ROCKET PROPULSION

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Tracing the history of rockets and showing why modern rockets must have liquid fuel for a propellant, the author discusses the theory of rocket design and shows how the various rocket components are designed. Future potential uses for rockets, both military and scientific, are enumerated and a plea made for Canadian scientists to take more interest in the subject.

History

There are few modern inventions and mechanical developments that are not based on the extensive work and research of scientists and inventors through the ages. The rocket, so often thought to be a product of the 20th century, actually has a history as extensive as gunpowder, and may be traced back many centuries.

Its beginning is not certain. However, the most ancient manuscripts in Chinese literature reveal the apparent use by that people of rockets, as far back as 500 B.C. Wherever the art of pyrotechnics spread, so did the use of the rocket, and with the introduction of gunpowder in Europe the art gradually became a science. Displays of fireworks were often held on a lavish scale, which boosted their manufacture and laid the foundations for the science of rocketry.

The military potential of the rocket was soon recognized, but it was not used on a wide scale in warfare until the beginning of the 19th century. At that time Sir William Congreve, in England, thoroughly investigated its possibilities as a weapon. His resulting designs for powder rockets have been only slightly improved upon since then. Although rockets were used with good effect in various battles of that time, their inaccuracy and instability, coupled with the development of more effective weapons, hastened their growing obsolescence as a military device. It remained for the second World War to revive them in a more fearful and potent form than ever, improved by modern scientific research.

The year 1919 marked the beginning of a new phase of reaction motor development. Professor Goddard of Clark University in the United States successfully burnt a mixture of oxygen and gasoline in a rocket motor with encouraging results. His subsequent researches, and those of others in Europe, laid the foundation of the liquid fuel propulsor, which has lifted the rocket from the level of a toy to the point where thundering giants weighing several tons ascend scores of miles into the ionosphere.

Rockets Need Liquid Fuel

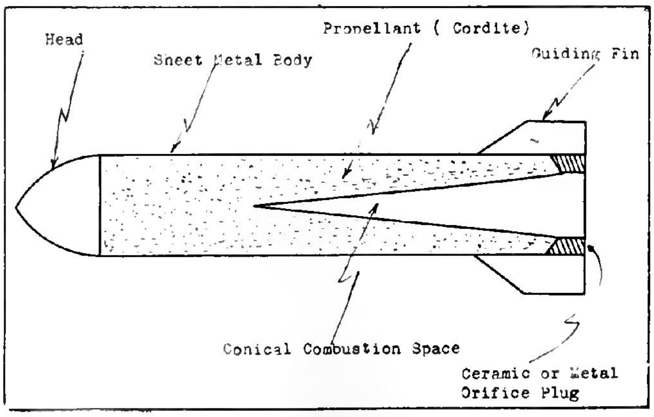
A simple dry fuel rocket usually consists of a tube filled with gun- or smokeless-powder, built and designed on principles established hundreds of years ago. The tube is of some light material and is fireproofed. A conical head of heavier material and a long wooden stick or vanes are attached for balance. A clay plug with an orifice is inserted in the open end of the tube, and the powder is distributed in the form of an open cone. (Fig. 1)

When the powder is ignited, great quantities of gas are created, which exert a back pressure or thrust upon the body of the rocket, as they escape through the clay orifice. Thus, a rocket consists merely of an expansion chamber, designed to withstand the great pressures and temperatures of expanding burning gases. This chamber or "motor" should be scientifically designed to provide for adiabatic expansion, and for the increased exhaust velocity of the ejected gases. The fuel must be gradually introduced into the blast chamber or motor, so that a steady burning or rapidly intermittent explosion occurs. The fuel must be capable of sudden expansion into a much larger volume, yet its flow into the chamber should be controllable if the rocket is to be guided over any great distance.

These fundamental conditions cannot be achieved with a dry fuel rocket. Explosive powders are too unstable; they burn so quickly that adequate control is impossible. Many devices for the mechanical injection of fuel pellets into a blast chamber have been tried, but almost inevitably have failed, due to flash-back, premature explosions, etc. Also, gunpowder and other explosives do not furnish the required propulsive power needed for sustained flight.

