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ANALYSIS AND DESIGN OF A PYROTECHNIC-POWERED SELF-STOPPING ACTUATOR

Vadim Kopytoff

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Analysis and Design of a Pyrotechnic-Powered Self-Stopping Actuator

By

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ABSTRACT

Safety and environment considerations necessitate the use of automatic emergency shut-off valves in nuclear power-plants, underground nuclear tests, oil pipelines and even oil wells. Such valves require actuators to move a member (e.g., a gate, a stem or a ball which may weigh hundreds of pounds) in a time that may be as short as a fraction of a second, and which must have some provision for decelerating the moving body at the end of its stroke to avoid a damaging impact. A device for satisfying these requirements with the high reliability required for such systems is proposed. This device consists of a double-acting piston driven by gas generated by the combustion of a propellant, with the novel feature of using a precisely determined straight hole through the piston to provide a gas cushion for deceleration during the last part of the stroke.

Predicting the performance of such an actuator required analysis and calculation of the rate of propellant gas generation, the rate of gas flow into the actuator cylinder, and that of gas flow through the piston hole. Because of the complexity of this analysis, a numerical solution was required. A computer subroutine for carrying out this solution was developed. Its applicability was verified by comparison of the predicted and experimentally measured performance of a specific actuator.

A complete program using this subroutine was then written for designing an actuator. This program incorporates a procedure which simultaneously satisfies seven design requirements by minimizing the sum of squares of the differences between calculated and required values of these requirements. The program is interactive with the user, communicating with him to report the progress of the design and to obtain design decisions during execution. Designs produced by the program were found to be efficient and consistent. No knowledge of thermodynamics or of the pyrotechnic gas generator process is required of the user.

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1. INTRODUCTION

An automatic control system generally incorporates feedback, that is, a sensor determines whether or not a certain desirable condition exists, and activates a correcting device when required. However, many systems that do not include a feedback loop may also be considered automatic controls. These are referred to as "Open Loop Controls", an important subgroup of which could be called "Emergency Only" systems. These systems are, hopefully, never to be actuated, but must always be ready for an emergency. Examples of such systems are temperature sensors that close fireproof doors and/or activate sprinklers, radiation detectors and pressure sensors that actuate valves to isolate a nuclear reactor in case of containment failure, and shut-off valves for the proposed Alaskan Pipeline to minimize oil spills in case of line break.

In general, such systems include:

a) A sensor, to detect the emergency.

b) An energy source, to ensure total independence of the system response from outside power.

c) A means of converting the energy to motion of the emergency controlling device.

d) A means of stopping the motion, once the desired effect has been attained.

In many systems, the time interval between receiving the activation signal and achieving the final state is of no great importance. One such example is a typical warehouse fire-door. It may be acceptable to have this door close in a fraction of a second to several seconds. The velocity of operation can be low, so relatively little energy is required and stopping the door at the end of its travel is not difficult. For low energy systems of this kind, the choice of energy source is dictated by reliability, cost, and convenience. Stored energy in the form of a raised weight, a compressed mechanical spring, high pressure gas, or electric batteries may be chosen by the designer, depending on available room, ambient conditions, or nearby presence of other energy systems. Similarly, stopping the motion is not difficult when the system kinetic energy is low or when it is required to just stop the moving mass, in whatever position it may be. Spring or rubber bumpers are cheap and reliable. Crushable bumpers -- like lead, honeycomb, or plastic foam -- can absorb great amounts of energy at very high impact velocities. Friction or hydraulic shock-absorbers are availbable as off-the-shelf items.

With large masses and high velocities design is less flexible. Only high pressure gas allows storage of sufficient energy in a reasonable volume. To stop a heavy, rapidly moving object at a very specific position (as the gate in a sealing valve) requires careful design. Bumpers cause bounce and crushable materials or friction pads may stop the moving mass too soon, failing to give the exact stroke required.

Hydraulic decelerators, while nominally designed to exert a constant retarding force throughout their stroke, are made to give this force at some small but non-zero velocity at the end of their stroke. This results in an impact at the end of the stroke, with about 5% of the initial energy dissipated in the blow. As a result, if the velocity of arrival is, for some reason, too low, the shock absorber can "float" the mass into final position, rather than bring it to a full stop before this desired final position is reached. For this reason, hydraulic decelerators are the preferred means of stopping moving masses at a definite position. Unfortunately, they are usually designed for high-mass low-velocity applications, such as stopping a truck or freight-car at a loading dock; for high speed applications a standard decelerator requires, at the very least, a minor redesign. Furthermore, their cost (especially for high energy ratings) is considerable (e.g., a commercial, off-the-shelf, decelerator, capable of absorbing 180,000 in. lb_f in a distance of two inches, was priced in 1972 at over $900.).

The present design study is focused on actuators that would move masses of 20 to 1000 pounds through a distance of 4 to 20 inches in a time of 0.02 to 1.0 seconds. Such actuators are needed for closing containment-valves in a nuclear power plant or in underground nuclear testing, or to shield personnel during fabrication of explosives.

The systems under consideration are for use in emergency situations; and because they may be unused, and hence neglected, for long periods of time, reliability of operation is of paramount importance. Failure to actuate, or failure to actuate properly, may have very serious consequences. Unintentional actuation is also highly undesirable. For these reasons, stored high-pressure gas is not an attractive solution: Leaks are always possible, requiring an inspection routine by skilled personnel versed in high-pressure gas technology. Safety of personnel located in the gas storage area requires gross over-design of the pressure system. Pyrotechnic gas generation avoids these problems, and simplifies remote initiation. Military and space exploration experience has given to pyrotechnic technology a very high level of reliability. Capacitor-discharge exploding-bridge-wire (EBW) initiators are now better than 0.9999 reliable at the 90% confidence level. The electrical system used to fire the initiator can be continuously monitored by a weak current, which would trigger an alarm if the circuit is interrupted. At the same time, a permissible no-fire current of over 200 amperes reduces the probability of accidental initiation to a negligible value.

Thus, pyrotechnic-powered piston actuators offer a means of satisfying the reliability requirements of these systems; they can be depended upon to accelerate the mass to be moved to the high velocity required in the short time available, and yet not to actuate accidentally.

The problem of stopping the mass at a definite position is presently handled, in such systems, by hydraulic decelerators. These are not only expensive and not readily available items, but are also a potential source of trouble. If they fail to operate properly due to their fluid leaking out or freezing, the traveling mass will reach the end of its travel at too high a velocity causing damage to some part of the sealing system. Not only will the operating system fail to seal, but any backup system may become inoperative.

Consideration of these deficiencies of hydraulic decelerators (i.e., nonexistence of high-speed-impact models, negative effect on system reliability, poor availability and high price) led the author to consider using the generated gas to decelerate as well as accelerate the moving mass. After some evolution, the system illustrated in Fig. 1 took form. It consists basically of a double-acting piston with a vent-hole. When the pyrotechnic gas-generator is fired, high-pressure gas flows into the cylinder head clearance-volume, accelerating the piston and the mass attached to the piston-rod. At the same time, the gas flows through the vent-hole into the buffer volume back of the piston, building up a gas cushion. If the cylinder volume, gas quantity, and vent area are properly proportioned, the piston will come to a stop just short of hitting the end of the cylinder.* Only a gross

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*The author is not aware of any application of this idea. However, the possibility of its use to cushion the travel of a moving piston at the end of its stroke has been investigated previously (Ref. 1).

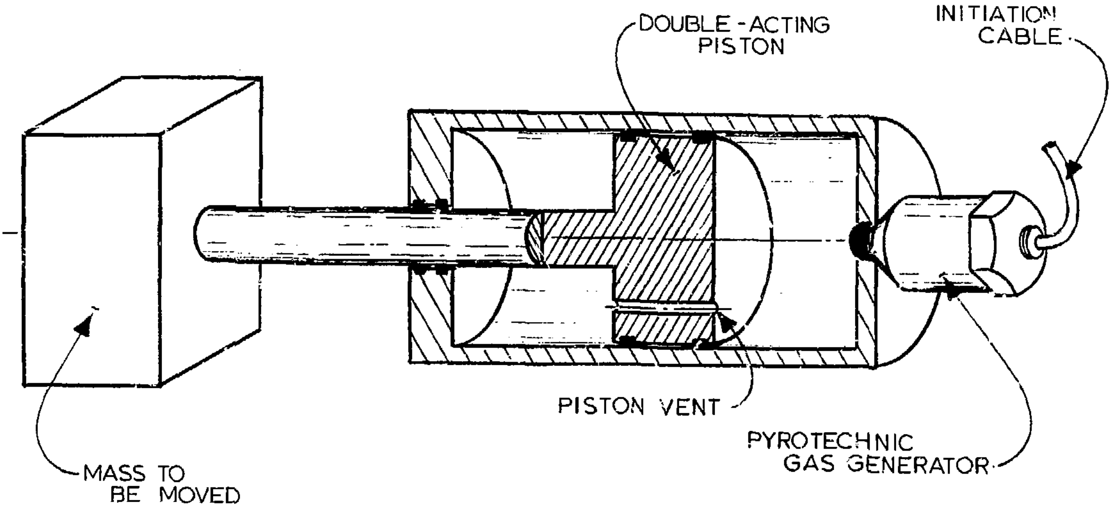

FIGURE 1 - SCHEMATIC OF PYROTECHNIC-POWERED SELF-STOPPING ACTUATOR

occlusion of the vent could prevent deceleration of the piston. In addition, drilling a vent-hole or two through the piston is much cheaper than buying a hydraulic decelerator.

Design of such a system involves analysis of the motion of a vented piston, driven by a gas produced by combustion of a suitable propellant. The rate of gas generation will vary with time, as will the temperature and pressure of the gas, subject to an equation of state other than the perfect-gas equation. The desired performance must be achieved without exceeding the limitations of the materials and components available. However, over-design should be avoided in order to make the cost of the system as low as possible. For example, actuation of the system in half the time required "just to be on the safe side" requires four times the energy. Stresses will increase, requiring more material, more expensive material, and more design effort. Costs will go up and reliability could even go down.

A procedure for accomplishing these objectives is presented in the following sections.

2. SYSTEM DESIGN PRINCIPLES

GENERAL DESCRIPTION OF THE PROBLEM

Typically the design of a self-stopping actuator presents itself in the following form: Given M, the mass of a specified element, design an actuator to move it through a distance of L inches in T seconds and bring it to a stop without damage at the end of that movement.

On the basis of the considerations detailed in Section 1, the general configuration of Fig. 1 will be utilized: i.e., the actuator will be powered by pyrotechnic gas, and will be self-stopping by means of a vent in the piston and a seal around the piston-rod.

The system will be completely defined when the following quantities have been determined:

1) Propellant charge in a specific pyrotechnic gas generator
2) The diameter and length of the piston vent-hole.*
3) The clearance-volume on the head-side of the piston.
4) The buffer-volume behind the piston.
5) The cylinder diameter.
6) The piston-rod diameter.

The design of the actuator involves, therefore, the determination of six independent variables that will give the desired values of stroke and time for the system shown in Fig. 1. These values of stroke and time must be realized while satisfying the constraints imposed by the geometry of the system, and such limits as the allowable stress in the piston-rod, and the maximum pressure the system seals can be expected to withstand.

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*To ensure a fully established pipe-flow, the length-to-diameter ratio will be taken to be fifteen. Hence only one variable is involved.

Table I lists the variables enumerated above, and those defining system performance and constraints, grouping them by type and specifying the units which will be used. The right-hand column gives a mnemonic symbol for each variable for use in the text and also in the Fortran programs to follow.

BASIC DESIGN PROCEDURE

The customary procedure for designing a system starts with selecting a configuration judged capable of the desired performance. An analysis of the system is made to express (analytically or numerically) the system performance as a function of the least possible number of independent variables. Then, intuition or past experience is used to assign a definite value to each of these independent variables, thus identifying a specific system. The performance of this system is now calculated and compared to the performance specified by the problem statement. If the calculated performance is found to be inadequate, the independent variables defining the system are assigned different values by a cut-and-try, or some other, more rational method, and the performance of the modified system is again evaluated. This procedure is repeated until the desired performance is adequately approximated by the calculated one, or until the designer decides that the problem is insoluble.

The above procedure implies two essential assumptions:

a) The performance of the system can be calculated, once its geometry, components, and dimensions are defined.

b) This performance can be evaluated, i.e., compared qualitatively to the desired performance.

The fundamental relationships involved in describing the performance of a pyrotechnic-powered self-stopping actuator will be outlined in the follow-

TABLE I

List of Variables Involved in the Design of a Pyrotechnic-Powered Self-Stopping Actuator.

Variables	Units	Symbol
Specifications given in the problem statement:		
Mass to be moved	lb_m	WLB
Stroke required	in.	STR
Time required for stroke	sec	TR
Independent variables defining system:		
Propellant charge	g	PWGR
Piston vent-hole diameter	in.	HD
Length of cylinder-head clearance volume	in.	HL
Length of cylinder buffer volume	in.	BL
Cylinder diameter	in.	CD
Piston-rod diameter	in.	PRD
Piston thickness (vent-hole length)	in.	PT
System constraints:		
Allowable final velocity	in./sec	VFAL
Allowable piston-rod stress	psi	STAL
Allowable gas generator pressure	psia	GPAL
Allowable cylinder pressure	psia	CPAL
Calculated system performance:		
Time of stroke	sec	TAC
Final velocity	in./sec	VFIN
Maximum piston-rod stress	psia	STMX
Maximum generator pressure	psia	GPMX
Maximum head-end pressure	psia	HPMX
Maximum buffer-end pressure	psia	BPMX

ing pages. It will be seen in the next Section that, given the values of the six independent variables listed in Table I, a numerical integration is required to solve the set of relations developed.

> *The critical remaining problem is to conceive and develop a rational and efficient procedure for determining those particular values of the independent variables which yield the desired system performance. In the present application there is no single variable to be optimized, but rather several requirements to be satisfied. The procedure developed is based on minimizing the sum of the squares of the differences between the desired and the calculated values of the dependent variables.*

ANALYTICAL REPRESENTATION OF THE DESIGN PROBLEM

It will be assumed that, in the physical system to be modeled, the length of stroke is fixed by some enclosing structure or sealing requirement. Thus, if the moving element stops short of the full movement required (for example a fire door that must close the opening in the wall), the actuation would be considered a failure.

For this reason, in the numerical solution determining the performance of the model, the iteration by time-increments will be stopped when the stroke is equal to the stroke required; i.e., the calculated stroke must always equal the required stroke. Another factor must be recognized, however: the moving element will arrive at the required stroke with a finite velocity, and hence a finite kinetic energy. This energy must not result in damage to the element or to the stopping structure.

Actually, it is advantageous to have some small final velocity at the end of the required stroke, because the calculated performance of any real system will never give exactly the actual performance, and if some velocity exists at the required stroke in the analysis, the stroke requirement is more likely to be satisfied by the real actuator. This final velocity is advantageous is another way: it gives a higher average velocity of travel, and hence permits the satisfaction of the time requirement with a lower maximum velocity. The penalty for these advantages is the possibility of damage to the moving element or to the stopping structure if excessive kinetic energy is present at impact. However, if the maximum allowable impact energy can be specified, or if past experience indicates a safe value for the final velocity, the actual final velocity can be made equal to this desired safe velocity, thus substituting the constraint of final velocity for that of the stroke as a problem requirement.

Introducing this change into the problem statement, the design objective can be represented by the following array of relations:

$$\mathrm{TAC}(\mathrm{PWGR},\mathrm{HD},\mathrm{HL},\mathrm{BL},\mathrm{CD},\mathrm{PRD}) = \mathrm{TR} \tag{2-1}$$

$$\mathrm{VFIN}(\mathrm{PWGR},\mathrm{HD},\mathrm{HL},\mathrm{BL},\mathrm{CD},\mathrm{PRD}) \leq \mathrm{VFAL} \tag{2-2}$$

$$\mathrm{STMX}(\mathrm{PWGR},\mathrm{HD},\mathrm{HL},\mathrm{BL},\mathrm{CD},\mathrm{PRD}) \leq \mathrm{STAL} \tag{2-3}$$

$$\mathrm{GPMX}(\mathrm{PWGR},\mathrm{HD},\mathrm{HL},\mathrm{BL},\mathrm{CD},\mathrm{PRD}) \leq \mathrm{GPAL} \tag{2-4}$$

$$\mathrm{HPMX}(\mathrm{PWGR},\mathrm{HD},\mathrm{HL},\mathrm{BL},\mathrm{CD},\mathrm{PRD}) \leq \mathrm{CPAL} \tag{2-5}$$

$$\mathrm{BPMX}(\mathrm{PWGR},\mathrm{HD},\mathrm{HL},\mathrm{BL},\mathrm{CD},\mathrm{PRD}) \leq \mathrm{CPAL} \tag{2-6}$$

with the variables as defined in Table I. Here, for example, Equation 2-1 indicates that the time actually taken (TAC) for the piston stroke is a function of PWGR, HD, HL, BL, CD, and PRD, and is equal to TR, the time specified. Equation 2-2 shows that the final velocity (VFIN) is a function of the same independent variables and must be less than or equal to VFAL, the allowable final velocity. Equations (2-3), (2-4), (2-5), and (2-6) have similar interpretations.

USE OF STANDARD COMPONENTS

The configuration shown in Fig. 1 permits the use of some standard components in the design. This may result in considerable saving in component cost and fabrication. Ability to adopt standard, readily available parts to carry out the functions required by the design is a most powerful weapon in the arsenal of the designer. He should design anything his problem requires, but he should also make use of available components of known reliability and performance.

For the configuration under discussion, it can be seen that the gas generator would require an extensive testing and development program. The piston-rings and piston-rod seals cannot be produced in the average machine-shop, and would also require a certain amount of development. The cylinder can be either obtained in some standard diameter and cut to length as required, or machined to the right dimensions from heavy-wall seamless tubing, and the two cylinder ends can be machined from solid material. If the cylinder is of some standard diameter, it and/or its ends can be purchased from a hydraulic-cylinder manufacturer.

In regard to the pyrotechnic gas generator (PGG), several are available commercially. They have different propellant loadings, actuation times, dimensions, and initiation schemes. Consideration of these features and general availability led to the selection of a particular type that could be loaded with 10.0 to 34.1 grams of IMR-4227 propellant with initiation in less than 200 microseconds and full-load pressure equilibrium in less than three milliseconds. These generators are available with reasonable delivery time, offer good flexibility of loading, and give extremely reproducible gas pressures. It is of course, understood that any other PGG could be used, provided its rate of gas generation is known, or determinable.

Piston-rings and piston-rod seals are also commercially available. They are made of many materials (e.g., cast iron to silicone rubber). To sustain gas pressures of the order of 30,000 psi, and give better sealing than can be expected from automotive-type metallic piston-rings, a hard-plastic ring impregnated with molybdenum disulphide was selected for both the piston-rings and the piston-rod seals. These rings are available in the range from one to twelve inches in diameter, in increments of one sixteenth or one eighth inch. Thus, the choice of piston-rings (and hence cylinder diameters) and piston-rod seals (and hence piston-rod diameters) is now constrained to about one hundred discrete values, rather than the theoretically continuous range between zero and some maximum dictated by the system geometry.

The designer is thus restricted to a propellant charge between 10. and 34.1 grams, and to one of about a hundred cylinder and piston-rod diameters. Of course, if he concludes that a charge greater than 34.1 grams is needed two or more gas generators can be used. The same logic applies to the number of cylinders, and to the number of vent-holes per piston. Unless some very unusual problems are encountered, it is desirable to use a minimum number of components (i.e., cylinders, gas generators, vent-holes). To ensure that this philosophy is followed, a preliminary design should be made, with no restriction on cylinder or piston-rod diameters, but with one cylinder, one vent-hole, and as many generators as required to accommodate the propellant needed, and seeking the least propellant weight that would satisfy the design requirements. This new requirement, i.e., minimizing the propellant charge, will ensure that the minimum number of gas generators is used in the design. Thus a new relation is added to the six relations given by 2-1 to 2-6.

Finally, four of the inequalities can be transformed into equations by the following rationale:

It is a well established principle in engineering that a system is over-designed if some component is working at a level below an acceptable limit, such as a maximum stress lower than the allowable stress, or a maximum pressure lower than the allowable pressure. For an efficient design, therefore, an equal sign can be substituted for the "less-than or equal" sign in the relations 2-2, 2-3, 2-5, and 2-6. Note that the same treatment cannot be applied to relation 2-4, since the adoption of a standard gas-generator forces the acceptance of its working at less than maximum efficiency.

The design problem is now reduced to solving the following seven relations:

$$\mathrm{PWS} \rightarrow \mathrm{MINIMUM} \qquad 2\text{-}7$$

$$\mathrm{TAC(PWS,HD,HL,BL,CD,PRD)} = \mathrm{TR} \qquad 2\text{-}8$$

$$\mathrm{VFIN(PWS,HD,HL,BL,CD,PRD)} = \mathrm{VFAL} \qquad 2\text{-}9$$

$$\mathrm{STMX(PWS,HD,HL,BL,CD,PRD)} = \mathrm{STAL} \qquad 2\text{-}10$$

$$\mathrm{HPMX(PWS,HD,HL,BL,CD,PRD)} = \mathrm{CPAL} \qquad 2\text{-}11$$

$$\mathrm{BPMX(PWS,HD.HL,BL,CD,PRD)} = \mathrm{CPAL} \qquad 2\text{-}12$$

$$\mathrm{GPMX(PWS,HD,HL,BL,CD,PRD)} \leq \mathrm{GPAL} \qquad 2\text{-}13$$

SOLUTION PROCEDURE

A convenient way of solving this array of nonlinear simultaneous relations is to use the optimizing computer program due to Powell (Ref. 2) which seeks those particular values of the n independent variables that minimize the sum of the squares of m nonlinear functions $(m>n)$ of these n variables. For this purpose, the relations 2-7 to 2-13 can be rearranged to give the following 7 functions:

$$F(1) = \mathrm{PWGR} * \mathrm{NOGC}^{\dagger} \tag{2-14}$$

$$F(2) = \mathrm{TAC} - \mathrm{TR} \tag{2-15}$$

$$F(3) = \mathrm{VFIN} - \mathrm{VFAL} \tag{2-16}$$

$$F(4) = \mathrm{STMX} - \mathrm{STAL} \tag{2-17}$$

$$F(5) = \mathrm{HPMX} - \mathrm{CPAL} \tag{2-18}$$

$$F(6) = \mathrm{BPMX} - \mathrm{CPAL} \tag{2-19}$$

$$F(7) \begin{cases} = 0. & \text{if } \mathrm{GPMX} < \mathrm{GPAL} \\ = \mathrm{GPMX} - \mathrm{GPAL} & \text{if } \mathrm{GPMX} > \mathrm{GPAL} \end{cases} \tag{2-20}$$

It can be seen that if a minimum of $FF = \sum_{i=1}^{m} F_i^{\,2}$ can be found, and if the individual values of F(2) through F(7) are sufficiently close to zero, the system of relations 2-14 through 2-20 may be considered as solved.

Once the unrestricted preliminary design is completed, and reported to the designer, he can select the standard piston-rod and cylinder diameters that are reasonably close to those determined in the preliminary design. If necessary, he can decide to use more than one cylinder (if no standard size can do the job by itself), and more than one gas generator per cylinder (if the minimum propellant required per cylinder is more than the maximum usable in one generator). If the vent-hole diameter determined in the preliminary design is more than can be accommodated in the annulus between the piston-rod and the bottom of the piston-ring groove, the designer can call for more than one vent-hole.

[†] This is the total propellant charge per cylinder, and will remain nearly unchanged if the number of gas generators is changed by the program when their maximum charge is exceeded.

Finally, the designer can weigh the advantages of having the simplicity of a single cylinder, of an awkwardly large diameter, versus the complexity of several cylinders of more conventional proportions. Similarly, a choice may have to be made to accept a higher maximum working stress in the piston-rod (requiring the use of a more expensive material) versus the complication and expense of using two actuating cylinders.

FINAL DESIGN

When all these decisions have been made, a final design-search must be undertaken. The same seven conditions (2-14 to 2-20) must be satisfied (or approximated), but now the number of cylinders, generators per cylinder, and vent-holes per piston is fixed. The cylinder and piston-rod diameters are defined to be some definite, standard value, and the four unknowns to be determined are the propellant charge per generator, the vent-hole diameter, and the head-volume and buffer-volume clearances.

The same seven functions are now determined by four independent variables, and the Powell Least-Squares Program can again be used. Since the two standard values selected for the cylinder and piston-rod diameters are presumably fairly close to the optimum diameters determined in the preliminary design, a final design-search can be initiated from a starting point involving the same head- and buffer-volumes, the same total vent area, and the same total propellant loading. The cylinder and piston-rod diameters are now fixed, as well as the number of cylinders, gas-generators, and vent-holes.

The procedure delineated above will determine the dimensions of a self-stopping actuator, and the propellant charge, required to move a given mass through a given distance in a given time, using the minimum number of standard components, and a minimum propellant charge, and not exceeding allowable values of final velocity, maximum piston-rod stress, and maximum cylinder pressures. The only condition required is that the preliminary design-search be started reasonably close to the desired optimum. Appendix III will describe one method of determining such a starting point.

3. DYNAMICS OF A GAS-DRIVEN VENTED-PISTON ACTUATOR

The proposed actuator system is shown schematically in Fig. 2, with labels to identify the items that will be used in the calculation of its performance, i.e., in predicting piston position and velocity as a function of time. The basic relation for this is Newton's second law of motion:

$$F = M \cdot A = M \frac{dU}{dt} \qquad 3\text{-}1$$

where F is the resultant force on the piston, M is the mass to be moved, A is the acceleration, U is the velocity, and t is time.

Since the system starts from a known position and state (usually with the gas volumes at atmospheric pressure and ambient temperature, with zero velocity and known initial displacement and with a known initial charge of propellant), the state of the system at any later time can be determined by forward integration with respect to time. However, the force on the piston varies with time in a complex manner, so no analytical integration of Equation 3-1 can be made. But by putting the equation in finite difference form:

$$F = M \frac{\Delta U}{\Delta t} \qquad 3\text{-}2$$

it can be solved numerically by stepwise forward integration.

FORCES ACTING ON THE ACTUATOR PISTON

The net force on the piston is primarily due to the gas pressure in the cylinder-head volume V_H and the buffer volume V_B. Combustion of the

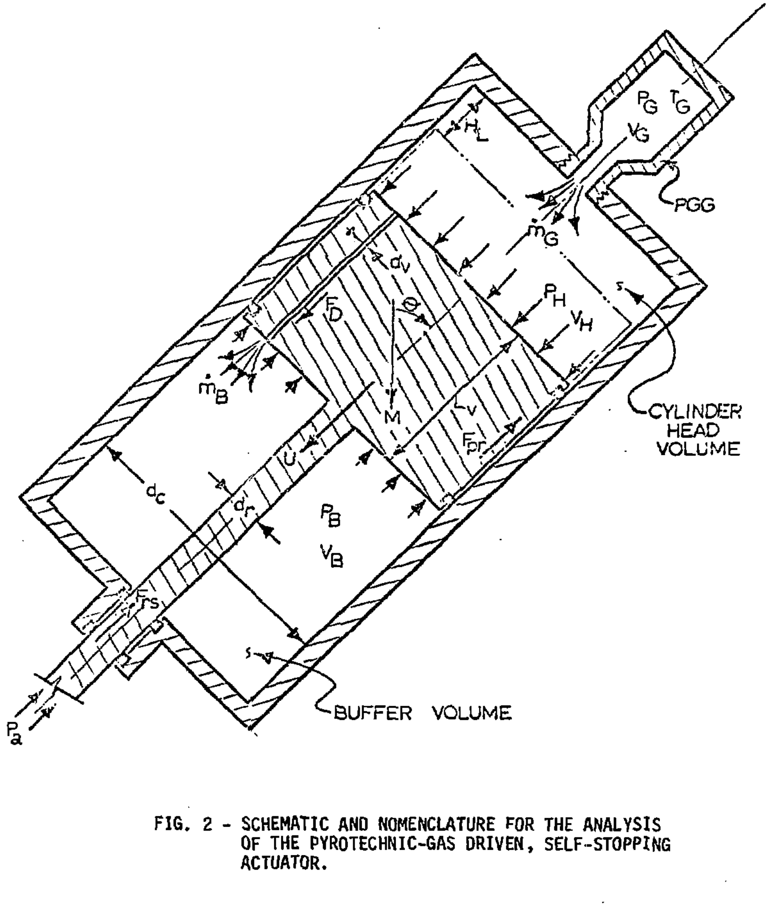

FIG. 2 - SCHEMATIC AND NOMENCLATURE FOR THE ANALYSIS OF THE PYROTECHNIC-GAS DRIVEN, SELF-STOPPING ACTUATOR.

propellant in the PGG produces gas at temperature T_G and pressure P_G. This gas flows into volume V_H (as indicated in Fig. 2 by the arrows labeled $\dot{m}_G$). The force F_H, exerted by the pressure P_H of this gas on the net piston area, is given by $F_H = \frac{\pi}{4} (d_c^2 - d_v^2) \cdot P_H$.

As pressure builds-up in V_H, a gas flow will be established through the vent in the piston (as indicated by the arrows labeled $\dot{m}_B$). In the buffer volume V_B, gas pressure P_B will rise, exerting a force F_B on the exposed piston area: $F_B = \frac{\pi}{4} (d_c^2 - d_v^2 - d_r^2) \cdot P_B$.

Additional forces acting on the piston include:

F_G - the force due to gravity acting on the moving parts, at an angle θ to the actuator axis: $F_G = M \cdot \cos \theta$

F_D - the force due to the frictional drag of the gas flow on the vent wall: $F_D = \frac{\pi}{4} d_v{}^2 (F_1 - F_2)$, where F_1 and F_2 are thrust functions (Ref. 5, p. 49) evaluated at the inlet and outlet of the vent.

F_a - the force due to atmospheric pressure acting on the piston-rod area: $F_a = \frac{\pi}{4} d_r \cdot P_a$

F_s - the force due to friction on the piston rings and piston-rod seals. This force can be calculated by an empirical equation derived from friction data submitted by the manufacturer (Ref. 12).

$$F_s = d_s \left(k_1 + k_2 (\Delta P) + k_3 (\Delta P)^{1/4}\right)$$

where k_1, k_2, and k_3 are empirical constants, d_s is the nominal seal diameter, and ΔP is the pressure differential across the seal.

