Space Journal

Volume 2 | Number 1 Article 13

9-1-1959

Thrust Control of Solid Propellant Motors

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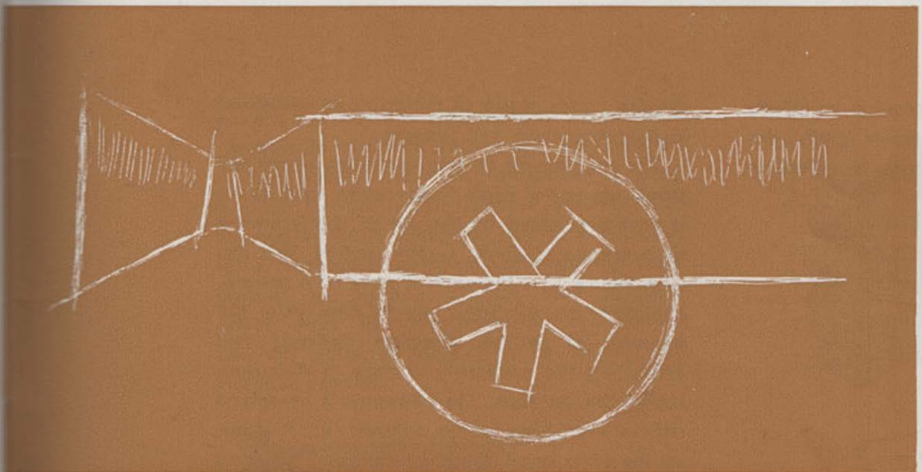


thrust control of solid propellant motors

Harold W. Ritchey received his Bachelor of Science degree in chemical engineering from Purdue University in 1934. In 1936 he received his Master of Science degree in physical chemistry. He also holds a Doctor of Philosophy degree in physical chemistry, from Purdue University, and a Master of Science degree in chemical engineering from Cornell University. A former petroleum chemist with the Union Oil Company of California, he served five years in the U. S. Navy during World War II. During his naval service, he was officer-in-charge of the Harbor Defense School at San Pedro, California, and was an instructor at the U. S. Naval Postgraduate School, where he taught, among other subjects, the mechanics and thermodynamics of jet propulsion. From 1948 until 1949 he was an atomic reactor engineer with the General Electric Company. In 1949 he joined the Thiokol Chemical Corporation. He is now vice president of the company and lives in Huntsville, Alabama. A member of Phi Lambda Upsilon honorary society, Sigma Xi honorary society, and the American Rocket Society, he received the C. N. Hickman award in 1954 for oustanding contributions to the field of solid propellant chemistry. Dr. Ritchey is the author of many technical papers and the popular article, "Rocket Mail to the Moon," which appeared in the spring 1958 Issue of SPACE Journal.

Thrust control of any type of liquid or solid propellant motor falls into one or more of the following categories which may be broadly defined as:

1. Thrust vector control or control of the direction of the vehicle, a process which involves generating a change in direction (pitch and yaw) along either of two axes perpendicular to the main line of thrust;
2. Thrust termination, which means simply shutting off the thrust;
3. Thrust modulation, which involves adjusting the amount of thrust at the command of some operational control.

The basic principles underlying the attainment of these three different types of thrust control have, in the past, given engineers much trouble in the design of practical solid propellant motors. However, due to the restrictions of security, it will not be possible to give detailed accounts of how solutions to these problems were approached or to describe actual devices that may now be in use.

First let us look at the problem of thrust vector control. It is needed primarily to maintain general direction and flight attitude (position of the vehicle with reference to Earth's surface). Moderate control may also be needed to correct for mechanical misalignment of the motor with the vehicle or for uneven thrust during the launching phase when the vehicle does not have enough velocity to permit aerodynamic control surfaces to function properly. Thrust vector control may also be needed at very high altitudes where the density of the atmosphere is not great enough to produce the required forces. In general, these applications do not demand very large changes in direction.

Thrust vector control may also be needed when the vehicle meets unstable aerodynamic conditions during flight. When these situations occur or when very high or varying wind direction and velocities are encountered, then

thrust vector control may require relatively large side (yaw) or up-and-down (pitch) deflections and very rapid means of effecting them.

