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A STUDY OF THE FEASIBILITY OF DIRECTLY APPLYING GAS GENERATOR SYSTEMS TO SPACE SHUTTLE MECHANICAL FUNCTIONS

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16. Abstract

This study, which is an extension of a previous NASA program (NASA CR-2292), examined the current status and potential application of pyrotechnic gas generators and energy convertors for the Space Shuttle program. While most pyrotechnic devices utilize some form of linear actuation, only limited use of rotary actuators has been observed. This latter form of energy conversion, using a vane-type actuator as optimum, offers considerable potential in the area of servo, as well as non-servo systems, and capitalizes on a means of providing prolonged operating times. Pyrotechnic devices can often be shown to provide the optimum means of attaining a truly redundant back-up to a primary, non-pyrotechnic system.

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FOREWORD

The work described in this report was performed by the Pyrotechnic Design Staff of the McDonnell Aircraft Company, McDonnell Douglas Corporation, for NASA Langley Research Center, under Contract NAS1-11740.

The author wishes to acknowledge the contributions of NASA-JSC and the Hydraulics Design Staff, McDonnell Aircraft Company. In addition, the technical assistance provided by the Bendix Company, Navigation and Controls Division, Teterboro, New Jersey, and their Research Laboratories, Detroit, Michigan, was particularly helpful.

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A STUDY OF THE FEASIBILITY OF DIRECTLY APPLYING GAS GENERATOR SYSTEMS TO SPACE SHUTTLE MECHANICAL FUNCTIONS

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SUMMARY

Solid propellant gas generators and both linear and rotary energy convertors were surveyed to determine their current technology status. While most pyrotechnic devices utilize some form of linear actuation, only limited experience with rotary actuators was found. The capability of hot-gas-operated rotary actuators, particularly in the area of servo systems, was noted, and appears to offer a potential area for future capitalization. A currently used aeronautical gas generator/linear actuator system was reviewed. Trade studies explained the logic for selecting the present system. The most recent Space Shuttle configuration was examined, and all major mechanical functions were identified. Current potential pyrotechnic approaches to support these functions, either as the primary or back-up mode, were present. Development guidelines were prepared for a selected system in each of three technology categories; namely, state-of-the-art, minimal modification, and new concepts.

INTRODUCTION

The NASA Space Shuttle, which is currently in the initial stages of design, development, test, and evaluation (DDT & E), will be a reflyable aerospace vehicle that provides routine earth-orbit transportation. In addition to the solid propellant rocket boosters (SRB's), each manned orbiter vehicle will have a variety of major mechanical functions that must be performed during each mission. These include such functions as operation of the payload doors, aerodynamic control surfaces, and landing gears. These tasks (in particular, operation of the aerodynamic control surfaces) will require considerable amounts of energy. This will be provided onboard the orbiter by auxiliary power units (APU's) to drive the hydraulically operated systems and by fuel cells for electric power. Some mechanical functions, however, will be performed directly by pyrotechnics in the form of solid propellant gas generator and energy convertor combinations, such as linear and rotary actuators. The possibility of complementing the existing power sources by increased application and more effective utilization of pyrotechnics could result in potential weight savings. For example, as a power source, solid propellant gas generator/energy convertors deliver their energy in an efficient single-step conversion directly to the required mechanical function. However, APU's require a triple energy conversion to arrive at the same point; namely, hot-gas-to-mechanical through turbines, mechanical-to-hydraulic or electric through pumps or generators, and finally hydraulic or electric energy to the required mechanical function. A possible means of increasing the effective utilization of pyrotechnics would be to use them in support of peak power requirements, which would then permit sizing of the APU's to some lower continuous power level, with resulting weight savings.

The objective of this study, which was essentially a continuation of work performed under a previous NASA program (ref. 1), was to survey existing gas generator and energy convertor technology, analyze by trade studies a currently flying aeronautical system, review potential Space Shuttle applications, and prepare technology development guidelines for three selected applications. Because the Shuttle program is in the early DDT & E phase, designs and requirements are still undergoing changes; therefore, it has been necessary to discuss some areas of the program in a general, rather than a specific, manner.

PROCEDURE

The program was divided into four specific phases of investigation. They are as follows.

Phase I - Gas Generator and Energy Convertor Technology Survey

Phase II - Analysis of a Currently Flying Aeronautical Gas Generator System

Phase III - Potential Gas Generator and Energy Convertor Applications on Shuttle

Phase IV - Gas Generator and Energy Convertor Technology Development Guidelines

Phase I - Gas Generator and Energy Convertor Technology Survey

A survey was conducted to determine the current state of the art of solid propellant gas generator and energy convertor technology. The principal companies active in the design, development, and production of both gas generators and energy convertors were consulted, and in several cases, visited.

Gas Generators. - A brief discussion is presented on the classification of solid propellant gas generators into hot and cool gas-producing devices and on their ability to provide a broad range of functioning times. A unique gas generator concept, currently under development, that can provide a varied, rather than a fixed, gas flow is reviewed. The advantages of solid propellant gas generators over stored-gas systems are summarized.

Energy Convertors. - Both linear and rotary actuators are reviewed, and gas-generator-operated devices employing both methods of actuation are tabulated. The characteristics of both types of actuators in servo systems are discussed briefly including the weight advantages that can also be realized.

Rotary actuators: Both expansion and non-expansion types of positive displacement rotary actuators are discussed in depth, including their respective capabilities for operating at high temperatures.

Vane actuator design parameters: Those parameters influencing optimum vane actuator design are reviewed and presented in a generalized form under "Results." A more detailed discussion will be found in Appendix A.

Phase II - Analysis of a Currently Flying Aeronautical Gas Generator System

The system selected for study in this phase was the emergency back-up operation of the aerial refueling slipway door system on the F-15 fighter. A trade study and the rationale for selection of the back-up system is presented along with a further trade study of various initiation methods. Installation and operation of the back-up system is described and design requirements for the two major back-up system components are also presented.

Phase III - Potential Gas Generator and Energy Convertor Applications on Shuttle

All major mechanical functions on the Space Shuttle were reviewed to determine the feasibility of applying gas generators and energy convertors for either their primary or back-up operation. Tabulations of these functions, and selected or possible approaches for their operation, are presented and represent the current NASA-JSC baseline. Each pyrotechnic application was categorized into one of three levels of technology, namely:

State-Of-The-Art. - Concepts that can be directly applied, based on established and proven design philosophies.

Minimal Modification. - Concepts that require scaling and/or combining individually proven concepts to produce essentially untried systems.

New Concepts. - Concepts that require development and demonstration of system principles, based on unproven or limited analytical experimental demonstrations.

Recommendations for a single mechanical function utilizing a gas generator and energy convertor system for each of the three technology categories, are also included.

Phase IV - Gas Generator and Energy Convertor

Development Guidelines

General guidelines are presented for as many design parameters as possible for each of the three mechanical functions selected in Phase III. Detailed specifications for each system or mechanical function were not possible, since Space Shuttle subsystem design details are presently unavailable.

RESULTS

Phase I - Gas Generator and Energy Convertor Technology Survey

Gas Generators. - Pressurized gas can be utilized as an energy source to perform many work functions. This gas can be compressed and stored for subsequent use, or it can be generated on demand by chemical conversion (ref. 1). This study was concerned with the controlled generation of gas pressure as part of a pyrotechnic device and its potential application to the Space Shuttle. Most frequently, the chemical conversion source is a moderate-burning-rate solid propellant. The cartridge, containing the igniter and the chemical conversion source, is referred to in broad terms as a "gas generator." It is primarily the compact size, light weight, and high reliability of the gas generator, as a source of pressurized gas, that make pyrotechnic devices so attractive.

Gas generators can be divided into two generic categories, based upon the temperature of their exhaust gases; namely, hot and cool. In the hot-gas type generator, the propellant exhaust gases, which generally fall in the 927°C to 1370°C (1700°F to 2500°F) range, are used directly as the energy source. In the cool-gas generator, however, excess heat is removed from the exhaust gases by vaporizing a liquified coolant material, such as a Freon-type refrigerant, ammonia, or even water (containing some antifreeze). The resulting cool exhaust gases are in the 93°C to 260°C (200°F to 500°F) range.

The functioning time of gas generators is extremely flexible and can be designed for as short as a few milliseconds or up to many seconds. The vast majority of gas generator applications, however, fall into the millisecond range. Examples of such short-duration applications are thrusters, pin pullers, guillotines, "explosive" valves, nuts, and bolts. Both hot and cool gas generators, on the other hand, have also been developed to support longer-duration functions as jet engine starting and the inflation of aircraft escape slides.

A relatively new concept in gas generator technology is the recent development of a Mach sensitive demand gas generator (ref. 2). The uniqueness of this system is its ability to supply a varied gas flow. Basically, it is a dual-propellant system, consisting of a continuously burning driver propellant grain and a demand grain. The latter burns only upon command; that is, when the gases from the driver grain are directed across its surface.

In the schematic representation shown in Figure 1, the driver exhausts gases are automatically vented through a pressure relief valve upstream of the demand grain, when the functioning device valve is closed. When the velocity of the driver gases passing across the surface of the demand propellant drops to zero, the latter stops burning because it is unable to support its own combustion in the absence of the driver gases. The pressure in the demand chamber, however, is maintained at operating level and can provide instant reponse when the functioning device valve is opened. This cycle can be repeated to provide a multicycle on-off capability. If a large enough surface area of the demand propellant is provided and is balanced with the port area of the demand grain, then the demand grain can generate more gas than the driver; i.e., the demand amplifies the driver output. This amplified output then provides the required mass flow. To date, generators that produced mass flow rates of 0.18 kg/sec (0.4 lbm/sec) at 345 N/cm^2 (500 psia) have been operated for periods of up to 90 seconds.

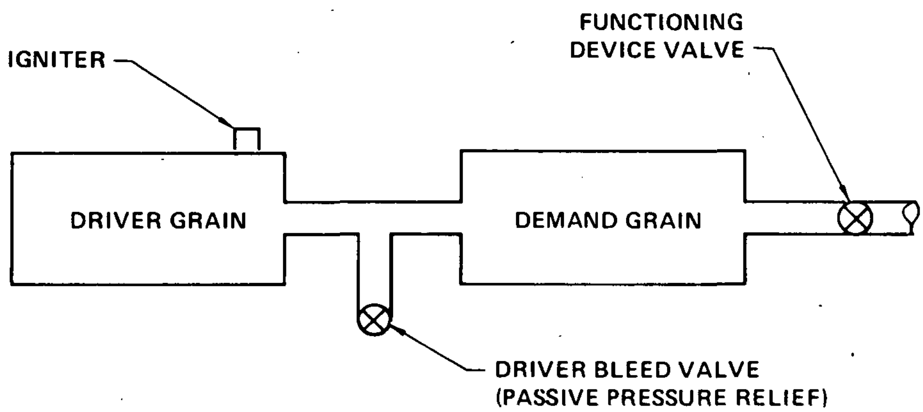


FIGURE 1
DEMAND-TYPE GAS-GENERATOR SCHEMATIC

The advantages of solid propellant gas generators can be seen best by comparing them to their only competitive energy source, stored gas (ref. 3). The advantages are as follows:

- o Volume - Regardless of pressure, considerably less volume is required for storage of a given weight of gas in the solid phase (solid propellant grain) than as compressed gas.

- Weight - The hot gas generator approach is substantially lighter when the weight of materials necessary to contain the pressurized gas is considered. This weight advantage is not quite as pronounced for cool gas generators, particularly in the smaller sizes.
- Safety - A potential hazard exists in all stored-gas systems because of the high pressures required to maintain the system. The gas generator, by comparison, is not under pressure until the device is ignited. Even then, the pressure is confined primarily to the combustion chamber. Further, the operating pressure of gas generators is usually much lower than that of stored-gas systems.
- Operation - Delivery of gas from a stored-gas system decreases with decreasing storage pressure and temperature, and normally takes longer than a solid propellant system. The latter approach can be designed to deliver its total output in a definite time and at a fixed rate. In addition, it can be designed to be essentially independent of storage temperature.
- Logistics - Because stored-gas systems are subject to leakage, they must be routinely inspected, either by checking each pressure gage, or if the latter is not present, by weighing. Gas-generator systems are not subject to this requirement; however, they do have a service life; i.e., a replacement schedule.

Energy Convertors. - In order to convert the potential energy of a gas generator to usable mechanical work, some form of energy convertor is required. Such convertors can be categorized best on the basis of their end function; namely, linear and rotary actuation, with the former exceeding by many times the latter in frequency of application. Figure 2 shows typical applications for both linear and rotary actuation. Inflation is also a form of using propellant gases to do work and has been included.

While gas generator operated linear actuators vary greatly in size from the tiny dimple motor with a typical 0.25 cm (0.1 in.) stroke to the emergency lid retractor and its 214 cm (84 in.) stroke for the Minuteman silo, they are all short-duration, single-shot devices. Rotary actuators, on the other hand, offer continuous operation for as long as gas is supplied by the gas generator.

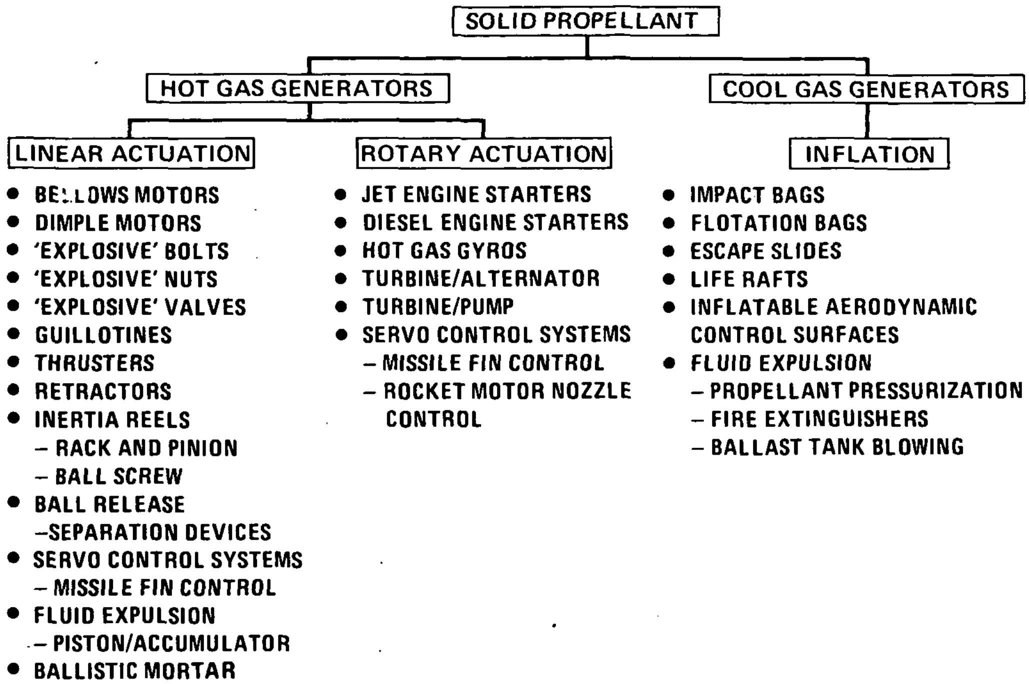


FIGURE 2
ENERGY CONVERTOR APPLICATIONS

One notable rotary actuator application is found in the Sidewinder missile (Figure 3), where hot gas is used to drive a turbine-powered alternator producing electric power for the full flight time of the vehicle. Subsequently, the exhaust gas from the turbine is further used to operate a control surface actuator. Rotary actuators have also been repeatedly used for both jet engines starting and more recently for commercial diesel engine starting (ref. 4), which demonstrates their additional capability to be reused.

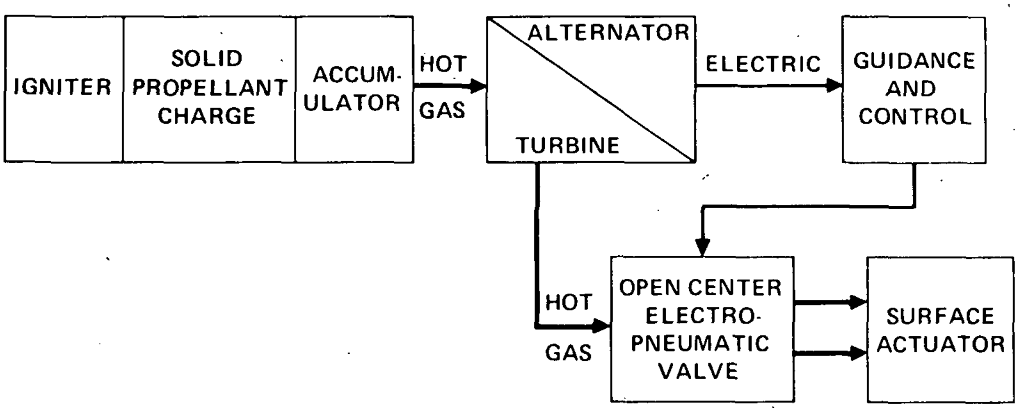


FIGURE 3
SIDEWINDER HOT GAS GENERATOR/ROTARY ACTUATOR SCHEMATIC

Both linear and rotary pneumatic operated actuators have also been successfully used in servo systems. Comparing the two, the rotary actuator tends to have a higher response capability than an equivalent linear (piston/cylinder) system (ref. 5). This is largely the result of the small volume under compression in a rotary actuator compared to the very large volume in the linear actuator, which must be constantly pressurized and depressurized under dynamic operation conditions. This results in substantially reduced performance in a linear servo, unless complex feedback systems are included (ref. 6). Even then the rotary actuator is still superior.

