Rocket Propulsion Elements

Seventh Edition

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PREFACE

This new edition concentrates on the subject of rocket propulsion, its basic technology, performance, and design rationale. The intent is the same as in previous editions, namely to provide an introduction to the subject, an understanding of basic principles, a description of their key physical mechanisms or designs, and an appreciation of the application of rocket propulsion to flying vehicles.

The first five chapters in the book cover background and fundamentals. They give a classification of the various propulsion systems with their key applications, definitions, basic thermodynamics and nozzle theory, flight performance, and the thermochemistry of chemical propellants. The next nine chapters are devoted to chemical propulsion, namely liquid rocket engines and solid rocket motors. We devote almost half of the book to these two, because almost all past, current, and planned future rocket-propelled vehicles use them. Hybrid rocket propulsion, another form of using chemical combustion energy, has a separate chapter. The new longer chapter on electric propulsion has been extensively revised, enlarged, and updated. Chapters 16–18 and 20 apply to all types of propulsion, namely thrust vector control, selection of a rocket propulsion system for specific applications, testing of propulsion systems, and behavior of chemical rocket exhaust plumes. Only a little space is devoted to advanced new concepts, such as nuclear propulsion or solar thermal propulsion, because they have not yet been fully developed, have not yet flown, and may not have wide application.

The book attempts to strike a balance between theory, analysis, and practical design or engineering tasks; between propulsion system and nonpropulsion system subjects, which are related (such as testing, flight performance, or exhaust plumes); and between rocket systems and their key components and materials. There is an emphasis on up-to-date information on current propulsion systems and the relation between the propulsion system, the flight vehicle, and the needs of the overall mission or flight objectives.

The new edition has more pages and extensive changes compared with the sixth edition. We have expanded the scope, reorganized the existing subject matter into a more useful form or logical sequence in some of the chapters, and updated various data. About one-third of the book is new or extensively revised text and figures. This new version has been heavily edited, upgraded, and improved. Altogether we count about 2500 changes, additions, new or rewritten sections or paragraphs, inserts, clarifications, new illustrations, more data, enlarged tables, new equations, more specific terminology, or new references. We have deleted the chapter on heat transfer that was in the sixth edition, because we learned that it was not being used often and is somewhat out of date. Instead we have added revised small specific sections on heat transfer to several chapters. A new chapter on liquid propellant thrust chambers was added, because this component is the heart of liquid propellant rocket engines.

Here are some of the topics that are new or completely revised. New sections or subsections include engine structures, two-step nozzles, multiple nozzles, gas properties of gas generator or preburner gases, classification of engine valves, a promising new monopropellant, gaseous rocket propellants, propellant additives, materials and fabrication of solid propellant motors, launch vehicles, elliptical orbits, new sample design calculations, vortex instability in solid rocket motors, design of turbopumps, design of liquid propellant engines, insensitive munitions requirements, aerospike rocket engines, solid rocket motor nozzles, and plume signatures. In addition there are new figures, for example, the payload variation with orbit altitude or inclination angle, some recently developed rocket propulsion systems, the design of shortened bell-shaped nozzle contours, and the expander engine cycle, and new tables, such as different flight maneuvers versus the type of rocket propulsion system, list of mission requirements, and the physical and chemical processes in rocket combustion. There are new paragraphs on rocket history, four additional nozzle loss factors, use of venturi in feed systems, extendible nozzles, and water hammer.

In the last couple of decades rocket propulsion has become a relatively mature field. The development of the more common propulsion systems is becoming routine and the cost of new ones is going down. For example, much R&D was done on many different chemical propellants, but just a few are used, each for specific applications. Although some investigations on new propellants or new propellant ingredients are still under way, a new propellant has not been introduced for a rocket production application in the last 25 years. Most of the new propulsion systems are uprated, improved, or modified versions of existing proven units in the chemical propulsion and electrical propulsion areas. There are only a few novel engines or motors, and some are mentioned in this book. We have therefore placed emphasis on describing several of the proven existing modern rocket propulsion systems and their commonly used propellants, because they are the heritage on which new ones will be based. It is not possible in any one book to mention all the varieties, types, and designs of propulsion systems, their propellants, or materials of construction, and we therefore selected some of the most commonly used ones. And we discuss the process of uprating or modifying them, because this is different from the design process for a truly new unit.

The number of countries that develop or produce rocket propulsion systems has gone from three in 1945 to at least 35 today, a testimony to proliferation and the rising interest in the subject. There are today more colleges that teach rocket propulsion than before. Prior editions of this book have been translated into three languages, Russian, Chinese, and more recently (1993) Japanese. People outside of the U.S. have made some excellent contributions to the rocket field and the authors regret that we can mention only a few in this book.