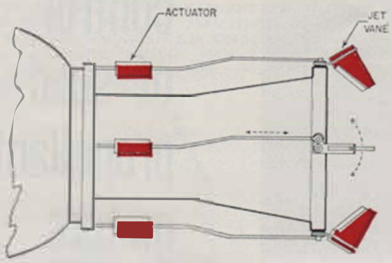


FIGURE NO. 1

Mechanically actuated jet vanes of the solid propellant motor provide thrust vector control and roll control of the vehicle by operating within the exhaust. Such vanes, coupled with aerodynamic surfaces, provided similar controls for the German V-2 guided missile.

One of the oldest methods of obtaining thrust vector control is by the use of jet vanes, a method used on the German V-2 and by several contemporary guided missiles. The most common application of this method has four vanes positioned within the jet exhaust stream of the motor, as shown in figure 1. Often these jet vanes are mechanically linked to aerodynamic surfaces called ailerons or elevons. They have the advantage of providing roll control (prevention of the vehicle from rotating about its long axis) as well as providing for side movements when they are applied to a single nozzle. There are, however, two disadvantages to the jet vane: (1) large side movements require proportionately large vanes and cross sections, both of which cause a drag loss in the jet stream; (2) the high velocity and high temperature of the exhaust gases

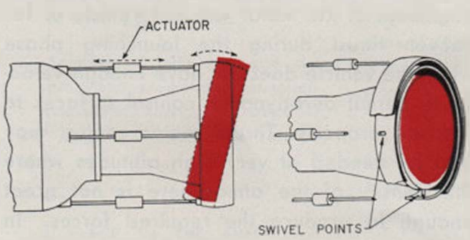


FIGURE NO. 2

The jetavator marks an improvement in the development of thrust vector control of solid propellant motors. While it does not provide roll control for single-motored vehicles, it does simplify the problems of thrust vector control.

require vanes made of materials to withstand high temperature and stresses.

The problem of finding materials which will stand up under high temperature and stress is partially solved by the use of the jetavator as a means of thrust vector control. This device, figure 2, is the central zone of a sphere, mounted on gimbals, which dips into the exhaust jet in the direction desired, thus producing the necessary change in direction. Unlike the jet vane, the jetavator is immersed only a short time in the exhaust jet. It does, on the other hand, have a relatively high drag loss during the time that it is used. Also, it is

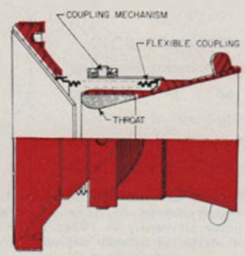


FIGURE NO. 3

The flexible nozzle represents a new and more sophisticated form of thrust vector control in solid propellant motors. Like the jetavator, it can not establish roll control in single motors.

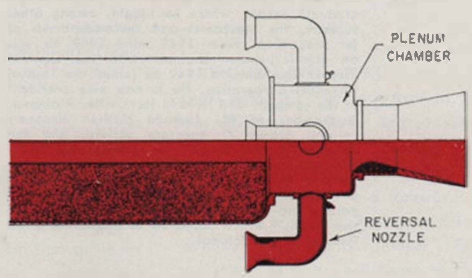


FIGURE NO. 4

Reversal nozzles, mounted around the main nozzle, offer a means of positive end of thrust for the solid propellant motor. However, they require the addition of a plenum chamber to the total weight of a solid propellant motor.

not capable of providing roll control unless the motor is fitted with multiple nozzles.

A third device for attaining thrust vector control is the flexible nozzle shown in figure 3. It is adapted from a control common to liquid propellant engines where the combustion chamber is mounted on gimbals. For the solid propellant motor use, the nozzle is attached to the combustion chamber by a flexible coupling and mounted on gimbals. It is

easy to see that this arrangement can produce changes in direction by moving the position of the nozzle. From a standpoint of drag loss the flexible nozzle is more efficient than the two methods described above. But it does raise mechanical problems by requiring seals against the escape of hot, high pressure gases. And, like the jetavator, roll control can be obtained only from a motor with multiple nozzles.

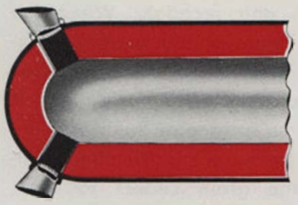


FIGURE NO. 5

Reversal nozzles can also be mounted on the forward or head end of the solid propellant rocket motor, but they must be mounted at an angle to avoid damage to the vehicle by the hot exhaust gases.

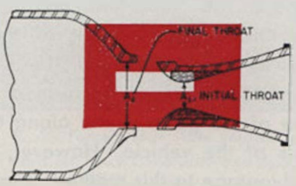


FIGURE NO. 6

A hypothetical arrangement for varying the ratio of the burning surface of a solid propellant grain so the nozzle area as a means of obtaining thrust modulation. Such a device is one means of controlling the range of a solid propelled rocket.