INITIAL CONDITIONS IN THE THREE GAS VOLUMES

The state of a body of gas is usually determined by having certain definite values for its temperature and pressure. However, in the present application it is more convenient to define each gas state by specifying its internal energy and its density, because the processes under investigation deal specifically with changes in gas energies, masses, and volumes. Therefore, before determining the change in state over the initial time interval Δt, it is necessary to express the initial system state, specified by its pressures and temperatures, in terms of gas internal energies and densities.

The gas occupying the three volumes V_G, V_H, and V_B at time $t = 0$ is atmospheric air. The mass and internal energy are small when compared to those of the propellant gas generated. Negligible error would therefore be introduced by assuming this original gas to be propellant gas. This will eliminate the need to consider, in subsequent calculations, the mixing of air and propellant gas in each volume. For this reason, although the perfect gas equation would be satisfactory for finding the initial gas specific volume, the propellant-gas equation of state will be used.

THE GAS EQUATION OF STATE

The Abel equation of state is commonly used in propellant calculations (Ref. 4, p. 243). It has the advantage of requiring only one more constant than the perfect gas equation of state, it is easily soluble for either P, v, or T, and is more accurate than most of the other approximations made in ballistic calculations. Corner (Ref. 3, p. 101) points out, however, that the virial equation:

$$P\ v = R\ T\ (1 + \frac{B}{v}) \qquad 3\text{-}3$$

is, "at each temperature a better representation" of the gas behavior than the Abel equation (errors of the order of 0.7 per cent vs 2 per cent). Since this improvement does not bring any penalties (same number of constants, same solvability for P, v, or T), the virial equation will be used. Rearranging Equation 3-3 into a quadratic in v and solving for the specific volume:

$$v = \frac{RT + \sqrt{R^2 T^2 + 4 P R T B}}{2P} \qquad \text{3-3a}$$

where R is the gas constant for the propellant gas and B is an empirical constant derived from pressure-temperature-density measurements.

The gas masses present at time t = 0 in each volume can then be calculated as follows:

$$m_{G,t=0} = \frac{V_G}{v}$$

$$m_{H,t=0} = \frac{V_H}{v} \qquad \text{3-4}$$

$$m_{B,t=0} = \frac{V_B}{v}$$

THE INTERNAL ENERGY OF THE GAS

Gas internal energies are usually calculated from an empirical expression for specific heat capacity. These expressions are available for many gases (Ref. 8 and 9), but their form is usually such that each equation is applicable to only a limited range of temperature, and extrapolates very badly outside this range. This approach serves fairly well for calculating specific heats, but complicates energy calculations, and seriously hinders solving the reverse problem, namely, that of finding the gas temperature corresponding to a certain internal energy. For this reason, a three parameter, readily integrable relation was developed, to cover the entire expected temperature range. This relation is:

$$c_p = c_1 + \frac{c_2}{T} + c_3 \frac{\ln T}{T} \qquad 3\text{-}5$$

where T is the absolute temperature.

This equation is compared, in Appendix I, with the more usual four parameter equation for the specific heat capacity, and is shown to be of comparable accuracy, while requiring a minimum of three experimental measurements (instead of 4) to be completely defined.

At the pressures and temperatures involved, pressure effects on specific heat capacity are of the order of one per cent (Ref. 7, Appendix). Assuming this to be negligible, gas specific enthalpy at absolute temperature T is given by:

$$\begin{aligned} h_T &= \int c_p \, dT = \int \left(c_1 + \frac{c_2}{T} + c_3 \frac{\ln T}{T}\right) dT \\ &= c_1 T + c_2 \ln T + \frac{c_3}{2} \ln^2 T + c_4 \end{aligned} \qquad 3\text{-}6$$

and the specific internal energy, by:

$$e_T = h_T - \frac{R}{J} T \qquad 3\text{-}7$$

The initial internal energy of the gas in each volume is then:

$$\begin{aligned} E_{G,t=0} &= m_{G,t=0} \cdot e_T \\ E_{H,t=0} &= m_{H,t=0} \cdot e_T \\ E_{B,t=0} &= m_{B,t=0} \cdot e_T \end{aligned} \qquad 3\text{-}8$$

CALCULATION OF THE RATES OF CHANGES

Now that the pressures, temperatures, energies, volumes and masses of the gases in the PGG, V_H, and V_B are known for the initial piston position and starting (i.e., zero) velocity, it is possible to calculate the following four time-rates of change:

a) the rate of propellant combustion $\dot{m}_p$.

b) the gas flow rate $\dot{m}_G$ out of the generator.

c) the gas flow rate $\dot{m}_B$ out of the volume V_H and into V_B.

d) the acceleration of the piston A.

RATE OF GAS GENERATION

The propellant burning rate is calculated by the Vieille Equation (Ref. 4, p. 412), commonly accepted for burning pressures between 10,000 and 50,000 psia (Ref. 3, p. 71).

$$\dot{m}_p = m_s K_B P^{\alpha} \qquad 3\text{-}9$$

where K_B and α are empirically determined constants characteristic of the propellant, m_s is the initial propellant charge, and P the pressure.

Assuming α to be a constant has been found adequate in gun internal ballastics, where maximum pressures do not vary appreciably from gun to gun and from round to round (Ref. 3). In the PGG, however, the charges vary between 10 and 34 grams, and the maximum pressures, between 2000 and 30,000 psia, with correspondingly longer times spent at lower pressures. Assuming that α is a constant made it impossible to reproduce the experimental performance of the PGG.

No data could be found on how to calculate α for any set of conditions, but references 3 (p. 72) and 4 (p. 412-414) agree that α is mostly dependent on pressure, and that it is usually found to be between 0.8 and 0.9 for gun applications. Reference 3 mentions that the highest value of α ever observed was 1.02, and that a particular propellant was found to show $\alpha = 0.96$ at 22,000 psia, with a steady decrease "to about 0.5 at 1800 psia". This last value theoretically corresponds to a single, first-order reaction, and can thus be assumed to extend to atmospheric pressure.

Thus, the following can be summarized: $\alpha = 0.5$ at very low pressures, it rises slowly, being still "about 0.5" at 1800 psia, then increases to about 0.96 at 22,000 psia for a particular propellant, and approaches 1.02 asymptotically at very high pressures. This behavior closely resembles the growth law called "the logistic curve" (Ref. 11, p. 202). This S-shaped curve is defined by specifying four parameters. Two of these can be the horizontal asymptote ($\alpha = 1.02$ for $p = +\infty$) and the value 0.5 at zero pressure. The remaining two parameters were found experimentally (Appendix III).

Thus, before using Equation 3-9, it is necessary to calculate α corresponding to the burning pressure by the equation:

$$\alpha = b_1 + \frac{1.02 - b_1}{1 + b_3 \exp(-(1.02 - b_1)b_2 P)} \qquad \text{3-10}$$

where $b_3 = \frac{1.02-0.5}{0.5 - b_1} = \frac{0.52}{0.5 - b_1}$, and b_1 and b_2 are two experimentally determined constants. This value of α is then used in Equation 3-9 to find $\dot{m}_p$. This is only done as long as there is some unburned propellant in the PGG, after which $\dot{m}_p$ is set to zero.

RATE OF FLOW INTO HEAD-VOLUME

The mass flow from the PGG to the volume V_H is very complex: the flow starts axially in the annualar propellant chamber, continues through eight radial ports, and flows out of the PGG through the circular central passage (Fig. 3). Flow would be approximated poorly by the constant-area adiabatic flow with friction as defined by the Fanno-Line relationships. Following (Ref. 13) the ASME Fluid Meter Report, it can be represented by a Bernaulli flow, with an average coefficient of discharge to account for frictional losses and effective flow area.

This yields the following expression for the flow rate:

$$\dot{m}_G = K_f \, D^2 \sqrt{(P_i - P_e) \, \rho_i} \qquad \text{3-11}$$

where K_f is a constant determined by experiment and uniting the coefficient of discharge with some dimensional constants, D is the diameter of the minimum section, P_i and ρ_i are the pressure and density in the combustion region, and P_e is either the downstream pressure P_H or the critical pressure P_* depending on the flow regime. Given the upstream and downstream temperatures and pressures, the applicable flow regime is determined by whether the critical pressure corresponding to the upstream pressure is higher or lower than the downstream pressure. The critical pressure ratio is a function of γ, which is a function of the gas temperature, and hence varies along the length of the flow path. However, the total range of this variation is not great, so an average γ can be calculated iteratively and used to define the critical pressure ratio, and thus determine the value of P_e. The steps in determining P_e are as follows:

a) assume the flow is choked at some throat location.

b) assume an "almost" Fanno flow from the inlet to the throat.

The Fanno relation for the flow temperature is (Ref 5):

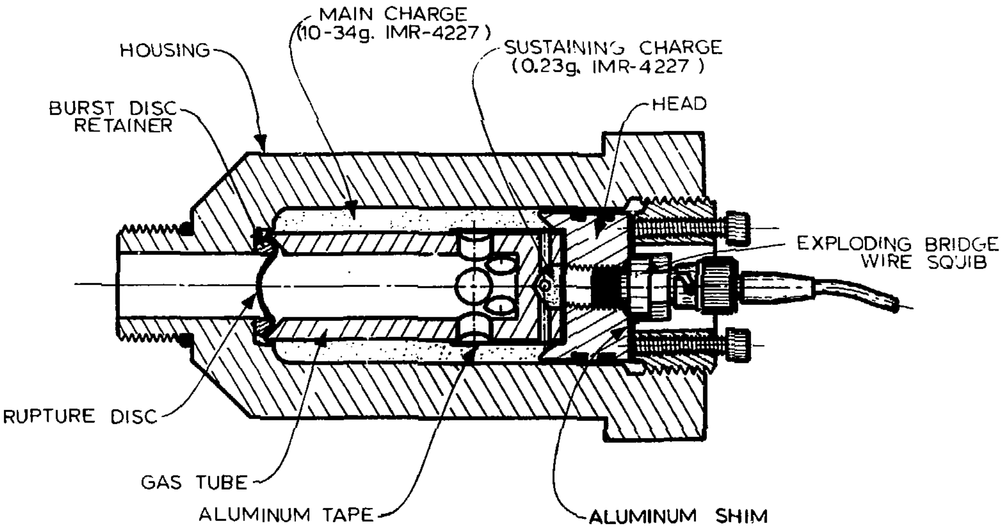

FIG. 3 - PYROTECHNIC GAS GENERATOR

$$\frac{T_i}{T_*} = \frac{\frac{\gamma + 1}{2}}{1 + \frac{\gamma - 1}{2} M^2} \to \frac{\gamma + 1}{2} \text{ as } M \to 0$$

therefore:

$$T_* = \frac{2}{\bar{\gamma} + 1} T_i \text{ where } \bar{\gamma} = \frac{\gamma_i + \gamma_*}{2} \qquad \text{3-12}$$

c) since γ_* is not known, an iterative solution must be used. Convergence is rapid because γ varies slowly with T. The sequence is:

1) Calculate γ_i corresponding to T_i by finding $c_p(T_i)$ from Equation 3-5, then:

$$c_v(T_i) = c_p(T_i) - \frac{R}{J} \qquad \text{3-12a}$$

and γ_i can be calculated by

$$\gamma_i = \frac{c_p}{c_v} \qquad \text{3-12b}$$

2) Find $T_* = \frac{2}{\gamma_i + 1} T_i$ 3-12c

3) Find γ_* corresponding to T_* , as in 1)

4) Set $\bar{\gamma} = \frac{\gamma_* + \gamma_i}{2}$ 3-12d

5) Find $T_*' = \frac{2}{\bar{\gamma} + 1} T_i$ 3-12e

6) Compare T_*' to T_*. If a significant difference is seen, set $T_*' = T_*$, and return to 3) to calculate a new value for γ_* and $\bar{\gamma}$. This procedure is repeated until $T_* \approx T_*'$

d) Calculate P_* corresponding to $\bar{\gamma}$:

$$P_* = P_i \left(\frac{2}{\bar{\gamma} + 1}\right)^{\frac{\bar{\gamma}}{\bar{\gamma}-1}} \qquad 3\text{-}13$$

e) If P_* is greater than P_H, the flow is choked, and $P_e = P_*$; otherwise, the flow is not choked, and $P_e = P_H$.

RATE OF FLOW INTO BUFFER VOLUME

The mass flow $\dot{m}_B$ through the piston-vent closely approximates an adiabatic, one-dimensional flow with constant area, and can thus be calculated by the Fanno Line relations. These are nonlinear, implicit simultaneous equations in pressures and temperatures of the gas at entrance and exit of the vent, including geometric parameters (such as wall relative roughness and diameter-to-length ratio). This system of equations can be solved numerically, as delineated below.

Given two volumes H and B (Fig. 4) connected by a constant area duct of length L and diameter D (Fig. 4), and given the pressures P_H, P_B $(P_H > P_B)$ and temperature T_H, it is required to calculate the flow. As a first approximation, assume a friction factor in the middle of the turbulent range, say $f = 0.02$.

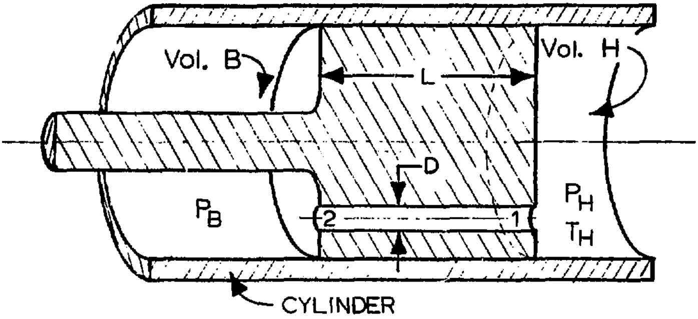

FIG. 4 - NOMENCLATURE FOR PISTON VENT FLOW ANALYSIS

The flow will consist of

(a) An isentropic expansion in Volume H, from rest just outside the duct entrance to a pressure P_1 just inside the duct with a velocity V_1 such that a certain Mach number M_1 exists at that point.

(b) Fanno flow along the length of the duct, with pressure dropping to P_2 just inside the exit. At this point, two possibilities exist:

1) The flow becomes choked at the end of the duct (i.e., $M_2 = 1$); in this case the flow expands explosively into B. For this to occur, P_2 must be greater than P_B. The flow comes to rest irreversibly in B, and the pressure in B

cannot affect the flow upstream of point 2.

2) The flow does not become choked (i.e., $M_2 < 1$); in this case there is a smooth variation in pressure between A and B, the flow again coming to rest irreversibly in B.

The essential probelm is to calculate M_1 and M_2 , the Mach numbers at tube entrance and exit, and $\dot{m}_B$, the mass flow rate through the tube. However, the two Mach numbers are related through the friction factor, which is itself dependent on the mass flow rate. Furthermore, the temperatures in the system may vary over a wide range (500 to 7000 R), and therefore, gas properties such as γ , the specific heat ratio (which enters into both the isentropic and the Fanno flow formulation) and μ , the viscosity (which enters into the Reynolds number, and hence the friction factor determination) must reflect this temperature variation.

The total variation in γ may be of the order of ten per cent, but the quantity $\frac{\gamma}{\gamma-1}$ (which enters as an exponent into one of the equations) will go through a corresponding variation of over 65 per cent. Gas viscosity over the same temperature range may change by about 15 per cent.

Instead of attempting to calculate the temperatures, and hence the related gas properties γ and μ along the length of the flow, it is convenient to use an average γ_i for the isentropic expansion as the arithmetic average of the values of γ at H (determined for T_H) and at 1. Similarly for the Fanno flow between 1 and 2, the average value of γ will be

$$\gamma_f = \frac{\gamma_1 + \gamma_2}{2} \qquad 3\text{-}14$$

and finally the average value of the viscosity $\overline{\mu}$ (to be used to determine the flow Reynolds Number) will be:

$$\overline{\mu} = \frac{\mu_1 + \mu_2}{2} \qquad 3\text{-}15$$

Thus, calculation of M_1 , M_2 , and $\dot{m}_B$ requires the determination of twelve auxiliary parameters:

γ_H	Specific heat ratio of the gas in Volume H.
T_1, γ_1, μ_1	Gas temperature, and corresponding specific heat ratio and viscosity, just inside the tube entrance.
T_2, γ_2, μ_2	Same properties evaluated just inside the tube exit.
$\gamma_i, \gamma_f, \overline{\mu}$	Average values of gas specific heat ratio for the isentropic expansion and for the Fanno flow, and the average flow viscosity.
Re, f	Reynolds number for the gas flow, and corresponding friction factor.

This gives a total of fifteen unknowns to be determined, and therefore requires a set of fifteen independent equations to be established. The following is one of the possible equation systems:

1) $$\gamma_H = \frac{c_p}{c_v} = \frac{c_p}{c_p - \frac{R}{J}} = \frac{c_1 + \frac{c_2}{T_H} + \frac{c_3 \ln T_H}{T_H}}{c_1 + \frac{c_2}{T_H} + \frac{c_3 \ln T_H}{T_H} - \frac{R}{J}} \qquad 3\text{-}16a$$

2) $$M_1 = \left[\gamma_f f \frac{L}{D} + \frac{1}{M_2^2} + \frac{\gamma_f - 1}{2} \ln \frac{M_2\left(1 + \frac{\gamma_f - 1}{2} M_1^2\right)}{M_1\left(1 + \frac{\gamma_f - 1}{2} M_2^2\right)}\right]^{-1/2} \qquad \text{3-16b}$$

(from Equation 7.54 Ref. 5)

3) $$M_2 = M_1 \frac{P_H}{P_B} \left(1 + \frac{\gamma_i - 1}{2} M_1^2\right)^{\frac{\gamma_i}{\gamma_i - 1}} \sqrt{\frac{1 + \frac{\gamma_f - 1}{2} M_1^2}{1 + \frac{\gamma_f - 1}{2} M_2^2}} \qquad \text{3-16c}$$

This equation was obtained by assuming $P_2 = P_B$ (i.e. unchoked flow) and combining the isentropic and Fanno pressure relations (Ref. 5, Equation 8.44 and 7.49).

4) $$T_1 = \frac{T_H}{1 + \frac{\gamma_i - 1}{2} M_1^2} \qquad \text{(Ref. 5, Equation 8.43)} \qquad \text{3-16d}$$

5) $$T_2 = T_1 \frac{1 + \frac{\gamma_f - 1}{2} M_1^2}{1 + \frac{\gamma_f - 1}{2} M_2^2} \qquad \text{(Ref. 5, Equation 7.30)} \qquad \text{3-16e}$$

6) $$\gamma_1 = \frac{c_1 + \frac{c_2}{T_1} + \frac{c_3 \ln T_1}{T_1}}{c_1 + \frac{c_2}{T_1} + \frac{c_3 \ln T_1}{T_1} - \frac{R}{J}} \qquad \text{(from 3-5)} \qquad \text{3-16f}$$

7) $$\gamma_2 = \frac{c_1 + \frac{c_2}{T_2} + \frac{c_3 \ln T_2}{T_2}}{c_1 + \frac{c_2}{T_2} + \frac{c_3 \ln T_2}{T_2} - \frac{R}{J}} \qquad \text{(from 3-5)} \qquad \text{3-16g}$$

8) $$\gamma_i = \frac{\gamma_H + \gamma_1}{2} \qquad \text{3-16h}$$

9) $$\gamma_f = \frac{\gamma_1 + \gamma_2}{2} \qquad \text{3-16i}$$

10) $$\dot{m}_B = A\, \rho_A M_1 \sqrt{\gamma_i g_c R T_1} \left(1 + \frac{\gamma_i - 1}{2} M_1{}^2\right)^{-\frac{1}{\gamma_i - 1}} \qquad \text{3-16j}$$

(by combining Equations 6.31 and 8.45 of Ref. 5)

11) $$\mu_i = \frac{C_{1i}\ T^{1.5}}{C_{2i} + T} \qquad \text{3-16k}$$

This is the Sutherland Formula, (Ref. 5, Equation 2.2) giving the viscosity of component i of the flowing gas at temperature T. The constants, C_{1i} and C_{2i}, are readily available for most common gases (e.g., Ref. 5, Table 2.1). For each gas in the flow, the viscosity at T_1 and T_2 must be evaluated, then the average viscosity for this component can be found:

$$\bar{\mu}_i = \frac{\mu_{1i} + \mu_{2i}}{2}$$

12) $$\bar{\mu} = \sum_{i=1}^{n} \frac{\bar{\mu}_i}{1 + \frac{1}{x_i} \mathop{}\limits_{\substack{j=1\\ j\neq i}}^{j=n} x_i\ \phi_{ij}} \qquad \text{3-16}\ell$$

where μ_i is the average viscosity of the i-th component, x_i is the mole fraction of the i-th component, and ϕ_{ij} is given by:

13) $$\phi_{ij} = \frac{\left[1 + \left(\frac{\mu_i}{\mu_j}\right)^{1/2} \left(\frac{M_j}{M_i}\right)^{1/4}\right]^2}{\frac{4}{\sqrt{2}}\left[1 + \frac{M_i}{M_j}\right]^{1/2}}$$ 3-16m

The Equations 3-16ℓ and 3-16m are due to Wilke (Ref. 10, Equations 13 and 14).

14) $$Re = \frac{Dv\rho}{\mu} = \frac{4\dot{m}_B}{\bar{\mu}\pi D}$$ 3-16n

15) $$f = 0.0055 \left[1 - \left(\frac{20000\varepsilon}{D} + \frac{10^6}{Re}\right)^{1/3}\right]$$ (Ref. 5, Equation 2.21) 3-16o

where ε is the roughness of the vent wall.

Since some of these fifteen equations are non-linear, an explicit solution is impossible, and iterative methods must be used. One of the simplest is the iterative back-substitution method. This equation system is arranged for this method, and gives a satisfactory convergence if started sufficiently close to the answer.

In this particular application, the equation system is used to find flow rates and Mach numbers in the piston vent. For the first time interval, the pressure differential is small, the flow is unchoked, gas velocities are low, and the flow rate is close to the ideal (frictionless) flow rate. The value of M_1 can be assumed to be equal to that determined from the ideal flow velocity, and the value of M_2 can be assumed to be equal to M_1. The flow temperature T_1 and T_2 can be assumed equal to the temperature of the gas in volume A. Substitution of these quantities as needed, starting with equation 1), and updating each quantity as soon as it is calculated, gives values for the Mach numbers to three decimal places after three or four iterations. The same equation system is used for choked and unchoked flow, the value of M_2 being set to 1 whenever a physically impossible value greater than one is obtained. After evaluating Equation 15), the old (stored) values of M_1, M_2, $\dot{m}_B$, and f are compared to the new values. If the agreement is within a certain desired percentage (.1 percent was used in this solution), the iteration is terminated.

For all succeeding time increments, the iteration is started from values of the variables found in the preceding time increment. Since the time increments are used in a forward integration, they are necessarily small, and thus each iteration is started very close to the answer, converging usually within two iterations.

PISTON ACCELERATION AND DISPLACEMENT

To calculate piston acceleration at time t, the forces acting on the piston (enumerated at the beginning of the chapter) must be found for time t. They are listed below for convenience:

Force due to gas pressure in the volume V_H:

$$F_H = \frac{\pi}{4} (d_c^2 - d_v^2)\ P_{H,t} \qquad 3\text{-}17$$

Force due to gas pressure in the volume V_B:

$$F_B = \frac{\pi}{4} (d_c^2 - d_v^2 - d_r^2)\ P_{B,t} \qquad 3\text{-}18$$

Force due to gravity:

$$F_G = M \cdot \cos\theta \qquad 3\text{-}19$$

Force due to drag of the vent flow on the vent walls:

$$F_D = \frac{\pi}{4} d_v^2 (F_1 - F_2) \qquad 3\text{-}20$$

where the thrust functions F_1 and F_2 are found from the Fanno flow solution, in terms of P_1, P_2, M_1, and M_2:

$$F_1 = P_1(1 - \gamma_f M_1^2)$$

$$F_2 = P_2(1 - \gamma_f M_2^2)$$

Force due to atmospheric pressure acting on the exposed piston-rod area:

$$F_a = \frac{\pi}{4} d_r^2 p_a \qquad \text{3-21}$$

Force due to piston-ring friction on the cylinder wall:

$$F_{pr} = d_c \left[k_1 + k_2 \, \Delta P_{HB} + k_3 (\Delta P_{HB})^{1/4} \right] \qquad \text{3-22}$$

Force due to seal friction on the piston-rod:

$$F_{rs} = d_r \left[k_1 + k_2 \, \Delta P_{Ba} + k_3 (\Delta P_{Ba})^{1/4} \right] \qquad \text{3-23}$$

The resultant force acting on the piston can now be calculated, using the sign convection of Fig. 2:

$$F_t = F_{H,t} + F_G + F_{D,t} - F_{B,t} - F_a - F_{pr,t} - F_{rs,t} \qquad \text{3-24}$$

This resultant force can be used in equation 3-2 to determine the rate of change of velocity for the piston and its load:*

$$\frac{\Delta U}{\Delta t} = \frac{F_t}{M} \qquad \text{3-25}$$

In order to use a simple forward difference procedure for integration, the time-increments Δt must be short enough so that

---

*The mass to be accelerated includes that of the load and of the piston and piston-rod. Since the latter is of the order of 2 to 3% of the load, this factor will be added to M in the design calculations.

the force on the piston (and hence the piston acceleration) remains constant during this time interval. The distance moved by the piston during the time increment Δt is then equal to

$$\Delta X_t = U_t \, \Delta t + \frac{1}{2} \frac{\Delta U}{\Delta t} (\Delta t)^2 \tag{3-26}$$

The new location of the piston is

$$X_{t+\Delta t} = X_t + \Delta X_t \tag{3-27}$$

and the velocity at the end of the time interval Δt is

$$U_{t+\Delta t} = U_t + \left(\frac{\Delta U}{\Delta t}\right) \Delta t \tag{3-28}$$

Now that the piston position for the end of the time increment is known (and hence the individual system volumes as well as the rates of change of energies and masses), the system state for time $t+\Delta t$ can be evaluated:

System Volumes:

$$V_{H,t+\Delta t} = V_{H,t} + \frac{\pi}{4} d_c^2 \, \Delta X_t$$

and 3-29

$$V_{B,t+\Delta t} = V_{B,t} - \frac{\pi}{4} (d_c^2 - d_r^2) \, \Delta X_t$$

Gas Masses:

$$m_{G,t+\Delta t} = m_{G,t} + \dot{m}_{P,t}\Delta t - \dot{m}_{G,t}\Delta t \tag{3-30}$$

$$m_{H,t+\Delta t} = m_{H,t} + \dot{m}_{G,t}\Delta t - \dot{m}_{B,t}\Delta t$$

$$m_{B,t+\Delta t} = m_{B,t} + \dot{m}_{B,t}\Delta t \qquad 3\text{-}30$$

Gas energies in each volume are found by adding to the internal energy of the gas at time t, the enthalpy of the gas inflow (evaluated at the temperature of its origin), subtracting the enthalpy of the gas outflow and adding (or subtracting) the work done on (or by) the gas due to piston movement.

The enthalpy and internal energy of the gas at each temperature are calculated from Equations 3-6 and 3-7. The internal energy gained by the gas in the PGG due to propellant combustion is determined as

$$Q_{p,t} = \dot{m}_{p,t} h \, \Delta t \qquad 3\text{-}31$$

where h is the effective propellant heat of reaction, experimentally determined so as to account for heat losses to the walls.

The work done on the piston by the gas in a volume is equal to the total force exerted by the gas pressure on the exposed piston area, multiplied by the distance the piston moved:

$$W_{H,t+\Delta t} = \frac{\pi}{4} (d_c^2 - d_v^2) \, P_{H,t} \, \Delta X_t$$

and 3-32

$$W_{B,t+\Delta t} = \frac{\pi}{r} (d_c^2 - d_r^2 - d_v^2) \, P_{B,t} \, \Delta X_t$$

The energy of the gas in each volume, at time t + Δt, is thus equal to:

$$E_{G,t+\Delta t} = E_{G,t} + Q_{P,t} - \dot{m}_{G,t}h_{G,t}\,\Delta t$$

$$E_{H,t+\Delta t} = E_{H,t} + \dot{m}_{G,t}h_{G,t}\,\Delta t - \dot{m}_{B,t}h_{H,t}\Delta t - W_{H,t+\Delta t} \qquad 3\text{-}33$$

$$E_{B,t+\Delta t} = E_{B,t} + \dot{m}_{B,t}h_{H,t}\Delta t + W_{B,t+\Delta t}$$

Note that the above equations assume the flows take place in the directions shown in Fig. 2, and flow enthalpies are evaluated at the temperature of flow origin. A suitable change must be introduced into the equations if any of the flows change direction.

With the gas energies known for each volume, the temperature corresponding to each energy can be found by solving the internal energy equation for T. This was done by a Newton-Raphson iteration, starting at the corresponding temperature determined in the last time increment. Convergence (to .1 R) was usually obtained in two iterations, given T_G, T_H, and T_B.

Knowing the gas masses in each volume, and the extent of this volume, the gas specific volume can be found for each mass. Substituting those, with the gas temperatures, into the gas equation of state, will give the gas pressures at time t + Δt, the last property to be evaluated for this time increment. Equation 3-3 is easily solved for pressure, giving:

$$P = \frac{RT}{v}\left(1 + \frac{B}{v}\right) \qquad 3\text{-}34$$

The state of the system at time t + Δt is now fully determined, and evaluation of the rates of change for the next time increment can now be undertaken, provided the end of integration is not yet reached.

END OF ACTUATION

The time integration should be stopped when either of two conditions is satisfied by the system:

a) If the new displacement X is greater than the maximum stroke allowed by the physical structure, the moving mass has impacted at a known velocity, and the maximum stresses, pressures, impact-velocity, and time of stroke are now known. It is now possible to make a judgement on how closely the system just analyzed came to satisfy the design requirements; i.e., whether the final velocity is too great, or the maximum cylinder pressure, whether the time is too long, or the piston-rod stress is excessive.

b) If the piston velocity changes sign before reaching the required stroke, the piston has reversed its direction of motion somewhere during the last time increment. During this increment, the velocity of the piston was zero, and a mechanical latch could have been engaged. This would demonstrate the full potential of a properly vented piston, but would be a less reliable design for a required stroke, as discussed in Section 2.

