AEROSPACE RECOMMENDED PRACTICE	ARP739	REV. A
	Issued 1963-08 Reaffirmed 2008-07 Stabilized 2014-11 Superseding ARP739	

Gas Power Servos and Reaction Control Systems

RATIONALE

This document has been determined to contain basic and stable technology which is not dynamic in nature.

STABILIZED NOTICE

This document has been declared "Stabilized" by the SAE A-6B1 Hydraulic Servo Actuation Committee and will no longer be subjected to periodic reviews for currency. Users are responsible for verifying references and continued suitability of technical requirements. Newer technology may exist.

1. PURPOSE: This ARP is intended to promote better understanding of gas system characteristics and operation in order to aid in system selection and design.

2. SCOPE: Various gas systems are classified in a broad sense, component operation is described in moderate detail, pertinent design parameters are discussed, and possible modes for system operation are listed.

3. CLASSES OF SYSTEMS: Classification of gas systems will necessarily be more complex than that of hydraulics because of the broader temperature ranges and the number of possible energy sources. For standardization, a four category identification system is used which considers the type of system, operating temperature, energy source, and mission time. These categories are defined in the following sections.

3.1 Type of System: Gas systems shall be identified and designated accordingly:

Identification	Designation	Remarks
Actuation System	A	Systems used for positioning, such as but not limited to, flight control surfaces, thrust vector devices, valve actuation and nuclear control devices.
Information System	C	Systems used for position sensing, computing control parameters, and performing control functions.
Reaction System	D	Systems achieving control by utilizing gas reaction forces.

3.2 Operating Temperature: Shall be defined as the temperature at which the complete system is capable of operating during the entire mission time. Specific considerations of working fluid temperature, duty cycle, insulation, and heat sink must be considered before this classification can be specified. Classes are as follows:

Classification	Lower Limit Temperature
Class I -	-300°F
Class II -	- 65°F

To define the upper limit temperature, add the operating temperature, as defined above, in degrees Fahrenheit to the class designation.

3.3 Gas Media: Types of energy sources will be specified as follows:

Energy Source	Designation
Stored or Compressed Gas (including ram air)	SG
Solid Propellant	SP
Monopropellant (liquid or gas)	MP
Bipropellant (liquid or gas)	BP
Gel Propellants	GP
Cryogenic Fluids	CF

3.4 Mission Duration and Duty: Each gas system identification shall include mission time classification accordingly:

Mission Time	Designation
0 to 10 sec	A
10 to 60 sec	B
60 to 300 sec	C
300 sec to 1.0 hr	D
1.0 hr to 24 hrs	E
24 hrs and over	F

The mission time consists of actual gas system operating period plus any high temperature soaking periods. To the designation letter add a "C" for continuous duty or an "I" for intermittent duty.

3.5 Identification: A four part system shall be used to identify each gas system.

Part 1	Part 2	Part 3	Part 4
Type of System	Temperature Class	Energy Source	Mission Duration

For example, an

A-CLASS II 300-SP-CC

system is an actuation device, operating in the -65 to +300°F range, using a solid propellant for a mission duration of up to 300 seconds, operating continuously.

4. DESCRIPTION OF VARIOUS GAS SYSTEMS: Control of a vehicle presents many problems ranging from the necessity of a high response system to packaging the system within the weight and volume limitations imposed. Aerodynamic, gravity, and misalignment forces act on vehicles and impart an angle of attack in pitch and yaw and unbalance in roll. To counteract these forces, the flight control system must impart corrective forces in the appropriate direction in response to a command from the autopilot. Static and dynamic characteristics of the flight control system must be considered along with those of the vehicle in order to design the autopilot and ensure that the intended missions can successfully be completed. Dynamic response required of the flight control system

will generally range from 5 to 10 CPS for large boost vehicles and up to 30 to 40 CPS for smaller intercept vehicles.

Gas systems for missile application can be divided into three broad categories: actuation, reaction control, and information systems. Examples and pertinent design and performance features of the various systems are presented in this section.

4.1 Gas Actuator Servos: Can be used for positioning jetevators, jet vanes, swivelled nozzles, jet paddles, or aerodynamic control surfaces. These systems can be made more temperature tolerant, and generally enjoy weight and potential reliability advantage over the more common hydraulic servos. However, dynamic compatibility of the gas system with the overall vehicle must be carefully studied. Interaction of pneumatic actuation frequency response with fuel sloshing, missile body bending, control surface flutter, and autopilot characteristics must be avoided.

