SAE Aerospace
An SAE International Group

AEROSPACE INFORMATION REPORT

SAE AIR1245 REV. A

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(R) Power Sources for Fluidic Controls

RATIONALE

This document has been reaffirmed to comply with the SAE 5-year Review policy.

FOREWORD

As noted by the symbol (R) preceding the title on the title block of this document, AIR1245A has been rewritten and expanded from a 10 page document to a 33 page document.

Fluidics is a control technology that relies on the interaction of fluid streams to provide sensing, amplification, filtering, signal conditioning, signal summing, fluidic logic, feedback sensing and implementation, and other control functions. Pure fluidics employs no moving part devices, but most operational fluidic systems employ moving part peripheral elements such as linear and rotary motion sensors, valves, actuators, switches, push buttons, and other devices that provide inputs to and outputs from the fluidic elements in the system.

Since the original release of this document, significant changes have occurred in fluidic technology, operating pressures, power conditioning, and the options available in the source of power, particularly in the case of hydraulic-oil-based fluidic systems. In the 1960s and 1970s fluidics was oversold both on its capabilities and on the state of the art at that time. The result was that engineers and managers who might have applied it became disenchanted and the natural evolution of high technology fluidics slowed drastically. In fact it is only now beginning to emerge as a viable technology for application in sensing, signal transmission, signal processing, and control of high power actuation systems. Current state of the art fluidics offers significant advantages over electronics when requirements call for:

a. Very high reliability
b. Operation in a harsh environment - high temperature, E3 (electromagnetic environmental effects), EMI, EMP, directed beam weapons, and vibration
c. Protection from or immunity to nuclear and electromagnetic radiation or directed beam weapons
d. Nonelectronic active control
e. Lightweight
f. Low cost

Fluidics is capable of relatively high performance in terms of band pass/frequency response. The response is not as high as that of electronic systems, but meets most requirements for aerospace applications, including flight control. The equivalent time delay, from input to output of the actuator, is approximately the same as that of a typical digital fly-by-wire flight control system.

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FOREWORD (Continued)

Fluidics may be implemented in either gas or liquid-based systems. Liquid-based systems usually use aerospace hydraulic system fluids and usually use prime hydraulic systems as their power source with pressure control and conditioning devices to provide the typical power supply for the fluidic systems. Gas-based systems are usually powered by bleed air from aircraft air-breathing engines, pneumatic pumps, or by hot or warm gasses from products of combustion or by bottled cold gas supplies. In addition to the functions noted, both gas and liquid-based fluidic systems, provide: interfaces with high power actuation systems; inputs from rate and acceleration sensors; gain changing; actuator ram position feedback; and inputs from manual and other mechanical inputs. Manual and other mechanical input devices, feedback interfaces, and actuation system interfaces include both moving parts and fluidic components, and they are usually integrated into a control module.

It is recognized that all of the information, specification parameters, nomenclature, symbology, test procedures, and instrumentation cannot be complete at this stage of development of fluidic technology. This document will be revised as the technology and applications develop.

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1. SCOPE:

This SAE Aerospace Information Report (AIR) presents a review of the types and general characteristics of power sources that may be used to provide the power for gaseous or liquid fluidic control systems. Fluidic definitions, terminology, units and symbols are defined in Reference 2.1.1.

1.1 Field of Application:

The power systems described and the data contained herein apply to all types of aerospace vehicles including: aircraft, helicopters, missiles, space vehicles, remotely piloted vehicles, or in any other vehicles or applications to which aerospace technology applies.

1.2 Definition:

Fluidics is a control technology that relies on the interaction of fluid (liquid or gaseous) streams to provide sensing, amplification, filtering, signal conditioning, and other control functions. Pure fluidics employs no moving-part devices, but most operational fluidic systems employ some moving-part peripheral elements such as linear and rotary motion sensors, valves, actuators, switches, push buttons, and other devices that provide inputs to and outputs from the fluidic elements in the system.

1.3 Purpose:

The information in this document is intended to be used as guidelines in the selection of power sources most appropriate to the requirements and characteristics of a particular vehicle or system. It may also be used verbatim or as a guideline in the preparation of system or power source specifications. Considerations, problem areas and benefits of the various power sources and configurations are presented in order to assist in conducting trade studies and evaluations.

More detailed information on fluidic control technology, fluidic test methods and instrumentation, and power sources for other applications is available in SAE AIRs and in SAE ARPs. These and other references are all listed in Section 2.

2. REFERENCES:

2.1 Applicable Documents:

The following publications form a part of this specification to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this specification and references cited herein, the text of this specification takes precedence. Nothing in this specification, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1.1 SAE Publications: Available from SAE, 400 Commonwealth Drive, Warrendale, PA 15096-0001.

2.1.1.1 ARP993 Fluidic Technology

2.1.1.2 AIR744 Auxiliary Power Sources for Aerospace Applications

2.1.2 U.S. Government Publications: Available from DODSSP, Subscription Services Desk, Building 4D, 700 Robbins Avenue, Philadelphia, PA 19111-5094.

2.1.2.1 James W. Joyce, "A Catalog of Fluidic C-Format Laminates", U.S. Army Electronics Research and Development Command, Harry Diamond Laboratories Report No. HDL-SR-83-2, March 1983

2.1.2.2 James W. Joyce, "Design Guide for Fluidic Laminar Proportional Amplifiers and Laminar Jet Angular Rate Sensors", U.S. Army Electronics Research and Development Command, Harry Diamond Laboratories Report No. HDL-SR-84-6, September 1984

2.1.2.3 James W Joyce and Richard N. Gottron, "Basic Components and Applications", U.S. Army Electronics Research and Development Command, Harry Diamond Laboratories Report No. HDL-SR-83-August 1983

