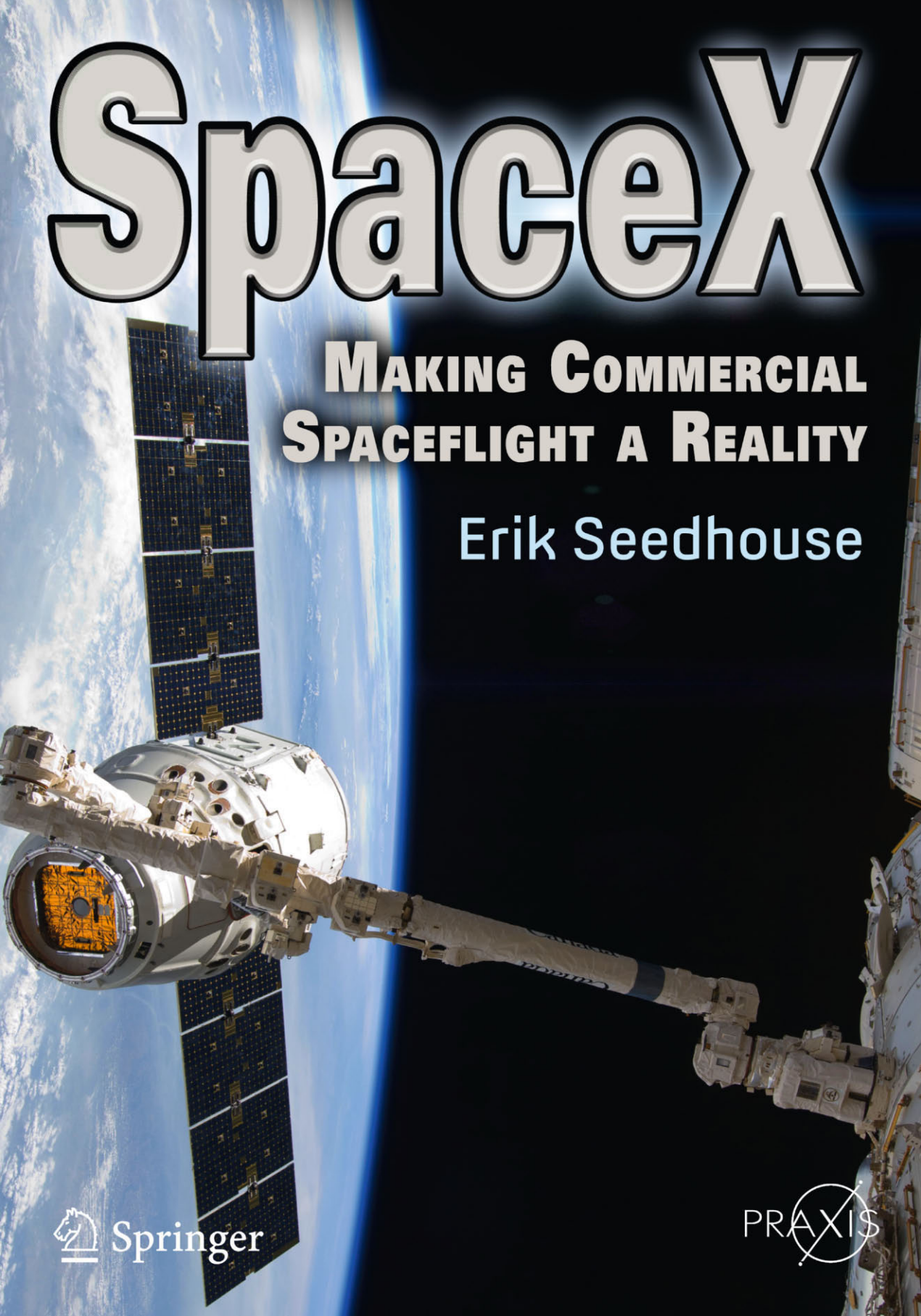
SpaceX

Making Commercial Spaceflight a Reality

Erik Seedhouse



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Published in association with
Praxis Publishing
Chichester, UK

PRAXIS

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SPRINGER–PRAXIS BOOKS IN SPACE EXPLORATION

ISBN 978-1-4614-5513-4 E-ISBN 978-1-4614-5514-1
DOI 10.1007/978-1-4614-5514-1

Springer Dordrecht Heidelberg London New York

Library of Congress Control Number: 2013941041

Cover design: Jim Wilkie
Project copy editor: Christine Cressy
Typesetting: BookEns, Royston, Herts., UK

