INDUSTRIAL INNOVATION CYCLE ANALYSIS OF THE ORBITAL LAUNCH VEHICLE INDUSTRY

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The analysis in this paper provides an initial look at the Orbital Launch Vehicle Industry within the Model for Industrial Innovation, proposed by James M. Utterback and William J. Abernathy in their article “Patterns of Industrial Innovation” (1978).

The paper starts with a summary of the Abernathy-Utterback Model, its phases (fluid, transitional and specific) and its characteristics, the concept of dominant design and the focus on product and process innovation.

This work then analyses the Orbital Launch Vehicle industry from a historical perspective of its major innovations and compares the development of this industry with the Abernathy-Utterback Model.

It as well highlights some interesting current developments and analyses certain technology innovations that will likely shape the industry in the future, namely serial production and incremental degrees of reusability.

Based on this analysis this paper finally draws some preliminary conclusions and proposes future work on the subject.

INTRODUCTION

This paper is part of a series of papers aiming at analysing the different sectors of the space industry from the point of view of different innovation models and industry structure theories. More information and access to other papers can be found at http://bit.ly/CSModels. This work applies the Abernathy-Utterback Innovation Model to the orbital launcher industry.

Recent developments in the orbital launcher industry such as the proposal and development of new systems like SpaceX’s Falcon family of launchers, Orbital’s Antares and Pegasus II as well as Europe’s Ariane 6 amongst others show an increased level of interest and participation in these efforts by both public and private entities.

Section 1 summarizes the Abernathy-Utterback Innovation Model, the three phases of Industrial Innovation and the concept of Dominant Design, establishing the scope and definitions used in later sections.

Section 2 analyses the orbital launcher industry from a historical perspective, covering major launcher industry innovations from the times of Robert H. Goddard up to nowadays. Example innovations analysed include solid propellants, liquid propulsion engines, staging, tanks and reusability. The section aims at defining the elements of the dominant design and determining which phase of the Innovation Model we are currently experiencing.

Section 3 reviews selected trends and current developments in the launcher industry that could turn into dominating technologies in the future. The serialization of production and different degrees of reusability such as ballistic first stage vertical take-off and landing, air launch platforms and air-breathing technologies have been identified as potential disruptive technologies that could bring the industry to a new fluid phase.

Finally, section 4 draws some conclusions from the analysis performed, the phases that the orbital launcher industry has gone through, the current components of the dominant design, and the key technologies that might shape the future of this industry.

I. THE ABERNATHY-UTTERBACK INNOVATION MODEL

This section summarizes the Abernathy-Utterback Innovation Model, further sections will address particularities of the orbital launch vehicle industry and will refer to concepts explained in this section. For more detailed explanation of the Innovation Model including examples from other industries the reader can refer to [1] and [2].
1.1 The three phases of Industrial Innovation

The Abernathy-Utterback model on Patterns of Industrial Innovation [1] published in 1978 proposes that the rates of product and process innovation appear to be interdependent and that industries exhibit a predictable behaviour when analysed as a whole over a period of time.

The model links this behaviour to changes in the characteristics of product, process, competition, and organization over time. It is through this model that Utterback attempts to model the life-cycle of the analysed industry itself.

For the purpose of analysing an industry, Utterback categorizes it into three phases: fluid, transitional and specific. The characteristics of each phase are described below and summarized in Table 1.

The fluid phase is a time in which relatively fast paced change is happening particularly at product level, product design is not matured, the product can be expensive and unreliable, but it finds its way into niche markets of early adopters that sometimes even contribute to further innovation of the product. The innovation does not yet have an established market and the market grows around the new technology, sometimes creating entirely new markets not previously foreseen. Technical uncertainty exists and the competing firms don’t really know where to focus on the R&D efforts and experiment very different designs in the marketplace. Manufacturing is characterized by skilled labour and general-purpose equipment, allowing for flexibility in product change, at the cost of high production cost per unit. Competition grows with the market, firms are relatively small and often founded by technical entrepreneurs, [2].

The transitional phase can be reached if the market for the new product grows sufficiently. It is in this phase that firms begin to focus the competition on more specific production methods, aiming a larger scale production and cost efficiencies. Process innovations start to increase as more specialized equipment is implemented in the manufacturing of the product. The increased rigidity of using specialized tools make product changes more expensive, [2].

The third, specific, phase arrives when a highly specified product is manufactured at high levels of efficiency. The quality/cost ratio is the main focus of competition. Products in the specific phase are highly defined and tend to be very similar in between competitors. The product is highly linked to the process and any small change in one tends to be expensive and affecting the other, [2].

A final characteristic of the evolution towards the stability of the specific phase is the merging of surviving firms towards vertical integration from materials to production to sales. Firms manufacturing the product can go back in the production chain and furnish their own components, subassemblies, and raw materials; or firms supplying components can reach forward and do more of the assembly and production of the final good for the market, [2], page 90. A clear example of this in the Orbital Launcher Industry is the case of SpaceX as they have verticalized the production of Falcon 9 including the manufacturing of their own Merlin engines (an activity normally subcontracted to a supplier in this industry). Europe is currently limited in taking advantage of verticalization due to ESA’s policy of geographic industrial return.

A graphical representation of the rates of major innovation in each of these phases can be seen in Fig. 1. In Fig. 1, the rates of product innovation and process innovation are charted over time. In the Fluid Phase product innovation has a more prominent role, while process innovation takes over during the Transitional Phase in order to be the leading parameter during the Specific Phase.

![Fig. 1: Rate of Major Innovations in each of the Abernathy Utterback Innovation model phases.](image)

As an industry reaches the maturity of the specific phase, a substantial innovation breakthrough in a new technology or product can alter the market sufficiently to start a new fluid phase and a new cycle. Particularly in assembled product industries, such major innovations mostly come from outsiders. However, in process-oriented industries, innovations very often come from the suppliers of process equipment, [2], page 178. Utterback points out that normally the major players in one cycle do not play a major role in the following cycle with few exceptions.
I.II. The concept of Dominant Design

Dominant Design is a technology management concept introduced by Utterback and Abernathy, a set key of technological features that become a de facto standard, [3]. A dominant design wins the marketplace, competitors and innovators must adhere to it if they hope to command significant market following. This design often takes the shape of a new product that combines different individual innovations introduces independently in prior product variants, design simplicity and so-called technological elegance are clearly characteristic of many dominant designs, [2]. The dominant design is not necessarily the one that shows the best technical performance, but the one that can satisfy a majority of the market at the cost of maybe not being the most optimized to every niche, [2]. The emergence of a dominant design is a signal that an important shift is about to take place with respect to the pace of innovation and the number of competing firms. Utterback and Suárez [4] argue that the competitive effects of economies of scale only become important after the emergence of a dominant design, when competition begins to take place on the basis of cost and scale in addition to product features and performance.