Determination of Constants:

Fourteen system constants were needed in the analysis. They were:

k_1, k_2, k_3	used in Equations 3-22 and -23 to determine seal friction forces. They were derived by fitting an arbitrary equation to experimental data obtained from the manufacturer.
ε	piston-vent wall roughness, used in Equation 3-16o to calculate flow friction factors. Vent wall roughness was measured by a profilometer and averaged by inspection. ε was found to be equal to 0.0018 in.
c_1, c_2, c_3, c_4	used in Equations 3-5 and -6 to calculate gas enthalpies and specific heats. These values were calculated from empirical data as detailed in Appendix I.

The following six constants were determined from experimental data as detailed in Appendix II.

K_B, b_1, b_2	used in Equations 3-9 and -10 to calculate propellant burning rates.
B	the first virial coefficient in the gas equation of state, used in Equations 3-3a and -34 to calculate specific valumes or gas pressures.
K_f	the flow coefficient of discharge, used in Equation 3-11.

h	the effictive heat of reaction of the propellant (the actual heat of reaction reduced to account for heat loss to the walls).

The last six constants were determined from experimental data as described in Appendix II.

4. EXPERIMENTAL VERIFICATION OF ACTUATOR ANALYSIS

PROGRAM STROKE

Following the steps outlined in Chapter 3, a computer program named STROKE was written for determining the position of a pyrotechnically actuated vented piston as a function of time. A listing of STROKE (a subroutine in the complete design program DESAC) is given in Appendix IV.

The input to STROKE consists of:

WLB	Mass to be moved	(lb)
STR	Maximum stroke length	(in.)
PWGR	Propellant charge per cartridge	(g)
HD	Vent-hole diameter	(in.)
HL	Length of head clearance-volume	(in.)
BL	Length of buffer volume	(in.)
CD	Cylinder diameter	(in.)
PRD	Piston-rod diameter	(in.)

The program follows the calculation steps described in Chapter 3, and its output consists of:

TAC	Time actually taken by piston to come to rest.	(sec)
VFIN	Final piston velocity (if the full stroke was achieved).	(ips)
or		
DST	Length of stroke (if piston stopped short).	(in.)
STMX	Maximum piston-rod stress.	(psi)
GPMX	Maximum generator-gas pressure.	(psia)
HPMX	Maximum gas pressure in head-volume.	(psia)
BPMX	Maximum gas pressure in buffer-volume.	(psia)

Experimental demonstration of the validity of a complicated computer program is essential to justify its use in the design of an expensive system. Therefore, before incorporating STROKE into a program that would solve the design problem described by Equations 2-14 to 2-20, an experiment was performed to compare the action of a real actuator to that calculated by STROKE. This experimental will now be described.

RESTRICTION ON TEST SCALING

The specific gas generator to be used in this design was originally intended to give between 1550 and 6500 psi of gas pressure in a 38 cubic inch volume, when loaded with a charge of between 10 and 24 g of propellant. It would be desirable to test experimentally the accuracy of STROKE calculations with an actuator using a similar gas pressure and head-volume. This sets a lower limit to the physical size of the test actuator. It was estimated that designing, fabricating and assembling such an actuator would entail approximately six months of time, and a cost of the order of ten thousand dollars.

AVAILABLE ACTUATOR

In order to avoid such a long delay and high expense, it was decided to use an existing (and available) 18 inch Fast-Closing Gate Valve shown in Fig. 5. This valve has a 347.5 lb gate which can be moved through a total stroke of 19 inches in a time of 0.030 sec by four three-inch cylinder actuators in parallel each actuator being pressurized by one generator loaded with 24 g of propellant. After approximately 11 in. of acceleration the bottom of the piston in each actuator contacts a pre-packaged quantity of silicone-grease, and extrudes it through a shaped slot in the cylinder wall. This provides a decelerating force that slows down the gate to approximately

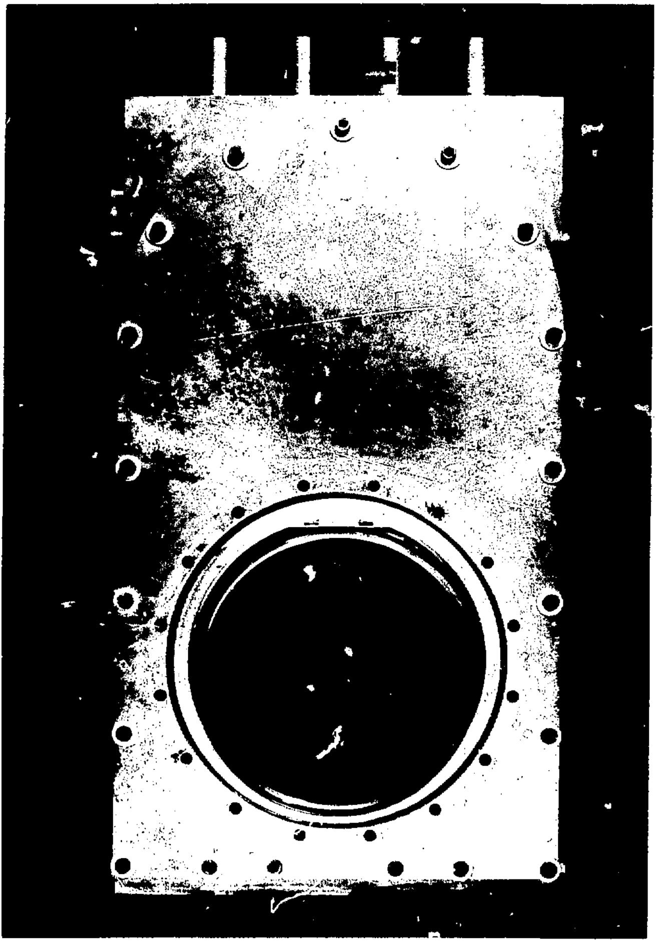

FIG. 5 - 18-inch FOUR CYLINDER FAST-CLOSING GATE VALVE. NOTE BACK EDGE OF GATE AT TOP OF OPENING.

FIG. 6 - ASSEMBLY OF THE 18-inch FAST-CLOSING GATE-VALVE.

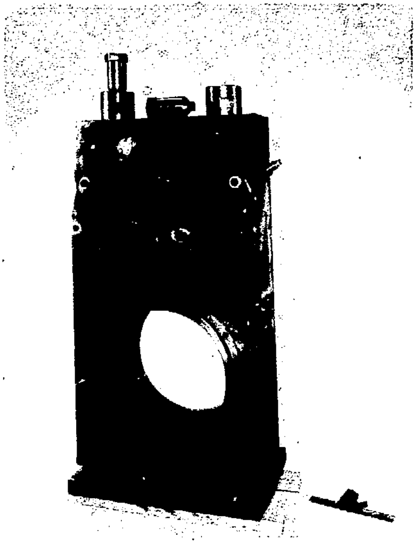

FIG. 7 - 18-inch GATE-VALVE ASSEMBLED IN THE TWO-CYLINDER MODE. NOTE ONE GAS-GENERATOR LYING ON THE BODY, AND ONE MOUNTED IN THE LEFT CYLINDER.

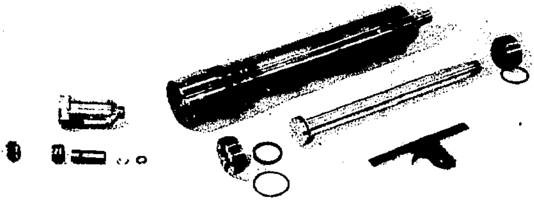

FIG. 8 - ACTUATOR AND GAS-GENERATOR ASSEMBLIES, WITH ONE SET OF INTERNAL COMPONENTS. NOTE VENT-HOLE IN TOP OF PISTON.

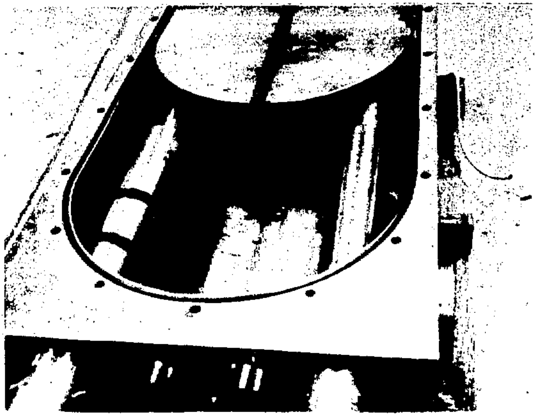

FIG. 9 - VALVE BODY AFTER ACTUATION, WITH COVER OFF. NOTE PRESSURE TRANSDUCERS ON BOTH ENDS OF LEFT CYLINDER, AND TEAR-BOLT BODY STILL IN THE GATE.

shows the valve body after actuation, with the front cover-plate removed.

INSTRUMENTATION

Pressures in head and buffer volumes were measured by piezzo-electric transducers*. They can be seen on the left-hand cylinder in Fig. 9. The transducer outputs were recorded by two oscilloscopes. Positions of the valve gate versus time were recorded by a high speed camera† aimed to get a view through the valve. The field of view was such that the far edge of the bottom of the gate was visible through the valve before any motion took place (see Fig. 5); thus movement could be measured before the gate entered the valve opening. To simplify measurement of gate motion after its lower edge had passed the bottom of the valve opening, a line of alternating quarter-inch black and white strips was painted on the face of the gate (Fig. 9). The exact gate position at each time increment was obtained by projecting the film on a film reader with a micrometer adjustment for a set of cross-hairs. The "O"-ring groove machined in the front panel of the valve was used to establish a reference for all Fastax frames. Front-edge and back-edge positions were then calculated from the known dimensions of the valve and camera distance.

Synchronization of the various measurements made during actuation was achieved by starting the high-speed camera first. When it reached its operating speed of 4000 frames per second (in about 2 seconds), a signal was sent to trigger the capacitance-discharge-unit (CDU) energizing the initiators in the two PGG's, one additional initiator suspended in the camera field of view, and the two oscilloscopes. Thus a zero-time signal was present in each measurement.

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*Kistler Model 603

†Fastax Model WF3T

FIG. 10 - 18-inch VALVE SET-UP FOR ACTUATION TEST, MOUNTED ON INERTIA BLOCK RESTING ON PLASTIC FOAM PADS. HIGH-SPEED CAMERA IS IN FOREGROUND.

INSTALLATION

The reaction force due to the acceleration of the gate would (with a simplified, linear system) have raised the 3300 lb valve body to a height of approximately 0.836 inches. This was undesirable because the gate would begin to decelerate while the valve body was still in free fall, introducing second-order effects into an already complex system. The gate would come to the end of its travel while the body was still over 0.7 in. off the ground. To limit this effect, the valve was mounted on a 5200 lb block of armor plate (Fig. 10). This reduced the jump to about 0.07 inches. At 0.065 sec (gate end of travel) the body (in free fall) would be about 0.003 in. off the ground, i.e., practically at rest. Thus, any secondary effects due to deceleration forces (and final impact) could not affect gate position by more than 0.07 in. which is close to the resolution limit of the film-reader position reading system.

To shield operating personnel from the exposed gas generators, and any fragments that could have resulted if the gate hit the body with excessive energy, the valve (mounted on its ballast block) was installed in a pit (Fig. 10). All control and data-acquisition wires were led out of the pit to the instruments on the ground floor. Lighting was arranged to illuminate the bolt-circle and "O"-ring groove region of the front panel of the valve, and the white cardboard placed behind the valve to faciliate observation of gate motion.

RESULTS

Figure 11 shows experimentally measured valve positons on a plot of calculated positions versus time.

Maximum pressures measured and calculated are compared in Table II.

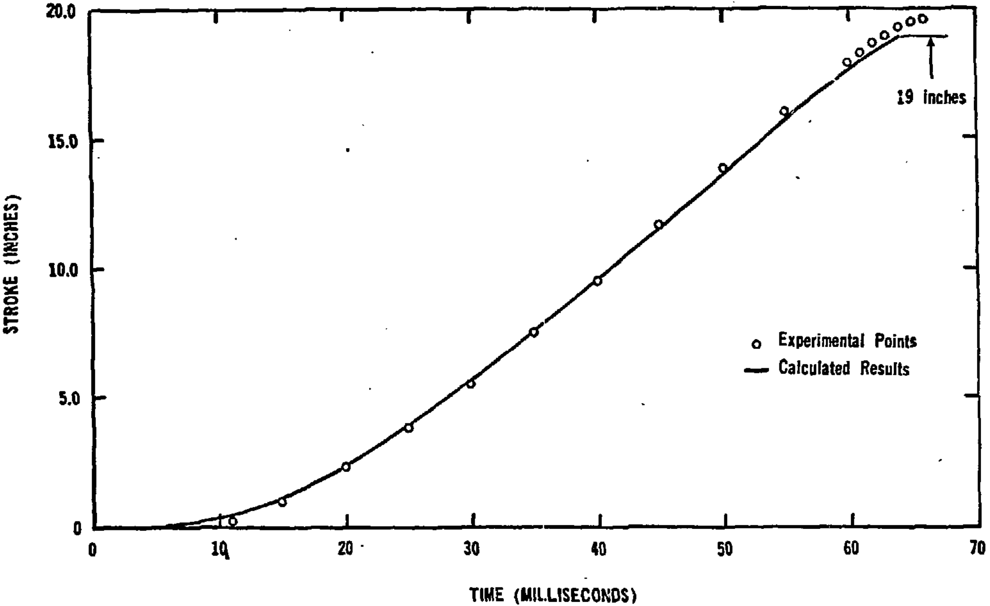

FIG. 11 - CLOSURE TEST ON 18-inch TWO-CYLINDER GATE VALVE.

TABLE II

	Measured	Calculated
Maximum Pressure in Head Volume (HPMAX)	1406 psia	1438 psia
Time of Occurrence of HPMAX	8.27 msec	8.30 msec
Buffer Pressure at 0.062 sec (i.e. just before transducer port occlusion)	3364 psia	3262 psia

It can be seen total travel time was calculated to within 1.5% and the time to reach maximum head-pressure within 0.4%. The calculated value of the maximum head pressure was within 2.3% of the value measured, and that of the maximum buffer pressure, within 3.1%. This agreement was considered good enough to justify using STROKE to predict the performance of any similar actuator.

5. THE ACTUATOR DESIGN PROGRAM

APPLICABILITY OF STROKE

It was shown in the last section that, given the seven parameters defining a self-stopping actuator (i.e. the propellant charge, piston vent-hole diameter and length, head-volume and buffer-volume length, cylinder and piston-rod diameters) and the weight to be moved through a specified distance, STROKE can calculate the piston position as a function of time (and hence velocity and acceleration) with a maximum error of 1.5% on the time of arrival.

Maximum piston-rod stress is easily derived from the maximum acceleration (or deceleration) value observed. Gas pressures in the generator, head-volume and buffer-volume are all calculated for each time increment, and their maximum values can be readily recorded. As shown in Table II, pressures are calculated with accuracies of the order of two or three per cent.

The next step is to utilize POWSQ to determine those values of the seven independent variables that define the actuator whose performance (calculated by STROKE) is sufficiently close to the performance desired.

OTHER CONDITIONS TO BE MET

Since a specific PGG is to be used in all actuators to be designed, the loading limit of the PGG (i.e. to 34 g) must not be exceeded. At the same time, two generators with 15 grams each should not be used when a single generator can be loaded with 30 grams, unless it is required to use two cylinders (with one generator each) to comply with geometry limitations on cylinder diameters.

The same design philosophy indicates the need for the least number of piston vents per piston; but if a vent length-to-diameter ratio of ten or fifteen (needed to form a well established Fanno flow) requires an unreasonably thick piston, then more than one vent (of smaller diameter) may be used.

All such decisions are very difficult to program in advance; yet they are routinely made by a designer. To facilitate these design decisions, it became clear that an interactive computer program was needed with an opportunity for the designer to make these decisions and introduce them into the design, as they become evident to him.

The actuator design program DESAC was written to do this. Its basic logic is shown in the flow-chart on Fig. 12, where the various options available to the designer can be readily followed.

GENERALIZED DESIGN OF AN ACTUATOR

The path used in designing a new actuator (with no information or limitations from past design) will now be shown step-by-step, with references to key points on the flow chart shown in Fig. 12.

The first step the designer takes is to give the program the three numbers defining the required system performance (WLB, STR, and TR) and the four system constraints (VFAL, STAL, GPAL, and CPAL). The program then asks the designer whether this is a redesign of an existing actuator

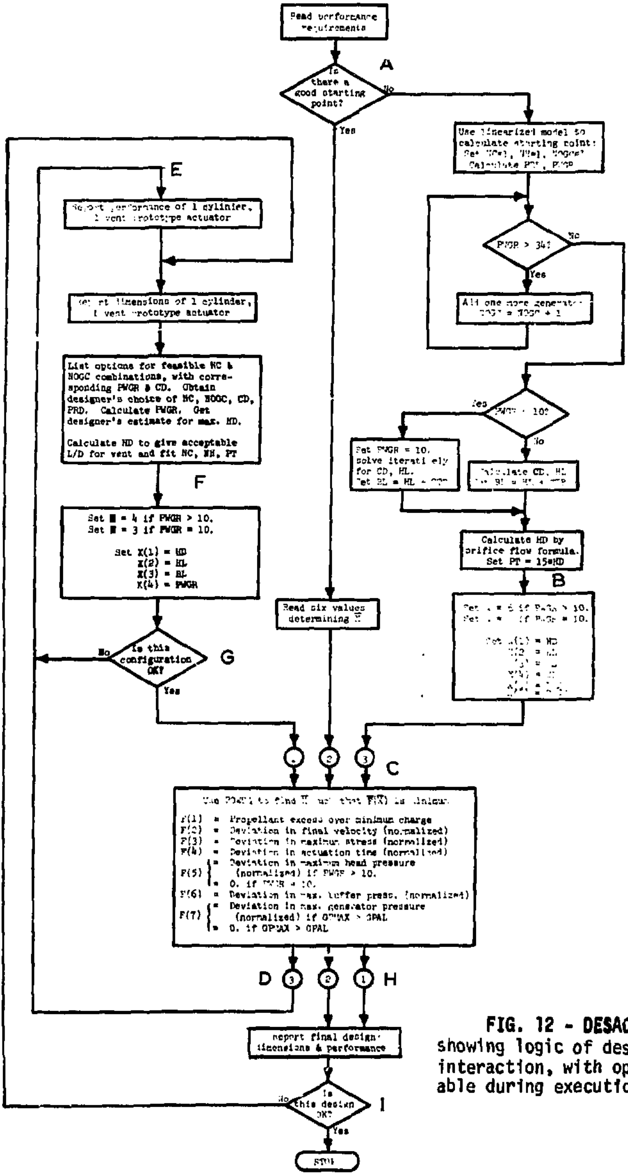

FIG. 12 - DESAC Flowchart showing logic of designer-program interaction, with options available during executions

whose dimensions and propellant loading would give a good point to start the POWSQ search (Point A in Fig. 12). Upon receiving a "NO" from the designer, DESAC uses the linearization detailed in Appendix III to calculate a feasible starting point. At this time the objective is to design a "prototype" actuator, that would merely satisfy the performance design requirements, ignoring for the time being such geometrical details as maximum usable cylinder diameters, and whether there is room for the piston vent-hole between the piston-rod and the piston-seal grooves. Therefore, it is assumed that there will be one cylinder, and one vent-hole. Since a specific gas generator will be used, the required total propellant charge will determine the number of gas generators supplying the one cylinder. To ensure a fully established Fanno flow through the vent-hole, a piston thickness of fifteen vent-hole diameters is assumed. DESAC is now at Point B in Fig. 12, and has the specifications of a feasible actuator that will come fairly close to some design requirements (as close as 1% on final velocity) but be badly off on others (30 to 50% on maximum buffer pressure).

The seven functions whose sum of squares is to be minimized are:

F(1) = (PWGR-10.)*NOGC* WT	Weighted propellant excess over minimum charge	5-1
F(2) = (VFIN-VFAL)/VFAL	Normalized final velocity deviation	5-2
F(3) = (STMX-STAL)/STAL	Normalized maximum stress deviation	5-3

F(4) = (TAC-TR)/TR	Normalized actuation time deviation	5-4
F(5) = (HPMX-CPAL)/CPAL	Normalized maximum head pressure deviation	5-5
F(6) = (BPMX-CPAL)/CPAL	Normalized maximum buffer pressure deviation	5-6
F(7) = (GPMX-GPAL)/GPAL (if GPMX>GPAL)	Normalized maximum generator pressure excess	5-7
or		
= 0 (if GPMX<GPAL)	Zero if generator does not exceed rated pressure	

Two possibilities now exist:

a) The propellant charge in the one or more gas generators is between 10 and 34 grams. The problem is to determine the six unknowns: HD, HL, BL, CD, PRD, and PWGR (since PT has been set to fifteen times HD). N, the number of unknowns is set at 6 and POWSQ receives the dimensions and loading of the linearized actuator, and proceeds with its search for the desired performance (Point C in Fig. 12). After 100 function evaluations (corresponding to 14 to 19 iterations), POWSQ has determined the five dimensions and the loading of a "prototype" actuator that will satisfy (to less than 10%) all seven design requirements (Point D).

b) The propellant charge is less than the ten gram minimum loading for the gas generator. The generator will be loaded with the minimum charge, and the propellant weight is no longer a variable to be manipulated by POWSQ. This is accomplished by setting N=5, and

POWSQ is allowed to reduce the thermodynamic efficiency of the system by allowing the generator gas to expand into an oversize head-volume, while still seeking the five independent variables that would define the desired "prototype" actuator.

Note that, during this search, POWSQ may switch back and forth between the two modes a) and b). Eventually, however, a definite "prototype" actuator will be specified, with definite values for HD, HL, BL, CD, PRD, and PWGR.

The program DESAC now proceeds to report to the designer (via teletype) the performance and specifications of the "prototype" actuator. Having the total propellant loading the performance seems to require, DESAC reports to the designer the possible permutations on the number of generators that can handle the required propellant loading, and the resulting number and diameters of the cylinders and piston-rods that are required to satisfy the allowable stress and pressure constraints (Points E to F in Fig. 12).

DESIGNER'S DECISIONS

Now DESAC enters the interactive mode, requesting the designer to give some preferred (i.e. standard) cylinder and piston-rod diameters, with the number of cylinders required to give the same approximate total piston area as was arrived at in the "prototype" design.

The annulus between cylinder and piston-rod is next given to the designer, as well as the diameter of the single vent-hole. The designer can now check the manufacturer's specifications on required diameters of piston-ring grooves and report to DESAC the maximum acceptable vent-hole diameter. One last design decision must be made by the designer, and that is to balance an acceptable piston thickness (which determines the length of the vent-hole) against a vent length-to-diameter ratio that would justify the assumption of Fanno flow in STROKE. The program allows the designer to repeat this decision until the designer signals his satisfaction by typing OK.

FINAL DESIGN SEARCH

The final design search will start with an actuator that will have essentially the same total propellant charge, total cylinder head- and buffer-volume, total vent-hole area, total approximate piston-rod and piston area, and a piston thickness and vent-hole diameter that will give a well-established Fanno flow through the vent-hole (Points F to G, Fig. 12).

The same two possibilities exist with respect to propellant charge, i.e. it can be greater than the minimum of ten grams, or less than ten grams.

The cylinder diameter and piston-rod diameter have now been definitely selected by the designer, and hence are no longer to be varied by POWSQ. If the propellant charge is greater than 10 g per generator, N is set to 4, and POWSQ begins the search for the final design by varying the remaining variables: HD, HL, BL, and PWGR. Otherwise, N is set to 3, and POWSQ adjusts the three variables HD, HL and BL, with PWGR set to the minimum ten-gram charge (Points G to H, Fig. 12).

POWSQ now has another 100 function evaluations (approximately 14 to

19 iterations), to determine the values of HD, HL, BL, and PWGR (for the specified values of CD and PRD) that minimize the same seven functions representing the design deviation from desired performance.

Upon completion of the final design search, the program reports to the designer the performance and specifications of the final design (Points H to I in Fig. 12).

Finally, the designer is given the choice of accepting the final design, or of returning to the stage immediately after Point E in Fig. 12, and making a new choice among the options offered.

DESAC has been used on ten test-designs and has met the performance requirements (within 3%) and the constraint requirements (within 10%), using approximately 7.5 minutes of CDC 7600 computer time on each double-search problem. Several of these test-designs will be described in the next Section.

6. TESTS AND APPLICATIONS OF DESAC

Importance of Smooth Changes in Dependent Variables During the Minimizing Process

Of the seven functions minimized by the program POWSQ while carrying out an actuator design, six are highly nonlinear. These functions involve the dependent variables (i.e., TAC, VFIN, STMX, MPMX, BPMX, and GPMX). Since POWSQ was specifically intended to minimize the sum of squares of nonlinear functions, this did not appear to be a problem. Satisfactory convergence to a good minimum from the linearized starting-point was observed on the very first trial design. However, when the manual starting-point option was tried with the same starting-point (except for manual input round-off of the independent variables), POWSQ did not converge to the same minimum. Instead it decreased the sum of squares of the seven functions faster on the first three iterations, then failed to improve for the next six, and stopped (as programmed) at a pseudo-minimum representing a very poor performance approximation. A study of the convergence history of these two cases, and of several additional examples of similar unpredictable behavior revealed the cause: subroutine STROKE (used to calculate the values of the six variables defining the actuator performance) calculated their values at exact multiples of the time increment. For example, VFIN was the velocity determined at the end of the time increment during which the required stroke had been exceeded. This sometimes produced a whole time-increment change in calculated actuation time, with considerable changes in the other five dependent variables, for a very small change in one or more of the independent variables changed by POWSQ. The result was a different convergence path for unpredictably small differences in starting point position, and a fortuitous convergence to a good minimum some (but not all) of the time. Reducing the time increment from 10^{-4} to 10^{-5} sec improved the situation, but at the expense of a tenfold increase in computation time.

The problem was resolved by calculating the time and velocity at the actual end of the stroke. This was done by backward calculation (assuming the same constant acceleration) once the stroke-length was exceeded, instead of taking the time and the velocity at the end of the time increment itself. This gave a smooth variation in time of action and final velocity. A Lagrangian interpolation was used (based on the last two values of buffer pressure, and the buffer pressure at the end of the time increment after the stroke length had been exceeded) to calculate the value of buffer pressure at the exact time of the end of travel. This, of course, was the maximum buffer pressure. The maximum head-volume pressure was found by assuming a parabola through the last two (increasing) and the first (decreasing) head-volume pressures, and finding the maximum point of the parabola. The maximum piston-rod stress was found by using either of these two methods, depending on whether the maximum stress occurred during acceleration or deceleration. This approach gave a smooth variation in calculated performance variables for any change, no matter how small, in the independent variables. POWSQ then converged reliably.

WEIGHTING FACTORS ASSIGNED TO THE FUNCTIONS TO BE MINIMIZED

The absolute values of the seven variables used to form the squares whose sum is to be minimized vary from 10^{-3} for actuation times, through approximately 3 for propellant charge and 30 for final velocity, to 10^{3} for maximum cylinder pressure. In view of this range, it is reasonable to normalize the functions which are squared so that they would all be quantities of the same order of magnitude, thereby refraining from creating a preferred minimization direction due to arbitrary choice of units. Dividing the difference between the desired and actual values of the dependent variables by the desired value gives a simple normalizing scheme, and results in function absolute values generally located between zero and one.

Note, however, that there is no desired (i.e., specified) propellant weight. For this variable, the minimum possible value is desired. Therefore, to give it the same order of magnitude as the other six functions calculated by subroutine STROKE, an arbitrary weighting factor WT was introduced, setting F(1)=(PWGR-10)*WT. The initial magnitude of WT was set to 0.02.

TEST A: REDESIGN OF EXPERIMENTAL ACTUATOR

The observed performance of the experimental actuator was to move a load of 356.5 lb through a distance of 19 in. in 0.065 sec, and arriving at the end of the stroke with a velocity of 300 isp. To this were added the constraints (not present in the original actuator) of maximum piston-rod stress of 20,000 psi, and of maximum cylinder pressures of 5000 psia and generator pressure of 32,000 psia. Test A used DESAC to design an actuator satisfying these specifications. Results are given in Appendix V with all the details of the POWSQ iterations.

Referring to pages 120-128 the steady decrease in FF (the sum of the squres of the seven functions to be minimized) can be followed iteration by iteration. Note how, during the prototype design, FF was reduced from 0.0847 (for the linearized model representation) to 0.0256, after 15 iterations (95 STROKE evaluations). The program then reported to the designer the calculated performance and specifications of the proposed prototype design, and entered the interactive communication mode. At this point the designer's judgement was introduced into the picture: he decided that a 1 inch piston-rod (the nearest standard diameter to the 1.045 in. diameter recommended for the prototype design) is too slender for a 19 inch stroke (and some 24 inch length), and selected a 1.25 inch diameter. This forced a proportional increase to 2.5 inches instead of 2 in. for the cylinder diameter. An arbitrary choice by the designer of 1.75 inches for piston thickness resulted in a 15.3 L/D ratio (calculated by the program) for the one vent-hole, and was approved by the designer's OK. Note that, due to the designer's change to non-optimum piston-rod and cylinder diameters, the value of FF jumped to 0.11 (an over forty-fold increase). It took twenty more iterations (and 101 function evaluations) to reduce it to 1.62×10^{-3}. A further reduction in FF could probably have been achieved by further iteration, but would have given only a small improvement in performance (3.6% error on time required is the largest error observed).

Appendix VIa gives the history of the same problem as it appeared on the designer's teletype (i.e., without showing all the intermediate POWSQ function evaluations). Table III compares the two-cylinder actuator used to verify STROKE, with the DESAC- designed system. Note that for the same actuation time (3.6% off for the DESAC design) and final velocity (1.2% off), the job can be done with one 2.5-inch cylinder instead of two 3-inch ones, and with one piston-rod 1.25 in. in diameter instead of two 1-11/16 ones. Finally, a total propellant charge of 10.6 g is required in only one gas generator, instead of 20 g in two generators.

The DESAC design is obviously the cheaper and more efficient of the two.

TEST B: EFFECT OF THE ARBITRARY WEIGHTING FACTOR ASSIGNED TO F(1).