Printed on acid-free paper

Springer is a part of Springer Science + Business Media (springer.com)

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Preface

January 23rd, 2012, marked the start of the Year of the Dragon in the Chinese calendar and, in May 2012, SpaceX's Dragon became the first privately developed spacecraft to visit the International Space Station (ISS). Space travel is one of the most difficult of all human endeavors, and success is never guaranteed. The Dragon flight introduced a series of new challenges and new magnitudes of complexity and, by docking with the ISS, SpaceX once again made history by becoming the first private company to send a spacecraft to the ISS.

Dragon is a spacecraft unlike any other. Not only is it the first privately developed spacecraft to successfully return from Earth orbit, it is also the only reusable spacecraft in operation today. It also happens to be just another element in Elon Musk's goal of making humanity a spacefaring civilization. Just as Elon Musk's PayPal product took internet payments that cost US$0.40 or more per transaction via credit cards and made them free, his SpaceX rockets and spacecraft are going to revolutionize space travel with new lower prices. While humanity becoming a spacefaring species may be inevitable in the long term, if personal income keeps growing, applying modern manufacturing, testing, control, and management techniques to spaceflight may allow us to see substantial strides this decade. Leading the charge will be SpaceX.

SpaceX is applying modern manufacturing techniques such as friction stir welding and modern CAD and production data management techniques to build its rockets. It's also developing its Falcon 1, 9, and other rockets in quick succession, reusing many components and design and manufacturing strategies. Not satisfied with business as usual, SpaceX doesn't rely on decades-old space-proven products or even the veteran aerospace testing firms; instead, it builds new components and tests them in-house.

SpaceX: Making Commercial Spaceflight a Reality is an account of commercial spaceflight's most successful start-up. It describes the extraordinary feats of engineering and human achievement that have placed SpaceX at the forefront of the launch industry and positioned it as the most likely candidate for transporting humans to Mars. Since its inception in 2002, SpaceX has sought to change the space launch paradigm by developing a family of launch vehicles that may ultimately reduce the cost and increase the reliability of space access by a factor of 10.

This book describes how SpaceX is based on the philosophy that simplicity, low cost, and reliability *can* go hand in hand. It explains how, by eliminating the traditional layers of management, internally, and subcontractors, externally, SpaceX reduces its costs while speeding decision-making and delivery. Likewise, by keeping the vast majority of manufacturing in-house, the book explains how SpaceX reduces its costs, keeps tighter control of quality, and ensures a tight feedback loop between the design and manufacturing teams.

Forged by Elon Musk in 2002, the founder of PayPal and the Zip2 Corporation, SpaceX has already developed two of the coolest new launch vehicles, established an impressive launch manifest, and been awarded funding by NASA to demonstrate delivery and return of cargo to the ISS. Supported by this order book and Mr. Musk's substantial resources, SpaceX is on an extremely sound financial footing as the company moves towards volume commercial launches.

Although drawing upon a rich history of prior launch vehicle and engine programs, SpaceX is privately developing the Dragon crew and cargo capsule and the Falcon family of rockets from the ground up, including main and upper-stage engines, the cryogenic tank structure, avionics, guidance and control software, and ground support equipment. The Falcon 9 and Falcon Heavy are the only US launch vehicles with true engine out reliability. They are also designed such that all stages are reusable, making them the world's first fully reusable launch vehicles. And the Dragon crew and cargo capsule, currently under development, may revolutionize access to space by providing efficient and reliable transport of crew and cargo to the ISS and other low Earth orbit destinations. This book explains how. Here is an up-close portrait of the maverick company that is, in short, one of the most spectacular aviation triumphs of the twenty-first century.

Acknowledgments

In writing this book, the author has been fortunate to have had five reviewers who made such positive comments concerning the content of this publication. He is also grateful to Maury Solomon at Springer and to Clive Horwood and his team at Praxis for guiding this book through the publication process. The author also gratefully acknowledges all those who gave permission to use many of the images in this book, especially Hannah Post at SpaceX Media Relations.

The author also expresses his deep appreciation to Christine Cressy, whose attention to detail and patience greatly facilitated the publication of this book, and to Jim Wilkie for creating the cover.

