Rocket MAN

Elon Musk is the Founder, CEO, and CTO of Space Exploration Technologies (SpaceX). He also is chairman of Tesla Motors, Solar City, and the Musk Foundation. He is a trustee of the X Prize Foundation, a member of the National Academy of Sciences, and a director of the Planetary Society.

From the Internet to manned spacecraft to electric cars to solar cells to education, Elon Musk is on a mission to develop innovative solutions to many of mankind's toughest challenges.

By any measure, Elon Musk is a true innovator. He made his fortune on developing innovative Internet-based tools. Now he hopes to expand that fortune by building cost-effective, reliable manned spacecraft. But his story doesn't stop there at all—he's also the chairman and the primary investor in the development of cost-effective electric cars and California's largest installer of innovative solar cell systems. But Musk isn't interested in building a fortune. He's interested in solving problems and solving them with a cost structure such that everyman can use them.

For these and the reasons noted below, Elon Musk has been selected by the editors of *R&D Magazine* as our 2007 *R&D* Innovator of the Year (IOY). Musk is the CEO and CTO of Space Exploration Technologies Corp. (SpaceX), El Segundo, Calif., a company he founded in 2002 to develop rockets

and spacecraft for missions to earth orbit and beyond. In 2006, SpaceX won the NASA competition to design, build, and demonstrate operation of a commercial replacement for the Space Shuttle, which is scheduled to be retired in just a little more than three years, in 2010. The NASA-designed replacement for the Shuttle, the Orion spacecraft, is not scheduled to be available until 2015 at the earliest, leaving a five-year gap in heavy-launch availability. This is where the SpaceX proposal is expected to step up—with its Falcon 9 Heavy, launch vehicle, its 30-ton payload to orbit capabilities, and the Dragon manned capsule with a 7-man crew capability.

Musk spends about 80% of his time at SpaceX. But unlike a lot of company executives, he isn't satisfied with managing the company—he leaves that part of the business to other people he's hired. He spends most of his time as the CTO in solving the myriad technical problems involved in developing all the aspects of building your own spaceship. In the various enterprises in which he's been involved, surely developing and building a spaceship is the most complex, the most prone to unforeseen problems, and the most costly to build and test.

Musk's philosophy is that he wants his company to build everything on the rockets, from engines to avionics to fuel tanks to the manned capsules. His primary goal is to build a cost-effective system. Once you start to outsource the development of one of those main subsystems to someone else, you lose control of the cost structure. The overriding feature in all of Musk's endeavors is cost. Cost controls everything, and keeping the cost down opens all sorts of opportunities for future growth. Part of Musk's savings is in the planned reusability of all of the rocket components. "There's a monstrous difference between usability and reusability," he says.

"Today's Space Shuttle fleet costs about $4.5 billion/yr to maintain," says Musk. "And with about five Shuttle flights/yr, that's a cost structure of about $1 billion/launch. Another large spacecraft system, the Delta IV-Heavy rocket costs about $250 million/launch. Our equivalent system, the Falcon 9 Heavy, has a projected launch cost of about $90 million—less than a tenth that of the Shuttle and about a third of the Delta IV."

The Internet boom

Elon Musk was born in South Africa and had sold computer games that he coded to a computer magazine by the time he was 12 years old. At 17, he moved by himself from South Africa to Canada and then registered at Queen's Univ., Kingston, Ontario. He quickly transferred to the Univ.

The X Prize—Creating a New Model for Innovation

An interesting feature about *R&D Magazine's* relatively recent Innovator of the Year (IOY) program is that many of the winners know each other. Their selection as IOY was not made based upon their relationships with each other–quite the contrary, it was made for their particularly individualistic contributions to solving a wide variety of design challenges. However, after they were chosen, it has been noted by the editors of *R&D Magazine* that they often meet and do things together.

