cross section (Courtesy Hamilton Sundstrand)

pressure blow-off and pressure loading forces are closely balanced. This provides a pressure-balanced seal between the end faces of the spur gears and the bearings. This minimizes leakage over a wide range of delivery pressures on low viscosity jet fuels. The overall arrangement provides the necessary flexibility to maintain the minimum possible leakage clearances between the discharge and inlet over the complete range of operating conditions for many thousands of hours of operating life. The inherent flexibility of the design provides it with the unique capability of automatically compensating for the differing rates of thermal expansion of the materials used in the construction of the pump and the wear that will inevitably occur in usage.

The gears are manufactured from highly alloyed tool steels and surface hardened to resist wear in the harsh environment of low viscosity and low lubricity aircraft gas turbine fuels. The gear profile, lead error, and tooth spacing are held to very low limits. The roundness of the gear journals is also held to a very close limit and a mirror-like finish is applied. These journal dimensional characteristics are required because of the very low film thickness (6 to 30 micro inches or 0.15 to 0.76 microns) encountered. This is attributed to the low viscosity of hot aircraft gas turbine fuel (1 to .5 centipoise). The bearing surfaces, radial and thrust, are a highly leaded bearing bronze alloy generally with a solid film lubricant coating to assist in the initial "bedding" in.

The bearings are designed to provide full film lubrication for all operating conditions with the exception of the starting condition. On some pumps, a hybrid bearing design that incorporates a high-pressure pad to augment the bearings load carrying capacity is used. The bearing thrust faces contain gear trapping relief cuts that control the gear mesh flow dynamics. This includes avoiding any fluid trapping conditions, controlling gear stage inlet and discharge pressure pulsations. Figure 15 is a photograph of a gear set with two of the bearings.

The design of the centrifugal boost stage is quite similar to that used for the airframe boost elements. The inlet must be sized to handle the total inlet flow rate consisting of the vapor phase and the liquid phase. The use of axial inducers has become common on all sizes of pumps because of the severity of the required inlet conditions. The selected overall pressure rise of the boost stage is primarily dependent upon the temperature and, therefore, vapor pressure of the fuel at the entrance to the high-pressure element and the various pressure losses between the boost stage discharge and the high-pressure element

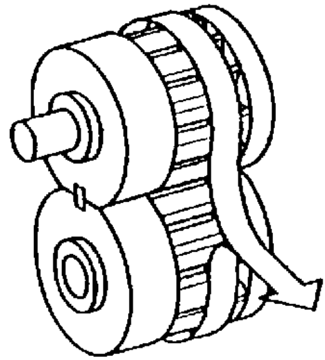

FIGURE 14 Pressure-loaded spur gear pump

FIGURE 15 Spur gear pump gears and bearings (Courtesy Hamilton Sundstrand)

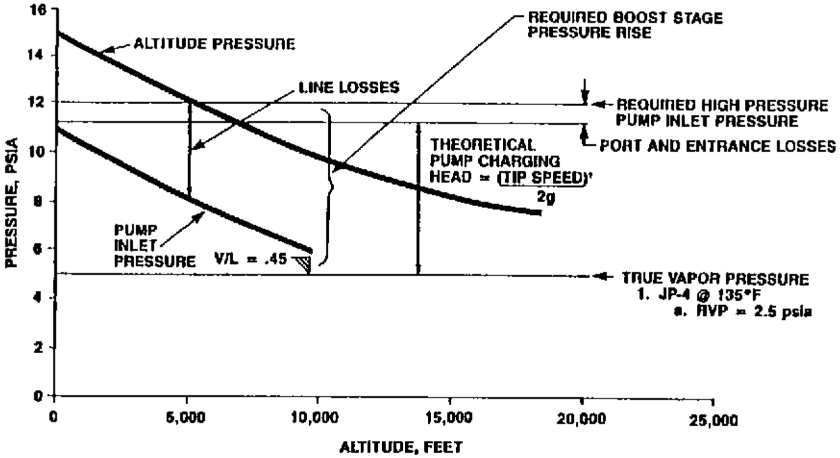

FIGURE 16 Typical pump inlet pressure stack (bar = 0.06895 × psi; °C = (°F − 32) × 0.556; m =ft × 0.3048)

inlet. These pressure losses include filter pressure losses (clean filter and clogged filter), oil-to-fuel cooler pressure losses, and various coring and plumbing pressure losses. A pressure "stack" analysis between the boost stage inlet condition and the gear stage inlet pressure requirement must be made for all operating conditions across the pump input speed range —including the emergency conditions—to determine which operating condition is the critical sizing point for the pressure rise of the pump boost stage. A simplified example of a pump pressure stack is presented by Figure 16. Reference 5 discusses boost impeller sizing. Figure 17 is a photograph of various impellers and inducers that have been used in airframe and engine fuel pumps. The specific speeds in units of feet of fluid, gpm, and rpm range from 500 to 6000 (universal specific speed $\Omega_s = 0.18$ to 2.2) and suction-specific speeds in the same units range up to 40,000 (14.6).