2.1.2.4 MIL-STD-1306 Fluerics: Terminology and Symbols, 8 December 1972

2.1.2.5 MIL-STD-1361 Fluidics: Test Methods and Instrumentation, 28 September 1973

2.1.2.6 MIL-H-5440 Hydraulic Systems, Aircraft, Types I and II, Design, Installation and Data Requirements

2.1.2.7 MIL-P-5518 Pneumatic Systems, Aircraft, Design, Installation and Data Requirements for

2.1.2.8 MIL-H-8891 Hydraulic Systems, Manned Flight Vehicles, Type III, Design, Installation and Data Requirements for

2.1.2.9 MIL-H-25475 Hydraulic Systems, Missile, Design, Installation, Tests and Data Requirements

2.1.2.10 MIL-P-5954 Pump Unit, Hydraulic, Electric Motor Driven, Fixed Displacement

2.1.2.11 MIL-P-5994 Pump, Hydraulic, Electric Motor Driven, Variable Delivery

2.1.2.12 MIL-C-6388 Compressor Unit, Air, Aircraft, Shaft Driven, General Specification for

2.1.2.13 MIL-C-6591 Compressor Unit, Aircraft, Electric Motor Driven, General Specification for

2.1.2.14 MIL-V-7909 Valves, Hydraulic, Pressure Reducer

2.1.2.15 MIL-P-19692 Pumps, Hydraulic, Variable Delivery, General Specification for

2.1.2.16	MIL-T-25363	Tank, Pneumatic Pressure, Aircraft, Glass Fiber
2.1.2.17	MIL-C-26805	Compressor Units, Air, General Requirements for
2.1.2.18	MIL-A-5498	Accumulators, Aircraft Hydropneumatic Pressure
2.1.2.19	MIL-F-5504	Filters and Filter Elements, Fluid Pressure, Hydraulic Micronic Type
2.1.2.20	MIL-P-7858	Pump, Hydraulic, Power Driven, Fixed Displacement
2.1.2.21	MIL-C-7905	Cylinders, Compressed Gas, Nonshatterable
2.1.2.22	MIL-R-8572	Reducers, Pneumatic Pressure, Aircraft
2.1.2.23	MIL-F-8815	Filter and Filter Elements, Fluid Pressure, Hydraulic Line, 15 Micron Absolute, Type II Systems
2.1.2.24	MIL-F-27656	Filter, Fluid, Pressure, Absolute 5 Micron, Hydraulic
2.1.2.25	MIL-H-5606	Hydraulic Fluid, Petroleum Base, Aircraft and Ordnance
2.1.2.26	MIL-H-83282	Hydraulic Fluid, Fire Resistant, Synthetic Hydrocarbon Base, Aircraft
2.1.2.27	MIL-H 6083	Hydraulic Fluid, Petroleum Base, Preservative
2.1.2.28	MIL-P-8686	Power Units, Aircraft Auxiliary, Gas-Turbine-Type, General Specification for
2.1.2.29	MIL-H-8446	Hydraulic Fluid, Nonpetroleum Base, Aircraft
2.1.2.30	MIL-H-46004	Hydraulic Fluid, Petroleum Base, Missile
2.1.2.31	MIL-H-81019	Hydraulic Fluid, Petroleum Base, Ultra-low Temperature
2.1.2.32	MIL- E-5007	Engine, Aircraft, Turbojet and Turbofan, General Specification for

3. POWER SOURCES FOR FLUIDIC CONTROLS:

A variety of power sources are available for fluidic control systems. Tables 1 and 2 list the typical sources of fluidic power and also include, for each power source, a list of applicable documents and military specifications. These applicable documents and military specifications are listed in Section 2.

The first decision, whether to use a gas or a liquid-based system, is usually defined by performance requirements, system requirements, the environment, and the unique advantages and problem areas associated with gas or liquid-based systems. With each type of system there is a choice of basic power sources available and a further choice in power supply configurations. Just as an electronic circuit needs a clean source of electrical power at a constant voltage and a dependable and clean ground, so does a fluidic circuit need a supply of clean gas, or oil, at a constant pressure and a constant return line pressure. Venting fluidic elements to return is akin to making a good ground in electronics; the quality of the ground has an important effect on overall system performance.

3.1 Types of Power Sources:

The most widely-used types of power sources are described below. These power sources provide energy in the form of gas or liquid flow at various pressures and temperatures. In some cases, energy conversion equipment may be required to convert the energy from another source to the gas or liquid supply, such as from a gearbox to a liquid- based system, or from one liquid/hydraulic-based system to a gas-based or another liquid-based power system.

The most widely used sources of fluidic power are:

a. Turbojet or turbofan engine bleed air
b. Bottle/accumulator stored cold gas for missiles
c. Warm or hot gas generator systems for missiles
d. Liquid-based systems using aircraft prime hydraulic system power with pressure reducers and power conditioning (usually pressure and flow reducers/conditioners)
e. Independent liquid (preferably hydraulic fluid) based systems including fluidic power system pump(s), accumulators, power conditioning, etc. These systems can be powered by hydraulic motors operating from: the aircraft prime hydraulic systems; engine driven gearboxes; electric motor(s) driven by the aircraft electric power systems; or other power sources.
f. Fuel from the engine fuel system

Each of the systems described above has distinct advantages, disadvantages and problems in terms of performance, influences of the operating environment, temperature ranges, influences of the operating medium, readily available power, reliability, maintainability, logistic support, cost, and weight (see Table 3). Relatively extensive trade studies are required to select a near-optimum medium and operating pressure. Table 3 presents some typical applications and typical power sources.

Note that other power sources may apply equally well to the same application on other vehicles, depending on the requirements.

TABLE 1 - Candidate Power Sources
Power Extraction From Prime Propulsion Engine(s)

Candidate Power Source	Applicable References
GAS TURBINE	
Bleed Extraction From Flow Path at -	2.1.2
Compressor Inlet (Inlet Diffuser)	
Fan Discharge	
Compressor Interstage	2.3.4, 2.3.19, 2.3.29
Exhaust Nozzle	
Fuel at High Pressure	2.3.11, 2.3.16, 2.3.20, 2.3.22
Aircraft Hydraulic System	2.3.3, 2.3.5, 2.3.6, 2.3.7, 2.3.8, 2.3.11, 2.3.12, 2.3.15, 2.3.16, 2.3.17, 2.3.20, 2.3.21, 2.3.22, 2.2.23, 2.2.24, 2.2.25, 2.2.26; 2.2.27, 2.2.28, 2.2.29
Independent Hydraulic System	Same as above (Aircraft Hydraulic System)
Pressurized Lubrication Oil	
RECIPROCATING PISTON ENGINE	
Bleed Extraction at	
Inlet Manifold	
Exhaust Manifold	
Fuel at High Pressure	2.3.11, 2.3.16, 2.3.20, 2.3.22
Coolant System Pressure	2.3.11, 2.3.16, 2.3.20, 2.3.22
Pressure Lubrication Oil	
Aircraft Hydraulic System	2.3.3, 2.3.5, 2.3.6, 2.3.7, 2.3.8, 2.3.11, 2.3.12, 2.3.15, 2.3.16, 2.3.17, 2.3.20, 2.3.21, 2.3.22, 2.3.23, 2.2.24, 2.2.25, 2.2.26, 2.2.27, 2.2.28, 2.2.29
Independent Hydraulic System	Same as above (Aircraft Hydraulic System)
ROCKET ENGINES	
Bleed Extraction at	
Combustor Discharge	
Exhaust Nozzle	
Fuel (liquid at high pressure)	2.3.11, 2.3.16, 2.3.20, 2.3.21
Vehicle Hydraulic System	2.3.3, 2.3.5, 2.3.6, 2.3.7, 2.3.8, 2.3.11, 2.3.12, 2.3.15, 2.3.16, 2.3.17, 2.3.20, 2.3.21, 2.3.22, 2.3.23, 2.2.24, 2.2.25, 2.2.26, 2.2.27, 2.2.28, 2.2.29

