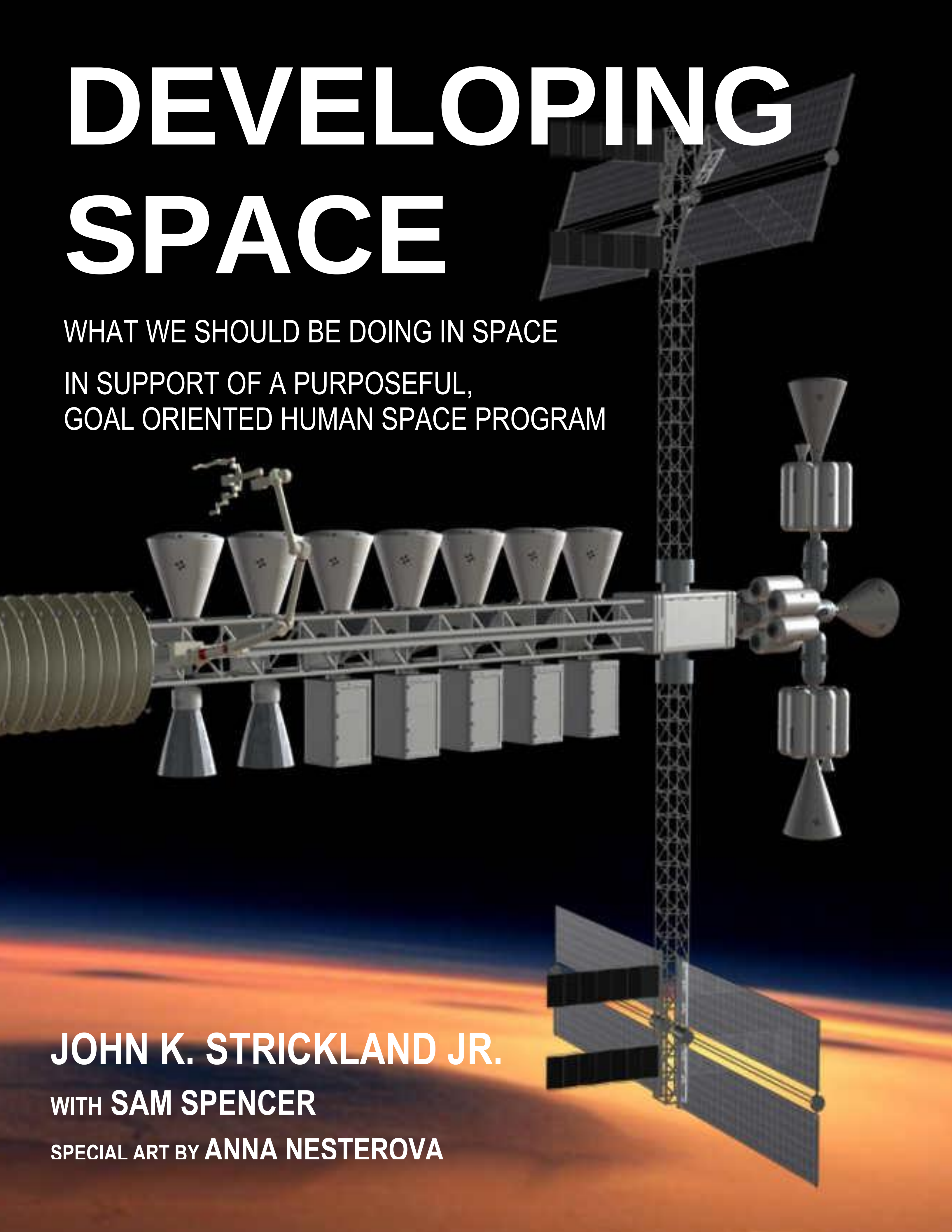
DEVELOPING SPACE

WHAT WE SHOULD BE DOING IN SPACE

IN SUPPORT OF A PURPOSEFUL,
GOAL ORIENTED HUMAN SPACE PROGRAM



JOHN K. STRICKLAND JR.

