Third Edition

Future Spacecraft Propulsion Systems and Integration

Enabling Technologies for Space Exploration

Paul A. Czysz
Claudio Bruno
Bernd Chudoba

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Foreword I

We are pleased to introduce the 3rd updated edition of *Future Spacecraft Propulsion Systems and Integration—Enabling Technologies for Space Exploration* by Czysz, Bruno and Chudoba.

The authors, a team of internationally renowned specialists in the fields of hypersonics, propulsion, and reusable vehicle conceptual design, are skillfully introducing the broad spectrum of past-to-present and present-to-future space missions. Starting with the historic-momentous flight of Sputnik 1 on October 4, 1957, this book step-by-step builds the case for future fully reusable and economically viable multi-flight space transportation systems for payloads and/or humans to Earth orbits and beyond. Adopting the mind-set *design-to-mission*, the authors are systematically introducing the potential and limitations of the full range of traditional to exotic propulsion cycles and flight vehicle design integration schemes.

In order to comprehend the variety of space missions, from Earth-orbit commerce to galactic space exploration, the authors begin with a highly interesting scenario of astronomical definitions, basics, and considerations of various interplanetary missions to still visionary journeys beyond our Solar System, e.g., to Alpha Centauri. This third edition of the book adds significant material emphasizing the comprehensive multi-disciplinary toolbox required for space mission and space technology forecasting. The overarching theme throughout this book is reusable systems, a necessary prerequisite toward a first-generation space infrastructure. In order to facilitate technology forecasting, the authors derive a system-level sizing methodology which is catalyst to correctly quantify what is needed to *design to mission*, a mandatory capability for futurists, decision-makers, CTOs, and engineers alike.

When reading this book, we are directly reminded of our own former professional career developing the reusable two-stage-to-orbit (TSTO) MBB SÄNGER II concept in Germany in the 1980s. This effort demanded us continuously screening international competitive concepts and technology preparatory activities including the development of dedicated technology demonstrators often requiring comprehensive international collaboration. During this highly stimulating era, the analogous conceptual and technological goals of the US single-stage-to-orbit (SSTO) National Aero-Space Plane (NASP) project created a tremendous hype which provided the impetus for the foundation of the *AIAA International Hypersonics Conference*, an international forum significantly promoted by Richard "Dick" Culpepper of Robert Barthelemey's NASP team. The first conference took place in 1992 in Orlando, Florida. Thanks to our increasing SÄNGER activities, the 1993 conference was hosted in Munich, Germany. Since then, the conference was renamed into *AIAA International Space Planes and Hypersonic Systems and Technologies Conference*. During the following decade, this conference was held each second year at various locations.

Two of the authors (Czysz and Bruno) were continuously attending and have been highly appreciated speakers and session chairmen. Their unique expertise delivered valuable inputs to upcoming reusable space transportation system concepts encompassing a variety of air-breathing propulsion systems and novel vehicle integration reasoning. It has been this rich and vibrant era of international reusable aerospace vehicle development which is uniquely reflected in this 3rd edition of *Future Spacecraft Propulsion Systems and Integration—Enabling Technologies for Space Exploration*.

Unfortunately, our friend and conference promoter “Dick” Culpepper passed away in 2003. Our colleague and appreciated adviser and author Paul Czysz passed in 2013 after having been a mainstay in hypersonics and reusable space access for several decades. The whole hypersonics community is grateful for their valuable and enduring contributions. We are especially pleased to see an effective knowledge continuation with author Czysz working with author Chudoba since 2004. The 3rd edition of this book is testimony that this crucial body of propulsion and vehicle integration knowledge will be retained and continued.

Working with this book the reader will experience the immense amount of knowledge which can be made applicable for his specific objective by applying these experts’ findings and recommendations. This book is a *must-read* for dedicated development work and studies in the field of spacecraft propulsion, flight vehicle integration, and its enabling technologies, as of today as well as for future missions and systems.

Heribert Kuczera & Peter W. Sacher
Members of the MBB-SÄNGER-Team (1988–1995), AIAA Associate Fellows
and authors of *Reusable Space Transportation Systems* (Springer, 2011)

Foreword II

It is indeed my pleasure to introduce the 3rd edition of *Future Spacecraft Propulsion Systems and Integration* by Czysz, Bruno, and Chudoba. This book starts by describing *the* seminal event in space exploration—the Russian launch of the Sputnik satellite—which occurred in 1957 and was the singular impetus for the creation of my agency, the Defense Advanced Research Projects Agency or DARPA one year later. DARPA is a bold agency that starts bold programs to explore unproven solutions to the most difficult problems for the Department of Defense. Like DARPA, this is a bold book that makes bold assumptions and hypotheses about how we should go about exploring the heavens. Many of these assumptions and hypotheses cannot be necessarily proven with what we know currently about the way the world works. However, I think the authors intentionally stretch our imaginations as they propose a vision for the exploration of our Solar System and beyond.

As I read this book, I found myself trying to imagine the heavens and the immensity of our universe. It humbles one to think about how large our world really is and Czysz, Bruno, and Chudoba do an excellent job of describing this world in a way that makes you want to suit up, jump in the next rocket, and go explore it.

But the rocket is the issue, isn't it? We don't have vehicles or propulsion systems that will let us explore the outer reaches of our world today. Czysz, Bruno, and Chudoba help the reader envision the propulsion concepts and flight vehicle systems that will be required to explore more of our universe. Using well-known equations and formulas, they offer vehicle and propulsion solutions that have the potential to help us break the bonds of Earth more efficiently than we can today. Will all of these concepts work? Do they all have merit? I would venture to say the answer is no but that should not stop us from applying the scientific method and some good, solid engineering rigor to these problem sets and from determining how we can build systems that take us to Mars and beyond.

Like DARPA's penchant for taking on high-risk, high-payoff projects, Czysz, Bruno, and Chudoba take on the high-risk but very high-payoff challenge of how to fully explore our solar system and beyond. So jump in, buckle up, and get ready for a wild ride.