TABLE 2 - Candidate Power Sources
Power Extraction From Secondary Power Sources

AUXILIARY POWER UNIT	
Bleed Extraction at	
Turbine Gas Generator	2.1.2, 2.3.4, 2.3.9, 2.3.13, 2.3.18, 2.3.19, 2.3.25
Piston Compressor Discharge	Same as above (Turbine Gas Generator)
Pressure Lubrication Oil	
Turbine Driven Liquid Pumps	
Backup to Primary Hydraulic Systems	2.3.3, 2.3.5, 2.3.6, 2.3.7, 2.3.8, 2.3.11, 2.3.12, 2.3.15, 2.3.16, 2.3.17, 2.3.20, 2.3.21, 2.3.22, 2.3.23, 2.2.24, 2.2.25, 2.2.26, 2.2.27, 2.2.28, 2.2.29
SERVO GAS GENERATORS	See AIR744A, Sections 4 and 5
Solid Propellant	2.1.2, 2.3.4, 2.3.9, 2.3.13, 2.3.18, 2.3.19, 2.3.25
Liquid Propellant	Same as above (Solid Propellant)
COMPRESSED STORED GAS	See AIR744A, Section 6
Air Vehicle Pneumatic System	2.1.2, 2.3.4, 2.3.9, 2.3.13, 2.3.18, 2.3.19, 2.3.25
Propellant Tankage Boil Off	Same as above (Air Vehicle Pneumatic System)
Life Support Gas	Same as above
RAM AIR VENTURI TUBE	
AIR VEHICLE SYSTEMS	
Flight Control Systems, Hydraulic	2.3.3, 2.3.5, 2.3.6, 2.3.7, 2.3.8, 2.3.11, 2.3.12, 2.3.15, 2.3.16, 2.3.17, 2.3.20, 2.3.21, 2.3.22, 2.3.23, 2.3.24, 2.3.25, 2.3.26, 2.3.27, 2.3.28, 2.3.29
Utility Power Systems, Hydraulic	Same as above (Flight Control Systems, Hydraulic)
Environmental Control Systems, Types A & B Servo Air	2.1.2, 2.3.4, 2.3.9, 2.3.13, 2.3.18, 2.3.19, 2.3.25

TABLE 3 - Typical Aerospace Fluidic Control Applications and Typical Power Sources

Control Application	Power Source	Power Conditioning	Power Source Advantages	Power Source Disadvantages
Flight Control	Turbojet or turbofan engine bleed air		Minimum effects of temperature variations (ambient and operating) and cost	Performance, leak detection, and contamination
Flight Control	One or more of aircraft prime hydraulic systems	Pressure regulation to the lower fluidic power pressure; filter pump ripple noise; temperature compensation to provide nearly constant Reynolds number in fluidic circuit or components as required	Performance; power source is same as power source for actuators; minimum weight for an oil based system; higher reliability	Small influence on survivability of the prime hydraulic system; survivability and reliability of the fluidic system; temperature variations; supply and return line pressure fluctuations
Flight Control	An independent hydraulic oil based fluidic power system powered from a motor/pump unit in one of two prime hydraulic systems	Temperature compensation to provide nearly constant Reynolds number in fluidic circuit or components as required; pressure regulation and filtration	Power conditioning easier to accomplish; performance due to improved power conditioning; improved survivability of the prime hydraulic system; more constant operating temperature	Reliability of the fluidic power source; cost and weight application dependent
Flight Control	An independent hydraulic oil based fluidic power system powered from two motor/pump units in each of two prime hydraulic systems or circuits of them	Temperature compensation to provide nearly constant Reynolds number in fluidic circuit or components as required; pressure regulation and filtration	Power conditioning easier to accomplish; improved survivability of the prime hydraulic system; improved mission reliability and survivability of the fluidic control system	Cost; weight; mean time between failures (MTBF) due to added pumps
Thrust Reverser Control	Engine bleed air	Pressure regulator and filtration	High temperature capability; reliability, cost, weight	Performance, leak detection, and contamination
Environmental Control System Valves	Engine bleed air	Pressure regulator and filtration	High sensitivity; no hysteresis; high reliability	

TABLE 3 (Continued)

Control Application	Power Source	Power Conditioning	Power Source Advantages	Power Source Disadvantages
Vortex Fuel Restrictor - Fuel Flow Control	Engine high pressure fuel	Pressure regulator and filtration	Unique pressure versus viscosity function; high reliability	
Gun Drive Speed Controls	Engine bleed air or stored compressed air	Two stages of regulation, two or more stages of filtration and dryers to remove moisture in stored compressed air supply	All-pneumatic technology; high reliability; less complex than hydraulic speed controls	
Automobile Windshield Washers	12 VDC electric motor driven pump in the washer fluid tank		Performance; cost; reliability	
APU Inlet Guide Vane Electrofluidic Transducers	All	Several stages of filtration and regulation	Low hysteresis; high response	
Missile Fluidic Angular Rate Sensors	Current systems are high pressure compressed gas, but fluid based systems could be used if fluid was available	Several stages of pressure regulation (also see comments under flight control applications on previous page)	Missile launch shock survivability; high reliability; no spin-up time delays	
Reaction Jet Controls	Combustion gas on solid fuel rockets; high pressure fuel on liquid fueled rockets or a gas generator	Filtration and pressure regulation	Launch shock survivability	Materials problems with very high temperature gas; contamination from combustion products
Fuel Density Sensor	Engine HP fuel	Pressure regulator and filtration	High reliability	
Engine Fuel Controls	Engine compressor air bleed or engine HP fuel	Pressure regulator and filtration	Low cost	
Anti-G Valve	Engine compressor air bleed (ECS supply)		All-pneumatic; rapid response; high reliability; easy retrofit	

TABLE 3 (Continued)

Control Application	Power Source	Power Conditioning	Power Source Advantages	Power Source Disadvantages
Diverter Valves	Combustion gas	Filtration	Very high temperature capability; high reliability	Materials problems with very high temperature gas; contamination from combustion products
Inlet Guide Vane Control on RB211 Engine	Engine compressor bleed air	Wire mesh filter; no pressure regulation	Supply pressure varies in line with system loads; supply pressure used as one of the control signals	

3.2 External Factors That Affect System Performance and Operation:

External conditions and influences can have an effect on fluidic system performance and operation. Some have more of an effect on gas-based systems while others may have more of an effect on liquid-based systems. The following influences must be kept in mind:

a. Atmospheric pressure and/or altitude
b. Ambient temperature, particularly at altitude or in space
c. Temperature of mounting surface
d. Oil, fuel, grease contamination
e. Water and salt spray
f. Vibration, shock, acceleration forces
g. Acoustic noise
h. Thermal shock

3.3 Pneumatic System Power Sources:

Three main types of gas are used to supply power used in pneumatic fluidic circuits: engine bleed air, high pressure stored gas, and gas generator output gas. Aircraft applications often use air obtained from an engine bleed air supply system. Missiles and other applications commonly use a gas such as nitrogen, stored in a vessel at pressures up to 10 000 psig (700 bar)[1]. Reaction jet and diverter valve controls usually run on the output of a chemical gas generator. Each of these power sources has certain unique qualities. Figure 1 is a schematic presentation of the three basic air/gas based fluidic power systems. Table 4 presents a comparison of gas and liquid powered fluidic systems in the areas of interest.

