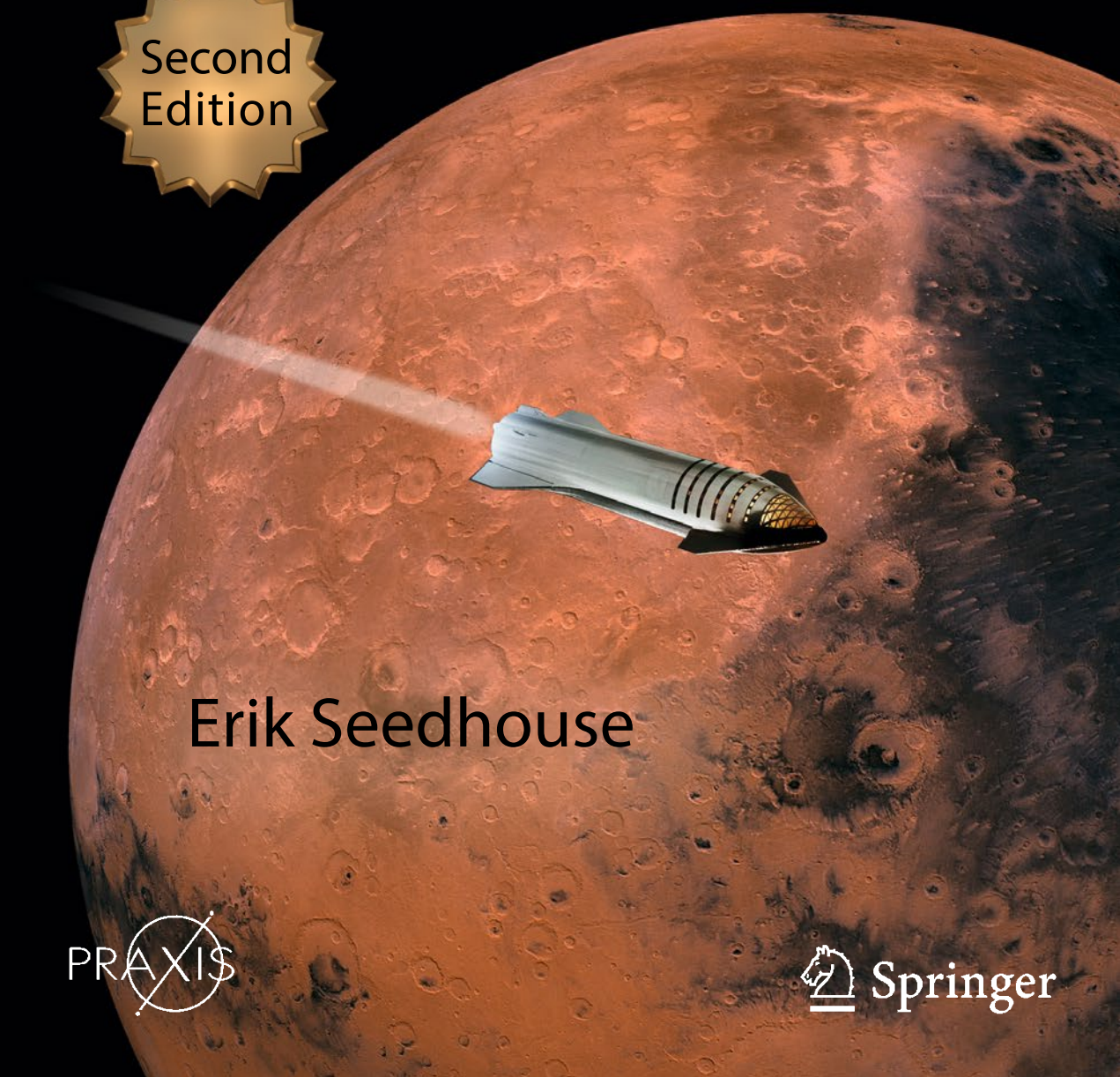
# SpaceX

## Starship To Mars
## The First 20 Years

Second Edition



Erik Seedhouse

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# Contents

**DEDICATION**

To Lava

Deeply loved, completely spoiled and missed beyond words.