Steven H. Walker Ph.D.
Acting Director, Defense Advanced Research Projects Agency (DARPA)
AIAA Fellow

Preface to Third Edition

The third edition of this book was born not only to update the state of the art of propulsion technology, but, more significantly, also to honor the memory of Paul A. Czysz, who was instrumental in proposing and leading the previous two editions. Paul Anthony Czysz died on August 16, 2013. He is credited with the development of a pragmatic system-level propulsion and aerospace design methodology. This was born from his design and testing experience in the USAF and at McDonnell Douglas, with the purpose of supporting the decision-maker by mathematically and visually identifying the available hardware solution space as a function of the mission. In addition to this book, Paul's work has been published in four books and in numerous technical articles. His original style in guiding and quantifying "design to mission" will remain a model for generations of engineers to come. A second difference with the two previous editions is the much greater emphasis placed on the integration of propulsion systems for hypersonic cruise aircraft and hypersonic accelerators facilitating space launch. This is the work of Professor Bernd Chudoba, the new co-author and specialist in this field.

The prime motivation for this book is the fact that humankind has been dreaming of traveling to space for a long time. In the early 1960s, there was a dedicated push to develop vehicle configurations that would permit us to travel to space and back through the atmosphere as readily and conveniently as flying on an airliner. That idea was unavoidably coupled with propulsion concepts that relied on capturing the oxygen within our atmosphere, instead of carrying it onboard from the ground up as expendable satellite launchers still do now. Given the slow technology progress since 1957, space access and space flight still suffer from limited performance due to high cost, mass consumption, and energy requirements, with consequent limited acceleration and relatively slow speed. During the 1960s, the concept of space travel extended beyond our planet, to our Solar System and the galaxy beyond (see Chap. 1), using power sources other than chemical, such as fission and fusion. It was then and still is recognized that any operational space flight transportation system is defined and limited by three key elements: (a) propulsion, (b) gravity, and (c) inertia. Future space flight requires advancing the understanding of all three areas. The first area (a) is primarily an engineering domain and is hardware driven, while the remaining two (b and c) are the domain of physics.

Accordingly, any significant advance in operational space capability will be a direct effect of revolutionary breakthroughs in high-thrust/high-efficiency propulsion and of gravity and inertia modulation. As the present outlook for breakthroughs in gravity and/or inertia is very uncertain, this book does focus on propulsion and the effect of its integration on the mission, the hardware and key technologies. The development of new manned space vehicles and launchers involves thousands of man-years. From the initial concept and through its gestation phase to the final product, how can the design team develop confidence in its performance and understanding of risks while committing very costly resources (see Chap. 2)? In this context, the trend toward space commercialization suggests the same approach seen with more conventional markets, where the mission objective is guided by continuous and sound evaluation of the product design and of its engineering or economics margins. This is in fact the integrated approach developed in Chap. 3.

Traveling to space in the near future is a multi-step process. The *first* is to realize a two-way transport to and from low Earth orbit (LEO); see Chaps. 4 and 5. This is a critical first step as it is the key to moving away from our Earth environment while being very expensive. In any future space scenario or market, economics dictates that travel to and from LEO must be frequent and affordable. From a vision of spacecraft parked in LEO, there are then several options. The geosynchronous orbit or geostationary orbit (GSO) is at an altitude of 35,853 km (22,278 statute miles) and has an equatorial orbital period of 24 hours, so it is stationary over any fixed point on Earth. These orbits are home to commercial telecommunication satellites.

The *second* critical step is an elliptical transfer orbit to the Moon. The orbital speed to reach the Moon is less than the speed to escape Earth's gravity, so the transfer orbit is elliptical (a closed curve) which does require less energy (but more logistics) than reaching GSO. Depending on the specific speed/orbit selected, the time to reach the Moon ranges from 56 to 100 hours. The Apollo program selected a 72-hour travel orbit from LEO (see Chap. 6). In terms of time, the Moon is truly close to us.

A *third* and far more eventful critical step is to achieve escape speed. This is a factor square root of two (about 1.41) faster than orbital speed. At escape speed and faster, the spacecraft trajectory is an open parabola or hyperbola. There is no longer a closed path for returning the spacecraft to Earth. So now we can move away from the gravitational control of Earth (not from gravity!) to explore our Solar System (see Chap. 7) and beyond.

There is a challenge of time, distance, and propulsion as we proceed farther and farther to explore our Solar System, then nearby Galactic space, and finally our galaxy. Exploring beyond our galaxy is technically far beyond our current or projected capabilities. Our understanding of propulsion, mass, inertia, and time will have to be different (see Chaps. 8 and 9). Understanding mass and inertia may be the most challenging. Inertia is a resistance to change of speed or direction. As we approach light speed, inertia/mass approaches infinity. As the mass approaches infinity, the thrust required to maintain constant acceleration approaches also infinity. Thus, at present, we do not know how to exceed the speed of light. If that remains the case, we are trapped within the environs of our Solar System.

An inertia-linked issue is human tolerance of continuous acceleration for long periods. Nominally that is assumed about three times the Earth's gravitational acceleration at sea level. At that acceleration, the time to reach a distant destination is numerically on the same order as the distance in light years. So, if a crewed spacecraft is to return to Earth within the lifetime of its occupants, we are again limited to about 20 light-years. That is within the distances to the seven or eight closest stars to our Sun.

As much as the authors would like to show how to travel in Galactic space, that will require breakthroughs in physics, not just propulsion. Until that time, we have much to explore and discover within the environs of our Solar System.

Coming down from Galactic space to life on Earth, these authors would like to acknowledge our spouses, Elena Prestini and Andrea Chudoba for their patience and support, and Christian Dujarric (formerly at ESA), Georg Poschmann (formerly at Airbus Industrie), Paul March at NASA, and Friedwardt Winterberg at The University of Nevada, for providing figures, articles, and comments. Special thanks go to our Editor at Springer, Ms. Janet Starrett-Brunner for her constant attention to our requests; without her, writing this book would have taken much longer.