[1] Note: 1 bar = 100 kilopascals (kPa)

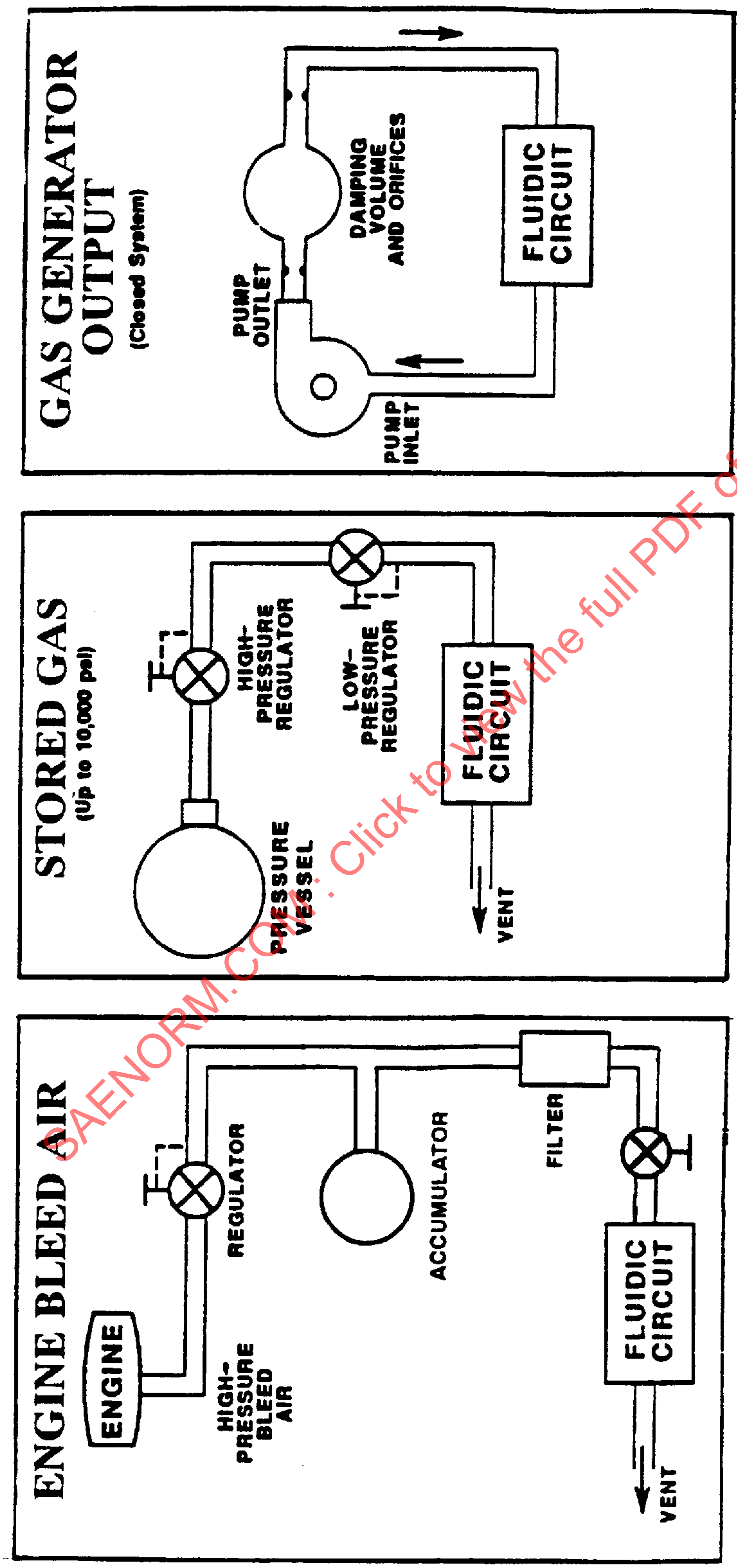


FIGURE 1 - Power Sources for Gas Based Fluidic Systems

TABLE 4 - Comparison of Gas Versus Liquid Fluidic Systems
Factors Comparison of Gas and Fluid Fluidic Systems

Factors	Gas Fluidics (Pneumatics)	Liquid Fluidics (Hydraulics)
Transmission Line Bandwidth	Lower	Higher
Weight	Lighter	Heavier
Fire Hazards	No	Yes
Altitude Compensation Requirement	Yes	No
Filter Requirement	Yes	Yes
Temperature Compensation Requirement	Yes (less severe)	Yes (severe)
Source for High Actuation Force	No	Yes
Trapped Air Bubble Concern	No	Yes
Icing/Dew Condensation Concern	Yes	No
Development Effort	Low	High
Instant Start	Yes	Yes
Leakage Tolerance	Yes	No
Operating Pressure Level	Low	High
Excellent Sealing Requirement	No	Yes
Power Consumption	Low	Higher

3.3.1 Engine Bleed Air Power: Engine compressor bleed air is commonly used for aircraft fluidic systems. The air is usually extracted from an existing bleed air system that supplies air pressures ranging from 15 to 50 psig (1 to 3 bar). Typical design factors include: temperature of the discharge air; variation of discharge pressure with altitude and/or engine speed; and contamination. Contamination occurs in the form of solid particulates, liquid lubricant droplets or vapors, and water droplets or vapor. Contamination is the only significant cause of failures in the field, so particular attention must be paid to this aspect of fluidic system design.

3.3.2 Stored Gas: Stored gas released from a pressure vessel is used most frequently in missile and reentry vehicle applications. The pressure vessel is pressurized and hermetically sealed at manufacture, and commonly uses nitrogen stored at 10 000 psi (700 bar). The vessel seal is designed to be broken by an electrically-initiated device which releases the gas pressure on command. A principal design issue is the volume of stored gas required versus the duty cycle of the application.

Transportation requirements present an issue for the use of pressure vessel stored gas as a fluidic power source. Pressure vessels require extensive qualification testing and documentation in order to permit transportation via commercial air transport because of the explosion hazard.

3.3.3 Gas Generator Power Source: The use of gas supplied by a gas generator is common for reaction jet controls and in some other missile or projectile actuation applications. The high temperature and pressure of the gas must be addressed in the material selection of the fluidic circuits. Key concerns include: material strength at or near the gas temperature; erosion and corrosion tendencies; gas volume and rate versus application duty cycle; and thermal shock capability of the base material and bonding method. The gas provided by a gas generator varies between 1700 and 4500 °F (900 and 2500 °C), or more, depending on the choice of propellant. This obviously restricts the selection of candidate materials to those with strength at the required temperatures, pressures, and other loads expected. Erosion and corrosion are problems that must also be addressed. The selected material must be chemically compatible with the constituents of the generated gas, or undesired reactions will proceed rapidly under the high temperature conditions. Thermal shock may exist from the extremely rapid heating that the fluidic circuit will undergo following initiation of the gas generator. These must be addressed, considering: the thermal shock resistance, coefficient of thermal expansion, heat transfer coefficient of the base material, and in the strength and ductility of any bond joints present.