In addition to thrust vector control, many vehicles require the positive end of thrust once they have reached a certain velocity. This is ncessary to control their range. One method of achieving thrust termination is the generation of an exhaust jet in a direction opposite to the main propulsion stream. In this way, a reverse thrust is obtained that is equal to or slightly greater than the forward thrust. Such a reverse jet may be accomplished by reversal ducts connecting into a plenum chamber at the aft end of the motor, as shown in figure 4. Reverse ducts or jets

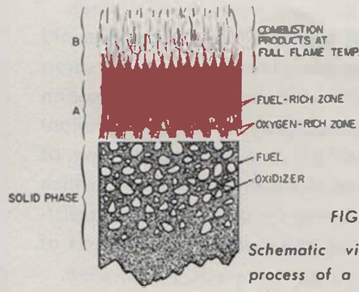


FIGURE NO. 7

Schematic view of the burning process of a solid propellant grain within a rocket motor. The face of the propellant grain actually contains a "foam" zone, consisting of liquefied propellant ingredients and some evolved gas. Zone A is known as the dark zone which contains a "fizz" zone and a flame reaction zone. Zone B is the flame zone which is luminous.

can also be used at the forward end of the motor, but in most cases they must be mounted at an angle so that the heat and shock of their exhausts do not damage the vehicle or its payload. This method is shown in figure 5. In either case the ducts must be opened rapidly and at exactly the some time. Failure of all ducts to open together could easily cause unbalanced side forces which could result in the vehicle's tumbling or yawing. One possible disadvantage of this method of thrust termination is that the plenum chamber necessary to feed the ducts would mean an increase in the weight of the motor.

Another method of terminating thrust is the quenching of the burning propellant grain. This can be done quite easily by setting up a shock expansion wave inside the combustion chamber of the motor as shown in figure 6. In this method a new nozzle throat area, A_2, opens when the old nozzle is blown from the combustion chamber. The new nozzle

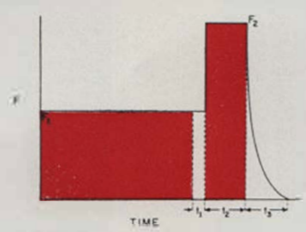


FIGURE NO. 8

Graph showing the duration of thrust transients which might be induced as a result of thrust termination in a solid propellant rocket motor.

Published by LOUIS, 1959

throat area has an area larger than the old one, A_1. This sudden increase in throat area sets up a shock wave inside the combustion chamber and puts out the burning propellant grain. A simplified and schematic view of how this is done is shown in figure 7, which represents a burning propellant grain consisting of an oxidizer and a fuel. The products of

Graph illustrating the chamber pressure-to-K_n relationship. It demonstrates that as the curve grows steeper, small changes in the value of K_n can effect large changes in P. Under certain conditions, this proves that auxiliary nozzles around a central nozzle can bring about thrust modulation in a solid propellant motor.