Although pneumatic servos may not achieve the response potential of an equivalent hydraulic system, adequate performance can often be attained. This is excellently illustrated in work performed on the Skybolt missile. Specifically, a hot gas servo system was successfully developed and qualified (ref. 7), as an eventual replacement for the initially developed, hot-gas-operated, hydraulic servo system. The work resulted in a substantial 36 percent weight saving over the equivalent hydraulic system, without any relaxation in the performance requirements. This capability of rotary actuators has received little attention and even less application; yet it offers one of the most potential areas for future application. For this reason, the review of energy convertors has concentrated on rotary actuators and particularly on their applicability to hot-gas operation. This decision is further supported by the well-established application of hot-gas-operated linear actuators in many pyrotechnic devices.

Rotary Actuators. - The principal rotary actuators that can be considered practical for high temperature gas operation can be classified as shown in Figure 4. As a preliminary criteria for this review, only the positive displacement actuators will be covered. Discussion of fluid dynamic devices such as turbines has been omitted because of their inherent high gas consumption when operating at high loads and at the low end of their speed range.

Positive-displacement actuators can be sub-divided into non-expansion and expansion-type hardware. Basically, the non-expansion actuators are capable of operating with either a liquid medium or a gas, while the expansion types derive their work output by utilizing the internal energy of a compressed gas. During the operating cycle of the expansion-type actuators, there are periods when volumes of gas are essentially isolated from the inlet and exhaust ports. At this point, the design of the actuators is such that the gas is allowed to

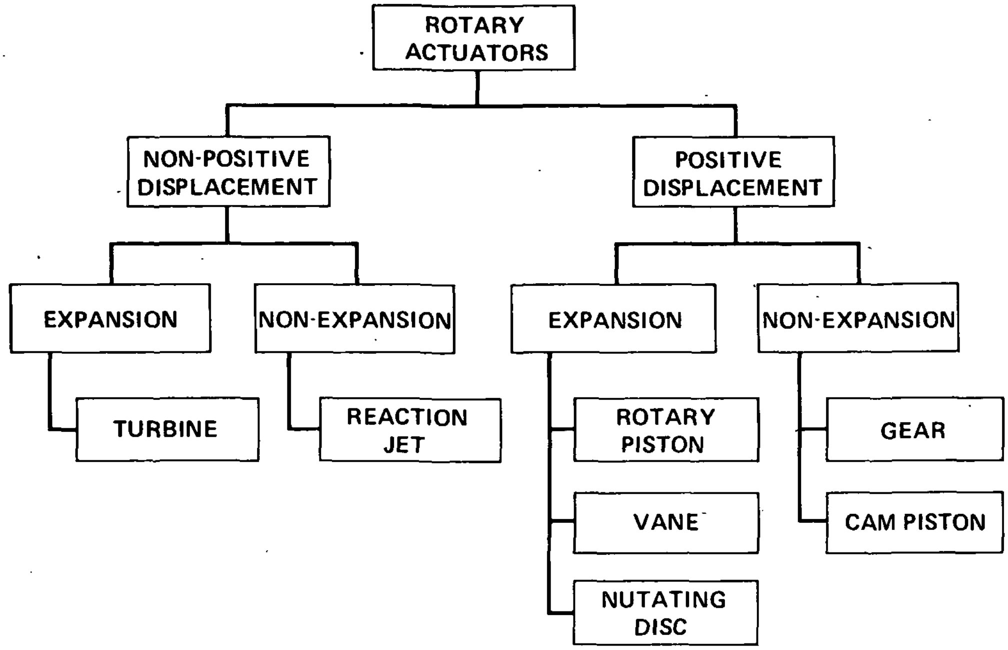


FIGURE 4
ROTARY ACTUATOR CLASSIFICATION

expand, trading pressure for volume. Expansion-type actuators are therefore capable of achieving more efficient utilization of the operating gas than the non-expansion types, when other factors are equal.

One factor that must be considered when selecting a rotary actuator for servo applications is the necessity that it be reversible, in order to avoid using complex clutch mechanisms. Also important are the volume under compression, which is pressurized and depressurized each time actuator direction is reversed, and low gas consumption which is desirable and dictates that this volume be kept small.

Rotary piston (bent axis) actuators: Figure 5 is a schematic diagram showing the operating principles of a typical rotary piston actuator. The actuator (ref. 8) consists of a number of parallel cylinders arranged to form a circle within a solid barrel. The axis of the barrel is inclined to the centerline of an output shaft and is attached so that the barrel rotates with the shaft by means of universal joint. One end of the barrel contains ports to each of the cylinders; and the barrel ports rotate over fixed valve plate ports for pressurization and exhaust. The pistons within each cylinder act against a drive plate that is connected concentrically and perpendicularly

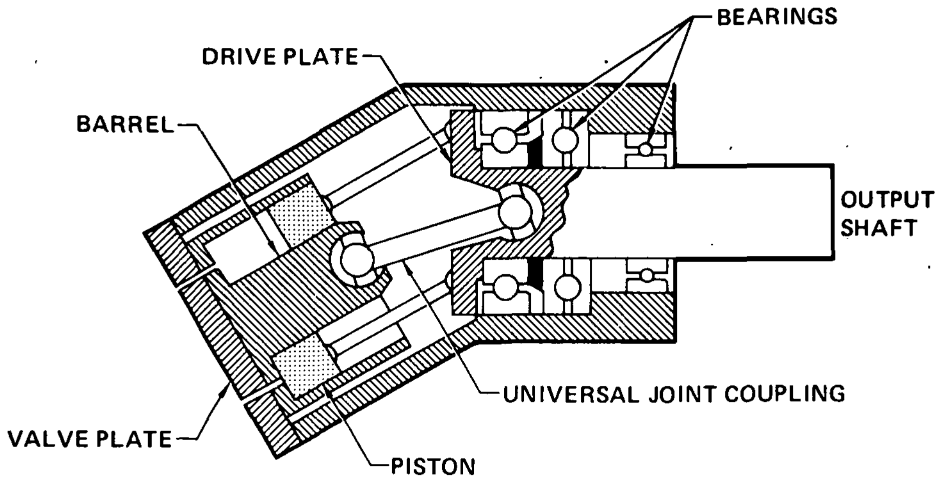


FIGURE 5
ROTARY PISTON ACTUATOR

to the output shaft. Because of the inclination between the piston lines of action and the drive plate, tangential forces are exerted on the plate; and this results in rotation of the output shaft.

Rotary piston actuators have been operated by hot gas at approximately 1093°C (2000°F) for a non-servo function on the Sprint missile. While this application requires a minimum operating time of sixty seconds, it is felt that actuators of this type possess the potential for continuous operation at slightly lower temperatures. Although the rotary piston has a higher inertia than either the vane or gear actuators, they have the lowest leakage rate of the actuators reviewed. This last characteristic is an advantage from an efficiency viewpoint; however, it also makes the actuator less tolerant of particulates in the operating gas, unless the clearances are optimized. The minimum specific fuel consumption for this type actuator is in the 15 to 20 lb/hp. hr. range.

Vane actuators: These actuators can be designed as either expansion or non-expansion devices, depending upon the location of the rotor within the actuator housing (ref. 8). A typical reversible, expansion-type actuator is shown schematically in Figure 6. In order for the actuator to be a non-expansion type, it is simply required that the rotor be mounted concentrically within the housing. For gas applications, expansion and non-expansion actuator designs can be compared on the basis of either actuator weight or fuel consumption. While the expansion motor offers the advantage of lower fuel consumption, the non-expansion design provides a smaller, lighter motor

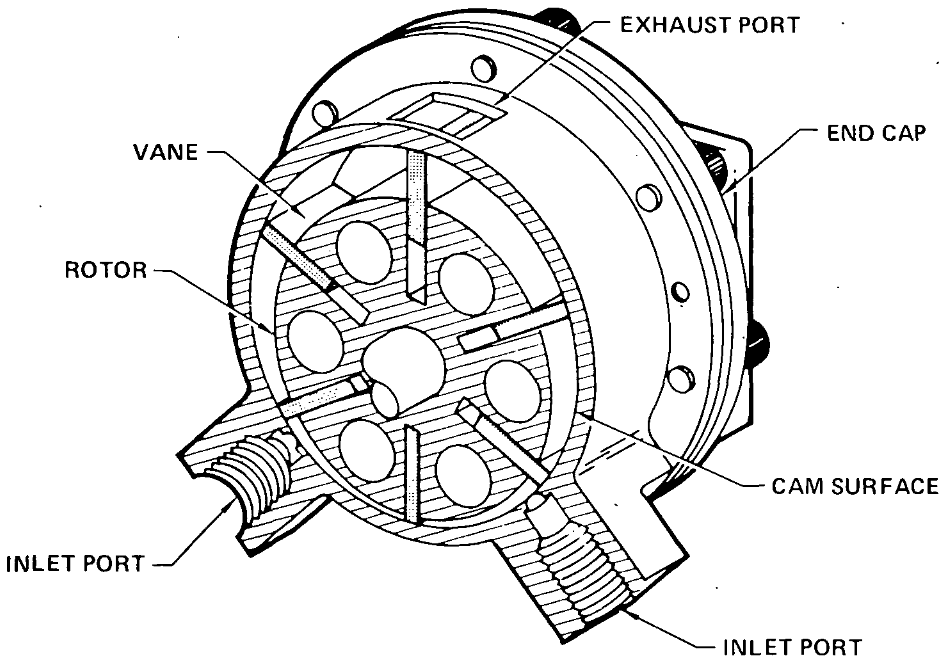


FIGURE 6
VANE ACTUATOR
(Reversible Expansion Type)

for a given output torque. If the system under consideration requires long operating times, the weight advantage offered by a non-expansion design is likely to be offset by the gas saving of the expansion design. For the purposes of this study, it was assumed that the more significant mechanical functions to which actuators could be applied would fall into the longer-operating-time category. For this reason, the following discussion on vane actuator design has been limited to the expansion type.

The depicted expansion-type vane actuator (ref. 7) consists of a slotted rotor, vanes, motor housing, and end caps. The spring-loaded vanes are installed in the rotor slots and the rotor is then mounted eccentrically inside the actuator housing. End caps are used to contain the gas and also support the rotor in its proper orientation within the housing. The sliding vanes in the rotor divide the actuator cavity into segments which change in volume as they rotate. The inlet port is offset from the centerline of symmetry, in the direction of desired rotation, to provide positive starting torque. As each segment rotates into position under the inlet port, it is filled with gas at the approximate supply conditions. The charging process continues until the trailing vane of the segment under consideration cuts off the gas supply.

As rotation continues, the gas within each segment expands with the increasing volume until the leading vane of each segment uncovers the exhaust port and permits the expanding gas to vent.

These actuators are characterized by their low inertia and low volume under compression. Because their efficiency is particularly good at low rpm it makes them well suited for servo operations. Minimum specific fuel consumption for these actuators lies between 30 to 40 lb/hp. hr. Vane actuators of the expansion type have also been successfully operated at gas temperatures as high as 1066°C (1950°F) for 90 second cycles and between 704°C to 843°C (1300°F to 1550°F) for 2 hour periods.

Nutating disc (wobble plate) actuators: The nutating disc actuator, illustrated schematically in Figure 7, is basically a non-expansion type device (ref. 8). Inlet and outlet ports are located on each side of a divider or separation plate which passes through a slot located on a nutating disc. When a pressure differential is applied across the divider, the disc does not rotate but nutates (tilts or rolls) as the gas makes its way around the actuator cavity to the outlet. The nutation of the disc produces a circular motion in a shaft located perpendicularly to the disc. This circular motion is converted to rotational output by means of cranks. These

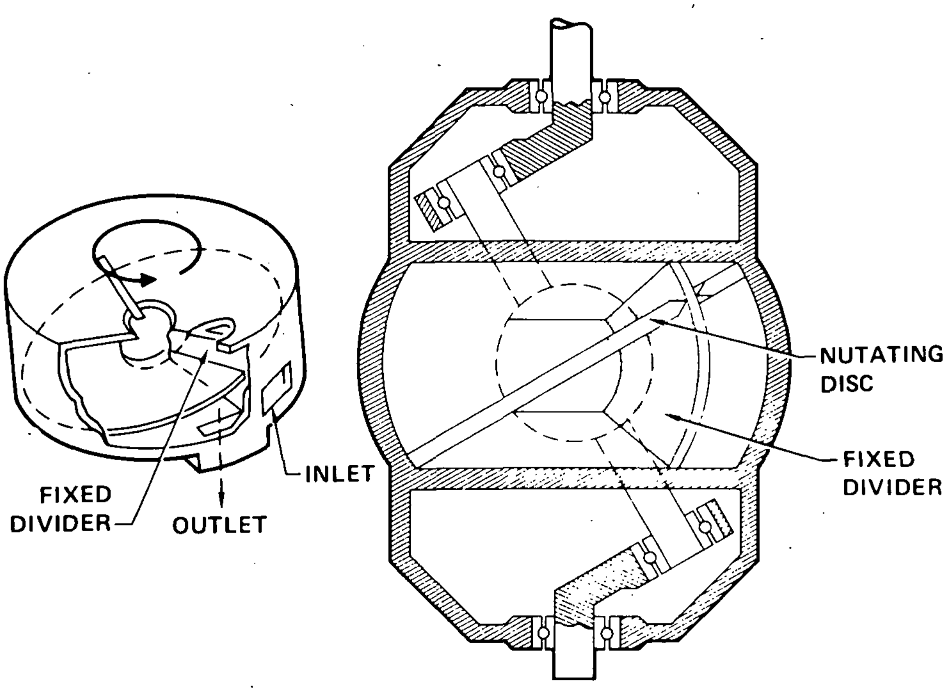


FIGURE 7
NUTATING DISC ACTUATOR

actuators exhibit poor efficiency at low speeds and are capable of only low output power. However, they do have a large displacement per revolution for an actuator of small dimensions. Minimum specific fuel consumption is in the order of 100 to 200 lbs/hp hour. One experimental actuator of this type has been operated successfully by hot gas, in a non-servo application, for varying periods of time at 649°C (1200°F) and for one-and-one-half hours at 871°C (1600°F).

Gear actuators: Figure 8 is a schematic representation of a gear actuator which is a non-expansion type device (ref. 8). It consists of dual inlet and exhaust ports located as shown, and a common variation also includes the addition of four vent ports. In the vent port variation, each of these ports is located halfway between each inlet and each exhaust port (ref. 9).

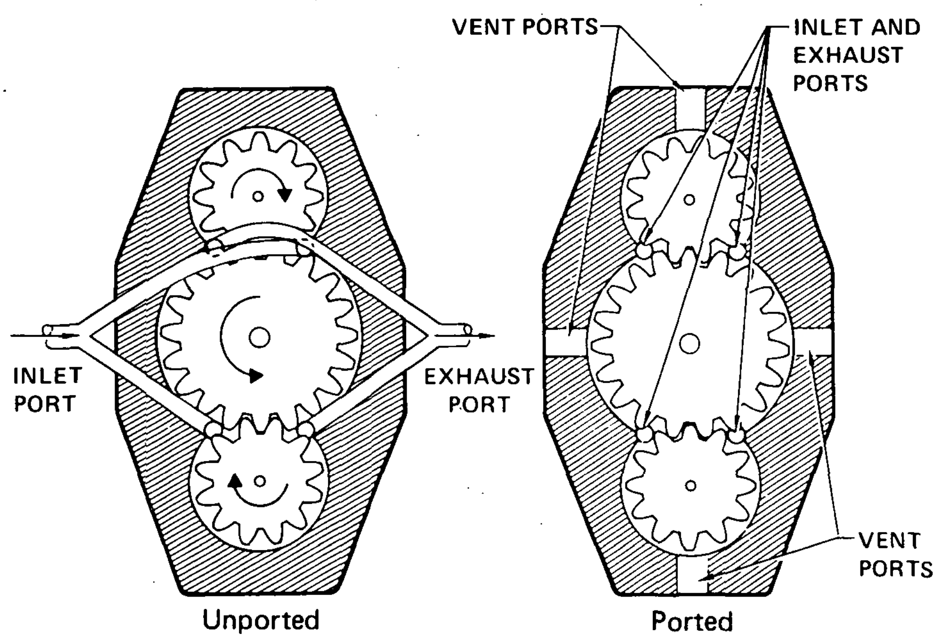


FIGURE 8
GEAR ACTUATOR

Both designs have three gears, with the power output from the center gear. Axially, the gears ride between two graphite insert plates which act as both bearing and sealing surfaces. In order to reduce oxidation of the graphite plates at high operating temperatures it is necessary to use special graphite compositions. Gear actuators are characterized by their small displacement per revolution and their high gas consumption caused by the high internal leakage. Minimum specific fuel consumption for the unported version is in the order of 300 to 400 lb/hp. hr. while the same actuator in a vented design is about 130 to 230 lb/hp. hr. Further, the ported design develops over four times as much power as the unported version. Gear actuators of the designs shown have been successfully used for high-temperature nuclear-reactor control applications in which they were exposed to 30 to 40 minute cycles at 649°C (1200°F.)