One of the things that's particularly noteworthy is their involvement in an organization called the X Prize Foundation. This organization (www.xprize.org) creates and manages prizes that drive innovators to solve some of the greatest challenges facing the world today. Three *R&D Magazine* IOYs (2002 IOY–Larry Page, Google's founder; 2006 IOY–Dean Kamen, Segway developer; and 2007 IOY–Elon Musk, SpaceX's founder), along with an *R&D Magazine* Scientist of the Year (SOY) (1998 SOY–J. Craig Venter, geneticist) are members of the 25-member board of trustees of the X Prize Foundation. Additionally, Scaled Composites' Burt Rutan (2004 *R&D* IOY) won the very first X Prize on October 4, 2004–the $10 million Ansari X Prize–for becoming the first private spacecraft to go into space. UK entrepreneur Richard Branson has since contracted with Rutan to build six commercial versions of his winning SpaceShipOne for Branson's commercial Virgin Galactic venture that promises to sell commercial flights into space within this decade.

Following its success with the Ansari X Prize (sponsored by the telecom-based Ansari family), which resulted in entries from 26 teams from seven different nations, the X Prize Foundation is preparing to launch a series of X Prizes to address humanity's grand challenges. The X Prize is now viewed as the leading model to leverage the elements of public interest, entrepreneurial spirit, and cross-disciplinary innovation to create breakthroughs that benefit mankind.

One of these programs is the $10 million Archon X Prize for Genomics, which challenges teams to sequence 100 human genomes in 10 days. This program was launched in late-2006. An Automotive X Prize (AXP) is also being created that invites design and development teams to focus on the development of super-efficient cars that people will want to buy–final details of this multi-million dollar prize will be released later this year. Some of the initial guidelines from a preliminary draft of the AXP include fuel economy of at least 100 miles/gal, no more than 200 g/ml of CO_2 emissions/mile, vehicle costs at 10,000 units/yr that are equivalent to those that the market will bear, designs embracing the current level of commercial safety features, and a clear business plan for bringing the vehicle to market.

Other X Prizes are envisioned in energy, the environment, medicine, education, water, poverty, and the social arena. The mission of the X Prize Foundation is to define a problem and then set a challenge to find the solution, thus shifting the paradigm of traditional innovation. It captures the public imagination and accelerates the pace of change. X Prizes are the ultimate contests–fusing audacity with the highest levels of credibility. X Prizes attract alternative funding sources, focus the media spotlight, and bypass bureaucracies and cross-disciplinary and national boundaries.

–Tim Studt

The Falcon 1 DemoFlight 2 prior to liftoff. On March 20, 2007, the test flight reached an altitude of about 290 km. Image: SpaceX

of Pennsylvania, Philadelphia, where he got a scholarship. He worked his way through college writing software and received a BS in physics and a BS in economics at the Univ. of Pennsylvania's Wharton School of Business. After graduation, he moved to Calif., with the intention of going to Stanford Univ. to develop high-energy capacitors—he had worked with Pinnacle Research for two summers developing high-energy-density ultra capacitors.

Once he got to Calif. in 1995, however, he noticed that the Internet was happening all around him, and he thought he wanted to work on something that would change the world—and capacitors weren't it. He wanted to work on something that would be as relevant as possible to the future of the world. He wanted to do the right thing. He dropped out of Stanford after just two days and started writing Zip2, which provided online content publishing software for news organizations, with investments from *The New York Times*, Knight-Ridder, MDV, Softbank, and Hearst.

Compaq Computer's Alta Vista division acquired Zip2 for slightly more than $300 million in 1999. Musk then co-founded X.com, an online financial services and email payments company. A year later, X.com merged with Confinity, a company with a product called PayPal, which was being used to transfer money between email accounts. These products were merged into PayPal in 2001. eBay acquired PayPal in October 2002 for about $1.5 billion in stock. At the time of the sale, Musk owned about 12% of the service. PayPal went public on NASDAQ in early-2002.

