

An aviation approach to space transportation

(A strategy for increasing space exploration within existing budget streams)

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ABSTRACT

This paper presents a strategy for developing the first orbital spaceplane soon and at low cost and risk. The paper then shows how this vehicle will introduce an aviation approach to orbital space transportation to replace the present missile paradigm, leading to far lower costs and improved safety.

To illustrate the potential benefits, the paper presents preliminary sizing and cost estimates of a simple lunar base. Even including the cost of developing the spaceplanes and other vehicles required, the total cost is about ten times less than that of present plans that use large new expendable launch vehicles. Timescales need not be greatly affected.

ABBREVIATIONS AND DEFINITIONS

Carrier aeroplane	an aeroplane used as the lower stage of a launch vehicle
BSP	Bristol Spaceplanes
ELV	expendable launch vehicle
ETO	Earth transfer orbit
GEO	geostationary orbit
GTO	geostationary transfer orbit
HSF	human spaceflight
HTP	high test peroxide. The name given to the hydrogen peroxide used in British rocket engines up to the 1970s
ISS	International Space Station
LEO	low Earth orbit
LH2	liquid hydrogen
LO	lunar orbit
LOX	liquid oxygen
RHLV	reusable heavy lift vehicle

RLV	reusable launch vehicle
Spaceplane	fully reusable piloted winged vehicle capable of flight to and from space, i.e., a particular type of RLV
SS1	SpaceShipOne
SS2	SpaceShipTwo
Sub-orbital	a trajectory with sufficient speed to zoom to space height (usually defined as 100km)
Sub-sub-orbital	A trajectory with sufficient speed to zoom to a height in the region of 50 to 60km, i.e., roughly twice as high as achievable by jet aeroplanes and one half of space height.

1.0 INTRODUCTION

This paper presents, as the basis for discussion, a strategy for greatly reducing the cost of access to space soon and at low risk. That such a paper might be useful is due to the fact that space transportation is in an unusual situation. Private sector start-up companies are pursuing a radically new approach that has the potential to transform spaceflight. For historical reasons, government agencies and major contractors are taking little interest and are continuing down the traditional path. However, the start-up companies at present lack the resources to complete the transformation and government backing would bring forward by several years a new age of low-cost access to orbit. The aim of this paper is therefore to encourage discussion of a public-private partnership.

Start-up companies are developing reusable aeroplane-like vehicles (spaceplanes). The Scaled Composites, SpaceShipOne (SS1) was the first such vehicle to fly, having reached space height (usually defined as 100km) in 2004. Virgin Galactic plan to use SS2,

which is an enlarged development of SS1, for carrying science payloads and passengers on brief space experience flights, starting around 2011 at a fare of about \$200,000. Xcor appear to be not far behind with the Lynx. Passengers will experience weightlessness for a few minutes, will see an area larger than the UK at one time, will see the earth's curvature, and will see the sky go black even in daytime.

The spaceplanes under development are sub-orbital in that they can fly fast enough to coast up to space for a few minutes, following a steep accelerating climb to supersonic speed, but cannot fly fast enough to reach earth orbit. Compared with present sub-orbital sounding rockets, which are expendable, spaceplanes offer a lower cost per flight, more rapid turnaround, and the opportunity for scientists to accompany their experiment. As the technology matures, costs will be reduced even further. It therefore seems but a matter of time before spaceplanes transform sub-orbital spaceflight by bringing in the aviation approach of reusable piloted vehicles each making several flights per day. A new age of sub-orbital spaceflight is in sight.

Orbital spaceplanes appear to have the potential to do the same for orbital spaceflight, for which the market is larger and more important than sub-orbital. In spite of this promise, there are no funded plans for orbital spaceplanes, which require about eight times the speed and twice the height of sub-orbital ones, and which will cost approximately ten times as much to develop. Such funding appears to be out of reach of the private sector alone, but this might change if sub-orbital passenger flights turn out to be a commercial success. Space agencies are showing little interest in spaceplane development. NASA is more or less re-inventing the mighty Saturn 5 expendable launcher of the 1960s for sending humans back to the moon. Other space agencies are planning to collaborate with this programme and are developing their own new or improved expendable launchers.

These government and private sector approaches can co-exist for a few more years because space agencies have only a peripheral interest in sub-orbital flight (for various scientific purposes) and their present plans do not appear to be challenged by the development of sub-orbital spaceplanes. This situation would change if the private sector did indeed develop an orbital spaceplane. This would undercut any expendable vehicle of comparable payload and NASA and ESA would then probably adopt it. The aviation approach to space transportation would thereby spread from sub-orbital to orbital flight and a new space age would be in sight.