To investigate the influence of the weighting factor WT used in the propellant function F(1), the design of the experimental actuator was repeated with the value 0.05 given to WT instead of 0.02. This encouraged minimization

TABLE III

	Experimental Actuator	DESAC-Designed "A" Actuator
Performance:		
Time to travel 19-inch stroke (sec)	.063	.065
Velocity of arrival at end of stroke (ips)	300.	303.5
Components:		
Cylinders	2	1
Gas generators	2	1
Dimensions:		
Cylinder diameter	2 x 3.00"	1 x 2.5"
Piston-rod diameter	2 x 1.6875"	1 x 1.25"
Vent-hole diameter	.165"	.1191"
Total propellant charge (grams)	20	10.6155

of propellant charge over that of the other six functions listed in Equations 5-2 to 5-7 by a factor of 2.5. Examination of the prototype design (pages 129-132) shows that this resulted in a considerably smaller charge for test B (10.746 g after 13 iterations for B against 14.868 g after 15 iterations for A). Also note that both prototype designs came to acceptable convergence in less than the maximum number of 100 function evaluations.

Table IV compares the two prototype designs.

It can be seen that test B yielded a faster convergence than test A, and arrived at a better performance approximation for all parameters except final velocity. As might be expected, the sum of squares is lower (0.00565 versus 0.0265).

Examination of the final design convergence (page 132) in test B shows that the sum of the squares FF has changed very little from the last iteration of the prototype design (0.0065 at Prototype Design Iteration 13 to to 0.025 at Final Design Iteration 0). This is due to the very small changes introduced by the designer in the interactive section.

TABLE IV

	Design A	Design B
Number of iterations (function evaluations)	15 (95)	13 (77)
Sum of squares minimized	.0256	.00565
Normalized Design Deviations (per cent)		
Excess over minimum propellant	9.736	3.730
Deviation from required time of travel	9.881	1.712
Deviation from allowable final velocity	1.849	2.719
Deviation of max. stress from allowable	5.194	4.019
Deviation of head-space max. pressure from allowable	4.631	3.887
Deviation of buffer max. pressure from allowable	-3.467	0.989
Excess of generator max. pressure over allowable	0.	0.

Further history of the two designs, however, breaks away from the previously established pattern. Design A continues for 100 more iterations, and is stopped before POWSQ is satisfied that a minimum is reached (i.e., that no reduction in FF can be made by taking steps smaller than the required accuracy on the independent variables). It can be seen, however, that only small changes are being made, and only very small improvements in FF are obtained between the 14-th and the 20-th iterations. Design B continues for only five more iterations (30 function evaluations), stopping with a very small improvement over iteration zero, and with a larger FF than the one found for the prototype design.

Table V summarizes the convergence history of the two final designs:

TABLE V

	Design A	Design B
Number of iterations (function evaluations)	20 (100)	5 (30)
Sum of squares to be minimized	.00162	.01927
Normalized Design Deviations (per cent)		
Excess over minimum propellant	1.231	3.478
Deviation from required time of travel	3.607	-0.281
Deviation from allowable final velocity	1.161	11.351
Deviation of max. stress from allowable	0.547	5.340
Deviation of head-space max. pressure from allowable	0.061	4.766
Deviation of buffer max. pressure from allowable	0.027	0.721
Excess over generator allowable pressure	0.	0.

Evidently Design A, handicapped by a wide deviation from the prototype design, utilizes another 100 function evaluations to good advantage and ends up with a very close approach to the desired performance, while Design B cannot find any major improvement to an already acceptable performance, and quits after only five iterations. Design A even requires 0.045 g less propellant than Design B (10.651 g versus 10.696 g), in spite of having a lower weight attached to propellant minimization.

Actually, either design would be acceptable, showing that weighting the functions to be minimized may affect the path of the design search, and hence the rate of convergence, but if convergence does occur (i.e., if all functions to be minimized do indeed reach small values), will not even guarantee that the most heavily weighted function will be the one most reduced, since it is the sum of the squares that POWSQ minimizes.

TEST C: EFFECT OF POOR STARTING VALUES

The linearized model used to calculate the starting point in tests A and B gave (perhaps fortuitously) a fairly good starting point (FF was 0.085

for test A and 0.11 for test B). To demonstrate that a less favorable starting point will not deter convergence by POWSQ to a minimum, test A was selected because it showed great improvement from designer-modified prototype to the final design. Each independent variable defining the modified prototype in test A was altered by the amount of its improvement in the final design, but in the opposite direction. For example, the head-space length was decreased from an initial value of 2.7057 in. to the final value of 1.4763 in. in test A. For test C, this space was increased by the same amount (i.e. 1.2294 in.) resulting in a head-space length of 3.9351. This was done to the other independent variables resulting in a starting point located (in the design six-space) in a direction away from the minimum previously found.

The option of answering "Yes" to DESAC's request for a starting point was used, and the calculated "poor" values for each variable were read-in. The program made a normal 18 iteration (101 function evaluations) search and converged to a good value for the sum of squares (FF = .001942). Another 100 function evaluations reduced the sum of squares to .001904, a very small improvement for double the computing time. The dimensions of the actuator obtained in tests A, B, and C are summarized in Table VI:

TABLE VI

Actuator		Test A	Test B	Test C
Cylinder diameter	CD	2.5	2.5	2.5
Piston-rod diameter	PRD	1.25	1.25	1.25
Piston vent-hole diameter	HD	0.1191	0.1094	0.1054
Head space length	HL	1.4763	1.3955	1.3328
Buffer length	BL	20.4019	20.3730	20.3628
Propellant charge	PWGR	10.615	10.696	10.152

It appears evident that all three designs are very close to each other, and that variations in manufactured dimensions are likely to be of the same order of magnitude as the differences between these three designs.

TEST D: PARTIAL REDESIGN OF AN EXISTING, FASTER ACTING VALVE

To investigate the behavior of DESAC under a different set of operating conditions, a partial redesign was made of the original four-cylinder valve described in Section 4 and illustrated in Fig. 5. The mass to be moved is slightly greater than that in the experimental valve (374 lb_m instead of 356.5 lb_m), but the actuation time is less than half that of the experimental valve (0.030 sec instead of 0.063 sec), and the final velocity is 200 ips instead of 300. This valve requires, therefore, a considerably more pronounced deceleration action.

To be able to re-use the major components of the four-cylinder valve (i.e. the body, cylinders and pistons), the option of by-passing the prototype design was utilized. The performance of the original four-cylinder valve was given as the required performance. The number of cylinders (4), and the cylinder and piston-rod diameters (3 in. and 1.6875 in.) corresponding to the existing valve were given to the program, as well as starting values for the four remaining independent variables: HD, HL, BL, and PWGR. Starting values for these four quantities were selected blindly, and proved to be very poor guesses (FF, the sum of the squares, was found to be 2.287, indicating a very poor approximation of the desired performance).

DESAC ran for 17 iterations (100 function evaluations) and arrived at a design that gave an actuation time of 0.0285 sec (0.030 desired), a final velocity of 210.7 ips (200 desired), and acceptable values for the maximum stress and pressures, while using 22.48 g of propellant in each actuator (instead of the 24 g originally used).

TELETYPE RECORDS

The designer - program interaction for all four test cases can be followed in Appendix VI, with designer's inputs marked by a suitable comment.

7. SUMMARY AND CONCLUSION

A computer subroutine STROKE has been written for the purpose of describing the action of a self-decelerating pyrotechnic actuator. It has been tested and found to reproduce experimental data of actuator performance with good accuracy. STROKE has been incorporated into an interactive computer program DESAC for the design of such actuators. DESAC has been tested and shown to operate as intended and to converge to consistent and efficient designs. DESAC may be used by a designer having only general actuator-design experience and a minimal understanding of the mathematics involved. No knowledge of thermodynamics or pyrotechnic gas generation is needed.

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APPENDIX I

A Four Parameter Equation For Calculating Gas Enthalpies

The enthalpy of a gas at a certain temperature T is calculated from the definition of specific heat capacity:

$$c_p = \frac{dh}{dT}$$

giving

$$h = \int c_p \, dT \qquad (1)$$

where c_p is the specific heat capacity at constant pressure.

To perform the intergration in Equation (1), an algebraic expression is needed giving c_p as a function of T. This expression is usually in the form of a polynomial in powers of T (sometimes these powers are negative or fractional). One of the better known is due to Mackay, Barnard and Ellenwood (Ref. 10), and the equations for c_p is:*

$$c_p = A + BT + CT^2 + DT^{-1/2} \qquad (2)$$

Integration of Equation (2) gives:

$$\begin{aligned} h &= \int A + BT + CT^2 + DT^{-1/2} \, dT \\ &= AT + \frac{1}{2} BT^2 + \frac{1}{3} CT^3 + 2DT^{1/2} + K \end{aligned} \qquad (3)$$

Equations (2) and (3) apply to narrow ranges of temperature. For example Ref. 10 gives, for air, two sets of coefficients for Equation (2):

a) from 400 to 1200 R $\quad A = 0.2405 \quad B = -1.186 \times 10^{-5}$
$\quad C = 20.1 \times 10^{-9} \quad D = D$

---

*The letters A, B, C and D are commonly used to denote the constants in such equations. Note, however that in the actuator analysis (Section 3) these constants are denoted by c_1, c_2, c_3 and c_4.

b) from 1200 to 4000 R $A = 0.2459$ $B = 3.22 \times 10^{-5}$
$C = 3.74 \times 10^{-9}$ $D = -0.833$

This dual equation system is awkward but usable when solving for enthalpy, given the temperature. It is much more complicated to solve for the temperature, given the enthalpy. Furthermore, gas temperatures over 5000 R were expected to occur, while Ref. 10 equations only extended to 4000 R.

The most recent enthalpy information available to the author was in the form of enthalpy tables (JANAF Thermochemical Tables, by the Dow Chemical Co., Midland, Michigan). It was decided to develop an independent equation to fit the JANAF data. Eleven uniformly spaced temperatures were selected (720 R to 7920 R at 720 R intervals) and enthalpy values for these temperatures were taken for each gas of interest in this study (i.e., nitrogen, carbon monozide, hydrogen, carbon dioxide, and steam). After trying several equation forms to fit this data in the least-squares sense, the following form was selected:

$$h = A + BT + C \ln T + D \ln^2 T \qquad (4)$$

that would fit the data over the total temperature range with a higher overall accuracy than the fit of Equation (3) to the same data, even though only four parameters are used in (4).

Table III compares the fit of both equations and the per cent error at six arbitrary points in the range of the data.

TABLE I.A

Comparisons of enthalpy[*] errors calculated by Equation (3) and (4) at six arbritrary temperatures, for the five propellant gases.

	720	1800	3060	4500	5760	7200
H_2 enthalpy per JANAF	1273	8899	18419	30326	41386	54571
enthalpy by Eq. (3)	1268	8872	18420	30276	41342	54572
per cent error	-0.394	-0.304	0.005	-0.165	-0.106	0.002
enthalpy by Eq. (4)	1263	8895	18401	30325	41402	54580
per cent error	-0.792	-0.045	-0.098	-0.003	+0.039	+0.016
H_2O enthalpy per JANAF	1495	11176	24817	42575	59177	78849
enthalpy by Eq. (3)	1473	11318	24901	42534	59231	79081
per cent error	-1.494	+1.271	+0.338	-0.096	+0.091	+0.294
enthalpy by Eq. (4)	1515	11135	24880	42577	59123	78839
per cent error	+1.338	-0.368	+0.254	+0.005	-0.091	-0.013
CO_2 enthalpy per JANAF	1724	14371	31617	52454	71127	92768
enthalpy by Eq. (3)	1711	14479	31661	52469	71178	92848
per cent error	-0.760	+0.752	+0.139	+0.029	+0.072	+0.086
enthalpy by Eq. (4)	1730	14375	31632	52444	71120	92773
per cent error	+0.348	+0.028	+0.047	-0.019	-0.010	+0.005
CO enthalpy per JANAF	1280	9329	19764	32276	43450	56369
enthalpy by Eq. (3)	1268	9448	19813	32274	43490	56456
per cent error	-0.946	+1.276	+0.248	-0.006	+0.092	+0.154
enthalpy by Eq. (4)	1288	9328	19784	32270	43438	56371
per cent error	+0.625	-0.011	+0.101	+0.019	-0.028	+0.004
N_2 enthalpy per JANAF	1278	9232	19544	31970	43090	55960
enthalpy by Eq. (3)	1266	9348	19587	31948	43112	56033
per cent error	-0.948	+1.256	+0.220	-0.069	+0.051	+0.130
enthalpy by Eq. (4)	1288	9227	19570	31962	43073	55961
per cent error	+0.782	-0.054	+0.133	-0.025	-0.039	+0.002

---

[*] In BTU/lb_m mole

TABLE I.B

Values of Constants in $h = A + BT + C \ln T + D \ln^2 T$, BTU/$lb_m$ mole

GAS	A	B	C	D
H_2	1.153E+5	1.152E+1	3.552E+4	-2.896E+3
H_2O	-1.156E+5	1.699E+1	3.829E+4	-3.398E+3
CO_2	1.172E+4	1.593E+1	-1.756E+3	-2.289E+2
CO	-5.761E+3	9.544E+0	2.223E+3	-3.338E+2
N_2	-1.084E+4	9.611E+0	3.825E+3	-4.609E+2

APPENDIX II

Determination of Six Gas Generator Constants

To calculate the performance of a given actuator by means of STROKE, six constants determining the functioning of the gas generator had to be evaluated. They were:

K_B, b_1, b_2	used in Equations 3-9 and 3-10 to calculate propellant burning rates.
B	the first virial coefficient in the gas equation of state, used in Equations 3-3a and 3-35 to calculate specific volumes or gas pressures.
K_f	the flow coefficient of discharge, used in Equation 3-11.
h	the effective heat of reaction of the propellant (the adiabatic heat of reaction reduced to account for the heat loss to the walls).

Three test firings of the PGG had been made, with propellant loadings of 34, 20 and 10 grams. All three were made with the PGG flow discharging into a 38 in.^{3} ullage volume, and gave the following seven data points:

34-gram charge:

1) Time to reach maximum generator pressure TPMAX = .00164 sec
2) Value of maximum generator pressure: PMAX = 28650 psia
3) Time to reach pressure equilibrium: TP34 = .00265 sec
4) Value of equilibrium pressure: PE34 = 6460 psia

20-gram charge:

5) Value of equilibrium pressure: PE20 = 3350 psia

10-gram charge:

6) Time to reach pressure equilibrium: TP10 = .0081 sec
7) Value of equilibrium pressure PE10 = 1532 psia

These seven data points were assumed to be functionally dependent on the six constants defined above. A simplified version of STROKE (obtained essentially by considering the mass to be moved to be infinite, the piston vent hole diameter to be zero, and the head volume to be 38 in.^{3}) was used to calculate the seven quantities corresponding to the seven experimental points. Program POWSQ was used to find those values of the six constants that would minimize the sum of the squares of the following seven functions:

$$\begin{aligned}
F(1) &= (\text{TPMAX} - .00164)/.00164 \\
F(2) &= (\text{PMAX} - 28650)/28650 \\
F(3) &= (\text{TP34} - .00265)/.00265 \\
F(4) &= (\text{PE34} - 6460)/6460 \\
F(5) &= (\text{PE20} - 3350)/3350 \\
F(6) &= (\text{TP10} - .0081)/.0081 \\
F(7) &= (\text{PE10} - 1532)/1532
\end{aligned}$$

This procedure gave the following values for the six constants:

$K_B = 3.9374$

$b_1 = 0.19079$

$b_2 = 0.043892$

$B = 0.13131$

$K_f = 0.0401636$

$h = 1241.58 \ BTU/lb_m$

The calculated values of the seven data points using the above results are compared to their experimental values in Table II.A.

TABLE II.A

Quantity	Experimental Value	Calculated Value	Per cent Error
TPMAX	0.00164	0.00195	18.9
PMAX	28650.00000	31180.000000	8.84
TP34	0.00265	0.002747	3.65
PE34	6460.00000	6469.000000	.138
PE20	3350.00000	3405.000000	1.63
TP10	0.0081	0.0080	1.17
PE10	1532.0000	1547.00000	1.03

The calculated total history of PGG pressure versus time is shown in Fig.II.A for all three loadings, with experimental values marked.

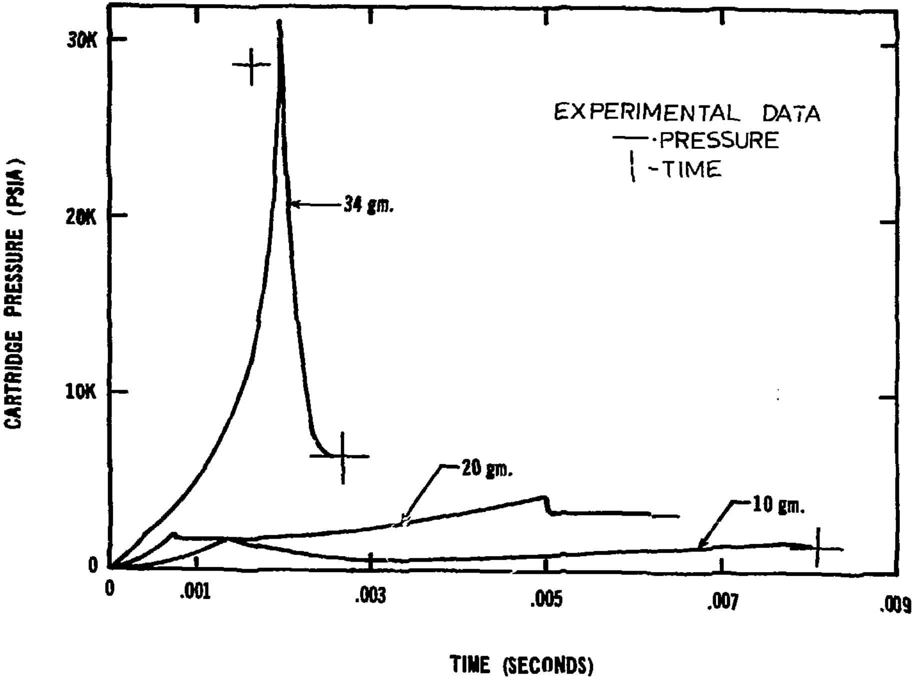

FIG. II.A CALCULATED GAS GENERATOR PRESSURE VERSUS TIME

APPENDIX III

Determination of a Realistic Starting Point

All solutions of nonlinear simultaneous equations are essentially trial-and-error solutions, and hence, require a starting point. In the case of mathematical models of real systems, this starting point must be a realistic point, i.e., one that will not give results contradictory to the basic limitations of the system being modeled (such as negative absolute temperatures or masses).

In the system being considered, desired performance is defined by specifying values for the following quantities:

t_t	total time of travel
V_f	final velocity at end of travel
S_r	maximum stress in piston-rod
P_c	maximum cylinder pressure

while moving a given mass W through a stroke S_t.

The starting point is defined when definite values are assigned to:

d_c	cylinder diameter
d_r	piston-rod diameter
W_p	propellant charge
L_H	length of head-volume
L_B	length of buffer-volume
d_h	vent-hole diameter
L_h	vent-hole length

To obtain an explicit (but approximate) solution for the above seven quantities, the following procedure was used for simplifying assumptions defining the actuator performance:

(1) Assume the piston moves with a constant acceleration A for an unknown acceleration time t_a, then decelerates at the same constant rate and arrives to the end of the stroke (S_t) at the desired total travel time t_t, with a final velocity V_f equal to the maximum velocity allowed. Application of the well-known constant acceleration equations for displacement and velocity, and considerable algebraic manipulation, gives the following quadratic equation in A:

$$t_t^2 A^2 + (2\ t_t V_f - 4\ S_t)\ A - V_f^2 = 0$$

This can be solved for A in terms of S_t, t_t and V_f:

$$A = \frac{4S_t - 2\ t_t V_f + \sqrt{(2\ t_t V_f - 4\ S_t)^2 + 4\ t_t^2 V_f^2}}{2\ t_t^2}$$

Knowing A, the acceleration time t_a can be found:

$$t_a = \frac{t_t + \frac{1}{2} V_f / A}{2}$$

and the force required to maintain the constant acceleration:

$$F = WA$$

(2) By making the assumption that the maximum gas pressure in the head cylinder was twice the average pressure, the values of d_c and d_r are then calculated:

$$d_c = \sqrt{\frac{2\ F}{\frac{\pi}{4} P_c}}$$

and

$$d_r = \sqrt{\frac{2\ F}{\frac{\pi}{4}\ S_r}}$$

(3) It can be shown that, for a mass M moving through a distance S in a time t under constant acceleration and deceleration, the kinetic energy at maximum velocity (i.e., energy input required) is independent of the relative magnitude of acceleration and deceleration, and of the final velocity, and is equal to:

$$KE = 2\ M\left(\frac{s}{t}\right)^2$$

Thus, the energy required for actuation is:

$$E = 2\ W\left(\frac{s_t}{t_t}\right)^2$$

Assuming a 50% efficiency in transforming propellant chemical energy into kinetic energy of the mass, the propellant charge required is:

$$W_p = \frac{2\ E}{778.3\ h} = \frac{E}{389.15\ h}$$

where h is the effective heating value of the propellant, in BTU/lb.

(4) After calculating propellant gas pressures for many loadings and ullage volumes (using the program developed in Appendix II), a 4-parameter expression was developed to fit this data in the least-squares sense. This expression (giving the final pressure P reached in a given volume V by a given propellant charge W_p), when solved for the volume, gives:

$$V = \frac{5.4254 + 1.3258 \ln W_p - \ln P_c}{.019489 + .004406 \ln W_p}$$

where P_c is the allowed (and desired) maximum cylinder pressure.

Substituting P_c and W_p into this equation gives V, the head-volume that will give the maximum desirable cylinder pressure with the given propellant loading. With the cylinder diameter already known, the length of the head volume can be readily found:

$$L_H = \frac{V}{\frac{\pi}{4} d_c^{\,2}}$$

With no more information readily available, a buffer length at the end of the stroke equal to the head-volume length was assumed:

$$L_B = L_H + S_t$$

(5) The vent-hole diameter is calculated by assuming an orifice (instead of a Fanno) flow. The ASME orifice flow formula gives:

$$\dot{w} = .525\, d_h^{\,2}\, K\, Y_1 \sqrt{\rho_1\, \Delta p}$$

where $\dot{w}$ is the gas flow rate, d_h is the vent-hole diameter in inches, Δp is the pressure differential across the orifice, in psi, and ρ_1 the upstream density in lb_m/ft^3, K is the flow coefficient (including the velocity of approach factor), and Y_1 is the compressibility correction factor.

Squaring and transposing:

$$d_h^{\,4} = \frac{\dot{w}^2}{(.525\, K\, Y_1)^2\, \rho_1}$$

Assuming an average value of .85 for (KY_1) and solving for d_h gives:

$$d_h = \sqrt[4]{\frac{\dot{w}^2}{.19914\, \rho_1\, \Delta p}} \simeq \sqrt[4]{\frac{5\, \dot{w}^2}{\rho_1\, \Delta p}}$$

It is now required to estimate $\dot{w}$, ρ_1 and Δp.

a) Assuming half the propellant gas flowed through the vent during t_a, the acceleration time, and the initial flow as double the average flow, the mass flow rate for the initial conditions is:

$$\dot{w} = \frac{W_p}{t_a}$$

b) The average temperature of the head-volume gas is estimated as follows:

The maximum temperature of the propellant gas is the isochoric flame temperature, which is approximately 5000 R. After the gas flows into the head-volume and comes to a stop, its temperature may be raised by a factor equal to γ , its specific heat ratio. Thus, the gas temperature in the head-volume may be as low as ambient (520 R) and as high as 5000 γ . An average value can be taken as:

$$T_{ave} = \frac{5000\,\gamma + 520}{2}$$

For this approximate calculation, the perfect gas equation of state can be used for finding ρ_1 the gas density at maximum head-volume pressure P_c :

$$\rho_1 = \frac{P_c\,V}{R\,T_{ave}}$$

(c) Flow can be assumed to be choked, and the pressure differential Δp is then:

$$\Delta p = P_c - P_c\left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma}{\gamma - 1}}$$

(6) To ensure that pipe flow is well established, a vent length equal to fifteen diameters is assumed for the prototype design:

$$L_h = 15\ d_h$$

This concludes the determination of the seven quantities specifying a realistic starting point for the design search.

