
2.1 Meeting the Challenge

Prior to the 1930s, flying in aircraft was costly and potentially dangerous. There were fewer passengers and less cargo than required for profitability without government subsidy. The Douglas Aircraft Company design team took the train to New York City to meet with TWA officials rather than flying the airliners of the day, as there just had been a series of accidents including the one that Knute Rockne, the Notre Dame football coach, had perished on. Gene Raymond, the Chief Engineer for Douglas integrated the following three novel elements: (1) He used the newly dedicated GALCIT wind tunnel at the California Institute of Technology (Caltech) to experimentally verify the advanced aerodynamics of the new aircraft. (2) Raymond used the latest aluminum-stressed skin structure developed by Jack Northrop for Lockheed's aircraft fuselages. (3) The engines were the new Wright Cyclones radial air-cooled engines that developed 900 horsepower. Hence, Gene Raymond integrated the three principal elements for a successful aircraft from the newly demonstrated "industrial capability" (Loftin 1985). In 1932, the Douglas Aircraft Company introduced the DC-2 followed by the DC-3 in 1934 (Ingells 1979). The result was a commercial airliner that offered speed, range, and safety to the passenger while being profitable to the airlines without subsidy. The aircraft was a sustained-use vehicle that flew hundreds of times per year and therefore at an affordable price. By 1939, the DC-3 was flying tens of thousands of passengers for the airlines worldwide (Davies 1964).

Like the DC-3, there were other aircraft built from the available state of the art. One such aircraft was the operational Mach 3-plus SR-71 developed by Clarence (Kelly) Johnson's *Skunk Works* team at the Lockheed Burbank plant (Rich and Janos 1993; Miller 1995). The other aircraft was the North American X-15 research aircraft developed to investigate speeds up to Mach 6 (Jenkins and Landis 2003; Gorn 2001; Jenkins 2007; Evans 2013). Extensive wind tunnel testing established the aerodynamic characteristics of both, the SR-71 and X-15. The structure was

high-temperature nickel-chrome alloys for the X-15 and β -titanium for the SR-71 in a structure analogous to a "hot" DC-3. The rocket engine for the X-15 was advanced from earlier rockets and has been developed to a level not yet installed on any aircraft. The turbo-ramjet propulsion for the SR-71 has yet to be duplicated 50 years later. For the X-15, one challenging goal was the flight-control system that had to transition from aerodynamic controls to reaction jet controls at the edge of space. For the SR-71, the challenge was to design an integrated control system for both the engine inlets and the aircraft for an operational range from high supersonic speeds to low landing speeds. This had not been done before, and it was accomplished before the era of integrated circuits and digital control. The goal for the X-15 was an approach to fly to space (by exceeding 100 km which is about 62 miles) as frequently as could be expected of an aircraft-launched experimental vehicle. By 1958, the X-15 was approaching 300 successful flights. The X-15 was achieving flight speeds of Mach 6.72 (7274 km/h or 4520 mph) and could briefly zoom to the edges of near-Earth space. Rockets of the day were single use and costly, with numerous launch failures. These aircraft were developed by engineers that did not ask "*What is the technology availability date?*" but rather, "*Where can we find a solution from what we already know or can discover?*" For both vehicles, the X-15 and the SR-71, solutions that were not previously known were discovered and used to solve the problems in a timely manner. From 1961 onward, that spirit enabled the Apollo team to fabricate a Saturn V rocket of a size that was previously inconceivable and succeed (Bilstein 1980).

2.2 Early Progress in Space

Also in 1957, during the International Geophysical Year (IGY), the USSR lofted the first artificial Earth satellite, *Sputnik I*, into low Earth orbit (Dickson 2001). Suddenly in the USA, the focus was on catching up, and space flight centered on vertical launch with expendable rockets, while

the experimental aircraft experience and capability were discarded. With Sergei Korolev as the designer (Harford 1997), the USSR adapted a military intercontinental ballistic missile, the R-7A (NATO name SS-6 Sapwood), to be the first launcher (Clark 1988; Stine 1991). That launcher had the growth potential to become the current, routinely launched Soyuz launcher (Lardier and Barensky 2013; Hall and Shayler 2007). The first Sputnik weighed 150 kg, while the payload capability of the launcher was about 1500 kg indicating an impressive launch margin!

At the time, the President of the USA rejected the suggestions coming from many sides to adapt military ballistic missiles and insisted on developing a launcher sized specifically for the 1957 IGY (International Geophysical Year) satellite. That launcher, Vanguard, had almost no margin or growth potential (Launius and Jenkins 2002). There was about a 4 kg margin for the payload weight. After a series of failures, the first United States Army military IRBM (intermediate-range ballistic missile), the Jupiter missile, was modified into a satellite launcher, and *Explorer I*, the first satellite of the USA, was successfully launched. Since then, the former USSR, Russia, the USA and all the other space launcher-capable nations have focused on expendable launchers with the same strategy in ballistic missile utilization: they are launched for the first, last and only time.

As discussed in Chap. 1, during the 1960s there was an enthusiasm to reach space together with a very intense effort to obtain the necessary hardware. Technical developments were ambitious yet technically sound whilst being based on available industrial capability customized to pragmatically address the problem at hand. However, the complication was that the most capable vehicle configuration development, system designs, boosters, and spacecraft were associated with a military establishment, primarily the US Air Force. One goal was to have an on-demand global surveillance system with either a hypersonic glider (X-20 Dyna-Soar) with an Earth circumference boost-glide range capability (Godwin 2003; Houchin 2006), or a hypersonic boost-glide vehicle (Project Isinglass and Project Rheinberry) with a half-Earth circumference range capability (Rose 2008). Another goal was to establish a manned orbital laboratory (MOL) to assure a human presence in space and enable space-based research and Earth/space observations (Anon 2015; Baker 1996). The spacecraft launchers proposed had the capability for frequent scheduled flights to support an orbital station with a 21–27 crew complement, crew members being on six months rotating assignments. With the US government’s decision that space is not a military but civilian responsibility, the civilian space organization (NASA) was tasked to develop their own hardware systems without the possibility to rely on military hardware. Consequently, most of the very successful system design efforts by the military organizations were

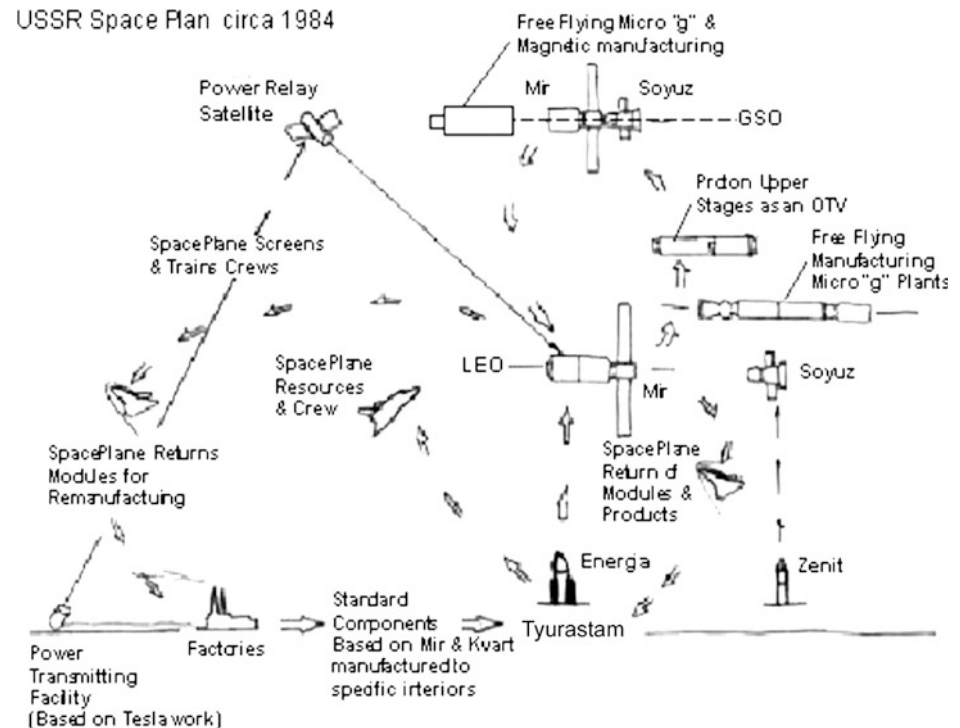
unfortunately discarded by the civilian organizations, with the result that their system(s) never achieved the superior performance capability offered by the military systems.

After the Saturn V Apollo Moon missions starting in 1961, the short-lived Skylab experiment (1970) and the Apollo-Soyuz rendezvous (1975), the USA did have a dream to establish a space infrastructure and operational space systems. However, with the demise of the Apollo program and the elimination of the Saturn V heavy-lift capability in view of a future, yet to be realized NASA Space Launch System (SLS) vehicle (Anon 2015), there followed a 12-year period in which no crewed space missions were conducted, as all waited for the Space Transportation System (STS, or Space Shuttle) to enter into operation (Jenkins 2001). The dreamers, engineers, scientists, and managers alike, with visions of future possibilities, were put indefinitely on hold; the subsequent developments became myopic and focused on day-to-day activities requiring decades in development, and larger and longer funding profiles for minimal performance improvements. Armies of paper-tracking bureaucrats replaced small, dedicated, and proficient teams.

The USA is not the only nation that considered the establishment of an operational space infrastructure. Figure 2.1 shows a diagram one of the authors (P.A. Czysz) drew during discussions with V. Legostayev and V. Gubanov during the 1985 IAF Congress in Stockholm, Sweden, illustrating the USSR vision of a space infrastructure (Legostayev and Gubanov 1985). The sketch remains as drawn, with only the handwritten call-outs replaced by typed captions. This sketch shows a total space exploration concept, with certain capabilities unique to the Russian concept. One capability is a ground-based power generator and transmitter with the capability to wireless power satellites, lunar and Mars bases, and space exploration vehicles directly and also, via relay satellites, capable of powering other surface sites. In the 1930s, Nikolai Tesla stated that, with his wave-based transmission system, a Mars base or spacecraft traveling to Mars could be powered from Earth with less than 10% energy losses (Tesla 2014). With many years spent translating Tesla’s notes and reports in the Tesla Museum in Belgrade, the Russians conducted numerous experiments using the cathode tubes that Tesla developed (Cook 2001). One of the authors (P.A. Czysz) saw such a tube when visiting the Tesla Museum in Smiljan, Croatia, in 1980, but most Western scientists are skeptical as to feasibility of such power transmitter.

The remaining elements of the Russian vision in 1985 are in common with other space plans. Their concept is built around an orbital station and free-flying manufacturing factories since manned space stations suffer from too many gravitational disturbances (“jitter”) in the microgravity environment to be considered true “zero gravity.” The space facilities are in low *Earth* orbit (LEO) and in geostationary

Fig. 2.1 A look at the future space infrastructure envisioned by Boris Gubanov and Viktor Legostayev of the former USSR based on having Energia operational. Circa 1984



orbit (GSO). An integral part of the Russian space plan is an orbital transfer vehicle (OTV) to provide movement of satellites and resources to and from LEO. Deep space exploration and establishing a permanent Moon base (Eckart 1999) were also part of the total space plan (see Chap. 6). The important part of the Russian concept is that it was based on hardware capability that they already had in use or was in development. The key difference from other space plans is that their now retired NPO Energia launcher (Hendrickx and Vis 2007) was a heavy-lift system that could launch either cargo payload vehicles (up to 280 t) or a manned glider (Buran) (Lozino-Lozinskiy 1989), see Figs. 2.7 and 2.11. NPO Energia was to provide a fully reusable heavy-lift system (Energia) and an aerospace plane (Buran) with the goal to support the orbital station and other human crewed systems.