Lava was a Nebelung, one of the more social and intelligent breeds. He used to walk with our dogs and became something of a minor celebrity where we live because people used to stop their cars and ask us if Lava was really a cat! Writing can be a lonely pursuit with long hours spent at a keyboard, and having written 30 books, that could have added up to a lot of time alone. But sitting next to me for much of my writing, purring like a tractor, was Lava, who very sadly crossed over the Rainbow Bridge shortly after this book was completed.

# Acknowledgements

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 Hannah Kaufman 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. The author also expresses his deep appreciation to Mike Shayler, whose attention to detail and patience greatly facilitated the publication of this book, and to Project Manager, Ms. A. Meenahkumary and her team for producing the final proof.

# About the Author

Erik Seedhouse works as a professor in Space Operations at Embry-Riddle Aeronautical University, located just up the road from the Space Coast in Florida. He lives in Flagler Beach, which means he can often watch SpaceX launches from his lanai. After completing his first degree in Sports Science at Northumbria University in the UK, Erik joined the 2nd Battalion the Parachute Regiment, the world's most elite airborne regiment. During his time in the 'Paras', Erik spent several months involved in various counternarcotics operations in Belize (anyone who has seen the series '*Narcos*' will be familiar with what these operations entailed). 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 at Sheffield University, also in the UK. He supported his studies by winning prize money in 100km running races. After placing third in the World 100km Championships in 1992 and setting the North American 100km record, the author turned to ultra-distance 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 38km, cycle 1,800km, and run 422km. Non-stop!

Returning to academia in 1996, Erik pursued his Ph.D. at the German Space Agency's Institute for Space Medicine through a grant from the European Space Agency – thanks ESA! 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 ultra-distance 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 post-doctoral studies at Simon Fraser University's School of Kinesiology in sunny Vancouver, Canada. In 2005, the author worked as an astronaut training consultant for Bigelow Aerospace and wrote 'Tourists in Space', a training manual for spaceflight participants. In 2009, he was one of the final group of candidates in the Canadian Space Agency's Astronaut Recruitment Campaign. He came close but not close enough. Between 2008 and 2012, he served as director of the Canadian Forces manned centrifuge and hypobaric chamber operations. In addition to his work as a professor, Erik works as a manned spaceflight consultant, professional speaker, triathlon coach and author. He has also worked as a film consultant to Hollywood on such productions as '*Into the Unknown*' featuring Mark Strong. He is an instructor for the International Institute of Astronautical Sciences and completed his suborbital scientist astronaut training in 2016. At the time of writing, Erik has written 30 books. When not writing, he can be found climbing big mountains or spending time with his wife Alice on the Big Island of Hawai'i, or in Sandefjord, Norway.

# Prologue

> "*We want the exciting things we see in sci-fi, in like sci-fi movies, books – we want them to come true one day.*"
>
> "*Consciousness is a very rare and precious thing, we should take whatever steps we can to preserve the light of consciousness. We should do our very best to become a multi-planet species, extend consciousness beyond Earth, and we should do it now.*"
>
> Elon Musk. The Rise of Elon Musk's Engineering Masterpiece

SpaceX is like no other rocket company. It was started by someone who knew nothing about rockets but who went on to become the chief technology officer of a company whose vehicles have turned the launch industry on its head in a very short span of time. Elon Musk does not have an aerospace degree; he is self-taught, meaning he read a lot of books and talked to a lot of people. Shortly after SpaceX was launched, Apollo astronauts Neil Armstrong and Gene Cernan – two of Musk's heroes who inspired the Mars Messiah to start his company in the first place – testified against commercial spaceflight, saying the way SpaceX was going about the business of building launch vehicles was all wrong. Yet despite the nay-sayers, despite the trauma of 2008 when Tesla was almost bankrupt and the American economy had tanked in the worst recession since the Great Depression, despite his first three rockets failing, despite crisis after crisis that would have crushed anyone else, Musk prevailed. When SpaceX finally managed to launch to orbit after three unsuccessful flights, NASA called Musk and told him the agency had awarded the company one and a half billion dollars. That launch was a supreme achievement, because at the time only four entities had launched a rocket into orbit – the United States, Russia, China… and SpaceX. Since then, SpaceX has racked up success after success as the company grabbed the headlines with

landing of a first stage, the launch of a Tesla on the Falcon Heavy, and of course, the development of the Starship.