Liquid fuel combinations, however, develop con-

Fig. 1. A cross-section of a simple modern powder rocket.



siderably greater thrusts, weight for weight, and higher efficiencies, since a thermodynamically sound expansion chamber may be utilized. Furthermore, since the rate of burning can be varied, the velocity of the rocket can be controlled, a refinement almost impossible to incorporate in a powder rocket. However, the use of liquid fuels has created new problems in chemistry, metallurgy and allied fields which have complicated the work of the research worker, although the rocket (or reaction motor) is basically a very simple device.

The same thermodynamic processes occur in the interior of a rocket engine as those in an automobile cylinder. A fuel (gasoline, alcohol, butane, etc.—liquid) or (carbon and sulphur—solid) is brought into contact with oxygen (liquid, or solid as nitre). The mixture is ignited, the resulting explosive expansion exerts a pressure upon the surrounding walls. However, here there is no piston to push; instead, the gases rush out through an orifice at great speed, pushing the rocket away from them. “This is in accordance with the principle of conservation of momentum; a certain quantity of motion being imparted to the leaving gases, an equal and opposite reaction must act upon the rocket body.”

Theory of Rocket Design

For practical purposes, many of the ordinary equations of hydraulics and gas flow may be applied to reaction motor design. A thorough mathematical treatment is both lengthy and complicated. Thus, an empirical equation (derived from Zeuner's equation) for evaluating the reaction developed by a nozzle, assuming a gaseous jet, may be used. It reads:

$$R = 2\,AP_1\sqrt{1-\left(\frac{P_2}{P_1}\right)^{\frac{S-1}{S}}}\;\sqrt{\left(\frac{2}{S+1}\right)^{\frac{2}{S-1}}\frac{S^2}{S^2-1}}$$

where R = reaction in ft. lbs.
A = nozzle area in ft.^{2}.
P_1 = abs. initial pressure lb./ft.^{2} of an expanding gas jet.
P_2 = abs. final pressure lb./ft.^{2} of an expanding gas jet.
V_1 = initial specific volume of gas ft.^{3}/lb.
V_2 = final specific volume of gas ft.^{3}/lb.
S = an exponent, experimentally determined for a variety of gases and conditions.

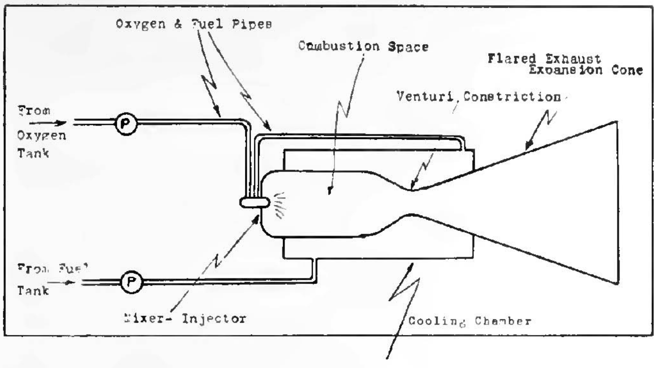


Fig. 2. Simplified diagram of the essential components of a regeneratively cooled rocket motor.

Since the expansion in a rocket nozzle takes place at almost constant entropy (and considering the high temperature prevailing here) the exponent “S” may be taken as $\simeq 1.3$. The exhaust gases consist largely of steam and CO_2. This formula permits the calculation of thrust, and precludes the necessity of measuring exhaust gas velocities directly—an almost impossible feat.