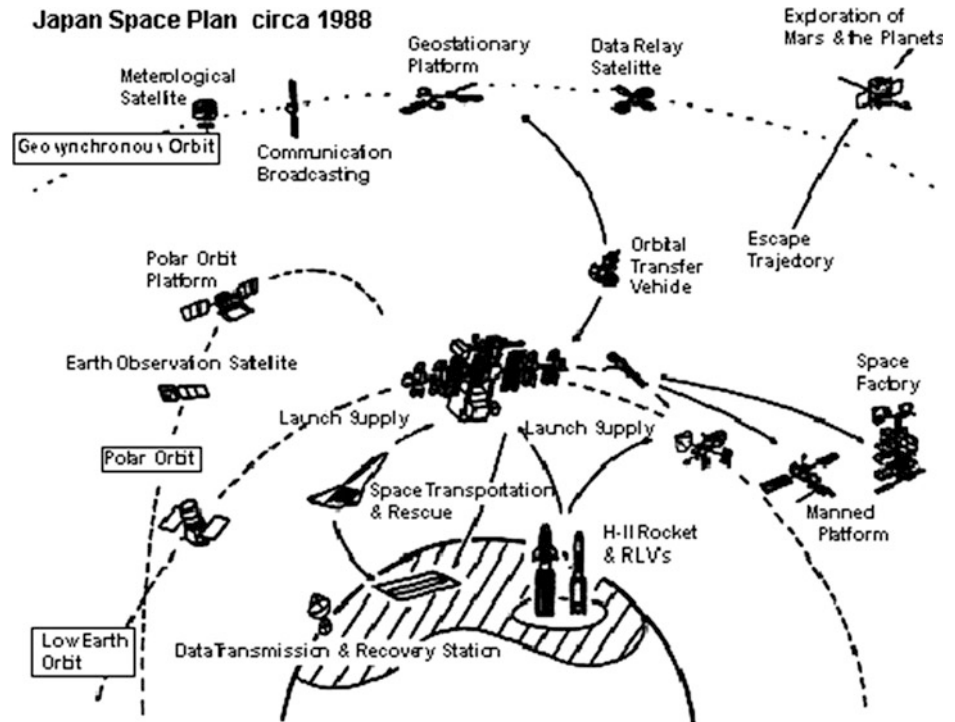
There was a space transportation vehicle in the works at TsAGI (Plokhikh 1983, 1989) that could be considered analogous to the US National Aerospace Plane (NASP X-30) (Schweikart 1998). In 1986 per government decrees of January 27 and July 19, 1986, it was decided to develop the Russian equivalent of NASP, which is a Soviet horizontal-takeoff-horizontal landing (HTHL) single-stage-to-orbit (SSTO) aerospace plane. A technical specification had been issued on September 1, 1986, for a single-stage reusable aerospace plane system. Little is known about the design bureaus who submitted designs proposals, among them Tupolev (Tu-2000), Yakovlev (MVKS), and Energia. This would be an orbital station resource supply vehicle, with

NPO Energia the workhorse of heavy-lift capability. N. Tol'yarenko, who worked at TsIAM on the strategic reconnaissance ramjet-powered La-350 *Burya* and RSS-40 *Buran* missiles, told one of these authors (C. Bruno) that, were these to have been further developed into a first stage vehicle, we "... would be on Mars by now ...".

Another goal for the Russian and Ukrainian space groups was to greatly reduce the source of space debris, that is, inoperative satellites and spent third stages that remain in orbit (Legostayev and Gubanov 1985). Their approach would be to use the Buran glider and the aerospace plane(s) to return nonoperative satellites to Earth from LEO for remanufacture. The OTV would return nonfunctional satellites from GSO to LEO. As mentioned before, the unique difference has been the addition of beamed power from *Earth* via orbital relay to satellites and orbital stations from a ground power station. The power generation and transmission was based, as said, on concepts developed by the late Nikola Tesla with a reported progression of transmitted power up to 10 MW and efficiency over 75% from ground station to space station. This historical database is archived in both the Tesla Museums in Belgrade (Serbia) and in Smiljan (Croatia).

Just as the USA and the former Soviet Union had plans to develop space, so did Japan. Figure 2.2 shows a representation of an analogous plan presented by Japan's space organizations (at the time ISAS, NASDA, and NAL, now unified as JAXA) as they considered the future. As with the Russian concept, the Japan space organizations' concept is

Fig. 2.2 A Japanese look to the future space infrastructure based on their development of an aerospace plane and significant orbital manufacturing assets, circa 1988



built around an orbital station and free-flying manufacturing factories, again independent from the station because of microgravity jitter. Their plan was very comprehensive and indicated a desire to establish commercial space operations. There are large space facilities in LEO, *Earth* observation platforms in polar Sun-synchronous orbit, and a variety of platforms in GSO. Integral to their space plan was an OTV to move satellites and resources to and from LEO. Deep space exploration and the establishment of a permanent Moon base was also part of the total space plan. There was an aerospace plane transportation vehicle in work at NAL (now JAXA) (Maita et al. 1991) that could be considered analogous to the US NASP. During the NASP project team visit to Japan in 1988, the Japanese concept was given significant print coverage and presented to the NASP team in considerable detail. Figure 2.3 shows an artist's rendition of the NAL aerospace plane. The configuration is a slender wing body with sharp leading edges and nose, required to minimize the hypersonic drag characteristics and to improve the reentry glide lift-to-drag ratio for *Earth* return. The plane is powered by a rocket-based combined-cycle (RBCC) propulsion system. The details are technically correct and indicate a competent design team working actual problems.

When the NASP team visited Japan, they received the vision of the Space Advisory Council of the international space activities shown in Fig. 2.4. Note that this Japanese perspective incorporated directly the world space plans as they existed in 1988. In fact, the Japanese plan indicates that in 1988 there was a multinational perspective toward

establishing a functional space infrastructure that benefited each nation. This future was to be built around orbital stations and free-flying manufacturing factories in LEO and in GSO (Transferring industrial manufacturing to space for environmental reasons is also in the vision of Jeff Bezos, the Chairman of Amazon and owner of the Blue Origin space company.). Deep space exploration spacecraft were planned to the Moon and planets. However, problems with the engines for their H-IIB expendable launch system and the downturn in the national economy placed much of the Japanese vision on hold (or stretched out their vision much farther in time).

Clearly, many concepts have envisioned the future indeed, but the pioneers that expanded the scope of aviation are no longer there to make the dream reality. All that remains, it seems, are the skeptics, who say it is too expensive, or too dangerous, or impractical, or irrelevant.

2.3 Historical Analog

Experience with expendable vehicles is not limited to rockets, as illustrated by Fig. 2.5. In the 1800s, St. Louis, Missouri, was the *Gateway to the West*, and hundreds of thousands of pioneers passed through on their way to the West over a 70-year period. There is no record of how many Conestoga wagons, that departed St. Louis in the early and mid-1800s, ever returned. The settlers were, per their destination, on a one-way trip. One exception was the three

Fig. 2.3 Aerospace plane concept from Japan’s National Aerospace Laboratories (Courtesy NAL)

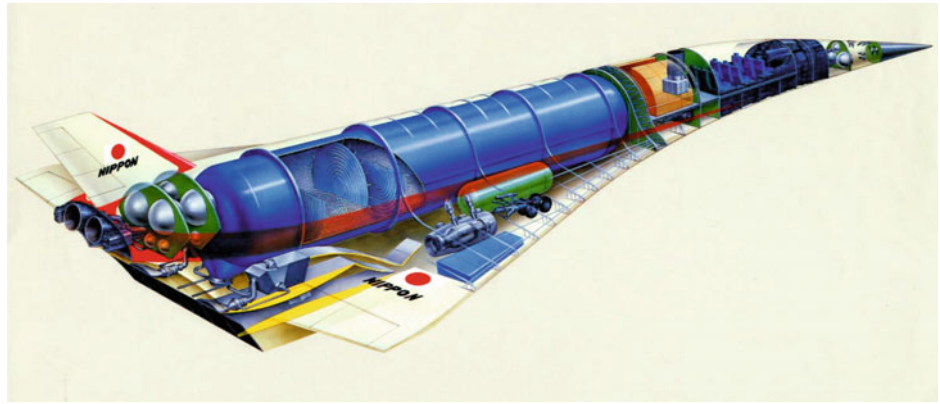


Fig. 2.4 International space plans as presented to the Space Advisory Council for the Prime Minister of Japan in 1988

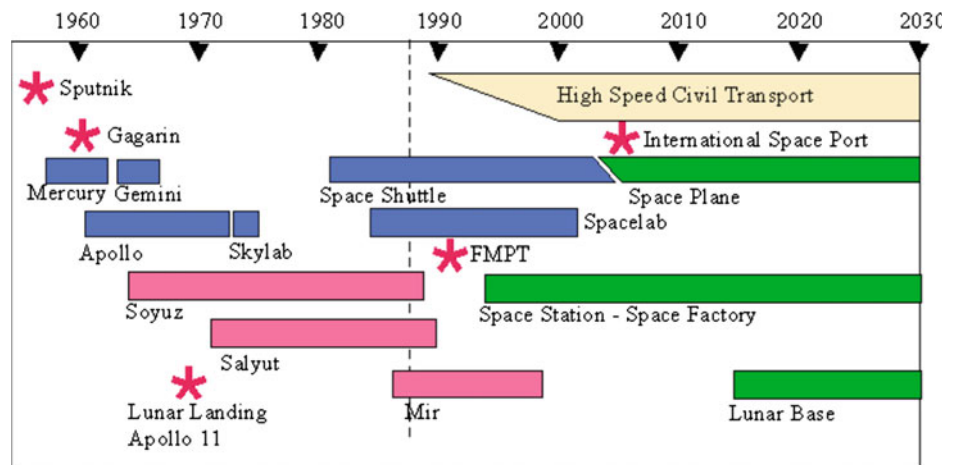


Fig. 2.5 Expendable vehicles are for pioneers to open up new frontiers and establish a one-way movement of people and resources (expendable Conestoga wagon, circa 1860)

super-sized wagons that were sent to Santa Fe to return Spanish gold to St. Louis; they returned empty. Unlike the Space Shuttle external tank, the wagons were reused as construction materials at their final destinations.

A significant space infrastructure could have been constructed from empty central tanks during the period when the Space Shuttle (STS) was operational (Hunt 1998). At best there are some expendable launcher parts that can be refurbished, as in reusable launch vehicle (RLV) and highly

reusable launch vehicle (HRLV) concepts, but this is a far cry from the sustained-use, long-life aircraft analog represented by the DC-3. The fact that each expendable launcher is launched for the first, last, and only time punctuates our failures. The expendable launcher market is limited, and so is the potential to justify further developments. All satellite-launching nations followed the same path, in a sort of “follow the leader” or “maintain the status quo” mind-set. The dream of a space transportation system was never permitted to become reality, unlike that of an airline transportation system.

The difficulty is that few transportation systems initially begun with an already existing, or ready-made, customer base. This is true for the first coal transport to the coast from York, England, in the early 1800s, or the US transcontinental railroad (Ambrose 2000). In the 1870s, the initial rail customer base established itself only after the transportation system was readily available and it was operated such to enable true two-way commerce. As depicted in Fig. 2.6, the railroad enabled the two-way transit necessary for the development of an economic frontier. According to the historical records, between 75 and 80% of the businesses founded in the westward expansion did not exist at the time



Fig. 2.6 Sustained-use vehicles industries used to open up new economic frontiers and establish scheduled, regular, sustained two-way flows of people, and resources

the railroad began. In the 6 years (1863–1869) that it took to build the transcontinental railroad, an enormous quantity of men and materials were consumed. Stephan Ambrose’s book, *Nothing Like It in the World*, documents the dedication of the dreamers, surveyors, tracklayers, graders, engineers, and laborers that made the transcontinental railroad possible.