In this book we examine the achievements of perhaps the most remarkable company in human history: one that may just transform the human race into becoming an interplanetary species. We discuss the development of the Dragon, the first privately developed spacecraft to visit the International Space Station (ISS). Not only was Dragon 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 another piece of the puzzle in Elon Musk's goal of making humanity a space-faring civilization. Then there is the family of launch vehicles developed, tested and flown in rapid succession. How? Well, we will see how SpaceX has applied modern manufacturing techniques, such as friction stir welding and modern CAD and production data management techniques, to building its rockets. SpaceX developed its Falcon 1, 9, Falcon Heavy and Starship so rapidly by reusing many components and applying cutting edge design and manufacturing strategies. Not satisfied with business as usual, SpaceX does not 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 – The First 20 Years*', 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 changed the space launch paradigm by developing a family of launch vehicles that have steadily reduced the cost and increased the reliability of space access by a factor of ten. Coupled with the newly emerging market for private and commercial space transport, this new model has re-ignited our efforts to explore and develop space. Here, in this book, is a portrait of perhaps one of the most spectacular aviation triumphs of the 21st century.

# 1


## Elon Musk: Mars Messiah

*"I think that when I say multi-planet species, that's what we really want to be. It's not like still being a single-planet species by moving planets. It's really being a multi-planet species and having civilization and life as we know it extend beyond Earth to the rest of the Solar System, and ultimately to other star systems. That's the future, that's exciting and inspiring, and I think that… you need things like that to be glad to wake up in the morning. Life can't be just about solving problems. There have to be things that are exciting and inspiring that make you glad to be alive."*

Elon Musk, Code Conference, June 2016

**Figure 1.0.** Credit NASA. Illustration by Dave Mosher



E. Seedhouse, *SpaceX*, Springer Praxis Books,
https://doi.org/10.1007/978-3-030-99181-4_1

The goal of creating a multi-planet species is a bold one; and it would probably be judged too bold if promoted by anyone other than Elon Musk (Figure 1.0). But, thanks to a string of successes for SpaceX with its Falcon family of rockets, myriad cargo and crew missions to the International Space Station (ISS), and the Starship, Musk's much touted crewed mission to Mars has gained and continues to gain traction. It is a welcome change for the thousands of die-hard Mars enthusiasts who have put up with decades of Mars conferences presenting PowerPoint slides and computer-generated imagery of hypothetical crewed missions that never went anywhere. NASA's Design Reference Mission (DRM) 1.0 anyone? DRM 5.0 perhaps? Or what about Inspiration Mars or Mars One? Given the pace at which Musk's company is developing the hardware necessary to transport humans to Mars, it is not surprising that many see the Chief Rocket Designer of SpaceX as a sort of Mars Messiah.

For a long time, the 'Mars in a Decade' crowd wanted to believe the myriad keynote speakers who promoted the idea that a crewed Mars mission could be achieved by 2010, or if not by 2010 then by 2020. Books were published about how a crewed Mars mission could be achieved in 2030, or by 2040; using government money, no less. As we know, these cry wolf claims were no more than pipe dreams perpetuated by the fake news narrative of the Cigarette Smoking Men of the Mars Underground. But no more. Since Musk's multiplanetary species announcement in 2016, his company has launched one trailblazing mission after another. There was that Tuesday afternoon in February 2018 when the world's most powerful rocket arced upward high above Florida's Space Coast (Figure 1.1). There was that Sunday in November 2020 when the first operational crewed mission to the ISS launched onboard the Crew Dragon (Figure 1.2). And, of course, there are all those Starship launches (Figure 1.3), featuring the very vehicle that will transport humans to the Red Planet sometime before the end of the 2020s.