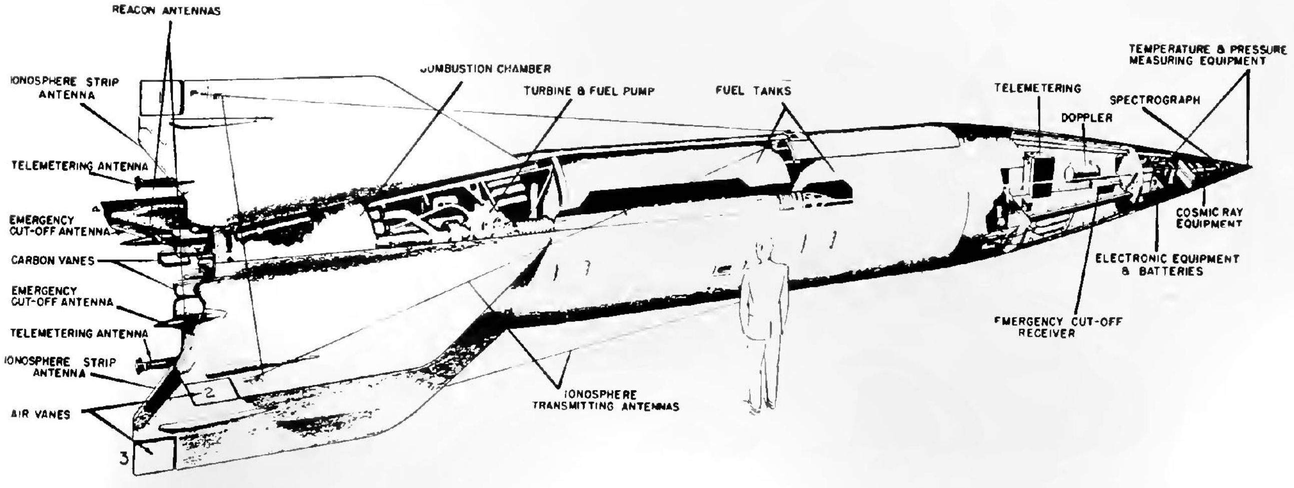
Design

Basically, modern liquid fuel rockets are all very similar, whether the rocket is a small model built by the University of Toronto Rocket Society, or the U.S. Army's converted V-2's. The two most important elements are:

(1) *The fuel reservoir.* This usually consists of two tanks, one containing so-called liquid air or oxygen, the other, some fuel such as alcohol, etc. These liquids are pumped or forced under pressure into the motor, wherein the fuel reacts with the oxygen.

(2) *The motor or blast-chamber.* The term “motor” as used in a rocket is not incongruous. It is true that there are no moving parts as in an aircraft jet engine, nevertheless, like any other motor it is an apparatus wherein force (i.e. expanding gas), is translated into motion, this motion being the forward movement of the rocket. Its thermodynamic characteristics can be calculated and determined experimentally, just as its thermal and mechanical efficiencies can be.

Fig. 3. V-2 equipped for upper atmosphere study. ***Official U.S. Navy diagram***



There are three integral sections in a typical motor:

(a) *The expansion chamber.* A space where the gases are mixed, exploded and expanded initially. Very high temperatures (2000 deg. C) exist in this section, and it is usually lined with some refractory material.

(b) *The constrictor or throat.* Its cross-sectional area must be carefully designed to increase the velocity of the exhaust gases, and yet not to impede their flow unduly.

(c) *The nozzle or expansion cone.* Ideally, a nozzle should be designed to discharge the gases axially, and at the pressure of the surrounding medium, without added frictional re-heating. If the mouth is too small the full expansion is not obtained. If it is too large, turbulences and eddies are set up which cause a back-pressure and decrease the velocity.

For determining the expansion ratio of the flared nozzle, Meyer's empirical equation may be used:

$$\frac{\text{Mouth Area}}{\text{Throat Area}} = 0.172\left(\frac{P_1}{P_2}\right) + 0.7 \text{ (when } \frac{P_1}{P_2} < 25)$$

$$= 0.172\left(\frac{P_1}{P_2}\right)^{0.94} + 0.7 \text{ (when } \frac{P_1}{P_2} > 25)$$

where P_1 = chamber pressure.

P_2 = pressure of surrounding medium.

(The above equation also shows that a rocket is most efficient in vacuum).

The purpose of the flared nozzle is to develop a high exit velocity for the escaping gas molecules, and consequently, thrust, as resulting from the increase of momentum. (See Fig. 2).

Considerable research with various nozzle shapes and chamber designs has shown that a venturi-shaped motor is the most efficient under most circumstances. Due to the high temperatures encountered, it has been found necessary to cool the motor, especially around the chamber and throat. Water and air cooling have been tried and discarded. Most liquid fuel rocket engines today are regeneratively cooled, i.e.—the fuel is circulated externally around the outer walls and cools the affected areas, being preheated during this process, with a consequent gain in overall efficiency. Also, it is thus possible to construct the motor of some easily machinable metal such as copper or aluminum, which are good heat conductors even though the melting point of these metals is far below the temperature of the burning gas.

To sum up, the motor should have the following properties:

1. High melting point of the metal used. Not less than approx. 1000 deg. C.
2. Good thermal conductivity.
3. High specific tensile strength at high temperatures.
4. Resistance to erosion of exhaust gases.
5. Practical fabrication possibilities.

Fig. 4. A comparison of the duration and amount of thrust between a liquid and dry fuel rocket motor.