Compared to the task of designing, surveying and building the US transcontinental railroad, developing and launching the first sustained-use aerospace plane appears to be, at a first glance, less labor-intensive and less of a challenge. With the current approach of analyzing a future market, based on current mental notions and concepts of operation, such tactics does indeed demonstrate that no market initially does exist. An early result is the conclusion, as currently observed, that today’s status quo (utilization of expendable launchers) may be sufficient, possibly even pointing to a perceived overcapacity. Clearly, planning a future space launch and in-space transportation system to such mental perception, that of a nonexistent market, will not yield a satisfactory argument for decision-makers today, nor in the future, nor would it have been convincing in the 1850s for trains nor in the 1930s for aircraft.

2.4 Evolution of Space Launchers from Ballistic Missiles

When the USSR lofted the first artificial *Earth* satellite (Sputnik I) into low Earth orbit by adapting a military ICBM, the R-7A (NATO’s name: SS-6 Sapwood) became their first space launcher, see Fig. 2.7 (Clark 1988). That can be defined as a typical Russian design procedure. The USA has developed its expendable and partially reusable launchers in a similar manner. The US Army Redstone IRBM was the vehicle to launch the first US astronaut (Alan Shepherd) into space on a ballistic trajectory. The USAF Titan ICBM became the mainstay of the McDonnell Douglas Gemini manned spacecraft program.

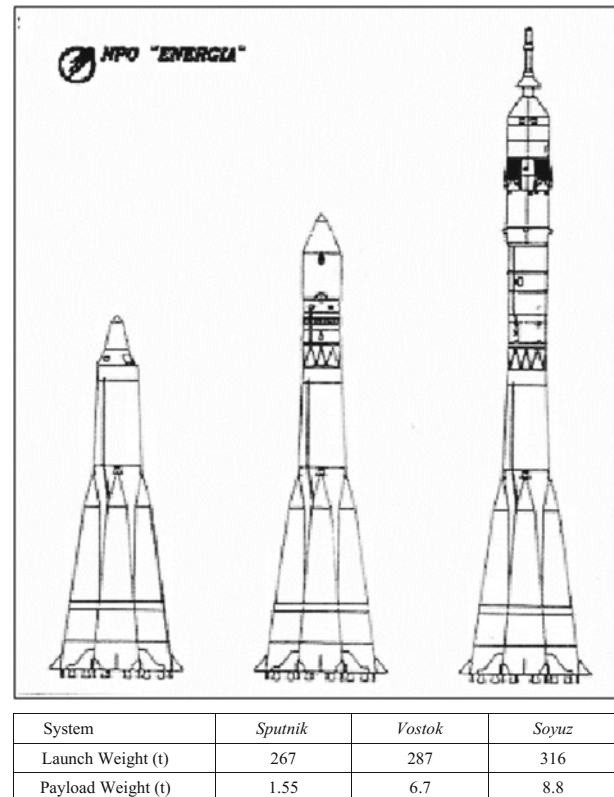


Fig. 2.7 The conventional path for launcher development is the adaptation of a military ballistic missile (SS-6 “Sapwood”) to a space launcher. “Sputnik” is an almost unmodified SS-6. “Soyuz” is a very capable, very reliable space launcher with hundreds of launches (over 90 per year)

The McDonnell Douglas Delta launcher began its career as the US Air Force Thor IRBM. The Thor core continues to serve even now, as the Boeing Delta II and Delta III launchers. The Convair Atlas launcher began as the USAF Atlas ICBM and was the launcher that puts the US astronaut John Glenn into the first Earth orbit in the Mercury capsule. The Atlas system keeps on living today, powered by the Russian-derived RD-170 rocket engines, as the Atlas V. Even in Europe, the ESA launchers have an industrial rocket hardware baseline approach to build on military-derived (e.g., the Vega) launching systems.

In fact, in order to begin, this was about the only alternative in existence. What it did, though, was to instill the operational concept of the expendable system as the most cost-effective approach, and with its low launch rate, to assure a continuing manufacturing base. Consider, for instance, the consequences if the first launchers were capable of just 10 launches before overhaul. In the early years, that might have meant only one or two launchers being fabricated, instead of 20. In comparison, the aircraft scenario was different because there were customers for all of the DC-3s that could be built, and literally hundreds of thousands of

potential and actual passengers. For space activities to change toward a dynamic infrastructure, a similar customer base has to develop requiring hundreds of flights per year, rather than 8–12.

In this context, the former USSR came closest. When one of the authors (P.A. Czysz) visited Baikonur in 1990, the civilian Soyuz launch complex had launched 90 Soyuz in the previous one-year period. The launch and countdown was based on a military counterstrike philosophy. There were about seven Soyuz and Soyuz payload combinations in active storage. These could be launched in about 12 h. On the day the author witnessed a Soyuz launch, the Soyuz arrived, transported horizontally on a train, at about 05:30 h. By 07:00 h, the Progress spacecraft (Progress is a Soyuz manned capsule reconfigured as a propellant and materials resupply vehicle) was horizontally integrated into the Soyuz launcher. It was then taken by rail to the launch site and erected. After 10:00 h, the propellant loading and countdown of the Soyuz launcher was executed by a neural network system of computers. The computer system “remembered” the Soyuz launch history over its several hundred launches. If any feature in the countdown matched a previous problem or potential problem, a service crew was sent to the launch pad to check the launcher. During this checking time, the countdown continued with only the item in question on hold. When the item status was confirmed as *ok*, that item was reinserted into the count. According to the Soviet launching officer on site, only 1 in 14 launches have had holds past the scheduled launch time for more than 15 min. During the visit, the Soyuz and Progress capsule was launched at 17:05 h that afternoon, see Fig. 2.8. In spite of the accomplishments of the Soyuz program, it remains until today an expendable launcher (Karashtin et al. 1990).

The heaviest lift launcher available in the former USSR was the Proton. The Proton was the result of an uncompleted

intercontinental ballistic missile program. The Proton is powered by a hypergolic propellant rocket engine, the RD-253, in a unique arrangement. That is, a central larger diameter oxidizer tank is surrounded by six smaller fuel tanks, each with an RD-253 engine installed, as shown in Fig. 2.9. The hypergolic propellant-driven turbopumps start up so abruptly, that the sound is almost like an explosion! The launcher is one of the more reliable launchers available for heavier payloads, but like Soyuz, it is completely expendable. The Proton continues to be produced today, being offered as a reliable heavy-lift launcher by a consortium that includes Lockheed Martin. It was an important element in the construction of the International Space Station (ISS).

The Russian space organization wanted a launcher that was recoverable, that was reusable, and that was capable of heavy lift to orbit for a spectrum of missions, going from the support of facilities in LEO to deep-space missions (Gubonov 1984, 1988). With the USA initiation of the “Star Wars” space defense program (SDIO) and the Space Shuttle (STS), the Soviet military was convinced and they needed to counter a new military threat. They perceived (correctly) “Star Wars” as a system to destroy their warheads and warhead delivery systems. But they also perceived the Space Shuttle program as a disguise to create a direct-attack fractional orbit “space bomber.” This perception would merge into what was to eventually produce the fully reusable heavy-lift vehicle Energia and the fully automatic military space plane Buran. By whatever method of calculation, the Soviets concluded that the Space Shuttle initiative was sufficiently important to build seven vehicles (Legostayev 1984). After NASA fielded the three operational shuttles, the Soviets were convinced that “the missing four” were hidden someplace, ready to launch at the Soviet Union in a manner similar to the ICBMs in missile silos (Lozino-Lozinskiy 1989). In fact, strange as it may seem, it was reported that

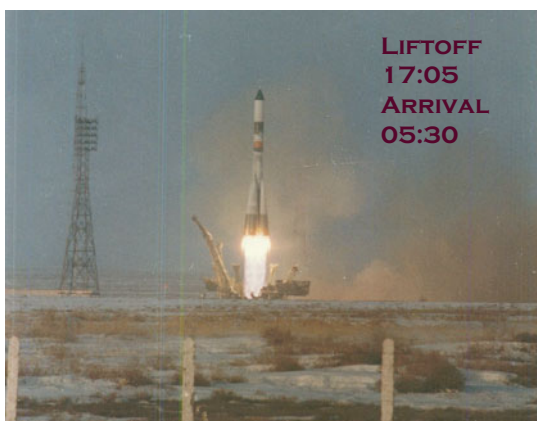


Fig. 2.8 Soyuz launch with Progress resupply capsule at 17:05 h in April 1991 from Baikonur Space Center, Tyuratam, Kazakhstan (photographed by the author P.A. Czysz)

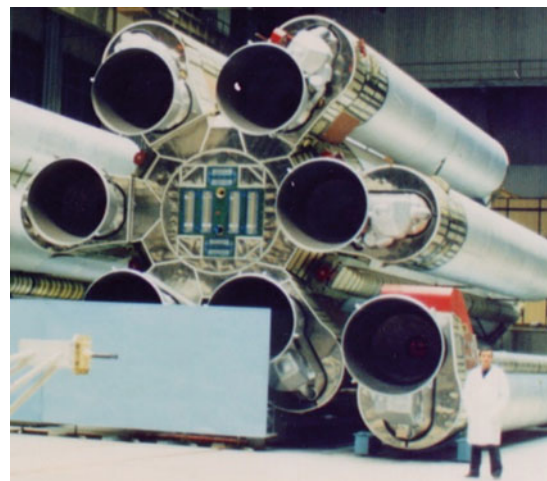


Fig. 2.9 Proton first stage in Moscow plant

just seven Buran airframes were fabricated, in a tit-for-tat response to the US shuttle program (Lozino-Lozinskiy 1990). The Buran glider was derived from Lozino-Lozinskiy's work on the BOR series of hypersonic gliders that began in the 1960s, analogous to the USAF Flight Dynamics Laboratory (FDL) efforts (Draper et al. 1971). According to Lozino-Lozinskiy, he had launched at least 24 test vehicles of the BOR family using scrapped ballistic missile stages (Lukashevich and Afanasiev 2009). The USAF Flight Dynamics Laboratory had launched several ASSET hypersonic glider test vehicles in the 1960s, but that has been the limit of the US flight experience (Draper and Sieron 1991; Hallion 2005).

The result of these Russian efforts was Energia, a heavy launcher capable of launching either cargo or a spacecraft (Buran) to space that was fully recoverable in its operational form. In its principal operational version, Energia was equipped with a side-mounted cylindrical cargo carrier that could be configured as a heavy-lift package to LEO, or a satellite package to GSO, a payload to be delivered to the Moon or Mars, and a deep space probe. Unlike the US Space Shuttle, the primary propulsion engines were all mounted on the center main tank, not on the Buran space plane itself. Because of the emphasis on astronauts, the US Space Shuttle evolved into a design that could never be flown without astronauts: the Space Shuttle had no heavy-lift canister or heavy-lift capability.

One of these authors (P.A. Czysz) drew the Energia concept of operation scenarios, see Fig. 2.10, during a lengthy discussion with Boris Gubanov at the IAC conference in 1984 (Gubanov 1984). There were few disposable parts. The side canister could be configured with just

sufficient propulsion to reach LEO, or with sufficient propulsion (and less payload) for a Moon, Mars, or deep-space mission. The Zenit-based strap-on boosters were equipped with lifting parasail parachutes at the front and rear of the booster. The intent was to glide in the vicinity of the launch site for recovery. Since the boosters were liquid boosters equipped with NPO Energomash RD-180 rocket engines, there was little refurbishment required unlike the US solid propellant strap-on boosters on the Shuttle. These cost as much to refurbish as to build new. The Buran center tank has a very low ballistic coefficient, and using a Lockheed concept to reduce the heating with the thermal and antistatic coating applied to the booster, the entry into the atmosphere could be relatively easy. The center tank did a fractional orbit and was recovered in the vicinity of the launch site. Although never implemented in the first two test flights, the eventual operational capability planned was to recover all major components.