Table 1: Summary of characteristics for each phase of the Abernathy-Utterback model [2] page 94.
II. HISTORICAL ANALYSIS OF ORBITAL LAUNCH VEHICLES FROM THE PERSPECTIVE OF THE ABERNATHY-UTTERBACK MODEL

The determination of the global orbital launch vehicle industry’s current phase according to the Abernathy-Utterback model can be based on the back tracing of innovations and design changes and the emergence of the dominant design that is then copied by the competitors. It can also be based (or supported or cross-checked) by the evaluation of the number of competitors over time and/or the types of innovations that have been performed over time.

When applying the Abernathy-Utterback-Model to the industry building Orbital Launch Vehicles (thus capable of achieving at least first orbital speed) the first question to tackle is, whether this analysis would need to be performed on national or global level. On global level the slowly but steadily increasing number of operational launch vehicles could be interpreted as that the dominant design according to Abernathy-Utterback has not yet emerged. The launch vehicle industry would then still be on the upsurge of industrial competitors and innovative vehicle designs.

But that is not the source for all of today’s growth, in fact for many countries the possession of a launch vehicle is of strategic need. Several countries developed launch vehicles that have never been in competition with other development programs for governmental funds, or have never been offered to paying foreign or commercial customers. Within this category some examples are:

- Brazil with VLS-1 (4 launches, no success), [5], page VLS-1
- Iran with Safir (7 launches, 3 successes), [5], page Safir_rocket
- Israel with Shavit (9 launches, 6 successes), [5], page Shavit
- North Korea with Paektusan (1 launch, no success), [5], page Paektusan-1 and Unha (3 launches, 1 success, [5], page Unha-2)
- South Korea with Naro-1 (3 launches, 1 success), [5], page Korea_Space_Launch_Vehicle
- Great Britain with Black arrow (4 launches, 2 successes), [5], page Black_Arrow
- and France with their Diamant series of launch vehicles (12 launches, 9 successes), [5], page Diamant

These launch vehicles need to be considered as conceived due to their respective parent country’s strategic needs using the know-how and technologies available at the time to each of the countries. They might copy the dominant design but are neither its first appearance nor the reason for assimilation of others.

Thus the search for a dominant design needs to focus on countries or economic regions with several concurrent launch vehicle developments, their succession and reasons why working vehicle designs were abandoned in favour of other designs.

Fig. 3 gives a timeline of inventions (during the fluid phase) that are discussed in this section, locating each by the date of its first launch (some by date of invention).

II.1 Common Roots

During WWII the German Army Research Centre in Peenemünde under the Scientific lead of Dr Wernher von Braun and the military lead of Major General Walter Dornberger had developed the “Aggregat 4” which became known to the world as “Vengeance Weapon 2” (V-2) with the bombing of London and later Antwerp (after having been liberated by allied forces) and several other European cities. Many of the innovations crucial for future orbital launch vehicles have been made for this rocket and subsequently spread out into the world by the transfer of remaining production lot rockets as well as German scientists to the US (“Operation Paperclip”) and the Soviet Union (“Operation Osaoaikhim”).

Even before the development of the V-2, in the US, Robert H. Goddard developed liquid fuelled rockets sponsored by the Guggenheim Foundation until his death on August, 10th 1945, not two months before Wernher von Braun’s arrival in the US. Although Goddard was a source of inspiration for the young von Braun, Goddard’s work was carried out in strict secrecy. In 1950 the patents filed by Goddard were shown to von Braun in the frame of a patent infringement lawsuit filed by the heirs of Goddard and the Guggenheim Foundation. In fact the V-2 had inadvertently “used” Goddard’s patents. Crucial elements for modern rocketry invented in parallel by Goddard and the Germans were

* Just after the war in October 1945, in the British-led “Operation Backfire”, three V-2 rockets were fired from Altenwalde near Cuxhaven in Germany in order to demonstrate the weapon to Allied personnel. For the third launch international attendees were invited. Theodore von Kármán, whose own research was concerned with solid rocket propellants, and Dr. William Pickering, the later director of the Jet Propulsion Laboratory, as well as Juri Pobedonostsev (Airbreathing Engines research) and Valentin Glushko (Rocket Engine research) were attending. Incidentally, Sergei Korolev had not been registered in time and thus not admitted forced to watch the launch from outside the barred area, [6], chapter “A-4-Starts unter britischer Aufsicht”.

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• the use of gyroscopes and rudders in the air stream as well as engine exhaust stream of the engine for balancing of the rocket and steering along the flight path, Fig. 2,
• the use of turbopumps to feed the liquid propellants from the low pressure tankage into the high pressure combustion chamber, both, [7], chapter “Eine Würdigung für Dr Robert Hutchings Goddard”
• regenerative cooling as well as the feeding of a fraction of the propellant alcohol onto the combustion chamber inner walls, so that a blanket of evaporating gas protected them from the combustion heat, [8].

![Image](dollars-by-1938.jpg)

Fig. 2: V-2 featuring large fins for aerodynamic stability with rudders in the air stream as well as engine exhaust, non-structural tanks enclosed inside the rocket body, both not elements of the future dominant design. However, the use of turbopumps, gyroscopic steering and combustion chamber cooling would become elements of the dominant design. Image from [5], page V-2.

Other important design and technological choices were the use of ethyl alcohol as propellant and liquid oxygen as oxidiser, the V-2 had non-structural tanks enshrouded inside the load-bearing rocket body which was designed to be aerodynamically stable to a large degree also for high supersonic speeds via large tail fins, Fig. 2. The turbines driving the turbo pumps were fed by decomposing hydrogen peroxide, a principle that survives until today for the Soyuz core stage and booster engines, [10], chapter “Soyuz”

II.II Evolution of launch vehicle designs in the USA

Starting in 1936, solid propulsion technology, primarily for short take-off for military aircraft, was developed under the purview of Theodore von Kármán at the “Guggenheim Aeronautical Laboratory at the California Institute of Technology (GALCIT)”, which would later become known as JPL. The scientists experimented with solid propellant formulae in order to control the burning speed of the propellant so that the rocket would not explode after some few seconds and also founded “Aerojet Engineering Corporation” in 1942 after a fruitless search for a commercial contractor, [6], chapters “Americas Raketenentwicklung 1930-1945” and following, page 282.

Also in 1942 the castable solid propellant was invented by John Whiteside Parsons, [5], page John_Whiteside_Parsons and in 1944 the first rockets were deployed and used by the US military (Tiny Tim) or under testing (Private A). A group around Frank Malina also developed the liquid-fuelled Corporal Missile, [5], page Frank_Malina.