Ideally, there would be a rational discussion between government agencies and the private sector on the best way to develop an orbital spaceplane. This might lead to some kind of public-private partnership and the phasing out of expendable launchers. Unfortunately, this discussion does not seem to be happening. Government agencies are all but ignoring the new space age and the private sector has not published a coherent strategy for collaborating with these agencies to develop an orbital spaceplane.

This paper presents the outlines of such a strategy aimed at serving as the basis for discussion.

To establish the background to this strategy, the second section briefly describes the history of spaceplanes to explore why space agencies are all but ignoring them. This section also describes current developments and investigates the potential of spaceplanes to reduce the cost of sending people to space. The third section describes a conceptual design exercise to establish some basic parameters concerning design features, cost, safety, technology availability, timescales, and markets. The fourth section outlines the logic behind the strategy and the next seven sections describe the strategy itself. To illustrate the potential cost savings, the remaining sections estimate the cost of establishing a simple lunar base using the aviation approach, and compare it with the cost of present plans.

The analysis described in this paper is inevitably at a preliminary level and involves some conjecture. Even so, robust and useful conclusions can be drawn.



Armadillo Aerospace Test Vehicle



EADS Rocketplane



SpaceShipTwo on WhiteKnightTwo



Xcor Lynx

Figure 1. Pioneering sub-orbital space tourism vehicles.

2.0 BACKGROUND

2.1 Historical

To date, all orbital spaceflight has used launchers with large and complex single-use components based on ballistic missile technology. The first satellites were launched using converted ballistic missiles rather than rocket-powered aeroplanes because the latter would have taken longer and cost more to develop. Due to pressures of the Cold War, the first men in space were also sent there on top of ballistic missiles, and the use of expendable launchers persisted during the 1960s race to the moon.

Even in the 1950s, it was recognised that aeroplane-like reusable vehicles (spaceplanes) have the potential to reduce launch costs by bringing in an aviation approach. A start was made in the 1960s when the X-15 experimental spaceplane made several brief flights to space height but this aeroplane was not followed up by an operational development.

The X-15 was only sub-orbital but was intended to pave the way for orbital spaceplanes. Thus, in the 1960s, there were numerous feasibility studies of spaceplanes that could reach orbit. The consensus was that they were the obvious next step in space transportation and just about feasible with the technology of the time. In the 1970s, the early designs of the Space Shuttle were indeed fully reusable. Budget pressures then forced NASA to choose between a smaller reusable design, which would have introduced the aviation approach, or giving up on full reusability. The habit of expendability was by then strong enough for NASA to choose the latter. The largely expendable Space Shuttle is as expensive and as risky as the vehicles that it replaced.

This history has created ways of thinking and institutions repeatedly reinforcing the throwaway launcher habit. This mind-set appears to be the largest obstacle in the way of spaceplane development. Even today, as already mentioned, NASA and other space agencies are developing new expendable launchers.

2.2 Present spaceplane developments

After a hiatus of several decades, the private sector has taken the lead and, as mentioned earlier, the experimental spaceplane SS1 flew to space height in 2004, 36 years after the X-15 last achieved this feat.

Several other companies are promoting sub-orbital spaceplanes

Table 1
Leading features of pioneering sub-orbital space tourism vehicles

Type	Armadillo	Rocketplane	SpaceShipTwo	Lynx
Number of stages	One	One	Two	One
Take-off and landing	Vertical	Horizontal	Horizontal	Horizontal
Type of rocket engine	Liquid	Liquid	Hybrid	Liquid
Jet engines?	No	Yes	Yes (carrier aeroplane only)	No
Number of passengers	Not published	Four	Six	One
Performance	Sub-orbital	Sub-orbital	Sub-orbital	Sub-sub-orbital

and these have a wide variety of design features. The four designs that appear to have the most backing are one by Armadillo Aerospace⁽¹⁾, the EADS Rocketplane⁽²⁾, the Virgin Galactic SS2⁽³⁾, and the Xcor Lynx⁽⁴⁾. These vehicles are shown in Fig. 1.

Armadillo Aerospace has not yet announced details of their operational vehicle, so a test vehicle is shown. The SpaceShipTwo spaceplane is shown while carried on WhiteKnightTwo, from which it is launched at some 55,000ft.

Some leading design features of these vehicles are shown in Table 1.

As will be noted, these vehicles have a wide variety of design features. The Armadillo design is the only one to take-off or land vertically. SS2 is the only vehicle to have two stages or a hybrid rocket engine. Lynx is the only one with sub-sub-orbital performance, although a later version is planned capable of full sub-orbital flight. Rocketplane is the only single-stage vehicle with jet engines.

Other differences, not shown in Table 1, are that Rocketplane is the only one with a straight high aspect-ratio wing, and that the passenger in the Lynx stays strapped in his/her seat whereas in Rocketplane and SS2 they are free to float around the cabin in zero-g. The accommodation details for the Armadillo design have not yet been published.