A crewed Mars mission is at the very edge of what is currently technologically possible and is a supremely risky proposition, but Musk loves risk. The naysayers, of which there have been many over the years, say he is reckless, but the gambles Musk has taken throughout, although risky, have almost always paid off. Take the example of perhaps his biggest gamble of all: the creation of SpaceX. This story is described in Ashley Vance's biography *Elon Musk: Tesla, SpaceX, and the Quest for a Fantastic Future*, which is well worth reading. Musk and a group of aerospace engineers were returning from Moscow, where they had been snubbed with their offer to buy refurbished Russian intercontinental ballistic missiles (ICBM) from ISC Kosmotras (the Russian sticker price was $8 million). During his meeting with the Russians, Musk was dismissed as a novice and was even spat on by one of the senior Russian rocket engineers. Not surprisingly, Musk was not happy, but after some feverish crunching of numbers on a spreadsheet, he announced he had a plan to build a rocket, cut launch prices by a factor of ten *and* still have a 70 percent gross margin. Accompanying Musk on the flight were founding SpaceX member and ex-Jet Propulsion Laboratory (JPL) employee Jim

**Figure 1.1.** The launch of the Falcon Heavy was the death knell for many of Musk's commercial spaceflight rivals[1], but more specifically its payload underscored the primary existence of SpaceX. Carried in the Falcon's upper stage was Musk's personal cherry red Tesla Roadster, piloted by a dummy astronaut listening to David Bowie's *Space Oddity*. After the launch, Musk voiced the hope that the Falcon Heavy could help NASA return to the Moon and perhaps prepare for an eventual landing on the Red Planet by the middle of the century. Credit NASA.

Cantrell, and future NASA administrator Mike Griffin, who both knew more than most about the challenges of launching rockets. They were skeptical to say the least, until they studied Musk's numbers on the spreadsheet. The spreadsheet detailed estimated performance characteristics of Musk's proposed rocket in exquisite detail. This surprised Cantrell and Griffin, because Musk had no background in aerospace engineering. But he had been studying. For months, Musk had immersed himself in the fundamentals of rocket propulsion, the theory of astrodynamics and the basics of aerothermodynamics. Having devoured as many seminal texts on these subjects as he could lay his hands on, Musk had turned himself into something of an expert and he used this expertise to redefine the launch vehicle arena and the commercial spaceflight industry.

[1] SpaceX priced a Falcon Heavy launch at about $90 million in 2016. This price compared to the $435 million cost of a Delta IV operated by United Launch Alliance. The main difference is that the Falcon Heavy can carry almost twice the payload of a Delta – and the fact that the Delta cannot be reused.


**Figure 1.2.** The SpaceX Crew-1 official crew portrait, with (from left) NASA astronauts Shannon Walker, Victor Glover, and Mike Hopkins, and JAXA (Japan Aerospace Exploration Agency) astronaut Soichi Noguchi. Credit NASA.

Yet despite the stratospheric rise of SpaceX over the past 20 years, there are still some who worry that risk-taking at the level that Musk is pursuing might be his undoing. The cynics often cite examples of other Musk companies to prove their point. For example, Musk's first company, Zip2, was bought by Compaq in 1999. Most of the $20 million Compaq paid Musk was channeled into another startup that became PayPal, which was bought by eBay in 2002. That transaction netted Musk $180 million, almost of all which was used to develop SpaceX and then Tesla, a venture for which Musk put almost his entire fortune at risk to support. In 2009, for example, Musk borrowed $20 million against SpaceX to use in his Tesla startup. This was not a problem because SpaceX was flush with money, having received $1.6 billion from NASA for cargo flights. Fast forward to 2018 and Musk was still using the same borrowing strategy, but the numbers – and the risks – were higher. In late 2018, Musk owed $625 million on his Tesla stock which was worth $10 billion. The problem was that, at the time, Tesla was billions of dollars in debt, a set of circumstances which prompted suggestions that SpaceX should acquire

**Figure 1.3.** Launch of Starship SN15 on May 5, 2021. The flight tested several upgrades and culminated in a smooth touchdown on the landing pad at Boca Chica, Texas. The test occurred amid preparations for the push to orbit that were taking place at the Orbital Launch Site. Credit Jack Beyer, NASA.