In New York “Reaction Motors Inc.” was founded in 1938 by members of the “American rocket society” (today dissolved into the AIAA), [6], chapter “Americas Raketenentwicklung 1930-1945” and following, page 282 and [5], page Reaction_Motors_Inc. As described in section 1.2, this and the founding of Aerojet Engineering Corporation are small companies set up by entrepreneurial persons typical for the fluid phase of the Abernathy-Utterback model.

The rocket scientists that had been relocated to the US in the frame of Operation Paperclip were launching the V-2s which were reassembled from spare parts that had been relocated alongside them. As confidence grew they were tasked to develop the Jupiter/Juno/Redstone Rocket family. These were direct descendants of the V-2, the main technological difference was the use of structural tanks first demonstrated by the Viking rocket. Still it required rudders in the exhaust and air stream and the ailerons, albeit the ailerons reduced size, [6], chapter “Amerikanische Raketenentwicklung 1945-1957”. The group and their developments would later form the nucleus of the “Army Ballistic Missile Agency” (ABMA).

Under William Pickering the JPL worked with the German scientists. Bumper was the first product, a V-2 as first stage with a WAC Corporal second stage on top to achieve high altitudes. Later, the Redstone rocket developed by the ABMA together with an array of scaled down sergeant solid rocket motors from JPL, which were to be ignited in sets of 11+3+3+1 as upper stages (Fig. 4) would send the first American satellite, Explorer 1, into orbit on 31st of January 1958, [11], chapter 1 and [6], chapter “BUMPER, das Riesending” and “Der Erkunder rettet die Ehre”.

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1 The lawsuit was amicably settled by a payment of 1 million dollars by the US government, half to Goddard’s widow, the other half to the Guggenheim Foundation, [7], chapter “Eine Würdigung für Dr Robert Hutchings Goddard”.

2 Aerodynamic stability at high supersonic speeds was tested by dropping rocket models made of solid iron with a mass of 250 kg, 20 cm diameter and 1.6 m length at 7000 m height off an airplane in 1938, [9], chapter „Die Greifswalder Ose – Beginn in Peenemünde”, page 70.
Fig. 3: Major product innovations of the orbital launch vehicle industry. As can be seen a major number of innovations happened between 1949 and 1969, which can be considered as the fluid phase of the industry according to the Abernathy-Utterback model.

Fig. 4: Array of downscaled sergeant rockets for use as upper stages for the launch of Explorer I on Juno I, [5], pages Jupiter-C and Juno_I

Starting as a branch in parallel to the ABMA activities, the “Naval Research Laboratory” developed the V-2-technology into the Viking sounding rocket which would feature a thrust vector actuation by gimballing of the whole engine. First launch would occur as early as 3rd of May 1949 whereas the first launch of the Redstone would only occur in 1953 still with rudders, [6], chapter “Die VIKING Rakete”. Also, the Viking had an essentially all-aluminium airframe with structural tanks that would carry general and aerodynamic loads. It would later serve as the first stage of the Vanguard rocket, [5], page Viking_(rocket).

The development of the Atlas ICBM started in 1951 with a contract placed with Convair, albeit with a low priority. In 1954 the program had been transferred to the Air Force’s “Western Development Division”, with the systems engineering company Ramo-Wooldridge Corporation managing the development. Due to its importance there were two independent developments for each subsystem of the rocket. As delays accumulated, the Thor IRBM development was started in 1956 in order to narrow the gap. Also, the development of the Titan ICBM was kicked-off in 1955 as a redundancy. Several technologies, which had been discarded for the Atlas, in order not to jeopardise its timely entry into service, were incorporated.

Several innovations were made within these developments: The Atlas was designed as a single-stage ICBM, thus needed a very good structural mass ratio, which was achieved by very thin-walled stainless steel structural tanks which were only stable when pressurised (balloon tanks), Fig. 5. Also, the jettisoning of the two outer engines after lift-off (stage and a half) was new. Both of these innovations resulted in in a launch vehicle with extremely low structural mass ratios, which in effect it would achieve orbital velocity during the first manned orbital launch of John Glenn on 20th February 1962, making it the first Single Stage to Orbit (SSTO) in rocket history (although jettisoning two engines). Despite its ground-breaking technical performance the concepts were not copied by competing designs as the balloon tanks were rather difficult to
handle. This is in line with the Abernathy-Utterback model, as the dominant design might not coincide with the technically most advanced solution but with the most economical one.

Atlas, as well as the Thor and initial Titan vehicles, were using Kerosene (RP-1) instead of ethanol, which would become the dominant main stage propellant of the next 20 years. The Titan vehicle would introduce further innovations in a long series of delta-developments. First, the stage separation technique by ignition of the upper stage while still attached to the first stage, thereby melting the inter-stage truss (fire in the hole), would be used. Then, with Titan II the propellants would switch to storable, hypergolic propellants.

Fig. 5: Atlas balloon tank production. Notice the lots of small bumps in the thin tank skin that would be straightened out only after the tank was pressurized (above). Note that there is no stringer or grid-stiffening on either side of the thin tank skin (below). Images from [12].

The Titan II ICBM, due to its storable propellants, could remain stored in a silo fully fuelled, ready for launch at any time. The solid propulsion technology invented by the JPL would prove to be even more appealing for ballistic missiles, as the storage life of the vehicle was greatly extended. This was first understood by the Navy which in 1954 pulled out of the joint Navy-Army Jupiter medium range missile program developed by the Army Ballistic Missile Agency in favour of the submarine-launched Polaris development, [5], page UGM_27_Polaris. Subsequently, all ballistic missiles would use solid propellants, which helped to scale-up and mature the technology and ultimately it would come back into the launch vehicle designs as a booster technology.

The Thor IRBM was developed into the Delta launch vehicle family by Douglas Aircraft Company under a contract from NASA Goddard Space Flight Centre in 1959. It would also incorporate the stages developed for the Vanguard rocket and later, for Delta D in 1964, solid strap-on boosters, [10], chapter “Delta”. Although parallel staging was already demonstrated with the R-9, forerunner of today’s Soyuz, on 4th October of 1957 with the launch of Sputnik, the use of solid propellant for this role was new. The Europeans copied the concept of strap-on boosters for Ariane 3 in 1984 and Ariane 4 in 1988, [10], chapter “Ariane”. Atlas would follow in 1993 for the Atlas IIAS version, [10], chapter “Atlas”.

In 1965 Titan IIC would be the first launch vehicle augmented by large (non-optimal for lift-off) solid propellant boosters. This concept would also be used for the Space Shuttle system, launched in 1981, and Europe’s Ariane 5, launched in 1996. When the Japanese started their launch vehicle developments with a derivative of the Thor-Delta called N-I in 1975 they retained the solid strap-on boosters. Likewise with Europe, solid boosters were part of all subsequent versions (N-II, H-I, H-II, H2A and H2B) of their launch vehicles. With the introduction of the H-II they became large (non-optimal for lift-off) boosters, all [10].