WITH **SAM SPENCER**

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ISBN: 978-0-692-89432-3

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Printed and bound in Austin, TX, USA

ISBN 978-0-692-89432-3 US$19.00

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CHAPTER 4 CHEAP ACCESS TO SPACE

Figure 4.1: SpaceX hanger with the first three landed Falcon First Stages (SpaceX Flickr, 2017)

The cost of reaching space is currently a core roadblock in the future development of space. There are multiple ways of reaching space but until cost reaches an appropriate level, the future development of space will not reach critical levels. This chapter outlines the current and near-future state-of-the-art and the methods we can use to reach space from our planet Earth.

I. Newspace Vs. Oldspace

What is ironic is that while parts of the government program are stultifying, critical parts are being under-funded or not funded and ignored, at the very time that some of the most critical cost factors to the program are about to drop rapidly. Normally, this would stimulate a program, the same way that dropping natural gas prices have created another economic boom in Texas and the Northern Great Plains. If the same forces that are in control of policy today prevail, there may be no near term stimulation, because the program would not be able to take advantage of the current launch cost reductions from SpaceX for a number of years. The bureaucracy and congressional committees that control the program have been very stubborn in their refusal to take advantage of new capabilities for decades. The Lockheed Martin X33 (an unmanned, suborbital spaceplane developed in the 1990s) could have been flown as a valuable research vehicle by simply replacing one composite tank with a metal tank. Instead, it sat, almost complete, for a year as a “hangar queen” and then they dismantled it, throwing away a billion dollars’ worth of work.

The **first** generation of space entrepreneurs failed because they relied on investors to support "rocket science". Note that there is a very good reason why phrases like **"*rocket science*"** and "***politically radioactive***" exist, and those who fail to recognize the reason such phrases exist are not in tune with reality. The second generation of entrepreneurs were only able to sustain their operations by using their own ample funds. This is one of the secrets of their success. SpaceX only survived by a thread as the first 3 Falcon 1 launches failed. The larger cash reserves that most rocket companies do not have allowed SpaceX a 4th launch attempt which was successful, as all of the design errors had been eliminated. Because of the presumed actions of the existing large legacy companies, forcing SpaceX to launch from a Pacific Atoll with its humid weather, (causing the first failure) instead of from dryer Vandenberg, they almost prevented the stunning success of the Falcon 9. SpaceX was almost stillborn.

The most important factor now recognized was the decision by Elon Musk to "go for the throat", the holy grail of the reusable rocket, in a way that no one else thought possible. As a synthesist, he was able to put a series of ideas together which will allow the Falcon 9 and succeeding generations of rockets to land without wings. This path of thinking was partly made possible by the series of successful flights by the DC-X or Delta Clipper starting over 20 years ago, in August, 1993.

It is unknown how much income the space tourist industry may generate, but few in the media understand how much harder orbital flight is compared to suborbital flight. However, the huge annual market represented by the Comsat industry will require a very large number of launches during the next decade, and SpaceX may well become the predominant global launch provider for anyone who is not locked to their own country's launcher.

Something like the current SLS design, if it had been accepted in 1987 as a response to the Challenger disaster, would have allowed a vastly cheaper and faster assembly of the space station, with larger modules and more capabilities. However the design is obsolete and will shortly be shown to be obsolete to any unbiased observer who understands the economics of the space launch industry.

Even though the Chinese and other countries programs are making rapid progress and showing strong technical skills, none of them will be able to match the launch prices that SpaceX, and eventually some other US companies, will be able to offer for years. What remains to be seen is whether the US government will take advantage of this astounding opportunity to revitalize its program. There is reasonably hope that the fear of being labeled the ones who let us "fall behind" in the visible coverage of space will push for more space spending, but they may not push for the right kind of spending and again squander our impending massive launch cost advantage.