To
Julian

About the author

Erik Seedhouse is a Norwegian-Canadian suborbital astronaut whose life-long ambition is to work in space. After completing his first degree in Sports Science at Northumbria University, the author joined the legendary 2nd Battalion the Parachute Regiment, the world's most elite airborne regiment. During his time in the "Para's", Erik spent six months in Belize, where he was trained in the art of jungle warfare. Later, he spent several months learning the intricacies of desert warfare on the Akamas Range in Cyprus. He made more than 30 jumps from a Hercules C130 aircraft, performed more than 200 abseils from a helicopter, and fired more light anti-tank weapons than he cares to remember!

Upon returning to the comparatively mundane world of academia, the author embarked upon a Master's degree in Medical Science at Sheffield University. He supported his studies by winning prize money in 100-km running races. After placing third in the World 100 km Championships in 1992 and setting the North American 100-km record, the author turned to ultradistance triathlon, winning the World Endurance Triathlon Championships in 1995 and 1996. For good measure, he also won the inaugural World Double Ironman Championships in 1995 and the infamous Decatriathlon – an event requiring competitors to swim 38 km, cycle 1,800 km, and run 422 km. Non-stop!

Returning to academia in 1996, Erik pursued his Ph.D. at the German Space Agency's Institute for Space Medicine. While conducting his Ph.D. studies, he still found time to win Ultraman Hawai'i and the European Ultraman Championships as well as completing the Race Across America bike race. Due to his success as the world's leading ultradistance triathlete, Erik was featured in dozens of magazines and television interviews. In 1997, *GQ* magazine nominated him as the "Fittest Man in the World".

In 1999, Erik decided it was time to get a real job. He retired from being a professional triathlete and started his post-doctoral studies at Vancouver's Simon Fraser University's School of Kinesiology. In 2005, the author worked as an astronaut training consultant for Bigelow Aerospace and wrote *Tourists in Space*, a training manual for spaceflight participants. He is a Fellow of the British Interplanetary Society and a member of the Space Medical Association. In 2009,

he was one of the final 30 candidates in the Canadian Space Agency's Astronaut Recruitment Campaign. Erik works as a manned spaceflight consultant, professional speaker, triathlon coach, and author. His spaceflight company, Suborbital Training (*www.suborbitaltraining.com*), provides customized training programs for commercial suborbital astronauts and tourists. He is the Training Director for Astronauts for Hire (*www.astronauts4hire.org*) and completed his suborbital astronaut training in May 2011. Between 2008 and 2012, he served as director of Canada's manned centrifuge operations.

In addition to being a suborbital astronaut, triathlete, centrifuge operator, and director, pilot, and author, Erik is an avid mountaineer and is currently pursuing his goal of climbing the Seven Summits. *SpaceX* is his eleventh book. When not writing, he spends as much time as possible in Kona on the Big Island of Hawaii and at his real home in Sandefjord, Norway. Erik and his wife, Doina, are owned by three rambunctious cats – Jasper, Mini-Mach, and Lava.

Abbreviations and acronyms

ARIS	Active Rack Isolation
ARRA	American Recovery and Reinvestment Act
ARS	Air Revitalization System
ASIL	Avionics Software Integration Laboratory
ATK	Alliant Techsystems
ATV	Automated Transfer Vehicle
C3PO	Commercial Crew and Cargo Program Office
CAM	Collision Avoidance Maneuver
CBM	Common Berthing Mechanism
CCDev	Commercial Crew Development
CCiCap	Commercial Crew Integrated Capability
CCP	Commercial Crew Program
CDR	Critical Design Review
CIR	Combustion Integrated Rack
COTS	Commercial Orbital Transportation Services
CRS	Commercial Resupply Services
CST	Commercial Space Transportation
DARPA	Defense Advanced Research Projects Agency
ECLSS	Environmental Controlled Life Support System
EDS	Emergency Detection System
EELV	Evolved Expendable Launch Vehicle
ESA	European Space Agency
FAA	Federal Aviation Administration
FDM	Free Drift Mode
FRR	Flight Readiness Review
GNC	Guidance Navigation and Control
GPS	Global Positioning System
GTO	Geosynchronous Transfer Orbit
ICD	Interface Control Document
IMU	Inertial Measurement Unit
ISBR	Integrated System Baseline Review

