Rocket and Spacecraft Propulsion

Principles, Practice and New Developments (Second Edition)

Martin J. L. Turner

Rocket and Spacecraft Propulsion

Principles, Practice and New Developments (Second Edition)

Springer

Published in association with
Praxis Publishing
Chichester, UK

PRAXIS

Professor M. J. L. Turner, CBE
Department of Physics and Astronomy
University of Leicester
Leicester, UK

SPRINGER–PRAXIS BOOKS IN ASTRONAUTICAL ENGINEERING
SUBJECT *ADVISORY EDITOR*: John Mason B.Sc., M.Sc., Ph.D.

ISBN 3-540-22190-5 Springer-Verlag Berlin Heidelberg New York

Springer is part of Springer-Science + Business Media (springeronline.com)
Bibliographic information published by Die Deutsche Bibliothek
Die Deutsche Bibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available from the Internet at http://dnb.ddb.de

Library of Congress Control Number: 2004111933

Reprinted 2006
First edition published 2001
Printed in Germany

Cover design: Jim Wilkie
Typesetting: Originator, Great Yarmouth, Norfolk, UK

Printed on acid-free paper


USA

Contents

Preface to the second edition

In the period since the publication of the first edition, rocket propulsion and launcher systems have experienced a number of major changes. The destruction of the Space Shuttle *Columbia*, on re-entry, and the tragic loss of seven astronauts, focused attention on NASA, its management systems, and on the shuttle programme itself. This led to a major re-direction of the NASA programme and to the plan to retire the Space Shuttle by 2010. At the same time, President Bush announced what was effectively an instruction to NASA to re-direct its programme towards a return of human explorers to the Moon, and to develop plans for a human Mars expedition. This has significant implications for propulsion, and, in particular, nuclear electric and nuclear thermal propulsion seem very likely to play a part in these deep space missions. The first example is likely to be the Jupiter Icy Moons Orbiter, to be powered by a nuclear electric thruster system.

I have thought it wise therefore to include a new chapter on nuclear thermal propulsion. This is based on the work done in the 1960s by both NASA and the Russian space agencies to develop and test nuclear rocket engines, with updates based on the latest thinking on this subject. There are also major revisions to the chapters on electric propulsion and chemical rocket engines. The rest of the book has been revised and updated throughout, and a new appendix on Ariane 5 has been provided. The planned update to the Space Shuttle sections has been abandoned, given its uncertain future.

Since its publication, this book has modestly fulfilled the hope I had for it, that it would prove useful to those requiring the basics of space propulsion, either as students or as space professionals. As a replacement for the now out of print first edition, I venture to hope that this second edition will prove equally useful.

Martin J. L. Turner
Leicester University, June 2004

Preface to the first edition

Rockets and launch vehicles are the keys to space exploration, space science and space commerce. Normally, the user of a launcher is several steps removed from the launcher itself; he may not even be present during spacecraft–launcher integration, and is usually far away at the moment of launch. Yet the few minutes of the launch can either fulfil the dreams and aspirations that have driven the mission for many years, or it can destroy them. As a space scientist I have worked on some half dozen missions in different space agencies; but it was not until I was present for the launch of Ginga, on a Japanese Mu-3-S rocket, that I actually came close to the vehicle and met the designers and engineers responsible for it. The Ginga launch was perfect, and I had agreeable discussions with the designer of the Mu rocket. I realised that I knew little about this most important component of a space mission; I had little idea of the engineering of rocket engines, and little knowledge of launch vehicle dynamics. In seeking to rectify this lamentable ignorance I found very few books on rockets which were accessible to non-specialists and yet were not trivial. Most of the work on rocket design was undertaken in the 1950s and 1960s, and many of the engineering books were published during that period. Moreover, since engineers care about numerical accuracy and precise detail (they have to) many of the books are extremely difficult for the non-specialist. It seemed, therefore, that there might be a place for a book dealing with the subject in a non-trivial way, but simplifying the mass of detail found in books intended for professional rocket engineers. I have never met a 'rocket scientist'.