3.4 Hydraulic Fluid-Based Power Sources:

Although there may be oils or other liquids that are a better fit with fluidic system requirements, aircraft hydraulic fluids are usually chosen because of logistic considerations. The incentives to reduce the costs of logistic support dictate that new liquids not be introduced. This applies to commercial operations as well as military operations. Also, the use of prime hydraulic system fluid eliminates any problems associated with a different fluidic fluid mixing with the aircraft hydraulic system fluid in the actuators and the control valves.

The candidate system configurations are defined in Tables 1 and 3. Table 1 lists candidate power sources and the references or specifications that apply to each one. Table 3 lists the major advantages and disadvantages of each power source. The choice of power sources for hydraulic fluid fluidic systems in fixed wing aircraft or helicopters is between a small, low pressure, independent hydraulic system dedicated to the fluidic system and one or more of the 3000 to 8000 psi (200 to 530 bar) prime hydraulic power systems of the aircraft. This independent system configuration appears to offer the most benefits and advantages for fluidic flight control systems but with a probable small increase in cost and weight. The cost and weight of the motor-pump unit must be traded against those of the supply and return pressure control and power conditioning. The advantages of the independent system are associated with:

a. Control of the temperature of the fluidic system
b. Noise in the system, primarily hydraulic pump piston ripple (pressure pulses caused by the action of the pistons in the pump)
c. Control of the pressure in the fluidic system return lines
d. Better isolation of fluidic system from pressure changes due to large actuator flow demands

Most nonflight critical applications would be powered from one of the aircraft hydraulic systems with a pressure reducer/control valve to condition the aircraft hydraulic system pressure to fluidic system requirements.

3.4 (Continued):

The normal operating temperature of commonly-used hydraulic fluids in aircraft hydraulic power systems appears to range between 100 and 210 °F (38 and 100 °C) after the initial warm-up period. Warm-up to 100 °F occurs in a very short time, with the fluidic system operating during warm-up at acceptable, but less than optimum performance levels. Warm-up characteristics and procedures are design considerations when selecting the system concept and design. In some cases warm-up characteristics can be tailored to specific requirements. It has been shown that temperature compensation techniques are effective in stabilizing the effects of Reynolds number and fluid viscosity changes with temperature. However, the compensation hardware could be simplified with attendant cost and weight reductions if the operational temperature range could be narrowed. System performance would also be improved. One way of doing this is to provide a small independent hydraulic system dedicated to providing power to the fluidic system. There are techniques to control the temperature of circuits of the primary hydraulic system (such as heat exchangers) but they generally add weight and cost.

The independent hydraulic system also addresses the issue of flight critical hydraulic system reliability and vulnerability being somewhat compromised by tapping off the prime systems for fluidic power. This is because of the added length and exposure of the fluidic lines. Additional benefits are that it can be driven or powered from a variety of power sources such as:

a. A motor-pump unit whose hydraulic motor is powered by one of the prime hydraulic systems or a circuit of one of those systems.
b. Two motor pump units, each unit powered by one of the prime hydraulic systems or circuits of them. This configuration assures separation of the hydraulic systems and yet assures operation of the fluidic system after failure of one of the prime hydraulic systems, or a circuit of them.
c. Mechanical power takeoff from an aircraft mounted accessory drive (AMAD), engine, or any other available gearbox
d. Electric-motor powered, although that generally defeats one purpose of the fluidic system, i.e., providing power to the fluidic signaling and computing system after loss of electrical power.

Disadvantages are:

a. Possible lower fluidic power source reliability due to use of small motor/pump unit and dedicated reservoir
b. Probable small weight and cost penalty

The choice is specific vehicle application dependent and results from tradeoffs influenced by the weighting of: hydraulic and fluidic system reliability; hydraulic and fluidic system survivability; weight; cost; and development risk. The choice is also dependent upon: the specific system application; the prime hydraulic system configuration; aircraft mission; and mission requirements.

3.4 (Continued):

Another benefit of the independent system is that it can be a lower pressure system than the aircraft prime hydraulic systems, with supply pressures in the range of 400 to 1200 psi. Proof pressures would also be appropriately lower. Trade studies for a given application would, in most cases, result in some combination of weight, overall cost and/or overall aircraft reliability benefits. If it were tapped off a 3000 psi (200 bar) or higher pressure system, the lower pressure fluidic system branch would have to be designed and proof-pressure tested to the higher pressures. That imposes some weight and cost penalties which would have to be traded against other weight changes and overall aircraft reliability requirements.

Conversely, tapping off the prime system is simpler, and it probably results in higher reliability of the fluidic system because the signaling system and the power systems (actuation power supply) share a common power source. The higher reliability of the fluidic system occurs primarily because the independent fluidic system pump is eliminated.

3.5 Other Liquid-Based Fluidic Systems:

There are a variety of other liquid-based systems that could be considered for various aerospace applications and vehicles. Almost any liquid can be used as the fluidic medium and for most aerospace applications the following could also be considered:

a. Liquid rocket fuels (LOX/LH-2; Hydrazine)
b. Air-breathing engine fuels (JP-4; JP-5, Jet A)
c. Engine lube oil
d. Gearbox oil (helicopter applications)

4. FLUIDIC POWER CONDITIONER:

As noted in Section 3, fluidics is similar to electronics in that just as an electronic circuit needs a clean source of electrical power at a constant voltage and a dependable and clean ground, so does a fluidic circuit need a supply of clean gas, or liquid, with a minimum of noise. Fluidic power supplies have the same fundamental design requirements as electronic power supplies. They need to:

a. Regulate
b. Attenuate line fluctuations
c. Absorb load fluctuations

Preferably, the supply and return line pressures should remain constant but, particularly with liquid powered systems, the critical thing is to maintain a constant ΔP (from supply to outlet) regardless of pressure level (ground or vent potential), primarily to minimize null offsets and to maintain a constant flow. Fluidic systems, particularly oil based systems, tend to maintain a constant performance level at constant flow. Gas powered systems generally benefit from a constant or controlled pressure ratio between inlet and outlet (vent). Venting fluidic elements to return is akin to making a good ground in electronics: the noise-free, ripple-free quality of the return greatly affects overall system performance. Output impedance is a primary design factor in any large system. Component flow variations, especially of output stages must not induce common

4. (Continued):

mode transient effects on low power input stages. Conditioning requirements for gas and for liquid-based systems are quite different because of the distinctly different characteristics of the power sources and of the medium itself, gas or liquid. For instance, gas based systems are generally vented to atmosphere while hydraulic fluid based systems collect fluid from vents and actuator signal returns in a common return line that discharges into the system reservoir. Each system has its own set of advantages, issues and problem areas that must be evaluated and traded against other configurations and operating mediums. Figure 2 depicts the parameters of interest when designing a fluidic power conditioner.

