M. Gruntman
Blazing the Trail. The Early History of Spacecraft and Rocketry,
AIAA, Reston, Va., 2004 p. 34

ROCKET BASICS 1: THRUST AND SPECIFIC IMPULSE

In a liquid-propellant rocket, a liquid fuel and oxidizer are injected into the combustion chamber where the chemical reaction of combustion occurs. The combustion process produces hot gases that expand through the nozzle, a duct with the varying cross section.

In solid rockets, both fuel and oxidizer are combined in a solid form, called the *grain*. The grain surface burns, producing hot gases that expand in the nozzle. The rate of the gas production and, correspondingly, pressure in the rocket is roughly proportional to the burning area of the grain. Thus, the introduction of a central bore in the grain allowed an increase in burning area (compared to “end burning”) and, consequently, resulted in an increase in chamber pressure and rocket thrust.

Modern nozzles are usually converging-diverging (De Laval nozzle), with the flow accelerating to supersonic exhaust velocities in the diverging part. Early rockets had only a crudely formed converging part. If the pressure in the rocket is high enough, then the exhaust from a converging nozzle would occur at sonic velocity, that is, with the Mach number equal to unity.

The rocket thrust T equals

$$T = \dot{m}U_e + (P_e - P_a)A_e = \dot{m}\left[U_e + \frac{(P_e - P_a)A_e}{\dot{m}}\right] = \dot{m}U_{\mathrm{eq}}$$

where $\dot{m}$ is the propellant mass flow (mass of the propellant leaving the rocket each second), U_e (exhaust velocity) is the velocity with which the propellant leaves the nozzle, P_e (exit pressure) is the propellant pressure at the nozzle exit, P_a (ambient pressure) is the pressure in the surrounding air (about one atmosphere at sea level), and A_e is the area of the nozzle exit; U_{eq} is called the equivalent exhaust velocity. Rocket performance is often characterized by specific impulse I_{SP} defined as

$$I_{\mathrm{SP}} = \frac{U_{\mathrm{eq}}}{g_E}$$

where g_E = 9.81 m/s^2 (or 32.2 ft/s^2) is the gravitational acceleration on the Earth's surface. Specific impulse is measured in the units of seconds. For chemically based rockets, the higher specific impulse I_{SP} usually means the more efficient rocket. (This characterization is not applicable directly to electric propulsion thrusters.)

Specific impulse less than 100 s was typical for Congreve rockets. Modern solid-propellant rockets achieve I_{SP} = 250–300 s. For comparison, a high-performing liquid-propellant rocket engine, such as the space shuttle main engine (SSME) using liquid oxygen and liquid hydrogen, would have I_{SP} = 410–450 s. Specific impulse and thrust usually increase with the increasing altitude as the ambient pressure decreases.

Congreve rockets had only a converging nozzle. At the exit of such a rocket, the exhaust velocity was thus typically equal to the local speed of sound, with exit pressure approximately one-half of the pressure inside the rocket, and the temperature 10–25% smaller than the gas temperature inside the rocket case.

A typical Congreve rocket would burn its propellant in a few seconds. During this time interval, the rocket thrust would accelerate the missile. After that, only forces of gravity and air drag would affect rocket flight on a ballistic trajectory.

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AIAA, Reston, Va., 2004 p. 42

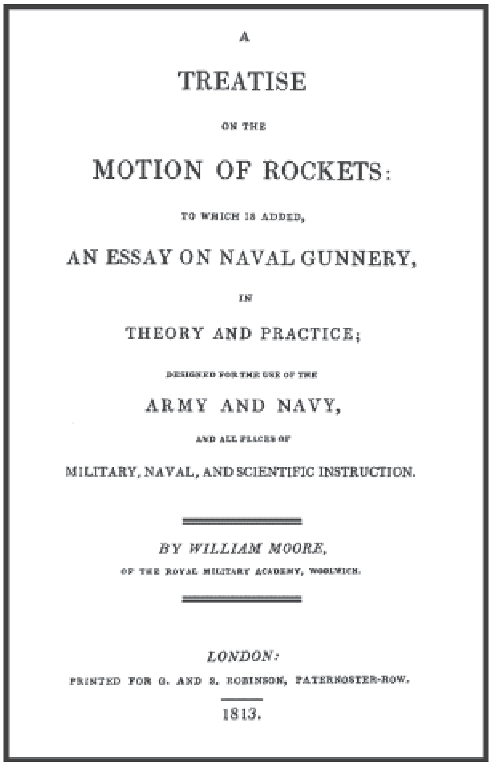
ROCKET BASICS 2: ROCKET DYNAMICS

Rocket acceleration is proportional to thrust of the rocket engine

$$T = M\,a$$

where T is thrust, M is the rocket mass, and a is acceleration. The calculation of rocket velocity is somewhat complicated because the rocket mass is not constant and decreases with time as the propellant being consumed.