Tesla. That sounds simple, but with Tesla struggling, managing that debt could have placed the plans for SpaceX in peril. As many remember, Tesla nearly toppled into bankruptcy, but the company has since become the most valuable and, by certain metrics, the most profitable carmaker on the planet. Once again, Musk's risk-taking paid off, reminding everyone that he is not just any CEO.

Back in 2002, Musk 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 Richard Branson's *SpaceShipOne*[2] was never going to satisfy the South African native; Musk wanted to fly resupply missions with astronauts to the ISS and use that as a stepping-stone to Mars. It was a bold goal because, as any space engineer will tell you, getting to orbit is more difficult than reaching

[2] That rocket, and the passenger version – *SpaceShipTwo* – that makes up Richard Branson's Virgin Galactic fleet, was supposed to fly to 100 kilometers altitude, but operational flights have so far only reached 85 kilometers.

suborbital altitudes, by several orders of magnitude. In fact, it is such a challenge that only eight countries and a few private companies have reached orbit successfully. Orbital flight also happens to be very, *very* expensive, but Musk maintained that he could do it cheaper *and* turn a profit. His plan? Run his company like an Internet startup and launch a new age in space exploration along the way.

One of the most intriguing aspects about how Musk works is the fact that he works at all. By his early thirties, his Internet ventures had made his net worth about $200 million (at the time of writing he is worth more than $300 billion, making him the richest person in history). He could have retired, but chose instead to enter the riskiest, costliest, and most unforgiving business there is: launching rockets. Born in South Africa in 1971, the son of a Canadian mother and a South African father, it did not take long for Musk to demonstrate his entrepreneurial spirit. He bought his first computer at the age of ten and quickly taught himself computer programming. Two years later, he wrote code for a video game called *Blastar*, which he subsequently sold to a computer magazine for $500. Then, when he was 17, and spurred on by the prospect of avoiding compulsory service in the South African military[3], 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 for one summer as a college intern. After Kingston, Musk moved to the U.S., 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 chose instead to devote the next four years to developing Zip2, a company that enabled other companies to post content on the Internet. In February 1999, Compaq Computer Corporation bought Zip2 for $307 million, in cash. It was one of the largest cash deals in the Internet era at the time, and Musk walked away with a cool $22 million. He was only 28.

He used $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 called PayPal. Musk increased his fortune when eBay bought PayPal for $1.5 billion in 2002, a deal that saw his net worth rocket past $100 million. By that time, he and Justine had moved to Los Angeles and had their first child. Tragically, Musk's son stopped breathing while having a nap one day, and by the time the paramedics had resuscitated him the ten-week-old infant had been without oxygen for so long that he was pronounced brain-dead. He spent three days on life support

[3] Musk has explained in several interviews that he does not have a problem with military service, but that he did not 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 because of the younger Musk's decision.

before Musk and his wife made the agonizing decision to have it turned off. The verdict was Sudden Infant Death Syndrome.

Having had enough of the Internet, Musk searched for a new challenge and founded Space Exploration Technologies, or SpaceX. To kick-start his company he tried buying that ICBM from Russia, but having been rebuffed he decided instead to build his own. Establishing a rocket company was seen by many in the space industry as an audacious move, particularly since Musk possessed 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 would not 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 prompted by Musk's frustration with both how much money NASA spent on the space program and how little the costs of space exploration had decreased since the end of the Apollo Program in the 1970s. 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 anyone to Mars, Musk first 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 U.S. had sent 429 rockets into orbit, a quarter of which had failed. At around the time Musk was looking to get into the rocket business, only governments had managed to harness the capital and intellectual muscle necessary to launch payloads into orbit, and building those rockets did not come cheap. The American, Russian and Chinese space programs required armies of engineers working with nearly unlimited budgets. For example, the Apollo Program employed more than 300,000 people and cost more than $150 billion in 2007 dollars, or more than three percent of the U.S. federal budget. Even the now-retired Space Shuttle required a ground crew of 50,000 and cost more than one billion dollars every time it flew. Incidentally, even the extraordinary amounts of money that were thrown at the Shuttle did not increase its safety; it is still the most dangerous rocket system ever created.