Cam piston actuators: The cam piston actuator illustrated schematically in Figure 9 has three pistons that are capable of moving along a common axis (ref. 8). Each piston is designed with a three-lobed face cam on each piston face. Located between the three pistons are two stationary plates; together with the two end plates, they carry cam rollers and make up the reacting members.

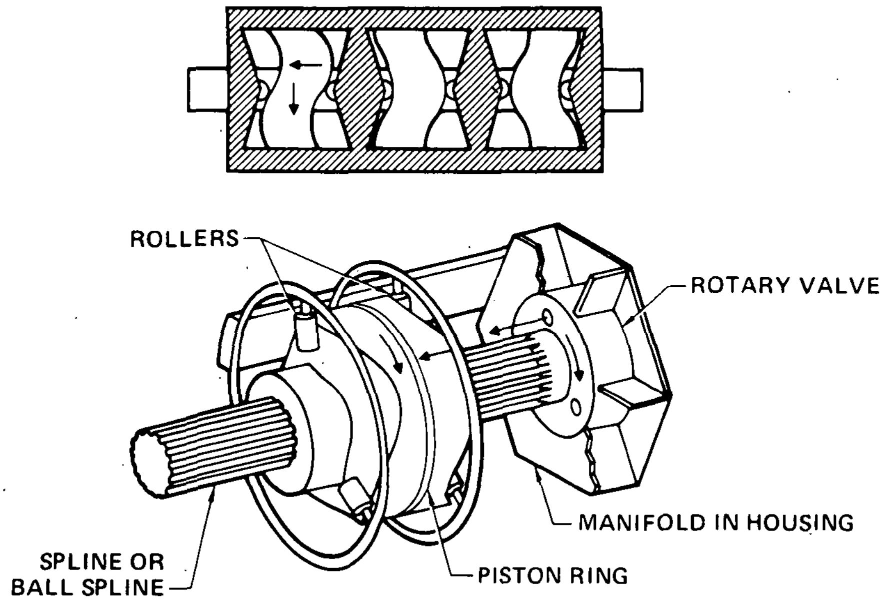


FIGURE 9
CAM PISTON ACTUATOR

Each piston is splined to a rotatable shaft in such a manner that the gas pressure slides the piston toward a stationary plate. As this occurs, the inclined cam faces contact the cam rollers, producing rotation of the piston and shaft. A maximum shaft rotation of 60° is produced by a single stroke of one piston; however, before the piston can complete its stroke, a rotary valve mounted to the shaft directs gas to another piston. This overlapping action is then repeated so that 18 piston strokes are made for each revolution of the shaft. Reversibility is accomplished by interchanging the inlet and exhaust ports.

Minimum specific fuel consumption for these actuators is in the order of 110 to 130 lbs/hp. hr. Limited testing has been successfully performed at gas temperatures of 316°C (600°F.)

In summarizing, Table I shows a brief comparison of the most significant parameters of the rotary actuators reviewed. While all five of the actuators discussed have been operated at elevated gas temperatures, only the rotary piston, vane, and nutating disc actuators have actually been operated at propellant exhaust gas temperature levels. In considering which of the three

TABLE I
COMPARISON OF ROTARY ACTUATORS

ACTUATOR	MINIMUM SPECIFIC FUEL CONSUMPTION (LB/HP HR)	OPERATING TIMES WITH HOT GASES	TOLERANCE TO GAS PARTICULATES
ROTARY PISTON	15 TO 20	60 SEC WITH 1093°C (2000°F) GAS	LOW TO MEDIUM TOLERANCE
VANE	30 TO 40	90 SEC WITH 1093°C (2000°F) GAS 2 HR WITH 710°C (1310°F) GAS	MEDIUM TO HIGH TOLERANCE
NUTATING DISC	100 TO 200	1.5 HR WITH 871°C (1600°F) GAS	MEDIUM TO HIGH TOLERANCE
GEAR	130 TO 400	30 CYCLES OF 25 MIN EACH WITH 399°C (750°F) GAS (ACTUATOR AT 566°C (1050°F) AMBIENT)	HIGH TOLERANCE
CAM PISTON	110 TO 130	SHORT PERIODS WITH 316°C (600°F) GAS	LOW TO MEDIUM TOLERANCE

actuators should be selected, the nutating disc can be discarded immediately because of its high inherent specific fuel consumption. The remaining two actuators can be considered about equal for either servo or non-servo applications. While the rotary piston actuator has a slight edge with respect to fuel consumption, the vane actuator appears to be less sensitive to particulates. This latter characteristic is probably the more significant when prolonged operation of the actuators is considered. For this reason, it was therefore decided to select the vane actuator for closer study.

Advanced rotary actuation technique: Recent developments have led to an advanced rotary actuation technique (ref. 10), in which an actuator and an epicyclic transmission have been integrated into a single package. The actuator is a positive-displacement, non-rotating vane motor, where captured vanes and displacement chambers are located radially around the outside of the transmission. Orbiting of the vanes imparts a radial force vector, which causes the input member of the transmission to orbit. This orbiting member is in turn geared directly to a rotating output shaft.

General Vane Actuator Design Parameters. - In designing a vane actuator, it is first necessary to establish the expansion ratio desired. This is based on the number of vanes, the location and shape of the inlet and exhaust ports, and the ratio of the motor eccentricity to the housing radius. While an increased expansion ratio improves fuel economy, it decreases power, reduces starting torque, and increases friction when actuator sizes are equal. Therefore, in selecting an expansion ratio, it is desirable to achieve a balance among power output, actuator size, and specific fuel consumption.

In general, increasing the number of vanes produces a smoother operation and improves resolution. When more than six vanes are used, however, the actuator size increases rapidly with the resulting reduction in performance due to increased inertia. In considering the optimum rotor length/diameter (L/D) ratio to select, two conflicting conditions exist. While a high L/D ratio is desirable for high response, because of the low moment of inertia, a long rotor will introduce clearance problems as a result of its large pressure deflections. On the other hand, a rotor with a low L/D ratio has a large diameter, and this limits the response due to its high moment of inertia. In the actuator design selected in Reference 7, it was found experimentally that a rotor L/D ratio of one gave the best performance. In addition, the rotor could be further lightened by drilling a series of holes, as shown in Figure 6.

A more detailed discussion of design parameters for both the unidirectional and reversible vane actuator is presented in Appendix A.

Phase II - Analysis of a Currently Flying Aeronautical Gas Generator System

The system selected for study in this phase was the emergency back-up method for opening the aerial refueling slipway doors of the F-15 fighter. In order to show how the back-up system was originally selected, it is first necessary to describe the normal or primary system operation. The primary system utilizes hydraulics to open (and close) the slipway doors, which provides a ramp-type guide for acceptance of the aerial refueling probe from a tanker. The system consists essentially of a solenoid valve which, upon command, ports hydraulic system pressure to a hydraulic actuator. This actuator is attached directly to a bell crank mechanism which, in turn, is attached to the slipway doors. The initial motion of the actuator first unlocks the mechanical linkage and then opens the doors, providing a ramp for correct positioning of the aerial refueling probe into the refueling receptacle.

Back-up System Trade Study. - Prior to reviewing various back-up methods, it was established that the back-up system should be capable of either paralleling or taking over operation of the hydraulic system. If a parallel system were selected, then a means of relieving the hydraulic system pressure was required. In addition, selection of a back-up system was also predicated upon the following constraints:

- No on-board high-pressure pneumatic system.
- No aircraft electric power available at time of emergency.
- No introduction of contaminants to the normal hydraulic system permitted.
- Preferably, the back-up system should provide a parallel redundant mode of operation to the normal hydraulically actuated system.

Three alternate back-up approaches were considered. These included a source of pressurized gas, a pyrotechnic (gas generator) pressurized hydraulic accumulator, and a pyrotechnic-operated actuator. Each approach is discussed below.

Air bottle: This approach would utilize stored-gas energy to operate the hydraulic actuator by porting the gas directly into the actuator. It would require the addition of check valves and a high-pressure gas-storage bottle. This would result in a fairly heavy bottle due to vulnerability (gun fire) requirements. A major disadvantage is the high rate of maintenance required, in addition to preflight checks. This approach does not provide a completely redundant mode of operation.

Pyrotechnic-pressurized hydraulic accumulator: This approach, coupled with an emergency selector valve, would utilize gas from a solid propellant gas generator to pressurize a hydraulic accumulator. This approach has one major disadvantage; namely, the accumulator is integral with the hydraulic system, which does not create a parallel and redundant back-up to the hydraulic system. In addition, there is also the possibility, though remote, of contaminating the hydraulic system with propellant gases and/or debris when the gas generator is fired.

Pyrotechnic actuator: This approach would require a separate gas generator/linear actuator that parallels the operating requirements of the hydraulic actuator. Such an actuator must be capable of stroking passively each time the hydraulic actuator is operated. In addition, it must also provide a means for relieving the hydraulic pressure when the emergency system is initiated.

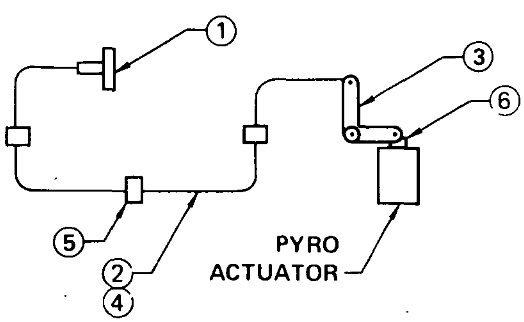
The optimum method selected from the three back-up approaches described above was the pyrotechnic actuator. The rationale for this choice was as follows:

- High energy-to-weight ratio inherent with pyrotechnics.
- The gas generator energy source (pressure cartridge) is not a pressure source until initiated upon command. The high gas pressure generated when the cartridge is fired is confined to a chamber within the actuator.
- The device can be placed at an optimum point in the operating system, such as in the mechanical linkage. This results in a *parallel mode of operation totally independent of the hydraulic* system.
- Minimum maintenance is required including scheduled cartridge replacement at three year intervals and actuator replacement every six years.

- o Demonstrated high reliability of pyrotechnic actuators on previous aerospace vehicles, including Mercury, Gemini, Apollo, and the F-111 Crew Module.
- o The actuator can be readily sized for possible ice loads without significant actuator growth. The primary hydraulic actuator is not sized to meet this environmental condition.

In selecting the pyrotechnic-actuator approach for the back-up system, the question of how to initiate it logically follows. Four different initiation techniques were considered; namely, purely mechanical, mechanically fired explosive stimulus system, mechanically fired ballistic hot gas stimulus system, and mechanically fired thermal battery system. These are discussed in detail below.

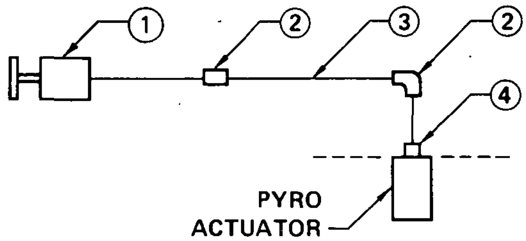
Mechanical: A purely mechanical approach would consist of a cable and bellcrank arrangement as shown in Figure 10. This design would provide a reliable method of signal transmission to fire a percussion primer located in the pressure cartridge. Because of the circuitous and lengthy routing of the cable between the cockpit and the actuator cartridge, frictional forces would limit the capability of the system. In addition, this approach would be heavy, compared to competing methods.



1. HANDLE
2. CABLE - STEEL (34 FT)
3. BELL CRANK ASSY (SPECIAL)
4. CONDUIT - STEEL
5. JUNCTION FITTING 3 REQD
6. FIRING PIN ASSY

FIGURE 10
MECHANICAL INITIATION OF AERIAL REFUELING ACTUATOR

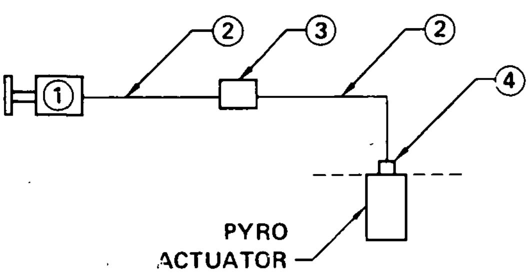
Mechanical/shielded mild detonating cord (SMDC): This method, shown in Figure 11, would utilize a mechanically fired initiator (detonator) located within the cockpit to initiate, in turn, an SMDC line. The explosive signal from this stimulus transfer line would then fire the cartridge in the pyrotechnic actuator. The system requires total replacement after firing, and would result in relatively high maintenance manhours, principally due to the required access necessitated by the rigid SMDC lines.



1. MECHANICAL INITIATOR
2. JUNCTION FITTING - 2 REQD
3. CONDUCTOR - SMDC (34 FT)
4. FIRING PIN ASSY

FIGURE 11
MECHANICAL/SMDC INITIATION OF AERIAL REFUELING ACTUATOR

Mechanical/ballistic hot gas: This method would utilize a mechanically fired initiator (gas generator), located within the cockpit, to produce hot ballistic gas (Figure 12). This gas pressure pulse would then be transmitted through Teflon-lined, metallic-sheathed hose to fire the cartridge in the pyrotechnic actuator. Because of the long hose length (34 ft.), one in-line gas generator would also be required to boost and maintain an effective pressure pulse. This system is both bulky and heavy. In addition, periodic leak checks are required, and the complete system must be replaced after firing.



1. MECHANICAL INITIATOR
2. RESISTOFLEX HOSE (34 FT)
3. GAS FIRED INITIATOR (BOOSTER)
4. FIRING PIN ASSY

FIGURE 12
MECHANICAL/BALLISTIC HOT GAS INITIATION OF AERIAL REFUELING ACTUATOR

Mechanical/electric (thermal battery): This approach, shown in Figure 13, would utilize a mechanically fired thermal battery located within the cockpit to provide an electric stimulus through twin conductor wire to an electrically initiated cartridge in the pyrotechnic actuator. Because this electrical system is isolated from the aircraft electrical system, simple twisting and shielding of the conductor and a suitable electric cartridge are sufficient to meet the RF requirements. No replacement of the twin electrical conductors are required after initiation.

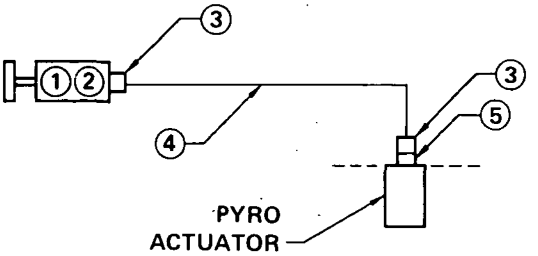


FIGURE 13
MECHANICAL/ELECTRIC (THERMAL BATTERY) INITIATION OF AERIAL REFUELING ACTUATOR

In addition to comparing the physical designs of the initiation methods described above, a comparison of estimated weights, cost and reliability is presented in Table II. The mechanically fired thermal battery was selected as the optimum initiation for the following reasons:

- The system is the lightest weight and second lowest in cost of those reviewed.
- The system is independent of aircraft electric power.
- The shielded conductors are installed during aircraft assembly, and do not require replacement when the back-up system is fired.
- The thermal batteries are highly reliable, as demonstrated by extensive use in nuclear devices.
- The thermal battery is easily replaced after firing.

TABLE II
COMPARISON OF INITIATION METHODS

INITIATION METHOD	WEIGHT (ESTIMATED) Kg (LB)	COST (ESTIMATED) ($)	RELIABILITY
MECHANICAL	1.24 (2.72)	335.00	0.9994
MECHANICAL/SHIELDED MILD DETONATING CORD	1.39 (3.07)	347.00	0.9988
MECHANICAL/BALLISTIC HOT GAS	1.88 (4.14)	248.00	0.9986
MECHANICAL/ELECTRIC (THERMAL BATTERY)	0.67 (1.49)	265.00	0.9981

Pyrotechnic Actuator Design Requirements.- A detailed presentation of the design requirements for the pyrotechnic actuator is listed in Appendix B.