This diversity of design features is perhaps comparable to that during the pioneering days of aeroplane development in the early 1900s, when a wide variety of ideas were tried out before the tractor biplane with the empennage mounted on the rear fuselage emerged as the predominant type. This raises the question of what basic design features are likely to predominate in future spaceplanes, and this is discussed in Section 3.2.

2.3 Cost potential

2.3.1 Spaceplane cost potential

A key question is the extent to which spaceplanes are capable of reducing the cost of access to orbit. There are few recent published estimates, but one such⁽⁵⁾ takes the MBB (now EADS) Sänger spaceplane design of the 1980s as an example and shows that, after a long production run and with mature technology, the cost per seat to orbit would be about 1,000 times less than the cost today. This is a measure of the benefits of using vehicles like airliners instead of those like ballistic missiles. A more up-to-date estimate is described later in Section 11.2.

These low costs assume aviation standards of design and operational maturity, and these in turn depend on a market large enough to support a fleet of several dozen spaceplanes each making several flights per day. To explore the relationship between cost and flight rate, we have carried out an illustrative estimate of how the cost per seat to orbit would reduce with increasing number of flights per year for expendable and reusable launchers. Table 2 shows some details of the vehicles used for the comparison and Fig. 2 shows the resulting costs.

To achieve a breakthrough into new markets for space, the cost per seat to orbit has to come down to a few tens of thousands of dollars. The cost of science in space would then become comparable

Table 2
Parametric data of expendable and reusable launch vehicles for cost comparison

	ELV	RLV
Launch mass, tonnes	400	400
Number of stages	2	2
Inert mass/stage mass less payload, %	12	18
Number of passenger seats	73	44
Unit production cost of 100th vehicle, \$m	75	500
Production learning curve (cumulative average), %	90	90

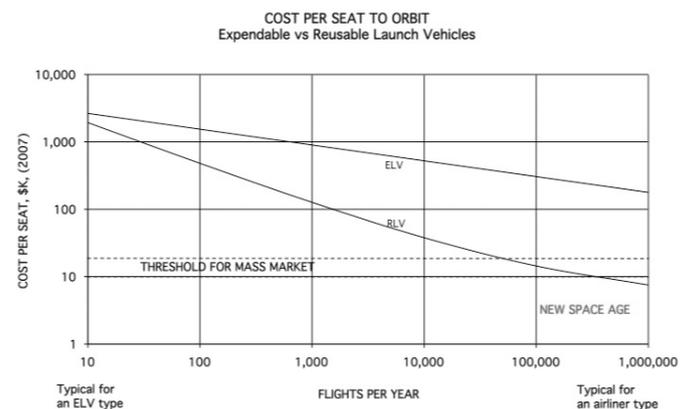


Figure 2. Cost per seat to orbit *versus* flights per year for expendable and reusable launch vehicles.

with that in Antarctica; space tourism would become affordable by middle-income people prepared to save; and we could begin to access the unlimited resources of space, possibly starting with solar power satellites.

Expendable launch vehicles (ELVs), even if mass-produced, cannot approach this cost threshold because the marginal cost per flight is that of a new vehicle. Reusable launch vehicles (RLVs) can indeed achieve the required low costs at high flight rates because they can then be operated like airliners. The marginal cost per flight is then fuel, crew, and maintenance, which, for airliners, is typically one thousandth of the cost of a new vehicle. (The cost per seat of ELVs at low flight rates shown in Fig. 2 is less than today's cost because new vehicles have been assumed, using existing technology but optimised for carrying people.)

Thus, the new space age depends on the combination of reusability and high traffic levels. As discussed later, space tourism is the new market most likely to demand these high traffic levels.

Figure 2 is based on a simplified analysis intended to illustrate trends and orders of magnitude. The analysis is, however, sufficiently accurate to justify the conclusions. More sophisticated analyses with similar conclusions are given in Refs. 6 and 7. An estimate of the operating cost of a mature spaceplane at high flight rates is given later in Section 11.2 and the result is consistent with the costs shown in Fig. 2.

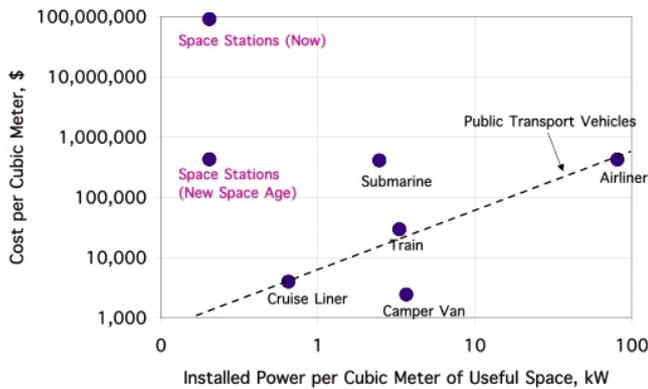


Figure 3. Cost comparisons of vehicles with accommodation for humans.