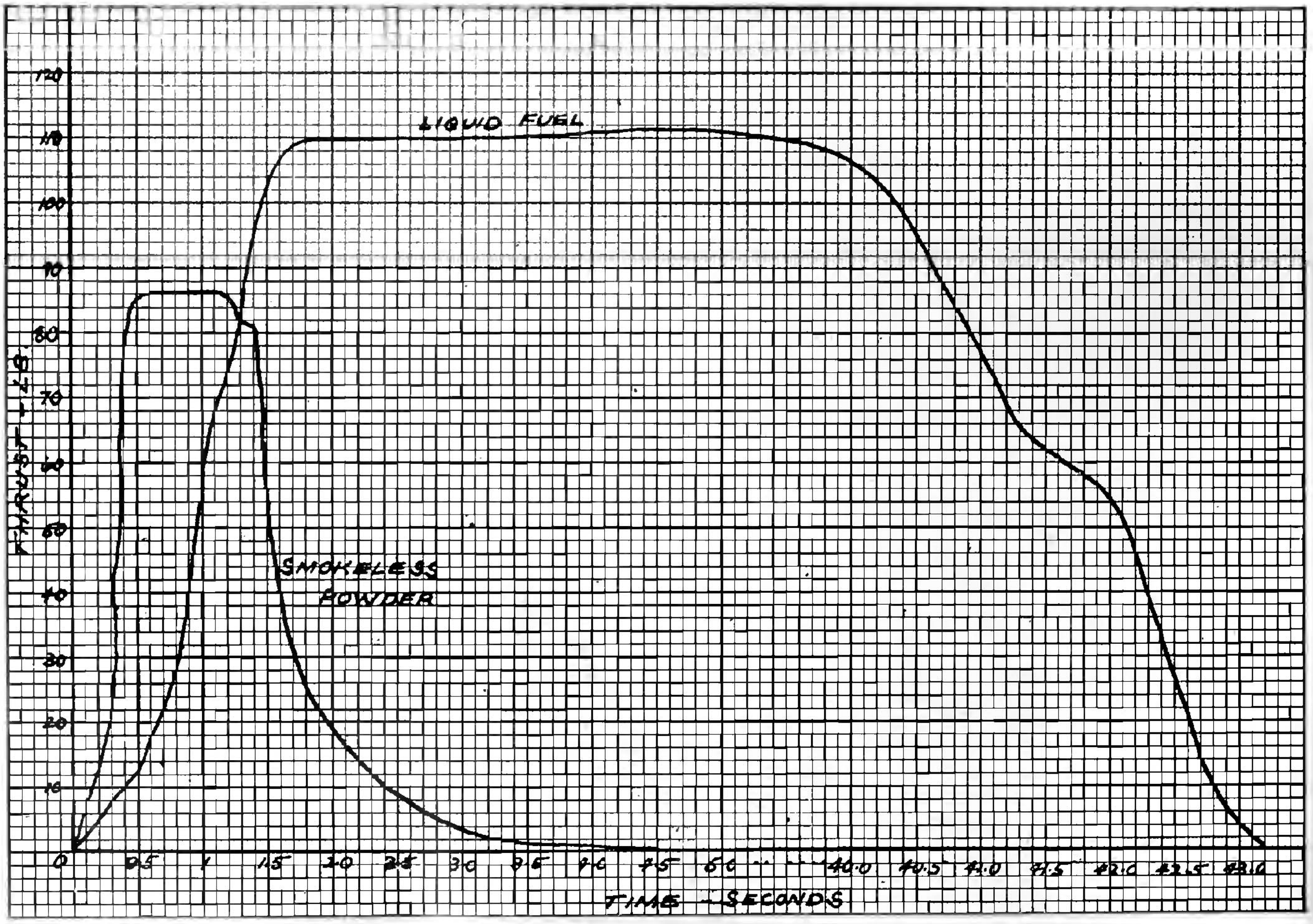


Fig. 5. Final instruments are placed in V-2 by technicians prior to flight into Ionosphere.
U.S.A.A.F. Photo

6. Good thermodynamic design.
7. Reasonably light weight.

It is obvious that the above conditions are difficult to achieve in practice, but present and future research will undoubtedly produce rocket motors far more efficient and durable than any in existence today.