While the discussions in this document address constant pressure systems, it should be pointed out that some systems have been found to operate better, with less supply conditioning, in the frequency domain. Null offset and temperature drift effects then do not come into play. They are high-passed. Compensation filters work better, and so do functional systems. Such techniques are not current state-of-the-art, but they will be options for the fluidic designer in the future.

4.1 Gas Based Power Conditioning:

This section describes designs that use pneumatic power for fluidic systems and will discuss the three main types of gas used to supply pneumatic power used in fluidic circuits: engine bleed air; high pressure stored gas; and gas generator output gas.

4.1.1 Engine Bleed Air Power Conditioning: Engine compressor bleed air is commonly used for aircraft applications. The air is usually extracted from an existing bleed air system that supplies air pressures ranging from 15 to 50 psig (1 to 3 bar). Typical design factors include: temperature of the discharge air; variation of discharge pressure with altitude and/or engine speed; and contamination. Contamination occurs in the form of solid particulates, liquid lubricant droplets or vapors, and water droplets or vapor. Contamination is the only significant cause of failures in the field, so particular attention must be paid to this aspect of fluidic system design.

Altitude compensation of a fluidic circuit is frequently accomplished by a standard technique. A differential pressure regulator maintains a constant ΔP ranging from a few psid to 15 psid (1 bar) from the supply to the vent side of a fluidic circuit. Vent flows from all stages of the fluidic circuit are collected and routed through a converging-diverging (Venturi) nozzle that may be integral to the fluidic circuit or a separate element attached to the manifold on which the fluidic circuit(s) is mounted. The nozzle is sized to create sufficient back pressure on the fluidic circuit vent lines to create a Venturi pressure ratio (upstream-to-throat) that is just barely sonic at sea-level. The fluidic circuit in terms of steady-state flow impedance may be replaced by an equivalent orifice. Because the differential pressure is held constant across the fixed-resistance fluidic circuit and the vent back-pressure nozzle is always sonic, the fluidic circuit sees constant absolute supply and vent pressures at all altitudes. This produces constant pressure ratios across each stage of the fluidic circuit. Also, with this technique air density changes only as a function of temperature, not altitude. Supply pressure from the bleed air system must remain above the constant absolute pressure required to maintain the design ΔP across the fluidic circuit.

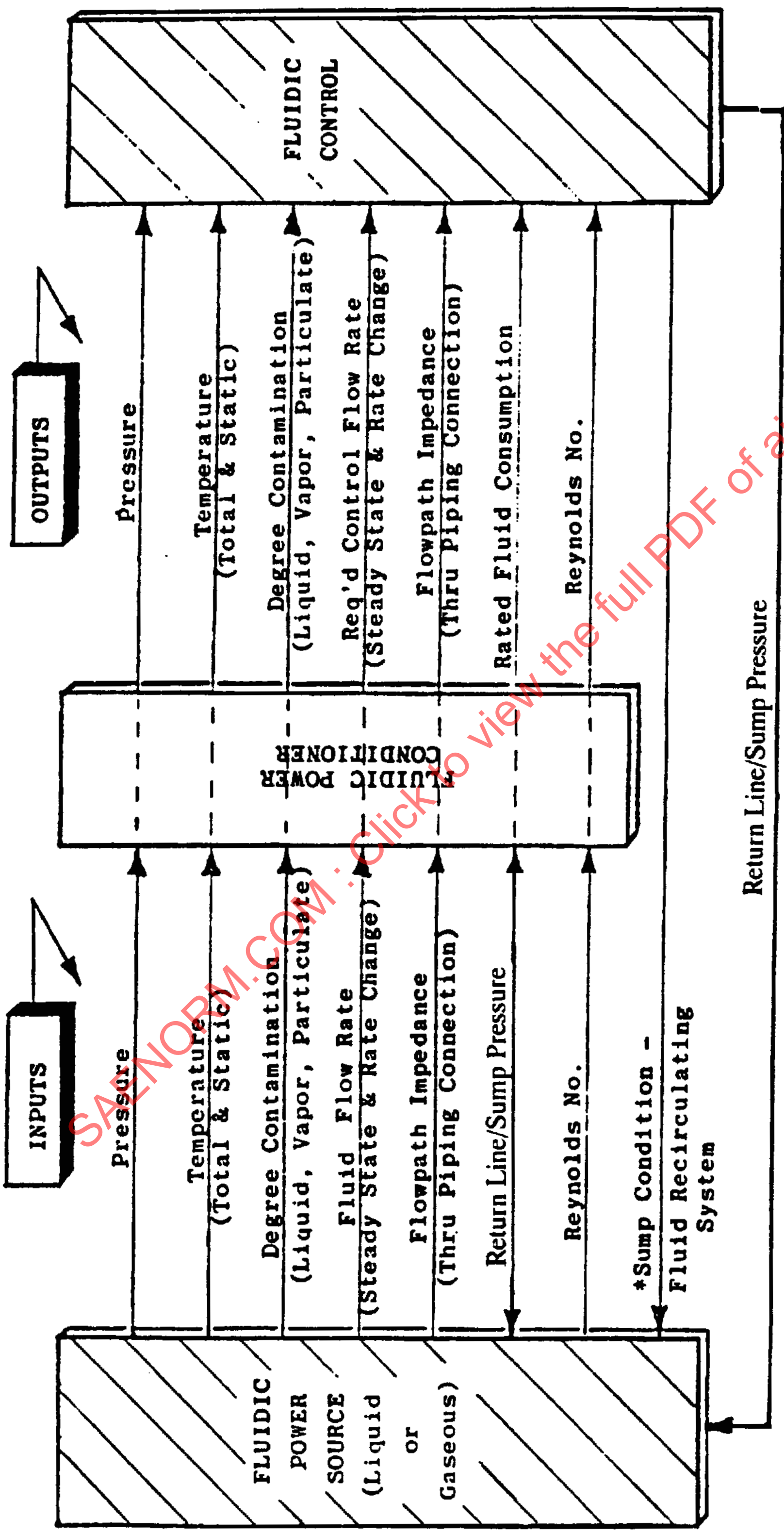


FIGURE 2 - Parameters of Interest for Design of Fluidic Power Conditioning

4.1.1 (Continued):

In some applications, insufficient pressure exists from the bleed air supply system to use the technique described in the preceding paragraph. At some altitude, minimum pressure from the bleed air system is less than the required fluidic system supply pressure.

Another technique may be used that allows the fluidic circuit to operate at a constant gauge supply pressure. This technique works well as long as the pressure ratio across each fluidic stage is kept below a certain maximum value. Active techniques including common mode rejection are used within the fluidic circuit to reduce altitude sensitivity to acceptable levels.

Apparent changes in, for example, a fluidic backup flight control circuit output to a control surface actuator may be observed when changes in bleed air system pressure occur due to events such as the pilot rapidly changing engine throttle setting. This may occur when system differential pressure regulators are overdamped and do not respond quickly to changes in upstream pressure. The circuit operating ΔP may be affected, causing temporary offsets. To minimize this sensitivity, regulator response should be addressed. Additionally, the circuit itself should be designed to operate with balanced differential pressure inputs to each amplifier stage to minimize null shifts caused by expected supply pressure variations.