2.3.2 Space station and satellite costs

An important use of spaceplanes will be to transport crews and supplies to and from space stations and to send up mechanics to service and repair unmanned satellites. Space stations are at present very expensive, largely because of:

- Low production rate
- High political profile
- Immature technology
- High cost of access, which makes maintenance and repair expensive and forces exceptional reliability standards
- Lack of access on demand, so that operators cannot plan on being able to rescue the crew in an emergency. This forces an exceptionally high standard of safety.

None of these factors need apply when spaceplanes enter service and space stations are built in significant numbers. As a first attempt to find a cost estimating relationship for space stations when the cost of access is low, Fig. 3 compares the cost of various vehicles capable of accommodating humans, using installed power per cubic meter of useful space as an indicator of complexity. Vehicles used for public transport — cruise liners, trains, and airliners — fall on a discernible trend line. Trains have a higher installed power per unit volume than ships and cost more, and likewise airliners compared with trains. Camper vans fall below the trend because most of their components are mass-produced, and submarines lie above it because they are built in small numbers to demanding naval specifications.

The International Space Station (ISS) is ‘off the scale’ by terrestrial standards, for the reasons mentioned above. This raises the question of what the cost of space stations will become when low-cost access is assured.

Space stations are inherently simpler than airliners. They can hardly get lost and do not have to land at night in bad weather. Imagine that you have just completed the conceptual design of a new airliner and you are told to convert it into a space station with the same useful volume. (This thought experiment serves to make a useful point although, even with today’s rapid changes in policy, the example is a bit extreme!) You would remove the wings, engines, landing gear, flaps, tail, and flying controls. You would then enhance the pressure integrity and life support, and add a solar power system, a docking port, and an attitude and orbit control system. The cost of these deletions and additions should be comparable, with the balance almost certainly in favour of space stations.

It is therefore almost certainly conservative to assume that the cost per cubic meter of space stations will fall to values comparable with airliners once low-cost access has been achieved and significant numbers are produced.

The cost of unmanned satellites can also be greatly reduced. They will not need to be so light because the cost per tonne to orbit will be lower. They will not require such a long untended life because it will be readily affordable to send up mechanics for service and repair. A higher level of modularity will be practicable because of more generous design margins.

2.3.3 Cost penalties of expendability

In view of the low costs predicted above, it is worth considering the precise reasons for the present high cost and risk of spaceflight. The fundamental cause is not hard to identify — it is the exclusive use to date of launchers with large and complex single-use components.

The obvious direct penalty arising from expendability is that expensive components have to be replaced for each flight. However, the cost of these could be reduced considerably by mass production, and indirect penalties are perhaps even more important.

The first of these indirect penalties is that the cost per launch, even with mass production, is too high for new commercial applications of space to evolve. For example, the cost per launch of the Space Shuttle might be reduced from \$1bn to some \$50m if it were built in sufficient numbers. However, even this cost is about a thousand times greater than that of a long-distance flight by an airliner of comparable 50-seat capacity. (The Shuttle actually carries up to ten astronauts, but could be configured to carry 50 passengers.) The cost per seat to orbit would then be \$1m, which is still too high for large-scale space tourism, for example.

Expendable vehicles are therefore restricted to the present 70 or so launches per year for carrying payloads funded by government agencies and for the few applications that are genuinely commercial, such as satellites for communication. There are nearly 20 types of launcher on the market, making an average of around four launches per year each. These low numbers prevent ELVs from even approaching aviation standards of operational maturity.

The second indirect penalty arising from expendability applies especially to human spaceflight (HSF). Launchers full of high-energy chemicals and designed for extreme lightness are inherently more difficult to make safe than conventional aeroplanes. This applies both to expendable vehicles and to spaceplanes. In the case of expendable vehicles, this problem is compounded by the inherent high cost per flight, which means that an adequate programme of flight-testing cannot be afforded. Thus, a new type of airliner makes typically one thousand test flights in one or two years before being allowed to carry passengers, whereas the Shuttle has made just 132 flights in 28 years.

This means that extraordinary, and very expensive, measures are required for astronaut safety. Even so, there are (approximately) one hundred flights per fatal accident for HSF, compared with more than one million for airliners. These extraordinary safety measures preclude expendable HSF launchers or spacecraft from being developed in experimental workshops (sometimes called skunk works). By contrast, prototype aeroplanes can be developed at remarkably low cost in experimental workshops—approximately ten times less than the cost to full certification—and the same can apply to spaceplanes. (This is one reason for the low development cost of SS1, discussed later in Section 5.2.)