APPENDIX IV

Listing of Actuator Design Program DESAC

```
      PROGRAM DESAC(TAPE59,DESOUT,TAPE3=DESOUT)
C
C
C     THIS INTERACTIVE PROGRAM PROVIDES THE DIMENSIONS (IN INCHES) AND
C     THE PROPELLANT CHARGE(IN GRAM) FOR A SELF-STOPPING GAS-POWERED
C     ACTUATOR, UTILIZING THE CTL-10359 HIGH PRESSURE CARTRIDGE FOR GAS
C     GENERATION. TELETYPE INPUT REQUEST ASKS THE FOLLOWING:
C
C            WLB      MASS TO BE MOVED (POUNDS)
C            STR      PHYSICAL LENGTH OF STROKE (INCH)
C            TR       TIME REQUIRED FOR STROKE (SECOND)
C            VFAL     FINAL VELOCITY ALLOWED (IPS)
C            STAL     MAXIMUM STRESS ALLOWED IN PISTON ROD (PSI)
C            GPAL     MAXIMUM PRESSURE ALLOWED IN GAS GENERATOR (PSIA)
C            CPAL     MAXIMUM PRESSURE ALLOWED IN ACTUATOR CYLINDER(PSIA)
C
C     AFTER A PRELIMINARY DESIGN RUN, THE PROGRAM WILL REPORT RESULTS
C     BY TELETYPE AND ASK FOR DESIGNER.S DECISIONS ON PREFERRED SIZES
C     AND NUMBER OF COMPONENTS BEFORE MAKING A FINAL DESIGN.
C
C     ALL IMPORTANT DATA ARE RECORDED IN DISK FILE DESOUT, WHICH CAN
C     BE ISSUED BY ALLOUT TO HSP OR RJET TO SUPPLEMENT THE INTERACTIVE
C     TELETYPE PAGE.
C
C
      COMMON /GEOM/ CD,PRD,HD,HL,BL,CEV,THET,PHI,PT,WLB,VHA,ELOD,STR
      COMMON /SPECS/ TVMAX,TITLE(10),REQU(7),NOS(3),NC,NOGC,NH
      DIMENSION X(6),F(7),XS(6)
      CALL DEVICE (6HCREATE,6HDESOUT,20000,NF)
      IF (NF.NE.0) PAUSE
      IN=IT=59 $NAG=0
      RSVP=3HNO
      WRITE (59,60)
      WRITE (3,60)
C
C     IDENTIFY DESIGN PROBLEM
      READ (59,65) TITLE
      WRITE (3,70) TITLE
      WRITE (59,75)
      WRITE (3,75)
C
C     OBTAIN NUMBERS DESCRIBING REQUIRED PERFORMANCE
      CALL DATA (REQU,7,IN,IT)
      WRITE (3,80) REQU
      WLB=REQU(1)
      STR=REQU(2)
      TR=REQU(3)
      VFAL=REQU(4)
      STAL=REQU(5)
      CPAL=REQU(7)
      WRITE (59,40)
      WRITE (3,40)
C
C     CHECK IF THIS IS A MODIFICATION OF AN EXISTING MODEL
      READ (59,105) RESP
      WRITE (3,110) RESP
      IF (RESP.EQ.3HYES) GO TO 30
C
C     MAKE LINEARIZED AND SIMPLIFIED FIRST MODEL
      CALL START (X)
```

```
      WRITE (3,85)
      CALL PROTOT (F,X)
C
C     RECORD PRELIMINARY DESIGN RESULTS FOR POSSIBLE RE-USE
      DO 5 I=1,6
 5    XS(I)=X(I)
 10   CALL HAGGLE (F,X,NAG)
 15   WRITE (3,85)
      CALL FINDES (F,X)
      WRITE (3,90)
      CALL REPORT (F,X)
      WRITE (59,100)

      WRITE (3,95)
      WRITE (3,100)
      READ (59,105) RSVP
      WRITE (3,110) RSVP
      IF (RSVP.EQ.3HYES) GO TO 25
C
C     RESET VALUES OF X TO STARTING POINT FOR NEW SEARCH
      DO 20 I=1,6
 20   X(I)=XS(I)
      GO TO 10
 25   WRITE (3,115)
      CALL EXIT
 30   WRITE (59,45)
      WRITE (3,45)
      CALL DATA (F,7,IN,IT)
      WRITE (3,80) F
      PT=F(7)
      DO 35 I=1,6
      X(I)=F(I)
 35   CONTINUE
      X(3)=X(3)-REQU(2)
      WRITE (59,50)
      WRITE (3,50)
      CALL DATA (NOS,3,IN,IT)
      WRITE (3,55) NOS
      NC=NOS(1) $NOGC=NOS(2) $NH=NOS(3)
      GO TO 15
C
C
 40   FORMAT (/47HDO YOU HAVE A REASONABLE FIRST GUESS≤ YES OR NO)
 45   FORMAT (38HGIVE VALUES OF HD,HL,BL,PWBR,CD,PRD,PT)
 50   FORMAT (26HGIVE VALUES FOR NC,NOGC,NH)
 55   FORMAT (21H(TELETYPE INPUT) --> ,3I5)
 60   FORMAT (///43HGIVE TITLE FOR THIS ACTUATOR DESIGN PROBLEM/)
 65   FORMAT (10A7)
 70   FORMAT (20H(TELETYPE INPUT) -->,/,X,10A7)
 75   FORMAT (/46HGIVE VALUES FOR WLB,STR,TR,VFAL,STAL,GPAL,CPAL)
 80   FORMAT (23H(TELETYPE INPUT)  -->  /7E10.3)
 85   FORMAT (//55HFOLLOWING IS THE POWSQ OUTPUT GIVING THE SEARCH HISTO
     1RY/)
 90   FORMAT (//,10X,35HREPORT ON THE FINAL DESIGN FOLLOWS:/)
 95   FORMAT (//46HPROGRAM IS AGAIN INTERACTIVE WITH THE TELETYPE/)
 100  FORMAT (//68HIS THE ABOVE DESIGN SATISFACTORY≤ TYPE YES TO EXIT, N
     1O  TO TRY AGAIN)
 105  FORMAT (A3)
 110  FORMAT (21H(TELETYPE INPUT) --> ,A3)
 115  FORMAT (//8HALL DONE)
      END
```

```
      SUBROUTINE CALFUN (M,N,F,X)
C
C     THIS SUBROUTINE IS CALLED BY POWSQ TO CALCULATE THE VALUES OF
C     F(I),I=1,7 EXPRESSING THE DEVIATION OF A PARTICULAR DESIGN FROM
C     THE DESIRED PERFORMANCE. IT CALLS SUBROUTINE STROKE TO FIND
C     THIS PERFORMANCE AND KEEPS TRACK OF THE PROPELLANT LOADING, ADDING
C     GENERATORS AS NECESSARY TO CONTAIN THE REQUIRED AMOUNT OF PROPEL-
C     LANT, OR ALLOWING USE OF A NON-OPTIMUM HEAD VOLUME TO AVOID OVER-
C     DRIVING THE PISTON BY THE GREATER-THAN-OPTIMUM 10 GRAM LOAD.
C
      DIMENSION X(6),F(7)
      COMMON /GEOM/ CD,PRD,HD,HL,BL,CFV,THET,PHI,PT,WLB,VHA,ELOD,STR
      COMMON /PERF/ TAC,HPMX,BPMX,GPMX,STMX,VFIN
      COMMON /SPECS/ TVMAX,TITLE(10),REQU(7),NDS(3),NC,NOGC,NH
      HD=ABS(X(1))
      HL=ABS(X(2))
      BL=ABS(X(3))+REQU(2)
      IF (N.LE.4) GO TO 10
      CD=ABS(X(4))
      PRD=ABS(X(5))
      PWGR=ABS(X(6))
      PWTOT=PWGR*NOGC
      NOGC=IFIX(PWTOT/34.)+1
      PWGR=PWTOT/NOGC
      IF (PWGR.LT.10.) PWGR=10.
 5    CALL STROKE (PWGR)
      F(1)=(PWGR-10.)*.002205*NOGC*NC
      F(2)=(VFIN-REQU(4))/REQU(4)
      F(3)=(STMX-REQU(5))/REQU(5)
      F(4)=(TAC-REQU(3))/REQU(3)
C
C     IF PWGR IS HELD AT 10 GRAM (I.E. MINIMUM CHARGE), HPMX IS ALLOWED
C     TO FLOAT TO REDUCE THERMODYNAMIC EFFICIENCY AS NEEDED, SO F(5)=0.
      F(5)=0.
      IF (PWGR.GT.10.00001) F(5)=(HPMX-REQU(7))/REQU(7)
C
C     IT IS ALWAYS DESIRABLE TO KEEP BPMAX AT ALLOWABLE PRESSURE.
      F(6)=(BPMX-REQU(7))/REQU(7)
C
C     AS LONG AS GENERATOR PRESSURE IS SAFELY BELOW GPAL, F(7)=0.
      F(7)=0.
      IF (GPMX.GT.REQU(6)) F(7)=(GPMX-REQU(6))/REQU(6)
C
C     IF BOTH TAC AND VFIN ARE NEGATIVE, PROBLEM IS NOT CONVERGING.
      IF (TAC.LT.0.AND.VFIN.LT.0) PAUSE
C
C     IF VFIN IS NEGATIVE, IT IS THE DISTANCE AT WHICH PISTON STOPPED
C     AT  MID STROKE, WITH A NEGATIVE SIGN. PERFORMANCE IS DEFINITELY
C     IN THE WRONG MODE, HENCE F(2) IS GIVEN A PENALTY FUNCTION.
      IF (VFIN.LT.0.) F(2)=REQU(4)*(REQU(2)+VFIN)+1.
      RETURN
 10   PWGR=ABS(X(4))
      CD=ABS(X(5))
      PRD=ABS(X(6))
      IF (PWGR.GT.34.1) PWGR=34.1
      IF (PWGR.LT.10.) PWGR=10.
      GO TO 5
      END
```

```
      SUBROUTINE FANNOF (P1,P2,T1,T2,EMUP,EMDN,FF,EMDOT,FORCE)
C
C     THIS FANNO SOLVER IS FOR FASTEST SOLUTION FROM A GOOD GUESS
C
      COMMON /GEOM/ CD,PRD,HD,HL,RL,CEV,THET,PHI,PT,WLB,VHA,ELOD,STR
      COMMON /GASP/ R,SB,BK,BC,BB,A,B,C,D,PHV
      COMMON /PARS/ PI,PIF,XJ,PA,TA,GC,SF,CUF
      COMMON /PPTT/ PSUP,PSDN,TSUP,TSDN
C
C     FIND DIRECTION OF FLOW
      IF (P1.LT.P2) GO TO 5
      PZ=P1
      TZ=T1
      PS=P2
      GO TO 10
 5    PZ=P2
      TZ=T2
      PS=P1
C     FIND SPECIFIC VOLUME OF GAS AT RESERVOIR CONDITIONS
 10   DISC=P*TZ*(R*TZ+576.*PZ*SB)
      SVA=(R*TZ+SQRT(DISC))/(288.*PZ)
      GAMAZ=GAMGAS(TZ)
      GAM1=GAMGAS(TSUP)
      GAM2=GAMGAS(TSDN)
      GAMIS=.5*(GAMAZ+GAM1)
      G=.5*(GAM1+GAM2)
      GM=G-1.
      GP=G+1.
C
C     CHECK FOR VERY LOW PRESSURE DIFFERENTIAL
      IF (ABS(PZ/PS-1.).LT..01) GO TO 20
C
C     RECORD PRESENT VALUES TO EVALUATE NEXT LOOP IMPROVEMENT
 15   EMUPO=EMUP
      EMDNO=EMDN
      TSUPO=TSUP
      TSDNO=TSDN
      EMDO=EMDOT
      FO=FF
      GAR=(1.+.5*GM*EMUP*EMUP)/(1.+.5*GM*EMDN*EMDN)
C
C     IMPROVE EMDN IF FLOW IS NOT CHOKED
      EMDN=EMUP*(PZ/PS)*SQRT(GAR)*(1.+.5*(GAMIS-1.)*EMUP*EMUP)**(GAMIS/(
     11.-GAMIS))
C
C     IF EMDN IS FOUND TO BE GT.1.0, FLOW WAS REAALY CHOKED
      IF (EMDN.GT.1.) EMDN=1.
C

C     FIND EMUP FOR EITHER CASE
      GARB=GAR*EMDN*EMDN/(EMUP*EMUP)
      EMUP=1./SQRT(G*FF*ELOD+1./(EMDN*EMDN)+.5*GP*ALOG(GARB))
C
C     IF EMUP AND EMDN ARE FAR FROM CONVERGED, IGNORE OTHER FACTORS
      IF (ABS(EMUP-EMUPO).GT..05.OR.ABS(EMDN-EMDNO).GT..05) GO TO 15
C
C     FIND TSUP AND TSDN FOR BETTER GAMAS AND VISCOSITIES
      TSUP=TZ/(1.+.5*(GAMIS-1.)*EMUP*EMUP)
      TSDN=TSUP*GAR
      GAM1=GAMGAS(TSUP)
      GAM2=GAMGAS(TSDN)
```

```
      GAMIS=.5*(GAMAZ+GAM1)
      G=.5*(GAM1+GAM2)
      GM=G-1.
      GP=G+1.
      IF (ABS(TSUP-TSUPO).GT..5.OR.ABS(TSDN-TSDNO).GT..5) GO TO 15
      CALL MUCOMP (TSUP,UPMU)
      CALL MUCOMP (TSDN,DNMU)
      AVMU=.5*(UPMU+DNMU)
C
C     FIND EMDOT FOR NEW CONDITIONS
      SVUP=SVA*(1.+.5*(GAMIS-1.)*EMUP*EMUP)**(1./(GAMIS-1.))
      VGUP=EMUP*SQRT(GC*GAMIS*R*TSUP)
      EMDOT=VHA*VGUP/(SF*SVUP)
C
C     FIND NEW REYNOLDS NO. AND FRICTION FACTOR
      REN=4.*EMDOT/(AVMU*PI*HD)
      FF=.0055*(1.+(36./HD+1.E6/REN)**(1./3.))
C
C     EVALUATE THE IMPROVEMENT ON IMPORTANT PARAMETERS
      IF (ABS(EMUP-EMUPO).GT..001.OR.ABS(EMDN-EMDNO).GT..001) GO TO 15
      IF (ABS(TSUP-TSUPO).GT..1.OR.ABS(TSDN-TSDNO).GT..1) GO TO 15
      IF (ABS(EMDO-EMDOT).GT..001.OR.ABS(FF-FO).GT..0001) GO TO 15
C
C     FIND DRAG FORCE ON WALL OF TUBE, POSITIVE IN DIRECTION OF FLOW
      PSUP=PZ/((1.+.5*(GAMIS-1.)*EMUP*EMUP)**(GAMIS/(GAMIS-1.)))
      PSDN=PSUP*EMUP*SQRT(GAR)/EMDN
      FORCE=VHA*(PSUP*(1.+G*EMUP*EMUP)-PSDN*(1.+G*EMDN*EMDN))
      RETURN
C
C     FOR VERY LOW PRESSURE DIFFERENCES USE BERNOULLI EQUATION
 20   VGUP=SQRT(2.*GC*SVA*(PZ-PS))
      EMDOT=VHA*VGUP/(SF*SVA)
      FORCE=0.
      RETURN
      END


      SUBROUTINE FINDES (F,X)
C
C     THIS SUBROUTINE STARTS POWSQ ON A FINAL DESIGN SEARCH ONCE THE
C     NUMBER OF COMPONENTS, AND THE CYLINDER AND PISTON-ROD DIAMETERS
C     HAVE BEEN SELECTED.
C
      COMMON /PERF/ TAC,HPMX,RPMX,GPMX,STMX,VFIN
      COMMON /SPECS/ TVMAX,TITLE(10),REQU(7),NOS(3),NC,NOGC,NH
      COMMON /PARS/ PI,PIF,XJ,PA,TA,GC,SF,CUF
      COMMON /GASP/ R,SR,BK,BC,BB,A,B,C,D,PHV
      DIMENSION X(6),E(6),F(7)
      M=7
      N=4
      DO 5 I=1,4
 5    E(I)=1.E-4
      ESCALE=250.
      IPRINT=1
      MAXFUN=100
      IF (ABS(X(4)).LT.10.000001) N=3
      CALL POWSQ (M,N,F,X,E,ESCALE,IPRINT,MAXFUN)
      CALL EMPTY (3)
      RETURN
      END
```

```
      SUBROUTINE HAGGLE (F,X,NAG)
C
C     THIS SUBROUTINE REPORTS THE RESULTS OF THE PRELIMINARY DESIGN AND
C     RECEIVES DESIGNER.S INSTRUCTIONS ON PREFERRED (STANDARD) CYLINDER
C     AND PISTON-ROD DIAMETERS, AND NUMBER OF COMPONENTS.
C
      DIMENSION F(7),X(6),DIAM(2),NI(2)
      COMMON /PERF/ TAC,HPMX,RPMX,GPMX,STMX,VFIN
      COMMON /GASP/ R,SR,RK,HC,BH,A,B,C,D,PHV
      COMMON /PARS/ PI,PIF,XJ,PA,TA,GC,SF,CUF
      COMMON /SPECS/ TVMAX,TITLE(10),REQU(7),NOS(3),NC,NOGC,NH
      COMMON /GEOM/ CD,PRD,HD,HL,BL,CEV,THET,PHI,PT,WLB,VHA,FLOD,STP
      IN=IT=59
      WLB=REQU(1)
      STP=REQU(2)
      TR=REQU(3)
      VFAL=REQU(4)
      STAL=REQU(5)
      CPAL=REQU(7)
      NAG=NAG+1
      IF (NAG.EQ.1) NG=NOGC
      IF (NAG.GT.1) GO TO 20
      WRITE (59,65) NOGC,TAC,VFIN,STMX,GPMX,HPMX,RPMX
      WRITE (3,65) NOGC,TAC,VFIN,STMX,GPMX,HPMX,RPMX
 5    HD=ABS(X(1))
      HL=ABS(X(2))
      BL=ABS(X(3))+STP
      CD=ABS(X(4))
      PRD=ABS(K(5))
      PWGR=ABS(X(6))
      HVOL=HL*PIF*CD*CD
      BVOL=BL*PIF*(CD*CD-PRD*PRD)
      WRITE (59,70) PWGR,HD,HL,BL,CD,PRD
      WRITE (3,70) PWGR,HD,HL,BL,CD,PRD
      WRITE (59,75)
      WRITE (3,75)
      CALL PROPOSE (PWGR,X,NOGC)
      WRITE (3,80)
      WRITE (59,40)
      WRITE (3,40)
      READ (59,115) RSVP
      WRITE (3,120) RSVP
      IF (RSVP.EQ.3HNO ) GO TO 30
      WRITE (59,85)
      WRITE (3,85)
      CALL DATA (NI,2,IN,IT)
      PWGR=PWGR*NOGC/(NI(1)*NI(2))
      NC=NI(1)
      NOGC=NI(2)
      WRITE (3,105) NI
      WRITE (59,90)
      WRITE (3,90)
      CALL DATA (DIAM,2,IN,IT)
      WRITE (3,95) DIAM
      CD=X(5)=DIAM(1)
      PRD=X(6)=DIAM(2)
      ANC=.5*(DIAM(1)-DIAM(2))
      IF (PWGR.LE.10.) GO TO 25
      X(6)=PWGR
      HL=HVOL/(PIF*CD*CD)
```

```
      X(2)=HL
      BL=BVOL/(PIF*(CD*CD-PRD*PRD))
      X(3)=BL*STR
 10   HD=HD/SQRT(FLOAT(NC*NH))
      X(1)=HD
 15   WRITE (59,100) ANC,HD
      WRITE (3,100) ANC,HD
      CALL DATA (DIAM,1,IN,IT)
      NH=IFIX(HD*HD/(DIAM(1)*DIAM(1)))+1
      HD=HD/SQRT(FLOAT(NH))
      WRITE (3,95) DIAM(1)
      WRITE (59,110) NH,HD
      WRITE (3,110) NH,HD
      PT=15.*HD
      WRITE (59,125) PT
      WRITE (3,125) PT
      CALL DATA (DIAM,1,IN,IT)
      PT=DIAM(1)
      WRITE (3,95) PT
      ELOD=PT/HD
      WRITE (59,45) ELOD
      WRITE (3,45) ELOD
      READ (59,115) RSVP
      WRITE (3,120) RSVP
      IF (RSVP.EQ.3HNO ) GO TO 15
      RETURN
 20   NOGC=NG
      WRITE (59,130) NAG,NOGC
      WRITE (3,130) NAG,NOGC
      GO TO 5
 25   PWGR=10.
      X(4)=10.
      X(2)=0.1667*DIAM(1)
      X(3)=X(2)
      GO TO 10
 30   WRITE (59,50)
      WRITE (3,50)
      CALL DATA (NOS,3,IN,IT)
      NC=NOS(1)
      NOGC=NOS(2)
      NH=NOS(3)
      WRITE (3,105) NOS
      WRITE (59,55)
      WRITE (3,55)
      CALL DATA (F,7,IN,IT)
      WRITE (3,60) F
      PT=F(7)
      DO 35 I=1,6
 35   X(I)=F(I)
      CALL EMPTY (3)
      RETURN
C
C
 40   FORMAT (//49HIS ONE OF THE ABOVE PROPOSE ACCEPTABLE< YES OR NO)
 45   FORMAT (/49HYOUR CHOICE OF VENT LENGTH GIVES AN L/D RATIO OF ,F5.1
     1,10H OK OR NO≤)
 50   FORMAT (62HSPECIFY YOUR VARIATION FOR THE FINAL DESIGN SEARCH: NC,
     1NOGC,NH)
 55   FORMAT (44HGIVE YOUR VALUES FOR HD,HL,BL,PWGR,CD,PRD,PT)
 60   FORMAT (22H(TELETYPE INPUT)  --> ,/,7F10.3)
```

```
 65   FORMAT (3/,26HFIRST TRY:       1 CYLINDER,,I2,26H GAS GENERATORS A 1
     1 VENT: ,3/14H    PERFORMANCE/21HTIME FOR FULL STROKE ,E10.3,22H SEC
     2.    FINAL VELOCITY,E11.3,4H IPS/14HMAX.ROD STRESS,7X,E10.3,22H PSI
     3     MAX.GEN.PRESS.,E11.3,5H PSIA/21HMAX. HEAD CYL. PRESS.,E10.3,23
     4H PSIA    MAX. BUFFER PR.,E10.3,5H PSIA/)
 70   FORMAT (/18H   ACTUATOR SPECS:/21HWEIGHT OF PROPELLANT ,F9.4,25H G
     1RAM    VENT-HOLE DIAM.   ,F7.4,5H INCH/14HHEAD CLEARANCE,7X,F9.4,25H
     2 INCH    BUFFER LENGTH     ,F7.4,5H INCH/21HCYLINDER DIAMETER     ,F9
     3.4,25H INCH    PISTON-ROD DIA.   ,F7.4,5H INCH)
 75   FORMAT (//,18HOPTIONS AVAILABLE:/68HCYLINDERS GEN./CYL. TOTAL GEN.
     1 CHARGE(GRAM)/GEN. CYL.DIA. P.ROD DIA./)
 80   FORMAT (///,10X,50HRECORD OF INTERACTIVE COMMUNICATIONS WITH TELET
     1YPE/)
 85   FORMAT (/46HSELECT OPTION - TYPE NO. OF CYL. AND GEN./CYL.)
 90   FORMAT (/48HTYPE PREFERRED CYLINDER AND PISTON-ROD DIAMETERS)
 95   FORMAT (21H(TELETYPE INPUT) --> ,2F10.5)
100   FORMAT (/33HTHERE IS AN ANNULAR CLEARANCE OF ,F5.3,24H INCH (VENT-
     1HOLE DIAM.= ,F5.3,1H)/36HTYPE MAX. ACCEPTABLE VENT-HOLE DIAM.)
105   FORMAT (22H(TELETYPE INPUT)  --> ,3I5)
110   FORMAT (/14HTHERE WILL BE ,I2,34H VENT-HOLES PER PISTON, OF APPROX
     1.,F5.3,11H INCH DIAM.;EOKORNO)
115   FORMAT (A3)
120   FORMAT (22H(TELETYPE INPUT)  --> ,A3)
125   FORMAT (/44HMIN. VENT LENGTH (I.E. PISTON THICKNESS) IS ,F6.3,6H I
     1NCH.,/,32HTYPE PREFERRED VENT-HOLE LENGTH.)
130   FORMAT (//,I2,25H -TH TRY WITH 1 CYLINDER,,I2,29H GAS GENERATORS A
     1ND    1 VENT:/)
      END


      SUBROUTINE INTERP (Y1,Y2,Y3,X3,DX,YMAX,N)
C
C     THIS SUBROUTINE FITS A PARABOLA THROUGH THREE DATA POINTS(Y1,Y2,
C     Y3) AT EQUAL INTERVALS DX, THEN FINDS THE VALUE OF THE MAXIMUM ON
C     THAT PARABOLA. N IS A SENTINEL TO INDICATE THE ROUTINE HAS BEEN
C     CALLED.
C
      DIMENSION Y(3),A(3,3),X(3),B(9),R(3),W(3),V(3)
      COMMON /MLRUNIT/ OUB
      OUB=0
      Y(1)=Y3
      Y(2)=Y2
      Y(3)=Y1
      DO 5 I=1,3
      A(I,3)=1.
      A(I,2)=X3-(I-1)*DX
      A(I,1)=A(I,2)*A(I,2)
 5    CONTINUE
      IM=M=N=3
      CALL MLR (IM,M,N,A,Y,X,B,R,W,V)
      YMAX=X(3)-X(2)*X(2)/(4.*X(1))
      N=1
      RETURN
      END
```

```
      SUBROUTINE MUCOMP (T,MUM)
C
C     THIS SUBROUTINE GETS THE VISCOSITIES OF THE 5 PROPELLANT GASES
C     THE MIXTURE COMPOSITION IS THE ONE GIVEN TO V.K. BY LOCKHEED FOR
C     THEIR RIFLE-POWDER GAS GENERATOR CTL-10359 LOADED WITH 32 GRAMS
C     OF IMR-4227 POWDER, DISCHARGED INTO AN ULLAGE VOLUME OF 38.5 IN.3
C                             C O M P O S I T I O N
C               SUBSTANCE     MOLE-PER-CENT      MOL. WT.
C     1           C-O2            43.988           44.011
C     2           CO               4.415           28.011
C     3           H2-O             3.856           18.016
C     4           H2              35.032            2.016
C     5           N2              12.709           28.016
C
C     VISCOSITIES OF INDIVIDUAL COMPONENTS ARE CALCULATED BY THE SEMI -
C     EMPIRICAL FORMULA DUE TO SUTHERLAND  MU=C1*T**(3/2)/(T+C2)
C     WITH CONSTANTS FOR EACH GAS INSERTED IN THE PROGRAM EQUATIONS
C
      REAL MUM
      DIMENSION U(5),X(5),WM(5)
      DATA X/.43988,.04415,.03856,.35032,.12709/
      DATA WM/44.011,28.011,18.016,2.016,28.016/
      P=T**(3./2.)
      U(1)=2.42E-8*P/(T+420.)
      U(2)=2.18E-8*P/(T+196.)
      U(3)=2.85E-8*P/(T+1185.)
      U(4)=1.01E-8*P/(T+127.)
      U(5)=2.16E-8*P/(T+184.)
      CALL MUMIX (U,X,WM,MUM)
      RETURN
      END

      SUBROUTINE MUMIX (MU,MF,MW,XMU)
C
C     THIS SUBROUTINE, DUE TO F.MORRISON, CALCULATES THE VISCOSITY
C     OF A GAS MIXTURE GIVEN THE COMPOSITION, AND THE VISCOSITIES AND
C     THE MOLECULAR WEIGHTS OF THE COMPONENTS. THE METHOD IS DUE TO
C     C.R.WILKE,(J.CHEM.PHYS. 18,517-519).
C
      REAL MU,MF,MW
      DIMENSION MU(5),MF(5),MW(5)
      XMU=0.
      DO 10 I=1,5
      DENOM=0.
      DO 5 J=1,5
      RB=1.+(SQRT(MU(I)/MU(J)))*(MW(J)/MW(I))**.25
      SB=(8.*(1.+MW(I)/MW(J)))
      DENOM=DENOM+MF(J)*RB*RB/SQRT(SB)
 5    CONTINUE
 10   XMU=XMU+MF(I)*MU(I)/DENOM
      RETURN
      END
```

```
      SUBROUTINE POWSQ (M,N,F,X,E,ESCALE,IPRINT,MAXFUN)
C
C
C     POWSQ MINIMIZES A SUM OF SQUARES OF NONLINEAR FUNCTIONS
C
C     M IS THE NUMBER OF FUNCTIONS IN SAID SUM
C     NOTE   M MUST BE GREATER THAN OR EQUAL TO N
C
C     N IS THE NUMBER OF INDEPENDENT VARIABLES
C     NOTE   N MUST BE GREATER THAN OR EQUAL TO 2
C
C     F IS A ONE DIMENSIONAL ARRAY OF LENGTH M CONTAIING FUNCTION
C        VALUES
C
C     X IS A ONE DIMENSIONAL ARRAY OF LENGTH N CONTAIING VALUES OF
C        THE INDEPENDENT VARIABLES
C        THE INDEPENDENT VARIABLES AND SHOULD BE SET TO A STARTING
C        POINT FOR THE SEARCH
C
C     E IS A ONE DIMENSIONAL ARRAY OF LENGHT N CONTAING ABSOLUTE
C        ACCURACY LIMITS FOR THE X(I).  CONVERGENCE WILL BE ASSUMED WHEN
C        X(I) HAS BEEN FOUND TO ACCURACY E(I) FOR ALL I
C
C     ESCALE LIMITS THE STEP SIZE OF THE SEARCH. NORMALLY X(I) WILL
C        NOT BE CHANGED BY MORE THAN ESCALE*E(I) IN A SINGLE STEP
C
C     IPRINT CAUSES THE VARIABLES AND FUNCTION VALUES TO BE PRINTED
C        OUT AFTER EVERY IPRINT ITERATIONS.  SET IPRINT TO ZERO FOR
C        NO PRINTOUT
C
C     MAXFUN LIMITS THE MAXIMUM NUMBER OF CALLS TO CALFUN
C
C     ON EXIT FROM THE ROUTINE.THE ELEMENTS OF F AND X WILL BE SET TO
C        THE BEST CALCULATED VALUES.  IF THESE ARE NOT THE DESIRED
C        MINIMUM VALUES AN APPROPRIATE MESSAGE WILL BE PRINTED OUT
C
C     THE COMMON BLOCK VD02ACM CONTAINS WORKING STORAGE FOR VD02A IN W
C        THE ARRAY W MUST BE OF LENGTH (N+(M+3*N/2)*(N+1))
C
C     THE USER MUST SUPPLY SUBROUTINE CALFUN(M,N,F,X).  THIS ROUTINE
C        MUST SET F(I) TO THE VALUE OF THE APPROPRIATE FUNCTION
C        AT THE POINT X FOR ALL I,1.LE.I.LE.M
C
C
      DIMENSION F(1),X(1),E(1)
      INTEGER UN
      COMMON / POWSQCM / W(1000)
      UN=3
      MPLUSN=M+N
      KST=N+MPLUSN
      NPLUS=N+1
      KINV=NPLUS*(MPLUSN+1)
      KSTORE=KINV-MPLUSN-1
      CALL CALFUN (M,N,F,X)
C
C     ALARM FOR CALFUN PROBLEMS
      IF (M.LT.0) RETURN
      NN=N+N
      K=NN
      DO 5 I=1,M
```

```
      K=K+1
      W(K)=F(I)
  5   CONTINUE
      IINV=2
      K=KST
      I=1
 10   X(I)=X(I)+E(I)
      CALL CALFUN (M,N,F,X)
C
C     ALARM FOR CALFUN PROBLEMS
      IF (M.LT.0) RETURN
      X(I)=X(I)-E(I)
      DO 15 J=1,N
      K=K+1
      W(K)=0.
      W(J)=0.
 15   CONTINUE
      SUM=0.
      KK=NN
      DO 20 J=1,M
      KK=KK+1
      F(J)=F(J)-W(KK)
      SUM=SUM+F(J)*F(J)
 20   CONTINUE
      IF (SUM) 25,25,35
 25   WRITE (59,410) I
      DO 30 J=1,M
      NN=NN+1
      F(J)=W(NN)
 30   CONTINUE
      GO TO 135
 35   SUM=1./SQRTF(SUM)
      J=K-N+I
      W(J)=F(I)*SUM
      DO 45 J=1,M
      K=K+1
      W(K)=F(J)*SUM
      KK=NN+J
      DO 40 II=1,I
      KK=KK+MPLUSN
      W(II)=W(II)+W(KK)*W(K)
 40   CONTINUE
 45   CONTINUE
      ILESS=I-1
      IGAMAX=N+I-1
      INCINV=N-ILESS
      INCINP=INCINV+1
      IF (ILESS) 50,50,55
 50   W(KINV)=1.0
      GO TO 95
 55   B=1.0
      DO 60 J=NPLUS,IGAMAX
      W(J)=0.
 60   CONTINUE
      KK=KINV
      DO 80 II=1,ILESS
      IIP=II+N
      W(IIP)=W(IIP)+W(KK)*W(II)
      JL=II+1
      IF (JL-ILESS) 65,65,75
```

```
 65    DO 70 JJ=JL,ILESS
       KK=KK+1
       JJP=JJ+N
       W(IIP)=W(IIP)+W(KK)*W(JJ)
       W(JJP)=W(JJP)+W(KK)*W(II)
 70    CONTINUE
 75    B=B-W(II)*W(IIP)
       KK=KK+INCINP
 80    CONTINUE
       B=1./B
       KK=KINV
       DO 90 II=NPLUS,IGAMAX
       BB=-B*W(II)
       DO 85 JJ=II,IGAMAX
       W(KK)=W(KK)-BB*W(JJ)
       KK=KK+1
 85    CONTINUE
       W(KK)=BB
       KK=KK+INCINV
 90    CONTINUE
       W(KK)=B
 95    GO TO (115,100), IINV
 100   I=I+1
       IF (I-N) 10,10,105
 105   IINV=1
       FF=0.
       KL=NN
       DO 110 I=1,M
       KL=KL+1
       F(I)=W(KL)
       FF=FF+F(I)*F(I)
 110   CONTINUE
       ICONT=1
       ISS=1
       MC=N+1
       IPP=IPRINT*(IPRINT-1)
       ITC=0
       IPS=1
       IPC=0
 115   IPC=IPC-IPRINT
       IF (IPC) 120,125,125
 120   WRITE (3,415) ITC,MC,FF
       WRITE (3,420) (X(I),I=1,N)
C
C      31 FORMAT(5X,9HVARIABLES,/(5E24.14))
       WRITE (3,425) (F(I),I=1,M)
       CALL EMPTY (3)
C
C      32 FORMAT(5X,9HFUNCTIONS,/(5E24.14))
       IPC=IPP
       GO TO (125,145), IPS
 125   GO TO (155,130), ICONT
 130   IF (CHANGE-1.) 135,135,150
 135   IF (IPRINT) 145,145,140
 140   WRITE (3,430)
       IPS=2
       GO TO 120
 145   RETURN
 150   ICONT=1
 155   ITC=ITC+1
```

```
      K=N
      KK=KST
      DO 165 I=1,N
      K=K+1
      W(K)=0.
      KK=KK+N
      W(I)=0.
      DO 160 J=1,M
      KK=KK+1
      W(I)=W(I)+W(KK)*F(J)
  160 CONTINUE
  165 CONTINUE
      DM=0.
      K=K1NN
      DO 190 II=1,N
      IIP=II+N
      W(IIP)=W(IIP)+W(K)*W(II)
      JL=II+1
      IF (JL-N) 170,170,180
  170 DO 175 JJ=JL,N
      JJP=JJ+N
      K=K+1
      W(IIP)=W(IIP)+W(K)*W(JJ)
      W(JJP)=W(JJP)+W(K)*W(II)
  175 CONTINUE
      K=K+1
  180 IF (DM-ABSF(W(II)*W(IIP))) 185,190,190
  185 DM=ABSF(W(II)*W(IIP))
      KL=II
  190 CONTINUE
      II=N+MPLUSN*KL
      CHANGE=0.
      DO 205 I=1,N
      JL=N+I
      W(I)=0.
      DO 195 J=NPLUS,NN
      JL=JL+MPLUSN
      W(I)=W(I)+W(J)*W(JL)
  195 CONTINUE
      II=II+1
      W(II)=W(JL)
      W(JL)=W(I)
      IF (ABSF(E(I)*CHANGE)-ABSF(W(I))) 200,200,205
  200 CHANGE=ABSF(W(I)/E(I))
  205 CONTINUE
      DO 210 I=1,M
      II=II+1
      JL=JL+1
      W(II)=W(JL)
      W(JL)=F(I)
  210 CONTINUE
      FC=FF
      ACC=0.1/CHANGE
      IT=3
      XC=0.
      XL=0.
      IS=3
       TEP=-MIN1F(0.5,ESCALE/CHANGE)
        (CHANGE-1.0) 215,215,220
  215 ICONT=2
```

```
C
C
 220  CALL SEARCH (IT,XC,FC,6,ACC,0.1,XSTEP)
      IF (ACC.GT.0.) GO TO 225
      M=-M
      RETURN
C
C
 225  GO TO (230,315,315,315), IT
 230  MC=MC+1
      IF (MC-MAXFUN) 240,240,235
C
C
 235  WRITE (3,435) MAXFUN
C
C
      ISS=2
      GO TO 315
 240  XL=XC-XL
      DO 245 J=1,N
      X(J)=X(J)+XL*W(J)
 245  CONTINUE
      XL=XC
      CALL CALFUN (M,N,F,X)
C
C     ALARM FOR CALFUN PROBLEMS
      IF (M.LT.0) RETURN
      FC=0.
      DO 250 J=1,M
      FC=FC+F(J)*F(J)
 250  CONTINUE
      GO TO (270,270,255), IS
 255  K=N
      IF (FC-FF) 260,220,265
 260  IS=2
      FMIN=FC
      FSEC=FF
      GO TO 300
 265  IS=1
      FMIN=FF
      FSEC=FC
      GO TO 300
 270  IF (FC-FSEC) 275,220,220
 275  K=KSTORE
      GO TO (280,285), IS
 280  K=N
 285  IF (FC-FMIN) 295,220,290
 290  FSEC=FC
      GO TO 300
 295  IS=3-IS