The large Titan booster casings were switched to be made of Carbon Fibre Reinforced Polymer (CFRP) instead of steel. The contract for the improved boosters was placed in 1987 and first flight occurred in 1997, [10], chapter “Titan”. The large boosters of the Japanese H-II were also changed to CFRP with the introduction of the H2A in 2001. It also introduced CFRP strap-on boosters complementing the non-optimal large boosters, [10], chapter “H-II”.

The next big step in launch vehicle technology was the development of hydrogen stages and engines.

II.11 Introducing hydrogen as propellant and high performance engines

The development of the first hydrogen stage was performed by Convair under contract from NASA Lewis Research Centre (today Glenn Research Centre) in 1956. The Centaur upper stage for the Atlas launch vehicle also shared its balloon tank design, needing to
be pressurised at all times to maintain stability. The Centaur was also used as upper stage for the Titan IIIE and subsequent versions. With the run-out of Titan production and the introduction of the Atlas V main stage (“common core booster”, Fig. 9) in 2002 the balloon tank design is limited to the Atlas V-Centaur upper stage.

![Diagram](image)

Fig. 6: The Gas-Generator-Cycle dumps the propellant proportion burnt in the gas-generator to drive the turbine(s) overboard, whereas the Expander-Cycle feeds heated but unburned propellants into the combustion chamber.¹

The RL-10 engine for this stage was developed by Pratt & Whitney as the first expander cycle engine. All engines need a certain amount of energy to drive the turbopumps feeding the propellants into the combustion chamber. It is usual that a small fraction of about 5% of the propellants is burned in a so called gas-generator, which is used to drive the turbines that then drive the pumps for the propellant feed of the combustion chamber (and of course the gas-generator). The exhaust of the gas-generator after having passed through the turbines is dumped overboard, Fig. 6, left image.

The RL-10 removes all this complexity. The hydrogen (as before with the Kerosene in other engines) regeneratively cools the combustion chamber thereby evaporating. This high pressure gas is then partly expanded to drive the turbines and pumps that feed the hydrogen into the cooling channels and the oxygen into the combustion chamber. The partly expanded hydrogen gas is also fed into the combustion chamber, Fig. 6, right image. This engine thus does not dump a proportion of the propellant as preceding engines do and consequently offers an increased efficiency, i.e. Isp, [13], chapter “Vereinigte Staaten”. On the downside this cycle cannot be scaled beyond ~300 kN thrust, [5], page Expander_cycle (rocket). The Atlas LV-3C with the Centaur upper stage launched 1962 for the first time.

The technology was copied in part by the Japanese, whose upper stage expander cycle engine LE-5 (introduced in 1986) would also remove the gas-generator but still dump the part of hydrogen used to drive the pumps overboard. The European Vinci Engine – currently under development – would be a complete implementation of the expander cycle, [10], chapters “H-IIA” and “Ariane”.

The Saturn launch vehicle family was developed starting with the Saturn-I on 15th August 1958 by the Army Ballistic Missile Agency. Its S-I first stage was ordered to use existing engines, which prompted a switch from the E-1 to the H-1 engine, both of which were from Rocketdyne, a subsidiary of North American Aviation. The S-IV second stage of the first configuration of the Saturn-I needed six RL-10 engines to achieve the required thrust level. Its later update, the S-IVB used on both Saturn-IB (development start 11th July 1962) and Saturn-V (development start 25th January 1962) would use the newly developed J-2 engine (also Rocketdyne). Due to the size limitation of the expander cycle the J-2 was again a conventional gas-generator cycle design, albeit transposed onto LOx/hydrogen as propellants. This engine was also used by Saturn-V’s S-II second stage, whereas the LOx/kerosene first stage S-IC used F-1 engines, which also was a gas-generator design from Rocketdyne. (All from [14], chapters 2 to 6.)

The development of the Saturn launch vehicles was a project of gargantuan dimensions, numerous problems were solved and countless (and untraceable from today’s perspective) process innovations needed to be made. However, such innovations are attributed to the transitional and even more so the specific phase of the Abernathy-Ulterback model (see comparison Table 1). The Saturn family was basically the first complete collection of dominant design innovations and elements consolidated into one single vehicle family (with the exception of the solid strap-on booster design), even the Centaur upper stage was at a time considered as a S-V upper stage on top of the S-IV/S-IVB for high delta V missions. Their role was also to then scale up this consolidated design to the proportions required for the moon landing. But they did not introduce innovations that change the design globally.

Interestingly, already in 1958, at the outset of the Saturn developments ABMA Rept. DSP-TM-10-58, dated 13 Oct. 1958 stated, as cited in [14], chapter 2, section “ARPA’s Big Booster”: “The SATURN,’ observed one ABMA report, ‘is considered to be the first real space vehicle as the Douglas DC-3 was the first real airliner and durable workhorse in aeronautics.’”. The DC-3 is also mentioned by

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¹ Note that the gas-generator unit is falsely labelled Pre-Burner. Images from [5], pages Gas_generator and Expander_cycle_(rocket)
Abernathy and Utterback as the first incarnation of the dominant design in the passenger aircraft sector”, [2], page 87.

However, the rapid decline of space transportation need after the moon race and the smaller sizes of all other payloads doomed the production of the Satsumis to cease on 1st of August 1968, almost one year before the first moon landing, [15], “Part II: Apollo Applications Program”.

At the end of the 1960ies almost all elements of the dominant design of expendable launch vehicles (ELVs) were invented and had been introduced on one or several of the Atlas, Delta, Saturn and Titan vehicle families, except high-pressure staged combustion engines.

In the mid-to end 1950’s both Russian and German engine scientists developed staged combustion engine cycles. Whereas this didn’t go beyond small test-bench demonstrator engines in Germany, the Russians developed several staged combustion engines. First the RD-253, RD-210/211 for N2O4/UDMH (storable hypergolic propellants) for the Proton launch vehicle in 1965. On 21st of February 1969 the N-1 moon rocket lifted off with the help of 30 NK-33 LOX/Kerosene engines on the first stage. The RD-171 and RD-120 for LOX/Kerosene for the Zenit launch vehicle followed in 1985. The Zenit’s first stage was also used as strap-on booster of the Energia launch vehicle using the RD-170 variant as well as the RD-0120 for LOX/Hydrogen for the Energia core stage in 1987, [13], chapter “Die Entwicklung des Erprobungstriebwerkes P111”, [16] and [10], chapters “Proton” and “Zenit”. The staged combustion cycle enabled to achieve higher efficiency (i.e. Isp alike) the RL-10 also for large engines and also for first stage applications operating at sea-level ambient pressure, Fig. 7. With staged combustion kerosene-fed engines operational, which would become an element of the dominant design later, the fluid phase of the A-U model came to an end, Fig. 3.