FIGURE 17 Various impellers and inducers (Courtesy Hamilton Sundstrand)

With respect to boost stages, particular attention must be paid to minimize the conduction of heat from the hot high-pressure stage to the relatively cool boost stage. This is required to avoid the possibility of vapor lock through fuel "boiling" in low-pressure regions of the boost stage under conditions of low fuel burn flow rates and, therefore, low boost stage through flow rates. These conditions generally occur at engine idle and descent operating conditions.

The pump-splined drive couplings are key to the reliability and safety criteria of the pump. Similar to the pump gears, the splined couplings are fabricated from high alloy steels with a surface hardening treatment. The design of the involute splines in terms of profile wear must take into account the lubricant used for the splines and the misalignment imposed by the various drive line elements. A spline design that will satisfy the wear conditions at rated speed will generally meet all overload conditions, including the maximum shaft shear torque requirements. Spline lubricants that have been successfully used include engine oil, fuel, and specially blended greases. Specific spline design parameters must be applied for each lubricant.

PERFORMANCE CRITERIA OF ENGINE MAIN FUEL PUMPS

The key performance criterion for the high-pressure positive displacement stage of a main fuel pump is to be capable of delivering the volumetric fuel flow rate required by the engine for all operating conditions. Before it is released for flight usage, the test sequence with which the positive displacement stage must successfully comply is primarily directed at evaluating the durability of the stage under the most extreme conditions it is expected to encounter in service. There are success criteria for these tests. At the completion of each individual test, the stage must meet its specified volumetric flow service limits. Upon completion of all the tests, the unit is subjected to a teardown inspection and the component parts must not exhibit any unusual wear or distress and must be in a condition that is deemed acceptable for continued service.

The key performance criterion of the boost stage is to provide adequate pressure to the inlet of the gear stage to suppress fuel vaporization and cavitation for all operating conditions; that is, with assistance from the airframe boost pumps and the emergency conditions without assistance from the airframe boost pumps. The tests that confirm this capability are run in conjunction with the positive displacement stage and are subject to similar success criteria. The performance criteria that specifically determine the design of the boost and high-pressure main fuel pump are presented in the following discussions.

GEAR STAGE VOLUMETRIC PERFORMANCE

The engine fuel flow requirements are specified in mass units. These must be converted to volumetric flow units for the lowest density fuel specified for all operating conditions. For these volumetric flow rates, the displacement required for each operating condition is determined by applying factors for pump volumetric efficiency that encompass the temperature of the fuel, production variance, and the service life flow deterioration. When the critical displacement sizing operating condition has been established, the overall volumetric performance of the pump can be defined for the complete input speed and pressure rise operating range including the required input power. Figure 18 presents the overall performance characteristic of a pressure-loaded external spur gear high-pressure stage of an aircraft engine main fuel pump.

GEAR STAGE CYCLIC DURABILITY

The ability of the pump to accept the cyclic duty imposed by modern engines without distress has been an accurate predictor of the pump's capability of meeting its service life requirement. The test is based upon the real-time pressure, temperature, and speed transients for engine operating conditions such as starting, ground idle, takeoff and climb, cruise, descent, and thrust reverse.

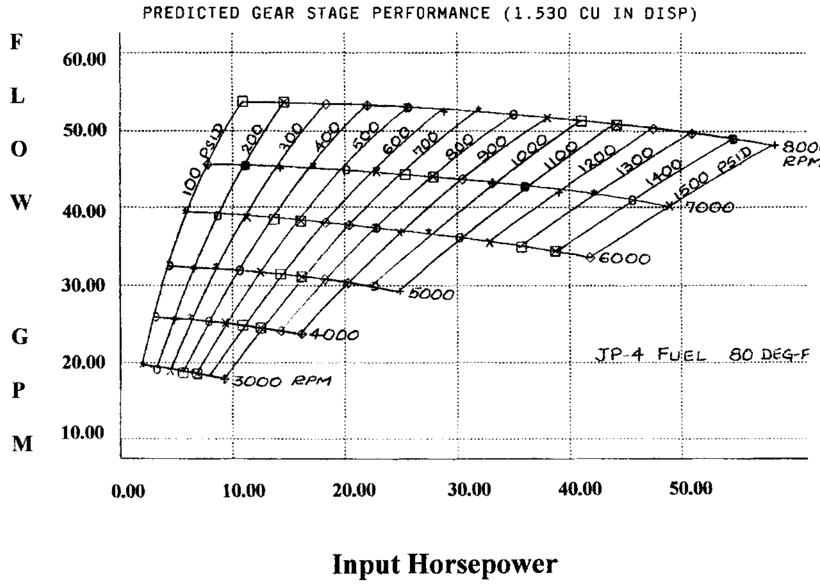

FIGURE 18 Gear stage performance (m³/h = 0.227 × gpm; kW = 0.7457 × hp; bar = 0.06895 × psi; liter = 0.0164 × in^3; °C = (°F − 32) × 0.556)