      FSEC=FMIN
      FMIN=FC
 300  DO 305 J=1,N
      K=K+1
      W(K)=X(J)
 305  CONTINUE
      DO 310 J=1,M
      K=K+1
      W(K)=F(J)
 310  CONTINUE
```

```
      GO TO 220
 315  K=KSTORE
      KK=N
      GO TO (325,320,325), IS
 320  K=N
      KK=KSTORE
 325  SUM=0.
      DM=0.
      JJ=KSTORE
      DO 330 J=1,N
      K=K+1
      KK=KK+1
      JJ=JJ+1
      X(J)=W(K)
      W(JJ)=W(K)-W(KK)
 330  CONTINUE
      DO 335 J=1,M
      K=K+1
      KK=KK+1
      JJ=JJ+1
      F(J)=W(K)
      W(JJ)=W(K)-W(KK)
      SUM=SUM+W(JJ)*W(JJ)
      DM=DM+F(J)*W(JJ)
 335  CONTINUE
      GO TO (340,135), ISS
 340  J=KINV
      KK=NPLUS-KL
      DO 345 I=1,KL
      K=J+KL-I
      J=K+KK
      W(I)=W(K)
      W(K)=W(J-1)
 345  CONTINUE
      IF (KL-N) 350,360,360
 350  KL=KL+1
      JJ=K
      DO 355 I=KL,N
      K=K+1
      J=J+NPLUS-I
      W(I)=W(K)
      W(K)=W(J-1)
 355  CONTINUE
      W(JJ)=W(K)
      B=1./W(KL-1)
      W(KL-1)=W(N)
      GO TO 365
 360  B=1./W(N)
 365  K=KINV
      DO 375 I=1,ILESS
      BB=B*W(I)
      DO 370 J=I,ILESS
      W(K)=W(K)-BB*W(J)
      K=K+1
 370  CONTINUE
      K=K+1
 375  CONTINUE
      IF (FMIN-FF) 385,380,380
 380  CHANGE=0.
      GO TO 390
```

```
 385  FF=FMIN
      CHANGE=ABSF(XC)*CHANGE
 390  XL=-DM/FMIN
      SUM=1./SQRTF(SUM+DM*XL)
      K=KSTORE
      DO 395 I=1,N
      K=K+1
      W(K)=SUM*W(K)
      W(I)=0.
 395  CONTINUE
      DO 405 I=1,M
      K=K+1
      W(K)=SUM*(W(K)+XL*F(I))
      KK=NN+I
      DO 400 J=1,N
      KK=KK+MPLUSN
      W(J)=W(J)+W(KK)*W(K)
 400  CONTINUE
 405  CONTINUE
      GO TO 55
C
C
 410  FORMAT (5X,8HPOWSQ E(,I3,20H) UNREASONABLY SMALL)
 415  FORMAT (//1X,9HITERATION,I4,I9,16H CALLS OF CALFUN,5X,2HF=,E24.14)
 420  FORMAT (5X,9HVARIABLES,/(3E23.13))
 425  FORMAT (5X,9HFUNCTIONS,/(3E23.13))
 430  FORMAT (//5X,45HPOWSQ FINAL VALUES OF FUNCTIONS AND VARIABLES)
 435  FORMAT (5X,5HPOWSQ,I6,16H CALLS OF CALFUN)
      END

      SUBROUTINE PDXTRAP (Y1,Y2,Y3,DT,T3,YMAX,TAC)
C
C     THIS SUBROUTINE USES A LAGRANGIAN POLYNOMIAL TO EXTRAPOLATE
C     DATA(Y1,Y2,Y3) AT EQUAL INTERVALS DT, TO GIVE THE VALUE OF Y FOR
C     TAC, BETWEEN T3 AND T4.
C
      T2=T3-DT
      T1=T2-DT
      FT=Y1*(TAC-T2)*(TAC-T3)
      ST=2.*Y2*(TAC-T1)*(TAC-T3)
      TT=Y3*(TAC-T1)*(TAC-T2)
      YMAX=(FT-ST+TT)/(2.*DT*DT)
      RETURN
      END
```

```
      SUBROUTINE PROPOSE (PWGR,X,NOGC)
      DIMENSION X(6)
      MING=IFIX(PWGR*NOGC/34.)+1
      MAXG=IFIX(PWGR*NOGC/10.)
      DO 10 I=1,MAXG
      DO 5 J=MING,MAXG
      IF (MOD(J,I).NE.0) GO TO 5
      NGPC=J/I
      PWPG=PWGR*NOGC/J
      OCD=X(4)/SQRT(FLOAT(I))
      OPRD=X(5)/SQRT(FLOAT(I))
      WRITE (59,15) I,NGPC,J,PWPG,OCD,OPRD
      WRITE (3,15) I,NGPC,J,PWPG,OCD,OPRD
      GO TO 10
 5    CONTINUE
 10   CONTINUE
      RETURN
C
C
 15   FORMAT (I5,5X,I5,5X,I5,10X,F7.3,6X,F7.3,4X,F7.3)
      END

      SUBROUTINE PROTOT (F,X)
C
C     THIS SUBROUTINE STARTS THE POWSQ PROGRAM ON A PRELIMINARY SEARCH
C     WITH NO CONSTRAINTS ON STANDARD SIZES BUT WITH PROVISION FOR
C     ADDITIONAL GENERATORS IF NECESSARY.
C
      DIMENSION X(6),E(6),F(7)
 5    M=7
      N=6
      DO 10 I=1,6
 10   E(I)=1.E-3
      E(2)=1.E-4
      ESCALE=250.
      IPRINT=1
      MAXFUN=100
C
C     ARRANGE FOR OPTIMIZING WITH A CONSTANT MINIMUM CHARGE IF NEEDED.
      IF (ABS(X(6)).LT.0.000001) N=5
C
C     GET PRELIMINARY DESIGN
      CALL POWSQ (M,N,F,X,E,ESCALE,IPRINT,MAXFUN)
      CALL EMPTY (3)
      RETURN
      END
```

```
      SUBROUTINE REPORT (F,X)
C
C     THIS SUBROUTINE REPORTS THE FINAL DIMENSIONS, LOADING, AND THE
C     PERFORMANCE OF THE OPTIMIZED DESIGN.
C
      DIMENSION F(7),X(6)
      COMMON /SPECS/ TVMAX,TITLE(10),REQU(7),NOS(3),NC,NOGC,NH
      COMMON /PERF/ TAC,HPMX,BPMX,GPMX,STMX,VFIN
      COMMON /GEOM/ CD,PRD,HD,HL,BL,CEV,THET,PHI,PT,WLB,VHA,ELOD,STR
      WRITE (59,5)
      WRITE (3,5)
      WRITE (59,10) NC,NOGC   $WRITE (3,10) NC,NOGC
      WRITE (59,15) X(5),X(6)
      WRITE (3,15) X(5),X(6)
      WRITE (59,20) HL,BL
      WRITE (3,20) HL,BL
      WRITE (59,25) PT,NH,X(1)
      WRITE (3,25) PT,NH,X(1)
      WRITE (59,30) X(4)   $WRITE (3,30) X(4)
      PCET=TAC/REQU(3)
      WRITE (59,35) TAC,REQU(2),PCET
      WRITE (3,35) TAC,REQU(2),PCET
      PCEV=VFIN/REQU(4)
      WRITE (59,40) VFIN,PCEV
      WRITE (3,40) VFIN,PCEV
      PCES=STMX/REQU(5)
      WRITE (59,45) STMX,PCES
      WRITE (3,45) STMX,PCES
      WRITE (59,50) HPMX,REQU(7)
      WRITE (3,50) HPMX,REQU(7)
      WRITE (59,55) BPMX,REQU(7)
      WRITE (3,55) BPMX,REQU(7)
      WRITE (59,60) GPMX,REQU(6)
      WRITE (3,60) GPMX,REQU(6)
      CALL EMPTY (3)
      RETURN
C
C
  5   FORMAT (//,19H   DESIGN COMPLETED)
 10   FORMAT (//,I2,16H CYLINDERS WITH ,I2,20H GAS GENERATORS EACH)
 15   FORMAT (/,18HCYLINDER DIAMETER ,F7.4,27H INCH, PISTON-ROD DIAMETER
     1 ,F7.4,5H INCH)
 20   FORMAT (18HHEAD CLEARANCE    ,F7.4,21H INCH, BUFFER LENGTH ,6X,F7.
     14,5H INCH)
 25   FORMAT (7HPISTON ,F6.3,17H INCH THICK WITH ,I3,10H VENTS OF ,F6.4,
     110H IN. DIAM.)
 30   FORMAT (20HPROPELLANT LOADING: ,F6.3,19H GRAM PER GENERATOR)
 35   FORMAT (//14H  PERFORMANCE:/,F6.4,15H SEC. TO CROSS ,F7.4,10H INCH
     1ES ( ,F5.3,18H OF TIME REQUIRED))
 40   FORMAT (22HVELOCITY OF ARRIVAL:  ,F6.1,6H IPS (,F5.3,27H OF FINAL
     1VELOCITY ALLOWED))
 45   FORMAT (26HMAXIMUM PISTON-ROD STRESS ,F7.1,6H PSI (,F5.3,19H OF ST
     1RESS ALLOWED))
 50   FORMAT (28HMAXIMUM HEAD-SPACE PRESSURE ,F7.1,22H PSIA (PRESSURE RA
     1TING,F7.1,6H PSIA))
 55   FORMAT (24HMAXIMUM BUFFER PRESSURE ,F7.1,23H PSIA (PRESSURE RATING
     1 ,F7.1,6H PSIA))
 60   FORMAT (27HMAXIMUM GENERATOR PRESSURE ,F7.1,23H PSIA (PRESSURE RAT
     1ING ,F7.1,6H PSIA))
      END
```

```
      SUBROUTINE SEARCH (ITEST,X,F,MAXFUN,ABSACC,RELACC,XSTEP)
C
C     THIS SUBROUTINE FINDS A MINIMUM OF A FUNCTION OF A SINGLE VARIABLE
C        A STARTING VALUE OF X MUST BE PROVIDED AS THE PROCEDURE IS
C        ITERATIVE,AND THE MINIMUM FOUND WILL NORMALLY BE THE NEAREST
C        ONE IN A DOWNHILL DIRECTION FROM THE STARTING VALUE
C        F(X) MUST BE SPECIFIED IN THE CALLING ROUTINE IN THE WAY
C        DESCRIBED BELOW.
C
C     ON ENTRY TO THE ROUTINE ITEST MUST BE SET TO 2 OR 3 AND X MUST BE
C        SET TO THE STARTING VALUE OF THE VARIABLE.  SET ITEST TO 3 IF
C        ON ENTRY F = F(X), AND SET IT TO 2 OTHERWISE.  IN THE FORMER
C        CASE A FUNCTION EVALUATION WILL BE SAVED.
C
C     DURING EXECUTION ITEST IS AN INDEX TO CONTROL A COMPUTED GO TO
C
C     ON THE FINAL EXIT OF SEARCH,F WILL BE SET TO THE MINIMUM VALUE
C        OF F(X), AND X WILL BE SET TO THE CORRESPONDING VALUE OF THE
C        VARIABLE
C
C     THE SUBROUTINE WILL BE LEFT AFTER MAXFUN FUNCTION EVALUATIONS
C
C     ABSACC AND RELACC MUST BE SET TO SPECIFY THE ACCURACY TO WHICH
C        THE FINAL VALUE OF X IS REQUIRED.  IF THE CURRENT POSITION OF
C        THE MINIMUM IS AT X, AND THE NEXT PREDICTED POSITION IS AT XX,
C        THE SUBROUTINE WILL BE LEFT IF EITHER
C                    ABS(X-XX).LT.ABS(ABSACC)
C        OR          ABS(X-XX).LT.ABS(XX*RELACC)
C
C     XSTEP SHOULD BE SET TO A REASONABLE CHANGE TO BE MADE IN THE
C        VARIABLE IN BEGINING TO SEARCH FOR THE MINIMUM.  A BAD
C        ESTIMATE WILL CAUSE MORE FUNCTION VALUES TO BE REQUESTED,BUT
C        SHOULD NOT AFFECT THE FINAL CONVERGENCE.
C
C     DURING EXECUTION THE SUBROUTINE WILL RETURN TO THE CALLING
C        PROGRAM FOR VALUES OF THE FUNCTION;  ON THESE RETURNS ITEST
C        WILL BE SET TO UNITY FOR A COMPUTED GO TO, AND THE CALLING
C        PROGRAM MUST SET F=F(X) AND THEN EXECUTE THE INITIAL CALL
C        OF THE SUBROUTINE AGAIN WITH ITEST SET TO UNITY.
C
C     ON THE FINAL RETURN ITEST WILL BE SET TO 2,3, OR 4.
C                    2    MINIMUM FOUND TO REQUIRED ACCURACY
C                    3    ROUNDING ERRORS HAVE PREVENTED CONVERGENCE
C                    4    MAXFUN FUNCTION VALUES HAVE BEEN USED
C        ON RETURN X AND F ARE SET TO THE BEST CALCULATED
C
C     THE CODING TO DRIVE SEARCH SHOULD APPEAR AS FOLLOWS
C     ITEST = 2  (OR 3)
C     5 CALL SEARCH(ITEST,X,F,MAXFUN,ABSACC,RELACC,XSTEP)
C     GO TO (1,2,3,4),ITEST
C     1 F = FUNC(X)
C     GO TO 5
C     2 CONTINUE
C
      GO TO (35,5,5), ITEST
 5    IS=6-ITEST
      ITEST=IINC=1
      XINC=XSTEP+XSTEP
      MC=IS-3
      IF (MC) 45,45,30
```

```
  10    MC=MC+1
        IF (MAXFUN-MC) 15,30,30
  15    ITEST=4
  20    X=DB
        F=FB
        IF (FB-FC) 30,30,25
  25    X=DC    $F=FC
C
  30    RETURN
C
  35    GO TO (85,75,50,40), IS
  40    IS=3
  45    DC=X    $FC=F
        X=X+XSTEP
        GO TO 10
  50    IF (FC-F) 60,55,65
  55    X=X+XINC
        XINC=XINC+XINC
        GO TO 10
  60    DB=X    $FB=F
        XINC=-XINC
        GO TO 70
  65    DB=DC
        FB=FC
        DC=X
        FC=F
  70    X=DC+DC-DB
        IS=2
        GO TO 10
  75    DA=DB
        DB=DC
        FA=FB
        FB=FC
  80    DC=X
        FC=F
        GO TO 135
  85    IF (FB-FC) 105,90,90
  90    IF (F-FB) 95,80,80
  95    FA=FB
        DA=DB
 100    FB=F
        DB=X
        GO TO 135
 105    IF (FA-FC) 115,115,110
 110    XINC=FA
        FA=FC
        FC=XINC
        XINC=DA
        DA=DC
        DC=XINC
 115    XINC=DC
        IF ((D-DB)*(D-DC)) 80,120,120
 120    IF (F-FA) 125,130,130
 125    FC=FB
        DC=DB
        GD TO 100
 130    FA=F
        DA=X
 135    IF (FB-FC) 140,140,145
 140    IINC=2
```

```
      XINC=DC
      IF (FB-FC) 145,205,145
 145  D=(FA-FB)/(DA-DB)-(FA-FC)/(DA-DC)
C
C     TRAP FO D.EQ.0.
      IF (D.NE.0.) GO TO 150
      WRITE (59,215)
      ABSACC=-ABSACC
      RETURN
 150  CONTINUE
C
      IF (D*(DB-DC)) 185,155,155
 155  D=0.5*(DB+DC-(FB-FC)/D)
      IF (ABSF(D-X)-ABSF(ABSACC)) 165,165,160
 160  IF (ABSF(D-X)-ABSF(D*RELACC)) 165,165,170
 165  ITEST=2
      GO TO 20
 170  IS=1
      X=D
      IF ((DA-DC)*(DC-D)) 10,210,175
 175  IS=2
      GO TO (180,195), IINC
 180  IF (ABSF(XINC)-ABSF(DC-D)) 190,10,10
 185  IS=2
      GO TO (190,200), IINC
 190  X=DC
      GO TO 55
 195  IF (ABSF(XINC-X)-ABSF(X-DC)) 200,200,10
 200  X=0.5*(XINC+DC)
      IF ((XINC-X)*(X-DC)) 210,210,10
 205  X=0.5*(DB+DC)
      IF ((DB-X)*(X-DC)) 210,210,10
 210  ITEST=3
      GO TO 20
C
C
 215  FORMAT (8HD EQ 0. )
      END


      SUBROUTINE SEEKT (GEN,XT,ACCU)
C
C     THIS SUBROUTINE FINDS GAS TEMPERATURES, GIVEN THE INTERNAL ENERGY,
C     USING THE NEWTON-RAPHSON ITERATIVE METHOD WITH THE VK EQUATIONS
C     FOR PROPELLANT GAS INTERNAL ENERGY AND SPECIFIC HEAT (USED AS THE
C     ANALYTICAL DERIVATIVE OF THE ENERGY).
C
      COMMON /GASP/ R,SB,BK,BC,BB,A,B,C,D,PHV
      COMMON /PARS/ PT,PIF,XJ,PA,TA,GC,SF,CUF
      NL=0
 5    FX=GASFN(XT)-GEN
      ELT=ALOG(XT)
      DER=B+C/XT+2.*D*ELT/XT-R/XJ
      COR=FX/DER
      XT=XT-COR
      IF (ABS(COR).LT.ACCU) RETURN
      NL=NL+1
      IF (NL.GT.100) PAUSE
      GO TO 5
      END
```

```
      SUBROUTINE START (XG)
C
C     THIS SUBROUTINE CALCULATES THE ACTUATOR DIMENSIONS AND LOADING
C     ASSUMING A VERY SIMPLE, LINEARIZED SYSTEM. THIS ALLOWS THE OPTI-
C     MIZING SEARCH TO BE STARTED FROM A FEASIBLE POINT.
C
      DIMENSION XG(6)
      COMMON /SPECS/ TVMAX,TITLE(10),REQU(7),NOS(3),NC,NOGC,NH
      COMMON /PARS/ PI,PIF,XJ,PA,TA,GC,SF,CUF
      COMMON /GASP/ R,SB,BK,BC,BB,A,B,C,D,PHV
      COMMON /GEOM/ CD,PRD,HD,HL,BL,CEV,THET,PHI,PT,WLB,VHA,ELOD,STR
      WLB=REQU(1)
      STR=REQU(2)
      TR=REQU(3)
      VFAL=REQU(4)
      STAL=REQU(5)
      CPAL=REQU(7)
      NC=NOGC=NH=1
C
C     CONSTANT ACCEL. A DECEL. TO VFAL FOR STR,TR GIVES A QUADRATIC IN A
      BQ=2.*VFAL*TR-4.*STR
      DISCR=BQ*BQ+4.*VFAL*VFAL*TR*TR
      ACC=(-BQ+SQRT(DISCR))/(2.*TR*TR)
      FORCE=ACC*WLB/386.088
      TVMAX=.5*(VFAL/ACC+TR)
C
C     ASSUME MAX GAS FORCE IS DOUBLE THE AVERAGE (CONST.ACCEL.) FORCE
      FMAX=2.*FORCE
      PRA=FMAX/STAL
      PRD=SQRT(PRA/PIF)
C
C     ESTIMATE ENERGY NEEDED FROM THE AVERAGE VELOCITY
      ENID=2.*WLB*STR*STR/(4633.056*TR*TR)
C
C     ASSUME 50% ENERGY CONVERSION EFFICIENCY
      PWS=ENID/(389.15*PHV)
      PWGR=PWS*453.6
 5    IF (PWGR.GT.34.) GO TO 15
      IF (PWGR.LT.10.) GO TO 20
C
C     USE CPAL AND FMAX TO FIND MIN. CD
      CA=FMAX/CPAL
      CD=SQRT(CA/PIF)
C
C     USE CURVE-FITTED CONSTANTS TO FIND HVOL NECESSARY TO GIVE CPAL FOR
C     THE ASSUMED PWGR.
      ELP=ALOG(PWGR)
      AK=5.4254+1.3258*ELP
      BKK=.019489+.004406*ELP
      HVOL=NOGC*(AK-ALOG(CPAL))/BKK
      HL=HVOL/CA
      IF (HL.LT.0.) GO TO 20
C
C     ASSUME AN END-OF-MOTION CLEARANCE EQUAL TO STARTING HEAD CLEARANCE
 10   BL=STR+HL
C
C     ASSUME A PISTON VENT-HOLE KNOWN TO BE TOO SMALL BY TREATING FANNO
C     FLOW AS SIMPLE ORIFICE FLOW.ASSUME AVERAGE GAS TEMPERATURE BETWEEN
C     FLAME AND AMBIENT, THE PERFECT GAS EQUATION OF STATE,AND THE
C     FLOW OF HALF THE GAS PRODUCED DURING THE ACCELERATION TIME
```

```
C       ASSUME THE ASME FLUID METER CONSTANT K(1)*Y = .85
C       ASSUME CHOKED FLOW
        TAV=(5000.*GAMGAS(5000.)+TA)*.5
        SVH=R*TAV/(CPAL*SF)
        G=GAMGAS(TAV)
        RC=(2./(G+1.))**(G/(G-1.))
        PDIFF=CPAL*(1.-RC)
        GMF=PWS/TVMAX
        HD=(5.*SVH*GMF*GMF/PDIFF)**.25
        PT=15.*HD
C
C       STARTING VALUES PACKED INTO XG(1) TO XG(6) ARE THUS
C
        XG(1)=HD
        XG(2)=HL
        XG(3)=PL-REQU(2)
        XG(4)=CD
        XG(5)=PRD
        XG(6)=PWGR
        RETURN
C
C       THERE MUST BE AT LEAST ONE MORE GENERATOR TO HOLD THAT MUCH
C       PROPELLANT, AT NOT MORE THAN 34. GRAM PER GENERATOR.
 15     PWTOT=PWGR*NOGC
        NOGC=NOGC+1
        PWGR=PWTOT/NOGC
        GO TO 5
C
C       SINCE 10. GRAM IS THE SMALLEST USABLE CHARGE, PWGR IS SET TO 10.,
C       AND OVERDRIVING IS AVOIDED BY ALLOWING HVOL TO ENLARGE, WITH
C       ATTENDANT LOSS OF AVAILABLE ENERGY DUE TO EXPANSION INTO BIGGER V.
 20     PWGR=10.
        ELP=ALOG(PWGR)
        CP=CPAL
        AK=5.4254+1.3258*ELP
        BKK=.019489+.004406*ELP
C
C       ASSUME HL=CD/6.,HENCE HVOL=PI*CD**3/24,BACK SUBSTITUTION FOR CD,HL
 25     CDN=SQRT(FMAX/(PIF*CP))
        HVOL=PIF*CD**3/6.
        CPN=EXP(AK-BKK*HVOL)
        IF (ABS(CD-CDN).LT..01.AND.ABS(CP-CPN).LT.1.) GO TO 30
        CP=CPN
        CD=CDN
        GO TO 25
 30     CD=CDN
        HL=CD*.16667
        GO TO 10
        END
```

```
      SUBROUTINE STROKE (PWGR)
C
C      THIS SUBROUTINE CALCULATES THE PERFORMANCE OF A SELF-STOPPING
C      ACTUATOR DRIVEN BY THE CTL-10359 HIGH-PRESSURE CARTRIDGE LOADED
C      PWGR GRAM OF IMR-4227 PROPELLANT. SELF-STOPPING ACTION IS
C      OBTAINED BY USING A VENTED PISTON.
C
      COMMON /GEOM/ CD,PRD,HD,HL,BL,CEV,THET,PHI,PT,WLB,VHA,ELOD,STR
      COMMON /PGGD/ EQA,CVOL,PVOL,CPAL
      COMMON /GASP/ R,SB,BK,BC,BB,A,B,C,D,PHV
      COMMON /SPECS/ TVMAX,TITLE(10),REQU(7),NOS(3),NC,NOGC,NH
      COMMON /PERF/ TAC,HPMX,BPMX,GPMX,STMX,VFIN
      COMMON /PARS/ PI,PIF,XJ,PA,TA,GC,SF,CUF
      COMMON /PPTT/ PSUP,PSDN,TSUP,TSDN
      DATA PI,PIF,XJ,PA / 3.1415926535898,.7853981633974,778.3,14.7/
      DATA A,B,C,D / -1324.36186,.52053028,1532.320597,-51.2364509/
      DATA R,SB,BK,BC,BB,PHV /60.497,.13131,3.9374,.19079,.04389,1241.6/
      DATA EQA,CVOL,PVOL,CUF /.22592,5.14118,.706858,1728./
      DATA THET,PHI,CEV,TA,GC,SF /0.,15.,2.6838,530.,32.174,144./
C
C     SET A FEW STARTING VALUES
      STMX=GPMX=HPMX=BPMX=VEL=ACC=TTE=EMDOTG=EMDOTB=FORCE=FC=DST=RPF=0.
      HGP=BGP=GGP=PA
      HGT=BGT=GGT=TSUP=TSDN=TA
      FF=.03
      BKC=BK
      TBF=4400.
      PWS=PWGR*.0022046
      PWL=PWS
      EMUP=EMDN=.03
      ACCUR=.1
      NST=NHP=NBP=0
      STMXO=STMXL=0.
      GPMXO=GPMXL=0.
      HPMXO=HPMXL=0.
      BPMXO=BPMXL=0.
C
C     FIND A FEW BASIC QUANTITIES
      HCA=PIF*CD*CD
      VHA=PIF*HD*HD
      PRA=PIF*PRD*PRD
      BCA=HCA-PRA
      DT=.0001
      GVOL=CVOL
      HVOLS=HCA*HL+CEV
      BVOLS=BCA*BL
C
C     CALCULATE SPECIFIC VOLUMES, GAS MASSES, GAS ENERGIES IN 3 VOLUMES
      DISC=R*HGT*(R*HGT+576.*HGP*SB)
      SSV=(R*HGT+SQRT(DISC))/(288.*HGP)
      SVHG=SVBG=SVGG=SSV
      GGM=(GVOL-PWL*17.1969)/(CUF*SVGG)
      HGM=HVOLS/(CUF*SVHG)
      BGM=BVOLS/(CUF*SVBG)
      SSGF=GASEN(TA)
      GGF=GGM*SSGF
      HGF=HGM*SSGF
      BGF=BGM*SSGF
      HVOL=HVOLS
      BVOL=BVOLS
```

```
C
C      START TIME INTEGRATION
  5    TTE=TTE+DT
C
C      AVOID UNREAL BURN IF THERE IS NO MORE PROPELLANT (I.E.BKC=0)
       DPB=0.
       IF (BKC.LT.1.E-12) GO TO 15
       DPB=BKC*PWS*DT*GGP**(CALALFA(GGP))
       IF (PWL.GT.DPB) GO TO 130
C
C      IF PWL.LT.DPB, BURNOUT OCCURRED DURING THE LAST TIME INCREMENT
C      FIND GGP = GPMX AT EXACT TIME OF BURNOUT BY EXTRAPOLATING THE LAST
C      THREE PRESSURE VALUES BY POXTRAP.
       FB=PWL/DPB
       DPB=PWL
       BKC=0.
       TPMX=TTE-(1.-FB)*DT
       TTM=TTE-DT
       CALL POXTRAP (GPMXC,GPMXL,GPMXN,DT,TTM,GPMX,TPMX)
 10    PWL=PWL-DPB
       GGVOL=GVOL-17.1960*PWL
C
C      USE SEALED SYSTEM BEFORE DISC BURST
       IF (FC.LT.1.E-12) GO TO 120
C
C      SELECT DIRECTION OF CARTRIDGE FLOW
 15    IF (GGP.LT.HGP) GO TO 20
       PUP=GGP
       PDN=HGP
       TUP=GGT
       FCC=FC
       GO TO 25
 20    PUP=HGP
       PDN=GGP
       TUP=HGT
       FCC=-FC
C
C      ITERATE FOR AVERAGE GAMA ACCROSS CARTRIDGE GAS FLOW
 25    GUPG=GAMGAS(TUP)
       TSTAR=2.*TUP/(GUPG+1.)
 30    GSTAR=GAMGAS(TSTAR)
       GAMAV=.5*(GUPG+GSTAR)
       TSTARN=2.*TUP/(GAMAV+1.)
       IF (ABS(TSTARN-TSTAR).LE.0.1) GO TO 35
       TSTAR=TSTARN
       GO TO 30
C
C      FIND CHOKED PRESSURE
 35    PSTAR=PUP*(2./(GAMAV+1.))**(GAMAV/(GAMAV-1.))
C
C      FIND PRESSURE PE AT EXIT FROM PGG, DETERMINING KIND OF FLOW
       IF (PSTAR.GT.PDN) GO TO 40
       PE=PDN
       GO TO 45
 40    PE=PSTAR
C
C      USE ASME FLUID METER FLOW FORMULA
 45    EMDOTG=FCC*SQRT((PUP-PE)/SVGG)
C
C      FIND FANNO FLOW THROUGH VENT(S)
```

```
      CALL FANNOF (HGP,BGP,HGT,BGT,EMUP,EMDN,FF,EMDOTB,FORCE)
      IF (HGP.LT.BGP) EMDOTB=-EMDOTB
      IF (HGP.LT.BGP) FORCE=-FORCE
C
C     FIND FORCES ON PISTON
      FH=HGP*(HCA-VHA*NH)
      FB=BGP*(BCA-VHA*NH)
      FG=WLB*COS(THET*PI/180.)/NC
C
C     CALCULATE VENT-WALL DRAG
      FD=NH*FORCE*(COS(PI*PHI/180.))
C
C     ATMOSPHERIC FORCE ON PISTON ROD
      FA=PRA*PA
C
C     PISTON-RING AND ROD-SEALS FRICTION FORCE (RINGS TURNED OUTWARD)
      FFPR=POLYPAK(HGP,PA,CD)+POLYPAK(BGP,PA,CD)
      FFRS=POLYPAK(BGP,PA,PRD)
      FFOP=FFPR+FFRS
C
C     TOTAL ACTIVE FORCES ACTING ON PISTON
      PAF=FH+FG+FD-FB-FA
C
C     FRICTION FORCES OPPOSE VELOCITY (IF ANY)
      IF (VEL.EQ.0) GO TO 50
      FDIR=FFOP*VEL/ABS(VEL)
C
C     ASSUME KINEMATIC FRICTION IS 25% LOWER THAN STATIC
      RPF=PAF-FDIR*.75
      GO TO 60
C
C     IF ACTIVE FORCES PREVAIL, NET FORCE PRODUCES ACCELERATION
   50 IF (ABS(PAF).LT.(FFOP+TBF/NC)) GO TO 55
      RPF=PAF-FFOP
      GO TO 60
C
C     IF FRICTION FORCES PREVAIL (AT VEL=0) NOTHING HAPPENS
   55 ACC=0.
      DDST=0.
      GO TO 65
C
C     CALCULATE ACCELERATION OF PISTON, THEN VEL AND DST
   60 ACC=RPF*386.088*NC/WLB
      DDST=VEL*DT+.5*ACC*DT*DT
      VEL=VEL+ACC*DT
      DST=DST+DDST
C
C     FIND NEW VOLUMES, GAS MASSES AND GAS ENERGIES.
      HVOL=HVOL+HCA*DDST
      BVOL=BVOL-BCA*DDST
   65 GGM=GGM+.9324*DPB-EMDOTG*DT
      HGM=HGM+EMDOTG*DT*NOGC-EMDOTB*DT*NH
      BGM=BGM+EMDOTB*DT*NH
C
C     FIND ENTHALPY OF FLOWS
      IF (GGP.LT.HGP) GO TO 70
      SHGG=GASEN(GGT)+R*GGT/XJ
      GO TO 75
   70 SHGG=GASEN(HGT)+R*HGT/XJ
   75 IF (HGP.LT.BGP) GO TO 80
```

```
      SHBG=GASEN(HGT)+R*HGT/XJ
      GO TO 85
 80   SHBG=GASEN(BGT)+R*BGT/XJ
C
C     FIND MECH. WORK DONE ON AND BY GAS, AND GAS INTERNAL ENERGIES
 85   WH=(HCA-VHA*NH)*HGP*DDST
      WB=(BCA-VHA*NH)*BGP*DDST
      GGF=GGF+DPB*PHV-EMDOTG*DT*SHGG
      ~~HGF=HGF+EMDOTG*DT*SHGG*NOGC-EMDOTB*DT*SHBG*NH-WH/9339.6~~
      BGF=BGF+EMDOTB*DT*SHBG*NH+WB/9339.6
C
C     FIND TEMPERATURES FROM SPECIFIC ENERGIES
      SGGE=GGE/GGM
      CALL SEFKT (SGGF,GGT,ACCUR)
      SHGE=HGF/HGM
      CALL SEFKT (SHGF,HGT,ACCUR)
      SBGE=BGE/BGM
      CALL SEFKT (SBGF,BGT,ACCUR)
C
C     FIND PRESSURES IN THE 3 VOLUMES, AFTER GETTING SPECIFIC VOLUMES
      SVGG=GGVOL/(CUF*GGM)
      GGP=R*GGT*(1.+SB/SVGG)/(SVGG*SF)
      SVHG=HVOL/(CUF*HGM)
      HGP=R*HGT*(1.+SB/SVHG)/(SVHG*SF)
      SVBG=BVOL/(CUF*BGM)
      BGP=R*BGT*(1.+SB/SVBG)/(SVBG*SF)
C
C     RECORD MAXIMUM STRESSES OR PRESSURES, IF ANY
      PRS=ABS(RPF/PRA)
      IF (PRS.LT.1.E-3) GO TO 100
      IF (STMXL.LT.PRS) GO TO 125
C
C     IF GROWTH OF A VARIABLE HAS REVERSED, USE INTERP TO GET MAXIMUM
C     OF PARABOLA THROUGH THE LAST THREE POINTS.
      IF (NST.EQ.0) CALL INTERP (STMXO,STMXL,PRS,DT,TTE,STMX,NST)
 90   IF (HPMXL.LT.HGP) GO TO 135
      IF (NHP.EQ.0) CALL INTERP (HPMXO,HPMXL,HGP,DT,TTE,HPMX,NHP)
 95   IF (BPMXL.LT.BGP) GO TO 140
      IF (NBP.EQ.0) CALL INTERP (BPMXO,BPMXL,BGP,DT,TTE,BPMX,NBP)
C
C     CHECK FOR EXCESSIVE RUNNING TIME
 100  IF (TTE.GE..5) GO TO 105
C
C     CHECK FOR SHORT STROKE
      IF (VEL.LT.0) GO TO 110
C
C     CHECK FOR END OF STROKE
      IF (DST.GT.STR) GO TO 115
C
C     REQUIRED STROKE NOT YET REACHED
      GO TO 5
C
C     POST SENTINEL FOR EXCESSIVE RUNNING TIME
 105  TAC=-DST
      VFIN=-VEL
      RETURN
C
C     POST SENTINEL FOR SHORT STROKE
 110  VFIN=-DST
      TAC=TTE
```

```
      RETURN
C
C     REQUIRED STROKE HAS BEEN OVERSHOT, RETURN WITH CONSTANT ACCELERATI
C     TO FIND TIME OF ACTUAL TRAVEL.
 115  STM=DST-STR
      DISC=VEL*VEL-2.*ACC*STM
      VFIN=SQRT(DISC)
      TDEC=(VEL-VFIN)/ACC
      TAC=TTF-TDEC
C
C     USE POXTRAP TO INTERPOLATE FOR BPMX AT TRUE END OF STROKE
      IF (NBP.EQ.0) CALL POXTRAP (BPMXO,BPMXL,BGP,DT,TTF,BPMX,TAC)
      RETURN
C
C     BURST DISC STILL INTACT
 120  GGM=GGM+.9324*DPB
      SVGG=GGVOL/(CUF*GGM)
      GGF=GGF+DPB*PHV
      SGGE=GGE/GGM
      CALL SFFKT (SGGE,GGT,ACCUR)
      GGP=R*GGT*(1.+SB/SVGG)/(SVGG*SF)
C
C     IF DISC STILL INTACT, REPEAT BURN IN SEALED SYSTEM
      IF (GGP.LT.2000.) GO TO 5
C
C     IF DISC BURST, BURN ON WITH NEW GEN. VOLUME AND WITH FLOW
      GVOL=CVOL+PVOL
      FC=EQA
      GO TO 5
C
C     RETAIN THE LAST 2 OR 3 VALUES FOR POSSIBLE INTERPOLATION
 125  STMXO=STMXL
      STMXL=PRS
      GO TO 90
 130  GPMXO=GPMXL
      GPMXL=GPMXN
      GPMXN=GGP
      GO TO 10
 135  HPMXO=HPMXL
      HPMXL=HGF
      GO TO 95
 140  BPMXO=BPMXL
      BPMXL=BGP
      GO TO 100
      END
```

```
      FUNCTION CALALFA(P)
C
C     THIS FUNCTION GIVES ALPHA FOR BURN-RATE EQUATION MDOT=K*P**ALPHA
C
      COMMON /GASP/ R,SB,BK,BC,BB,A,B,C,D,PHV
      X2=0.5-0.52/BC
      TP=P*0.0001
      TOP=1.02-X2
      BTM=1.+BC*EXP(-TOP*BB*TP)
      CALALFA=X2+TOP/BTM
      RETURN
      END
```

```
      FUNCTION GAMGAS(T)
C
C     THIS FUNCTION GIVES THE SPECIFIC HEAT RATIO FOR THE PROPELLANT
C     GAS USING THE ENTHALPY EQUATIONS DEVELOPED BY VK
C
      COMMON /GASP/ R,SB,BK,BC,BB,A,B,C,D,PHV
      ELT=ALOG(T)
      CP=B+C/T+2.*D*ELT/T
      CV=CP-R/778.3
      GAMGAS=CP/CV
      RETURN
      END
```

```
      FUNCTION GASEN(T)
C
C     THIS FUNCTION GIVES THE PROPELLANT GAS INTERNAL ENERGY USING THE
C     ENTHALPY EQUATIONS DEVELOPED BY VK
C
      COMMON /GASP/ R,SB,BK,BC,BB,A,B,C,D,PHV
      COMMON /PARS/ PI,PIF,XJ,PA,TA,GC,SF,CUF
      ELT=ALOG(T)
      GASEN=A+B*T+C*ELT+D*ELT*ELT-R*T/XJ
      RETURN
      END
```

```
      FUNCTION POLYPAK(PHI,PLO,DIA)
C
C     THIS FUNCTION FINDS THE POLYPAK-SEALS FRICTION FORCE BY AN
C     EXPERIMENTALLY FITTED EQUATION.
C
      PDIF=ABS(PHI-PLO)
      POLYPAK=DIA*(2.9247*PDIF**.25+.013528*PDIF+38.107)*0.01
      RETURN
      END
```