Later, a staged combustion engine for LOX/-Hydrogen was developed for the Space Shuttle system with first flight in 1981, [10], chapter “Space Shuttle”. An expendable derivative of these engines are unforeseen to power the first stage of NASA’s future SLS, [17]. For the H-II LV Japan had developed their own staged combustion engine LE-7 with first launch in 1994. Due to the special circumstances of the Shuttle and, Energia/Buran systems it is today undecided whether LOX/hydrogen staged combustion engines are representing the dominant design or not.

Since 2000 the new versions Atlas III and Atlas V use the RD-180 which is essentially a variant of the RD-171 scaled down by 50%. Also Orbital Science’s newly inaugurated Antares LV uses a Russian engine, surplus NK-33s from the cancelled N-1 which had been acquired and refurbished by Aerojet under the name AJ26-62, [18], section 2.2.1. Thus, although slowly, staged combustion engines seem to become the dominant design for ELV core stages.

II'V Seekings breakthrough cost reductions in space transportation through reusability

With the declining political support for NASA after the Apollo project the only development activity allowed to commence under the Nixon administration was the Space Shuttle, even that with a too small development budget to build it fully reusable, plus the mandate to respect design-driving requirements dictated by the Department of Defence, [19], chapter “Shuttle”. A lot of new technologies were introduced in order to cope with these requirements: “Developing a vehicle that could conduct a wide variety of missions, and do so cost-effectively, demanded a revolution in space

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**Notes:**

- “The DC-3 was a culmination of previous innovations and it set the standard for commercial aircraft for two decades. It was not the largest, or the fastest, or the longest-range aircraft to fly when it was introduced, but it was simply the only economical, large, fast, plane able to fly long distances. The DC-3 satisfied combined market needs so well that it provided the basic concepts of commercial aircraft design from the time of its introduction in the mid-1930s until jet powered aircraft appeared in the 1950s. Some design concepts introduced in the DC-3 continue to be in use today” [2], page 87
- “Notes: In the left image the gas-generator unit is wrongly labelled pre-burner. The right image is depicting a fuel-rich pre-burner, Russian engines mostly feature oxygen-rich pre-burners. Images from [5], pages Gas_generator and Staged_combustion_cycle_(rocket)"
technology. The Space Shuttle would be the first reusable spacecraft, the first to have wings, and the first with a reusable thermal protection system. Further, the Shuttle would be the first to fly with reusable, high-pressure [i.e. staged combustion] hydrogen/oxygen engines, and the first winged vehicle to transition from orbital speed to a hypersonic glide during re-entry.”, [20], chapter 1.2.

“Although an engineering marvel that enables a wide-variety of on-orbit operations, including the assembly of the International Space Station, the Shuttle had few of the mission capabilities that NASA originally promised. It could not be launched on demand, did not recoup its costs, stopped carrying national security payloads, and was not cost-effective enough, nor allowed by law, to carry commercial satellites. Despite efforts to improve its safety, the Shuttle remained a complex and risky system that remained central to U.S. ambitions in space. Columbia’s failure to return home was a harsh reminder that the Space Shuttle was a developmental vehicle that operated not in routine flight but in the realm of dangerous exploration.”, [20], chapter 1.6.

Although a lot of elements of the space shuttle orbiter’s design were also developed by the Russians for the short-lived Buran vehicle it is safe to say that the winged reusable orbital vehicle did not become the dominant design according to the Utterback definition.

The failure of the Space Shuttle system to deliver access to space at low cost prompted a plethora of design concepts for reusable air breathing single stage to orbit (X-30 and NASP, US; HOTOL, GB; AB-SSTO, JP) and two stage to orbit (Sänger, DE) launch vehicles, [21], chapter “Geflügelte ‘Transport-Systeme’. Later, the focus moved to rocket engine powered reusable systems (e.g. DC-X, X-33/VentureStar). Eventually, all these developments were cancelled, [22]. Despite their similar purpose to launch payloads into space and partial commonality in propulsive elements with Expendable Launch Vehicles (ELVs), none of the innovations made were incorporated in the dominant design of ELVs until today.

The return-to-flight efforts undertaken after the Space Shuttle Challenger accident decreased the system’s payload performance: “The ET [External Tank] Project was challenged to redesign the Lightweight External Tank (LWT) to support the ISS launch requirements, through design changes and the use of a new aluminium alloy, aluminium lithium (AL) 2195, a weight reduction of approximately 7500 lb. [3400 kg] was achieved. In just under three years, the NASA ET Project took a new material, AL 2195, from a development state to a fully qualified metal. [...] New techniques were successfully developed and the first LWT was successfully built, tested, and then launched on STS-91 2nd June 1998”, [23].

Subsequently, a friction stir welding (FSW) was introduced with the reasons as outlined in [24]: “FSW technology is [...] implemented as a Space Shuttle upgrade on the ET program for longitudinal welds [Fig. 8]. This new material joining process will improve the margin of safety for welds, reduce cost, and mitigate schedule challenges presented by fusion arc welding of 2195 aluminium lithium on the Super Lightweight External Tank (SLWT). This technology replaces the existing fusion arc weld process and its associated weld repairs with a solid-state process, which provides superior welds, is less labour intensive, less technically complex and easier to control.”

![Fig. 8: Shuttle ET longitudinal weld seams performed with Friction Stir Welding process [24]](image)

**ILV A new generation of expendable launch vehicles**

In 1995 the US Air Force initiated the “Evolved Expendable Launch Vehicle” (EELV) program, within which the Atlas and Delta vehicles were evolved to carry much larger payloads. Lockheed Martin procured some subsystems for Atlas V as the 5.4 m fairing and inter-stage adapters on the global marketplace. Especially, the RD-180 (core stage) main engine was procured via Pratt & Whitney from NPO Energomash in Russia, which is a downscaled derivative of the RD-170 staged combustion engine of Zenit/Energiya. The Centaur upper stage was slightly stretched.

While the Atlas V core stage remained to be propelled by kerosene, the Delta IV core stage was switched to LOx/Hydrogen. This needed the development of a new engine, the RS-68. In order to reduce cost, the engine is a gas-generator design with an ablative cooled expansion nozzle. The upper stage

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11 The ablative cooling was later also adopted by SpaceX for their Merlin 1A and 1B engines and applied to nozzle as well as combustion chamber walls. However, the design was abandoned on the Merlin 1C, which was regeneratively cooled, as is today’s Merlin 1D, see also section II. V.
was switched from N2O2/Aeroxine storable propellants to cryogenic LOx/hydrogen, also applying the RL-10 expander cycle engine, which is an alignment with the dominant design represented at that time by the Atlas, H-II, Titan and Ariane launch vehicle families (albeit Ariane’s upper stage engine was no expander cycle).