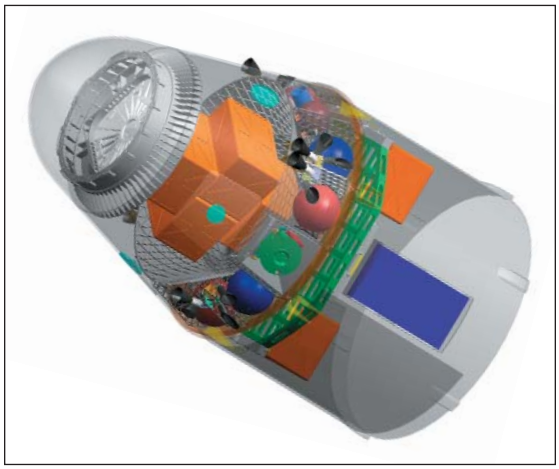
In June 2002, Musk took his earnings from Zip2 and PayPal and invested them to found his third company, SpaceX (www.spacex.com).

In March 2004, Musk invested in and founded Tesla Motors, an all-electric car company, reflecting on his previous physics background in electric vehicle power sources and ultra-capacitors. He currently serves as chairman of the board at Tesla, a company that is building small production runs of battery-powered sports cars. "Capacitors have the advantages of extremely long life cycles, low charge/discharge losses, and charge times measured in minutes for a car-sized pack," explains Musk. "If the capacitor energy density problem is solved, the electric car wins."

In September 2006, Musk invested in a Tesla-partner company, Solar City, becoming its chairman of the board as well. Solar City is already the largest installer of photovoltaic (PV) panels in Calif. with 28% market share, and by default then the United States.' The main problem, and the biggest cost item, in a solar installation, according to Musk, is the balancing system that connects the PV panels to the grid—it's 60% of the cost of the installation. If it costs $9.00/W to install a system, then $5.50 of that cost is in the balancing system, which is what Solar City concentrates on minimizing.

"With just a small 10-ft by 15-ft solar panel tucked away on the roof of your garage, you will generate enough electricity to travel about 400 miles/week in the Tesla Roadster," says Musk. "If you travel less than that, you will be energy positive with respect to transportation and the excess electricity will offset your home's power usage."

Musk also has established the Musk Foundation, where grants are made in support of renewable energy research and advocacy, human space



The Dragon spacecraft is made up of a pressurized capsule and unpressurized trunk used for Earth to LEO transport of pressurized cargo, unpressurized cargo, and/or crew members. Image: SpaceX

exploration research and advocacy, pediatric research, and science and engineering education.

SpaceX to the future

Musk has an enviable record of development and achievements in his SpaceX venture over the past five years. He's focusing his efforts on three launcher versions—the Falcon 1, Falcon 9, and Falcon 9 Heavy—and one manned orbital capsule, the SpaceX Dragon, capable of carrying seven passengers or a mixture of personnel and cargo to and from low-earth orbit.

SpaceX design and manufacturing facilities (2,323 m^2) are in El Segundo, Calif., near the Los Angeles International Airport, which takes advantage of the large pool of aerospace talent available in Southern Calif. Extensive propulsion and structural test facilities are located in McGregor (central), Texas, at the former 300-acre test facilities of Beal Aerospace. Launch facilities are at Kwajalein Atoll in the Marshall Islands and Vandenberg Air Force Base, Calif. A third launch site is being prepared at Cape Canaveral AFS, Fla., which is expected to be available in 2008.

Two test flights of the Falcon 1 vehicle have taken place. The first was on March 24, 2006, and failed due to corrosion on an aluminum nut

Previous *R&D* Innovators of the Year

2001 Dr. Stuart Parkin, IBM Almaden Research Center, Calif.
Developer of giant magnetoresistance (GMR)

2002 Larry Page, Google, Mountain View, Calif.
Co-founder of Google

2003 Dr. Ian Foster, Argonne National Laboratory/Univ. of Chicago, Ill.
Developer of Globus Toolkit for distributed computing