APPENDIX V

A Complete History of Test Designs A and B

a. Complete History of Test Design A

```
GIVE TITLE FOR THIS ACTUATOR DESIGN PROBLEM

(TELETYPE INPUT) -->
 10 X 2 PERFORMANCE. EFFECT OF WT(PM) ON FINAL VALUE OF FWGR. WT=.02

GIVE VALUES FOR WLB,STR,TR,VFAL,STAL,GPAL,CPAL
(TELETYPE INPUT)   -->
 3.965E+02 1.900E+01 6.300E-02 3.000E+02 2.000E+04 3.200E+04 5.000E+03

DO YOU HAVE A REASONABLE FIRST GUESS? YES OR NO
(TELETYPE INPUT) --> NO


FOLLOWING IS THE POWSO OUTPUT GIVING THE SEARCH HISTORY


 ITERATION    0           7 CALLS OF CALFUN        F=     8.47614598220317E-02
     VARIABLES
    1.2770392091589E-01      2.4492104289085E+00      2.4492104289084E+00
    2.3338363681464E+00      1.1009181840732E+00      1.3140817700140E+01
     FUNCTIONS
    6.2816351002791E-02      1.0294440327089E-02      5.7196025057090E-02
    6.6597526783139E-02      5.3548192386690E-02     -2.6475710382614E-01
                .0E+00

 ITERATION    1          13 CALLS OF CALFUN        F=     7.72569067327116E-02
     VARIABLES
    1.2700193842264E-01      2.2382891108003E+00      2.3425677584701E+00
    2.3595143560759E+00      1.1790421459959E+00      1.2814704155526E+01
     FUNCTIONS
    5.6295283110523E-02      1.1680418811306E-02      5.8044985838817E-02
    5.7390179420408E-02      5.5768033773013E-02     -2.5448176755558E-01
                .0E+00

 ITERATION    2          19 CALLS OF CALFUN        F=     3.51443408245466E-02
     VARIABLES
    1.1923266913724E-01      3.1935871780088E+00      2.3764472000812E+00
    2.1709651165636E+00      1.0863928782150E+00      1.4095290492125E+01
     FUNCTIONS
    8.1965609842497E-02      1.2410791340529E-02      6.8378545672930E-02
    8.4133323192082E-02      6.3901644255558E-02     -1.1151004514279E-01
                .0E+00

 ITERATION    3          25 CALLS OF CALFUN        F=     3.51443408245466E-02
     VARIABLES
    1.1923266913724E-01      3.1935871780088E+00      2.3764472000812E+00
    2.1709651165636E+00      1.0863928782150E+00      1.4095290492125E+01
     FUNCTIONS
    8.1965609842497E-02      1.2410791340529E-02      6.8378545672930E-02
    8.4133323192082E-02      6.3901644255558E-02     -1.1151004514279E-01
                .0E+00
```

```
ITERATION    4          29 CALLS OF CALFUN      F=      2.70790548863801E-02
   VARIABLES
  1.14324380204886E-01      3.83173773214818E+00      2.39370841360486E+00
  2.08052502879895E+00      1.04144794187346E+00      1.49292358166640E+01
   FUNCTIONS
  9.83647163327836E-02      1.87886193548528E-02      5.83864847712228E-02
  9.98854791832806E-02      5.07312859353206E-02     -3.57180188853127E-02
                  .0E+00

ITERATION    5          35 CALLS OF CALFUN      F=      2.57332235807205E-02
   VARIABLES
  1.14682093457767E-01      3.88471900801866E+00      2.39313810848814E+00
  2.08750887747489E+00      1.04489065001066E+00      1.48787269181165E+01
   FUNCTIONS
  9.75345383232299E-02      1.83263357472000E-02      5.21004382384443E-02
  9.80124471640555E-02      4.64693307678821E-02     -3.47428219283398E-02
                  .0E+00

ITERATION    6          41 CALLS OF CALFUN      F=      2.57332235807205E-02
   VARIABLES
  1.14682093457767E-01      3.88471900801866E+00      2.39313810848814E+00
  2.08750887747489E+00      1.04489065001066E+00      1.48787269181165E+01
   FUNCTIONS
  9.75345383232299E-02      1.83263357472000E-02      5.21004382384443E-02
  9.80124471640555E-02      4.64693307678821E-02     -3.47428219283398E-02
                  .0E+00

ITERATION    7          47 CALLS OF CALFUN      F=      2.57064925607530E-02
   VARIABLES
  1.14568867353356E-01      3.88335931116015E+00      2.39312688854090E+00
  2.08759837531180E+00      1.04488280024763E+00      1.48751846870634E+01
   FUNCTIONS
  9.75036934126674E-02      1.83322841617784E-02      5.20431345891635E-02
  9.69793907557757E-02      4.64131472241797E-02     -3.46967116548856E-02
                  .0E+00

ITERATION    8          53 CALLS OF CALFUN      F=      2.57064925607530E-02
   VARIABLES
  1.14568867353356E-01      3.88335931116015E+00      2.39312688854090E+00
  2.08759837531180E+00      1.04488280024763E+00      1.48751846870634E+01
   FUNCTIONS
  9.75036934126674E-02      1.83322841617784E-02      5.20431345891635E-02
  9.69793907557757E-02      4.64131472241797E-02     -3.46967116548856E-02
                  .0E+00

ITERATION    9          59 CALLS OF CALFUN      F=      2.56279650379675E-02
   VARIABLES
  1.14725367681292E-01      3.87576566258812E+00      2.39302819920700E+00
  2.08855040431131E+00      1.04541142137765E+00      1.40679297346699E+01
   FUNCTIONS
  9.73565946339,6E-02       1.84928082546266E-02      5.19363391444403E-02
  9.86070838661395E-02      4.63140046738896E-02     -3.46709524646617E-02
                  .0E+00
```

```
ITERATION  10          63 CALLS OF CALFUN       F=     2.5627965037967 5E-02
     VARIABLES
   1.1472536781292E-01      3.8767656625612E+00      2.3930291920700E+00
   2.0885694043131E+00      1.0454114213765E+00      1.4867929734699E+01
     FUNCTIONS
   9.7358594693976E-02      1.8492808254626E-02      5.1936339144403E-02
   9.8807083861395E-02      4.6314004673896E-02     -3.4670952484617E-02
                .0E+00

ITERATION  11          71 CALLS OF CALFUN       F=     2.5627965037967 5E-02
     VARIABLES
   1.1472536781292E-01      3.8767656625612E+00      2.3930291920700E+00
   2.0885694043131E+00      1.0454114213765E+00      1.4867929734699E+01
     FUNCTIONS
   9.7358594693976E-02      1.8492808254626E-02      5.1936339144403E-02
   9.8807083861395E-02      4.6314004673896E-02     -3.4670952484617E-02
                .0E+00

ITERATION  12          77 CALLS OF CALFUN       F=     2.5627965037967 5E-02
     VARIABLES
   1.1472536781292E-01      3.8767656625612E+00      2.3930291920700E+00
   2.0885694043131E+00      1.0454114213765E+00      1.4867929734699E+01
     FUNCTIONS
   9.7358594693976E-02      1.8492808254626E-02      5.1936339144403E-02
   9.8807083861395E-02      4.6314004673896E-02     -3.4670952484617E-02
                .0E+00

ITERATION  13          83 CALLS OF CALFUN       F=     2.5627965037967 5E-02
     VARIABLES
   1.1472536781292E-01      3.8767656625612E+00      2.3930291920700E+00
   2.0885694043131E+00      1.0454114213765E+00      1.4867929734699E+01
     FUNCTIONS
   9.7358594693976E-02      1.8492808254626E-02      5.1936339144403E-02
   9.8807083861395E-02      4.6314004673896E-02     -3.4670952484617E-02
                .0E+00

ITERATION  14          89 CALLS OF CALFUN       F=     2.5627965037967 5E-02
     VARIABLES
   1.1472536781292E-01      3.8767656625612E+00      2.3930291920700E+00
   2.0885694043131E+00      1.0454114213765E+00      1.4867929734699E+01
     FUNCTIONS
   9.7358594693976E-02      1.8492808254626E-02      5.1936339144403E-02
   9.8807083861395E-02      4.6314004673896E-02     -3.4670952484617E-02
                .0E+00

ITERATION  15          95 CALLS OF CALFUN       F=     2.5627801833951 2E-02
     VARIABLES
   1.1472560838074E-01      3.8767837754149E+00      2.3930280783217E+00
   2.0865733696971E+00      1.0454133690471E+00      1.4867897769010E+01
     FUNCTIONS
   9.7357955380195E-02      1.8492110873900E-02      5.1936807497864E-02
   9.8806517579068E-02      4.6314531277097E-02     -3.4670974849013E-02
                .0E+00
```

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     POWSQ FINAL VALUES OF FUNCTIONS AND VARIABLES

  ITERATION  15        95 CALLS OF CALFUN      F=     2.56276018339512E-02
      VARIABLES
    1.1472560838874E-01      3.8767337754149E+00     2.3930280783217E+00
    2.0885733696971E+00      1.0454133690471E+00     1.4867897769010E+01
      FUNCTIONS
    9.7357955380195E-02      1.8492110873800E-02     5.1936807497864E-02
    9.8806517579066E-02      4.5314531277097E-02    -3.4670974849013E-02
                  .0E+00


FIRST TRY:      1 CYLINDER, 1 GAS GENERATORS & 1 VENT:

   PERFORMANCE
TIME FOR FULL STROKE  6.922E-02 SEC.    FINAL VELOCITY  3.055E+02 IPS
MAX.ROD STRESS        2.104E+04 PSI     MAX.GEM.PRESS.  5.335E+03 PSIA
MAX. HEAD CYL. PRESS. 5.232E+03 PSIA    MAX. BUFFER PR. 4.827E+03 PSIA

   ACTUATOR SPECS:
WEIGHT OF PROPELLANT   14.8679 GRAM   VENT-HOLE DIAM.     .1147 INCH
HEAD CLEARANCE          3.8767 INCH   BUFFER LENGTH     21.3930 INCH
CYLINDER DIAMETER       2.0886 INCH   PISTON-ROD DIA.    1.0454 INCH

OPTIONS AVAILABLE:
CYLINDERS GEN./CYL. TOTAL GEN. CHARGE(GRAM)/GEN. CYL.DIA. P.ROD DIA.

    1          1          1              14.868        2.089      1.045


          RECORD OF INTERACTIVE COMMUNICATIONS WITH TELETYPE


IS ONE OF THE ABOVE PROPOSE ACCEPTABLE? YES OR NO
(TELETYPE INPUT)  --> YES

SELECT OPTION - TYPE NO. OF CYL. AND GEN./CYL.
(TELETYPE INPUT)  -->      1    1

TYPE PREFERRED CYLINDER AND PISTON-ROD DIAMETERS
(TELETYPE INPUT) -->     2.50000   1.25000

THERE IS AN ANNULAR CLEARANCE OF   .625 INCH (VENT-HOLE DIAM.=   .115)
TYPE MAX. ACCEPTABLE VENT-HOLE DIAM.
(TELETYPE INPUT) -->      .25000

THERE WILL BE  1 VENT-HOLES PER PISTON, OF APPROX. .115 INCH DIAM.

MIN. VENT LENGTH (I.E. PISTON THICKNESS) IS  1.721 INCH.
TYPE PREFERRED VENT-HOLE LENGTH.
(TELETYPE INPUT) -->     1.75000

YOUR CHOICE OF VENT LENGTH GIVES AN L/D RATIO OF  15.3 OK OR NO?
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(TELETYPE INPUT)  --> OK

FOLLOWING IS THE POWSO OUTPUT GIVING THE SEARCH HISTORY


 ITERATION   0         5 CALLS OF CALFUN      F=     1.10378797729055E-01
     VARIABLES
    1.14725608388874E-01     2.70573608179610E+00     1.66899330304060E+00
    1.48678977690100E+01
     FUNCTIONS
    9.73579553801950E-02     3.00777811250790E-01     4.61037806157900E-02
   -7.63046443861010E-02     4.07039853208580E-02    -2.87772866610360E-02
                   .0E+00

 ITERATION   1         9 CALLS OF CALFUN      F=     4.54936677335440E-02
     VARIABLES
    1.18881570411930E-01     2.46277065054860E+00     1.42430645613660E+00
    1.33843890463330E+01
     FUNCTIONS
    6.76877609266560E-02     1.41814384051730E-01    -3.08587708217370E-03
   -2.15924468793020E-02    -8.10063935012440E-03     1.42335293463400E-01
                   .0E+00

 ITERATION   2        13 CALLS OF CALFUN      F=     1.48360585478776E-02
     VARIABLES
    1.20233781219111E-01     1.58174978507480E+00     1.35938051527310E+00
    1.12058107678710E+01
     FUNCTIONS
    2.41162153574240E-02     3.08623002501430E-02     6.41100274309630E-02
    1.42376567777400E-02     5.95650899354020E-02     7.36997882354600E-02
                   .0E+00

 ITERATION   3        19 CALLS OF CALFUN      F=     1.99071497419373E-03
     VARIABLES
    1.21210609337800E-01     1.58744096419090E+00     1.44277735344960E+00
    1.08990360625410E+01
     FUNCTIONS
    1.79807212508170E-02     1.23231383338380E-02     1.36352908940350E-02
    3.51209863977130E-02     9.20344444393410E-03     2.43852605313300E-03
                   .0E+00

 ITERATION   4        23 CALLS OF CALFUN      F=     1.97992759327270E-03
     VARIABLES
    1.21206382207020E-01     1.59105828334900E+00     1.43363975101580E+00
    1.09048411523300E+01
     FUNCTIONS
    1.80968230465560E-02     1.17399962666660E-02     1.32058077589900E-02
    3.51733262070750E-02     8.57148449661320E-03     5.43861111115550E-03
                   .0E+00

 ITERATION   5        28 CALLS OF CALFUN      F=     1.92285383273286E-03
     VARIABLES
    1.21176083050520E-01     1.59642064909790E+00     1.44701335179590E+00
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    1.0910064128619E+01
     FUNCTIONS
    1.8201282572371E-02     1.3361063959443E-02     1.1282839308836E-02
    3.5210188133234E-02     6.6345505710400E-03    -1.4042944131584E-03
                 .0E+00

ITERATION   6         32 CALLS OF CALFUN      F=      1.84966517499457E-03
     VARIABLES
    1.2096834745770E-01     1.6006831693909E+00     1.4349207295913E+00
    1.0908708538632E+01
     FUNCTIONS
    1.8174170772637E-02     1.2501203228130E-02     8.1585000348219E-03
    3.5340542772627E-02     3.4760535110428E-03     5.9570609596441E-03
                 .0E+00

ITERATION   7         36 CALLS OF CALFUN      F=      1.82442417557668E-03
     VARIABLES
    1.2053034534305E-01     1.5846263319001E+00     1.4234168971599E+00
    1.0862495038021E+01
     FUNCTIONS
    1.7249900772421E-02     1.2217433069716E-02     5.3578470062697E-03
    3.5498029631602E-02     6.1697477104794E-04     9.4021084910840E-03
                 .0E+00

ITERATION   8         40 CALLS OF CALFUN      F=      1.81141668433674E-03
     VARIABLES
    1.2087876310256E-01     1.6074908898838E+00     1.4294821692907E+00
    1.0912342571166E+01
     FUNCTIONS
    1.8246851423322E-02     1.2051533844551E-02     5.0345284129435E-03
    3.5609430975970E-02     3.2944974399286E-04     6.3042082420143E-03
                 .0E+00

ITERATION   9         44 CALLS OF CALFUN      F=      1.77393882637968E-03
     VARIABLES
    1.2074246551172E-01     1.5948378558774E+00     1.4332478107348E+00
    1.0883694838799E+01
     FUNCTIONS
    1.7673896775977E-02     1.2860222499918E-02     4.8298633016234E-03
    3.5674118363572E-02     1.0069330978345E-04     4.5256385711837E-04
                 .0E+00

ITERATION  10         49 CALLS OF CALFUN      F=      1.74319569027510E-03
     VARIABLES
    1.2035534029901E-01     1.5667356494543E+00     1.4273115473721E+00
    1.0817866233683E+01
     FUNCTIONS
    1.6357324673668E-02     1.2568117239308E-02     3.8849846495017E-03
    3.5919390653676E-02    -8.7611555502703E-04    -3.3325826854794E-03
                 .0E+00

ITERATION  11         55 CALLS OF CALFUN      F=      1.74319569027510E-03
     VARIABLES
    1.2035534029901E-01     1.5667356494543E+00     1.4273115473721E+00
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    1.0817866232680E+01
     FUNCTIONS
    1.6357324673468E-02       1.2588117239308E-02       3.8843845495017E-03
    3.5919390653676E-02      -8.7811555602703E-04      -3.3925823854794E-03
                 .0E+00

ITERATION  12          61 CALLS OF CALFUN      F=      1.73071928726155E-03
     VARIABLES
    1.2028023821194E-01       1.5620580349701E+00       1.4270546751032E+00
    1.0510445060043E+01
     FUNCTIONS
    1.6208301200907E-02       1.3058936269954E-02       4.8070397696167E-03
    3.5397874646523E-02       4.0083742240676E-05       8.6604192387312E-05
                 .0E+00

ITERATION  13          64 CALLS OF CALFUN      F=      1.72680987502532E-03
     VARIABLES
    1.2032203367021E-01       1.5645308051928E+00       1.4259273922201E+00
    1.0815406307504E+01
     FUNCTIONS
    1.6308136110080E-02       1.2637162402019E-02       4.6287164261837E-03
    3.5773049146541E-02      -1.3648953280644E-04       1.3970870415797E-04
                 .0E+00

ITERATION  14          70 CALLS OF CALFUN      F=      1.62547980792550E-03
     VARIABLES
    1.1895772723611E-01       1.4666789983870E+00       1.4001820515074E+00
    1.0596712670383E+01
     FUNCTIONS
    1.1934253407663E-02       1.1563992960237E-02       6.7554266646853E-03
    3.6013209163519E-02       1.9021008232667E-03       1.7670481384615E-03
                 .0E+00

ITERATION  15          75 CALLS OF CALFUN      F=      1.62308759486076E-03
     VARIABLES
    1.1900943964435E-01       1.4691882654592E+00       1.4015409970467E+00
    1.0602406010910E+01
     FUNCTIONS
    1.2048120273198E-02       1.1583189553736E-02       6.5045183713839E-03
    3.6036087102449E-02       1.6509738813329E-03       6.5273633708712E-04
                 .0E+00

ITERATION  16          81 CALLS OF CALFUN      F=      1.62306967036432E-03
     VARIABLES
    1.1901399858770E-01       1.4694128557192E+00       1.4016672049711E+00
    1.0602395746776E+01
     FUNCTIONS
    1.2057914935514E-02       1.1585288664682E-02       6.4819020310882E-03
    3.6036392740520E-02       1.6284191677230E-03       5.3069672776619E-04
                 .0E+00

ITERATION  17          85 CALLS OF CALFUN      F=      1.62144419313977E-03
     VARIABLES
    1.1900389270155E-01       1.4739481233395E+00       1.4015110468359E+00
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     1.0610276227277E+01
      FUNCTIONS
     1.2205524545543E-02      1.1843497267704E-02      5.6948352714360E-03
     3.6017575807708E-02      8.3738491762196E-04      1.3426864283276E-03
                 .0E+00

 ITERATION  18        91 CALLS OF CALFUN      F=      1.62144419313977E-03
      VARIABLES
     1.1900389270155E-01      1.4739481233395E+00      1.4015110468359E+00
     1.0610276227277E+01
      FUNCTIONS
     1.2205524545543E-02      1.1843497267704E-02      5.6948352714360E-03
     3.6017575807708E-02      8.3738491762196E-04      1.3426864283276E-03
                 .0E+00

 ITERATION  19        96 CALLS OF CALFUN      F=      1.62023644161241E-03
      VARIABLES
     1.1903829779026E-01      1.4753764044835E+00      1.4021122662789E+00
     1.0613291684025E+01
      FUNCTIONS
     1.2265833680509E-02      1.1755804697556E-02      5.5322092472634E-03
     3.6062009741672E-02      6.7606520822155E-04      2.3637199009536E-04
                 .0E+00
      POWSQ   100 CALLS OF CALFUN

      POWSQ FINAL VALUES OF FUNCTIONS AND VARIABLES

 I1ERATION  20       101 CALLS OF CALFUN      F=      1.62023644161241E-03
      VARIABLES
     1.1905852123763E-01      1.4763228961750E+00      1.4018544718167E+00
     1.0615497465812E+01
      FUNCTIONS
     1.2309949316243E-02      1.1615573433428E-02      5.4687894723087E-03
     3.6079795798878E-02      6.1311672545853E-04      2.7481764563709E-04
                 .0E+00

          REPORT ON THE FINAL DESIGN FOLLOWS:


    DESIGN COMPLETED

  1 CYLINDERS WITH  1 GAS GENERATORS EACH

CYLINDER DIAMETER  2.5000 INCH, PISTON-ROD DIAMETER  1.2500 INCH
HEAD CLEARANCE     1.4763 INCH, BUFFER LENGTH       20.4019 INCH
PISTON  1.750 INCH THICK WITH   1 VENTS OF  .1191 IN. DIAM.
PROPELLANT LOADING: 10.615 GRAM PER GENERATOR

   PERFORMANCE:
 .0653 SEC. TO CROSS 19.0000 INCHES ( 1.036 OF TIME REQUIRED)
VELOCITY OF ARRIVAL:   303.5 IPS (1.012 OF FINAL VELOCITY ALLOWED)
MAXIMUM PISTON-ROD STRESS 20109.4 PSI (1.005 OF STRESS ALLOWED)
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MAXIMUM HEAD-SPACE PRESSURE  5003.1 PSIA (PRESSURE RATING 5000.0 PSIA)
MAXIMUM BUFFER PRESSURE  5001.4 PSIA (PRESSURE RATING  5000.0 PSIA)
MAXIMUM GENERATOR PRESSURE  4915.1 PSIA (PRESSURE RATING 32000.0 PSIA)

PROGRAM IS AGAIN INTERACTIVE WITH THE TELETYPE


IS THE ABOVE DESIGN SATISFACTORY? TYPE YES TO EXIT, NO  TO TRY AGAIN
(TELETYPE INPUT) --> YES

ALL DONE
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b. Complete History of Test Design B

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GIVE TITLE FOR THIS ACTUATOR DESIGN PROBLEM

(TELETYPE INPUT) -->
 18 X 2 PERFORMANCE WITH MINIMUM PROPELLANT. WT(PW)=.05. ESCALE=5000.