For example, the James Webb telescope is spending almost $20 Billion dollars on a scope which must deploy itself at its Beyond LEO (BLEO) destination, and which if the deployment fails, will have wasted that $20 Billion. This would be catastrophic for NASA, far worse than the initial failure of the Hubble telescope mirror. For just twice that, a complete cis-lunar development program with a lunar mining base could be undertaken, if based on reusable rockets. For another lesser amount, assuming that most of the cis-lunar components are standardized and reusable, continuing human Mars expeditions could begin before 2030. Until recently, NASA has refused to admit that reusable rockets are even possible. This is what was told by NASA representatives to

Vice President Quayle during presentation of the concept for the DC-X program over 20 years ago. When their position becomes totally moot, this should result in some very interesting realignment of thinking at NASA HQ and in Huntsville.

II. Rockets

In this section we will review the current state and possible future of chemical rockets and aircraft that use liquid fuel and a liquid oxidizer or air for propellants. Nuclear Thermal and Electric Drive rockets are discussed in CHAPTER 5.V.B. Nuclear Thermal rockets release some radiation and so are not deemed practical for operation in an atmosphere, but they can be used safely in space. Electric drive (ion and plasma) rockets do not have sufficient thrust for launches from the surfaces of planetary objects or even large asteroids, so they are not covered here.

A. Reusable Rockets

Many people continue to point to the shuttle as a “failed reusable launch system”, proving that reusable rockets are a waste of time. The reality of the Shuttle system, which required a huge “standing army” of thousands of workers to refurbish a single orbiter in about 3 months, the fact that the solid rocket boosters needed to be re-manufactured, and included an expendable external tank, make the Shuttle a non-starter as an example of a reusable booster. The X15 would be a far fairer example.

Some people have even argued that the supposedly far greater cost of developing, building and refurbishing a reusable booster would make them more expensive than the current expendable boosters. The analogy with the economics of an expendable airplane is still valid, in spite of the fact that rockets do have some very significant differences from airplanes. Rick Tumlinson came up with this analogy about 1990, just before the DC-X program first proved vertical landings were possible.

Figure 4.2: The DC-X, the first large rocket to take off and land vertically in 1993 (4th flight 1994) (McDonnell Douglas, 1994)

A rocket's engines may comprise a larger volume and mass than those of an airplane, and the total engine thrust of course must be much higher as the rockets mass is supported by the thrust, not wings. Due to the higher stresses and vibrations that the engines and their associated fuel lines and turbo-pumps are subjected to, they do have a history of failing in flight and also exploding. Without the engine's continuing thrust, a rocket that has just taken off will fall back to the ground with disastrous and explosive results. The fact that a rocket's mass is mostly propellants and that its powered flight lasts less than 10 minutes in most cases, concentrates the use of energy all at the beginning of the flight.

However, engineering and testing advances are making rocket engines much more reliable, and innovations such as anti-fragmentation compartments, as used by the Falcon Rocket family, protect the other engines from a problem with one engine. This also makes an engine-out capability (the ability to continue flying with one or more engines shut down) more useful, as previously the other engines would have been damaged by an explosion of any other engine. In many cases a problem developing with an engine can be detected and the engine shut down before any damage occurs. A number of rocket engines are now deliberately being developed to be reusable, so it makes sense that they would only be used on reusable rocket vehicles.

B. SpaceX Overview

SpaceX needs detailed coverage since it was the first company to develop a commercially viable reusable rocket that can carry payloads into orbit. (The first successful landing of a Falcon 9 took place in 2015, and the first re-use of one to put a payload into orbit occurred on March 30, 2017 (Caleb, 2017)), only 15 years after the company was founded. Like all of the other successful entrepreneurial space companies, SpaceX relies on existing capital instead of needing committed investors. The initial Falcon 1 has developed into a whole family of revolutionary rocket boosters. Starting with the Falcon 1 and the Merlin 1 engine in the mid 2000's, SpaceX has proceeded steadily ahead based on several principles: commonality and standardization of components, reduced use of outside suppliers, designing for future reusability and crew safety, with a policy of continuous improvement and cost reduction in all areas of operation. The Falcon 9R rocket is a good example of this. All of the rocket's engines are the same, with the exception being the extended skirt or bell on the nozzle and restart capability for the single Merlin engine on the upper stage. All of the other stages are the same diameter, to reduce manufacturing costs.