Temperature compensation is required in pneumatic fluidic circuits, although not to the degree required in hydraulic fluidic circuits. The usual method is to use capillary elements for temperature compensation. The pressure drop across a capillary tends to increase as a function of temperature because the viscosity of a gas increases with temperature. The pressure drop across an orifice tends to decrease with temperature because density decreases. Used in combination, the individual temperature effects of capillaries and orifices may be made to cancel over the desired operating range.

4.1.2 Stored Gas Power Conditioning: Stored gas released from a pressure vessel is most frequently used in missile and reentry vehicle applications. The released gas is ducted to a high pressure regulator which regulates the high pressure down to a workable level, such as 300 psi (20 bar). A second stage regulator is used to drop the pressure to an appropriate level for the fluidic circuit supply, such as 20 psi (1.5 bar).

4.1.3 Gas Generator Power Conditioning: The use of output gas from a gas generator is common for reaction jet controls and other missile or projectile actuation applications. The contamination present in the output gas of the gas generator must be addressed. Typically, the gas generator output gas is quite dirty by fluidic standards; the particulate size and content is a function of propellent selection and combustion temperature. Generally speaking, the higher the propellent temperature, the cleaner the gas, but this rule does not always apply. Because the particulate content and high velocities from the gas generator is particularly erosive, it will tend to cause erosion problems at any point where high velocity flow impacts. Fluidic amplifier splitter points are sensitive areas. The general approach to accommodating gas particulates in fluidic systems is to design the fluidic elements such that the smallest passage dimension exceeds the largest particle size: minimum dimensions of .020 to .040 in are typical. Methods to filter gas generator gas include inertial separators and high-temperature screens.

4.1.3 (Continued):

Another issue concerning the use of gas generators as fluidic power sources is that of the requirements for transportation. Gas generators are classified as explosives, and must meet rigorous testing, documentation, and packaging requirements before they may be shipped on common carriers.

Temperature is a critical consideration for pneumatic systems because of the high gain needed. Even though the per stage change in performance may be small, one needs more gain with an air/gas system as compared with an hydraulic oil system. However, temperature compensation is easier to accomplish in air than in oil.

4.2 Power Conditioning of Hydraulic Fluid-Based Systems:

This section describes designs using aircraft hydraulic systems as a source of power for the fluidic systems. To date, hydraulic fluid has been the only liquid considered for aerospace fluidic systems. These are closed loop, 3000 to 8000 psi (200 to 500 bar) systems powered by piston pumps and with a vent collector line that returns fluid to the system reservoir. Base pressure in the return line is typically 80 to 120 psi (5 to 8 bar). However, when large actuators (such as the stabilizer or landing gear actuators) are operating at maximum rate the return line pressure increases significantly, to as high as 200 to 800 psi (13 to 50 bar) for short periods of time. This is highly dependent upon the hydraulic system design and characteristics and where the fluidic system vents interface with the hydraulic system. If return line pressure fluctuations are allowed at the vents of fluidic rate sensors and amplifiers, system performance can be seriously compromised.

As described at the beginning of Section 4, the critical issue is to maintain a constant ΔP between supply pressure and return line pressure. To assure that this ΔP is maintained at all times, the fluidic system supply pressure must be maintained precisely, and the vent and return line pressures must also be controlled precisely. Ideally, a constant flow system is desired. It is generally not a problem to maintain the fluidic system supply constant since the aircraft hydraulic system pressure is typically 3000 to 8000 psi (200 to 500 bar) and the commonly used fluidic system pressure, Ps, is typically less than 1200 psi (80 bar). Even when there are high flow demands on the prime hydraulic system, 3000 psi (200 bar) systems are designed not to drop below approximately 1800 to 2200 psi (120 to 150 bar). The fluidic system supply pressure reducer and regulator can therefore provide a constant design pressure, but it must be designed to meet dynamic response requirements.

It is also critical to minimize any noise that propagates through the system and results in outputs at the actuator. The most serious sources of noise in the system are pump "ripple" and noise generated in some of the fluidic elements. Hydraulic pump "ripple" is associated with the pressure pulses from the pistons of the typical aircraft hydraulic pump. Long signal lines tend to attenuate the pulses and techniques are available to minimize the effect of the pulses.

4.3 Filtration of Gas Powered Systems:

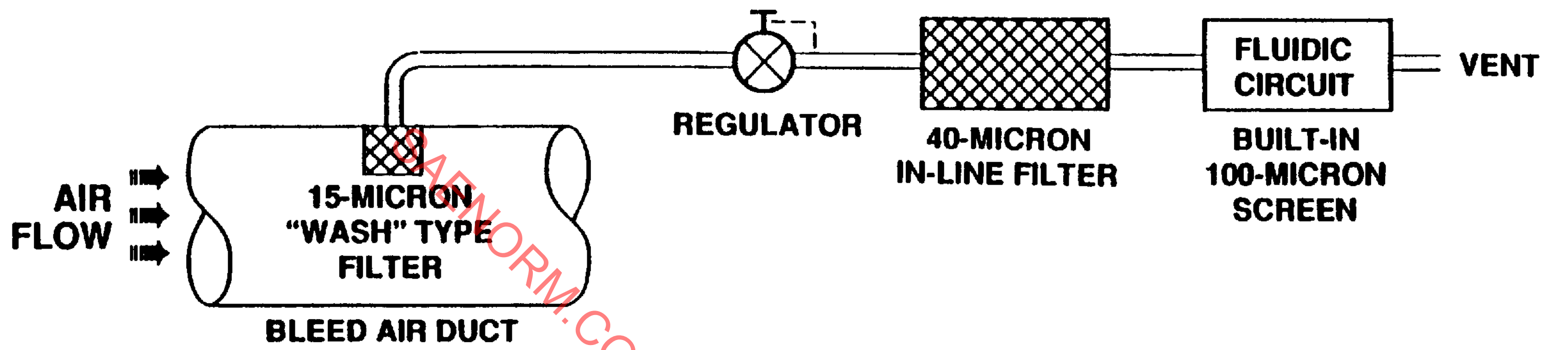
Although there is considerable controversy over filtration requirements it appears that the requirements depend upon the application, the system configuration and components, the materials used, and the pressures and flow rates, and the duty cycles. Pressures, flow rates and to some extent, duty cycles are minor influences, but higher levels tend to minimize or eliminate silting problems that have been encountered in some systems or components.

There are two erosion mechanisms, peculiar to particle contamination, that must be considered. The first is the cutting action of the dirt particles as they impact the surface and slide along. This is mainly associated with ductile materials at an angle to the flow such as the sides of splitters. The second mechanism is associated with hard, brittle, fluidic materials set perpendicular to the flow, such as splitter noses. In the latter case, particle impact energy is dissipated either by shattering the particle, or by shattering the surface of the boundary (e.g., the splitter nose). In either case, material selection and the choice of filters and/or centrifugal separators is very important.