Thermal Battery Initiator Design Requirements. - A detailed presentation of the design requirements for the thermal battery initiator is listed in Appendix C.

Back-up System Installation and Operation. - The back-up system pyrotechnic actuator is installed beside the primary hydraulic actuator, and both are connected to a common bell crank and mechanical linkage as shown in Figures 14 and 15.

Functioning of the back-up actuator (Figure 16) first causes operation of a small thruster (Rod #1) mounted at right angles to the long axis of the actuator. This triggers a hydraulic dump valve, and thereby removes hydraulic pressure from the system. At approximately 60 percent stroke of the thruster, the internal propellant gases are then ported to the substantially larger retractor. The gas pressure first acts on the larger diameter piston, which strokes approximately 5.71mm (0.225in.) and locks after first shearing a locking pin and overcoming any external loads. The gases next act on the smaller piston, causing the locking pin to shear and stroking it until it also locks. Changing to this smaller diameter piston avoids the passing of unnecessarily high loads into the mechanical linkage in the event high opposing loads (ice) are not present or at the moment of their sudden release.

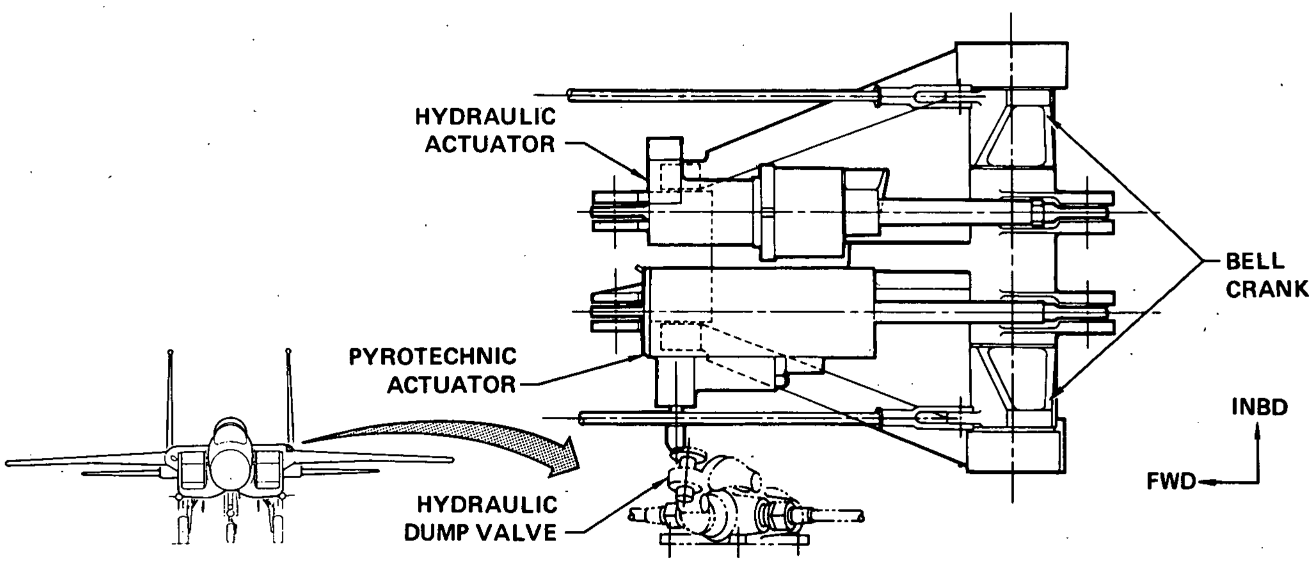


FIGURE 14
DETAIL OF AERIAL REFUELING SLIPWAY MECHANISM

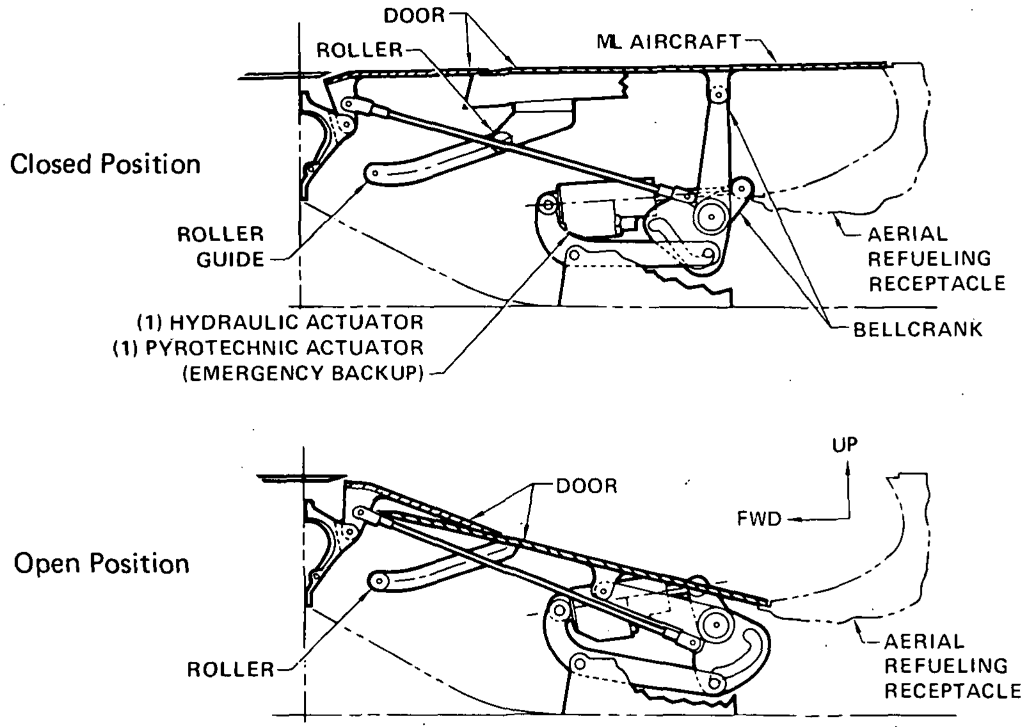


FIGURE 15
DETAIL OF AERIAL REFUELING SLIPWAY MECHANISM (Cont)

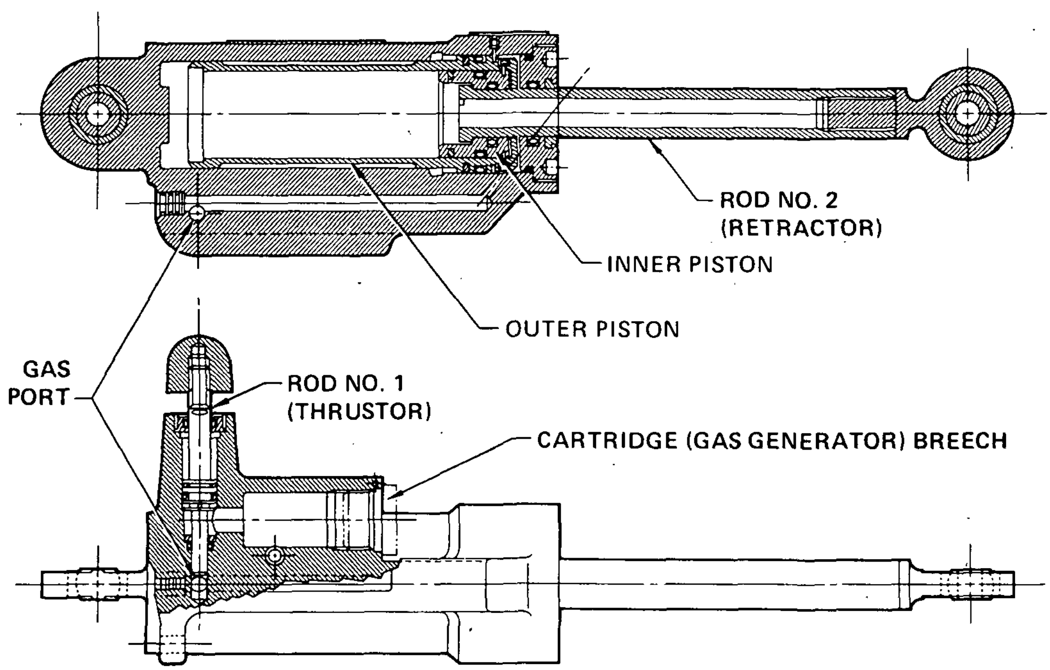
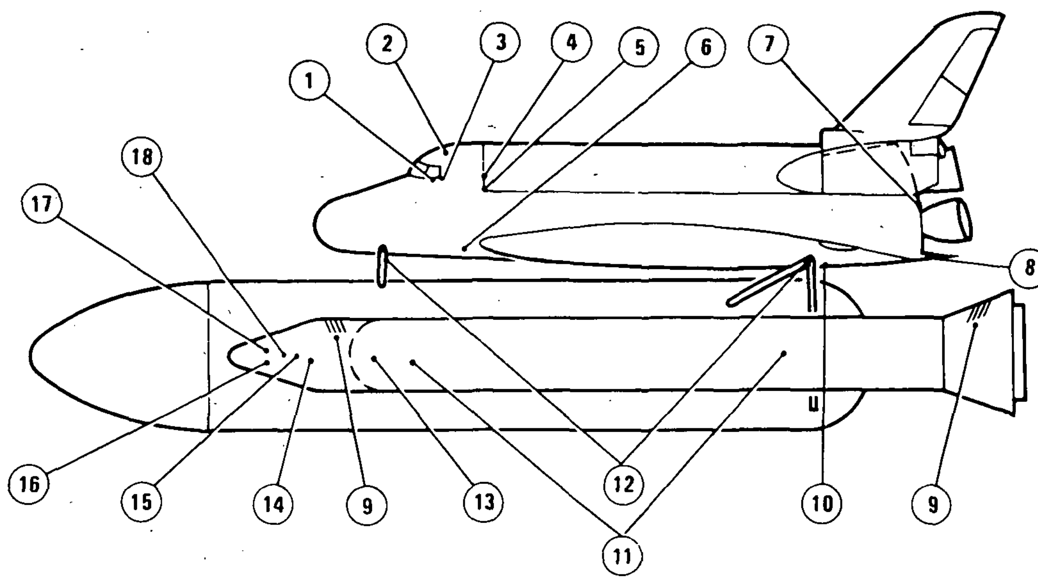


FIGURE 16
DESIGN DETAIL OF PYROTECHNIC ACTUATOR FOR AERIAL REFUELING SLIPWAY DOOR

Phase III - Potential Gas Generator and Energy Convertor Applications on Shuttle

Mechanical Functions and Selected Approaches. - This program phase examined the feasibility of applying pyrotechnic devices to accomplish tne major mechanical functions likely to be found on the Space Shuttle. The Space Shuttle consists of the orbiter vehicle, external tank, and two solid rocket boosters (SRB's).

Figures 17 is a graphic presentation of the Space Shuttle components showing mechanical functions that can be performed pyrotechnically. In some situations, however, over-riding system constraints may dictate that non-pyrotechnic means be used. Where a pyrotechnic approach has been chosen, a Space Shuttle requirement presently specifies that previously NASA-qualified hardware from their preferred part list receive first consideration for use.



1. PERSONNEL EJECTION SEATS (FLIGHT TEST) (B)
2. EMERGENCY JETTISON EGRESS HATCH (FLIGHT TEST) (B)
3. POSSIBLE REPOSITIONING EJECTION SEATS (FLIGHT TEST) (B)
4. EMERGENCY JETTISON MANIPULATOR ARMS (P)
5. EMERGENCY OPERATION PAYLOAD DOOR (P)
6. LANDING GEAR DEPLOYMENT (NOSE-C; MAIN-P)
7. DECELERATION CHUTE DEPLOYMENT (B)
8. BODY FLAP POSITIONING (P)
9. SRB SEPARATION MOTORS-IGNITION (B)
10. ET/ORBITER UMBILICAL PLATE (B)
11. SRB/EXTERNAL TANK STRUCTURAL SEPARATION (B)
12. EXT TANK/ORBITER STRUCTURAL SEPARATION (FWD-B; AFT-C)
13. SRM INITIATION (B)
14. SRB RECOVERY AIDS DEPLOYMENT (B)
15. MAIN CHUTE DISCONNECT (B)
16. DROGUE CHUTE DEPLOYMENT (B)
17. SRB NOSE CONE SEPARATION (B)
18. DROGUE CHUTE DISCONNECT (B)

B = CURRENT BASELINE
C = UNDER CONSIDERATION
P = POSSIBLE - NOT UNDER CURRENT CONSIDERATION

FIGURE 17
SPACE SHUTTLE - MAJOR MECHANICAL FUNCTIONS WHERE PYROTECHNICS MAY BE APPLIED

For example, the Standard Manned Spaceflight Initiator (SMSI), formerly designated as the Single Bridgewire Standard Initiator (SMASI), will be the standard electroexplosive device for all electrically initiated pyrotechnic functions. If this hardware will not fulfill the specific requirement, then modification of this hardware, use of other qualified hardware, or development of new hardware should be followed in this order of precedence. Table III is understood to represent the current approaches to fulfilling the various mechanical functions presented in Figure 17.

<u>Recommended Mechanical Functions for Detailed Study</u>. - Each function utilizing a pyrotechnic approach required that it be categorized as either "state-of-the-art," "minimal modification," or a "new concept." With the exception of a pyrotechnic back-up to the operation of the payload bay doors, all functions utilizing pyrotechnics fall into the state-of-the-art category. Back-up operation of the payload bay doors, if selected, would require use of a gas generator and rotary actuator combination. In view of the work previously performed in this field (ref. 8), this approach should be considered to be in the minimal-modification category. None of the functions discussed above, however, provide an example for the new-concepts category. A rather radical idea was therefore conceived for utilizing APU derived hot gas to directly drive the primary control surfaces of the Space Shuttle through the use of rotary actuator servos. Although this concept may be open to considerable discussion, it does appear to be feasible. Each category is further discussed below:

State-of-the-art: For the purpose of the study, the NASA-JSC pyrotechnically operated landing gear concept was selected, since it utilizes a combination of strap cutters and thrusters. Schematically depicted in Figure 18, this system could replace the conventional hydraulic approach. Specifically, it is designed to open each landing gear door and release the gear pyrotechnically, after which it free falls into position and mechanically locks in place. A back-up system is also present to pyrotechnically drive the gear down and lock it, in the event it should hang up during deployment.

TABLE III
MAJOR MECHANICAL FUNCTIONS - SELECTED AND/OR POSSIBLE APPROACHES

Orbiter

FUNCTION	PRIMARY MODE	BACK-UP
EMERGENCY EGRESS (FLIGHT TEST ONLY)		
• JETTISON ESCAPE HATCH	PYRO - LINEAR EXPLOSIVES	BREAKER BAR ON SEAT
• SEAT REPOSITIONING	PYRO - LINEAR ACTUATOR	–
• PERSONNEL EJECTION	PYRO - EJECTION SEAT	–
DECELERATION CHUTE DEPLOYMENT	PYRO - APOLLO-CM PILOT MORTAR	
BODY FLAP POSITIONING	HYDRAULIC - LINEAR ACTUATOR	PYRO - LINEAR ACTUATOR
DOCKING TUNNEL - EMERGENCY SEPARATION	PYRO - APOLLO-CM SEPARATION CONCEPT	–
MANIPULATOR ARMS - EMERGENCY JETTISON	ELECTRO-MECHANICAL SEGMENTED NUT	–
PAYLOAD BAY DOORS - EMERGENCY OPERATION	ELECTRO-MECHANICAL	PYRO - ROTARY ACTUATOR
EXTERNAL TANK/ORBITER STRUCTURAL SEPARATION		
• FORWARD	PYRO - APOLLO TOWER EXPLOSIVE NUTS	–
• AFT	ELECTRO-MECHANICAL - LATCH RELEASE	–
EXTERNAL TANK/ORBITER UMBILICAL PLATE	PNEUMATIC LATCH AND EXPLOSIVE NUTS	–

Solid Rocket Booster (SRB)

FUNCTION	PRIMARY MODE	BACK-UP
SOLID ROCKET MOTOR (SRM)		
• SAFE AND ARM	ELECTRO-MECHANICAL	–
• IGNITION	PYRO - PYROGEN IGNITER W/SMSI	–
SRB/EXTERNAL TANK STRUCTURAL SEPARATION		
• FORWARD	PYRO - APOLLO TOWER EXPLOSIVE NUTS	–
• AFT	PYRO - APOLLO TOWER EXPLOSIVE NUT AND GUILLOTINE	–
SRB SEPARATION MOTORS - IGNITION	PYRO - PYROGEN IGNITER W/SMSI	–
SRB RECOVERY SYSTEM		
• NOSE CONE SEPARATION	PYRO - LINEAR EXPLOSIVE OR EXPLOSIVE NUTS AND/OR BOLTS	–
• DROGUE CHUTE DEPLOYMENT	PYRO - APOLLO-CM PILOT MORTAR	–
• DROGUE CHUTE DISCONNECT	PYRO - APOLLO-CM RISER GUILLOTINE	–
• MAIN CHUTE - DISCONNECT	PYRO - APOLLO-CM RISER GUILLOTINE	–
• DISREEFING DROGUE AND MAIN CHUTES	PYRO - APOLLO REEFING LINE CUTTERS	–
• FLOATION BAG - MAIN CHUTE CLUSTER	PYRO - GAS GENERATORS	–
• RECOVERY AIDS DEPLOYMENT	PYRO - PIN PULLERS	–
• TAPE RECORDER JETTISON AND FLOATION*		
• TV CAMERA RECOVERY*		