Said otherwise, Energia was to be the USSR's fully recoverable Saturn V equivalent. The booster configurations on the right side of Fig. 2.10 show the payload to LEO for the different strap-on booster configurations. For the four-pair configuration, the payload was carried in tandem with the center tank in a special powered stage. For the two-pair configuration, two payloads are shown, the canister and the Buran. The Energia M was a two strap-on booster arrangement for a lesser payload. The author (P.A. Czysz) saw Energia M in the Energia assembly building in 1990 (there is no reported flight of this version). Note the intended fly rate from three launch complexes: 1800 flights in 20 years, for an annual fly rate of 90, about the same as from the Soyuz launch sites. If the cost is the same as for the US

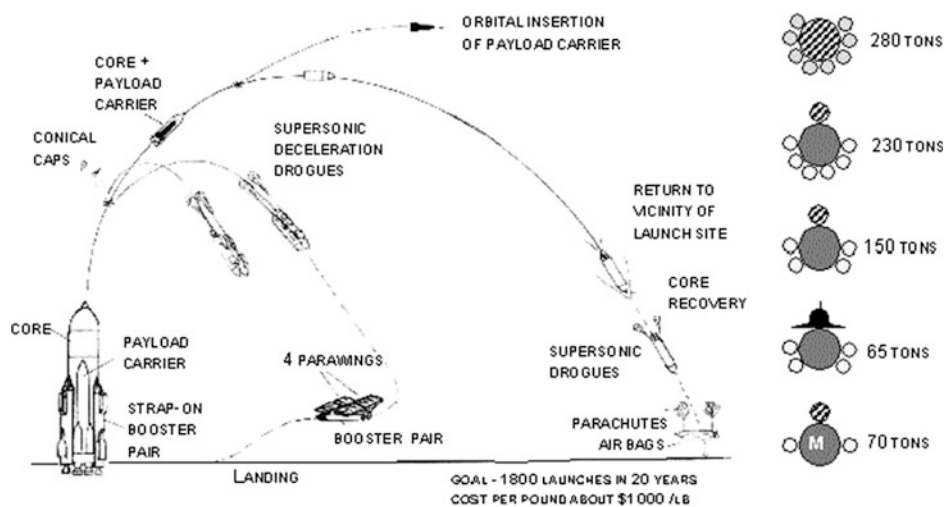


Fig. 2.10 Energia was an approach to achieve a fully reusable (all major components recoverable), extended-life launcher (at least 50 launches without overhaul) with an equivalent Saturn V heavy-lift capability that the USA discarded. The *right side* shows the strap-on

booster configurations and payload to LEO. Energia M was developed as the smallest design configuration as a Proton rocket replacement, but lost the 1993 competition to the Angara rocket

Space Shuttle, US\$1.32 billion for five flights and US\$100 million for each additional flight, then with a mix of Buran and canister payloads, the payload cost to LEO ranges between US\$450 and 650 per payload pound. Clearly, frequent flights of cargo-configured vehicles lower costs: the Energia would have been a wise investment. The Russians thought very highly of the Saturn V, but they were dismayed that the USA would summarily discard the Saturn V heavy-lift vehicle capable of lower cost to orbit (about \$US5700 per pound payload in the 1980s) compared with the Space Shuttle.

The Energia had several launch configurations to optimize different size payloads for different orbits. The Zenit-derived (SS-16 missile) strap-on boosters were assembled together in pairs. The standard configuration was two coupled pairs, for a total of four individual strap-on boosters. In this configuration, the Energia could deliver 150 t to LEO in the cargo canister configuration and 60–70 t when carrying Buran. With three Zenit pairs, Energia could place 230 t in LEO with the side-mounted cargo canister. If an in-line cargo section was added to the center tank in lieu of the side-mounted canister, overall increasing the payload to 280 t that could be delivered to LEO, such payload capability would be an astonishing figure nowadays (the US Space Shuttle could only deliver less than 4% of this payload to LEO, and NASA's under construction SLS Block I capability is 70 t). It was this latter configuration that was the counter-*Star Wars* configuration.

Figure 2.11 shows a model of Energia (left) from an AIAA technical meeting display, with the side cargo canister mounted. Clearly visible is the forward and aft parachute

packs on each strap-on booster. Utilizing the Zenit launcher as the strap-on booster meant that this part of the system was already a reliable component of the operational launch system. On the right is a night picture of Energia with Buran mounted and being prepared for launch (Gubanov 1998). The gray horizontal cylindrical tube is the crew access to Buran. The angled tube is an escape path to an underground bunker, in the event of a launch mishap. The two horizontal tubes in the lower part of the figure represent ducting that leads to the rocket exhaust chute under the vehicle. These are attached to eight vacuum cylinders on each side, equipped with compressors and a vent stack. When the hydrogen flow is initiated to the rocket engines, this system is opened and any vented hydrogen is drawn off, compressed, and burned in a vent stack.

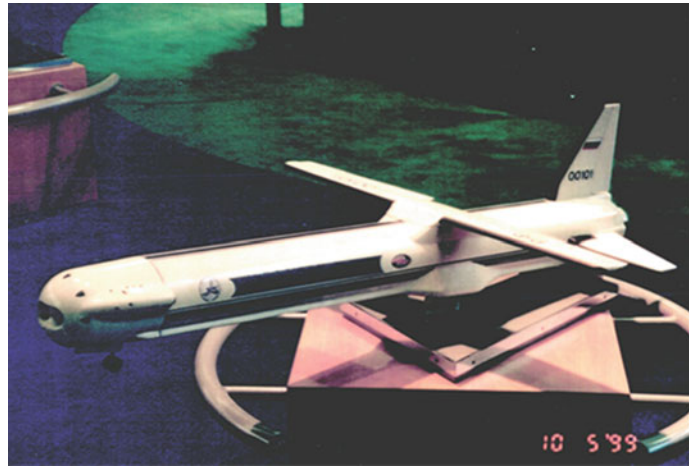
The original plan was to construct three launch sites in close proximity, so that nine Energia/Buran and Energia/canister configured vehicles could be launched within three days in case of a Space Shuttle Star Wars attack. None of this was ever accomplished. The Russian space organization wanted also to replace Proton with a reusable vehicle. When one of the authors (P.A. Czysz) visited Baikonur in 1989, there was an Energia M being assembled consisting of only two Zenit strap-on boosters instead of four. It was their intent to make this the medium-lift launcher Proton replacement. With the side payload placement, Energia M could accommodate a payload canister or a smaller hypersonic glider, such as a crew rescue vehicle based on the BOR vehicles.

Figure 2.12 shows a modification to the Zenit strap-on booster, incorporating a skewed-axis wing (instead of four sets of lifting parachutes) and a turbojet with a nose inlet in

Fig. 2.11 A model of the Energia showing the strap-on booster parachute packs and cylindrical payload container (left) and the Buran space plane on the Baikonur launch complex (right). The RD-0120 engines are on the center tank, which is recoverable



Fig. 2.12 Fly-back version of the Zenit strap-on booster as an alternative to lifting parafoils



the front of the booster for a powered return. This arrangement was shown at an American Institute of Aeronautics and Astronautics technical meeting in 1992 and has been retained in the reusable Baikal flyback booster for the Russian Angara family of modular launchers. Baikal has foldable wings and is powered by a turbojet with a nose air inlet that is faired during ascent and part of the reentry.

For readers who may wonder, the Buran arrangement is not a US Space Shuttle, or a copy of it. The Buran's intent was very different. P.A. Czysz visited the Buran assembly building at Baikonur in 1989. The glide angle-of-attack for maximum lift-to-drag ratio is 10° – 15° less compared to the US Space Shuttle glide angle-of-attack. Buran is a fully automatic vehicle with a neural network-based control system. It landed for the first, last, and only time at the specially constructed runway at Baikonur without any human intervention. This took place during a snowfall and with significant 90° crosswind; it touched down within a few meters of the planned touchdown site (Buran Site Director 1989). As with all Soviet spacecraft, it was never intended to be controlled by a human pilot, except in a dire emergency. Its thermal protection system was (and still remains) unique due to its ability to handle lost surface tiles without risking damage to the airframe structure (Neyland 1988).

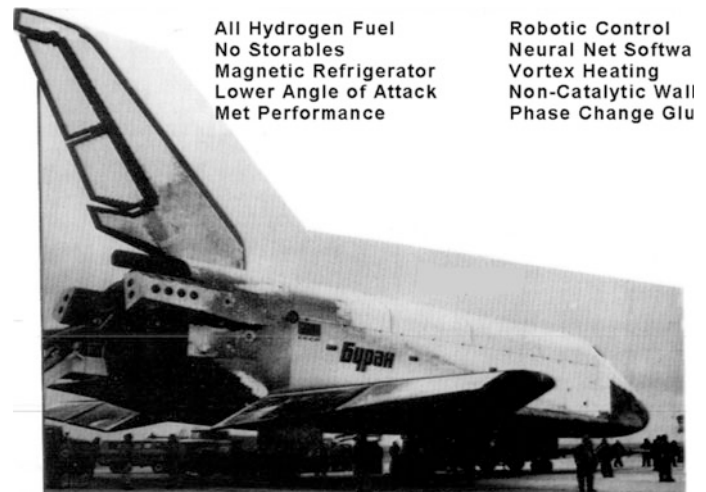
The manoeuver Buran reportedly performed during landing was much discussed in a 2002 article in *Air and Space*, but it was not a poorly executed automatic landing; in fact, it was strictly the result of the neural network flight-control computer decision. The computer was developed by the USSR Academy of Sciences, Siberian Branch, in Krasnoyarsk in the 1980s (Bartsev and Okhonin 1989) and built by a company in the Ukraine. The flight-control system had determined that during the entry, the actual lift-to-drag ratio (L/D) had exceeded the estimates used in the preplanned flight trajectory. As a result, the aerodynamic heating encountered by Buran during reentry would have been larger than expected due to the trim control surfaces deflections

required at this modified L/D trim point. In order to avoid this flight point, Buran entered the approach pattern much faster than anticipated. If Buran was to land successfully, the excess speed had to be bled off. The neural network controller executed, without any input from ground control, a 540° turn rather than the initially planned 180° turn, thereby bleeding off the excess speed (Lozino-Lozinskiy 1990). As a consequence, Buran touched down at the planned landing point with the correct speed (Hendrickx and Vis 2007).

Figure 2.13 is a photograph taken from the Buran display in the Memorial Museum of Cosmonautics in Moscow. It shows conclusively that Buran is more closely related to the USAF Flight Dynamics Laboratory (FDL) hypersonic glider designs than to the Space Shuttle. In order for the leading edge vortex (a main source of lift) not to burst, the angle-of-attack would have been limited to the 25° – 30° angle-of-attack range, not the 40° – 45° operated with the Space Shuttle during the early reentry phase, a design approach causing stability and control challenges for the US design. In many aspects this is a very revealing photograph, as it documents the similarity of Buran with the high-performance (low-entry angle-of-attack) military hypersonic gliders that Draper, Buck, Goetsch, Dahlem, Neumann, Melvin and Sieron developed at the Flight Dynamics Laboratory (FDL) in the 1960s (Kirckham et al. 1975).

The burn marks on the visible right-wing elevon, see Fig. 2.13, indicate that its deflections during the entry portion of the flight were larger than anticipated, resulting in more severe heating exposure. Additional pictures in the Memorial Museum of Cosmonautics in Moscow show the underside of Buran after the flight; there are white streaks emanating from the gaps in the tiles. This indicates that the tile/aluminum interface temperature would have exceeded 100°C had not the tile adhesive/phase-change material been present and active. This Russian adhesive incorporated a phase-change material that, in the event a tile was damaged

Fig. 2.13 Buran after landing on its first, last, and only flight. Note the trace of vortex heating emanating from the junction of wing and fuselage (apex). This matches the thermal mapping test at TsAGI and proves that the angle-of-attack was sufficiently low to prevent vortex bursting as it does on the Space Shuttle. The burned spot on the inboard elevon is the vortex core location



or lost, was capable of maintaining the interface with the aluminum structure at no more than 100 °C for several minutes at peak heating conditions, thereby preventing thermal damage. The intentional gaps with plastic spacers in the tiles permitted the vapor from the phase-change material to escape (they, as well, were mounted with a unique adhesive that acted as a thermal safety layer). V.Y. Neyland, one-time Deputy Director of the oldest Russian gasdynamic center TsAGI (founded in 1918) tested this strategy in one of the TsAGI wind tunnels, and one of these authors (B. Chudoba) has a copy of the data report (Neyland 1988). The thermal protection employed by the Buran was structurally robust in contrast to the brittle Space Shuttle tiles. During a 1989 visit to Russian research institutes, at the Komposit OKB, the author (P.A. Czysz) saw a Buran tile heated to white heat with an oxyhydrogen torch and then dropped into water, with no structurally visible damage to the tile.