A later development in attitude control involves injecting gases or liquids into the exhaust nozzle of the rocket to create shock interaction and achieve thrust vector deflection. In these systems, gas servos can be used to position the injection valves. It is a favorable application for gas servos because the low inertia load causes pneumatic resonance to occur at a very high frequency which will likely be filtered by other system characteristics. Also, high pressure gas may already be included in the system for other functions.

4.2 Reaction Controls: These systems are used for vehicle attitude control and impart restoring moments by discharging gas through expansion nozzles. Widest application for these systems is on vehicles or payloads operating near the outskirts or completely out of the earth's atmosphere. Stored gas, monopropellant, and bipropellant systems are used.

For low thrust applications where total impulse requirement is less than 1000 lb sec, stored gas systems offer distinct advantages. Proven reliability is high, and a simple system capable of rapid, repeatable transient response can be obtained. System weight is low because the low specific impulse (about 60 sec) is offset by the relatively few and light-weight components required.

For vehicles requiring reaction control systems in the 1000 to 10,000 lb sec and over category, the choice is not so clear. Monopropellant systems using hydrazine or hydrogen peroxide for fuel offer a high degree of development and past experience and usually prove lightest in the 1000 to 5000 lb sec range. However, transient response is not particularly rapid (.040 to .100 seconds) and varies with propellant temperature and the condition of the catalyst bed. Heating of the catalyst bed, or even the propellant, is sometimes required. Specific impulse varies downward from a maximum of about 180 seconds with propellant and catalyst bed temperature and thrust pulse width.

Bipropellant systems using hypergolic fuel-oxidizer combinations offer many potential advantages in the higher total impulse category. Specific impulse on the order of 300 seconds, transient response is rapid (less than 0.010 second) and is relatively insensitive to fuel temperature and thrust pulse width. Although many prototype bipropellant systems have been developed and current vehicles are committed to these systems, there is less background and past experience here than with monopropellants. Bipropellant systems are more complex because they require twice the number of lines, tanks and valves as the other systems and also because certain oxidizers are very difficult to incorporate into a positive expulsion system.

In general, all of these characteristics must be considered before the best suited reaction control system can be selected for any particular vehicle.

4.3 Information Systems: These systems sense and/or transmit information or perform computations by pneumatic means. In general, this field is quite new, but devices for sensing controlled variable position, torquing and position sensing of gyroscopes, signal shaping, and performing mathematic functions, have been built and tested. More recently developed flip-flop devices provide means for pneumatic logic circuits. Computing devices provide the means for obtaining completely pneumatic systems.

5. CONTROL VALVE: The importance of selecting the proper control valve in gas system design cannot be overemphasized. Overall system efficiency and compatibility determine the general type of valve arrangement, while the porting arrangement and size are closely tied to servo dynamic performance requirements.

Control valves are described by the following characteristics:

(a) Open center or closed center (overlapped, zero lapped or under lapped).

(b) Three way or four way.

(c) Flow control, pressure control, or dynamic pressure control.

(d) One, two, or three stage.

Item (a) refers to the valve's null leakage characteristic; an open center valve permits considerable flow at null, a closed center valve restricts null leakage to nearly zero. Pressure-flow characteristics are also different for the two types. A three way valve has a porting arrangement suited to single acting actuators, while four way valves are used with double acting actuators. In flow control valves the metering area varies in a linear manner with input signal. Thus, for small input signals, the flow through the valve also varies in an approximate linear manner with input signal. Pressure control valves modulate pressure drop across the load as a function of input signal. These valves are closed loop devices using pressure feedback paths. The dynamic pressure valve displays flow control characteristics during steady state operation and pressure control characteristics during transient operation.

Force and power amplifying stages are used to control the power stage in multistage valves in order to increase frequency response and reduce input signal power requirements. The power stage of single stage valves is positioned directly by a transducer operated by the input signal. Single stage valves, though physically more simple, are more apt to bind from working fluid contamination or thermal effects due to the lower force available at the power stage.