*Possible Functions

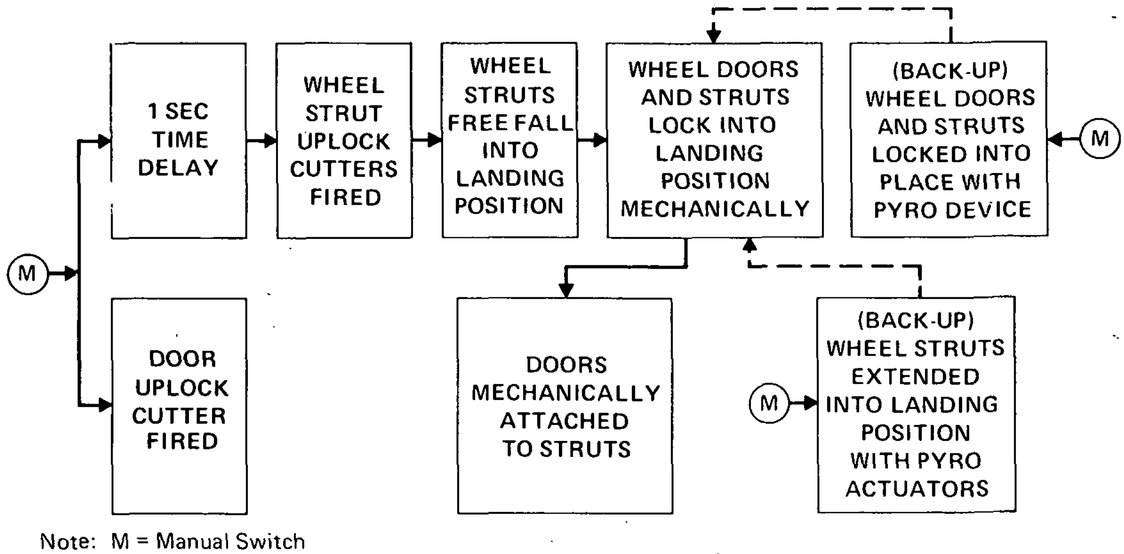


FIGURE 18
STATE-OF-THE-ART RECOMMENDATION FOR PYROTECHNIC LANDING GEAR DEPLOYMENT SYSTEM

Minimal modification: As discussed above, the pyrotechnic back-up operation of the payload bay doors was selected as the example for this category. The normal system operation, shown in Figure 19, utilizes an electrically driven

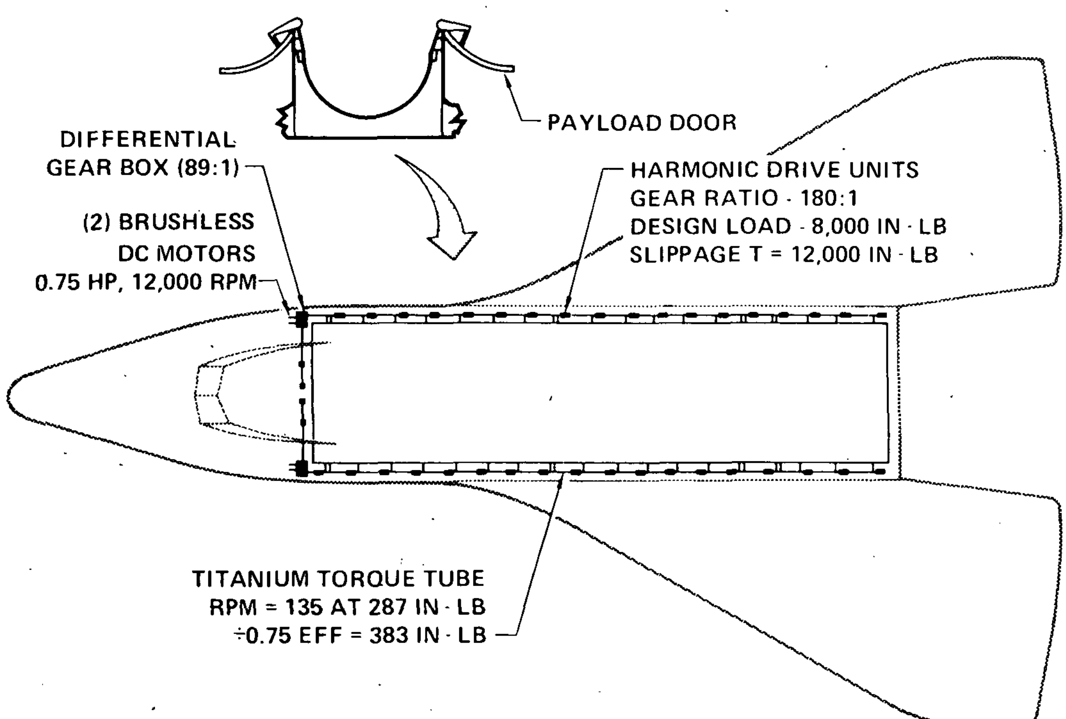


FIGURE 19
PRIMARY PAYLOAD DOOR DRIVE MECHANISM

system to provide the primary mode of operation. A gas generator/vane actuator arrangement, coupled with a transmission and manual clutch, make up the pyrotechnic back-up system (Figure 20). This system is designed to tie directly into the differential output shaft of the primary system, thereby providing a totally independent emergency approach. The back-up design also incorporates two gas generators and a selector valve to provide both an opening and a closing capability.

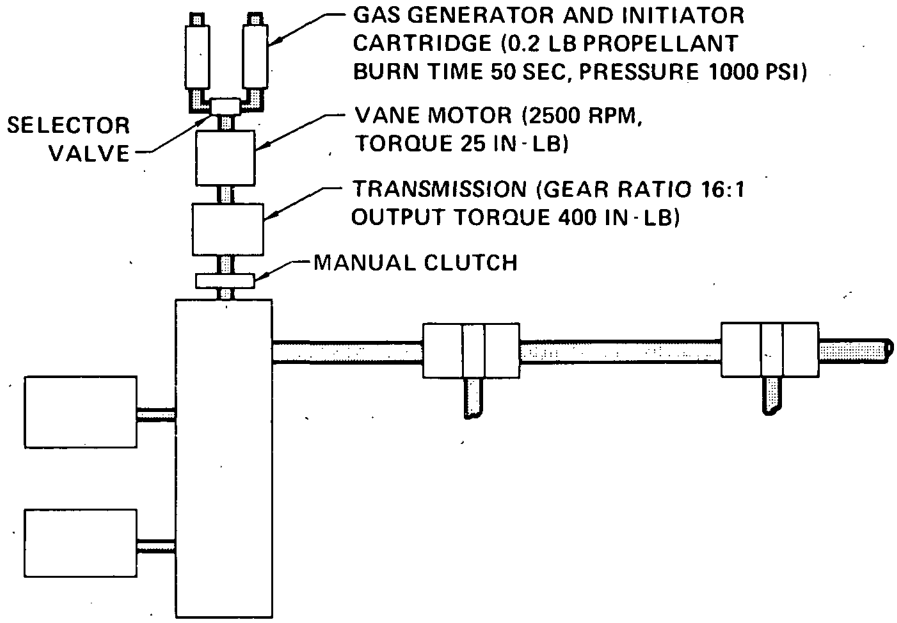


FIGURE 20
MINIMAL MODIFICATION RECOMMENDATION
Payload Bay Door Pyrotechnic Backup Drive Mechanism

An alternate arrangement of the back-up system is shown in Figure 21. While providing some weight saving, it has the disadvantage of reduced reliability through elimination of one of the redundant electric motors, and also requires driving through the common differential. In addition, the rotary actuator would have to operate at a substantially higher speed which, in turn, introduces lubrication problems.

New concepts: Figure 22 is a schematic representation of the operation of the primary control surfaces (elevons and/or rudder) by direct application of APU generated hot gas. The proposed system consists basically of a flow-control valve, rotary actuator, transmission, possibly a gear reducer, a ball-screw actuator attached to the control surface, and an electrical position feedback arrangement.

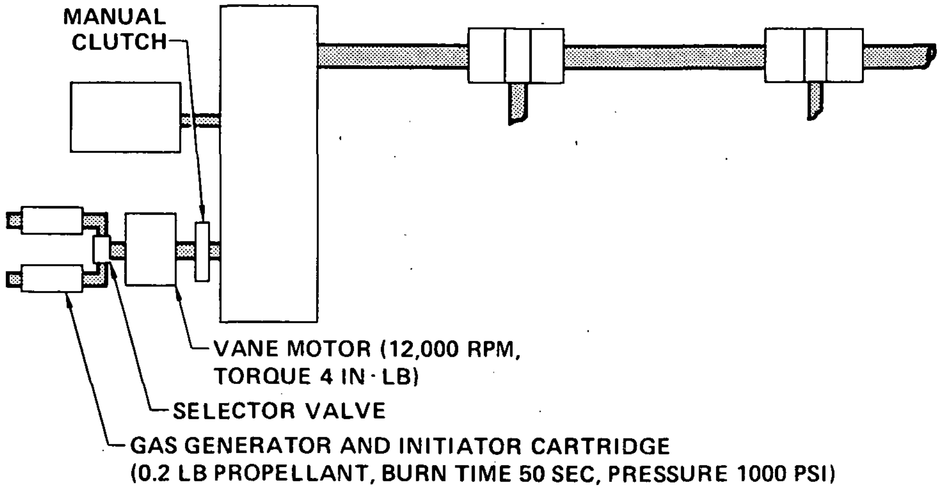


FIGURE 21
ALTERNATE MINIMAL MODIFICATION RECOMMENDATION
Payload Bay Door Pyrotechnic Backup Drive Mechanism

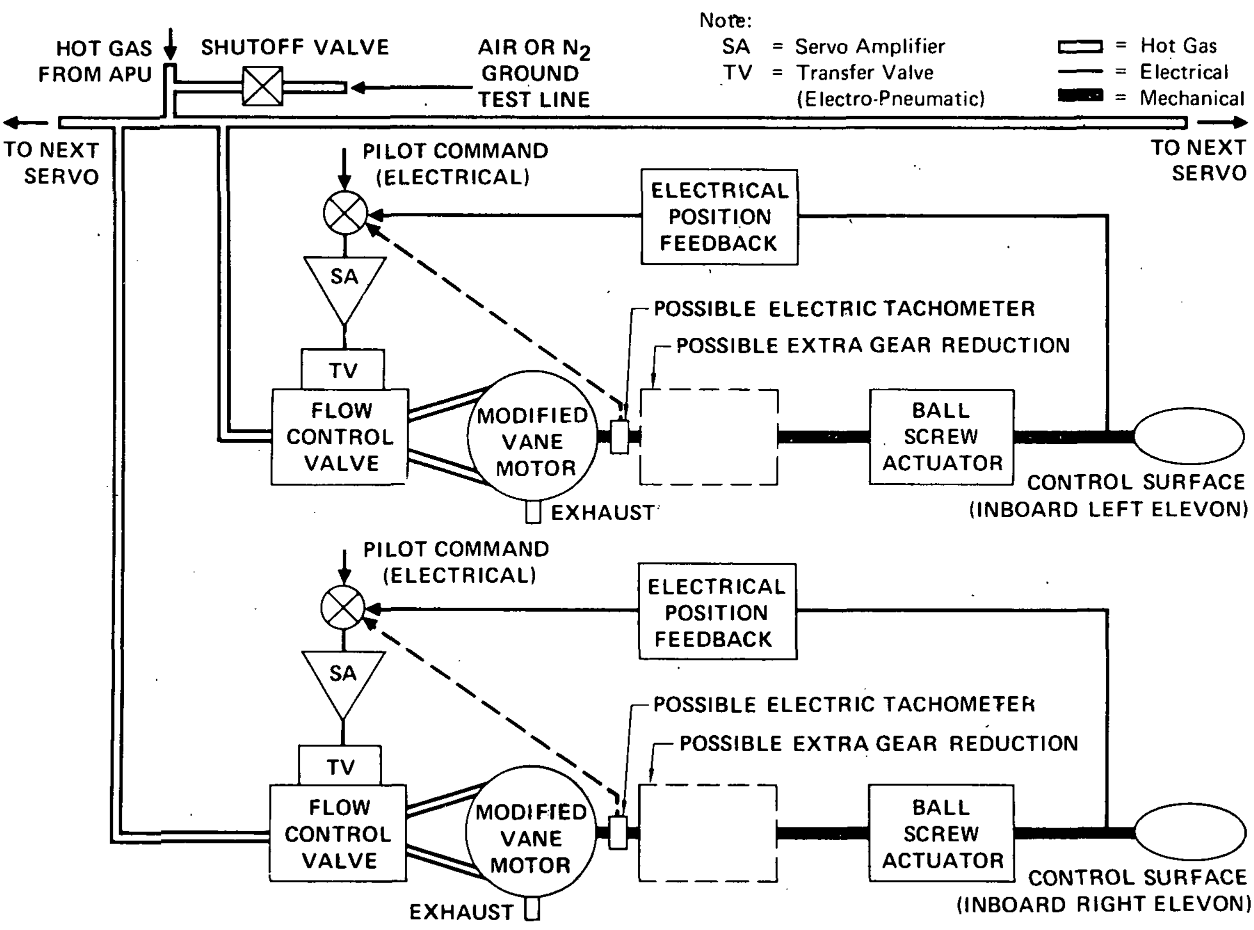


FIGURE 22
NEW CONCEPT RECOMMENDATION
Hot Gas Operation of Primary Control Surfaces

The advanced rotary actuation technique (ref. 10) was selected because of its reduced size and weight, high response, lower cost, and improved reliability. Only a single motor is shown for each ball-screw actuator; however, it may be necessary to provide them in tandem to meet the load or redundancy requirements. In terms of hardware development, one of the most critical items would be the rotary actuator. This actuator would have to operate with 760°C (1400°F) gas for periods of approximately 30 minutes per flight. While this does not appear to be insurmountable, it will require some further development, particularly in the application of current state-of-the-art materials.

Phase IV - Gas Generator and Energy Convertor

Technology Development Guidelines

The lack of Space Shuttle subsystem design details available at the present time has restricted the development of detailed specifications. Instead, as many design parameters and guidelines as possible are presented.

State-of-the-Art-Category. - The selected system, the primary and back-up deployment of the landing gears (NASA-JSC concept), consists essentially of electric initiators, strap cutters (guillotines), and linear actuators (thrusters).

General

Preliminary design parameters of the candidate system will be substantially defined by the mission environments.

Determine all operating, non-operating, and storage conditions.

Define the performance requirements for the installed system during flight operations.

Specific Initiator

Use of SMSI (Standard Manned Space Flight Initiator) mandatory for electrical initiation of the candidate system.

Determine redundancy philosophy to be applied to the initiation of each strap cutter and each linear actuator.

Detonator

Select suitable explosive components compatible with the upper temperature limits of the mission environment and low sublimation rates compatible with hard vacuum.

Select material for end closure or cup that provides the optimum detonation transfer characteristics.

Storage life of the detonator shall be compatible with that of the initiator, because they are normally permanently welded together.

Strap Cutter (Guillotine)

Utilize established Apollo program design of opposed, linear, explosively driven cutter blades.

Determine severance margin by demonstrating the severance of either increased strap thickness or maximum strap thickness with reduced core loads of explosive.

The housing retaining the blades and explosive cords can deform after the device if functioned, but it must not fracture or generate shrapnel.

Select explosive cord compatible with upper temperature limits of the mission environment and low sublimation rates compatible with hard vacuum.

Gas Generator (Pressure Cartridge)

Select suitable propellant compatible with the upper temperature limits of the mission environment and low sublimation rates compatible with hard vacuum.

Select suitable propellant configuration to match the rate of gas production with the flow requirements of the load.

Storage life should be compatible with that of the initiator, because the latter is normally permanently welded to its mating cartridge.

Linear Actuator (Thruster)

Establish thrust-time and load-stroke requirements.

Select a design that avoids fluid damping.

Select a passive means not subject to leakage to achieve load control. Consider use of crushable aluminum honeycomb to limit peak loading.

Minimal Modification Category. - A pyrotechnic back-up to the payload bay door drive mechanism was selected for this category. The candidate approach recommended an electrically initiated, solid-propellant gas-generator operated vane actuator of the expansion type, together with an appropriate transmission and clutch. While the advanced rotary actuator technique does provide a very compact package, for this exercise the following guidelines have been written with only the fundamental vane actuator in mind.