2004 Burt Rutan, Scaled Composites, Mojave, Calif.
Developer of SpaceShipOne, first commercial spacecraft

2005 Dr. Mark Humayun, Univ. of Southern California, Los Angeles
Developer of the first implantable human retina

2006 Dean Kamen, DEKA Research and Development Corp., Manchester, N.H.
Developer of the Segway, Slingshot water vapor distillation system, and founder of FIRST (For Inspiration and Recognition of Science and Technology)

Made to Cell

When Lyndon Rive and Elon Musk began brainstorming a business that would put a clean form of energy in everyone's hands, they knew they would have to be creative. It didn't take a couple of Silicon Valley whizzes to realize the solar panel business was not the hottest venture out there. The average American is not about to spend a lot of money to go through the hassle of installing solar panels, especially when faced with uncertain savings, no support structure, and a lack of interest from utility companies.

However, the entrepreneurs did realize that solar panels work. Made from photovoltaic silicon, solar panels can be manufactured in bulk and have a life expectancy of up to 40 years. Once they're up on the rooftop, it's potential energy in the bank.

Take away the hassle and show the customer some savings right away, Musk and Rive theorized, and people will get on board.

"We looked at creating panels and quickly realized that's a market that's somewhat saturated," says Rive. "We looked at inverters and realized a lot of people are doing that already. We finally looked at installation and realized that it's an extremely fragmented market."

By leveraging the expertise of two local companies that had already spent seven years in the solar panel installation business, SolarCity, Foster City, Calif., (www.solarcity.com) was able to launch itself with a measure of expertise in hand.

"You need a trusted brand," says Rive. "You want to know a company will be around to support you. It's so easy to lie or mislead a consumer, and that's the last thing you want to do." The key has been a bulk approach to the business, which enables SolarCity to show savings to customers quickly.

"If you buy in bulk, by installing many solar systems in a two-mile range, you gain efficiencies in the system. You can pass these efficiencies on to the customer," says Rive. By gaining market share and protecting it with customer service, he believes, SolarCity will help ensure its growth.

Customers of SolarCity get a yearly electric bill. Actual results depend largely on customer usage. A large home might mean solar panels can only offset a portion of energy use. Plus, homes with small roofs have a smaller available area for solar cells. But usually, a solar cell user is pleased at the change, which averages an immediate 10% to 20% savings.

Because building permits for solar panels are free in Calif., they can be installed in five to seven days depending on the facility. Installing solar panels can lead to credit for home developers as well, and as federally-funded programs such as Leadership in Energy & Efficient Design (LEED) standardize requirement for homes and businesses alike, solar panels will likely be a significant part of a homeowner's experience.

Energy companies such as PG&E are supportive and are running radio advertisements that talk about SolarCity's potential. Utilities like the idea because power grids are already be experiencing strain, which solar panels can help alleviate, especially at times of peak demand.

"It tells you how everybody is aware of the problem," says Rive. People are looking for ways to help and by "taking on the fight with their neighbors, they're not just working alone toward solving global warming."

It's a psychological effect that feeds on itself. Over time, Rive sees neighbors feeling a sense of pride in owning solar panels. Neighbors will compare notes about their energy generation prowess, and it may even engender some healthy competition. Every new SolarCity customer, he says, is just a drop in the bucket, but it's a start.

—Paul Livingstone

Merlin second flight engine test. Image:Thom Rogers/SpaceX

that resulted in a fuel leak and main engine failure. The second test occurred on March 20, 2007, and was partially successful—the second stage engine shut down about 1.5 min before schedule due to a control issue. SpaceX stated that "the second flight was otherwise functioning well and even deployed the satellite mass simulator ring at the end of the flight." SpaceX declared this success to conclude the test phase of the Falcon 1 program and they are now moving on to the operational phase.

The third Falcon 1 launch is scheduled for late-2007 or early-2008. The maiden launch of the Falcon 9 (an upgraded Falcon 1 design with nine Merlin rocket engines—3,400 kN thrust vs 454 kN thrust on a Falcon 1/Merlin system) is scheduled for the second quarter of 2008 with a U.S. government payload. The Falcon 9 is intended to compete with the United Launch Alliance (ULA, Boeing/Lockheed Martin collaboration) Delta IV and Atlas V rockets. Unlike the ULA systems, however, both first and second stages of the Falcon 9 system are designed to be reusable, thereby significantly lowering the launch cost of the vehicle. The second launch of the Falcon 9 already is scheduled to launch a payload for the Canadian MDA Corp.