A block diagram of a typical gas servo system is shown in Figure 1 and is presented to show relationship between the control valve and the rest of the control loop. C_1 accounts for change in valve flow at constant pressure drop as a function of applied signal. C_1 is largely a function of valve port size and directly affects loop gain. C_2 is the change in valve flow at constant metering area caused by changes in load pressure drop, and is a function of metering area and gas conditions. Note in Figure 1 that C_2 forms a closed loop around the actuator internal volume and therefore enters into the servo's dynamic characteristics as well as in loop gain. The C_2 term has been shown to increase load damping. In general, a large C_1 value is desirable for steady state accuracy (high loop gain) and a large C_2 has been shown to increase the stability of systems working with resonant loads. Thus the load characteristics are an important factor in control valve design.

Figure 1 provides a description of the dynamic and static relationship of the control valve to the rest of the servo. The following sections will deal with physical and performance characterisitcs of the valves.

5.1 Open Center Valves: In this type valve, working fluid is continuously circulated through the valve, some being transferred to the load and the remainder exhausted. Generally, two restrictions in series pass the full flow, and the ratio of the area of these restrictions is varied to obtain pressure modulation. Schematics of the more common open center valves are shown in Figure 2.

In the flapper valve, pressure drop across the load is a function of flapper position and load flow. The upstream restrictions are generally operating choked so that total flow through the valve is constant. The jet pipe valve modulates working fluid conditions by directing flow to or away from the receiver holes. Like the flapper, the jet pipe also passes constant total flow.

Underlapped spool valves operate in the same manner as the flapper valve except that the restrictions are simultaneously varied in a "push-pull" manner.

Typical load - pressure drop characterisitcs of open center valves are shown in Figure 2 (d). In practice, the constant metering area lines need not be linear. Moderate values of C_1 and C_2 are obtained and the valve is "load sensitive" in that some offset in metering area is required to hold against steady loads, a condition that creates steady state error or droop in the servo system.