Then, at the beginning of 1990, Russia had the hardware in test for a family of fully recoverable and reusable rocket-powered vehicles for medium and heavy lift. Despite such knowledge and capability accumulation, by the beginning of the twenty-first century, neither the USA nor Russia has an operational heavy-lift launcher on the order of the Saturn V (140 t payload to LEO). The Space Shuttle was limited to about 27.5 t payload to LEO with the Proton offering in excess of 100 t payload to LEO until its retirement in 1988. Thus, with both the US Saturn V discarded in lieu of the 2011 retired Space Shuttle and the demise of the Energia, there is no affordable heavy-lift launcher available to either the USA or Russia since the last 25 years. In the USA, the SLS, under development with engines derived from Saturn and the Space Shuttle, is promising a payload to LEO range of 70–130 t (for Block II). Its first flight is envisioned no sooner than November 2018 (Anon 2015).

2.5 Conflicts Between Expendable Rockets and Reusable Airbreathers

The fundamental question always posed is: “*Why airbreathers?*” One observation is that in-orbit specific energy (energy/mass) is a function of speed squared.

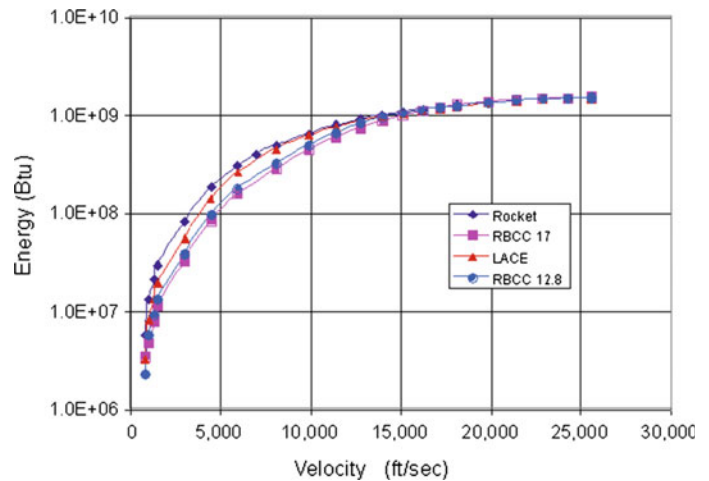
$$h_s = \frac{m \cdot g \cdot h + \frac{1}{2} \cdot m \cdot V^2}{W} \quad (2.1a)$$

$$h_s = \underbrace{h}_{\text{Potential energy}} + \underbrace{\frac{V^2}{2 \cdot g}}_{\text{Kinetic energy}} \quad (2.1b)$$

In Eq. (2.1a), W stands for mass. Then, if an airbreather reaches 12,000 ft/s rather than orbital speed of 25,573 ft/s, it achieves only 22% of the orbital energy. Using *specific energy*, this is correct. However, the launcher is much heavier at launch compared when entering orbit. Consequently, the *total energy* spent (Btu or MJ) is a very different value. Figure 2.14 shows the total energy for launch vehicles with four different propulsion systems and I_{sp} . The value of total energy at 12,000 ft/s (3658 m/s) is 70% of the orbital value, a much more significant value. Note also that all of the different propulsion system curves plateau to a single total energy value above 15,000 ft/s (4572 m/s) for an energy level of 10^9 Btu (1.055×10^9 kJ). The energy does not continuously increase with the square of the velocity, because the rocket engines are consuming the mass almost as fast as the specific energy is increasing.

However, as consistent as the energy levels are, the weight (mass) levels are not. Figure 2.15 shows the weight (mass) along the trajectory is a unique characteristic of each propulsion system. The weight-time history during the

Fig. 2.14 As velocity increases, total vehicle energy approaches a plateau. Mass is being spent as fast as kinetic energy is increasing for all propulsion systems



ascent to orbit is given for four different propulsion systems as a linear function of the logarithm of the flight path energy. All have essentially the same on-orbit weight; note that a correctly selected propulsion system has little impact on the vehicle empty weight. For the three airbreathing concepts, once the “all-rocket” propulsion-stage is reached, the weight histories are essentially identical. Even simple airbreathing rockets like the LACE (Liquid Air Cycle Engine) or deeply cooled rocket that operates only to Mach 5 or 6 result in a substantial reduction in liftoff weight. In fact, increasing the airbreathing speed to Mach 17 from Mach 12 has much less impact compared to moving from Mach 6 to Mach 12. As shown, the propulsion system directly affects the oxidizer-to-fuel ratio at the beginning of the flight, when the thrust required is the greatest. Clearly, a reduction in the oxidizer-to-fuel ratio has the greatest effect, as the liftoff weights on the left-hand ordinate show in Fig. 2.15.

As developed in this chapter, system studies with what appear to be rational assumptions, such as turbojet low-speed propulsion or a combination of engines, doom the airbreathing launcher from its inception. In contrast, a combined-cycle propulsion system in which a single propulsion system can transition from one mode to another is the key to the success of the airbreathing launcher. As implied by Fig. 1.1 in Chap. 1, a multitude of design, build and test efforts have been chronicled from the past to the present, aimed at building an aircraft-like hypersonic vehicle that could fly to space and return. (Anon 1967; Hannigan 1994). However, as many valid programs that were initiated, there were as many programs seeking to discredit the airbreathing vehicle efforts.

Figures 2.16 and 2.17 show one such example of the conflict as presented in a briefing in the 1970s. The three aircraft shown in Fig. 2.16 are, from top to bottom: (a) an

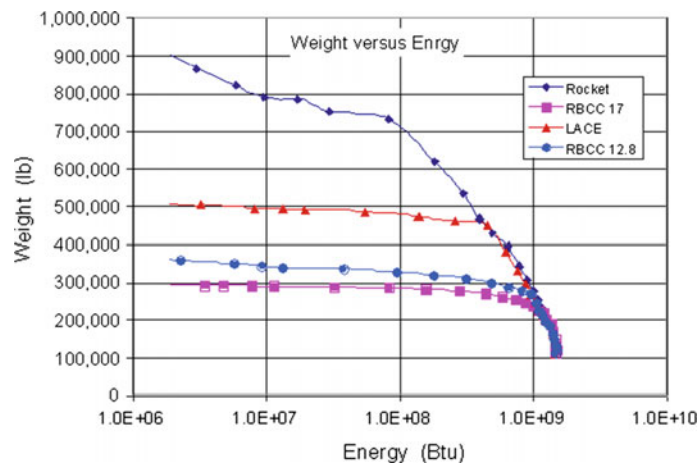


Fig. 2.15 The mass or weight history shows the differentiation of the propulsion systems in terms of initial (liftoff) weight and the convergence to a single on-orbit value

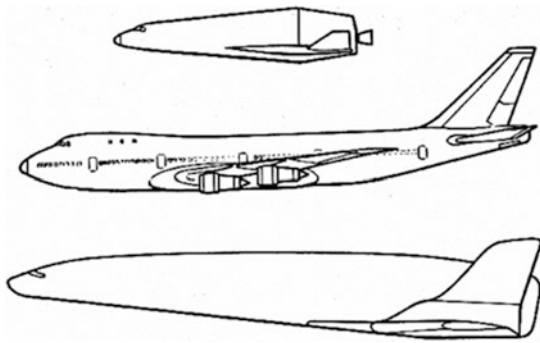


Fig. 2.16 Rocket advocate's vision of launchers that fly regularly to space. The all-rocket SSTO launcher (*top*) is smaller but heavier than the B747 (*center*). The airbreather launcher powered by a combination of 35 engines of four different types (*bottom*) is larger and heavier than the B747, discouraging the airbreather concept

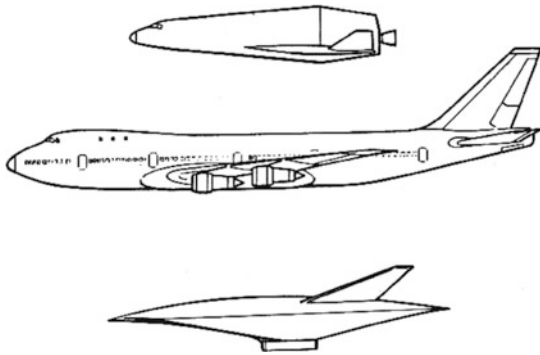


Fig. 2.17 A balanced vision of launchers that fly regularly to space. The all-rocket SSTO launcher (*top*) is smaller than the B747 (*center*). The airbreather launcher powered by a combined-cycle ejector ramjet/scramjet (*bottom*) is smaller and lighter than both, but is never been pursued as a launcher or hypersonic cruiser

all-rocket single-stage-to-orbit (SSTO) launcher, (b) a Boeing B747-100, and (c) an airbreather/rocket SSTO powered by a combination of 35 turbojet, ramjet, scramjet, and rocket engines. Such accumulation of nonintegrated individual propulsion systems does result in a clear weight penalty, since 3/4 of the installed propulsion systems are being carried as dead weight. As correctly depicted in Fig. 2.16, a very large airbreathing/rocket SSTO is the outcome because of the inert weight carried as nonoperating engines. Note that the turbojet is a very poor acceleration propulsion system that can consume more fuel compared to a rocket in some flight regimes. For many in the aerospace design community, this was a legitimate comparison considering the low launch rate of rocket launchers, the nonexistence of a viable civil need to increase the launch rate, and, for the rocket advocate, the absence of a good reason to replace the rocket.

However, the advocates of an integrated combined-cycle airbreathing/rocket SSTO have been proposing a very

different system based on the integration of several different engines into a weight and volume optimized single combined propulsion system. The combined-cycle propulsion system can recover rejected heat and convert most of the recovered heat into thrust or system work. The three aircraft depicted in Fig. 2.17 are from top to bottom: (a) the all-rocket single-stage-to-orbit (SSTO) launcher, (b) the Boeing B747-100, and (c) an integrated combined-cycle airbreather/rocket SSTO vehicle. This not only saves energy, but also reduces entropy formation and drag.

The integrated combined-cycle airbreather/rocket SSTO aircraft depicted is from McDonnell Douglas Corporation, McDonnell Aircraft Company, St. Louis, Missouri, as presented by the USAF Flight Dynamics Laboratory (AFFDL). The combined-cycle propulsion system is integrated, thermally and physically, into one synergistic system. Then, the rocket, ramjet, and scramjet represent one and only one integrated propulsion system. The result is a vehicle with slightly less volume and empty weight than the all-rocket vehicle but about one-third its gross weight. The airframe and propulsion system had been designed for at least 100 flights before overhaul. At the flight rate anticipated in 1968, such operational requirement was sufficient for 8- to 10-year operation with commercial aircraft-type inspection and maintenance.

At the time, the perception has been that the simpler and increasingly reliable rocket was the least costly for the low launch rate required. A “catch-22” situation emerged since the launch rate could not be increased because of the selection of the rocket launcher as the primary space launcher system. With such presumption, the payloads that required a high launch rate never appeared, therefore self-justifying the rocket launcher selection. As a consequence, the expendable rocket launchers prevailed, and none of the integrated hypersonic airbreathing engine-airframe systems of the late 1950s and early 1960s were ever realized. Historically, much of the work done on these vehicles was for highly classified military programs with very limited access to information. It is a sad reality that most of this documentation is now shredded, lost, and forgotten. References (such as Stephens 1965; Anon 1966a, b; Brewer 1966) are the program references that document a small portion of what was accomplished.