ISS	International Space Station
JSC	Johnson Space Center
KSC	Kennedy Space Center
LAS	Launch Abort System
LCPE	Low Cost Pintle Engine
LEM	Lunar Excursion Module
LEO	Low Earth Orbit
LIDAR	Light Detection and Ranging
LLM	Liberty Logistics Module
LMLE	Lunar Module Landing Engine
LOX	Liquid Oxygen
LRR	Launch Readiness Review
LVA	Launch Vehicle Adapter
MDA	McDonald Dettweiler and Associates
MPCV	Multi-Purpose Crew Vehicle
MSRR	Materials Science Research Rack
NERVA	Nuclear Engine for Rocket Vehicle Applications
OMAC	Orbital Maneuvering and Attitude Control
OSC	Orbital Sciences Corporation
PAF	Payload Attach Fitting
PCM	Pressurized Cargo Module
PDR	Preliminary Design Review
PICA	Phenolic Impregnated Carbon Ablator
RGPS	Relative Global Positioning System
SAA	Space Act Agreement
SDS	Spacecraft Docking System
SHERE	Shear History Extensional Rheology Experiment
SLS	Space Launch System
SNC	Sierra Nevada Corporation
SRB	Solid Rocket Booster
SRB	Safety Review Board
SRR	System Readiness Review
SSC	Stennis Space Center
SSME	Space Shuttle Main Engine
TEA	Triethylaluminum
TEB	Triethylborane
TIM	Technical Interface Meeting
TRL	Technology Readiness Level
TVC	Thrust Vector Control
UHF	Ultra High Frequency
ULA	United Launch Alliance
USAF	United States Air Force
VAIL	Vehicle Avionics Integration Laboratory
VTHL	Vertical Take-off Horizontal Landing
VTVL	Vertical Take-off Vertical Landing

1

Elon Musk: The space industry's Tony Stark

After a near flawless nine-day mission, the Dragon capsule splashed down on target in the Pacific Ocean just off the coast of Mexico, marking the end of the first commercial mission to ferry supplies to the International Space Station (ISS). Tethered to three large parachutes, the unmanned gumdrop-shaped capsule (Figure 1.1), which had carried food, water, clothing, and equipment to the orbiting outpost, hit the water at 8:42 a.m. local time on May 31st, 2012, about 900 kilometers west of Baja, California, witnessed by technicians from the remarkable company that had built and flown it – Space Exploration Technologies, or SpaceX:

1.1 Dragon capsule. Courtesy: SpaceX

E. Seedhouse, *SpaceX: Making Commercial Spaceflight a Reality,*
DOI 10.1007/978-1-4614-5514-1_1, © Springer Science+Business Media New York 2013

1.2 Elon Musk. Courtesy: NASA

> "This really couldn't have gone better. I'm overwhelmed with joy. It's been 10 years, and to have it go so well is incredibly satisfying."
>
> Elon Musk, SpaceX chief executive, speaking at a televised news conference from the company's headquarters in Hawthorne, California

The Dragon had separated from the ISS about seven hours before splashdown, after astronauts had loaded it with used equipment, experiment samples, and trash. The success of what was really just a trial run for the spacecraft positioned SpaceX to begin regular supply missions with bigger payloads to the ISS and paved the way for manned missions perhaps as early as 2015. The flight of the Dragon was also notable for the fact that, since the Space Shuttle program had ended the previous year, the station had been resupplied by Russian and European spacecraft.

In 2002, Elon Musk (Figure 1.2) was just another Internet mogul starting a commercial space company. But Musk was bolder than his peers. Simply providing a suborbital trip to space like Sir Richard Branson's *SpaceShipOne*[1] wouldn't satisfy the South African native; Musk wanted to fly resupply missions with astronauts to the ISS.

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[1] That rocket, and the passenger version that will make up Sir Richard Branson's Virgin Galactic fleet reached an altitude of more than 100 kilometers in 2004.

It was a bold goal because, as any space engineer will tell you, getting to orbit is by several orders of magnitude more difficult than reaching suborbital altitudes. In fact, it is such a challenge that only eight countries and a few private companies have reached orbit independently. Orbital flight also happens to be very, *very* expensive, but Musk reckoned he could do it cheaper *and* turn a profit. His plan? Run his company like an Internet start-up and launch a new age in space exploration.

Perhaps one of the most intriguing aspects about how Musk works is the fact that he works at all. After all, by his early thirties, his Internet ventures had made his net worth about US$200 million. He could have retired but chose instead to enter perhaps the riskiest, costliest, and most unforgiving businesses there is: launching rockets.