Overall, SpaceX has already sold at least 11 contracts for flights on various Falcon vehicles. Musk and SpaceX have also stated that they are in the preliminary design stages of building a substantially larger thrust Merlin 2 engine, a "very large rocket" to accompany the new engine and even a "super-heavy" vehicle if there is customer demand.

Charging Forward

Zero to 60 miles per hour in about four seconds. A top speed of 135 miles per hour. The agility of a sports car with the accoutrements of a luxury car.

It's called the Tesla Roadster, and it is powered by batteries.

In a risky move, *R&D Magazine* Innovator of the Year Elon Musk and entrepreneur Martin Eberhard started a company whose goal is no less than giving American drivers freedom from the gas pump.

Batteries of the type pioneered by Serbian-turned-American Nikola Tesla have proved commercially indispensable throughout the world, but for automobiles, the internal combustion engine has always been more capable. Tesla Motors, San Carlos, Calif.,(www.teslamotors.com) is working to change this trend, and their first step is the launch of the world's first volume production electric sports car this fall. It's certainly not the first electric car, but only the Roadster can beat a Ferrari or a Corvette off the line.

Under the skin of the Roadster is a battery box, air ducts that double as energy-absorbing zones, and a high-performance AC motor.

Elon Musk states his motivations for backing the company and serving as board chairman: "I think global warming is a very serious issue and it's something we have to address. The only way to address that is to come up with a car that doesn't add carbon emissions to the environment."

Tesla Motors believes the way to do it, according to communications director David Vespremi, is with an electric car that is user-friendly, highly efficient, and, most importantly, something that people want to drive.

"I came here from the automotive industry as an enthusiast, and I was worried that because it is almost silent, does this car have any soul or character?" says Vespremi, who has driven the car. He says it has its own characteristic futuristic sound, a high-pitched whirr that becomes more pronounced as the electric whirrs up past 13,500 rpm, where it produces 182 kW, or the equivalent of 244 hp. It performs, he says, like a sports car should.

It also has the expensive sports car price: $75,000. Tesla executives felt the best way to launch an electric sports car would be to build the best one possible, using multiple innovative designs and top-shelf materials and components.

Development mules and engineering eventually led to production prototypes able to meet safety requirements as well as fulfill design parameters led by the first priority–range–and the second priority–performance. To do so meant designing an entirely new network of systems:

- Energy storage system (ESS): Tesla's battery module is equivalent to an internal combustion car's fuel tank. To deliver the target 200-mile driving range, the Roadster uses 6,831 lithium-ion cells packaged in a 450-kg aluminum pack. The ESS can be recharged in 3.5 hours.
- Power electronics module (PEM): The Roadster's "brain" handles nearly 200 kW of electricity during full acceleration and manages all electrical systems in the car, including the motor.
- Motor: The Roadster's powerplant is a three-phase, four-pole induction unit weighing 35 kg. It has a single free-floating rotor assembly with a two-seal bear-

Musk and SpaceX are also firmly committed to developing the manned commercial space program through the end of the decade. NASA is planning for SpaceX demonstration flights to occur between 2008 and 2010, which could result in up to $278 million in awards if SpaceX meets all the NASA milestones.

All in all, the SpaceX programs are very aggressive and impressive for such a young company that is committed to building all new systems from engines to electronics. This performance is all due to Elon Musk and his driving vision to create reliable, cost-effective space launch systems. "We have become very vertically integrated very quickly," he says.

Musk is the first to note that building rockets is a tremendous learning experience. In building software systems, the iteration interval is very short, with changes that can almost be made on the fly. With hardware, and in particular with rocket science, it takes a much longer time to change and there are lots of nuances along the way. "It is a massive learning curve."