The other great debate was single-stage-to-orbit (SSTO) versus two-stage-to-orbit (TSTO). Both have advantages and disadvantages depending on operational concept and geographical location. It is the operational requirement (mission, in military terms) that makes the decision. For the support of an orbital station, as discussed in Chap. 3, with a very specific payload requirement and specific launch sites to a given orbital inclination and altitude, a SSTO makes a good minimum operational equipment choice. If the operational mission is to deliver both crew and crew supplies in addition

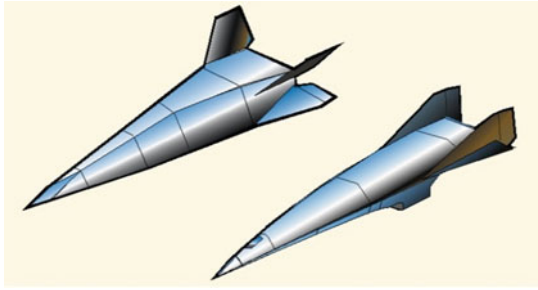


Fig. 2.18 Airbreather/rocket-derived hypersonic glider single-stage-to-orbit (SSTO) configuration (*left*), and airframe-integrated rocket ramjet/scramjet combined-cycle single-stage-to-orbit (SSTO) configuration (*right*)

to large orbital payloads from different launch sites for different orbital inclinations and altitudes, then the TSTO offers a wider range of options and versatility. Figure 2.18 shows two SSTO configurations. The left configuration is an airbreathing-rocket propulsion system integrated into a hypersonic glider. The right configuration represents an airframe-integrated rocket ramjet/scramjet combined-cycle airbreathing propulsion system. Nominally, these are in the 7–10 metric ton internal payload class. Chapter 3 provides a discussion of the rocket propulsion hypersonic glider that was proposed in 1964 to support the Manned Orbiting Laboratory (MOL) with a 7 t crew or supplies payload. Except for the vehicle configuration, the overall concept was analogous to the Russian Soyuz-Progress capsule. Although many concepts were analyzed and designed, these concepts were not able to dislodge the expendable rocket as the dominating configuration concept for *any* mission role (due to the “catch-22” phenomenon discussed before).

For operational missions that deliver both crew and crew supplies, in addition to large orbital payloads from different launch sites for different orbital inclinations and altitudes, the TSTO offers a wide range of versatility. As shown in Fig. 2.19, there are two TSTO concepts and these have rocket-powered hypersonic gliders for second stages. Just as is shown for Energia in Fig. 2.10, a faired payload canister can be substituted for the hypersonic glider. If the nominal payload of the second stage returnable hypersonic glider is 7 metric tons, then the payload for the expendable canister second stage could be as large as 23 metric tons or a space station component approaching 28 metric tons. Then, the payload capability to orbit spans a 4:1 range.

With the flying capability of an airbreathing propulsion first stage, considerable offset is available to reach a latitude different from that of the launch site or to expand the launch window by flying either east or west to intercept the orbital launch plane. With this versatility to provide launch capability to different sites worldwide, the TSTO makes an excellent choice for a commercial space launcher. Note that

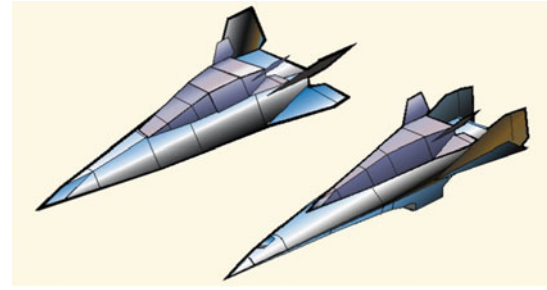


Fig. 2.19 Airbreather/rocket-derived hypersonic glider two-stage-to-orbit (TSTO) configuration with all-rocket second stage (*left*), and airframe-integrated rocket ramjet/scramjet combined-cycle two-stage-to-orbit (TSTO) configuration with all-rocket second stage (*right*)

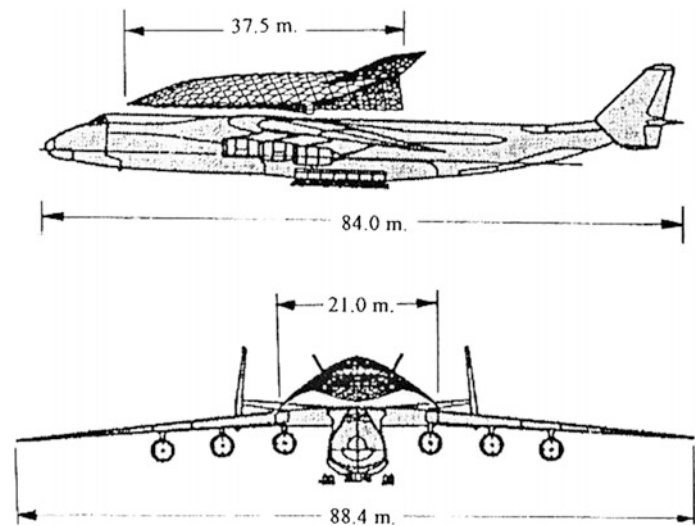
the upper stage can have either a pointed nose or the spatular two-dimensional nose. The latter reduces the nose shock wave drag by as much as 40% (Pike 1977) and enables increasing vehicle volume without altering substantially aerodynamic characteristics. Pike began his work on minimum drag bodies in the mid-1960s. The spatular nose can be used on almost any hypersonic configuration, whether the SSTO or TSTO, whether a first stage or second stage.

Even though some excellent designs have originated in Germany, France, Russia, and the USA based on available hardware and existing industry capability with sufficient performance to LEO, none were ever able to dislodge the expendable rocket status quo. The launchers remained as they began, as ballistic missiles.

The hypersonic first stage can require more runway than what is available at airports worldwide. V. Plokhikh and the late Lozino-Lozinskiy proposed a TSTO based on the transonic Antonov An-225, an An-125 large cargo aircraft modified to carry a space launcher atop the fuselage (Plokhikh 1983). The NPO Molniya began to realize the MAKS (multipurpose aerospace system) project in the 1980s. The second stage can weigh up to 300 t. In this case, the fuselage of the An-225 can carry a portion of the launch crew and equipment. A second An-225 has sufficient volume to carry the liquid hydrogen required for the space launcher. In this case, the An-225 is more of a mobile launch platform than a first stage. With the range of the An-225, and the low-noise operation of the six turbofans that power it, the An-225 can make almost any commercial international airport a launch site.

Figure 2.20 shows the An-225 with a combined-cycle ramjet/scramjet-powered waverider mounted on top. The payload capability of the second-stage launcher is 7 t. This particular approach has the An-225 operating on hydrogen fuel and is equipped with an air collection and enrichment system in the cargo hold. That is, the hydrogen that is used to power the engines liquefies air and then separates the oxygen and nitrogen. The oxygen is liquefied and pumped into the launcher oxidizer tank (the launcher has no liquid

Fig. 2.20 Large transonic transport-based TSTO configuration with a combined-cycle powered waverider second stage



oxygen in its oxidizer tank at takeoff, only the liquid hydrogen tank is filled). This means that the two aircraft are heaviest not on takeoff but near the launcher separation point (Czysz and Little 1993). A LACE, deeply cooled air-breathing rocket, or the original HOTOL airbreathing rocket engine (RB545) would have provided a successful solution, see Chap. 4.

The use of the An-225 as a mobile launch platform is indeed a very practical commercialization concept for both space tourism (Mach 4 and 100 km altitude) and for a commercial point-to-point cargo delivery system (12,000 nmi in 90 min) as it eliminates noisy rocket launchers, provides an independent heading and altitude launch, and makes any commercial airport a potential launch point. This “Flying Circus” concept brings the launcher to the customer for a worldwide launch service for any country wishing to put a payload into orbit, send cargo to another point on Earth, or launch citizens on a tourist flight from their own country, not from the geographic location of possibly a foreign dedicated launch site. In the USA, Paul Allen’s Scaled Composites Model 351 Stratolaunch or “Roc” is a

similar concept currently under construction, see Fig. 2.21. Contrary to the An-225 carrier aircraft for HOTOL, the carrier airplane is being built from scratch. Powered by six turbofan engines, the carrier lifts the rocket second stage slung under the central wing section to a still unspecified “high altitude”, where it is released and reaches orbit. According to press releases, the maximum take-off weight will be 1.3 million pounds, probably requiring a specially built runway. The Stratolaunch has been rolled out of its hanger for the first time on June 01, 2017. First flight is scheduled in late 2017, and first second-stage launch is planned for 2018 with commercial flights to be expected in the 2019 timeframe.

Steve Wurst of Space Access LLC, a RLV start-up, recovered some of the historic hardware from the “bone-yard” of The Marquardt Company, as its property was being sold in bankruptcy. Steve transformed hardware elements into a modern combined-cycle access to space launcher concept on private financing. As discussed before, reusable access to space launcher concepts did not fit the preconceived concepts of the government at the time and, short of

Fig. 2.21 Artist’s rendition of Scaled Composites Model 351 for Stratolaunch Systems (Courtesy NASA). The design wingspan is 385 ft



Fig. 2.22 Result is that the possibilities were never developed and impediments were sufficient to prevent any further hardware development of a truly sustained-use space launcher

DISTANCE MILESTONES = PROPULSION CHALLENGES			
EARTH-ORBIT LAUNCHERS	EARTH MOON	SOLAR SYSTEM	GALAXY
Commercialization Possible	Research and Exploration	Electro-magnetic exploration	
Commercialization limited by focus on expendable rockets derived from military ballistic missiles rather than sustained-use long-life, maintained vehicles analogous to commercial aircraft	Exploration limited by the reliance on chemical rockets and the avoidance of nuclear power to our Solar System. Limited to near Earth with solar-powered craft.		

turning the project into a government-sponsored program with government control, the project remained in the shadows. However, the overabundance of naysayers and skeptics, and the lack of dreamers continues to prevent the realization of a transportation system to space. Although reusing the first stage is being experimented with and operationally implemented by SpaceX (Falcon 9) and Blue Origin (New Shepard), the financial advantage of vertical-landing (VL) recovery by using pure rocket propulsion still must be demonstrated. For instance, the Falcon 9 flight that recovered the first stage lifted 22.3 t to LEO at the cost of \$62M, thus still in the many tens of K\$/kg. For the time being, we are still left with *Space Conestoga Wagons* and have yet to see the “railroad to space” evolve.

As indicated in Fig. 2.22, progress toward the future for both, Earth-based launchers and space exploration, appears to be impeded by the acceptance of the status quo. The key to breaking this stalemate is a propulsion system integrated into a sustained-use vehicle that can provide routine, frequent flights, and advance our space capabilities. The US X-planes proved that even high-speed research aircraft could be operated frequently and safely (Miller 2001), despite the need to air launch these aircraft from a modified B-50 in the early flight operations, and later from a modified B-52 (Lockett 2009).

Similarly, in space, nuclear propulsion is a vital necessity if we are ever to travel significant distances in practical times. Here, the mind-set is shaped by the fear of nuclear explosions in the atmosphere in case of accidents. Nuclear submarine reactors are reported to outlive the hull and are historically without nuclear accident. Accepting the disposable rocket, as today’s standard space access system, and despite some inroads made by electric thrusters, this situation prevents scientific and safe crewed missions to deep-space destinations, see Chap. 7.

The missing elements are the dreams, determination, and resources analogous to those that were committed to the building of the transcontinental railroad (Ambrose 2000). In

many respects, the challenges are less daunting although the environment is a great deal harsher nowadays. Note that we are not short of dreamers today, but we are lacking informed decision-makers due to outdated *future projects environment* tools, mind-sets, and overall poor design knowledge retention of past aerospace projects. Most hypersonic projects of the past were classified, thus the documentation necessary to dissipate skepticism tends to be unavailable. A modern generic design methodology, representing the foundation of a modern *Future Projects Office* capable of correctly advising the decision-maker, is introduced in Chap. 3.