Born in South Africa in 1971, the son of a Canadian mother and a South African father, it didn't take long for Musk to demonstrate his entrepreneurial spirit. He bought his first computer at the age of 10 and quickly taught himself computer programming. Two years later, he wrote code for Blastar, a video game, which he subsequently sold to a computer magazine for US$500. Then, when he was 17, spurred by the prospect of avoiding compulsory service in the South African military,[2] Musk moved to Canada, spending two years at Queen's University, Kingston. He had planned a career in business and worked at a Canadian bank one summer as a college intern. After Kingston, Musk moved to the US, where he earned degrees in physics and business at the University of Pennsylvania. He had intended to begin a graduate program at Stanford in 1995 but, after just two days, chose instead to devote the next four years to developing Zip2, a company that enabled companies to post content on the Internet. In February 1999, Compaq Computer Corporation bought Zip2 for US$307 million – in cash. It was one of the largest cash deals in the Internet business at the time and Musk walked away with a cool US$22 million for his 7% share. He was only 28.

He used US$10 million to start X.com, an online bank, which went online in December 1999. The following month, Musk married his first wife, Justine, whom he had met while studying in Canada. Two months later, in March 2000, X.com merged with Confinity, which had developed a service you may have heard of – PayPal, which provides customers with payment transactions over the Internet. Musk increased his fortune when eBay bought PayPal for US$1.5 billion in 2002. The deal saw his net worth rocket past US$100 million. By that time, he and Justine had moved to Los Angeles and had their first child, a boy named Nevada Alexander. Tragically, while having a nap one day, Musk's son stopped breathing and, by the time the paramedics had resuscitated him, the 10-week-old infant had been without oxygen for so long that he was pronounced brain-dead. He spent three days on life

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[2] Musk has explained in several interviews that he doesn't have a problem with military service but he didn't like what the South African military was doing in the late 1980s, especially the brutal oppression of the black majority. When he moved to Canada to avoid conscription, it was against the wishes of his father and the two rarely speak as a result of the younger Musk's decision.

support before Musk and his wife made the agonizing decision to take him off it. Sudden Infant Death Syndrome was the verdict.

Having had enough of the Internet, Musk searched for a new challenge and founded Space Exploration Technologies, or SpaceX, in June 2002. To kick-start his company, he tried buying a rocket from Russia, but soon realized the proposition was too risky and instead considered building his own rocket. Establishing a rocket company was seen by many in the space industry as an audacious move. After all, Musk possessed very little background in the field of rocket science. He could have been forgiven if he had chosen to buy rockets from established rocket-building companies but that just wouldn't have been Musk. Instead, he decided to build SpaceX from the ground up. His initial goal was to reduce the cost of launch services – a milestone spurred by Musk's frustration with not only how much money NASA spent on the space program, but also how little the costs of space exploration have decreased in the decades since the end of the Apollo Program. Once he had solved the inefficiencies of the space program, Musk had his sights set on low-cost human travel into orbit and establishing a colony on Mars. But, before he could send humans to Mars, Musk needed to get his rockets into orbit.

The challenges facing Musk were formidable. Between 1957 and 1966, just as the space age was gaining momentum, the US had sent 429 rockets into orbit, a quarter of which failed. To date, only governments have managed to harness the capital and intellectual muscle necessary to launch rockets into orbit. In fact, practically every Russian, Chinese, and American rocket that exists today is a legacy of ballistic missiles. And building those rockets didn't come cheap. The American, Russian, and Chinese space programs required small armies of engineers working with nearly unlimited budgets. For example, the Apollo Program employed more than 300,000 people and cost more than US$150 billion in 2007 dollars, or more than 3% of the US federal budget. Even the now-retired Space Shuttle required a ground crew of 50,000 and cost more than half a billion dollars *every* time it flew. Incidentally, even the extraordinary amounts of money that were thrown at the Shuttle didn't increase safety because it is still the most dangerous rocket system ever created. (NASA administrators originally stated the risk of catastrophic failure was around one in 100,000; NASA engineers put the number closer to one in 100; a more recent report from NASA said the risk on early flights was one in nine. The eventual failure rate was two out of 135.)