Delta IV were first launched in 2002, [ 10], chapters “Atlas” and “Delta”.

![Structurally stable, grid-stiffened Atlas V common core booster tank. Image from [ 25].](image1.png)

Fig. 9: Structurally stable, grid-stiffened Atlas V common core booster tank. Image from [25].

For Delta V a new comprehensive production plant was constructed at Decatur, Alabama. Atlas main and upper stage production was also planned to be relocated to Decatur after the formation of “United Launch Alliance” by Boeing and Lockheed Martin, [ 26].

![Friction stir welding benches for Delta II (left) and Delta IV (right) tank barrel longitudinal welding, image from [ 27].](image2.png)

Fig. 10: Friction stir welding benches for Delta II (left) and Delta IV (right) tank barrel longitudinal welding, image from [27].

Friction Stir Welding was introduced for the Space Shuttle ET as a follow-on to the change of material to AL 2195. While not changing the material, “Boeing has been a real pioneer in introducing FSW into industrial manufacturing. In the Delta II and IV programs, FSW has been widely adopted and used for manufacturing rocket-fuel tanks, [Fig. 10]”, [ 27]. Both, Atlas V and

In 2002, “SpaceX was founded on the philosophy that simplicity, reliability, and low-cost are closely coupled”, [ 29], section 1.3. “Like Falcon 1, Falcon 9 is a two-stage, liquid oxygen (LOX) and rocket grade kerosene (RP-1) powered launch vehicle”, section 2.1.1. Reading from section 1.6.1: “The Merlin engine features a robust, reliable turbopump design incorporating a single shaft for both the liquid oxygen and fuel pumps, and a gas generator cycle versus the more complex staged combustion. The regeneratively-cooled combustion chamber uses a milled copper alloy liner chamber that provides large margins on heat flux. In addition, the pintle injector was selected for its inherent combustion stability.” None of these concepts were new in 2002, pintle injectors even date back to work performed at JPL in 1957, [ 30]. Originally, the Merlin 1 was conceived as an ablatively-cooled engine, [ 31], section 1.6.2, which was applied by Boeing for the Delta IV before.

Also the structural technologies given in [ 29], section 2.1.1 reveal no unprecedented elements “The Falcon 9 propellant tank walls and domes are made from an aluminium lithium alloy. SpaceX uses an all friction stir welded tank, [ ...]. Like Falcon 1, the Falcon 9 inter-stage, which connects the upper and lower stages, is a carbon fibre aluminium core composite structure.” Aluminium-Lithium and FSW had been pioneered for LV applications with the Space Shuttle ET and also composite inter-stages were state of the art, for instance Atlas V and Ariane 5 ECA, both first launched in SpaceX’s founding year 2002, featured CFRP composite interstages.

Originally, the tank “barrel sections [were] constructed from rolled aluminium sheet with stringers
stir welded in for stiffness”, Fig. 11. SpaceX claimed “substantial cost savings over the conventional launch vehicle approach of using machined isogrid. With isogrid and its variants, you start with a plate of aluminium that can be as thick as two inches and then machine away up to 90% of the material, leaving behind sheet with integral stiffeners. This is obviously very inefficient use of material and requires thousands of hours of machining time.”, [32]. However, in the aerospace industry, assembling lots of small parts is a dated manufacturing technique and has been replaced by integrally milling structural parts due to the high labour costs. SpaceX’s manufacturing technology has not (yet) been copied by competitors.

“The separation system is a larger version of the pneumatic pushers used on Falcon 1.,” section 2.1.1 and “the separation system between the first and second stages does not incorporate electro-explosive devices, instead relying upon a pneumatic release and separation system that allows for acceptance testing of the actual flight hardware. This is not possible with a traditional explosive-based separation system”, section 1.6.1 might be unprecedented designs invented by SpaceX. However, the technology has not yet been copied for other vehicles and it is not clear whether the updated Falcon 9R design still incorporates the pneumatic release system.

The other recently inaugurated LV is the Antares entrant with first flight on 21st April 2013. It features, as mentioned above, the Aerojet AJ26-62, thus joining the trend to use high performance staged combustion kerosene-fed engines for main stage propulsion. Surprisingly, it features a solid propellant second stage, [18]. While solid kick-stages for high delta-V missions are commonplace, the use of solid propellant as a nominal second stage is surprising, such designs had been abandoned long since.

Summarising, this new generation of launch vehicles follows three major trends, (a) to align with the dominant design, (b) concentrate on material and process innovations and to (c) concentrate the production in one large facility***. In the A-U model (a) would represent the transitional phase whereas (b) and (c) represent the specific phase of the A-U model, compare Table 1.

### II.VI A word on small launch vehicles

The discussion above covers the evolution of orbital launch vehicles from their roots until today, focusing on today’s larger launch vehicles, capable of delivering payloads to geostationary transfer orbit (GTO).

However, there has also been a plethora of small launch vehicle developments for payloads to synchronous and low earth orbits. Partially, these are based on converted ballistic missiles (e.g. the Minotaur family, [33], first flight on 27th Jan 2000, [5], page Minotaur (rocket family)), some based on the boosters of larger vehicles (e.g. Epsilon using the booster of H-IIA with first flight on 14th Sept 2013, [5], page Epsilon (rocket)) or purpose-built stages (e.g. Vega with first flight on 13th Feb 2012, [5], page Vega (rocket)). These launch vehicles usually feature three or four (or even more) stages, all of which are solid propellant stages, except the last stage, which uses hypergolic storable propellants. But for some vehicles this last stage is optional (e.g. Epsilon).

These design elements can be found across more than the three vehicles mentioned as examples and it then follows that the dominant design for small launch vehicles is based on solid propulsion stages, with three stages minimum and thus is considerably different from the dominant design of their large siblings. The first appearance of this design was the Scout rocket, first launched on 1st July 1960 (first success 16th February 1961), [34], chapter “Scout”.

### II.VII Summary of the historical analysis

The authors believe that the dominant design for large, GTO-capable LVs feature the following characteristics:

- **Solid propellant boosters**
  - Large (non-optional) boosters (H2A, Ariane 5, Space Shuttle, future SLS)
  - Strap-on boosters with CFRP booster casings (Delta IV, Atlas V, H2A-202X)
- **Liquid propellant core stages**
  - Kerosene main stages
    - Gas generator cycle engines (Soyuz, Falcon 9)
    - Staged combustion engines (Atlas V, Antares, Zenit)
  - Hydrogen main stages
    - Gas generator cycle engines (Delta IV, Ariane 5)
    - Staged combustion engines (H2A/B, Space Shuttle, future SLS)
- **LOx/Hydrogen upper stage (Ariane 5 ECA)**
  - with expander cycle engine (Atlas V, Delta IV, H2A/B, future Ariane 5 ME)
- **Gimballing of all engines (all LVs)**
- **Stiffened aluminium structural tanks (all LVs)**

As can be seen, some choices have not yet been fully consolidated. The most important not fully converged design is the core stage propellant choice between

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*** SpaceX employs this concept even more, see section III.1.