2.6 Commercialization and Exploration Road Map

Incorporation of airbreathing offers many propulsion options. However, vehicle design choices are not arbitrary, since requirements and propulsion performance define the practical (technologically and commercially feasible) solution space. A priori assumptions and decisions can doom a complex project that without them would instead be successful.

2.6.1 Commercial Near-Earth Launchers Enable the First Step

One of the difficulties is the identification of the transportation need, and this at a time when there is an overabundance of expendable launchers that do not have the capability of high fly rates with the accompanying reduction of payload cost, per definition, see Fig. 3.1. This issue brings back the Conestoga wagon versus railroad comparison. Commerce with the western USA was never possible with the Conestoga wagons, as none ever returned since they were becoming building materials for the settlers instead. All of projections of future space business based on expendable

or limited reuse launchers are as valid as the business projections for the future railroad business based on Conestoga wagons in the early 1860s.

The late Dr. William Gaubatz, formerly of McDonnell Douglas Astronautics and manager of the Delta Clipper program, addressed this issue in his briefings on space development. Figure 2.23 represents our current status. Remember, however, that since Dr Gaubatz made his presentation, MIR has deorbited and crashed into the Pacific Ocean and the ISS has replaced it in 55° inclination orbit, followed by the retirement of the Space Shuttle after completion of ISS assembly in 2011. Expendable launchers can of course readily meet the military and commercial need, that is, suited to expendable launcher. Until a sustained-use launch system is operational, the payloads that warrant a high launch rate system will remain the subject of design studies only. In other words, without the railroad there will be no railroad-sized payloads for Conestoga wagons! The USA missed the opportunity to slightly modify the Space Shuttle main propellant tank to permit its use as a space structure, like the Saturn S-IVB. This could have been the starting point for building a space infrastructure (Taylor 2000). Note that the Space Shuttle main tank was intentionally not permitted to remain in Earth orbit and was deliberately crashed into the ocean.

For a true space transportation system to exist, a transportation system network has to be built, just as it was for the USA transcontinental railroad. Dr Gaubatz attempted to anticipate what the future might hold *if* an enabling space transportation system actually did exist. As shown in Fig. 2.24, the future space world envisioned becomes a crowded and busy place. Clearly, the availability of

cost-effective near-Earth space launchers will enable this first step. One of the key enabling space structures is the “fuel station spaceport” network. Without these fuel stations, movement between orbital planes and altitudes is limited to specific satellites, such a GSO communication satellites with integral GEO-transfer propulsion. Note the “construction module storage” that can supply components for orbital, lunar and deep-space vehicle assembly in space. The “operations center” and “space station” provide a system to launch and control missions to the Moon, planets, and deep space. The “power station warehouse” provides hardware for the “power satellites” in GEO-Earth orbit. That, coupled with an “orbital servicing vehicle,” can maintain this and other space resources. As seen earlier with the USSR space plan, there are “lunar spaceports” and “lunar orbiting satellites.” There are also “space deployment and retrieval vehicles” as well as a “waste storage and processing facility” in high orbit. Hence, Fig. 2.24 provides a very comprehensive projection of future space if a suitable *scheduled, frequent, sustained* transportation, and heavy-lift capability is available. That is what is needed to plan for the future, not the current status quo.

There is a first step that can be made in propulsion to anticipate the future much as Steve Wurst did with his proposal. The key first step is off-loading some of the carried oxidizer by utilizing even partially airbreathing rockets, and designing for sustained operations over a long operational life with normal maintenance, not continuous overhaul and rebuilding. The design space available with current industrial capabilities and materials is readily identifiable, see Chap. 3. A cross section of propulsion options that are based on available and demonstrated hardware and materials is

Fig. 2.23 Our current space infrastructure with MIR replaced by the ISS is limited to specific LEO and GSO without significant intra-orbit operations. Hubble is in the space-based warning orbit and is not shown

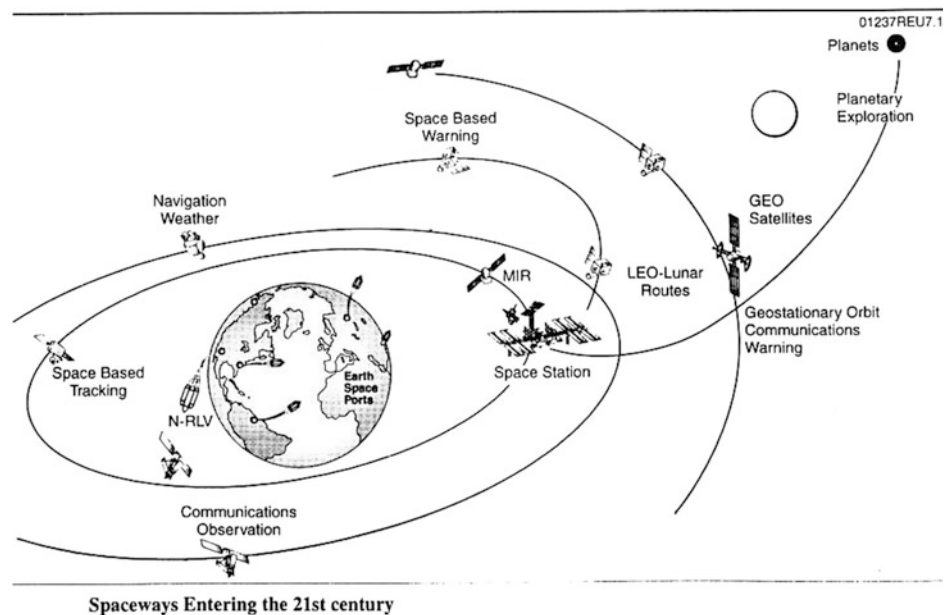
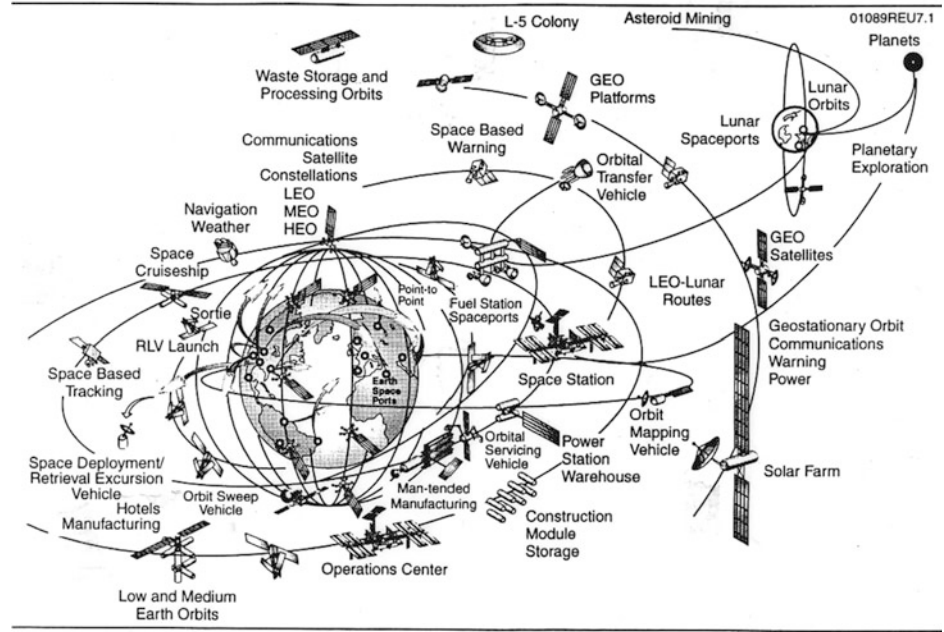


Fig. 2.24 One US look to the future space infrastructure that fully utilizes the space potential if a suitable *scheduled, frequent, sustained* transportation and heavy-lift capability is available



presented, and its pros and cons are discussed also in Chap. 3. The propulsion systems that are necessary to reach LEO are evaluated in Chap. 4 in terms of takeoff size and weight required for a specified payload.

For many decades the focus of the discussion has been, and rightly is, on the enabling space transportation system. As with the railroad analogy, emphasis has to be placed on an efficient two-way transportation system to and from LEO. The vehicle configurations discussed in what follows all have high hypersonic lift-to-drag (*L/D*) ratios. The reason for that is the corollary to the argument that if waiting times and launch delays are economically penalizing to commercial launch vehicles, the waiting times and return delays are also

economically penalizing. However, the way the continents and national boundaries are distributed on the surface of *Earth* means that a returning vehicle may have to wait until its landing site comes within the lateral range (cross-range) capability, that is, with *L/D*. Figure 2.25 shows the waiting time in terms of orbits, as functions of the spacecraft lateral range capability and orbital inclination.

This chart was salvaged from the original 1964 work done for the MOL support vehicle, the McDonnell Douglas Astronautics *Military Model 176*. For Cape Kennedy orbital inclination, the waiting times for an Apollo type ballistic capsule (with very limited lateral range capability) can be 14 orbits or about 21 h. For nominal lifting bodies like Sierra

Fig. 2.25 Waiting time is costly for commercial space operations. Greater lateral (cross) range reduces orbital waiting time

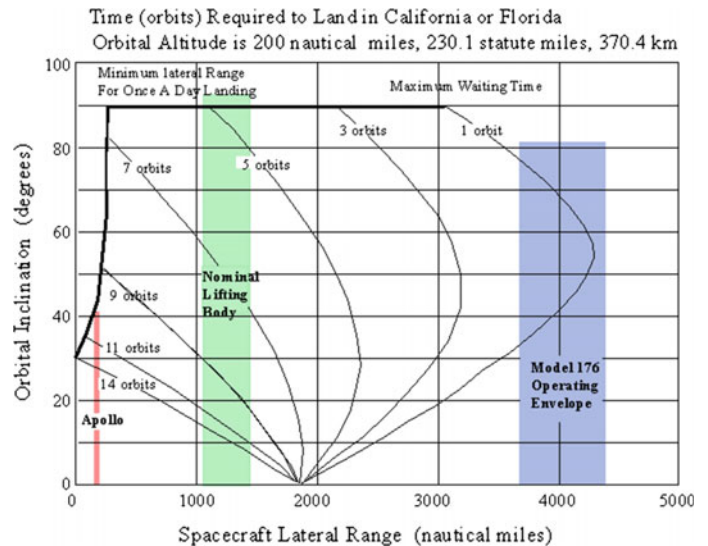


Table 2.1 Return from orbit performance is configuration dependent

<i>L/D</i> (-)	0.5	1.3	1.7	2.2	2.7	3.2
LR (nautical miles)	200	1080	1700	2600	3540	4470
DR (nautical miles)	5800	9900	12,900	17,100	21,600	25,900
Waiting time at 28.7° (orbits)	14	11	8	4	1	<1

Nevada Corporation’s *Dream Chaser* which is based on the Russian BOR and NASA’s HL-20 mid-performance lifting body (Hoey 1994; Thompson and Peebles 1999; Reed and Lister 1997), the wait times vary from 11 orbits or about 16.5 h to 8 orbits and about 12 h delay. The class of vehicles discussed in Chap. 3, in contrast, would have no wait times. They can return at any time, any location in the orbit they are in, and land in CONUS (Continental United States). The longest return would be if the spacecraft were directly overhead the landing site: the spacecraft would have to circumnavigate the *Earth* in space, that is, in one orbital period of about 1.5 h. The spacecraft hypersonic aerodynamic performance and its resultant glide performance are shown in Table 2.1 in terms of lateral range (LR) and down range (DR) together with the maximum waiting time.