We have had an ongoing disparity about units. Today in U.S. propulsion companies, most of the engineering and design and almost all the manufacturing is still being done in English engineering (EE) units (foot or inch, pounds, seconds). Many of the technical papers presented by industry authors use EE units. Papers from university authors, government researchers, and from a few companies use the SI (International Standard—metric) units. If a customer demands SI units, some companies will make new drawings or specifications especially for this customer, but they retain copies with EE units for in-house use. The planned transition to use exclusively SI units is complex and proceeding very slowly in U.S. industry. Therefore both sets of units are being used in this revised edition with the aim of making the book comfortable for colleges and professionals in foreign countries (where SI units are standard) and to practicing engineers in the U.S. who are used in the EE system. Some tables have both units, some sections have one or the other.

The use of computers has changed the way we do business in many fields. We have developed computer programs for many an engineering analysis, computer-aided design, computer-aided manufacturing, business and engineering transactions, test data collection, data analysis or data presentation, project management, and many others. In fact computers are used extensively in some companies to design new propulsion devices. Therefore we identify in this book the places where computer programs will be helpful and we mention this often. However, we do not discuss specific programs, because they take up too much space, become obsolete in a short time without regular upgrading, some do not have a way to provide help to a user, and some of the better programs are company proprietary and thus not available.

The first edition of this book was issued in 1949. With this new revised seventh edition this is probably the longest active aerospace book (51 years) that has been upgraded regularly and is still being actively used in industry and universities. To the best of the authors' knowledge the book has been or is being used as a college text in 45 universities worldwide. It is a real satisfaction to the authors that a very large number of students and engineers were introduced to this subject through one of the editions of this book.

The book has three major markets: it has been used and is still used as a college text. It contains more material and more student problems than can be given in a one-semester course. This then allows the choosing of selected portions of the book to fit the student's interest. A one-term course might consist of a review of the first four or five chapters, followed by a careful study of Chapters 6, 10, 11, 14, and 19, a brief scanning of most of the other chapters, and the detailed study of whatever additional chapter(s) might have appeal. The book also has been used to indoctrinate engineers new to the propulsion business and to serve as a reference to experienced engineers, who want to look up some topic, data, or equation.

We have tried to make the book easier to use by providing (1) a much more detailed table of contents, so the reader can find the chapter or section of interest, (2) an expanded index, so specific key words can be located, and (3) five appendices, namely a summary of key equations, a table of the properties of the atmosphere, conversion factors and constants, and two derivations of specific equations.

All rocket propellants are hazardous materials. The authors and the publisher recommend that the reader do not work with them or handle them without an exhaustive study of the hazards, the behavior, and the properties of each propellant, and rigorous safety training, including becoming familiar with protective equipment. Safety training is given routinely to employees by organizations in this business. Neither the authors nor the publisher assume any responsibility for actions on rocket propulsion taken by readers, either directly or indirectly. The information presented in this book is insufficient and inadequate for conducting rocket propulsion experiments or operations.

Professor Oscar Biblarz of the Naval Postgraduate School joins George P. Sutton as a co-author in this edition. We both shared in the preparation of the manuscript and the proofreading. Terry Boardman of Thiokol Propulsion (a division of Cordant Technologies) join as a contributing author; he prepared Chapter 15 (hybrid rocket propulsion) and the major portion of the section on rocket motor nozzles in Chapter 14.

We gratefully acknowledge the help and contributions we have received in preparing this edition. Terrence H. Murphy and Mike Bradley of The Boeing Company, Rocketdyne Propulsion and Power, contributed new data and perspective drawings to the chapters on rocket propulsion with liquid propellants. Warren Frick of Orbital Sciences Corporation provided valuable data on satellite payloads for different orbits. David McGrath, Thomas Kirschner, and W. Lloyd McMillan of Thiokol Propulsion (a division of Cordant Technologies, Inc.) answered questions and furnished data on solid propellant rocket motors. Carl Stechman of Kaiser-Marquardt furnished design information on a small bipropellant thruster. Carl Pignoli and Pat Mills of Pratt & Whitney (a United Technologies Company) gave us engine data and permission to copy data on turbopumps and upper-stage space engines with extendible nozzle skirts.

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COVER ILLUSTRATIONS

The color illustrations on the cover show several rocket propulsion systems, each at a different scale. Below we briefly describe these illustrations and list the page numbers, where more detail can be found.

The front cover shows the rocket nozzles at the aft end of the winged Space Shuttle, shortly after takeoff. The two large strap-on solid rocket motors (see page 545) have brightly glowing white billowy exhaust plumes. The three Space Shuttle main engines (page 199) have essentially transparent plumes, but the hot regions, immediately downstream of strong shock waves, are faintly visible. The two darker-colored nozzles of the thrust chambers of the orbital maneuvering system and the small dark nozzle exit areas (pointing upward) of three of the thrusters of the reaction control system of the Space Shuttle (see page 208) are not firing during the ascent of the Shuttle.

The back cover shows (from top to bottom) small illustrations of (1) an image of a stress/strain analysis model (see page 461) of a solid propellant rocket motor grain and case, (2) a small storable bipropellant thruster of about 100 lbf thrust (page 307), (3) a three-quarter section of a solid propellant rocket motor (page 9), and (4) an experimental aerospike rocket engine (page 298) during a static firing test.