Another potential problem is the presence, in some applications, of very fine oil type droplets or any small, sticky contamination that tends to stick to the surfaces of passageways. Incidentally, it is not necessary for very fine particles to be sticky for them to adhere to the surfaces of the passageways. Particles adjacent to the surface can build up an electrostatic charge, which can cause them to stick to the surface. If these particles are substantially smaller than the thickness of the boundary layer, they are not under the influence of free stream velocity to move them off. As more particles stick, the effective position of the surface moves, thereby reducing the flow area and causing calibration errors.

Methods for filtration of engine bleed air have been developed over the past 25 years. The most effective method involves the use of three stages of filtration. The first stage is an annular or insertion-type self cleaning filter that is constructed of sintered metal with a rating of 15 µm nominal, 25 µm absolute, and includes a net surface area of 2 to 4 in^2 (13 to 26 cm^2). The first stage filter is located at the bleed air duct where the fluidic supply pressure and flow is extracted. The second stage is an in-line filter with a 40 µm nominal rating and is located immediately upstream of the fluidic circuit. The net surface area of this filter is 3 to 5 in^2. Last chance screens with closely spaced 100 to 200 µm holes are included as an integral part of each fluidic stack. Figure 3 shows a typical filtering scheme for a bleed air system.

The most common design approach is to use fluidic passageways having a minimum cross-sectional dimension of 1 mm (.040 in) to minimize the risk of blockage due to airborne contamination. Large dirt particles are kept out by the use of inlet filter screens of 250 µm (.010 in) pore size. When necessary, due to the nature of the contamination, 5 µm filters are added upstream and centrifugal separators may be added upstream of these. In applications with severely contaminated engine bleed air from an auxiliary power unit, for example, a self-cleaning centrifugal separator type first stage filter may be necessary. These filters are over 90% efficient in removing particulates down to 5 µm in size as well as liquid droplets of approximately the same size.



Filter	Function
15-micron 'wash" type	To eliminate dirt particles
40-micron cartridge in-line	To prevent contamination during assembly and maintenance
100-micron screen	To prevent machining chips from entering fluidics

FIGURE 3 - Filtration of Engine Bleed Air

4.3 (Continued):

One aspect of filtration is the possible need to remove dirt and grit which would erode the fluidic devices, particularly the splitters. Depending upon the contamination, application and duty cycle, another approach is to allow the dirt to pass through the fluidic system, and to select erosion resistant materials for the fluidic laminates and components.

There has been a great deal of discussion about the merits and demerits of fine filtration. The obvious argument is that any filtration is better than none. However, the alternate argument suggests that if very fine or sticky particles are present, then the choice is between:

a. Filtering the larger particles and allowing the medium fine dirt and grit to pass through, "sandblasting" off any very fine dirt that may have stuck to the surfaces.

b. To use extremely fine filtration to filter out all particles of significance. In the particular example chosen here, medium-fine filtration is worse than no filtration, since it removes the medium fine grit while leaving the very fine dirt to adhere to the internal surfaces of the fluidic elements.

Generally, moisture is not a problem with engine bleed air systems since, at most engine operating conditions, any water exists as superheated steam. However, a problem can exist after the engine has been shut down. Then condensation can form and freeze. Consideration must be given to the location and attitude of the fluidic system and components installed on the engine to determine where condensation may form and collect. Sump(s) must be provided to collect that moisture, and they must be large enough to accommodate the condensation with a generous flow path for air over it. After the next engine start-up, hot air would flow over the frozen condensate, melt it, and evaporate it. Sump volume requirements must consider size and length of line runs as well as fluidic components.

The above discussion presents: a number of problem areas, not all of which would occur in the same application and of solutions to those problem areas. Experience has shown that the proper selection of materials and filtration can result in practical systems with very high reliability.

4.4 Filtration of Hydraulic Fluid Powered Systems:

If the minimum size orifice in the fluidic components is larger than the orifice in a typical hydraulic servovalve, the normal 5 or 10 μm filtration in an aircraft hydraulic system is adequate. Minimum sized servovalve orifices are .002 in (50 μm) for nozzle flapper valves and .007 in (180 μm) for jet pipe valves. The smallest passages normally used in oil based fluidic systems are .010 in (.25 mm).

Silting can be a potential problem since particulate contamination problems are not uncommon in aircraft oil and fuel systems. However, experience has not shown silting to be a problem in fluidic systems.

PREPARED BY SAE COMMITTEE A-6, AEROSPACE FLUID POWER, ACTUATION & CONTROL TECHNOLOGIES

APPENDIX A
CASE HISTORIES OF
LABORATORY AND FLIGHT TEST PROGRAMS

A.1 CASE HISTORY NO. 1 - NADC/ROCKWELL INTERNATIONAL CORPORATION T-2C AIRCRAFT FLUIDIC ROLL AND YAW FLIGHT CONTROL SYSTEM FLIGHT TEST PROGRAM:

In 1987, a T-2C jet trainer aircraft based at the Naval Air Development Center in Warminster, Pennsylvania was modified with an engine bleed air based fluidic flight control system. The fluidic system controlled the roll and yaw axes of the airplane and included a yaw stability augmentation system with inputs from a fluidic rate sensor. The program met the goals of the program, which were to demonstrate that a fluidic flight control system could perform maneuvers which are required of a backup flight control for a Navy aircraft. The aircraft demonstrated satisfactory flying qualities for Field Carrier Landing Practice (FCLP) and for formation flying.

In the application of fluidic flight control systems, great attention must be paid to obtaining a stable, relatively noise-free source for the working fluid--whether it be air or hydraulic fluid. Most of the difficulties in the Navy's T-2C pneumatic flight control demonstration program were caused by pressure leaks. In the aircraft installation phase, much time was expended and many hundreds of soap bubbles observed in tracking and securing these extremely small air leaks from fittings.

The fluidic flight control system on this aircraft used engine bleed air collected from both engines through the 8th stage compressor taps. At this point a 10-µm filter was installed from which the air was distributed to both the lateral and directional fluidic control circuits. The fluidic system supply pressure was displayed in the cockpit. The fluidic supply pressure was routed to each of the fluidic control modules. A 20-µm air filter was placed immediately upstream of each fluidic control module. Each fluidic module had an individual pressure regulator, each with a different setting. Altitude compensation was accomplished by exhausting the fluidic control air through sonic nozzles to ambient. The mass flow of control air became choked at about 8000 ft AGL and remained constant upwards from there as long as the engines delivered sufficient compressor bleed to supply the system.

In general bleed air systems on aircraft are less well-maintained than is the hydraulic system. Leaks may go unnoticed as long as all the equipment deriving power from bleed air is operating nominally. Some aircraft systems, such as the cockpit Environmental Control System (ECS), cycle on and off during flight causing surges in the system pressure. These surges and pressure transients can affect the operation of the pneumatic fluidic controls to the point of causing noticeable surface motions and the consequent aircraft motions in flight.