General

Preliminary design parameters of the candidate system will be substantially defined by the mission environments.

Determine all operating, non-operating, and storage conditions.

Define the performance requirements for the installed system, both for ground check-out (system should be capable of being tested by compressed gas) and for flight operations.

Specific Initiator

Use of SMSI (Standard Manned Space Flight Initiator) mandatory for electrical initiation of the candidate system.

Determine whether single or redundant initiation of each gas generator is required.

Igniter Cartridge (may not be necessary)

Select suitable igniter material, compatible with mission environments, for ignition of gas generator propellant.

Storage life of cartridge shall be compatible with that of initiator, because initiator is normally permanently welded to its mating cartridge.

Gas Generator

Select a stable propellant compatible with the upper temperature limits of the mission environment and low sublimation rates compatible with hard vacuum.

As a first choice, avoid propellants whose combustion products are corrosive, and preferably select one that contains the very minimum of solid particulates.

The propellant grain should be designed for neutral or cigarette burning. Accurate matching of the propellant burning with changing gas flow requirements of the load, to maintain uniform pressure, should be considered, but may not be justified for the small system size.

An energy margin in the form of increased propellant burning time is highly desirable. While no ground rule exists, providing a burn time equal to twice the nominal operating time of the primary system seems reasonable.

Vane Actuator

Select an expansion-type actuator, in order to capitalize on its lower specific fuel consumption.

System requires a reversible actuator design, in order to support either opening or closing of the payload bay doors.

Select materials for compatibility with the hot propellant exhaust gas environment. Total duration and number of operating cycles must be defined, based on the estimated frequency of use of the system and the total number of flights per vehicle.

Select materials for the actuator vanes that have some self-lubricating qualities, in order to keep wear to a minimum.

The actuator vanes should be spring loaded in order to keep gas leakage to a minimum during starting and reversing. A suitable balance should be established between the need for keeping gas leakage and friction, respectively, to a minimum.

Design the actuator to facilitate easy internal inspection and cleaning.

The actuator should be capable of operation by compressed gas for ground check-out purposes.

Transmission

Must be compatible with the torque requirements of the primary system.

Manual Clutch

Required to prevent back driving of the back-up system. Passive operation of the back-up system every time the primary system is operated will produce unnecessary wear on the actuator components.

Select a positive engagement (non-slip) type, compatible with the reversing capability of the back-up system.

New Concept Category. - The candidate system for this category was operation of the Space Shuttle's primary control surfaces by direct application of APU-generated hot gas. Specifically, operation of the elevons was selected. The pneumatic design baseline utilizing advanced rotary actuators (ref. 10), concluded that three parallel pairs of rotary/ball screw actuators would be required per elevon (Figure 23), based on the assumed loads and redundancy requirements. A typical dual elevon pneumatic drive is shown in Figure 24. The design approach assumed that each actuator pair should be capable of carrying one-half of the total elevon load, but in application would only share one-third of the load. The design also provides that if one actuator in a pair should fail, its mate would continue to operate and would also back-drive the failed unit. Because of the relative complexity of the candidate system, estimated performance requirements (Table IV & V) were prepared instead of the development guidelines presented in two previous categories.

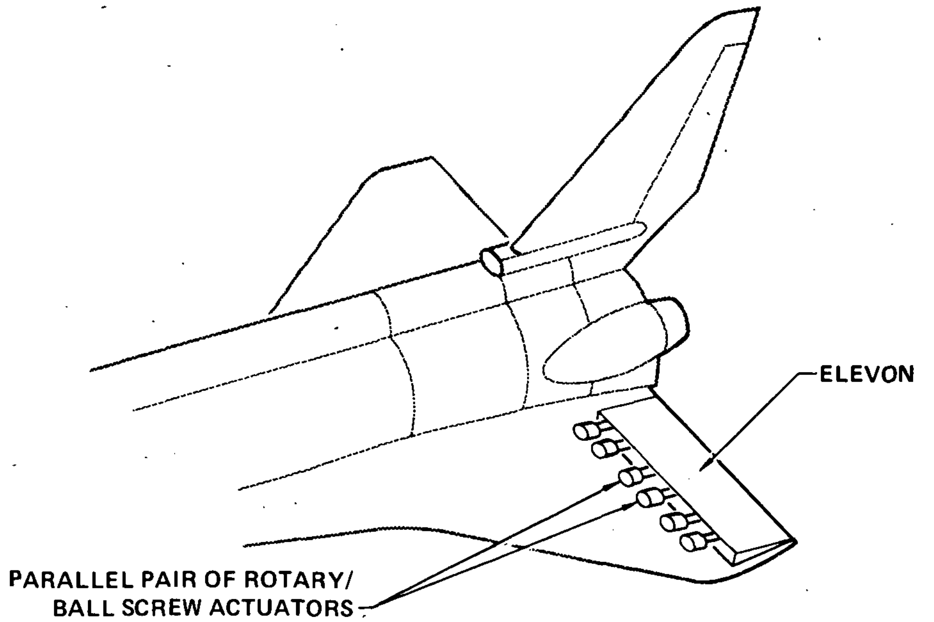


FIGURE 23
ELEVON PNEUMATIC ACTUATOR INSTALLATION

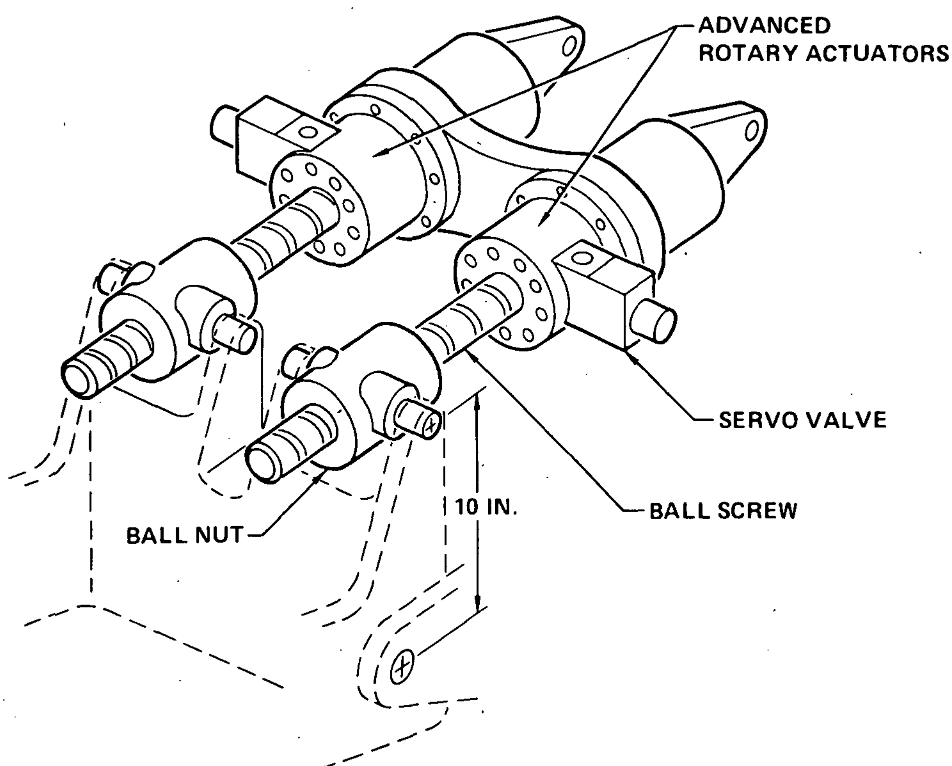


FIGURE 24
PARALLEL PAIR OF ROTARY/BALL SCREW
ACTUATORS FOR ELEVON

TABLE IV
DESIGN REQUIREMENTS FOR ELEVON BALL SCREW/ROTARY ACTUATORS

BALL SCREW ACTUATOR OUTPUT LOAD				ROTARY ACTUATOR TORQUE	
HINGE TORQUE PER ACTUATOR J (IN.-LB)	MAX. FORCE WITH 25.4 cm (10 IN.) ARM kg (LB)	ACTUATOR DISPLACEMENT FROM NEUTRAL cm (IN.)	RATE AT MAX. FORCE cm/SEC (IN./SEC)	ACTUATOR OUTPUT RATE AT MAX. TORQUE WITH 2.54 cm (1.0 IN.) LEAD (DEG/SEC)	MAX. TORQUE PER SINGLE ACTUATOR WITH 2.54 cm (1.0 IN.) LEAD J (IN.-LB)
96,900 (855,000)	49,377 (109,000)	+16.3 TO −4.3 (+6.4 TO −1.7)	10.2 (4.0)	1444	2,187 (19,300)

TABLE V
ELEVON BALL SCREW ACTUATOR DESIGN PARAMETERS

AVG. THRUST PER BALL SCREW kg (LB)	SCREW			NUT			LIFE (REV.)
	BALL CIRCLE DIA. cm (IN.)	LEAD cm (IN.)	LENGTH cm (IN.)	O.D. cm (IN.)	LENGTH cm (IN.)	NO. OF BALL CIRCUITS	
43,941 (97,000)	12.7 (5.0)	2.54 (1.0)	45.7 (18.0)	17.8 (7.0)	20.3 (8.0)	6	1.14×10^6

CONCLUSIONS

Gas generators (solid propellant) and energy convertors (linear actuators), which were well proven on the Mercury, Gemini, and Apollo programs, will continue to offer minimum-weight, highly reliable methods of performing many short-duration, linear-type mechanical functions. Similarly, many Space Shuttle mechanical functions can be accomplished by this type of gas generator/energy convertor combination. Pyrotechnic devices of this type can often be shown, through trade studies, to provide the optimum method of attaining a truly redundant back-up to a primary, non-pyrotechnic system. Such approaches can be designed to stroke passively, in parallel with the primary system, until initiated. While not frequently utilized, linear actuators can also offer additional design flexibility by permitting multifunction-sequenced operation of integrally packaged thruster/thruster and thruster/retractor combinations.

As a result of the gas generator/energy convertor survey, it was found that solid propellant operated rotary actuators have also been successfully developed and available for a number of years, although they have seen very limited application to date. Such rotary actuator combinations have been operated for period of up to ninety seconds; however, this does not appear to be their upper limit. Their potential as a compact, reliable, short-term source of rotary power for either servo or non-servo functions should not be overlooked by the designer.

A major effort of this study was to review potential applications of gas generators and energy convertors on the Space Shuttle. While linear-type actuators were found to fulfill most mechanical requirements, either as state-of-the-art or by minimal modification, a new concept was proposed for rotary actuator application. The proposed concept entailed using the Space Shuttle's auxiliary power units (APU) to directly operate the primary control surfaces by means of a rotary actuator/ball screw actuator combination. Such an approach may appear to be a radical departure from the conventional APU-driven hydraulic system. However, hot gas pneumatics offer improved efficiency through a single energy conversion and lower operating pressure, extreme temperature compatibility, no return lines, long-term dry storage, and leakage tolerance. While long-term hot gas operation of rotary actuators is currently not state-of-the-art technology, successful short-duration operation by the hotter solid-propellant-generated gases, has established a baseline from a materials standpoint. On this basis, it appears reasonable that satisfactory component hardware could be developed to meet the very demanding thermal environment required by such a system. In selecting possible direct operation of the Shuttle's primary control surfaces by APU-derived hot gas, it was not the intent of the program to enter into a treatise on the philosophy between pneumatics and hydraulics for the suggested application. Instead, it was purely an attempt to show potential new areas for technology expansion in the gas generator/energy convertor field.

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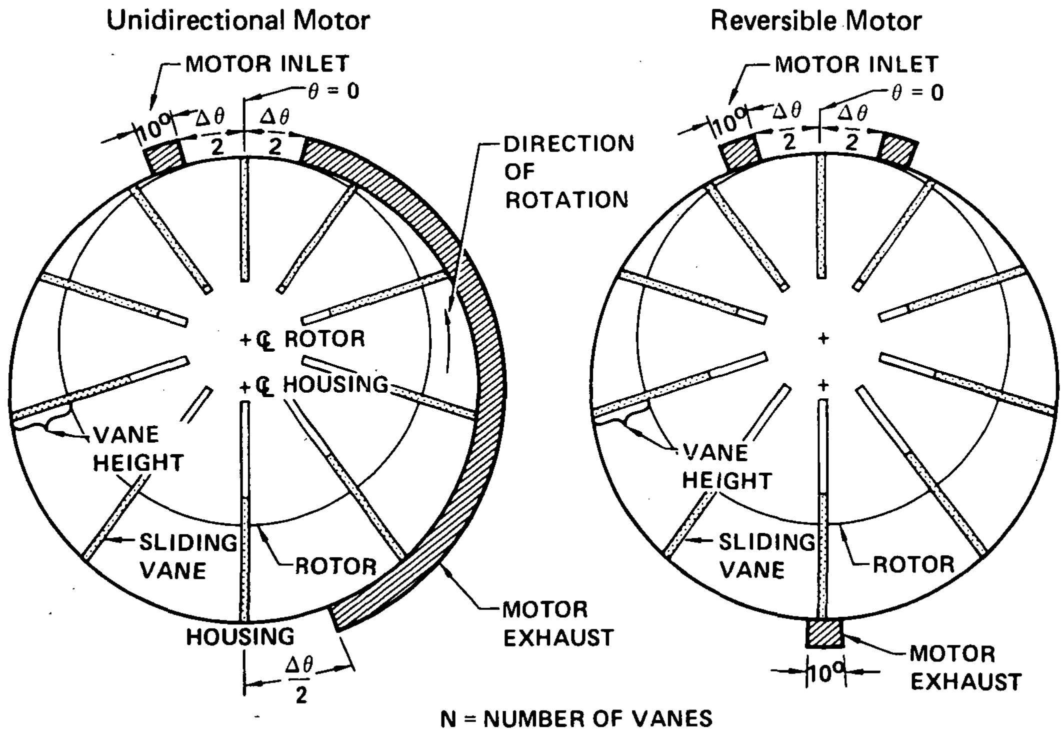
APPENDIX A

VANE ACTUATOR DESIGN CHARACTERISTICS

Since vane actuators can be designed for either unidirectional or reversible operation (Figure A1), differences exist in the design optimization of the exhaust port for each method. In the unidirectional design, exhausting can be accommodated throughout the majority of the second half of the cycle, negating essentially all recompression. With the symmetry required for the reversible design, the exhaust port size is limited, and some recompression of trapped gas will occur until the leading vane uncovers the opposite inlet port, allowing the captured gas to escape. This recompression of trapped gas will result in some negative torque. In order to keep the recompression losses within reasonable limits, full gas expansion cannot be realized. Instead, the gas is expanded to some intermediate pressure which is exhausted to ambient. The reversible vane motor design, therefore,

FIGURE A1
VANE ACTUATOR CONCEPTS



N = NUMBER OF VANES
$\Delta\theta = 360/N$

suffers from two sources of inefficiency not found in the unidirectional motor design. The first of these is the energy lost by not fully expanding the gas; the second is the energy required for recompression. The design parameters affecting torque output are:

- o Exposed vane area.
- o Moment arm of the exposed vanes.
- o Inlet gas pressure.
- o Gas expansion (recognizing the penalties of recompression for the reversible actuator design).
- o Flow losses due to location and shaping of inlet and exhaust ports.
- o Friction losses due to vane and bearing drag.
- o Efficiency losses due to leakage.