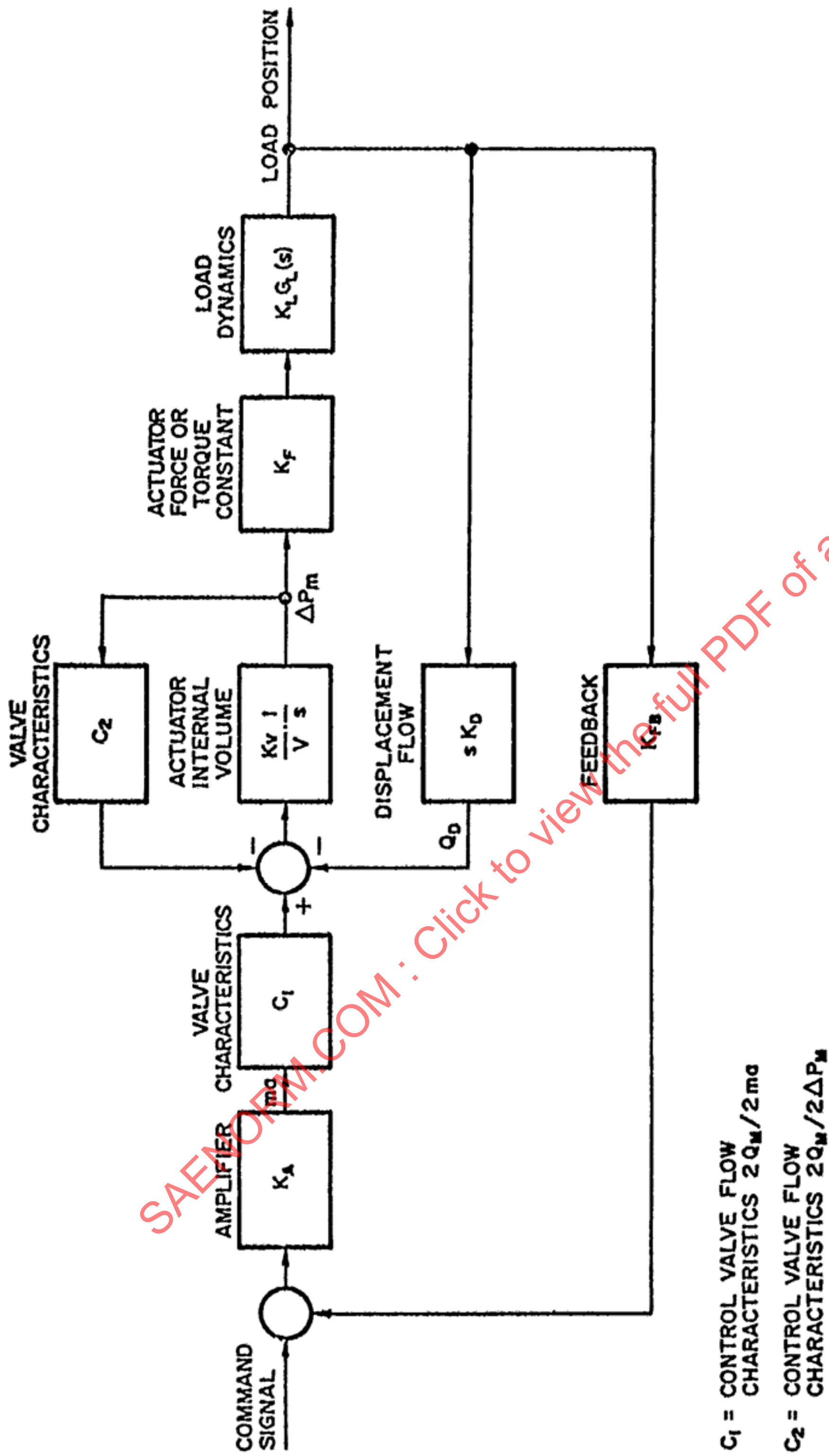
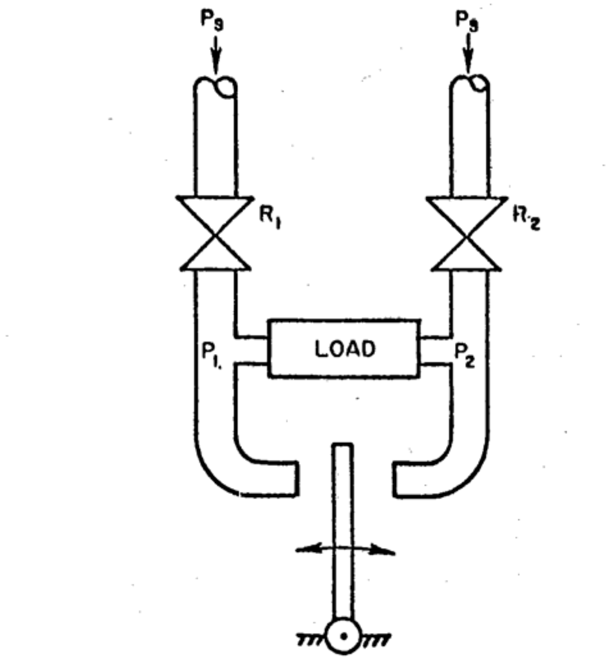
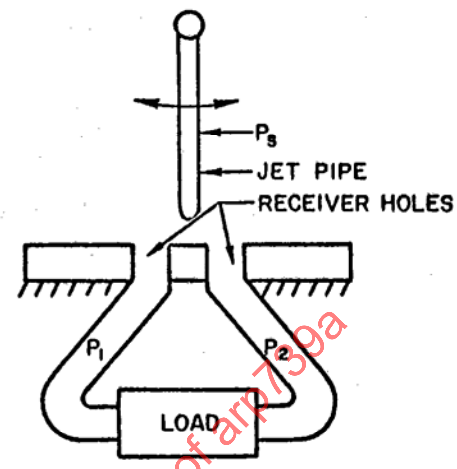