Elon Musk had an idea as to how to recover the rocket's first stage by using a rocket without wings, which was first proved effective in 2016. With the SpaceX deliberate policy of *continuous improvement*, the company has shown its willingness to make radical design changes to its vehicles right after the first design is proved, risking the chance of introducing a new design failure in order to further improve the performance and reduce cost. This policy is being applied to the problem of reusability, and will make it very hard for any competitor to compete or catch up to SpaceX unless they come up with an equally radical design that totally leapfrogs over the Falcon rocket family in performance, such as a reusable air-breathing rocket.

There are several possible ways for a rocket both to survive reentry and also be recovered. The thick steel Shuttle Solid Rocket Boosters (SRB) survived many reentries and splashdowns, as they ignored the mass issue to allow reuse. For the last 40 years or so, everyone assumed that a truly reusable rocket booster would need to have wings (and wheels) to land. Just like the strong SRB segments, or the fuel the Falcon 9 first stage can use to slow down before reentry, the wings and wheels are extra mass and would require more propellant to launch the booster, or would have a smaller payload with the same amount of propellant. To support wings, the structure of the rocket has to be more like that of an airplane, creating the problem of designing an airframe, which can be much more costly than designing a rocket body.

However, for most companies, the cost of a large rocket is quite comparable to a large airliner, usually over $100 Million dollars, and if you can recover the rocket, the launch cost would decline dramatically. If your objective is a reusable rocket with a specific payload mass, you would simply make the rocket about 30% larger to cover the extra mass of extra propellant, wings or stronger structure. The oft-repeated phrase "*rockets are expensive, propellant is cheap*," is very true.

C. How SpaceX Does It

The question from many is: how does SpaceX succeed so well in the launch business? Up to 2017, the four main reasons had been (1) low design cost, (2) low manufacturing cost (3) low operational cost (time efficient operations design and low man-hours needed per launch) and (4) high efficiency performance in flight. The first two have already been demonstrated by the Falcon 9, and they continue to be improved, such as a two-thirds reduction of fuel loading time. The SpaceX paradigm is still truly one of a deliberate policy of "continuous improvement". (The main exception to this policy will be a design freeze for any version that will be launching crews a certain number of launches before the first crew launch on that version.)

The first reason is probably due to the small design team and the singleness of purpose that SpaceX was founded on. NASA's own study said it would take up to 10 times as much for NASA to have had the Falcon developed under NASA's own rules. The second reason, low manufacturing cost, is related to standardization, reuse of existing systems and simplification. The standard rocket engine (Merlin 1D) is used for both stages and all current systems. It probably costs SpaceX about $25 million to manufacture each first stage Falcon booster.

The fourth reason, high efficiency in flight, is partly achieved by the standard methods of making the engines fuel efficient, with high thrust and low mass, and making the overall structural mass of each stage as low as possible. Musk has apparently done this better than anyone else. For example, the two side boosters used for the Falcon Heavy (Falcon 9 first stages) have an astonishingly high fully fueled to empty mass ratio of 30 to 1 (Kyle, 2016).

A fifth reason, reusability, was added in 2015-2016 and started to bring financial returns in 2017 with the first reuses of Falcon 9 boosters for commercial satellite launches.

D. How to Land a Rocket Vertically

Elon Musk previously indicated that while he is not interested in building re-usable winged vehicles, he is interested in recovering as many as possible of his boosters for re-use, which he admits has been a really tough challenge. The initial problem he faced was structural breakup of the first stage due to dynamic pressure during entry. The side boosters of the Falcon Heavy would be very good prospects for recovery attempts as they would have relatively lower velocity at stage separation. This kind of damage is now prevented during entry by slowing the vehicle before entry and using attitude control to keep the stages aligned with the entry flight path, making sure the structure of the rocket bodies are stiff enough, and protecting the engine compartments. Plans for the recovery of the upper stage of a Falcon 9 have been on and off and the stage would require full re-entry protection, but it would be easier to stabilize during entry since it is so much shorter. The core stage of a Falcon Heavy would be the hardest to recover due to its extra high speed at burnout if fuel transfer is used between the "cores" during flight. The first test of a core recovery, in the first Falcon Heavy launch on the 6th of February 2018, was unsuccessful, however as per previously SpaceX will learn from the failure, and likely try again.