East Hartford, Storrs, USA
Arlington, Texas, USA
June 2017

Claudio Bruno
Bernd Chudoba

Preface to First and Second Edition

Humankind has been dreaming of traveling to space for a long time. Jules Verne thought we could reach the moon with a giant cannon in the 1800s. In the early 1960s, there was a dedicated push to develop the vehicle configurations that would permit us to travel to space, and back through the atmosphere, as readily and conveniently as flying on an airliner to another continent and back. That idea, or intuition, was necessarily coupled with advanced propulsion system concepts, that relied on capturing the oxygen within our atmosphere instead of carrying it onboard from the ground up, as rockets developed in Germany in the 1940s did, and as satellite launchers still do. During the 1960s, the concept of space travel extended beyond our planet, to our Solar System and the galaxy beyond (see Chap. 1), using power sources other than chemical, such as fission and fusion. Not much is left nowadays of those dreams, except our present capability to build those advanced propulsion systems.

Traveling to space in the foreseeable future is a multi-step process. The first step is to achieve a two-way transport to and from orbit around our Earth, that is, a low Earth orbit (LEO); see Chaps. 2, 4, and 5. This is a critical first step as it is the key to moving away from our Earth environment. For any future development in space, travel that transits to and from LEO must be frequent and affordable. From a vision of spacecraft parked in LEOs, there are then several options. One is a geosynchronous orbit or geostationary orbit (GSO) that is at an altitude of 35,853 km (22,278 statute miles) and has an equatorial orbital period of 24 hours, so it is stationary over any fixed point on Earth. Another option for the next step is an elliptical transfer orbit to the Moon. The orbital speed to reach the Moon is less than the speed to escape Earth's orbit, so the transfer orbit is elliptical, and requires less energy to accomplish (but more logistics) than reaching GSO. Depending on the specific speed selected, the time to reach the Moon is between 100 and 56 hours. In fact, the Apollo program selected a speed corresponding to a 72-hour travel time from LEO to the vicinity of the Moon (see Chap. 6): in terms of the time needed to reach it, the Moon is truly close to us. All circular and elliptical orbits are, mathematically speaking, closed conics.

Another and far more eventful option is to achieve escape speed, that is a factor square root of two faster than orbital speed. At escape speed and faster the spacecraft trajectory is an open conic (i.e., a parabola or hyperbola), and there is no longer a closed path returning the spacecraft to Earth. So now we can move away from the gravitational control of Earth (not from gravity!) and proceed to explore our Solar System and beyond. However, after taking such a step, there is a challenge of time, distance, and propulsion as we proceed farther and farther to explore our Solar System, then nearby Galactic space, and finally our galaxy. Exploring beyond our galaxy is technically beyond our current or projected capabilities. In order to achieve travel beyond our galaxy, our current understanding of thrust, mass, inertia, and time will have to be different (see Chaps. 8 and 9). Mass/inertia may be the most challenging. An article by Gordon Kane in the July 2005 Scientific American entitled "The Mysteries of Mass" explains our current understanding of what we call mass. From another paper presented by Theodore Davis at the 40th Joint Propulsion Conference [Davis, 2004], we have the following statement:

> E = mc2 is the expression of mass-energy equivalence and applies to all forms of energy. That includes the energy of motion or kinetic energy. The faster an object is going relative to another object, the greater the kinetic energy. According to Einstein mass and energy are equivalent, therefore the extra energy associated with the object's inertia manifests itself in the same way mass manifests itself ... As a result, the kinetic energy adds to the object's inertial component and adds resistance to any change in the objects motion. In other words, both energy and mass have inertia.

Inertia is a resistance to change in speed or direction. As we approach light speed, the inertia/mass approaches infinity. As the mass approaches infinity the thrust required to maintain constant acceleration also approaches infinity. Thus, at this point we do not know how to exceed the speed of light. If that remains the case, we are trapped within the environs of our Solar System.

There is a second major issue. Human tolerance to a continuous acceleration for long periods has yet to be quantified. Nominally that is considered about three times the surface acceleration of gravity. At that rate of acceleration the time to reach a distant destination is numerically on the same order as the distance in light years. So if a crewed spacecraft is to return to Earth within the lifetime of its occupants, we are again limited to 20 light years of so. That is within the distance to the seven or eight closest stars to our star, the Sun.

As much as the authors would hope to travel in Galactic space, it will require a breakthrough in our understanding of mass, acceleration and propulsion. Until that time we have much to explore and discover within the environs of our Solar System.

Coming down from Galactic space to intelligent life on Earth, the authors would like to acknowledge the contributions of Elena and David Bruno, Catherine Czysz, Dr Babusci at the INFN (Italian Nuclear Physics Institute), Dr Romanelli at the ENEA Fusion Laboratories, Mr Simone, GS, H. David Froning, Gordon Hamilton, Dr Christopher P. Rahaim and Dr John Mason, Praxis Subject Advisory Editor. Special thanks go to Clive Horwood of Praxis, for his patience, constant encouragement, and prodding, without which writing this book would have taken much longer.