Reusability means that an adequate flight test programme can be afforded. As discussed later in Section 3.4, even prototype spaceplanes should be far safer than ELVs and so it should be permissible for them to carry payloads on test flights. In this way, spaceplanes could progress down the learning curve towards airliner safety at an affordable cost.

Approaching airliner safety will be difficult enough with spaceplanes — this task is all but impossible with ELVs.

It may seem paradoxical at first sight, but it is precisely because spaceplanes are inherently so much safer and less expensive to fly than man-rated expendable launchers that they can cost less to develop. Operational prototypes can be built in experimental workshops and their marginal cost per flight is not a barrier to adequate testing.

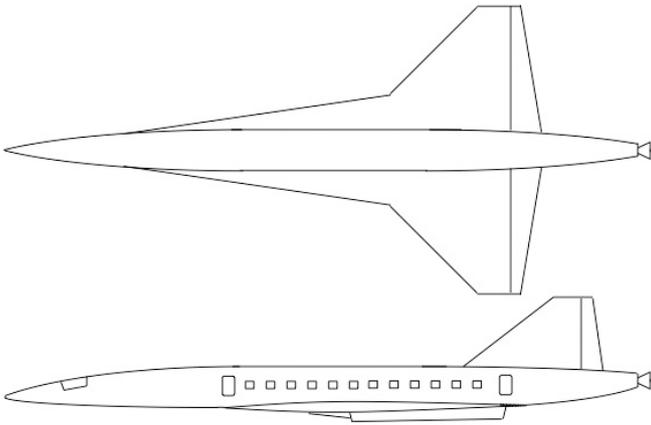


Figure 4. First concept sketch of second-generation sub-orbital spaceplane (Quarter Concorde).

3.0 CONCEPT DESIGN EXERCISE (SECOND GENERATION SUB-ORBITAL SPACEPLANE)

3.1 General

The conclusions of the previous sections can be summed up as follows:

- Several pioneering sub-orbital spaceplanes are under development, with widely differing basic design features.
- Orbital spaceplanes following on from these pioneering designs can reduce greatly the cost of access to orbit. The cost is potentially low enough to enable large new commercial markets to develop.
- Low-cost access to orbit will enable the cost of space stations and satellites to be greatly reduced.
- The first orbital spaceplane is therefore the key to the new space age.

The spaceplanes under development are all first-generation pioneering designs. Several key questions remain concerning more advanced vehicles. Which design features will predominate? What will they cost to operate? How safe will they be? How soon can they be developed? How big will be their market?

To gain insight into these issues, we have carried out the conceptual design of a second-generation sub-orbital spaceplane. We have assumed that the pioneering designs will lead to an established and competitive market with several manufacturers and operators. The main criteria for selecting the basic design features for more advanced vehicles will then be commercial, as they are with airliners and business jets today.

3.2 Basic design features

Using simple logic, we have derived a conceptual design as shown in Fig. 4. Because it is approximately one quarter the weight of Concorde and has a broadly similar configuration, we have called it 'Quarter Concorde', as shorthand for 'Bristol Spaceplanes (BSP) Second-Generation Sub-Orbital Spaceplane'. The windows shown in the sketch are notional only. Ideally, large areas of the cabin would be transparent to give the best view, but the weight would probably be prohibitive. It is more likely that each passenger will have his/her own 'viewing port'.

The reasoning behind the selection of the basic design features is described in the following paragraphs.

3.2.1 Number of stages

The weight of propellant needed for sub-orbital flight with a single-stage vehicle using only rocket engines is approximately 60% of the take-off weight. If jet engines are used for the early part of the flight, this can be reduced to below 50%. These propellant mass fractions are feasible for practical and robust spaceplanes; so two stages are not required for engineering reasons alone.

Using a carrier aeroplane to air-launch the spaceplane would allow a higher payload to be carried. However, by analogy with long-range air travel, the gains would almost certainly not outweigh the additional cost and complexity of two stages. In the pioneering days of trans-Atlantic airline operations, the case was made for the use of carrier aeroplanes or in-flight refuelling to permit non-stop operations. Indeed, in the late 1930s, the Short-Mayo composite aeroplane made several successful experimental long-range flights. However, airlines considered that the additional payload did not justify the cost and complexity of using two aeroplanes, and there has never been significant commercial use of two-stage operations. Flight refuelling is, of course, used routinely for military missions, where considerations of cost are less important.

It is therefore reasonably certain that second-generation sub-orbital spaceplanes will have a single stage.

