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

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

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 $I_{SP} = 80$ 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 $U_{eq} = I_{SP} \times g_E = 80 \times 9.81 \approx 785$ 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

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

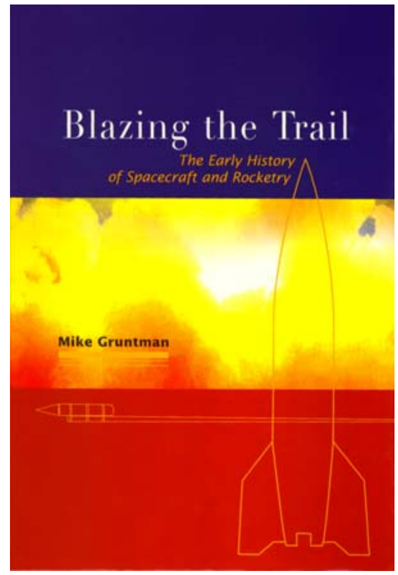
in the absence of gravity and air drag. For a typical 3-s propellant burning time, Moore's equations (Rocket Basics 2, Chapter 4) for vertical launch (with gravity but disregarding air drag) would give the velocity and altitude at burnout 289 m/s and 401 m, respectively. Such a rocket would have reached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

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.

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