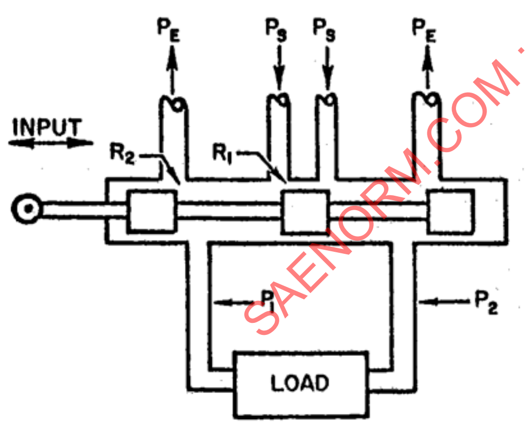
Figure 1. Servo Block Diagram



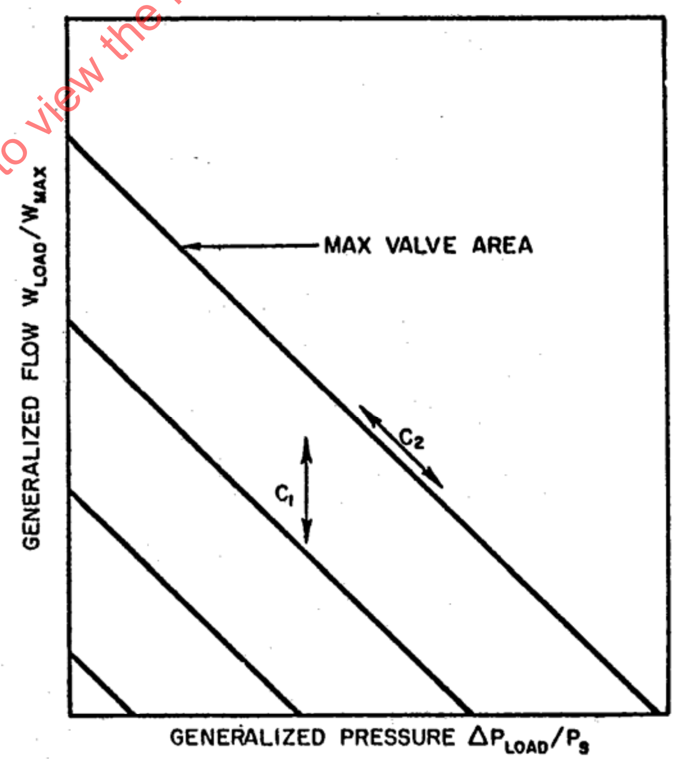
(a) FOUR WAY FLAPPER VALVE



(b) FOUR WAY JET PIPE VALVE



(c) FOUR WAY UNDER LAPPED SPOOL VALVE



(d) TYPICAL OPEN CENTER FLOW-PRESSURE CHARACTERISTICS

Figure 2. Common Open Center Valve Types

Open center valves, especially flapper and jet pipes, offer simplicity as their prime advantage. There are few, if any, close tolerance parts, and adjustments are rugged and straightforward. These advantages are particularly suited to high temperature applications.

In summary, open center valves are physically simple, provide some load damping because of a finite value of C_2, are load sensitive, and are generally inefficient in conservation of the gas energy source.

5.2 Closed Center Valves: Poppets, spools, or plate configurations are generally used in the power stage of a closed center valve and are designed to reduce null flow to near zero. As a further breakdown, flow control, pressure control, and dynamic pressure control closed center valves are considered.

5.2.1 Flow Control Valve: This type is shown schematically in Figure 3 (a). A single stage spool valve is shown for clarity. Pressure flow characteristics of this valve are shown in Figure 3 (b). The term "flow control valve" is applied because for small input signals, an output flow is obtained which is nearly linear with input signal. Two things are obvious from Figure 3 (b).

(a) C_2 is nearly equal to zero; therefore, this valve will contribute little or no load damping, and artificial damping must be used with underdamped resonant loads.

(b) The valve is not load sensitive. At even the smallest area opening, maximum pressure drop will be developed across the load at zero flow. Therefore, servos using this type valve will exhibit excellent steady state accuracy and high "servo stiffness."

5.2.2 Pressure Control Valves: A schematic of this valve type is shown in Figure 3 (c). The function of this valve is to provide a pressure drop across the load in a linear manner with input signal, regardless of flow conditions. Physically, this is accomplished by applying a force on the power stage as a function of input signal, then using the load pressures and diaphragms or bellows for a feedback signal. Input force is applied directly by an electro mechanical force transducer or by an initial force amplifier stage. Again, two things are obvious from the valve characteristics shown in Figure 3 (d).

(a) The pressure control valve produces very large C_2 values and, therefore, will provide load damping and will be more suited to resonant loads.

(b) Steady state load pressure drop is a function of input signal. Therefore, this valve is load sensitive and will exhibit less steady state accuracy and servo stiffness than flow controlled systems. Accuracy and stiffness of pressure controlled systems can be improved by using stability compensation techniques and high static gains in the servo loop.