William Moore, an instructor of the Royal Military Academy in Woolwich, England, seemed to be the first to correctly calculate the velocity and altitude of a rocket at burnout (i.e., when all propellant is consumed). Moore was in an excellent position to follow the experiments with Congreve's rockets at Woolwich and got further interested in the subject "when the Academy of Copenhagen proposed [in 1810] as a prize question, the curve that a rocket describes, when projected, in any oblique direction, in vacuo ..." (Moore 1813, iii).



A

TREATISE

ON THE

MOTION OF ROCKETS:

TO WHICH IS ADDED,

AN ESSAY ON NAVAL GUNNERY,

IN

THEORY AND PRACTICE;

DESIGNED FOR THE USE OF THE

ARMY AND NAVY,

AND ALL PLACES OF

MILITARY, NAVAL, AND SCIENTIFIC INSTRUCTION.

BY WILLIAM MOORE,

OF THE ROYAL MILITARY ACADEMY, WOOLWICH.

LONDON:

PRINTED FOR G. AND S. ROBINSON, PATERNOSTER-ROW.

1813.

Fig. 4.8. Cover of William Moore's book on rocket dynamics published in 1813.

In 1813, Moore published a book, *A Treatise on the Motion of Rockets*, where he addressed various aspects of rocket dynamics. In fact, Moore introduced dynamics of a body with the varying mass, coming close to obtaining the rocket equation. Moore began his work with considering a vertical launch of a rocket with a constant thrust T, constant propellant mass consumption rate, and in absence of atmospheric drag. He obtained the velocity V_B and altitude H_B at burnout (in modern notation),

$$V_B = \frac{T t_B}{M_P}\ln\left(\frac{M_0}{M_0 - M_P}\right) - g_E t_B$$

$$H_B = \frac{T t_B^2 \left(M_0 - M_P\right)}{M_P^2}\ln\left(\frac{M_0 - M_P}{M_0}\right) + \frac{T t_B^2}{M_P} - \frac{g_E t_B^2}{2}$$

where M_0 is the initial rocket mass, M_P is the total mass of the consumed propellant, and t_B is the burnout time. These formulas (usually expressed through specific impulse and the mass ratio) can be found in modern textbooks.

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ROCKET BASICS 3: ROCKET EQUATION

The equation that describes rocket acceleration is of such fundamental importance for rocket flight that it is called *the rocket equation*. The equation relates the velocity acquired by a rocket with the equivalent exhaust velocity, U_{eq} (Rocket Basics 1 and 2; Chapter 4), and the amount of the consumed propellant. The latter quantity is conveniently expressed through the dimensionless mass ratio

$$R = \frac{M_0}{M_B}$$

where M_0 is the initial rocket mass; $M_B = M_0 - M_P$ is the rocket mass at burnout; and M_P is the mass of the consumed propellant. According to the rocket equation, the rocket velocity increment ΔV would be

$$\Delta V = U_{\text{eq}} \ln R$$

for constant U_{eq} in the absence of gravity and air drag.

The rocket equation combines dynamics of a body with the varying mass and the relation between the accelerating force (thrust) and the propellant exhaust velocity. In 1813, William Moore described the relevant dynamics for constant thrust and constant propellant consumption rate acting on a rocket with the varying mass. Moore however did not relate thrust and the exhaust velocity and, therefore, did not relate the rocket velocity increment and the exhaust velocity of the propellant flow.

Derivation of the rocket equation is rather elementary. By the middle of the 19th century, problems related to rocket flight (requiring derivation of the rocket equation) had been given to university students as a standard exercise in particle dynamics (Tait and Steele 1856, 255). Many researchers would independently obtain this simple equation again and again throughout many years. Konstantin Tsiolkovsky described it in 1903. (Another Russian, Ivan V. Meshchersky, 1859–1935, obtained in 1897 a differential equation describing dynamics of a point with a variable mass.) Esnault-Pelterie, Goddard, Oberth, and many others independently derived the equation later.

Consider, for example, a Congreve or Hale rocket with specific impulse $I_{\text{SP}} = 80$ s and propellant constituting one-third of the total rocket mass, $M_P = M_0/3$ and correspondingly the burnout mass $M_B = M_0 - M_P = 2M_0/3$. The equivalent exhaust velocity would be $U_{\text{eq}} = I_{\text{SP}} \times g_E = 80 \times 9.81 \approx 785$ m/s, and the mass ratio $R = M_0/M_B = 1.5$. When all rocket propellant is consumed, the rocket would achieve the velocity

$$\Delta V = U_{\text{eq}} \ln(R) = 785 \times \ln(1.5) \approx 318 \text{ m/s}$$

in the absence of gravity and air drag. For a typical 3-s propellant burning time, Moore's equations (Rocket Basics 2, Chapter 4) for vertical launch (with gravity but disregarding air drag) would give the velocity and altitude at burnout 289 m/s and 401 m, respectively. Such a rocket would have reached an altitude of 4.65 km (2.89 miles) in the absence of air drag.