St. Louis, USA Paul A. Czysz
East Hartford, Storrs, USA Claudio Bruno

Contents

Notation

Abbreviations

AB	Airbreather (engine cycle), All-Body
AC	Alternating Current
ACES	Air Collection and Enrichment System (engine cycle)
AEC	Atomic Energy Commission
AEDC	Arnold Engineering Development Complex
AERE	Atomic Energy Research Establishment
AeroMech	conceptual design stability & control (software)
AFB	Air Force Base
AFFDL	Air Force Flight Dynamics Laboratory
AFRL	Air Force Rocket Laboratory
AGARD	Advisory Group for Aerospace Research and Development
AIAA	American Institute of Aeronautics and Astronautics
AI	Aerospace Institute
AIP	American Institute of Physics
ALES	Air Liquefaction and Enrichment System
ALHL	Air Launch Horizontal Landing
ALSS	Apollo Logistics Support Systems
AMTEC	Alkali Metal Thermal-to-Electric Conversion
ANSER	Analytic Services Inc
AoA	Angle-of-Attack
APL	Applied Physics Laboratory
ARC	Aerodynamics Research Center (at UTA), All Regeneratively Cooled (rocket)
ARCC	Air-breathing Rocket Combined Cycle
ARM	Asteroid Redirect Mission
ASEE	American Society for Engineering Education
ASI	Agenzia Spaziale Italiana (Italian Space Agency)
ASME	American Society of Mechanical Engineers
ASP	Aerospace Plane
ASPL	Advanced Space Propulsion Laboratory (NASA)
ASSET	Aerothermodynamic Elastic Structural Systems Environmental Tests (USA)
ATREX	Air Turbo Ramjet Engine with eXpander cycle
ATV	Automated Transfer Vehicle
AU	Astronomical Unit
AVD	Aerospace Vehicle Design (AVD Laboratory at UTA MAE, AVD Services LLC)
AVDS	Aerospace Vehicle Design Synthesis (software)
AW&ST	Aviation Week and Space Technology
BB	Blended Body

BEPR	Breakthrough Energy Physics Research
BG	Boost-Glide
BGRV	Ballistic Glide Reentry Vehicle
BNTEP	Bimodal Nuclear-Thermal Electric Propulsion
BOL	Beginning-Of-Life
BOR	Bespilotniye Orbitalniye Raketoplan (USSR unpiloted orbital rocketplane)
C/C	Carbon/Carbon (composites)
CBFR	Colliding Beam Fusion Reactor
C	Compressor, Chemical
CECE	Common Extensible Cryogenic Engine
CEM	Crew Exploration Module
CEO	Chief Executive Officer
CERMET	CERamics-METal
CERN	Conseil Européen pour la Recherche Nucléaire (European Organization for Nuclear Research)
CEV	Crew Exploration Vehicle
CFD	Computational Fluid Dynamics
CFR	Compact Fusion Reactor
CG	Center of Gravity
CGS	Centimeter-Gram-Second system of units (= cgs)
CIAM	Central Institute of Aviation Motors
CLV	Crew Launcher Vehicle
CO_2	Carbon dioxide
COIL	Chemical Oxygen-Iodine Laser
CONEU	Contiguous Continental Europe
CONUS	Continental United States
COPS	Comparative Operational Propulsion Systems
CRV	Crew Return Vehicle
CSP	Cryo-Solid Propulsion
CSS	Coaxial Slow Source
CT	Computerized Tomography
CTR	Controlled Thermonuclear Reactions
CTX	Compact Torus Experiment
CW	Continuous Wave
CXO	Corporate eXecutive Officer
DARPA	Defense Advanced Research Projects Agency
DB	Data-Base
DC	Deeply Cooled, Direct Current
D	Deuterium
DFP	Diluted Fusion Products (rocket)
DGLR	Deutsche Gesellschaft für Luft- und Raumfahrt
DNA	DeoxyriboNucleic Acid
DoD	Department of Defence
DOE	Department of Energy
DPF	Dense Plasma Focus
DRA	Design Reference Architecture
DR	Down Range
DRM	Design Reference Mission
DS	Decision-Support
DSN	Deep Space Network (NASA)
EAR	Excess Absolute Risk
ECH	Electron Cyclotron Heating

ECR	Electron Cyclotron Resonance
EM	Electromagnetic
ENEA	Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile (Italian National Agency for New Technologies, Energy and Sustainable Economic Development)
EP	Electric Propulsion
ERR	Excess Relative Risk
ERV	Earth Return Vehicle
ESA	European Space Agency
ESH	Expendable Spacecraft Hardware
ESI	Electrostatic Ion Thruster
ET	External Tank, Electric Thruster, Electrothermal
ETW	Engine Thrust-to-Weight ratio
EU	European Union
EVA	Extravehicular Activity (as in EVA suit)
EX	Exchanger
FDL	Flight Dynamics Laboratory (USAF)
FEL	Free Electron Laser
FF	Fission Fragments
FFRE	Fission Fragment Rocket Engine (NASA)
F	Fuel
FI	Fast Ignition
FIREX	FIeld-Reversed ion ring EXperiment
FMPT	First Materials Processing Test (program, Japan)
FOCAL	Fast Outgoing Cyclopean Astronomical Lens
FRC	Field-Reversed Configuration
FRM	Field-Reversed Mirror
FRX	Field-Reversed configuration plasma injector for magnetized target Experiment
FTL	Faster Than Light
GALCIT	Guggenheim Aeronautical Laboratory at the California Institute of Technology
GALEX	galaxy Evolution Explorer (NASA/JPL)
GCR	Galactic Cosmic Radiation, Galactic Cosmic Rays, Gas Core Reactor
GDL	Gas Dynamics Laboratory
GDM	GasDynamic Mirror
GEO	Geostationary Earth Orbit
GIE	Gridded Ion Engine
GMT	Greenwich Mean Time
GNIPGS	State Hypersonic Systems Research Institute (Russia)
GRASP	Gravity Research for Advanced Space Propulsion
GRC	Glenn Research Center (NASA)
GSFC	Goddard Space Flight Center (NASA)
GSO	Geosynchronous Orbit
GTO	Geostationary Transfer Orbit
GW	Gross Weight, Giga-Watt
H_2	Chemical formula for hydrogen gas
HALE	High-Altitude Long-Endurance
HC	Hypersonic Convergence
HED	High-Energy Density
HEO	Highly Elliptical Orbit
HL	Horizontal Landing
HMX	High Melting eXplosive (octogen)
HOTOL	Horizontal Take-Off and Landing