> "*What is 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 Low Earth Orbit (LEO).

The few private companies that *had* managed to get something into orbit had used hardware developed under government programs, and their services were not cheap. 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 with the result that the cost of putting something into LEO still cost around $10,000 per pound – before SpaceX came along. 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 were high. He knew 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 problem 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, where he 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. Mueller was born in St. Maries, Idaho, a logging community of about 2,500 people. His father 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 worked, which explains why he took his father's lawn mower apart. His dad was upset when found the parts, because he did not think he could put the pieces back together, but the younger Mueller re-assembled it and the machine ran pitch perfectly.

From rebuilding lawn mowers, Mueller moved on to building and flying toy rockets. He bought Estes rockets from his local hobby shop, although they did not 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 carrying crickets in it to see what the effects of acceleration were on the insects. Unfortunately, the parachute failed and the deceleration when the rocket hit the ground killed the crickets. Not wanting to kill anymore wildlife, Mueller restricted his next project to building a rocket engine out of his father's oxy-acetylene welder, making a rocket engine 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 at Layola Marymount University, and received job offers for work in Idaho and Oregon, though they were unrelated to rocketry. 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 were lost in a company for which rocket engines were not a core component. 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. By 2002 he had almost completed the world's largest amateur liquid-fueled 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 Mueller if he could build a bigger one.

Having recruited a slew of rocket engineers, Musk now needed someone to run day-to-day operations. Gwynne Shotwell (Figure 1.4) ran into Musk when she dropped off a friend, who had just started working at SpaceX, from lunch. The friend had mentioned to Musk that he should hire a business developer and Musk agreed, hiring Shotwell, who became the company's seventh employee, as Vice President of Business Development. In that position she built the Falcon vehicle family manifest to over 100 launches, representing over $3 billion in revenue. Today, as President, Shotwell is still the powerhouse of the company, responsible for day-to-day operations and for managing all customer and strategic relations to support company growth.

**Figure 1.4.** Gwynne Shotwell is President and Chief Operating Officer (COO) of SpaceX. Joining SpaceX in 2002 as Vice President (VP) of Business Development, Shotwell built the Falcon vehicle manifest to more than 100 launches. In 2018, Fortune Magazine listed Shotwell at #42 on their list of the World's 50 Greatest Leaders. Credit NASA.

Prior to joining SpaceX, Shotwell had spent more than ten years at the Aerospace Corporation, where she held positions in Space Systems Engineering and Technology and Project Management. She was promoted to the role of Chief Engineer of a medium launch vehicle-class satellite program, managed a landmark study for the Federal Aviation Administration (FAA) on commercial space transportation, and completed an extensive analysis of space policy for NASA's future investment in space transportation. Shotwell was subsequently recruited to be Director of Microcosm's Space Systems Division, where she served on the executive committee and directed corporate business development.

With his team in place, all Musk had to do was to get on with the business of building rockets… and rocket engines. Traditionally, rocket manufacturers bought engines from established companies, because the prospect of designing and building your own rocket engines was complex, time-consuming and expensive. But building his own rockets and engines was *exactly* what Musk intended to do. Not content with the challenges of establishing a rocket company, Musk also found time to co-found Tesla Motors[4] in 2004. One of the main objectives of Tesla Motors (named after electrical engineer and physicist Nikola Tesla) was to develop an environmentally-friendly sports car. To that end, the company built the snappy Tesla Roadster, a car that charges overnight, uses no gasoline, and sprints from zero to 96 kph in less than four seconds. This vehicle was followed by a family of all-electric cars, including the Model S (Figure 1.5) which became the company's flagship.

While Musk developed the Tesla venture, his SpaceX team began building a two-stage rocket, powered by 'Merlin', a compact, durable engine designed to lift a first stage, and 'Kestrel' for the second. The rocket, christened the Falcon 1 (Figure 1.6), was designed to lift 1,400 pounds into LEO. Getting the payload into orbit proved a tougher task than Musk had envisaged, however.