This book, then, is the result. I have tried to examine rockets and rocket engines from the point of view of a non-specialist. As a physicist I am inclined to look for the physical principles and for accessible explanations of how the rocket works. This necessarily requires some mathematics, but I have included as many graphs of functions as possible, to enable those who would prefer it, to eschew the formulae, and yet gain some feeling for the dependence of a rocket's performance on its design. Whether or not I have succeeded, the reader will judge. To illustrate the principles I have used examples of real engines and launch vehicles, although the inclusion or exclusion of a particular engine or vehicle has been governed by convenience for

explanation, rather than the excellence or currency of the item itself. Appendix 2 includes a table of present-day launch vehicles, although this is not exhaustive, and new vehicles are constantly appearing.

My early research for this book indicated that the development of modern rockets took place mostly during the middle years of the last century, and that we were in the mature phase. The Space Shuttle had been around for 20 years, and was itself the epitome of rocket design; this is still true, but the closing years of the twentieth century have seen a renaissance in rocketry. While engines designed in the 1960s are still in use, new engines are now becoming available, and new vehicles are appearing in significant numbers. This seems to be driven by the rapidly growing commercial demand for launches, but is also the result of the opening up of Russian space technology to the world. I have tried to reflect this new spirit in the last two chapters, dealing with electric propulsion – now a reality – and the single stage to orbit, which is sure to be realised very soon. However, it is difficult to predict beyond the next few years where rocket design will lead us. The SSTO should reduce space access costs, and make space tourism possible, at least to Earth orbit. Commercial use of space will continue to grow, to support mobile communication and the Internet. These demands should result in further rocket development and cheaper access to space. Progress in my own field of space science is limited, not by ideas, but by the cost of scientific space missions. As a space scientist I hope that cheaper launches will mean that launches of spacecraft for scientific purposes will become less rare. As a human being I hope that new developments in rocket engines and vehicles will result in further human exploration of space: return to the Moon, and a manned mission to Mars.

This preface was originally written during the commissioning of the XMM–Newton X-ray observatory, which successfully launched on Ariane 504 in December 1999. The Ariane 5 is the latest generation of heavy launcher, and the perfection of its launch, which I watched, is a tribute to the rocket engineers who built it. But launching is still a risky business, however carefully the rocket is designed and assembled. There is always that thousand to one chance that something will go wrong; and as space users we have to accept that chance.

Martin J. L. Turner
Leicester University, March 2000

Acknowledgements

I have received help in the preparation of this book from many people, including my colleagues in the Department of Physics and Astronomy at Leicester University and at the Space Research Centre, Leicester, and members of the XMM team. I am particularly grateful to the rocket engineers of ISAS, Lavotchkin Institute, Estec, and Arianespace, who were patient with my questions; the undergraduates who attended and recalled (more or less satisfactorily) lectures on rocket engines and launcher dynamics; and, of course, my editor, Bob Marriott. While the contents of this book owe much to these people, any errors are my own.

I am grateful to the following for permission to reproduce copyright material and technical information: Société National d'Etude et Construction de Moteurs d'Aviation (SNECMA), for permission to reproduce the propellant flow diagrams of Ariane engines (Figures 3.5, 3.6, 3.7 and 3.9 in the colour section); Boeing–Rocketdyne and the University of Florida, for permission to reproduce the SSME flow diagram (Figure 3.8, colour section) and the aerospike engine (Figure 7.11); NASA/JPL/California Institute of Technology, for permission to reproduce the picture of the Deep Space 1 ion engine (Figure 6.16 and cover); the European Space Agency, for the picture of the XMM–Newton launch on Ariane 504 (cover); and Mark Wade and *Encyclopaedia Astronautica*, for permission to use tabular material which appears in Chapters 2 and 3 and Appendix 2. Figure 6.15 is based on work by P.E. Sandorf in *Orbital and Ballistic Flight* (MIT Department of Aeronautics and Astronautics, 1960), cited in Hill and Peterson (see Further Reading). Other copyright material is acknowledged in the text.

List of figures

List of tables

List of colour plates (between pages 150 and 151)