HRLV	Highly Reusable Launch Vehicle
HSCT	High-Speed Civil Transport
HTHL	Horizontal-Takeoff-Horizontal Landing (= HTOL)
HTOL	Horizontal-Takeoff-Horizontal Landing
HTPB	Hydroxyl-Terminated PolyButadiene
HTSC	High-Temperature SuperConducting
HyFAC	Hypersonic Research Facilities Study (NASA-sponsored study)
IAC	International Astronautical Federation Congress, International Astronautical Conference
IAEA	International Atomic Energy Agency
IAF	International Astronautics Federation
IAU	International Astronomical Union
ICAS	International Council of the Aeronautical Sciences
ICBM	Intercontinental Ballistic Missile
ICES	International Conference on Environmental Systems
ICF	Inertial Confinement Fusion
ICR	Inertial Confinement fusion Reactors
ICRP	International Commission on Radiological Protection
ICRU	International Commission on Radiation Unit
IEC	Electrostatic-Inertial Confinement
IEEEAC	Institute of Electrical and Electronics Engineers Aerospace Conference
IEEE	Institute of Electrical and Electronics Engineers
IGY	International Geophysical Year
IMLEO	Initial Mass in LEO
INEL	Idaho National Engineering Laboratories
INL	Idaho National Laboratories
IOC	Initial Operational Capability, In-Space Operations Corporation
IQ	Intelligence Quotient
IRBM	Intermediate-Range Ballistic Missile
IR	Infrared Radiation
ISABE	International Symposium on Air-breathing Engines
ISAS	Institute of Space and Astronautical Science (Japan)
ISECG	International Space Exploration Coordination Group
ISS	International Space Station
ISTC	International Science and Technology Center
ISTS	International Symposium on Space Technology and Science
ITAR	International Traffic in Arms Regulations
ITER	International Thermonuclear Experimental Reactor
JANNAF	Joint Army Navy NASA Air Force
JAXA	Japan Aerospace Exploration Agency
JBIS	Journal of the British Interplanetary Society
JHU	Johns Hopkins University
JIMO	Jupiter's Icy Moons Orbiter
JP	Jet Propellant
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center (NASA)
JUICE	JUpiter ICy moons Explorer
JWST	James Webb Space Telescope
K shell	Electron shell labeling (principal energy level)
KB	Knowledge-Base
KBO	Kuiper Belt Objects

KLIN	Meaning wedge in Russian, thermally integrated deeply cooled turbojet and rocket engine
KREEP	K = potassium, REE = rare earth elements, and P = phosphorus
KSC	NASA Kennedy Space Center
L shell	Electron shell labeling (principal energy level)
LACE	Liquid Air Cycle Engine
LANL	Los Alamos National Laboratory
LANTR	LOX-Augmented NTR
LASL	Los Alamos Science Laboratories
LDEF	Long Duration Exposure Facility
LDX	Levitated Dipole eXperiment
LEA	Liquid-Enriched Air
LEO	Low Earth Orbit
LESA	Lunar Exploration System for Apollo
LH_2	Liquid Hydrogen
LHC	Large Hadron Collider
LIGO	Laser Interferometer Gravitational-Wave Observatory
LLNL	Lawrence Livermore National Laboratories
LLO	Low Lunar Orbit
LND	Landing
LOCA	Loss Of Coolant Accident
LOX	Liquid Oxygen
LRE	Liquid Rocket Engine
LR	Lateral Range
LSS	Life Span Study
LTSC	Low-Temperature SuperConductors
LUNOX	Lunar-derived LOX
ly	Light-years
M shell	Electron shell labeling (principal energy level)
MagLev	Magnetic Levitation linear induction accelerator
MagLift	Magnetic Lifter
MAI	Moscow Aircraft Institute
MAKS	Multi-purpose Aerospace System
MAR	Mass Annihilation Rocket
MAV	Mars Ascent Vehicle
MBB	Messerschmitt-Bölkow-Blohm
McAIR	McDonnell Aircraft Company
MCF	Magnetic Confinement Fusion
MC	Magnetic Confinement
MCR	Magnetic Confinement Reactors, Magnetic Confinement Rocket
MDA	Multi-Disciplinary Analysis
MDC	McDonnell Douglas Corporation
MD	Module
MEO	Medium Earth Orbit
MFE	Magnetic Fusion Energy
MFPS	Mirror Fusion Propulsion System
MFTF	Mirror Fusion Test Facility
MGS	Manned Geosynchronous Earth Orbit (GEO) Servicing
MHD	Magneto-Hydro-Dynamic
MICF	Magnetic-Inertial Confinement Fusion
MIC	Magnetic-Inertial Confinement
MIF	Magnetic-Inertial Fusion

MIR	Lit. *peace* (space station run by the Soviet Union and later by Russia)
MITEE	Miniature Reactor Engine
MMC	Metal Matrix Composites
MMH/NTO	Monomethylhydrazine + Nitrogen Tetroxide (hypergolic propellants)
MMO	Mini-MagOrion (Miniature Magnetic Orion)
MMSEV	Multi-Mission Space Exploration Vehicle
MOL	Manned Orbiting Laboratory
MP^2	Multi-Purpose Plasma
MPD	Magneto-Plasma-Dynamic (= MHD thruster)
MR	Mass Ratio
MRX	Magnetic Reconnection Experiment
MSL	Mars Science Laboratory
MST	Madison Symmetric Torus
MSTO	Multi-Stage-To-Orbit
MTBM	Mean Time Between Maintenance
MTF	Magnetized Target Fusion
MTV	Mars Transfer Vehicle
NACA	National Advisory Committee for Aeronautics
NAL	National Aerospace Laboratory (Japan)
NASA	National Aeronautics and Space Administration
NASDA	National Space Development Agency (Japan)
NASP	National Aero-Space Plane
NATO	North Atlantic Treaty Organization
NBI	Neutral Beam Injection
NEA	Near-Earth Asteroid
NEO	Near-Earth Objects
NEP	Nuclear-Electric Propulsion
NERVA	Nuclear Engine for Rocket Vehicle Application
NEXIS	Nuclear-Electric Xenon Ion System
NextSTEP	Next Space Technology Exploration Partnership
NFL	National Football League
NFRC	Nuclear Fuels Reprocessing Coalition
NH	New Horizons
NIA	National Institute of Aerospace
NIAC	NASA Innovative Advanced Concepts (program)
NIF	National Ignition Facility
NIST	National Institute of Standards and Technology
n	Neutron
NP	Nuclear Propulsion
NPR	Nuclear Propulsion Research
NRC	National Research Council
NRL	Naval Research Laboratory
NRX	Nuclear Rocket Experimental
NSI	Nuclear Systems Initiative
NTER	Nuclear-Thermal Electric Rocket
NTO	Nitrogen Tetroxide
NTP	Nuclear-Thermal Propulsion
NTR	Nuclear-Thermal Rocket
NTREES	Nuclear-Thermal Rocket Element Environmental Simulator
NuSTAR	Nuclear Spectroscopic Telescope Array
N_2O_4	Dinitrogen Tetroxide
O_2	Oxygen