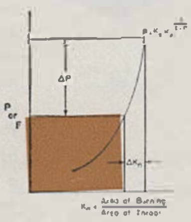


FIGURE NO. 9

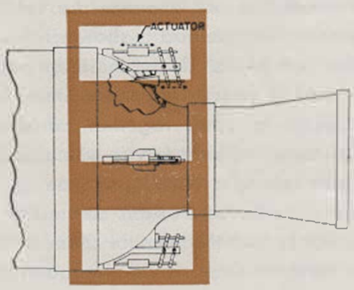


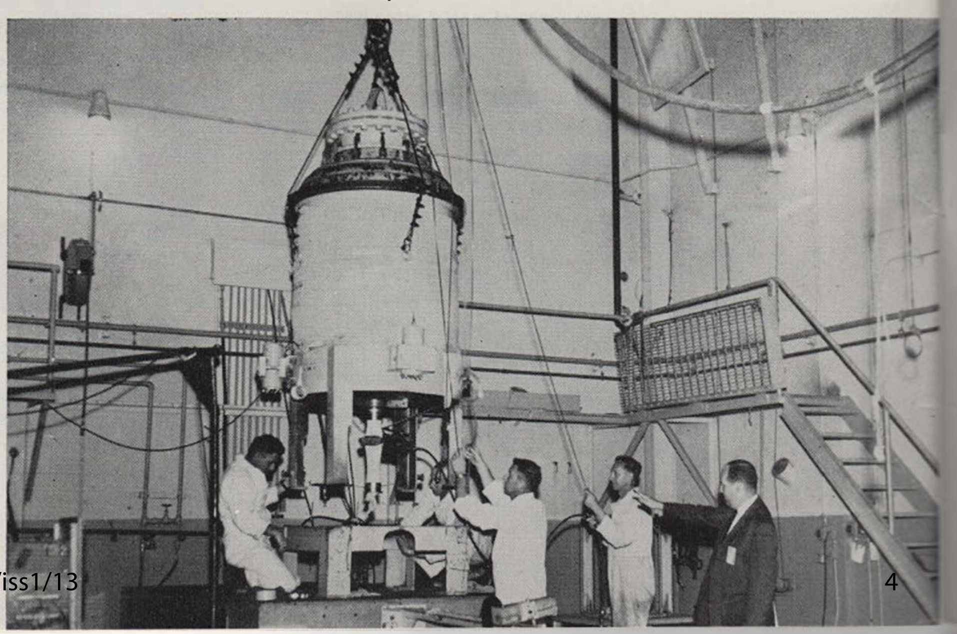
FIGURE NO. 10

The blow-off nozzle actually quenches the fire within the combustion chamber of the solid propellant rocket motor, thus providing a positive means of thrust termination.

the burning, at combustion chamber temperature, occupy region B. Between region B and the surface of the propellant grain, there is region A where the oxygen-rich and the fuel-rich gases formed by the burning propellant grain mix and react. During normal combustion, heat is transferred from region B to the surface of the propellant grain, through region A, at exactly the right rate to support the burning process as the surface of the grain is used up and recedes. When the nozzle, shown in figure 6, blows off, an expansion wave travels through the combustion chamber. The reacting gases in region A expand and cool the surface of the propellant grain to a point below combustion temperature. Naturally the grain ceases to burn. Under atmospheric conditions it is normal for the grain to reignite after several seconds. But at high altitudes, region A is so diffuse and the reaction is so slow that combustion energy is not generated close enough to the surface of the propellant grain to reignite it.

There are two important advantages to thrust termination: the weight of the motor need not be increased, and the possibility of tumbling is minimized because of the exhaust flow of the gases is still along the main thrust axis of the vehicle. However, there is one disadvantage to this method: it introduces a thrust transient, or momentary instability, that could be troublesome for a payload in the vehicle. Suppose, as shown in figure 8, that the motor has an initial thrust of F_1 and that the time interval T_1 is necessary for the mechanical system to blow off the nozzle. At

Preparations are made for casting a solid propellant motor in Thiokol Chemical Corporation's Huntsville, Alabama plant.



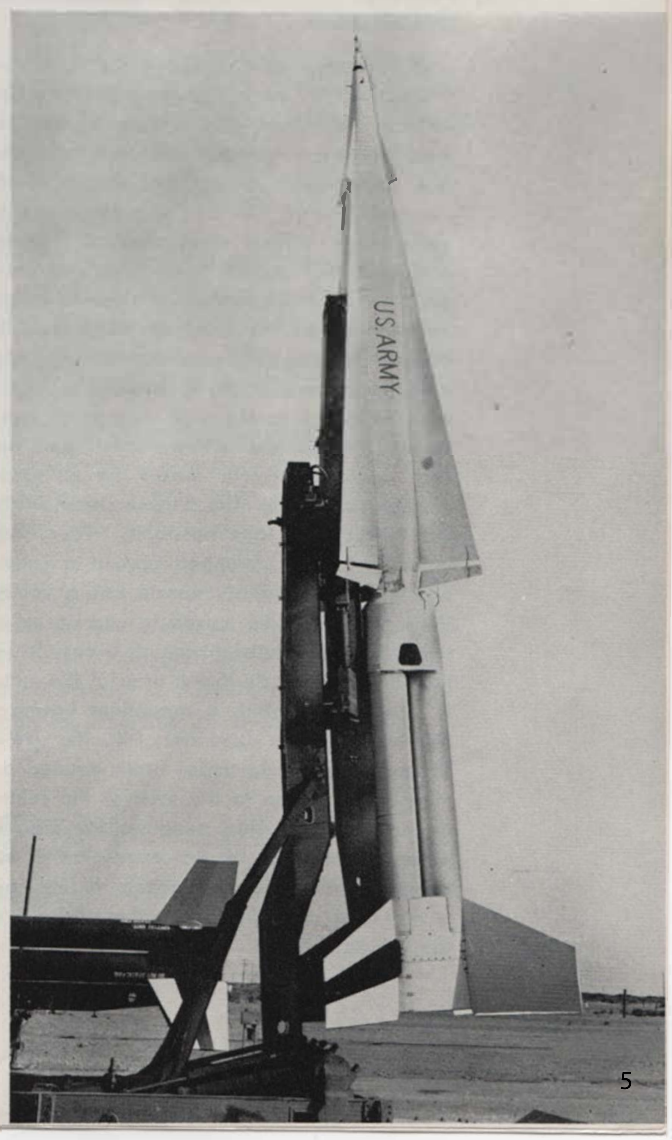
The U. S. Air Force's Thor Able vehicle is a three-stage missile used for Nose Cone tests and Space experiments. The missile's third stage has a solid propellant rocket motor while the first and second stages are liquid propelled. (U.S. AIR FORCE Photo)