IAC-13-E6.2.6
hydrogen or kerosene. While for kerosene main stages the dominant design comes along with staged combustion engines, for hydrogen core stages the engine cycle is yet undecided, maybe with a slight dominance of the gas-generator cycle.

For small launch vehicles (w/o significant payload to GTO) the dominant design has three or more solid propellant stages topped by a storable propulsion stage.

### III. CURRENT TRENDS AND DEVELOPMENTS (AND THEIR ROLE IN THE A-U MODEL)

As described in the previous chapter, major innovations occurred during the last 60 years setting the foundation of the launcher space sector. This chapter will focus on the current trends and development in the launcher sectors.

<table>
<thead>
<tr>
<th>Launch Vehicle</th>
<th>Launches in 2012</th>
<th>Country / Region</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton</td>
<td>11</td>
<td>Russia</td>
</tr>
<tr>
<td>Soyuz †††</td>
<td>12</td>
<td>Russia</td>
</tr>
<tr>
<td>Long March</td>
<td>10</td>
<td>China</td>
</tr>
<tr>
<td>Ariane 5</td>
<td>7</td>
<td>Europe</td>
</tr>
<tr>
<td>Atlas</td>
<td>6</td>
<td>United States</td>
</tr>
<tr>
<td>Delta IV</td>
<td>4</td>
<td>United States</td>
</tr>
<tr>
<td>Falcon 9</td>
<td>2</td>
<td>United States</td>
</tr>
<tr>
<td>Safir 2</td>
<td>3</td>
<td>Iran</td>
</tr>
<tr>
<td>PSLV</td>
<td>2</td>
<td>India</td>
</tr>
<tr>
<td>Unha</td>
<td>2</td>
<td>North Korea</td>
</tr>
<tr>
<td>Zenit 3SL</td>
<td>3</td>
<td>Multinational</td>
</tr>
</tbody>
</table>

Table 2: Example Number of launches per vehicle in 2012 (more than one launch), [35]

There has been in 2012 78 launches worldwide from 1 launch per vehicle up to 11 as depicted in Table 2. The Orbital Launch Vehicle Industry produces no more than 11 launches per model per year as defined in the same table. Economies of scales are very challenging with these figures, while serial production of components is a key element to reduce cost [36]. In addition, all launch vehicles are expendable, which is source to enormous recurring costs. The Space shuttle was the only launch vehicle to have reusable boosters. A reusable launch vehicle could increase profitability margins by reducing production costs.

This section of the paper will present how serial production and partial reusability may be a trend in the launching industry. The first approach is to increase the production rate of components; a higher volume of production would decrease the fixed cost per unit, also with an accelerated production learning curve and through increments of efficiency in the production line, the cost per unit could be further decreased. The second approach is to introduce incremental degrees of reusability, with an opposite approach to serial production, the re-use of components would distribute the cost of said component between its different uses, decreasing the cost per use.

This analysis focuses on projects that have already received a considerable amount of funding and have or aim to perform hardware testing within a year. The selected concepts are not exhaustive. If successful these game-changing launching systems may disrupt the Orbital Launch Vehicle Industry.

#### III.I Serial production of components

A clear example of the serialization of the production during the last decade is the MERLIN Engine developed by SpaceX in the United States. This section will describe how SpaceX transitioned from Falcon 1e to Falcon 9 and eventually Falcon Heavy using respectively 1, 9 and 27 core stage engines. Then it will analyse how the European Space Industry intends to meet the same goal with the current Ariane 6 chosen architecture.

SpaceX’s Falcon family of launchers

SpaceX is a privately held company established in 2002 by the entrepreneur Elon Musk. The Falcon 1 was the first rocket developed by SpaceX. It was a two-stage semi-reusable launch vehicle, [37]. The first stage was propelled by the Merlin 1D engine. The Merlin is a turbo pump-fed gas generator driven engine, working with REP-1 kerosene and liquid oxygen. This concept has been used on several engines before like Atlas, Thor/Delta and Titan I, see section II.II. The Merlin was developed at SpaceX and is based on a long heritage of space proven engine designs (section II.V) but not today’s dominant design of staged-combustion kerosene engines (section II.III). After two successful launches of Falcon 1, SpaceX announced the upgraded version to Falcon 9 which was first launched in 2010. Nine Merlin 1C engines power the Falcon 9 first stage. The second stage of Falcon 9 is very similar to the first stage and uses most of the same tooling material and manufacturing techniques resulting in cost savings in the vehicle production, it is powered by one Merlin Vacuum engine. “Falcon 9 makes use of ten Merlin 1C engines on each vehicle (nine on the first stage, one on
the second stage) resulting in high volume engine production", [29], section 1.6.1. “Right now our engine production rate is around 50-60 a year with the Merlin I-C. Merlin I-D – in addition to a thrust and performance upgrade – it is really designed for manufacturing ability as well. I’m very confident we can build 400 engines a year, or even 500-600 engines per year if we need to.” expressed Elon Musk in an interview in 2011, [38].

To have economies of scale, improvements on the production efficiency are a key factor. For that, SpaceX vertically integrates the production: “More than 80 percent of the Falcon rocket and Dragon spacecraft are built in-house. From the combustion chamber and nozzle at the bottom of the engine, to the capsule and its protective shield at the top. SpaceX designs and builds just about everything itself in a factory at the Hawthorne Airport”, [39]. SpaceX’s strategy after the development phase is to reach a high production rate while manufacturing up to 85% of the launcher in-house [34]. The factory is organized into distinct production islands; parts go from one island to the next the product becomes more and more complex. All manufacturing machines are owned and operated by SpaceX.

SpaceX also introduced robotic production processes built on the know-how acquired in the automobile industry. As an example of process innovation, for tank production traditionally a welding is inspected with ultrasound after the welding is done, which is a time-consuming process. An in-house developed system performs simultaneously the welding and the ultrasonic scan, which saves time and money.

Another improvement during the production is the plating of nickel cobalt on the Merlin engine combustion chamber. This coating takes the primary stress off the pressure vessel and the plating process is very slow. SpaceX uses another process using a metal sheet, which is moulded into the right shape and then braised on into the chamber, [36]. This process is much faster than the plating one and can be repeated several times a day.

All these characteristics are typical of the specific phase according to the Abernathy-Utterback model.