GIVE VALUES FOR WLB,STR,TR,VFAL,STAL,GPAL,CPAL
(TELETYPE INPUT)    ->
 3.565E+02 1.900E+01 6.300E-02 3.000E+02 2.000E+04 3.200E+04 5.000E+03

DO YOU HAVE A REASONABLE FIRST GUESS? YES OR NO
(TELETYPE INPUT) --> NO


FOLLOWING IS THE POWSQ OUTPUT GIVING THE SEARCH HISTORY


 ITERATION    0          7 CALLS OF CALFUN      F=     1.05477404856402E-01
    VARIABLES
   1.2778492391589E-01     2.4492104289085E+00     2.4492104289084E+00
   2.3338363651464E+00     1.1669181840732E+00     1.3140817700140E+01
    FUNCTIONS
   1.5704088500698E-01     1.0254440327099E-02     5.7196025057090E-02
   6.6897626793189E-02     5.3548192386690E-02    -2.6475710582614E-01
                .0E+00

 ITERATION    1         11 CALLS OF CALFUN      F=     9.52539036319293E-02
    VARIABLES
   1.2085686878595E-01     2.1992104289084E+00     2.3228094186436E+00
   2.3642718746830E+00     1.1823551749710E+00     1.2754354221699E+01
    FUNCTIONS
   1.3771771108497E-01     1.1575646095825E-02     6.8041677976207E-02
   5.6041246333308E-02     6.5019220109383E-02    -2.5329024830591E-01
                .0E+00

 ITERATION    2         17 CALLS OF CALFUN      F=     2.25232793871223E-02
    VARIABLES
   1.1308827048007E-01     2.0197233055626E+00     1.5496534003747E+00
   2.3832710115560E+00     1.1932788456639E+00     1.2014946550793E+01
    FUNCTIONS
   1.0074732753966E-01    -8.7557024303351E-03     4.3098324833589E-02
   4.4574297324662E-02     4.0898991600587E-02     8.2337913237436E-02
                .0E+00

 ITERATION    3         23 CALLS OF CALFUN      F=     2.01876105321799E-02
    VARIABLES
   1.1493135417834E-01     1.6508230227415E+00     1.3684783211745E+00
   2.4860161805564E+00     1.2446744343395E+00     1.1364854495357E+01
    FUNCTIONS
   6.8242724767845E-02    -2.5239255002064E-02     3.4596516069560E-02
   3.2699997512008E-02     3.3315085684234E-02     1.0731923108090E-01
                .0E+00
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ITERATION    4          26 CALLS OF CALFUN       F=      1.45386019184651E-02
   VARIABLES
  1.0791300281077E-01      1.8659821792336E+00      1.5048140549805E+00
  2.3964012624153E+00      1.2003122846847E+00      1.1559580467344E+01
   FUNCTIONS
  7.7979023367200E-02      2.7756844857577E-02      4.0205618844222E-02
  3.5095036482260E-02      3.8201843274617E-02      5.7521362308576E-02
                .0E+00

ITERATION    5          29 CALLS OF CALFUN       F=      6.62705619330645E-03
   VARIABLES
  1.0806031999426E-01      1.4039565104593E+00      1.3998495519038E+00
  2.5157052181090E+00      1.2598225686803E+00      1.0776493689039E+01
   FUNCTIONS
  3.8844684451925E-02      2.9384365579275E-02      4.1874204376602E-02
  1.7787297706368E-02      4.0485311031301E-02      2.3362542271759E-02
                .0E+00

ITERATION    6          35 CALLS OF CALFUN       F=      5.65714214208962E-03
   VARIABLES
  1.0932151940575E-01      1.3879585679712E+00      1.3945622265569E+00
  2.5225393730122E+00      1.2632113491443E+00      1.0752008454102E+01
   FUNCTIONS
  3.7600422705097E-02      2.8113951548591E-02      4.0283056151325E-02
  1.7224287827179E-02      3.8920046934036E-02      4.3342050255392E-03
                .0E+00

ITERATION    7          41 CALLS OF CALFUN       F=      5.64737911316818E-03
   VARIABLES
  1.0934557866020E-01      1.3845000085442E+00      1.3889000350601E+00
  2.5240051379422E+00      1.2639528625641E+00      1.0745905631014E+01
   FUNCTIONS
  3.7295281550681E-02      2.7186928089080E-02      4.0193695668067E-02
  1.7124651720697E-02      3.8867117814341E-02      9.8930436716822E-03
                .0E+00

ITERATION    8          47 CALLS OF CALFUN       F=      5.64737911316818E-03
   VARIABLES
  1.0934557866020E-01      1.3845000085442E+00      1.3889000350601E+00
  2.5240051379422E+00      1.2639528625641E+00      1.0745905631014E+01
   FUNCTIONS
  3.7295281550681E-02      2.7186928089080E-02      4.0193695668067E-02
  1.7124651720697E-02      3.8867117814341E-02      9.8930436716822E-03
                .0E+00

ITERATION    9          53 CALLS OF CALFUN       F=      5.64737911316818E-03
   VARIABLES
  1.0934557866020E-01      1.3845000085442E+00      1.3889000350601E+00
  2.5240051379422E+00      1.2639528625641E+00      1.0745905631014E+01
   FUNCTIONS
  3.7295281550681E-02      2.7186928089080E-02      4.0193695668067E-02
  1.7124651720697E-02      3.8867117814341E-02      9.8930436716822E-03
                .0E+00
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ITERATION  10          59 CALLS OF CALFUN       F=     5.64737911316818E-03
     VARIABLES
   1.09345578660020E-01      1.38450000085442E+00      1.38890000350601E+00
   2.52400051379422E+00      1.26395286625641E+00      1.07459056310014E+01
     FUNCTIONS
   3.72952815506810E-02      2.71869280089080E-02      4.01936956680067E-02
   1.71246517208970E-02      3.88671178143410E-02      9.89304367168220E-03
                .0E+00

ITERATION  11          65 CALLS OF CALFUN       F=     5.64737911316818E-03
     VARIABLES
   1.09345578660020E-01      1.38450000085442E+00      1.38890000350601E+00
   2.52400051379422E+00      1.26395286625641E+00      1.07459056310014E+01
     FUNCTIONS
   3.72952815506810E-02      2.71869280089080E-02      4.01936956680067E-02
   1.71246517208970E-02      3.88671178143410E-02      9.89304367168220E-03
                .0E+00

ITERATION  12          71 CALLS OF CALFUN       F=     5.64737911316818E-03
     VARIABLES
   1.09345578660020E-01      1.38450000085442E+00      1.38890000350601E+00
   2.52400051379422E+00      1.26395286625641E+00      1.07459056310014E+01
     FUNCTIONS
   3.72952815506810E-02      2.71869280089080E-02      4.01936956680067E-02
   1.71246517208970E-02      3.88671178143410E-02      9.89304367168220E-03
                .0E+00

ITERATION  13          77 CALLS OF CALFUN       F=     5.64732717924302E-03
     VARIABLES
   1.09345551277000E-01      1.38450305371270E+00      1.38890142464460E+00
   2.52400399710640E+00      1.26395229297160E+00      1.07459107110300E+01
     FUNCTIONS
   3.72955355514790E-02      2.71871730287720E-02      4.01934533998780E-02
   1.71247576672310E-02      3.88668549742840E-02      9.89062146245270E-03
                .0E+00

     POWSQ FINAL VALUES OF FUNCTIONS AND VARIABLES

ITERATION  13          77 CALLS OF CALFUN       F=     5.64732717924302E-03
     VARIABLES
   1.09345551277000E-01      1.38450305371270E+00      1.38890142464460E+00
   2.52400399710640E+00      1.26395229297160E+00      1.07459107110300E+01
     FUNCTIONS
   3.72955355514790E-02      2.71871730287720E-02      4.01934533998780E-02
   1.71247576672310E-02      3.88668549742840E-02      9.89062146245270E-03
                .0E+00
```

```
FIRST TRY:      1 CYLINDER, 1 GAS GENERATORS & 1 VENT:

   PERFORMANCE
TIME FOR FULL STROKE   6.408E-02 SEC.   FINAL VELOCITY   3.082E+02 IPS
MAX.ROD STRESS         2.080E+04 PSI    MAX.GEN.PRESS.   5.095E+03 PSIA
MAX. HEAD CYL. PRESS.  5.194E+03 PSIA   MAX. BUFFER PR.  5.049E+03 PSIA

   ACTUATOR SPECS:
WEIGHT OF PROPELLANT    10.7459 GRAM   VENT-HOLE DIAM.      .1093 INCH
HEAD CLEARANCE           1.3845 INCH   BUFFER LENGTH      20.3889 INCH
CYLINDER DIAMETER        2.5240 INCH   PISTON-ROD DIA.     1.2640 INCH

OPTIONS AVAILABLE:
CYLINDERS GEN./CYL.  TOTAL GEN.  CHARGE(GRAM)/GEN.  CYL.DIA.  P.ROD DIA.

    1          1          1            10.746         2.524       1.264


          RECORD OF INTERACTIVE COMMUNICATIONS WITH TELETYPE


IS ONE OF THE ABOVE PROPOSE ACCEPTABLE? YES OR NO
(TELETYPE INPUT)   --> YES

SELECT OPTION - TYPE NO. OF CYL. AND GEN./CYL.
(TELETYPE INPUT)   -->      1    1

TYPE PREFERRED CYLINDER AND PISTON-ROD DIAMETERS
(TELETYPE INPUT) -->     2.50000     1.25000

THERE IS AN ANNULAR CLEARANCE OF   .625 INCH (VENT-HOLE DIAM.=   .109)
TYPE MAX. ACCEPTABLE VENT-HOLE DIAM.
(TELETYPE INPUT) -->       .25000

THERE WILL BE  1 VENT-HOLES PER PISTON, OF APPROX. .109 INCH DIAM.

MIN. VENT LENGTH (I.E. PISTON THICKNESS) IS  1.640 INCH.
TYPE PREFERRED VENT-HOLE LENGTH.
(TELETYPE INPUT) -->     1.75000

YOUR CHOICE OF VENT LENGTH GIVES AN L/D RATIO OF  16.0 OK OR NO?
(TELETYPE INPUT)   --> OK

FOLLOWING IS THE POWSQ OUTPUT GIVING THE SEARCH HISTORY

 ITERATION    0          5 CALLS OF CALFUN      F=     2.4976907212912OE-02
     VARIABLES
   1.0934555127700E-01      1.4112175778549E+00      1.4142411432786E+00
   1.0745910711030E+01
    FUNCTIONS
   3.7295535551479E-02      1.2275290173056E-01      5.6374103707500E-02
  -4.8032280906814E-03      5.0602124812297E-02     -5.0114707916893E-02
                 .0E+00
```

```
ITERATION    1          10 CALLS OF CALFUN       F=      1.92780558645806E-02
   VARIABLES
  1.0941948098266E-01      1.3955046082157E+00      1.3729615127104E+00
  1.0695536905062E+01
   FUNCTIONS
  3.4776845253100E-02      1.1351215253864E-01      5.3401800225419E-02
 -2.8148908926101E-03      4.7664436051075E-02      7.2141376994841E-03
                .0E+00

ITERATION    2          16 CALLS OF CALFUN       F=      1.92780558645806E-02
   VARIABLES
  1.0941948098266E-01      1.3955046082157E+00      1.3729615127104E+00
  1.0695536905062E+01
   FUNCTIONS
  3.4776845253100E-02      1.1351215253864E-01      5.3401800225419E-02
 -2.8148908926101E-03      4.7664436051075E-02      7.2141376994841E-03
                .0E+00

ITERATION    3          22 CALLS OF CALFUN       F=      1.92780558645806E-02
   VARIABLES
  1.0941948098266E-01      1.3955046082157E+00      1.3729615127104E+00
  1.0695536905062E+01
   FUNCTIONS
  3.4776845253100E-02      1.1351215253864E-01      5.3401800225419E-02
 -2.8148908926101E-03      4.7664436051075E-02      7.2141376994841E-03
                .0E+00

ITERATION    4          28 CALLS OF CALFUN       F=      1.92780558645806E-02
   VARIABLES
  1.0941948098266E-01      1.3955046082157E+00      1.3729615127104E+00
  1.0695536905062E+01
   FUNCTIONS
  3.4776845253100E-02      1.1351215253864E-01      5.3401800225419E-02
 -2.8148908926101E-03      4.7664436051075E-02      7.2141376994841E-03
                .0E+00

ITERATION    5          30 CALLS OF CALFUN       F=      1.92780558645739E-02
   VARIABLES
  1.0941948098273E-01      1.3955046082149E+00      1.3729615127141E+00
  1.0695536905062E+01
   FUNCTIONS
  3.4776845253120E-02      1.1351215253865E-01      5.3401800225588E-02
 -2.8148908925820E-03      4.7664436051255E-02      7.2141376963875E-03
                .0E+00

   POWSQ FINAL VALUES OF FUNCTIONS AND VARIABLES

ITERATION    5          30 CALLS OF CALFUN       F=      1.92780558645739E-02
   VARIABLES
  1.0941948098273E-01      1.3955046082149E+00      1.3729615127141E+00
  1.0695536905062E+01
```

```
     FUNCTIONS
   3.4776845253120E-02     1.1351215253865E-01     5.3401600225588E-02
  -2.8149908925020E-03     4.7664436051255E-02     7.2141376963875E-03
                 .0E+00

          REPORT ON THE FINAL DESIGN FOLLOWS:


    DESIGN COMPLETED


  1 CYLINDERS WITH  1 GAS GENERATORS EACH

CYLINDER DIAMETER  2.5000 INCH, PISTON-ROD DIAMETER  1.2500 INCH
HEAD CLEARANCE     1.3955 INCH, BUFFER LENGTH       20.3730 INCH
PISTON  1.750 INCH THICK WITH   1 VENTS OF  .1094 IN. DIAM.
PROPELLANT LOADING. 10.636 GRAM PER GENERATOR

   PERFORMANCE:
 .0628 SEC. TO CROSS 19.0000 INCHES (  .997 OF TIME REQUIRED)
VELOCITY OF ARRIVAL:   334.1 IPS (1.114 OF FINAL VELOCI   ALLOWED)
MAXIMUM PISTON-ROD STRESS 21068.0 PSI (1.053 OF STRESS    OWED)
MAXIMUM HEAD-SPACE PRESSURE  5238.3 PSIA (PRESSURE RATING  5000.0 PSIA)
MAXIMUM BUFFER PRESSURE  5036.1 PSIA (PRESSURE RATING  5000.0 PSIA)
MAXIMUM GENERATOR PRESSURE  5331.2 PSIA (PRESSURE RATING 32000.0 PSIA)

PROGRAM IS AGAIN INTERACTIVE WITH THE TELETYPE


IS THE ABOVE DESIGN SATISFACTORY? TYPE YES TO EXIT, NO  TO TRY AGAIN
(TELETYPE INPUT) --> YES

ALL DONE
```

APPENDIX VI

a. Teletype printout for Test Design A

b. Teletype printout for Test Design B

c. Teletype printout for Test Design C

d. Teletype printout for Test Design D

Test Design A

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DESAC / 8 4

GIVE TITLE FOR THIS ACTUATOR DESIGN PROBLEM

(TELETYPE INPUT) -->
 18 X 2 PERFORMANCE, WEIGHT ON EXCESS-OVER-MINIMUM PROPELLANT = 0.02

GIVE VALUES FOR WLB,STR,TR,VFAL,STAL,GPAL,CPAL
(TELETYPE INPUT)  -->
 3.565E+02 1.900E+01 6.300E-02 3.000E+02 2.000E+04 3.200E+04 5.000E+03

DO YOU HAVE A REASONABLE FIRST GUESS? YES OR NO
(TELETYPE INPUT) --> NO


FIRST TRY:      1 CYLINDER, 1 GAS GENERATORS & 1 VENT:


   PERFORMANCE
TIME FOR FULL STROKE  8.922E-02 SEC.   FINAL VELOCITY  3.055E+02 IPS
MAX.ROD STRESS        2.104E+04 PSI    MAX.GEN.PRESS.  5.335E+03 PSIA
MAX. HEAD CYL. PRESS. 5.232E+03 PSIA   MAX. BUFFER PR. 4.827E+03 PSIA


   ACTUATOR SPECS:
WEIGHT OF PROPELLANT    14.8679 GRAM   VENT-HOLE DIAM.     .1147 INCH
HEAD CLEARANCE           3.8767 INCH   BUFFER LENGTH     21.3930 INCH
CYLINDER DIAMETER        2.0886 INCH   PISTON-ROD DIA.    1.0454 INCH


OPTIONS AVAILABLE:
CYLINDERS GEN./CYL. TOTAL GEN. CHARGE(GRAM)/GEN. CYL.DIA. P.ROD DIA.

    1         1          1            14.868        2.089      1.045


(TELETYPE INPUT)  --> YES

SELECT OPTION - TYPE NO. OF CYL. AND GEN./CYL.
(TELETYPE INPUT)  -->    1    1

TYPE PREFERRED CYLINDER AND PISTON-ROD DIAMETERS
(TELETYPE INPUT) -->   2.50000   1.25000

THERE IS AN ANNULAR CLEARANCE OF   .625 INCH (VENT-HOLE DIAM.=  .115)
TYPE MAX. ACCEPTABLE VENT-HOLE DIAM.
(TELETYPE INPUT) -->    .25000

THERE WILL BE  1 VENT-HOLES PER PISTON, OF APPROX. .115 INCH DIAM.

MIN. VENT LENGTH (I.E. PISTON THICKNESS) IS  1.721 INCH.
TYPE PREFERRED VENT-HOLE LENGTH.
(TELETYPE INPUT) -->    1.75000

YOUR CHOICE OF VENT LENGTH GIVES AN L/D RATIO OF  15.3 OK OR NO?
(TELETYPE INPUT)  --> OK







  DESIGN COMPLETED


 1 CYLINDERS WITH  1 GAS GENERATORS EACH

CYLINDER DIAMETER  2.5000 INCH, PISTON-ROD DIAMETER  1.2500 INCH
HEAD CLEARANCE     1.4763 INCH, BUFFER LENGTH       20.4019 INCH
PISTON  1.750 INCH THICK WITH   1 VENTS OF  .1191 IN. DIAM.
PROPELLANT LOADING: 10.615 GRAM PER GENERATOR


  PERFORMANCE:
 .0653 SEC. TO CROSS 19.0000 INCHES ( 1.036 OF TIME REQUIRED)
VELOCITY OF ARRIVAL:   303.5 IPS (1.012 OF FINAL VELOCITY ALLOWED)
MAXIMUM PISTON-ROD STRESS 20109.4 PSI (1.005 OF STRESS ALLOWED)
MAXIMUM HEAD-SPACE PRESSURE  5003.1 PSIA (PRESSURE RATING 5000.0 PSIA)
MAXIMUM BUFFER PRESSURE  5001.4 PSIA (PRESSURE RATING  5000.0 PSIA)
MAXIMUM GENERATOR PRESSURE  5115.1 PSIA (PRESSURE RATING 32000.0 PSIA)


IS THE ABOVE DESIGN SATISFACTORY? TYPE YES TO EXIT, NO  TO TRY AGAIN
(TELETYPE INPUT) --> YES

ALL DONE
```

Test Design B

```
DESAC / 8 4

GIVE TITLE FOR THIS ACTUATOR DESIGN PROBLEM

(TELETYPE INPUT) -->
 18 X 2 PERFORMANCE. WEIGHT ON EXCESS-OVER-MINIMUM PROPELLANT = 0.05

GIVE VALUES FOR WLB,STR,TR,VFAL,STAL,GPAL,CPAL
(TELETYPE INPUT)  -->
 3.565E+02 1.900E+01 6.300E-02 3.000E+02 2.000E+04 3.200E+04 5.000E+03

DO YOU HAVE A REASONABLE FIRST GUESS? YES OR NO
(TELETYPE INPUT) --> NO


FIRST TRY:      1 CYLINDER, 1 GAS GENERATORS & 1 VENT:


   PERFORMANCE
TIME FOR FULL STROKE  6.408E-02 SEC.   FINAL VELOCITY  3.082E+02 IPS
MAX.ROD STRESS        2.080E+04 PSI    MAX.GEN.PRESS.  5.291E+03 PSIA
MAX. HEAD CYL. PRESS. 5.194E+03 PSIA   MAX. BUFFER PR. 5.049E+03 PSIA


   ACTUATOR SPECS:
WEIGHT OF PROPELLANT   10.7459 GRAM   VENT-HOLE DIAM.     .1093 INCH
HEAD CLEARANCE          1.3845 INCH   BUFFER LENGTH     20.3889 INCH
CYLINDER DIAMETER       2.5240 INCH   PISTON-ROD DIA.    1.2640 INCH


OPTIONS AVAILABLE:
CYLINDERS GEN./CYL. TOTAL GEN. CHARGE(GRAM)/GEN. CYL.DIA. P.ROD DIA.

    1         1          1            10.746        2.524      1.264


IS ONE OF THE ABOVE OPTIONS ACCEPTABLE? YES OR NO
(TELETYPE INPUT)  --> YES

SELECT OPTION - TYPE NO. OF CYL. AND GEN./CYL.
(TELETYPE INPUT)  -->      1    1

TYPE PREFERRED CYLINDER AND PISTON-ROD DIAMETERS
(TELETYPE INPUT) -->    2.50000    1.25000

THERE IS AN ANNULAR CLEARANCE OF   .625 INCH (VENT-HOLE DIAM.=  .109)
TYPE MAX. ACCEPTABLE VENT-HOLE DIAM.
(TELETYPE INPUT) -->      .25000

THERE WILL BE  1 VENT-HOLES PER PISTON, OF APPROX. .109 INCH DIAM.

MIN. VENT LENGTH (I.E. PISTON THICKNESS) IS  1.640 INCH.
TYPE PREFERRED VENT-HOLE LENGTH.
(TELETYPE INPUT) -->     1.75000

YOUR CHOICE OF VENT LENGTH GIVES AN L/D RATIO OF  16.0 OK OR NO?
(TELETYPE INPUT)  --> OK


   DESIGN COMPLETED


 1 CYLINDERS WITH  1 GAS GENERATORS EACH

CYLINDER DIAMETER  2.5000 INCH, PISTON-ROD DIAMETER  1.2500 INCH
HEAD CLEARANCE     1.3955 INCH, BUFFER LENGTH       20.3730 INCH
PISTON  1.750 INCH THICK WITH   1 VENTS OF  .1094 IN. DIAM.
PROPELLANT LOADING: 10.696 GRAM PER GENERATOR


  PERFORMANCE:
 .0628 SEC. TO CROSS 19.0000 INCHES (  .997 OF TIME REQUIRED)
VELOCITY OF ARRIVAL:   334.1 IPS (1.114 OF FINAL VELOCITY ALLOWED)
MAXIMUM PISTON-ROD STRESS 21068.0 PSI (1.053 OF STRESS ALLOWED)
MAXIMUM HEAD-SPACE PRESSURE  5238.3 PSIA (PRESSURE RATING 5000.0 PSIA)
MAXIMUM BUFFER PRESSURE  5036.1 PSIA (PRESSURE RATING  5000.0 PSIA)
MAXIMUM GENERATOR PRESSURE  5331.2 PSIA (PRESSURE RATING 32000.0 PSIA)


IS THE ABOVE DESIGN SATISFACTORY? TYPE YES TO EXIT, NO  TO TRY AGAIN
(TELETYPE INPUT) --> YES

ALL DONE
```

Test Design C

```
DES^C / 6 4

GIVE TITLE FOR THIS ACTUATOR DESIGN PROBLEM

(TELETYPE INPUT) -->
 POOR START OBTAINED BY REVERSING IMPROVEMENT IN FINAL A DESIGN

GIVE VALUES FOR WLB,STR,TR,VFAL,STAL,GPAL,CPAL
(TELETYPE INPUT)  -->
 3.966E+02 1.900E+01 5.300E-02 3.000E+02 2.000E+04 3.200E+04 5.000E+03

DO YOU HAVE A REASONABLE FIRST GUESS? YES OR NO
(TELETYPE INPUT) --> YES
GIVE VALUES OF HD,HL,BL,PWGR,CD,PRD,PT
(TELETYPE INPUT)  -->
 1.104E-01 3.995E+01 2.094E+01 1.912E+01 2.500E+00 1.250E+00 1.750E+00
GIVE VALUES FOR NC,NOGC,NH
(TELETYPE INPUT) -->       1     1     1


   DESIGN COMPLETED

 1 CYLINDERS WITH  1 GAS GENERATORS EACH

CYLINDER DIAMETER  2.5000 INCH, PISTON-ROD DIAMETER  1.2500 INCH
HEAD CLEARANCE     1.3328 INCH, BUFFER LENGTH        20.3628 INCH
PISTON  1.750 INCH THICK WITH  1 VENTS OF  .1054 IN. DIAM.
PROPELLANT LOADING  10.152 GRAM PER GENERATOR

  PERFORMANCE:
 .0555 SEC  TO CROSS 1[illegible].0000 INCHES ( 1.042 OF TIME REQUIRED)
VELOCITY OF ARRIVAL    301.9 IPS (1.006 OF FINAL VELOCITY ALLOWED)
MAXIMUM PISTON-ROD STRESS 20117.5 PSI (1.006 OF STRESS ALLOWED)
MAX. IN HEAD-SPACE PRESSURE  5003.0 PSIA (PRESSURE RATING 5000.0 PSIA)
MAX. IN BUFFER PRESSURE  5012.1 PSIA (PRESSURE RATING  5000.0 PSIA)
MAX. IN GENERATOR PRESSURE  5109.5 PSIA (PRESSURE RATING 32000.0 PSIA)

IS THE ABOVE DESIGN SATISFACTORY? TYPE YES TO EXIT, NO  TO TRY AGAIN
(TELETYPE INPUT) --> YES

ALL DONE
```

Test Design D

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DESAC / 6 3

GIVE TITLE FOR THIS ACTUATOR DESIGN PROBLEM

(TELETYPE INPUT) -->
 REDESIGN OF 4 CYL. 18 INCH VALVE TO ELIMINATE GREASE-PACK DECELERATOR

GIVE VALUES FOR WLB,STR,TR,VFAL,STAL,GPAL,CPAL
(TELETYPE INPUT)  -->
 3.745E+02 1.900E+01 3.000E-02 2.000E+02 2.000E+04 3.200E+04 7.500E+03

DO YOU HAVE A REASONABLE FIRST GUESS? YES OR NO
(TELETYPE INPUT) --> YES
GIVE VALUES OF HD,HL,BL,PWGR,CD,PRD,PT
(TELETYPE INPUT)  -->
 2.500E-01 1.500E+00 1.925E+01 2.000E+01 3.000E+00 1.688E+00 4.000E+00
GIVE VALUES FOR NC,NOGC,NH
(TELETYPE INPUT) -->      4    1    1


   DESIGN COMPLETED

 4 CYLINDERS WITH  1 GAS GENERATORS EACH

CYLINDER DIAMETER  3.0000 INCH, PISTON-ROD DIAMETER  1.6875 INCH
HEAD CLEARANCE     2.1573 INCH, BUFFER LENGTH        19.1725 INCH
PISTON  4.000 INCH THICK WITH   1 VENTS OF  .2809 IN. DIAM.
PROPELLANT LOADING: 22.460 GRAM PER GENERATOR

  PERFORMANCE:
 .0285 SEC. TO CROSS 19.0000 INCHES (   .949 OF TIME REQUIRED)
VELOCITY OF ARRIVAL:    210.7 IPS (1.053 OF FINAL VELOCITY ALLOWED)
MAXIMUM PISTON-ROD STRESS 20705.5 PSI (1.035 OF STRESS ALLOWED)
MAXIMUM HEAD-SPACE PRESSURE  6705.4 PSIA (PRESSURE RATING 7500.0 PSIA)
MAXIMUM BUFFER PRESSURE 11782.0 PSIA (PRESSURE RATING  7500.0 PSIA)
MAXIMUM GENERATOR PRESSURE  7754.4 PSIA (PRESSURE RATING 32000.0 PSIA)


IS THE ABOVE DESIGN SATISFACTORY? TYPE YES TO EXIT, NO  TO TRY AGAIN
(TELETYPE INPUT) --> YES

ALL DONE
```