3.2.2 Take-off and landing

Safety will be a major consideration for early spaceplanes because passenger carrying is likely to be their first large-scale use. There is unlikely to be enough demand for military or scientific spaceplanes to build up the operational experience needed to approach airliner standards of safety.

This favours horizontal rather than vertical take-off and landing. Vertical take-off aeroplanes (such as the Harrier and helicopters) have significantly higher accident rates than horizontal take-off types. This is because loss of power near to the ground is more critical if that power is required to generate lift as well as thrust. Moreover, achieving stability and control is more difficult at speeds below the conventional stalling speed. Vertical take-off types also require greater mechanical complexity.

It is therefore reasonably certain that second-generation sub-orbital spaceplanes will take off and land horizontally.

3.2.3 Jet engine size

Spaceplanes can have jet engines in four size categories:

3.2.3.1 No jet engines

Jet engines are not strictly required for sub-orbital flight. The X-15 and SS1 had only rocket engines, although both were air-launched. The same applies to SS2. The Armadillo design and the Lynx do not have jet engines.

3.2.3.2 Jet engines for safety and practicability

Jet engines use in the region of ten to twenty times less propellant than rockets of the same thrust over the same time and are therefore more practical for taxiing, ferry flights, aborted landings, and diversion to other airfields. They can provide back-up thrust in case of rocket engine failure on take-off. Jet engines in this size category are small because they do not provide the primary thrust needed for take-off. Even so, they do add deadweight to the rocket part of the climb in thin air where jet engines cannot operate.

None of the four vehicles mentioned in Table 1 has jet engines in this thrust category, although Ascender, described later in Section 5, does.

3.2.3.3 Jet engines to subsonic speed

The EADS Rocketplane uses jet engines for take-off and climb at subsonic speed before the rocket engines are started. This lowers the propellant weight fraction because the rocket engines have to operate for less time to achieve the velocity required for a ballistic climb to space height. Another advantage is that the rocket nozzle can be optimised for high altitude flight.

3.2.3.4 Jet engines to supersonic speed

If larger jet engines are fitted, capable of accelerating the spaceplane to supersonic speed, the propellant weight fraction is reduced further because the rocket engines operate for even less time. Our internal studies show that the weight saved more than compensates for the heavier engines.

As shown later in Section 3.3, spaceplane operating costs will be dominated by propellant because they use in a short flight the amount of fuel that an airliner uses in a long one. Using jet engines to supersonic speed will therefore reduce the direct operating cost. Another advantage of supersonic jet propulsion is that it is more in line with longer-term developments, which will probably use even faster air-breathing engines.

It is therefore reasonably certain that second generation sub-orbital spaceplanes will have jet engines to supersonic speed.

3.2.4 Type of rocket propellant

Because of the importance of propellant cost, it is reasonably certain that liquid oxygen (LOX) will be used as the oxidiser and kerosene or methane as fuel, as these are the least expensive practical propellant combinations.

3.2.5 Cabin size

As mentioned earlier, some proposed spaceplanes have a cabin large enough for passengers to float around in zero-g — in at least one of the others, the passenger remains strapped in and the view of the earth is the primary experience. We are inclined to favour the latter, at least for early spaceplanes, because:

- Astronauts say that looking at the Earth is the most enjoyable feature of spaceflight, even more than weightlessness⁽⁸⁾.
- Parabolic zero-g flights in modified airliners have been available commercially for several years but remain a niche market.
- More passengers can be carried in a given cabin if they remain strapped in.
- If passengers are allowed to float around, there is a risk of them not regaining their seats before a four to six-g re-entry, which could result in injury.
- Combining the two experiences of the view and weightlessness in one short flight may result in 'sensory overload' for inexperienced passengers.

However, we will probably have to wait for operational experience to see whether strapped in or free-floating passenger accommodation results in greater profit for the operators.

3.2.6 Leading data

Table 3 summarises the leading data of Quarter Concorde and of Concorde itself. The starting point for the design was to divide Concorde weights by four, and subsequent checks showed that this provided the basis for a feasible design. The wing was sized to

Table 3
Leading data for Quarter Concorde

	Concorde	Quarter Concorde
Span, m	26	13
Length, m	62	27
Operating weight, tonnes	80	20
Payload	9	2.2
Propellant	96	24
Take-off weight	185	46

maintain the same wing loading, and the fuselage to accommodate 22 passengers two abreast with room for some of the propellant. A simple trajectory calculation showed that the resulting fuel fraction (the same as in Concorde) is adequate for sub-orbital flight, and a simple check showed that there is enough volume for the required propellant.