The first SpaceX booster recovery concept was a direct but soft water landing, which would have subjected the engines to severe salt water corrosion. The initial plan was to land the Falcon stages in the water without deceleration in space, but the corrosion problem, even with brief immersion, would have resulted in massive refurbishment costs. Landing on dry land is preferred for any flying vehicle not specifically designed for salt water landings. A sea plane can generally keep the salt water spray out of its engines, but this would be hard for a rocket.

When it was realized the Falcon's first stages were breaking up high in the atmosphere due to extreme dynamic stress from the force of reentry, long before they hit the water, it was decided to slow them down to reduce the turbulence and the structural stress on the stages. This also requires the stages to be stabilized during entry so that they enter with the engine section facing the entry air stream, instead of tumbling so they were sidewise to the air stream part of the time. The fuel lines and other 'plumbing' around each rocket engine's combustion chamber are very well protected against some level of entry heating. This step is one of the most amazing of the combination of solutions used, even though most of the plumbing is above the partition through which the nozzle extends. There is an obvious tradeoff between the structural mass of the stage and how much propellant must be used to slow it down. A Falcon 9 without its landing legs was probably the first large commercial rocket to survive reentry without breaking up and was under attitude control until near the surface of the water after its launch in the fall of 2013.

Surviving reentry without breaking up was actually the toughest part of the problem, and has now coincidently demonstrated Supersonic Retro-Propulsion (SRP) which will be needed for landing on Mars. SRP simply means firing the rocket engines forward in the same direction the rocket is moving, while moving faster than sound. Instead of being blown directly back against the base of the rocket, the exhaust plume forms a protective cushion of hot air below it, and by 2017, multiple decleration burns and subsequent re-entries had proved the effectiveness of this method.

At his 2011 National Press Club announcement Elon Musk (Musk, National Press Club Luncheon, 2011) showed that the recovery plan included the option of having the first stage actually reverse course and land vertically back near the launch pad. This meant that the rocket had to cancel all eastward velocity and gain westward velocity, as well as decelerating again before entry and also during landing. This required a significant amount of delta-V that would reduce the payload capacity of the Falcon 9, but with the Falcon Heavy, which has extra payload capacity and where at least two first stages would be recovered, the payload size reduction may not be that big an issue. The landing site selected was determined by the weather, and the amount of fuel remaining, either on land, or on a drone ship based at Port Canaveral. The actual landing would take place with extendable landing legs on a level surface (without a flame bucket) and would normally use only a single engine since the remaining mass of the stage is so light.

The first success SpaceX had with landing the Falcon 9 Full Thrust rocket's first stage did in fact involve a return to the launching site area. It was made on December 21st 2015 on land, followed by one on April 8th, 2016 on a drone ship and with a more complex successful landing made quickly afterwards on May 6th, 2016. These, (along with additional launches and landings during 2016 and 2017), represent a great success in the search for reusability, as the stages have been examined and tested, with Elon Musk commenting "No damage found, ready to fire again" (Space News, 2016).

On March 30, 2017 SpaceX launched the first satellite (a SES 10 communications satellite) into orbit on one of its used Falcon 9 first stages, marking the first time that a landed rocket has been re-used (Caleb, 2017). That day marks the culmination of the process that began first with the proposal for the DC-X program, the DC-X first flights and landings in 1993, the creation of SpaceX in 2002, and the first Falcon rocket landing in 2015. In addition, SpaceX announced that part of the huge launch fairing, large enough to hold a bus and costing SpaceX $6 million to build, was also recovered. The fairing is a major portion of a Falcon rocket launch.

The strategies for landing the Falcon rockets have continued to evolve rapidly. As of 2016 it has been possible to land the first stages either back at the Cape or on one of the drone ships. However, that depended on having enough fuel left to land after the second stage departs on its way to orbit. Many of the SpaceX customers need their satellites delivered to GTO, (Geosynchronous Transfer Orbit), which requires a bigger boost than a typical Low Earth Orbit delivery. As a result, these launches do not have enough propellant left to perform the return to base maneuver, and many of them have run out of fuel while attempting to land on the drone ships, resulting in failed landing attempts. It is probable that since the propellant mass gap preventing landing success is so small that a solution to this problem, such as using Falcon Heavies for such launches with recovery of all the first stages, will eventually be found. By 2017, the policy was to simply allow a stage without enough remaining propelant to fall into the water with no recovery attempt.