OCO	Orbiting Carbon Observatory, Oort Cloud Object
OD	Outer Diameter
ODWE	Oblique Detonation Wave Engine
OECD	Organization for Economic Cooperation and Development
OKB	Opytnoye Konstruktorskoye Buro (Russian, Experimental Design Bureau)
OMC	Open Magnetic Confinement
OMF	Open Magnetic Field
OMV	Orbital Maneuvering Vehicle
ONERA	Office National d'Etudes et Recherches Aérospatiales
OOPC	Other OPerational Costs
O	Oxidizer
OPA	Oxygen-Poor Air
Ops	Operations
OSTP	Office of Science and Technology Policy (White House)
OTV	Orbital Transfer Vehicle
OWE	Operating Weight Empty
OWEv	Operating Weight Empty (volume budget)
OWEw	Operating Weight Empty (weight budget)
PAMELA	Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics
PBR	Particle Bed Reactor
PDE	Pulse Detonation Engine
PDRE	Pulse Detonation Rocket Engine
PDR	Pulse Detonation Rocket
PEMT	Purely Electro-Magnetic Thruster
PF	Poloidal Field
PP	Parametric Process
p	Proton
PY	Per Year
QED	Quiet Energy Discharge
QI	Quasi-Interstellar (= QIS)
QSH	Quasi-Single-Helicity
R&D	Research and Development
RAD	Radiation Assessment Detector
RAE	Royal Aircraft Establishment
RAM	Ramjet
RASC	Revolutionary Aerospace Systems Concepts
RAS	Russian Academy of Sciences
RBCC	Rocket-Based Combined-Cycle
RC	Right Circular (RC cone)
RDE	Rotating Detonation Engine
RDT&E	Research, Development, Technology, and Engineering
RFC	Reverse Field Configuration
RFI	Request For Information
RF	Radio Frequency
RFP	Reversed Field Pinch
RIAME	Research Institute of Applied Mechanics and Electrodynamics
RIT	Radio Frequency Ion Technology
Rkt	Rocket
RLV	Reusable Launch Vehicle
RMF	Rotating Magnetic Field
RSH	Reentry Spacecraft Hardware
RS	Rocket System (propulsion cycle, as in Ejector RS)

RSR	Roll Speed Ratio, Rapid Solidification Rate
RSS	Reentry Spacecraft Spares
RTG	Radioisotope Thermoelectric Generator
SABRE	Synergetic Air-Breathing Rocket Engine
SAE	Society of Automotive Engineers
SAFE	Subsurface Active Filtering of Exhaust
SAFFIRE	Self-sustained, Advanced-Fueled FIeld REversed mirror reactor
SAIC	Science Applications International Corporation
SBW	Switch-Blade Wing (= SWB)
SCORE	Stoichiometric COmbustion Rocket Engine
SCRAM	Scramjet
SCRJ	Supersonic Combustion Ramjet (also scramjet)
SCR	Solid Core Reactor
SC	Superconductor
SDIO	Strategic Defense Initiative Organization
SDI	Strategic Defense Initiative
SEI	Space Exploration Initiative
SEP	Solar-Energy Propulsion
SERJ	Supercharged Ejector Ram Jet
SL	Sea Level
SLS	Space Launch System, Sea-Level Static
SNAP	System for Nuclear Auxiliary Power
SNC	Sierra Nevada Corporation
SNRE	Small Nuclear Reactor Engine
SNTP	Space Nuclear-Thermal Propulsion
SOAR	Space Orbiting Advanced fusion power Reactor
SOX	Solid-Oxygen
SOZ	Solid-Ozone
SPACE	Space Propulsion Annular Compact Engine
SPHEX	SPHeromak EXperiment
SRM	Solid Rocket Motor (booster)
SR	Solar Radiation
SSME	Space Shuttle Main Engine
SSO	Sun-Synchronous Orbit
SSPX	Sustained Spheromak Physics Experiment
SS	Steady State
SSTC	Single-Stage To Cruise
SSTO	Single-Stage To Orbit
SST	Supersonic Transport
SSX	Swarthmore Spheromak Experiment
STAIF	Space Technology and Applications International Forum
STAR	Spaceplane Technology and Research
STP	Standard Temperature and Pressure
STS	Space Transportation System (Space Shuttle)
T III C	Martin Titan III C
TAD	Technology Availability Dates
TARC	Transmutation by Adiabatic Resonance Crossing
TAV	Trans-Atmospheric Vehicle
TCS	Training Course Series
TD	Thoria-Dispersed
TEPCO	Tokyo Electric Power Company, Inc
TESS	Transiting Exoplanet Survey Satellite