The implication of commercial operational requirements is the need to be able to return to the landing site from any orbital location on the current orbit. That requires a high hypersonic lift-to-drag (*L/D*) ratio glider. The Space Shuttle orbiter had a hypersonic *L/D* of between 1.1 and 1.3, sufficient to land at its intended site after one missed orbit, or a 1500 nmi lateral range. The hypersonic *L/D* performance of the class of high-performing lifting bodies such as X-24B, FDL-7, and Model 176 has, as discussed in Chap. 3, hypersonic *L/D* values from 2.7 to 3.2, meaning they can land in CONUS from any position on a low Earth orbit (400 nautical miles or less). Reed shows on page 156 of (Reed and Lister 1997) the cross-range distances plotted against hypersonic *L/D* for several vehicles returning from orbit. He

does notice that the flat-bottom “race-horse” vehicles, such as the X-24B and Hyper III, have the greatest cross-range capability. An updated figure is presented in Fig. 2.26, showing the superiority of the FDL delta concepts and their derivatives (Model 176) in achieving the goal of no waiting in orbit. With the lateral range determined by the hypersonic *L/D* ratio, that is, the ability to turn (generate lift) with a minimum drag penalty, the significance of a sufficiently high hypersonic *L/D* is obvious for the return-from-orbit requirement. With the lateral range (cross-range) determined, the down range performance can now be established, that is, the glide range in a straight-ahead glide.

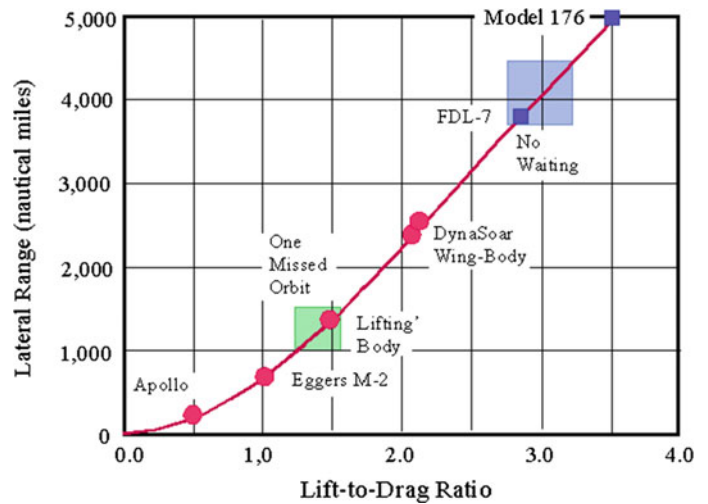
Hence, this class of spacecraft can have a scheduled launch and return capability that minimizes waiting time and, more importantly for commercial passengers and crew, that can return in an emergency without waiting time. The correlation of lateral range, LR (in nmi), hypersonic *L/D*, and the resulting down range, DR (in nmi) is given by Eqs. (2.2) and (2.3) below.

$$LR = 1.667 + 68.016 \cdot \left(\frac{L}{D}\right) + 706.67 \cdot \left(\frac{L}{D}\right)^2 - 91.111 \cdot \left(\frac{L}{D}\right)^3 \quad (2.2)$$

$$DR = 4866.6 + 4.70417 \cdot LR \quad (2.3)$$

For continental Russia, the longitudinal span is twice that of the USA, hence the *L/D* requirement for any time return is less, at approximately $L/D \approx 1.7$. Lozino-Lozinskiy was a

Fig. 2.26 Hypersonic lift-to-drag enables lateral (cross) range performance



strong advocate of the “no waiting emergency return,” and his round-bottom BOR vehicles were capable of meeting the Russian *L/D* requirement (Lukashevich and Afanasiev 2009). Lozino-Lozinskiy had a forceful way of making his emergency return requirement much as Mr. McDonnell (Old Mac) had for the MOL support vehicle in 1964 (McDonnell 1999).

2.6.2 On-Orbit Operations in Near-Earth Orbit Enable the Second Step

The concept of the train yard as a center of operations for switching, long-haul train assembly, transfer of goods, refueling, and repair is applicable to a space marshaling facility. The remoteness of space parallels remote bases on Earth’s surface, where the environment forces significant logistics operations to include propellant, cargo, repair parts, pilot accommodation, structures, and support items. The late Frederick (Bud) Redding formed a company, In-Space Operations Corporation (IOC), to exploit his orbital servicing and crew rescue vehicle *Space Cruiser* (Redding 2003). As originally conceived in 1980, the Space Cruiser was a low-angle conical hypersonic glider based on the McDonnell Douglas Model 122 (BGRV) experimental vehicle that was flown in 1966 (Hallion 2005). As initially conceived, the Space Cruiser had a length of 26 ft and could be folded to a length of 13.5 ft, see Fig. 2.27.

Redding adapted the design to incorporate an aft plug cluster engine configuration and storable propellants to create 13.3 kN (3000 lb) of thrust. The 4453 kg (10,000 lb) vehicle could perform a variety of missions using the 8 ft³ forward payload bay and the 4 ft³ aft payload bay. The Space Cruiser is capable of atmospheric entry and uses a small drogue parachute at Mach 1 followed by a multi-reefed

parafoil to land safely on any flat surface. The Space Cruiser was intended to be operated by a pilot in an EVA suit (Griswold et al. 1982; Redding et al. 1983; Redding 1984). In 1983, Redding modified the configuration to an elliptical cross section which expanded the propellant quantity, as shown in a McDonnell Douglas Corporation trans-atmospheric vehicle (TAV) artist illustration from 1983, see Fig. 2.27. This particular configuration is based on a hypersonic glider research vehicle proposed to the US Air Force in 1964. It has sufficient volume and cross-range to act as a three-person rescue vehicle.

The Space Cruiser is a LEO service vehicle that can utilize the refueling station shown in Fig. 2.24. With its hypergolic propellant and small mass ratio, refueling was always a critical issue for the original Space Cruiser size. There were four basic tasks for the Space Cruiser as envisioned by Redding: (1) providing a one- or two-seat resource mover between spacecraft or orbital stations in close proximity; (2) providing a “Lifecraft” or emergency rescue vehicle; (3) providing a movable orbital workshop for repairing or maintaining nearby satellites; and (4) in the folded configuration, providing a camera mounted in the folded nose to act as a vehicle/satellite scanning system or an ad hoc reconnaissance vehicle free of the space station or shuttle.

For orbital transfer from low Earth orbits (LEO) to GSO and return, for collecting nonfunctional satellites in LEO for repair or disposal, for GSO refueling of sustained-use satellites, orbital busses, and tugs, there is a real need for a nuclear-powered tug. This nuclear-electric-powered tug can sustain in-orbit operations and maintain a functional orbital infrastructure, including space habitats, free-flying facilities, and power stations. In Chap. 5, several levels of space tug development are depicted using prior work of Dr. William Gaubatz, Tom Taylor, and “Bud” Redding. The most important determination is the quantity of propellant required (a) in LEO to implement the space infrastructure concepts represented in Figs. 2.23 and 2.24, and (b) to lift and accelerate the LEO propellant to low Earth orbit, unless both airbreathing launchers and nuclear-electric space propulsion are operationally available.

2.6.3 Earth-Moon System Enables the Third Step

The Earth-Moon system provides clear advantages which enable the next step to establish a solar system presence (Eckart 1999; Mendell 1985). Unlike artificial LEO orbital stations (MIR and ISS), the Moon as our natural space station is not devoid of indigenous resources, including water and gravity. Using Tom Stafford’s report to Congress (Stafford 1991) as a data source on why we should return to



Fig. 2.27 “Bud” Redding’s Space Cruiser launched from a transatmospheric vehicle to accomplish a satellite repair. The Space Cruiser is also able to serve as a three-person rescue vehicle

the Moon, the report summarizes the advantages of the Moon station compared to an Earth orbital station. It also shows the advantages of testing and evaluating human operations on a foreign, inhospitable planet before venturing far from Earth (possibly Mars), without the capability of easy and fast return. It also identifies the resources that can be obtained from the lunar surface and interior. With the discovery of water in the polar regions of the Moon in 2009, a clear incentive is provided to utilize the Moon as a resource depot for drinking water, fuel, and oxygen. A unit mass of liquid oxygen sent to LEO from the Moon may actually cost less than the same mass sent up from the Earth's surface. Mining of Helium-3 on the Moon could provide an energy source to power deep space exploration. Again, as in Earth orbit, the commercialization of sustained operations on the Moon is needed. Chapter 6 discusses Stafford's Congressional report and the need to return to the Moon.

2.6.4 Nuclear or High-Energy Space Propulsion Enables the Fourth Step

Nuclear or high-energy space propulsion is needed as a next step to explore the solar system. As discussed in Chap. 1, achieving much higher velocities in space compared to those velocities generated by practical rockets, requires high-energy and high-specific-impulse propulsion systems. Chapter 7 presents some specific systems that were under development or in conceptual formulation. Researchers at the high-energy particle research facilities speak of space-available energy in a different way than chemical propulsion engineers. If developments continue in our understanding of energy, we may actually be able to traverse the solar system nearly as quickly as the Earth–Moon system.

If someone had told Donald Douglas Sr. that just 35 years after the first DC-3 flew (first flight in 1935) a prototype supersonic transport would cross the Atlantic at Mach 2.0 (Concorde's first Atlantic crossing took place in 1971), he would have laughed in disbelief. In fact, he delayed the development of the DC-8 because he believed turboprops would hold the commercial market for over a decade before turbojets were commercially and economically practical. Nikola Tesla, before 1930, stated that with his electromagnetic energy transmitter he could power a base on Mars from Earth (the Russians have done it on an orbiting satellite). Leik Myrabo has done experiments on the laser powered vehicle LightCraft at Holloman Air Force Base, see Chap. 6. All these avenues are explored in the attempt to fulfill the need for a high-specific-impulse propulsion system. In planetary exploration, the *Holy Grail* is a propulsion system enabling a manned round trip to Mars in about 1 year; longer than that, cosmic radiation, solar flares, and re-adaptation to

both Mars's and Earth's gravity may be lethal or crippling to the human crew. We need also to get to Pluto and the gas planets in a reasonable time. All of these systems can operate within the acceleration tolerances of the human being and spacecraft structures. For humans to be in a sustained acceleration much larger than 1g is probably untenable. Automatic, robotic spacecraft could accommodate instantaneous accelerations between 8 and 10g and sustained accelerations on the order of perhaps 3g. This and other issues are explored and discussed in Chap. 7.

2.6.5 Very High-Energy Space Propulsion Enables the Fifth Step

Very high-energy space propulsion is essential for expanding our knowledge to nearby interstellar space, with fusion research eventually supplying the means. This would be simplified if we had an operational base on the Moon to mine helium-3, since in principle it would enable releasing thermonuclear energy with a minimum of neutronic radiation. Mastering of fusion, either steady or impulsive, to explore Galactic space would be an extremely ambitious next step, as distances are in the tens and hundreds of light-years. Even the closest stars are farther than a human lifetime away at current chemical rocket speeds, and even at fractional light speeds. This next step depends on the previous four and will probably not be realizable until they are accomplished. Nevertheless, it is possible to identify propulsion systems that can work and why and how they work. The difficulty in achieving even near light speed is the acceleration required, that is, by providing sufficiently large thrust. This is discussed in Chap. 8.

2.6.6 Light Speed-Plus Propulsion Enables the Sixth Step

This step requires an understanding of the physics of mass and inertia, both essential to reach speeds comparable to light speed or even above. If these are to be realized, then means to reduce or eliminate mass and inertia effects are likely required, unless the spaceship and its contents be flattened to a disk by the acceleration.

Light speed-plus propulsion is essential for expanding our knowledge to our Galaxy. Researchers can now theorize approaches for traveling at fractional light speed and even at greater than light speed based on General Relativity results. Our Galaxy is about 100,000 light-years in diameter and about 20,000 light-years thick at the center. It might contain up to 100 billion stars. The Earth is about 32,000 light-years from the center. Without the ability to travel in some sort of "hyperspace," as described in Chap. 1, the Galaxy is isolated

from our ability to explore it in any other way than by remote sensing. Except for our nearby galactic neighbors, our Galaxy is off-limits. The distances are almost not comprehensible. At 1000 times the speed of light, it would take 32 years for us to reach the galactic center.

Yet to consider super light speed is no more daunting than for the prior century researchers considering supersonic travel. There are concepts that are based on solid physics and some will be discussed in Chap. 9 in terms of what might be possible.

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