If the delivery is to LEO, such as to the space station, the first stage will normally have plenty of propellant reserve to cancel all of its eastward velocity, accelerate back to the west, decelerate before it re-enters, and then do the final landing at the Cape at an old pad site reserved for such landings. Each landing where there is little or no damage to the stage probably saves SpaceX over 25 million dollars.

The original plan may have been to create a reusable upper stage for the Falcon 9, but Elon Musk stated in October 2014 (Ananian, 2014), and SpaceX President Gwynne Shotwell confirmed in March 2016 (Space News, 2016), that at that time, SpaceX had no intention of attempting to recover the second stage. It would require full entry protection, and would probably need to enter with a forward heat shield at its top with the engines facing backwards. However, such a recoverable second stage is anticipated to be used on the SpaceX first stage BFR (Big Falcon Rocket) super-booster, as part of its concept for a multipurpose large booster which can carry passengers. The remaining question on this is whether a reusable dedicated cargo-only stage will be built for it. In April, 2017, SpaceX happily changed course and announced that attempts may be made to recover the second stage, starting as early as late 2017. A rapid switch to BFR production may still doom this plan.

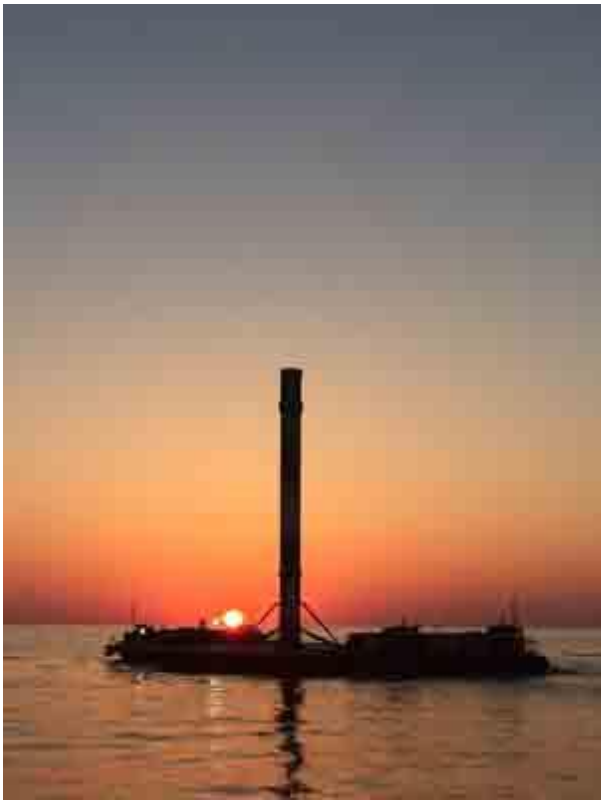

Figure 4.3: The Dawn of a New Age - Falcon 9 reusable first stage after landing on the drone ship (SpaceX Flickr, 2017)

It is important to note that Blue Origin successfully landed its New Shepard vehicle vertically beginning in November 2015, just before the first successful landing by SpaceX. These tests did not deliver anything into orbit, were at much lower maximum speeds (Mach 3 vs. Mach 30) and the New Shepard was a third of the height of the Falcon 9. However, before the end of 2016, the same New Shepard vehicle had been reused 5 times and retired.

This chapter continues with the following sections, available in the full book:

II.E – Launch Competition
II.F – Falcon 9
II.G – Economics
II.H – Falcon Heavy
II.I – Big Falcon Rocket
II.J – Blue Origin New Glenn
II.K – Reusable vs. Expendable
III – Air Breathing Space Launch Vehicles
IV – Ultra-High Launch Acceleration Methods
V – Other Exotic Launch Methods