The worst cases for the sequencing of the transients are selected to achieve the highest levels of stress in the gear and bearing system. The real transient times are halved and the steady state operating times minimized to accelerate the test. The number of test cycles and overall test time are based upon the expected service life of the pump.

LOW LUBRICITY FUEL

The use of the pumped fuel as the lubricant for the pump and all components within the fuel system is an established and required practice. Unfortunately, there is no requirement for lubricity in the fuel specifications. Therefore, some knowledge of the minimum lubricity to be expected in the field is necessary. The key factor to determine is the lubricity of the fuel under boundary lubricating conditions for evaluating the wear characteristics of the gear tooth profiles and the fuel lubricated spline teeth. An intensive cooperative industry and government evaluation effort has identified the Exxon ball and cylinder wear test machine as an accurate and reliable method of evaluating the lubricity characteristic of aircraft gas turbine fuels. The pump specification will contain the fuel lubricity level with which the pump will be required to demonstrate operation for its intended service. The pump designer must select gear materials and geometries that are compatible with the specified lubricity level and operating conditions. Wear experienced on low-lubricity fuel is a threshold type of surface failure. Therefore, this threshold limit must be avoided for all operating conditions. The test for compliance with this requirement is usually operation at take-off and cruise conditions on the specified fluid at controlled lubricity conditions. The fluid lubricity level is checked periodically to ensure compliance is met. See Reference 6 for a detailed description of the test procedure.

COLD STARTS

Cold start tests demonstrate the capability of the pump to provide the performance necessary to start the engine under the most severe cold conditions expected and to demonstrate that the fits and clearances in the pump are compatible with the low temperatures. The cold start requirement ranges from −40°F (−40°C) to −65°F (−53.9°C), depending upon the fuel used and service expected.

CONTAMINATED FUEL

The large amount of fuel an engine burns in operation and the widely varying service conditions worldwide virtually ensures that some contaminants will be introduced into the engine's fuel system. In addition to these operational contaminants, there will be built-in contaminants because of the complexity of the airframe and engine fuel system that will be experienced in the initial operation of the pumps. Tests are specified that define operation of the pump at various operating conditions on fuel containing both liquid and solid contaminants. These included salt water, quartz crystals, sand, and iron oxide ranging in particle sizes from 1500 microns to less than 5 microns. These tests are more severe for military applications than commercial applications. Military applications usually require the contamination to be metered into the inlet of the pump in relation to the fuel flow rate and then removed from the system downstream of the pump by a filtration system. Hence, the contaminant is passed through the pump in a continuous single pass manner. In all modern fuel systems, the high-pressure positive displacement stage is protected by the engine-mounted fuel filter element. The low-pressure boost stage is not protected by the engine-mounted filter element. Although the centrifugal boost stage is inherently capable of operating on the specified contaminant, special design features are employed to minimize the abrasive wear effects of swirling contaminated fuel.

V/L CAPABILITY

The reason for the need of the boost stage of an engine main fuel pump to have a V/L capability and some detail of the design requirements has been presented in previous discussions. The test set-up used for V/L testing is similar to the example shown in Figure 7. The testing is usually accomplished in two parts. Both parts are run with the maximum fuel RVP expected in service. The first part is to evaluate the V/L performance of the pump at all of the specified emergency conditions and prove all conditions can be met. The second part is an endurance test at high V/L conditions to ensure that no excessive cavitation erosion damage occurs that could limit the performance or life of the pump.

MINIMUM INLET PRESSURE

As long as the main fuel pump is being assisted by the airframe boost pumps, it must meet a minimum inlet pressure requirement. This inlet pressure is 5 lb/in^2 (0.345 bar) above the true vapor pressure (TVP) of the fuel. At this condition, the main fuel pump is required to supply the required engine fuel flow for all operating conditions. The design procedure and details for meeting this requirement were previously discussed.

The test set-up is arranged to ensure that vapor-free fuel is provided to the inlet of the fuel pump at 5 lb/in^2 (.345 bar) above TVP for all operating conditions. Heat exchangers are introduced into the system as required to establish the required boost and gear stage inlet temperatures. The full range of hot operating conditions, including the critical altitude idle conditions, are run to ensure vapor lock conditions do not occur. The maximum fuel RVP expected in service is used.

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