If the thrust of the exhaust gases were acting truly along the longitudinal axis of the rocket, and if there were no atmosphere or gravity to contend with, its motion would be along a straight line. Since these conditions are not met with in practice, it is necessary to stabilize the rocket with some mechanical device such as a gyroscope. This is needed only if great heights and distances are to be attained. The Germans employed elaborate gyroscopic stabilizers along with movable vanes in their V-2's. The Americans are building rockets with movable motors which can change the rocket's direction when it deviates from the normal line of flight.

Future Developments

The science of rocketry is a relatively young one, and there is a great need for extensive research. Consider the problem of fuels. For many years experimenters have burned hydrocarbons, such as gasoline, alcohol and butane, in an atmosphere of pure oxygen carried along as a liquid, in the rocket. Lately, other combinations have been tried, such as aniline and nitric acid, nitromethane (which reacts explosively at certain temperatures) and hydrogen peroxide. (See Table I).

If rockets are to reach greater altitudes, and in fact, escape from the earth, much more powerful fuels than existing ones are required. Most rocket experimenters (or Astronauts) openly or secretly hope that the rocket will some day leave our planet and reach outer space (where it would be most efficient).

Using known or theoretical fuel combinations, none of which permits a greater exhaust velocity than 10,000 ft. per second, it would require a complex rocket weighing hundreds of tons to escape from the gravitational field of the earth, as may be seen in the next paragraph. The most powerful and largest rocket in existence, the V-2, weighs eight tons, and reaches a maximum height of 130 miles, and a maximum velocity of 3,000 m.p.h., truly a great engineering achievement. Therefore, to construct a rocket weighing hundreds of tons, and having a maximum speed of 26,000 m.p.h. (in order to counteract gravity—i.e., a terminal velocity) would seem to be an almost insurmountable feat.

It may be asked how a space rocket can reach the required maximum speed of 26,000 m.p.h. (or seven miles per sec.) if the exhaust jet has a velocity of only two m.p.s. approximately. The answer lies in the construction of a "step-rocket." This is a large multiple rocket, consisting of two or more parts. The first or largest section would carry the other sections. At a

Fig. 6. This 10-ft.-long "GAPA" (Ground to Air Pilotless Aircraft), made by Boeing, is a potential defence against high altitude enemy aircraft.
U.S.A.A.F. Photo

certain altitude, say 100 miles, when the rocket has reached a speed of say two m.p.s., the second section would be ejected. This would have an initial velocity of two m.p.s., plus the velocity it could develop by itself, namely two m.p.s. The second section's final velocity would therefore be four m.p.s. This process can be extended until the desired velocity of seven m.p.s. is reached. Obviously the above system is too cumbersome to be practical, and we may have to wait until atomic energy can be harnessed.

While it is fascinating to speculate upon space and interplanetary travel, there are more immediate and obvious uses to which rockets may be put. Some such uses are:

Military—the smokeless powder dominates this field, due to its compactness and ease of handling. The Bazooka, A-A rockets, aeroplane rockets, etc., are all potent weapons developed during the late war. The German V's may be the portent of the shape of things to come. The Germans had developed a rocket, the A-8, capable of crossing the Atlantic Ocean. It needs little imagination to foresee the use to which such missiles could be put in any possible future war.

Scientific—High altitude rockets capable of travelling hundreds of miles into the stratosphere can gather invaluable data on cosmic ray activity, weather conditions (useful for long range forecasts), and other phenomena, which, when understood, can shed new light on radio propagation, etc.

TABLE 1

Table showing some properties of certain common propellants.

Nitro-methane is a very promising fuel developed at the California Institute of Technology.

Fuel	Oxidant	Btu./lb. Fuel	Exhaust Vel. Meters /sec.
Hydrogen.......	Oxygen	51900	5170
Methane........	"	21400	4490
Pentane.........	"	19300	4000
Ethyl Alcohol	"	12100	4180
Gasoline.........	"	19100	4500
Aniline..........	"	?	5500

Conclusion

Many of the future advances of rocket science will be made by engineers. Canada and the Empire as a whole are lagging in rocket research. From a defensive and scientific viewpoint it will be necessary for Canadians to interest themselves in this useful and portentous science. Why shouldn't we use our native initiative and do more original work, instead of imitating or improving on the work of other countries?

The rocket, a machine unfettered by atmosphere or climate, will surely conquer the vacuous space beyond our atmosphere. To deny this fact is to deny the power of pure and practical science and the ingenuity of man. Interplanetary travel may seem impossible at present; but no more so than did an aeroplane trip across the Atlantic ocean seem in 1910.