Using limited available data and correlating this with theoretical considerations, mathematical models simulating both unidirectional and reversible expansion-type vane actuators have been established. In these models, the pressure variations due to expansion (rotation) in a typical motor were calculated (Figures A2 & A3). Similarly, the torque

FIGURE A2
PRESSURE VARIATION WITHIN VANE MOTOR
Unidirectional Design

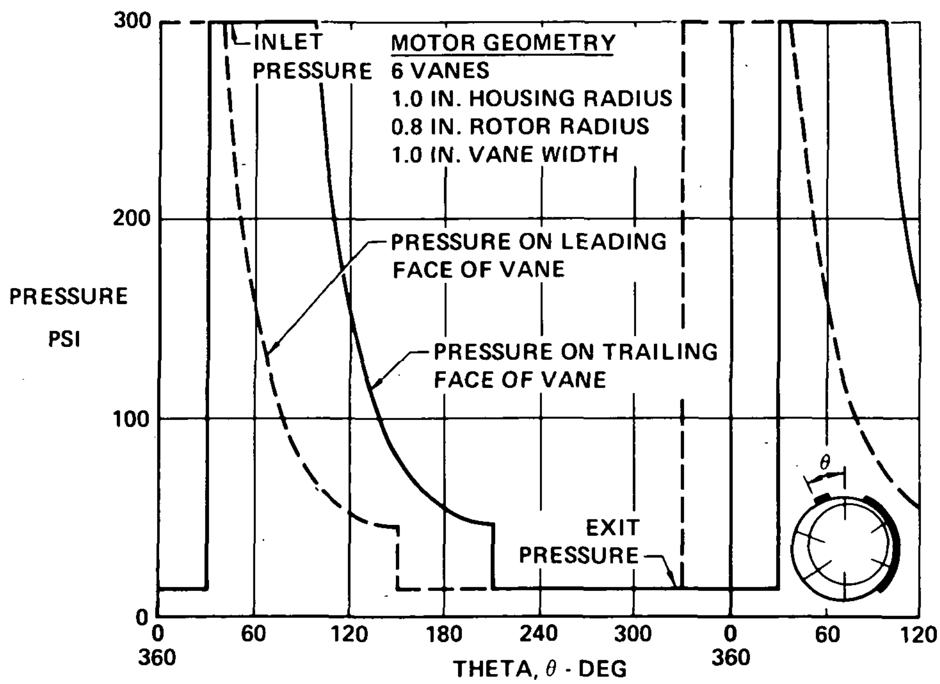
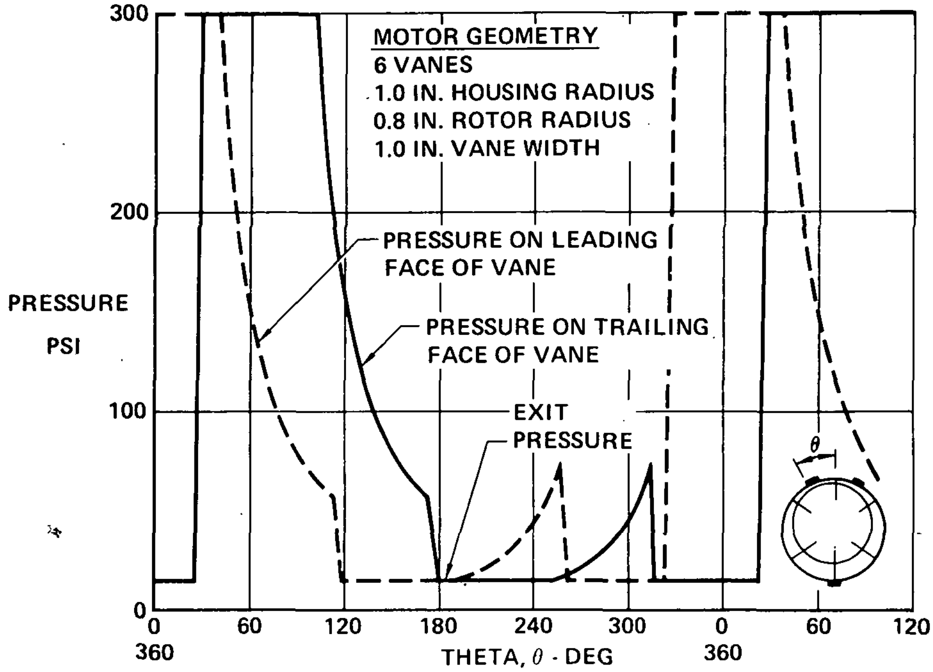


FIGURE A3
PRESSURE VARIATION WITHIN VANE MOTOR
Reversible Design



resulting from the pressure differential across each vane, minus the negative torque due to frictional drag of each vane against the housing, was also calculated and summed (Figures A4 & A5). This resulting

FIGURE A4
TORQUE ON VANES OF VANE MOTOR
Unidirectional Design

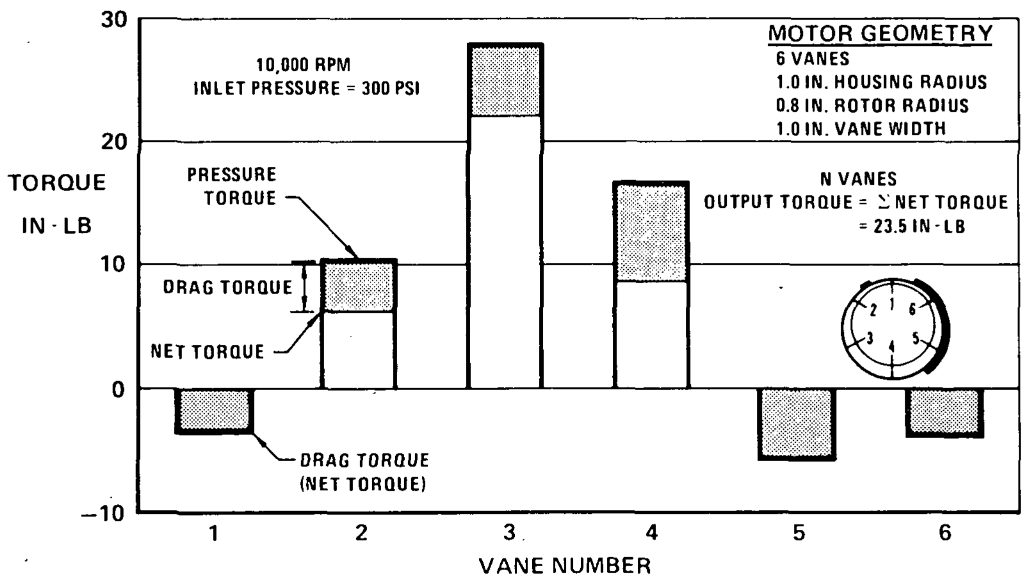
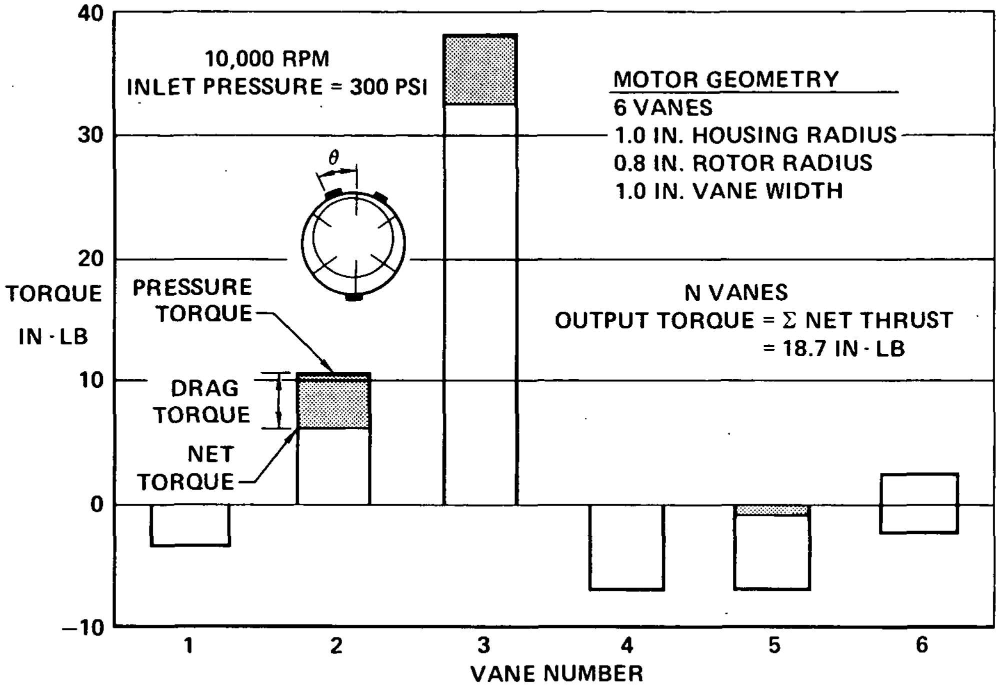


FIGURE A5
TORQUE ON VANES
Reversible Design



actuator torque varies cyclically as the motor rotates producing a ripple effect. Figures A6 & A7 shows this ripple effect as a function of inlet pressure and angle of rotation.

This varying torque can then be averaged to yield the characteristic torque at zero rpm as a function of pressure. The effect of increasing rpm is manifested by increasing frictional drag of the vanes against the housing, due to increasing centripetal force on the vanes. The resulting vane motor performance equation can be expressed as follows:

$$\tau_N = \tau_o - K_N N^2$$

where $\tau_o = aP + b$

and τ_N = torque at rpm N

τ_o = torque at zero rpm

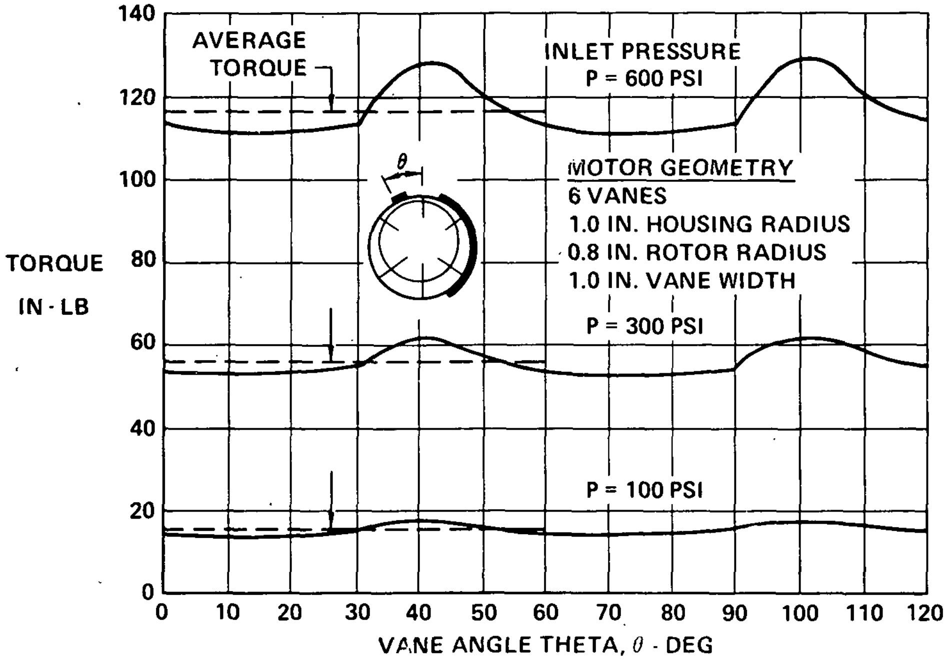
N = rotational speed (rpm)

P = inlet pressure

K_N, a & b = constants, depending on motor geometry

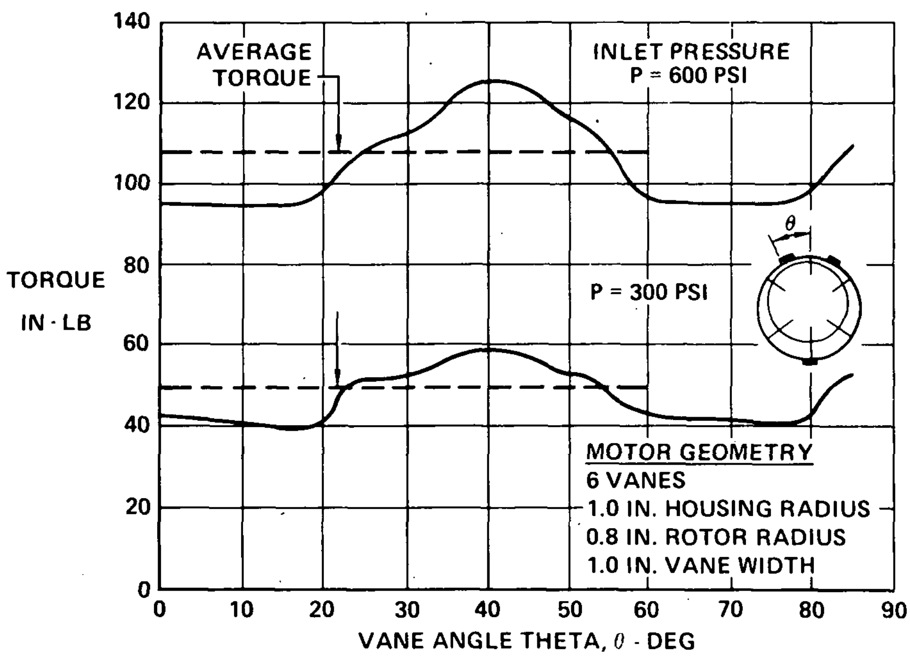
VANE MOTOR TORQUE VARIATION WITH CHANGING VANE ANGLE AND INLET PRESSURE

Unidirectional RPM = 0



VANE MOTOR TORQUE VARIATION WITH CHANGING VANE ANGLE AND INLET PRESSURE

Reversible Design RPM = 0



Gas consumption can be computed per revolution, and for a given motor geometry, depends only upon pressure and temperature. The expression for gas consumption is as follows:

$$\frac{d\omega}{d\theta} = \frac{2\pi \; P \; D \; (\alpha + \gamma)}{RT} \left\{ 1 - \frac{\gamma \; (k - 1)}{k \; (\alpha + \gamma)} \left[1 + \frac{P_o}{P} \left(\frac{1}{k - 1} \right) \right] \right\}$$

where the influence of motor geometry can be shown. The nomenclature is:

P	Supply pressure, psia
P_o	Exhaust pressure, psia
R	Gas constant ft-lb/lb deg R
T	Temperature, deg R
D	Motor volume displaced per radian, in^3/rad
α	Ratio of admission volume to total volume displaced
γ	Ratio of clearance volume to total volume displaced
k	Ratio of gas specific heats

Typical vane motor performance, torque and gas consumption curves are presented in Figures A8 and A9.

FIGURE A8
VANE MOTOR AVERAGE TORQUE VARIATION WITH CHANGING MOTOR SPEED AND INLET PRESSURE

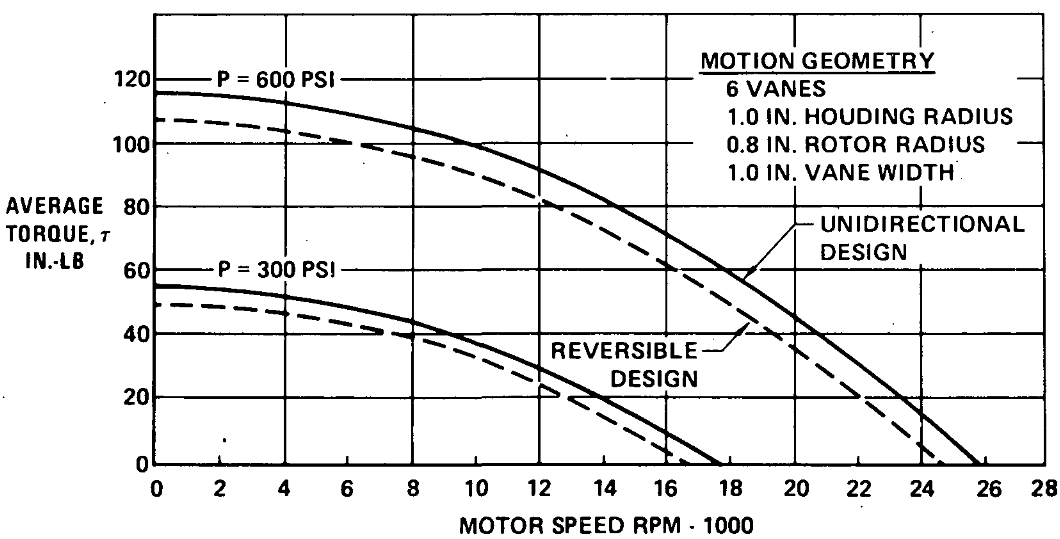
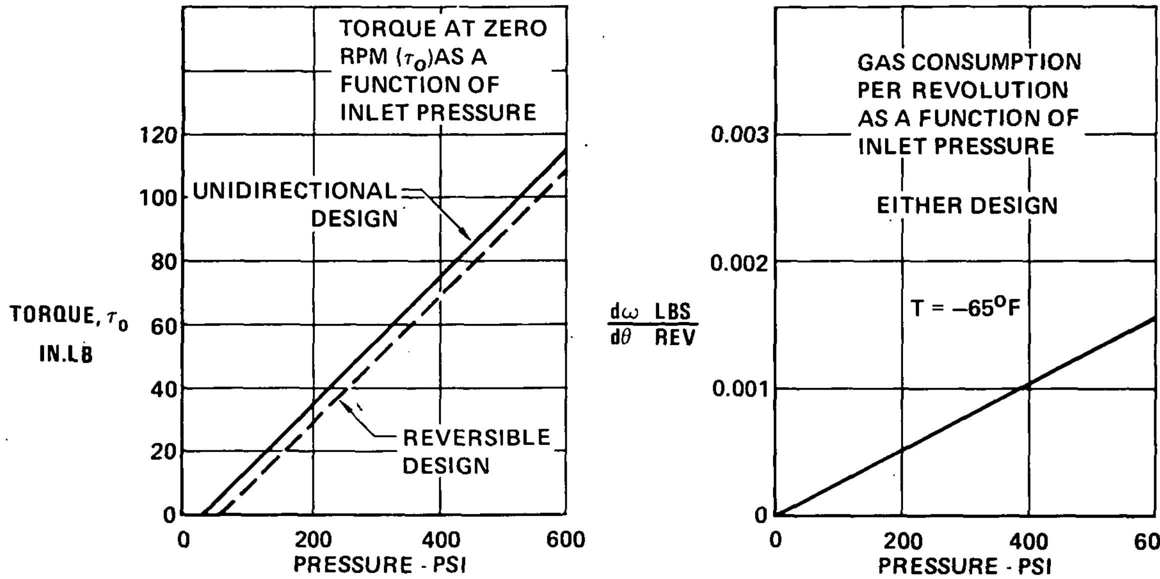