Quarter Concorde uses afterburning turbofan engines to a maximum speed of Mach 1.7. It also uses a long-life LOX/kerosene rocket engine, which is started at Mach 1.7. The vehicle then pulls up into a steep climb, reaching about Mach 3 before the rocket propellant is consumed. It then follows an unpowered ballistic trajectory to a height above 100km before re-entering the atmosphere, pulling out of the dive, and flying back to the airfield that it took off from. It spends about three minutes in space.

3.3 Operating cost

Appendix 1 shows a preliminary estimate of the operating cost of Quarter Concorde after a long production run and when all the technology is mature. The starting point is a breakdown of the operating cost of a typical regional airliner of comparable take-off weight. These costs are then scaled using simple factors that are intended to be conservative.

With these assumptions, the direct cost per seat in Quarter Concorde is \$830, with propellant as the largest item. To this must be added indirect costs and profits, which would bring the total up to somewhat more than \$1,000. Allowing for the uncertainties in this estimate, it is safe to conclude that the cost per seat in a mature second-generation sub-orbital spaceplane will be less than two thousand dollars. This is about 100 times less than the fare at present on offer for a sub-orbital flight and is affordable by large numbers of people.

It must be emphasised that this cost assumes maturity comparable with an airliner, which will require a long production run with continuous product improvement.

3.4 Safety

First generation spaceplanes are being exempted from full certification on entry into service, at least in the USA, which would be prohibitively expensive for an emerging industry funded by the private sector. Operators will be allowed to carry passengers on an 'informed waiver' basis⁽⁹⁾. It is difficult to predict what safety levels can actually be achieved with designs that are not fully developed. However, flight testing airliners and business jets has a fatal accident rate of approximately one per ten thousand flights, which is about 100 times better than HSF with ELVs and more than 100 times worse than scheduled airliners. Prototype spaceplanes should therefore be far safer than ELVs.

In the longer term, safety authorities and spaceplane manufacturers and operators will presumably aim for full type certification for carrying fare-paying passengers, as required for airliners. There will be little difference between the operations of spaceplanes and of

business jets, apart from the use of rocket propellants, some training for the passengers, and additional training for the pilots. However, there are several new airworthiness issues, such as:

- Aborted launches
- Thrust vector control of rocket engines
- Cabin pressure integrity in the vacuum of space and the related question of passenger pressure suits
- Reaction controls
- Re-entry orientation, stability, and control
- Thermal protection
- The safety of the rocket propulsion system, especially the containment of high-energy propellants and the avoidance of explosions in the combustion chamber.

Clearly, a major development effort will be needed for spaceplanes to approach airliner standards of safety.

3.5 Technology requirements

Quarter Concorde requires less demanding aerodynamic and structural efficiencies than did Concorde itself, largely because it has only to accelerate to maximum speed and does not have to maintain it for more than two hours. The wings and the air intakes, for example, can therefore be simpler. The systems can also be simpler. For example, the droop nose of Concorde will not be needed because the drag penalty can be tolerated of a fixed nose that provides adequate visibility for the pilot at low speeds.

There will probably be a requirement for some thermal protection, but SS1 has shown that this need be no more than some insulation on the wing leading edge and on the nose. (Quarter Concorde is subjected to a far smaller heat pulse than the Shuttle Orbiter, for example, because it re-enters the atmosphere at about Mach 3 and takes about two minutes to slow down to subsonic speed, whereas the Orbiter re-enters at about Mach 25 and takes about twenty minutes to slow down.)

Most of the systems can be derived from airliner practice. Existing technology for rocket engines is adequate for prototype spaceplanes but will need extensive development to provide long life with low maintenance cost.

Given the demonstrated practicability of SS1 and of Concorde itself, Quarter Concorde is almost self-evidently a feasible concept.

3.6 Timescale for prototypes

Prototypes of advanced aeroplanes require typically three and a half years between go-ahead and first flight. Given that advanced new technology is not required, the time to develop a prototype spaceplane should be comparable. SS1 took this time between contract signature in April 2001 and winning the X-Prize in October 2004, and the X-15 required three months less. In the past, war (hot and cold) promoted rapid development, but the SS1 timescale (and that of many other programmes) shows that an efficient and motivated company can make rapid progress in peacetime.

Allowing three years before go-ahead for feasibility studies and project definition, and six months after first flight for an incremental flight-test programme, a prototype of Quarter Concorde could be making regular sub-orbital flights in seven years, given the necessary priority.

3.7 Timescales for maturity

With existing technology, Quarter Concorde prototypes would inevitably have a short life and high maintenance cost, and would have a long turnaround time between flights (by airliner standards).

The time taken to reach airliner maturity clearly depends on the effort devoted to this task, which will in turn depend on how rapidly the new commercial markets build up, especially space tourism. Considering the various technologies involved (aerodynamics, structures, systems, seals, transparencies, propellant tanks, thermal protection, propulsion, avionics, etc.), it seems likely that the critical path will be the development of a rocket engine with a life measured in thousands of flights compared with the present tens.