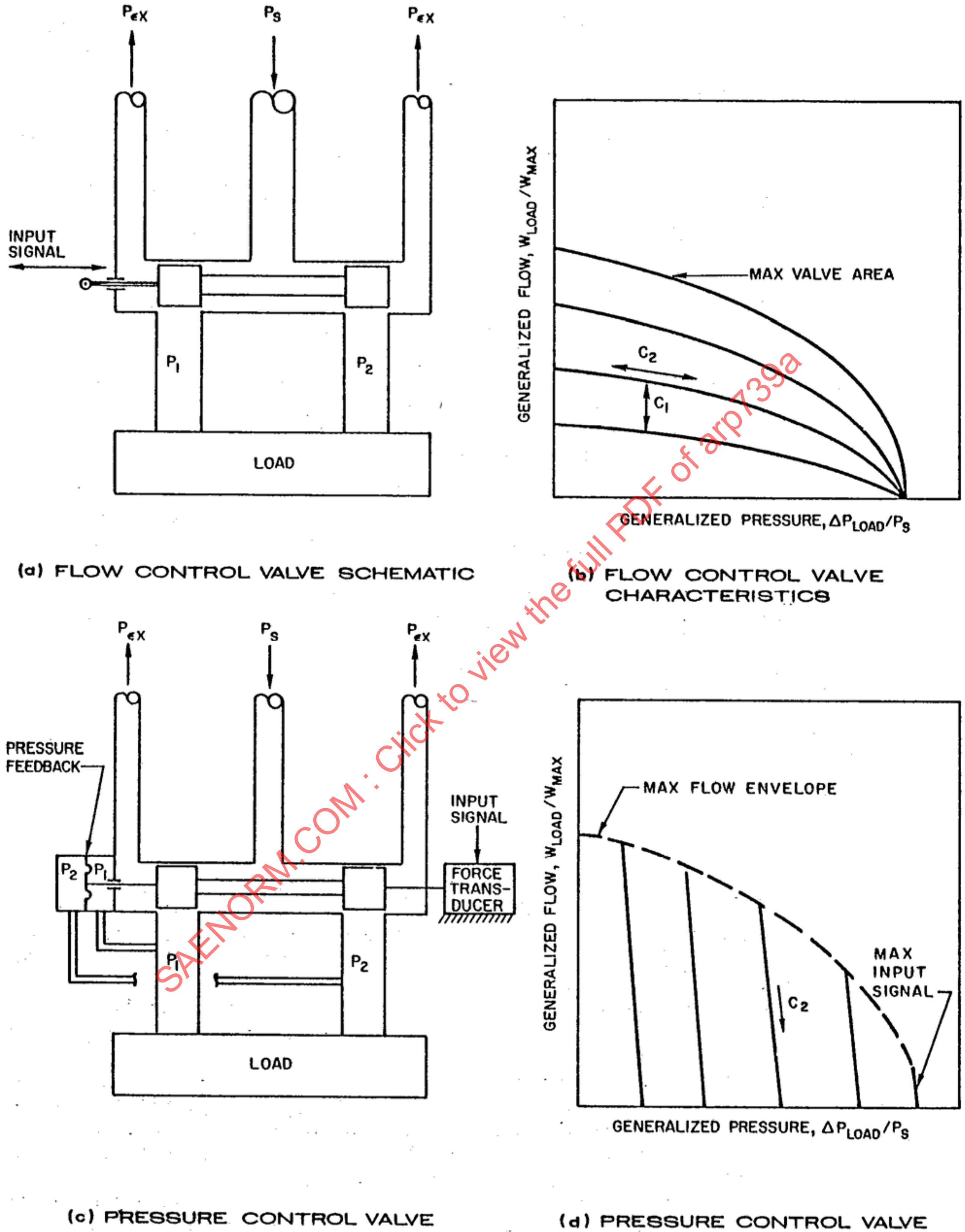


Figure 3. Closed Center Valves (Continued on Page 11)

5.2.3 Dynamic Pressure Control Valve: This valve exhibits flow control characteristics at low frequencies and pressure control characteristics at higher frequencies. It therefore is capable of providing both static system stiffness and damping at load resonance frequencies. Load pressure P_2 in the left side of the pressure feedback device is attenuated at higher frequencies by the fixed restrictor-flow barrier combination. During static operation, P_2 is effective in both chambers, and the pressure feedback device is therefore not effective. Typical transient and static flow-pressure characteristics are shown in Figure 3 (f). Static and transient advantages offered by this type of valve are obtained through some increase in system complexity.