Europe’s Ariane 6

As Europe is developing the next generation launcher, Ariane 6, the chosen concept could align to the same philosophy. In July 2012, the European Space Agency released a request for consultation, [40]. The Ariane 6 Launcher architecture is based on a lower composite with 4 solid motors and a cryogenic upper stage propelled by the Vinci engine. The upper stage will include commonalities with the adapted Ariane 5ME launcher as well as it possesses re-ignition capability and direct de-orbiting of the upper stage. The lower part is composed of two segments. Three solid motor arranged linearly (in opposition to parallel staging) will compose the first stage. The second stage is a similar solid rocket motor mounted on the top of the central solid rocket motor of the first stage. The motors of the first and second stage have the same definition (four identical motor case nozzle, igniter, thrust vector control...). If as stated, the launch cadence will be of 9 to 14 times per years, [40]. This would mean a production of 36 to 56 solid rocket motors per year (3 to 5 per month). The high volume production of the solid rocket motor could benefit from economies of scale.

III. Approaches to Incremental degrees of reusability

Air Launch (Stratolaunch, “Pegasus”, SOAR, LauncherOne)

The first Air Launch occurred in 1971 with the rocket Pegasus developed by Orbital Sciences Corporation in the Washington DC area. It can carry up to 440 kg in Low Earth Orbit.

The vehicle is air-dropped from a Lockheed-built L-1011 aircraft. Since 1994, the Pegasus XL has flown 31 times with 2 failures in the 1990s, [35]. Currently several companies are developing air launch to orbit system such as Virgin Galactic (LauncherOne), Orbital Sciences (Stratolaunch’s Pegasus II) and Swiss Space Systems’ (S3) SOAR (Sub Orbital Aircraft Reusable).

Stratolaunch will launch the Pegasus II rocket (produced by Orbital Sciences) from the Stargazer L-1011 carrier aircraft (produced by Scaled Composites), [41]. The company is based in the Mojave Desert and plan to perform the first test flight by 2013, [42].

Virgin Galactic plans to launch LauncherOne using WhiteKnightTwo (also created by Scaled Composites) as a first stage. The WhiteKnightTwo aircraft was design for the suborbital SpaceShipTwo. The WhiteKnightTwo is approaching the end of test program, having successfully completed captive carry missions with SpaceShipTwo. LauncherOne plans to reach a performance of 225 kg Payload to LEO.

In March 2013, S3 announced the development of a Sub Orbital Aircraft Reusable (SOAR) which should fly by 2017 delivering payload up to 250kg, [43] into low earth orbit. The launch will be performed in three steps: first the spaceplane will be take-off on an aircraft to an altitude of 10km from which the shuttle will start its engine and deliver an upper stage at an altitude of 80km. This Upper-Stage will perform the last phase of
the journey delivering the payload to a 700km orbit, [44]. Compared to a classical launcher, the plane would act as a booster, the space plane as a second stage.

Some other companies such as Zero2Infinity are investigating air launch systems from a balloon platform.

**Reusable Boosters**

SpaceX plans to manoeuvre the first stage in such a way that it will fall down into the pacific ocean for a soft water landing, [45]. In the future the booster should land vertically to make it reusable, this concept is called the Grasshopper. In August 2013, the Falcon 9 Grasshopper completed a divert test, flying to a 250m altitude with a 100m lateral manoeuvre before returning to the centre of the pad. Three test flights were also performed in 2012 and one in June 2013. The Grasshopper would guarantee the reusability of the first stage, [46].

Masten Space Systems, Blue Origin and Armadillo Aerospace are also considering similar concepts of Vertical Take-off and Vertical Landing.

**SSTO & Air Breathing Engines**

Skylon is a single stage to orbit (SSTO) reusable launch vehicle proposed by the UK firm Reaction Engines Ltd [47]. The technology is based on heritage of HOTOL which was a British design for an air-breathing space plane designed in the 80’s, [21] and [5], page HOTOL. The key technology is the SABRE engine, based on a pre-cooler heat-exchanger that can cool air from 1,000°C to -150°C in less than 1/100th of a second [48], allowing to use liquid air as the oxidiser and reducing the mass of liquid oxygen required for orbital speed.

**IV. SUMMARY AND CONCLUSIONS**

The Abernathy-Utterback model as outlined in the first section of the paper can very well be mapped onto the orbital launch vehicle industry.

The analysis of the innovations introduced in the design of orbital launch vehicles from a historical perspective is presented in section II. It focuses on the US industry during the fluid phase, but includes the European and Japanese launchers when relevant and covers Russian launchers and esp. engines since they contribute to the global dominant design. The analysis points out that a fluid phase took place between 1949 and 1969 when most of the innovations that form today’s dominant design were first introduced, Fig. 3.

The dominant design has two liquid propellant stages, the use of LOX/hydrogen upper stages with expander cycle engines is part of the dominant design. A kerosene core stage comes along with staged combustion engines, hydrogen core stages may show a slight dominance of gas-generator cycle engines. However, the preference between kerosene or hydrogen is not consolidated yet, the use of solid boosters is undecided between optional (depending on mission needs), mandatory or not part of the design at all.

The new innovations introduced with the recent launch vehicle developments clearly show that the industry currently experiences a transitional or even specific phase, where the focus of industry is on process innovation, streamlining, and use of proven designs.

The paper observed as well a current focus on process optimization and serial production of components (e.g. Merlin engines and Ariane 6 solid motors), with the aim of reducing recurrent costs.

The small launch vehicles (w/o significant payload to GTO) were also briefly discussed, pointing that the dominant design is based on three or more solid propulsion stages, as opposed to the larger launchers.

Regarding the configuration chosen for Ariane 6 (four similar solid motors and cryogenic upper stage), it not only tries to take advantage of mass production of its solid motors, but it also scales up the dominant design of small launch vehicles into the domain of large (GTO capable) vehicles. This is an important novum, with quite some risk attached. But risk taking is a part of achieving innovation and maybe changing the dominant design.

SpaceX deliberately chooses to deviate from the dominant design. Particularly in the case of the Merlin engine they choose a kerosene gas-generator design, they do not use solid propellants, despite being part of all other launch system designs, they do not use a hydrogen upper stage. Whether this concept survives or in the long term may even change the dominant design remains to be seen.

Finally, while reusable vehicles and winged spacecraft have been in the plans for long time, or even developed as the Space Shuttle, they have not really been disruptive, nor have they taken the market from the current dominant design of ELVs. However, the current trend of partial reusability, either by recovering the first stage like Grasshopper, having an aircraft as first stage like Stratolaunch, or using an air-breathing engine like SABRE, might be the incremental innovation approach needed by the industry to finally start a new fluid phase in the orbital launch vehicle industry.
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