Musk and SpaceX have been helped along this path with some very experienced help from rocket and rocket engine designers like Tom Mueller from TRW and Chris Thomson from Boeing. "They've done some impressive stuff, because they haven't been hindered by any bureaucratic limitations that often stifle larger organizations—it's all been very organic and very enjoyable."

Overall, if you can improve the cost and reliability of space transportation systems, you can improve everything, even the speed of the journey to get there (i.e., the development phase), according to Musk. Musk firmly believes that his organization can improve the overall cost effectiveness of these systems by up to two orders of magnitude—and he continues even now to raise his sights a little bit.

All of this optimism and success hasn't changed Musk's vision for change. One of the "other" things that he sometimes dreams about is creating double-decker freeways made out of cost-effective prefabricated sections.

Musk's recommendations for young engineers and scientists are simple: don't be afraid to take risks when you're young, keep on trying new things, and be aware that once you get settled and raise a family, your risk profile will become more limiting. That strategy doesn't seem to have affected Musk that much, as he has five young children at home, and he's as aggressive as ever in creating and developing new ideas. Truly an innovative spirit!

—Tim Studt

ing on either end, and it generates the equivalent of almost 250 hp and 200 lb/ft of torque. The motor is able to convert 85% to 95% of the energy stored in the ESS to rotational propulsion.

- Chassis: To keep the Roadster under 1,200 kg, Tesla designed a custom underbelly made of extruded, bonded aluminum panels. In addition, the body is made entirely of carbon fiber.
- Automatic transmission: The Roadster uses a two-speed transmission.

The overall package, the company says, is the most efficient car on the road. To substantiate this claim, Tesla calculated the "well-to-wheel" efficiency of the Toyota Prius and the Roadster. The Prius generates 0.56 km/MJ based on EPA-rated fuel mileage, while the Tesla Roadster gets 1.14 km/MJ.

Similarly, the company calculated the well-to-wheel carbon dioxide emissions to capture the entire energy-use cycle. According to Tesla, their Roadster emits 46.1 g/km, a little more than a third of the 131.3 g/km generated by the Prius.

How did such a venture get off the ground? Musk mustered $60 million in investment dollars to help Eberhard launch the company in 2003, and successful capital campaigns have kept the ball rolling. Also

The Tesla Motors Roadster can go from zero to 60 miles per hour in about four seconds. Images: Tesla Motors

joining the Tesla board were Google founders Sergey Brin and 2005 *R&D Magazine* Innovator of the Year Larry Page. By attracting highly qualified individuals to the company on the promise of making something truly extraordinary, Eberhard and Musk were able to establish an aura of excellence that drew in skilled people.

Taking advantage of hard-earned intellectual capital, Tesla Motors has also launched Tesla Energy Group to develop and sell licensing for their product as way to bring innovations to market more quickly. The group has recently signed a $43 million deal with Think Cars in Norway, which plans to produce a city car using Tesla's technology.

"Development takes place in working with other manufacturers, and benefits other carmakers. Deals like this provide third-party validation," says Vespremi.

Tesla Motors also draws on global expertise as well. R&D takes place in Rochester Hills, Mich., near the epicenter of American automotive manufacturing. Roadster motors will be built in Taiwan, and the cars will be assembled at Lotus Cars Ltd., Hethel, England.

The Roadster will be the first of what Tesla Motors hopes will be a line of cars. Originally code-named "Dark Star," the Roadster will be joined by the "White Star," a four-door sedan at a cheaper price, and later, a smaller city-type car, at a much cheaper price.

According to Eberhard, the buyer does not have to compromise. The customer gets a car that's desirable and beautiful which is also the most efficient car on the road.

Musk, meanwhile, keeps his other ventures in mind. He claims the purchase of a Roadster is an investment in future Tesla products and the future of clean energy. He wants people to take the next step by also installing solar panels from SolarCity. The goal, he says? Generate more electricity than you might use in a daily commute, and become "energy positive."

—Paul Livingstone