The few private companies that *have* managed to get something into orbit have used hardware developed under government programs. And their services aren't cheap. If you want to launch a satellite into orbit on a Sea Launch Zenit (Figure 1.3), it will set you back a cool US$50 million to US$75 million. Even if you happen to be the US Air Force (USAF), putting a 200-kilogram payload into low Earth orbit (LEO) on an Orbital Sciences *Pegasus* will cost around US$30 million.

> "What's the fastest way to become a commercial space millionaire? Start as a commercial space billionaire."
>
> Hackneyed joke spawned by the number of companies that have tried and failed to launch rockets into LEO

1.3 Sea Launch Zenit. Courtesy: Sea Launch

To Musk, launch prices were a damning indictment of the state of space exploration, a business that had spent hundreds of billions of dollars on rocket technology in the past 50 years with the result that, before SpaceX came along, the cost of putting something into LEO was still around US$10,000 per pound. It was this lack of progress that particularly frustrated Musk, who decided he would aim to reduce those costs by half – or more.

To many space industry observers, it was a tall claim.

Musk knew the stakes would be high. After all, he knew very little about the rocket industry and had never actually built anything – except Internet companies – in his life. The odds were hardly in his favor. But Musk had thrived in businesses where the default expectation was failure, so why not roll the dice on building rockets? The question was how to do it.

Musk started by going to the heart of the aerospace world in El Segundo, California, one of the beach cities just south of Los Angeles International Airport,

and began recruiting industry veterans for SpaceX. One of his first hires was Tom Mueller, one of the world's leading propulsion experts. Designing propulsion systems had come naturally to Mueller, who came from a hands-on background. Born in St Maries, Idaho, a tiny logging community of about 2,500 people, Mueller's dad was a log truck driver and he wanted his son to be a logger, so it was only natural that the younger Mueller grew up around logging trucks and chainsaws. It was an environment that spurred an interest in figuring out how things work, which probably explains why he took his dad's lawnmower apart. When his dad found the parts, he was upset because he didn't think he could put the pieces back together, but the younger Mueller reassembled it and the machine ran pitch perfect. From rebuilding lawn mowers, Mueller moved on to building and flying toy rockets. He bought Estes rockets from his local hobby shop, although they didn't last long because he usually crashed them or blew them up. In junior high, Mueller submitted a hybridized life sciences propulsion project to the science fair which was to fly an Estes rocket with crickets in it to see what the effects of acceleration were on the crickets. Unfortunately, the parachute failed and the deceleration when the rocket hit the ground killed the crickets. Not wanting to kill any more wildlife, Mueller restricted his next project to building a rocket engine out of his dad's oxyacetylene welder and made a rocket engine out of it by injecting water into it to see what effect that had on its performance. The first time he ran it, the engine burned a hole through the side of the chamber but, with some minor modifications, he was able to run it in a steady state – an achievement that allowed him to reach the regional round of the science fair.

Mueller earned a master's degree in mechanical engineering from the Frank R. Seaver College of Science and Engineering and received job offers for work in Idaho and Oregon, but it was for non-rocket stuff. So Mueller decided to move to California to get a rocket job, eventually taking a position with TRW Space and Electronics, where he spent 14 years running the Propulsion and Combustion Products Department. Along the way, he earned the TRW Chairman's Award and filed several patents in propulsion technology. Mueller was happy working there, but his ideas about rocket engine design in a company in which rocket engines weren't a core component were lost. To satisfy his creative impulses, Mueller turned to the Reaction Research Society, building his own engines and launching them in the Mojave Desert with fellow rocketeers.

Even for an experienced propulsion engineer like Mueller, building rocket engines wasn't easy; these engines rely on myriad valves and seals to control the flow and need super-cooled oxidizers to mix with the fuel so it can ignite. The resulting combustion, which can be described as a controlled explosion, is channeled at high pressure into the nozzle, creating the thrust that propels the rocket. These challenges didn't deter Mueller though. By 2002, he had almost completed the world's largest amateur liquid-fuel rocket engine, capable of producing 13,000 pounds of thrust. Musk met the enterprising propulsion engineer in January 2002 just as Mueller was preparing to attach his monster engine to an airframe. For Musk, building rocket engines was the key to his commercial spaceflight enterprise. He took one look at the rocket engine and asked whether Mueller could build a bigger one.

1.4 Gwynne Shotwell was recruited by CEO Elon Musk in 2002 to be vice president of business development. Shotwell is responsible for day-to-day operations of SpaceX and manages customer and strategic relations, including those with NASA. Courtesy: NASA