A similar solid-propellant rocket with a modern propellant and nozzle design could have $I_{SP} = 260$ s. In the absence of gravity and air drag, such a rocket with the same mass ratio would achieve the velocity 1034 m/s. In a vertical launch and in the absence of drag, the rocket would reach the velocity and altitude at burnout 1004 m/s and 1402 m, respectively, and the total altitude 52.8 km (32.8 miles). This example demonstrates how superior specific impulse dramatically improves rocket performance.

ROCKET BASICS 4: ROCKET IN VACUUM

(COMMON MISCONCEPTION)

A common misconception for many, many years emphasized the importance of ambient air for rocket propulsion. It was claimed that the rocket needs some medium to "push against." The fundamentals of rocket performance, particularly in vacuum, were not understood until the 20th century.

For example, William Moore wrote in his 1813 treatise on rocket dynamics:

> If the rocket burns in a medium, then, as there is a body reacting against the fluid [propellant] that rushes from the rocket, there is not so instantaneous a dissipation of the force of the latter the moment after it is generated; but a time of its action upon the rocket which is greater or less according to the surrounding medium is more or less dense and elastic. In this case, therefore, more motion is communicated to the body than in the former, and but for the resistance of the forepart of the rocket it would move farther in a medium than in vacuum. (Moore 1813, 25)

A standard textbook on ordnance and gunnery prepared for cadets of the U.S. Military Academy in West Point in the second half of the 19th century instructed:

> A rocket is set in motion by the reaction of a rapid stream of gas escaping through its vents. If it be surrounded by a resisting medium, the atmosphere for instance, the particles of gas, as they issue from the vent, will impinge against and set in motion certain particles of air, and the force expended on the inertia of these particles will react and increase the propelling force of the rocket. It follows, therefore, that, though a rocket will move *in vacuo*, its propelling force will be increased by the presence of a resisting medium. (Benton 1883, 95)

Konstantin E. Tsiolkovsky wrote in his 1903 seminal publication on rocketry:

> The effect of the atmosphere [ambient air] on an explosion [propulsion] is not completely clear: on the one hand, because the exploding substances [propellant] have some support in the ambient material medium, which they involve in their motion and thus contribute to the increase of the rocket velocity; but on the other hand, the same atmosphere [ambient air] inhibits [exhaust] gas expansion beyond a certain limit because of atmosphere's density and elasticity, with the result that the explosives [propellant] does not achieve the velocity they could have had expanding in vacuum. (Tsiolkovsky 1954, 32)

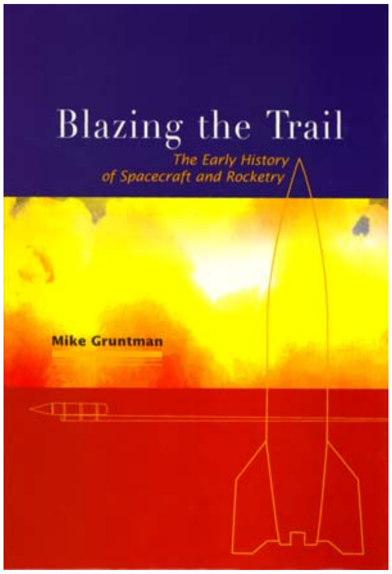
The rocket principle is based on conservation of momentum. A rocket does not need air to push against, and in reality, the ambient air decreases thrust. The rocket thrust contains (Rocket Basics 1, Chapter 4) an item $(P_e-P_a)\,A_e$, where P_e and P_a are the exit and ambient pressure, respectively, and A_e is the exit area of the nozzle. Thus, the reduction of the ambient pressure P_a results in increase of thrust in addition to decrease in air drag on a missile.

Winner of the *Luigi Napolitano Book Award* (2006) from the International Academy of Astronautics

Blazing the Trail

The Early History of Spacecraft and Rocketry

Mike Gruntman



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505 pages with 340 figures
Index: 2750+ entries, including 650 individuals

This book presents the fascinating story of the events that paved the way to space. It introduces the reader to the history of early rocketry and the subsequent developments which led into the space age. People of various nations and from various lands contributed to the breakthrough to space, and the book takes the reader to far away places on five continents.

This world-encompassing view of the realization of the space age reflects the author's truly unique personal experience, a life journey from a child growing on the Tyuratam launch base in the 1950s and early 1960s, to an accomplished space physicist and engineer to the founding director of a major U.S. nationally recognized program in space engineering in the heart of the American space industry.

Most publications on the topic either target narrow aspects of rocket and spacecraft history or are popular books that scratch the surface, with minimal and sometimes inaccurate technical details.

This book bridges the gap. It is a one-stop source of numerous technical details usually unavailable in popular publications. The details are not overbearing and anyone interested in rocketry and space exploration will navigate through the book without difficulty. The book also includes many quotes to give readers a flavor of how the participants viewed the developments. There are 340 figures and photographs, many appearing for the first time.

Table of contents

Book details (including **index** and **reviews**) at: **http://astronauticsnow.com/blazingthetrail/**

About the author. Dr. Mike Gruntman is professor of astronautics at the University of Southern California. Accomplished physicist, Mike is actively involved in research and development programs in space science and space technology. He has authored and co-authored 300 publications, including 4 books.

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