FIGURE A9
VANE MOTOR PERFORMANCE



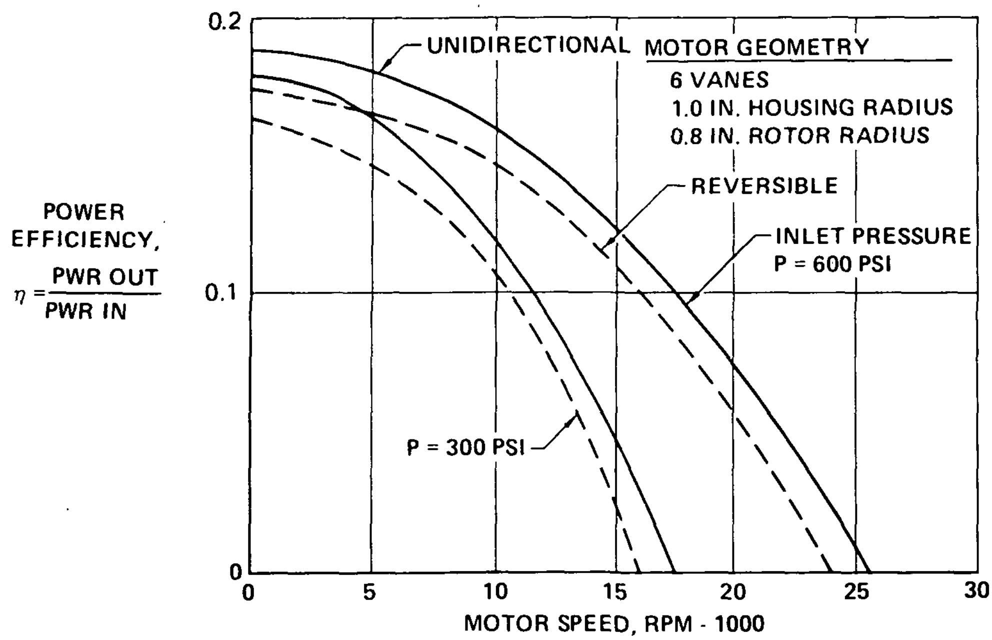
Vane motor power efficiency can be computed using the following expression:

$$\eta = \frac{\text{Power out}}{\text{Power in}} = \left(\frac{aP + b - K_N N^2}{CPT^2}\right) k_1$$

where K_1 = constant.

Typical efficiency curves are shown in Figure A10.

FIGURE A10
POWER EFFICIENCY OF VANE MOTOR AS A FUNCTION OF MOTOR SPEED AND INLET PRESSURE



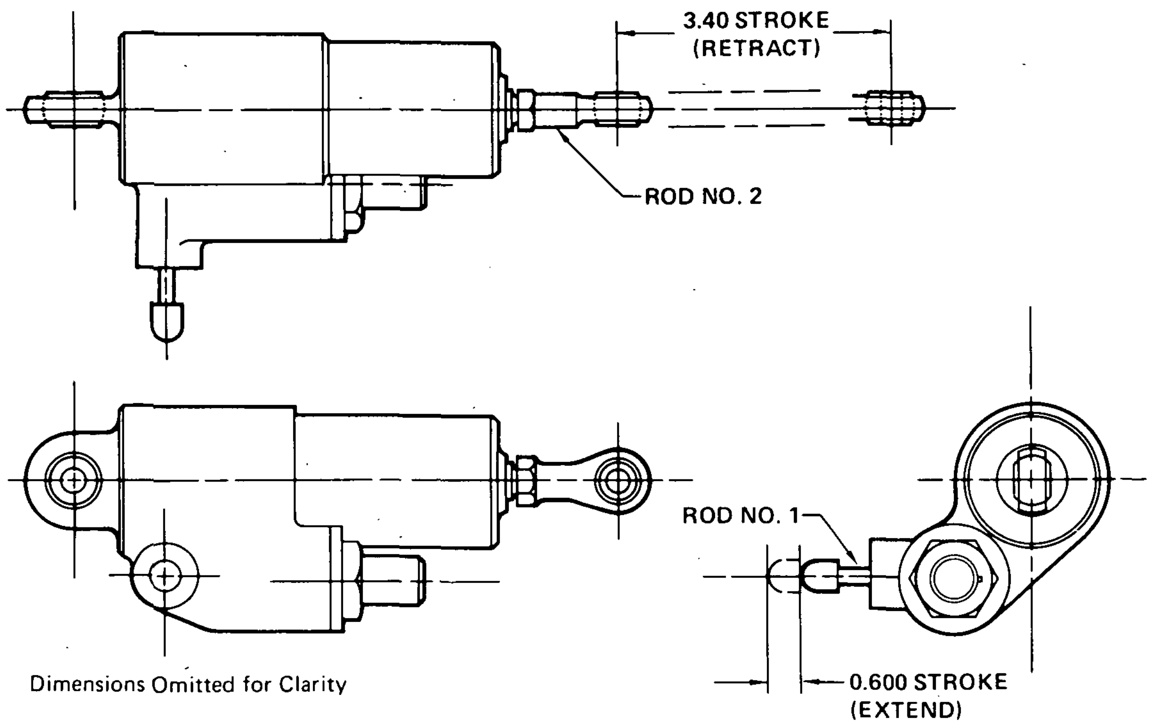
APPENDIX B

PYROTECHNIC ACTUATOR DESIGN REQUIREMENTS

The following selected design requirements apply to the actuator.

General Performance. - During emergency operation of the aerial refueling system, the electrically initiated cartridge shall provide sufficient energy for the actuator (Figure B1) to overcome the dump valve (rod #1) and slipway door loads (rod #2) throughout the stroke(s) and within the time(s) specified. During normal operation of the aerial refueling system, connecting rod #2 shall stroke freely.

FIGURE B1

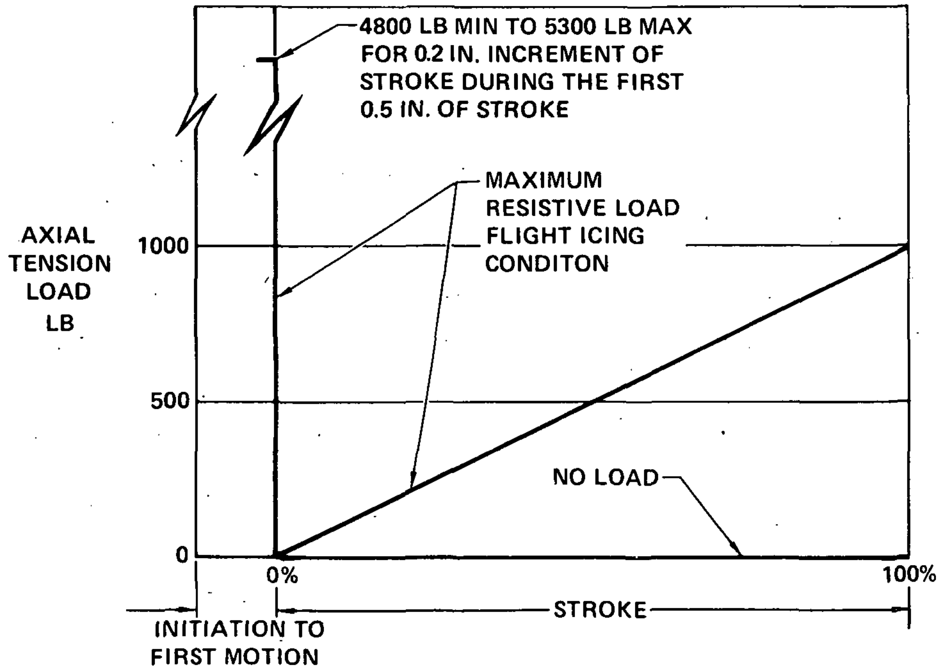


Dimensions Omitted for Clarity

Actuator Requirements. -

Thrust: The thrust produced by initiation of the cartridge in the actuator shall not exceed 5300 pounds tension (rod #2) throughout the entire stroke against the applicable loads per Figure B2, and over the temperature range.

FIGURE B2



Stroke: The actuator shall provide the stroke(s) shown in Figure B1 against the applicable loads shown in Figure B2, when fired by the cartridge. The pistons (Figure B1) shall stroke in sequency starting with rod #1. Rod #2 shall not begin movement until rod #1 completes at least 60% of its stroke.

Time: During normal operation, rod #2 shall stroke completely upon application of 20 lbs. maximum external force with the following time limits:

Extend - 0.9 sec. max.

Dwell - 2.0 sec. max.

Retract - 0.3 sec. max.

During emergency operation, the actuator, upon initiation of the cartridge, shall stroke with the following time limits:

Rod #1 extend - 0.3 sec. max.

Rod #2 retract - 0.3 sec. min. to 2.0 sec. max.

The stroke time shall be met against the applicable minimum and maximum loads per Figures B2 and B3.

Locking: The actuator shall contain a locking mechanism to keep the connecting rods in the position shown in Figure B1 when operated by firing of the cartridge. Rod #2, when in the locked position, shall be capable of withstanding 6000 lbs. limit load.

Cartridge requirements: The actuator shall have a replaceable electrically initiated cartridge containing a single bridgewire circuit.

Autoignition: The cartridge (when installed in the actuator) shall not cook-off when subjected to any environmental conditions specified herein.

No-fire current: The cartridge shall not fire nor be degraded when subjected to sufficient current to require dissipation of one watt minimum (this shall not be less than one ampere) for a minimum of five minutes when stabilized at 340°F. This requirement must be met without the use of external shunts or heat sinks.

All-fire current: The cartridge shall fire within .010 seconds upon application of 3.5 amperes maximum, when being subjected to any temperature from -65°F to +345°F.

Firing performance: Performance data for the cartridge output shall be determined. A curve shall be developed for peak pressure, time-to-peak, and decay rate throughout the stroke. Output behavior data obtained from cartridges fired in a simulated actuator shall be correlated with the data obtained from the firings of qualification actuators. The maximum and minimum cartridge output performance requirements over the temperature range of -65°F to -200°F shall not be exceeded when three times the standard deviation (3 sigma), computed at the 80 percent confidence level, is added to, or subtracted from the arithmetic average, computed at each specified firing temperature from the actual firing data generated during qualification testing. The data shall be grouped at -65°F, +70°F, and +200°F and shall be analyzed at each temperature condition. The 80-percent confidence level of the standard deviation shall be computed through the use of a table of percentiles of the chi-square distribution. Reported data for each firing at each condition of temperature must be used for these calculations. During sample acceptance testing, the actual firings must fall within the upper and lower (3 sigma 80 percent confidence) limits that were calculated from the qualification test program.

Physical Requirements. -

Proof pressure: The ballistic chamber(s) of the actuator prior to assembly shall withstand a hydrostatic pressure of 1.5 times the maximum operating pressure for a minimum of 15 seconds. The chamber(s) shall withstand the hydrostatic pressure without permanent deformation.

Burst pressure: With the connecting rod #2 restrained in the extended position, the ballistic chamber(s) shall withstand a hydrostatic pressure 1.15 times the lock-shut pressure applied to the ballistic chamber(s) for a minimum of 15 seconds. The actuator shall not rupture, although permanent deformation will be permitted.

Lock-shut pressure: The actuator, when either or both connecting rods are fully restrained, shall withstand the propellant gas pressure without rupturing, although permanent deformation will be permitted.

Environmental Requirements: The thruster and cartridge shall not suffer damage, deterioration, or degradation of performance beyond the limits of this specification, when subjected to any environment or any natural combination of environments specified herein and in MIL-STD-210.

Temperature: The thruster and cartridge shall be capable of meeting the requirements of this specification during and after exposure to temperature in the following table. The items shall also be capable of meeting the requirements of this specification after non-operating exposure to temperatures from -80°F to +160°F.

-65°F to +200°F continuous
+345°F for 10 min.
+420°F for 1 min.

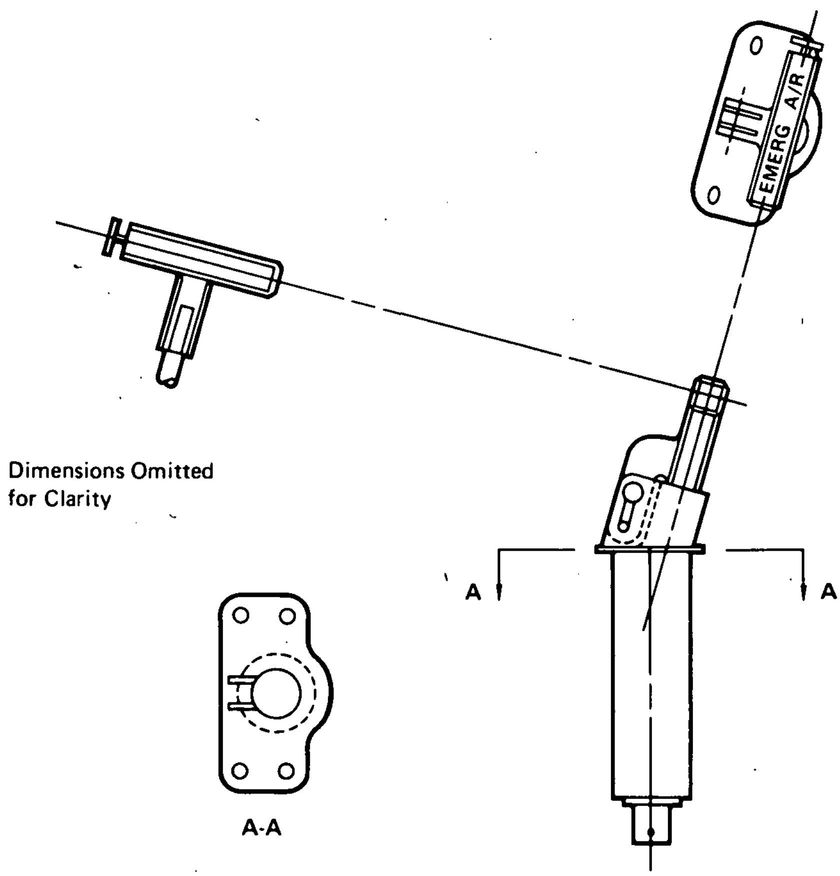
APPENDIX C

THERMAL BATTERY INITIATOR DESIGN REQUIREMENTS

The following selected design requirements apply to the thermal battery:

General Performance. - The thermal battery initiator assembly, as shown in Figure C1, shall have a handle that is attached to a single initiator firing pin. When the handle is operated, the firing pin is cocked and released, firing a percussion primer. The thermal battery, upon actuation by the primer, must produce electric power for a specified period of time at a sufficient ampere level to fire the cartridge located in the back-up aerial refueling slipway actuator.

FIGURE C1



Initiator Requirements. -

Firing Mechanism: The initiator assembly shall be actuated by a manual translation of the handle. The initiator assembly shall be so designed that the handle shall be retained after actuation and shall not be capable of reinstallation. After actuation, the initiator handle shall be locked in the extended position, with a minimum of .375 inches of the shaft (firing handle) exposed. Pre-cocked spring mechanisms shall not be used. The firing mechanism shall be normal to the primer face in the initiator assembly. No washers, press fit or captive, shall be used in the firing mechanism.

Actuation Force & Stroke: The total force required to actuate the firing mechanism shall be from 20 to 38 pounds. The handle stroke necessary to actuate the initiator assembly shall be from 0.40 to 0.75 inch. The force required to release the flight safety lock on the initiator handle shall be from 5 to 10 pounds. The stroke to release the flight safety lock shall be from 0.100 to 0.125 inch.

Firing Pin Energy: The energy delivered to the primers of the initiator assemblies by the manual initiator firing pins shall be at least $2(\overline{H} + 5\sigma)W$, where $\overline{H}$ is the mean firing height, σ is the standard deviation, and W is the drop weight listed in the primer manufacturer's specification. Analysis or suitable statistical testing of the Bruceton type shall be performed on the firing pin and primer interface to determine the minimum energy available to the primer.

Thermal Battery Requirements. -

Output: The thermal battery for the initiator assembly shall be capable of supplying a minimum of 5.0 amperes at -65°F, through the specified wiring harness to a single cartridge located in the back-up aerial refueling slipway actuator. The battery, when initiated at -65°F, must be capable of reaching the required amperes within 0.30 seconds and maintaining this current level for a minimum time of 0.10 seconds.

NASA-Langley, 1974 CR-2454

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