First, there was the issue of finding a launch site. Musk had originally hoped to launch the Falcon 1 booster (carrying a TacSat-1 satellite built by the U.S. Naval Research Laboratory) from Vandenberg Air Force Base (VAFB) in California, but that plan was stymied by a delay in launching a Titan-4 rocket carrying a classified payload. After spending an estimated $7 million on its VAFB facilities, SpaceX was told to leave the Complex 3 West launch site at Vandenberg. "It is just, I think, a travesty," Musk told *SPACE.com* in an interview at the 19th Annual Conference

[4] The Tesla enterprise started in 2003 when two teams, one consisting of Martin Eberhard and Marc Tarpenning, and the other of Ian Wright, JB Straubel and Musk, were trying to think of ways to commercialize the T-Zero prototype electric sports car created by AC Propulsion. One of Musk's goals had been to commercialize electric vehicles, starting with a premium sports car before moving to mainstream vehicles. It was suggested that the teams join forces to maximize the chances of success, so Musk became chair, Eberhard took on the role of Chief Executive Officer (CEO) and Straubel became Chief Technology Officer (CTO).

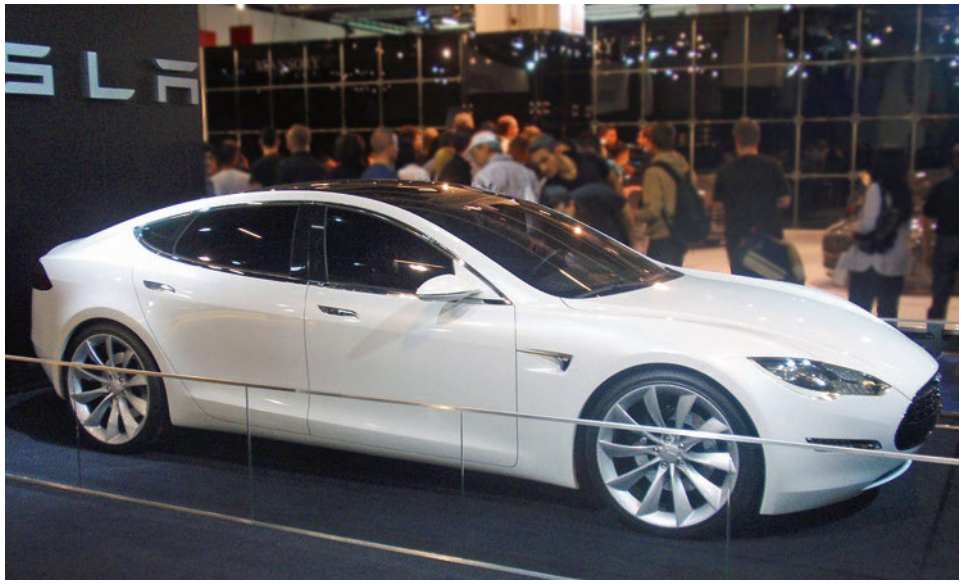

**Figure 1.5.** Tesla Model S. Credit. El Monty. Public domain.

**Figure 1.6.** Falcon 1 Flight 4 on September 29, 2008. Credit SpaceX.

on Small Satellites. Having signed an agreement with the U.S. Air Force to use Complex 3 West, and having made investments in the site as well as having paid for requisite environmental assessments, Musk had cause to be annoyed.

Fortunately, SpaceX had an alternate launch site on Omelek Island in the Kwajalein Atoll, a location that had been part of the company's plans to orbit payloads from there as well as from California and Florida. Kwajalein Atoll, which is part of the Republic of the Marshall Islands (RMI), lies in the Ralik Chain, 3,900 km southwest of Honolulu, Hawaii. On February 6, 1944, the atoll was claimed by the United States and was taken, together with the rest of the Marshall Islands, as a Trust Territory of the United States. In the years following the American invasion, the atoll was converted into a staging area for further campaigns in the advance on the Japanese homeland in the Pacific War, and as a command center for Operation Crossroads and for nuclear tests at the Marshalls atolls of Bikini and Eniwetok. Kwajalein Atoll is controlled by the United States military under a long-term lease and is part of the Ronald Reagan Ballistic Missile Defense Test Site.