TF	Toroidal Field
TLC	Telecommunications
TMI	Three Mile Island
TM	Tandem Mirror
TMX	Tandem Mirror Experiment
TNO	Trans-Neptunian Objects
TOGW	Takeoff Gross Weight
Tokamak	To (roidal) ka (chamber) mak (machine)
TO	Takeoff
TPS	Thermal Protection System
TRISO	Tristructural Isotropic (fuel)
TRITON	TRImodal, Thrust Optimized, Nuclear Propulsion and Power System for Advanced Space Missions
TRL	Technology Readiness Level
TsAGI	Russian Central Aerodynamics Institute
TsIAM	Central Institute of Aviation Motor Development or CIAM
TsNIIMash	Central Research Institute of Machine Building
TSTO	Two-Stage-To-Orbit
T	Turbine, Tritium
TUG	Tugboat
TWA	Trans World Airlines
TWTO	Thrust-to-Weight ratio at Take Off
UAV	Unmanned Aerial Vehicle
UDMH	Unsymmetrical Diethyl-Hydrazine
UFO	Unidentified Flying Object
UHTC	Ultra-High-Temperature Ceramics
ULA	United Launch Alliance
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
UPS	United Parcel Service
USAF	United States Air Force
USA	United States of America
USN	United States Navy
USSR	Union of Soviet Socialist Republics (Soviet Union)
US	United States (America)
UTA	University of Texas at Arlington
UW	The University of Washington
VASIMR	VAriable Specific Impulse Magneto-plasma-dynamic Rocket
VATES	Virtual Autonomous Test and Evaluation Simulator (software)
VCCW	Vortex Combustion Cold-Wall (thrust chamber)
VCTR	Variable Cycle Turbo Ramjet
VDK	Jean Vandenkerckhove
VHRE	Vortex Hybrid Rocket Engine
VIRTIS	Visible and Infrared Thermal Imaging Spectrometer
VISTA	Vehicle for Interplanetary Space Transport Applications
VKI	Von Kármán Institute
VPK	Military-Industrial Commission of the Russian Federation
VTHL	Vertical-Takeoff-Horizontal Landing (= VTOHL)
VTOHL	Vertical-Takeoff-Horizontal Landing
VTOL	Vertical Takeoff and Landing
VT	Total volume, vertical takeoff
VTVL	Vertical-Takeoff-Vertical Landing
WB	Wing-Body

WHO	World Health Organization
WR	Weight Ratio
Wt	Weight
WU	Whittle Unit
W	Work
X	Experimental
ZFW	Zero-Fuel Weight
ZPE	Zero-Point Energy

Symbols

a	Cross-sectional semi-axis, semi-major axis of the transfer ellipse (Kepler's *elliptical* orbit), constant acceleration, plasma radius in the solenoid
a_0	Constant acceleration
a_{normal}	Acceleration perpendicular to flight path necessary to maintain a curved path
a_{sc}	Spacecraft acceleration
a_{x}	Axial acceleration
A	Propellant molecule, inlet area, atomic mass number, cross section of the reactor
$\vec{A}$	Vector potential
A, B	Constants for slender aircraft (state-of-the-art)
A_α	Mass number (nucleus emits an alpha particle)
A^+	Ion
$A^*, A_{\mathrm{sonicthroat}}$	Rocket nozzle throat area
A_0	Airbreathing engine cowl stream tube area (inlet)
A_1	Airbreathing engine module cowl area (inlet)
A_2	Airbreathing engine module minimum area (inlet)
A_C	Airbreathing engine geometric air capture area (inlet)
A_{base}	Base cross-sectional surface area
A_c	Airbreather cowl area
A_C	Inlet air capture area
A_{cowl}	Airbreather cowl area
$A_{\max}$	Maximum cross-sectional surface area
A_z	Launch azimuth from true north
b	Cross-sectional semi-axis
$\vec{b}$	Local unit vector along $\vec{B}$
b/a	Vehicle normal cross-sectional geometry description (height and width)
B	Buildup factor, $B \equiv \lvert\vec{B}\rvert \equiv \sqrt{\vec{B}\cdot\vec{B}}$, $\vec{B} = B(x)\cdot\vec{b}$, poloidal magnetic field in the (r-z) plane
$\vec{B}$	Magnetic induction or magnetic field, magnetic field strength
$\vec{B}_{\min}, \vec{B}_{\max}$	Minimum value in the middle and a maximum value at the coil location
B_0	Mean magnetic field within the bottle
$\vec{B}_0$	Magnetic field necessary to stop pellet debris at a safe distance from the wall, magnetic field value in the solenoid
B_{ab}	Magnetic field value in the absorber
B_e	Magnetic field outside the separatrix (determined by the poloidal coil current)

$\vec{B}_{ext}$	External imposed magnetic induction or magnetic field, magnetic field strength
B_m	Magnetic-field intensity at the midplane
$B_{\max}$	Peak magnetic field within the bottle, magnetic field value in the mirror
$\vec{B}_p$	Tokamak magnetic field
$\vec{B}_{0p}$	Vacuum magnetic field
B_θ	Toroidal magnetic field along θ
c	Speed of light
c^*	Characteristic velocity
c_s	Plasma sound speed
C	Curve fit coefficient
C^*	Effective exhaust velocity
C_0	Collimation or coupling factor < 1 empirically accounting for the fraction of the impulse transmitted to the thrust plate by the debris
C_3	Characteristic energy (measure of the excess specific energy over that required to just barely escape from a massive body)
C_D	Drag coefficient (aircraft)
C_{D_0}	Drag coefficient (aircraft) for zero angle-of-attack (zero-lift drag coefficient)
C_L	Lift coefficient (aircraft)
$C_{L_{L/D\,max}}$	Lift coefficient (aircraft) at maximum aerodynamic efficiency
C_p	Heat capacity at constant pressure
C_{sys}	Constant system weight
C_T	Coupling coefficient
C_v	Heat capacity at constant volume
C/K	Kinetic energy losses chemical combustion can overcome
CO/F	Onboard (carried) oxygen-to-fuel ratio
CR	Inlet geometry contraction ratio ($A_{capture}/A_{throat}$)
d	Diameter of the receiving mirror on the spacecraft, distance
d_{acc}	Distance travelled at constant acceleration
dC	Number of neutrons captured by a nucleus
D	Aerodynamic drag (flight vehicle), cylinder diameter, diameter of the beaming mirror, absorbed dose, radiation dose
D_{Brems}	Bremsstrahlung radiation
D_{recom}	Radiation heat transfer due to recombination of electrons and ions
DR	Down range
e	Eccentricity, factor
e^-	Electron
E	Energy, energy to reach escape speed, internal energy, effective dose
$\vec{E}$	Electric field, radial electrostatic field
ΔE	Energy loss
E_B	Pellet energy release
E_f	Fusion heat release
E_{fus}	Energy released in a fusion reaction
$E_{fus,ij}$	Energy released in the reaction
E_i	Extraction potential, ion energy
E_{in}	Injection energy
E_k	Kinetic energy, kinetic energy of the fission fragments
$E_{\max}$	Maximum energy
E_p	Potential energy
E_{TW}	Engine thrust-to-weight ratio, sea-level static (SLS)
E/m	Energy density
f	Factor