5.3 A logical process for selecting and setting the type of valve can proceed as follows:

(a) Open or closed center operation is decided on the basis of economy, environment, and power source.

(b) Three or four way operation is selected on the basis of actuation requirement (single or double acting).

(c) Single or multi-stage configuration is selected on the basis of available input signal power, response requirement, and operating environment.

(d) Flow or pressure control operation is selected as a function of load dynamics, steady state accuracy, and servo stiffness requirements.

A detailed description of control valve characteristics and performance evaluation is presented in ARP 742.

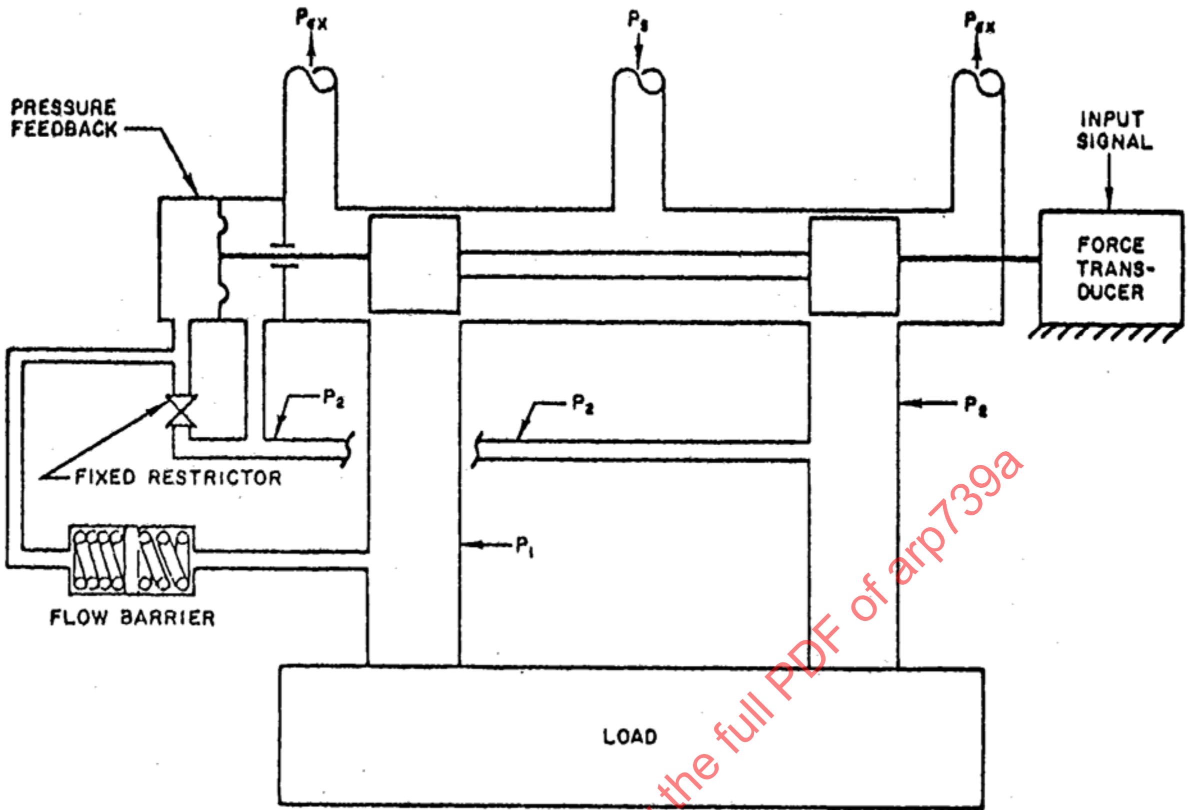
6. POWER SOURCES:

6.1 Hot Gases:

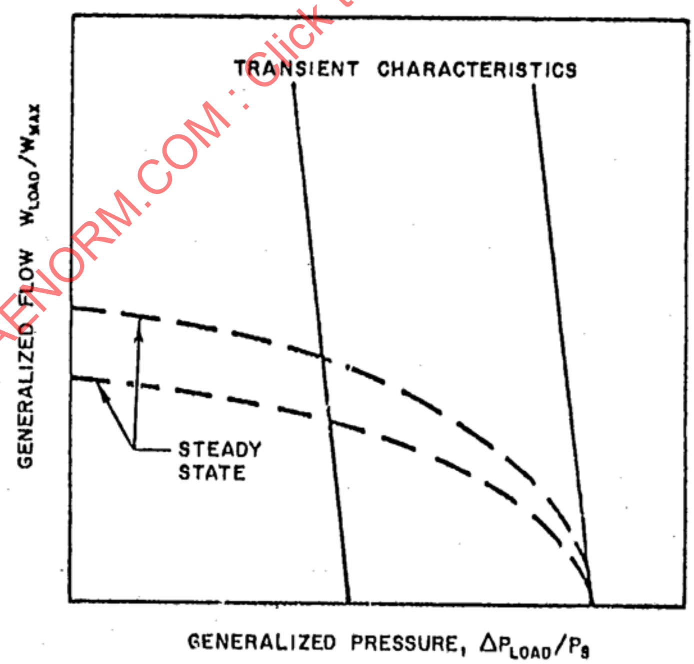
6.1.1 Sources of Hot Gas:

Liquid Propellants: Liquid propellants are divided into two primary categories: monopropellants and bipropellants. Either type of propellant can be used in intermittent (on-off) or throttleable operations. This source of hot gas is ideal for laboratory studies on servos and APUs because no firm limitation on duration for continuous operation is established; i.e., pumps or propellant feed system, combustion chamber, and miscellaneous hardware.

Monopropellants are either mixtures of oxidizing agents and fuels or a single chemical compound. They may be a mixture of several compounds such as hydrogen peroxide mixed with alcohol, or they may be a homogeneous chemical agent, such as nitromethane. Monopropellants are normally stable at ordinary atmospheric conditions but decompose and yield hot combustion gases when heated and pressurized. The feed system of a monopropellant gas generator is usually simple, because only one liquid needs to be supplied. The combustion products of most monopropellants are clean and non-corrosive.



3(e) SCHEMATIC OF DYNAMIC PRESSURE CONTROL VALVE



3(f) DYNAMIC PRESSURE CHARACTERISTICS

Figure 3. Closed Center Valves (Continued from Page 9)

Bipropellant gas generator systems utilize two separate propellants which are mixed inside the combustion chamber. The bipropellant systems make use of the oxidation process to provide the temperature and exhaust gases necessary for generator operation. In these systems it is usual to refer to one of the liquids as fuel, the other as oxidizer.

6.1.2 Solid Propellants: Solid propellants are divided into two main categories; i.e., composite and double base. Both composite and double base propellants are made up of an oxidizer and a fuel, with the fuel acting as the binder in many cases. The propellant is formed into a usable charge configuration by casting, molding, or extruding. The most common configuration for gas generator application is an end-burning charge. To prevent burning on all exposed surfaces, an inhibitor or restrictor, a non-oxidized material, is bonded to the surfaces on which no burning is desired.

Double base propellants contain nitrocellulose and nitroglycerin as the primary ingredients. The flame temperatures are normally in the Very Hot Gas region (2500 to 4000°F); however, diluents have been used to reduce the gas temperatures.

Composite propellants contain an oxidizer, usually in the form of a nitrate compound, and a fuel-binder having a plastic consistency. This fuel may be cast, molded, or extruded to the desired shape. Combustion gas temperatures are generally available to as low as 1750°F.

6.2 Handling: The techniques and methods of handling both liquid and solid propellants must include special precautions. These will be different for each fuel used.

6.3 Storage:

6.3.1 Solid Propellants: Composite solid propellants having a nitrate oxidizer have one major storage problem; i.e., protection against moisture. Two means of protection are readily attainable. One method is to design gas generators with adequate moisture seals and have all loading done by the propellant vendor. A second method is to have propellant grains shipped in hermetically sealed containers from the vendor and so retained until immediately prior to use. All loading of nitrate oxidized grains should be done in a dehumidified atmosphere. Double base propellants are much less sensitive to moisture.

Many solid propellants can be stored at temperatures from -85 to 180°F for prolonged periods up to 5 years. Before establishing a storage requirement for a particular propellant system, the limitations of that formulation should be established. At temperatures above 180°F many binders decompose with long term storage. At temperatures below -85°F many propellants become brittle and crack due to internal stresses.