Falcon 1 was shipped to Omelek Island by barge for a projected launch date of September 30, 2005, although Musk acknowledged delays were likely. While Omelek Island was remote, the location offered some advantages. To begin with, there are no population centers nearby, making range safety easier. Secondly, just about any orbit is achievable from Kwajalein, thanks to its proximity to the equator. Thirdly, any work done at Kwajalein only had to satisfy one entity – the Environmental Protection Agency – whereas in California, multiple federal agencies had to be engaged, along with state and county entities. The downside to launching from Omelek was the problem of hauling all the equipment needed to launch a rocket, as well as the challenge posed by the humidity, temperature and sea spray, which, in combination, created just about the most corrosive environment on the planet. It was this last factor that proved costly.

At about the same time Falcon 1 was being shipped to Omelek Island, and despite his company not having flown a single rocket, Musk had already signed three launch contracts (with the Swedish Space Corporation, MacDonald, Dettweiler and Associates Ltd – MDA – of Canada, and a commitment by an unspecified U.S. company), and had invested about $100 million in SpaceX. There was *a lot* riding on that first launch.

The 21-meter-high Falcon 1 was the first in a family of boosters planned by SpaceX to offer a more affordable option to launch satellites. Cost-capped at just $6.7 million, Falcon 1 launch vehicles were designed to carry up to 570 kilograms into LEO. Fueled by kerosene and liquid oxygen, the booster featured the SpaceX in-house-designed Merlin engine and a reusable first stage which, if everything went according to plan, would parachute back to the ocean for later recovery and reuse on a future flight. Falcon 1's first launch attempt came on

March 24, 2006 and Musk played down the chances of success, telling reporters that the likelihood of a new rocket launching from a new launch pad successfully on its first attempt was low. Musk's prediction proved right on the mark, because a fuel leak 25 seconds after launch caused a fire in the first stage, with the result that the 20-kilogram Falconsat fell through the roof of the SpaceX machine shop. "We had a successful liftoff and Falcon made it well clear of the launch pad, but unfortunately the vehicle was lost later in the first stage burn," Musk said in an update posted to the company's website. Shortly after the launch, and accompanied by engineer Tim Buzza, Mueller, the range safety officer, and the vice presidents of avionics and structures, Musk boarded a helicopter and flew over Omelek. Except for a fuel slick just offshore and a few scattered pieces of debris, there was little left of the rocket, the culmination of four years, tens of millions of dollars and endless seven-day work weeks. For the engineers, many of whom had quit steady jobs with Boeing and Lockheed, it was not the payoff they had been hoping for.

After poring over video footage, data points and flight telemetry, the cause of the launch failure was identified as a small fire that had broken out on the first-stage engine. The fire had been caused by a fuel leak, and the fuel leak was caused by the failure of an aluminum nut from the fuel pump. The nut had cracked, having been corroded in the salty, humid air. The choice to go with aluminum fittings rather than more durable stainless steel had been a cost-saving decision; in the business of launching rockets, weight equals money and aluminum is much lighter than steel. Unfortunately, that aluminum had been sitting in the humid tropical environment for ten weeks, with predictable – and costly – results.

Fixing the nut corrosion problem was simple; SpaceX replaced the aluminum with stainless steel. The team also added fireproof baffling around the engines and, as a further precaution against the heavy tropical air, kept the rocket inside a Quonset hut until a few days before liftoff. They also updated the launch software. Computers had recorded the fuel leak that destroyed the first Falcon 1 but nobody had noticed, so a new launch system was devised that would abort a countdown automatically in the event of an anomaly. In all, engineers made 112 changes to the rocket and the launch sequence.

Once the changes had been made, the modifications were tested rigorously and, nearly one year to the day after the failed first attempt, the rebuilt Falcon 1 was ready to go again. It stood on the launch pad under a blazing yellow sun, the first new launch system in 30 years. In many ways, Musk had already made history even before the launch; he had brought a privately built rocket to the launch pad twice in one year, something no one else had ever done. Launch attempt #2 took place on March 21, 2007, but liquid oxygen slosh occurred in the second stage which triggered an oscillation 90 seconds into the burn. The instability continued for another 30 seconds and caused the stage to enter an uncontrollable