$\vec{f}$	Lorentz force
f_b	Measure of the fuel burn fraction
f_{crw}	Crew member specific weight
f_D	Fraction for direct conversion
f_{ij}	Fraction of the fusion energy transferred to the plasma
f_n	Fraction of fusion energy associated with neutrons
f_s	Stoichiometric condition (stoichiometric fuel/air ratio)
f_{sys}	Variable system weight coefficient
f_T	Fraction used directly for thrust
ff	Fuel fraction (W_{fuel} / W_{TOGW})
$fuel/air$	Fuel-to-air ratio
F	D. Taylor correlation parameter, thrust, efficiency
$\vec{F}$	Lorentz force
$\vec{F}_g$	Gravitational force
g	Acceleration due to gravity
g_0	Gravitational acceleration at the surface of Earth
G	Universal gravitational constant
GW/S_p	Gross weight planform loading
h	Potential energy, altitude, altitude above surface, Planck constant
h_a, h_p	Geometry parameters for the example elliptical transfer orbit
h_0	Static enthalpy, freestream static enthalpy
h_S	Specific energy (energy/mass)
h_t	Total energy (stagnation energy)
H	Magnetic field intensity, equivalent dose
i	Orbital inclination, ionic current
i/F	Current absorbed per unit thrust (electric thruster)
I	Plasma current, radiation intensity, neutron flux
$\vec{I}$	Plasma current
I_{dsp}	Density specific impulse
I_p	Propulsion index, propulsion-propellant index
I_{pp}	Propulsion-propellant index
I_{ref}	Reference index
I_{sp}	Specific impulse, propulsion efficiency
I_{spe}	Effective specific impulse
I_{spf}	Fuel specific impulse
I_{str}	Structural index
$I_{sp} \cdot \rho_{ppl}$	Density impulse
I_{sp}/V_c	"Normalized" specific impulse
ICI	Industry capability index (= I_{TC})
$\vec{j}$	Current flux or current density (Lorentz force)
J	Potential energy per unit mass, fission heat release per unit propellant mass, energy density, potential energy per unit mass, microscopic kinetic energy per unit mass of the medium where potential energy has been released, heat of combustion, energy yield
$\vec{J}$	Current density vector
J_{II}	Current density component parallel to the equilibrium field
k	Boltzmann constant, boundary values
k_0	Constant of order unity that depends on the details of the trajectory
k_B	Boltzmann constant
k_{crw}	Crew member volume
k_{eff}	Effective neutron multiplication factor

k_m	Magnet constant
k_{mix}	Fuel-air mixing losses in combustor, as a fraction of the freestream kinetic energy
k_{ve}	Engine volume coefficient
k_{vs}	System volume coefficient
k_{vv}	Void volume coefficient
K	Constraint of constant helicity
K_{str}	Scaled structural fraction, correlation term
K_v	Scaled propellant volume fraction, maximum propellant volume available, correlation term, correlation parameter
K_{v_0}	Initial scaled maximum propellant volume fraction
K_w	Area ratio correlation parameter, wetted area to planform area ratio, correlation term
$K_{w_{78^\circ}}$	Area ratio correlation parameter for 78° wing/body leading edge angle
K/C	Kinetic energy/available chemical energy
KE	Kinetic energy, initial kinetic energy of the fusing pellet
L	Aerodynamic lift (flight vehicle), multiplier for body length, length of track, length of "bottle," trajectory distance (length), length of the solenoid
L_1, L_4, L_5	Lagrangian points
L_{ex}	Length of the expander
L_m	Length of the mirror
La	Launch site latitude
L/D	Lift-Drag ratio, aerodynamic efficiency
$(L/D)_{\max_{hypersonic}}$	Maximum hypersonic aerodynamic glide ratio
$(L/S)_{plan}$	Lift loading
LR	Lateral range
m	Mass, propellants combustion forms molecules of average mass, relativistic mass, mass of charged particle, propellant mass consumed
$\dot{m}$	Propellant consumption, mass flowrate of propellants, instantaneous propellant mass, mass flowrate
m_0	Rest mass (body at rest), fuel mass at rest, mass at rest
m_1, m_2	Mass of two bodies
m_e	Mass of electron
m_i	Mass of the plasma ion
m_{ppl}	Mass of propellant
$m_{spacecraft}$	Mass defect
Δm	Mass, propellants combustion forms molecules of average mass, relativistic mass
M	Mach number, mass of the central body, mass, generic "third body", spacecraft mass, mass (energy) of the parent nucleus
M_0	Initial Mach number, spacecraft mass
M_{aux}	Mass of the auxiliary system
M_{AB}	Maximum airbreathing Mach number
M_{cryo}	Cryoplant mass
M_f	Final mass of the ship at destination
$M_m = M_{mag}$	Magnet mass
$M_{powerplant}$	Powerplant mass
$M_{ppl} = M_p$	Mass of propellant, inert mass, inert propellant
M_{ppl_0}	Propellant mass at rest
M_R	Mass ratio ($M_R = W_R$)
M_{rad}	Radiator mass
M_{ref}	Refrigerator mass