the end of T_1 the thrust climbs rapidly to the value F_2. Since the expansion wave travels at the speed of sound (approximately 3000 feet per second) through the combustion chamber, the duration of the transient T_2 can be estimated by dividing the length of the motor by 3000 feet per second. The pressure on the head of the motor causes a more or less level peak in thrust for this period. After this, the thrust decays rapidly to zero during the interval T_3. In connection with this transient force, it is also possible that other transient forces could be caused by the relaxation of tensile stresses in the combustion chamber.

Since thrust is approximately proportional to the operating pressure of the motor, a method for varying this pressure appears to be the best approach to controlling the amount of thrust or—in other words—to obtain *thrust modulation*. Since chamber pressure is affected by the ratio of the burning surface of the propellant grain to the nozzle throat area, any such method must be based upon varying the ratio between the burning surface of the propellant grain and the nozzle throat area. This relationship is shown graphically in figure 9.

Perhaps a little painless mathematics will help clarify the meaning of this graph. It is obvious that as the curve grows steeper the changes in P (pressure) become proportionately larger as the changes in K_n become smaller. K_n represents the ratio of the area of the burning propellant surface to the area of the nozzle throat. The exponential *n* here is

The U. S. Army's Nike Hercules antiaircraft guided missile has a solid propellant sustainer motor and a solid propellant booster motor. (U. S. Army Photo)



derived from the burning rate equation ($r = a_T P^n$), which states that the burning rate for a specific solid propellant is a function of the chamber pressure. In reality, the values of n range between 0.2 and 0.85. Thus it can be seen that if *n* has a value of 0.8, then the exponent of K_n in our first equation becomes 5. It then follows that even a small change in throat area (or K_n) will produce substantial changes in pressure and the amount of hot gas produced. All of this indicates that thrust modulation by means of auxiliary jet nozzles, as shown in figure 10, becomes easier when the value of n in the burning rate equation is high and, therefore, when the exponent of K_n is high, resulting in a very steep curve for the K_n-pressure relationship. Naturally, it is to our advantage that we have a large number of solid propellants with a wide range of burning rate exponents.

Mathematics and graphs aside, it is very impractical to vary the propellant burning surface. So, then, the nozzle throat area must be varied. But this does not mean that one nozzle with a variable throat is the answer. Indeed, this arrangement would involve many difficult mechanical and design problems. The nozzle throat area can, however, consist of the *sum* of the areas of several nozzle throats, the *total* of which can be varied. By using solid propellants having high pressure exponents, it is possible to get a wide range of control with very small variations in the *total* nozzle throat area. And, too, such an arrangement makes for a simple mechanical device. The scheme shown in figure 10 illustrates one possibility. Four auxiliary nozzles are arranged around a central nozzle. Each auxiliary nozzle has a conical insert which can be moved in and out of its throat by an actuator device. It is easy to see how the total nozzle throat area of the motor is thus varied. With a propellant having a high value for the exponent of K_n, the size of the auxiliary nozzle throat areas needed decreases in relation to the area of the central or main nozzle. Thus penalties for drag or other inefficiencies of the expansion of exhaust gas in the auxiliary nozzles would have a very small overall effect on the efficiency of the vehicle.

In conclusion, it should be obvious that it is possible to combine two or more of these thrust control devices in order to provide all three types of control on a single rocket motor. All are relatively simple mechanical components. And their simplicity increases their reliability. They demonstrate that the solid propellant motor has at last proven its worth in a field once dominated by the liquid propellant motor. In short, the solid propellant motor has outgrown the names *jato* and *booster*.