The development of the jet engine provides some insight into how long it might take to develop a long-life rocket engine. Jet engines progressed from quasi-experimental operations in 1944 (the Messerschmitt Me262 and Gloster Meteor) to the first airliner services in 1952 (the de Havilland Comet). During this period, jet engine development was a high priority in the leading aeronautical countries. Given priority, the development timescale of long-life rocket engines should be comparable to that of long-life jet engines, i.e., they should be available within about eight years of early models entering service on prototypes. This provides a preliminary indication of the minimum time required for spaceplanes to progress from prototype to approaching airliner standards of maturity.

3.8 Development cost

Using the simple parametric cost method describe later in Section 5.2, the development cost of a prototype of Quarter Concorde works out at about \$500m and of a fully certificated version at about \$5bn. Clearly, these are approximate figures, but they should be in the right ballpark. If the informed waiver regime were still in place when Quarter Concorde first flew, it should be possible for it to enter service at the prototype stage. If, on the other hand, earlier designs were approaching maturity, a full programme of certification would probably be required.

3.9 Markets

A key question is whether the markets for Quarter Concorde will be large enough for a good return on investment. Quarter Concorde can be used as a reusable sounding rocket for science experiments. (SS1 itself could have been pressed into service as a reusable sounding rocket, given some modifications to avoid repeating the unplanned flight events that occurred during its three flights to space.) It can also be used as a carrier aeroplane for rocket upper stages for launching small satellites. The Orbital Sciences Pegasus has demonstrated that subsonic air launch provides flexibility of launch site. Launching at supersonic speed clear of the effective atmosphere leads to significantly greater performance gains, and Quarter Concorde would be a competitive launch platform.

While the sounding rocket and launcher markets would be useful, the required number of launches is almost certainly too small to provide a good financial return.

The largest market will almost certainly be carrying passengers on space experience flights. There have been several market surveys to estimate demand, and these give encouraging results. Moreover, six people have each paid some \$20m for a visit to the International Space Station, which of course is an orbital experience, and Virgin Galactic have taken more than \$40m in deposits for sub-orbital flights at the present premium fare⁽¹⁰⁾.

However, these surveys and the real market so far are for such high fares that it is difficult to extrapolate the results to the low fares (up to \$2,000) made possible by a mature second-generation spaceplane. However, we can obtain a conservative preliminary estimate of the market size by assuming that the world's industrialised population is one billion people and that just 1% of these would be prepared to pay \$2,000 for a brief trip to space. The initial market then works out at \$20bn. This should be enough for a good return on investment, but the margin of error of these preliminary estimates is such that there is significant uncertainty in this conclusion.

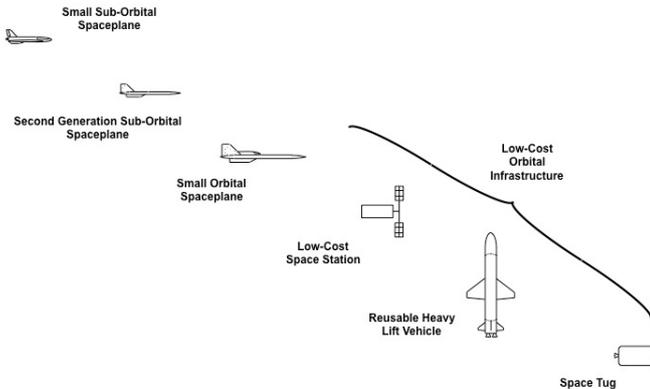


Figure 5. Development strategy for low-cost orbital infrastructure.

3.10 Conclusions from concept study of a second generation sub-orbital spaceplane

We are well aware that we have carried out very little design work on Quarter Concorde. We have done little more than prepare a concept sketch, prepare a top-level weight breakdown, carry out a trajectory analysis, and read across some concepts from vehicles that have been the subject of a full feasibility study. Nonetheless, we have been able to derive some important conclusions about the likely characteristics of second-generation sub-orbital spaceplanes, as follows:

- They will have a single stage.
- They will take-off and land horizontally.
- Operating cost will be dominated by propellant because a spaceplane uses in a short flight the amount of fuel that an airliner uses in a long one.
- They will use liquid-fuelled rocket engines with low-cost propellants, probably LOX and kerosene or methane.
- They will use jet engines for take-off and climb to supersonic speed and rocket engines thereafter.
- If the demand is large enough for a long production run leading to mature technology, especially a long-life rocket engine, the cost per seat should be at most \$2,000, which is two orders of magnitude lower than the present fare and affordable by a large number of people.
- This level of maturity could be achieved in about 15 years, given priority (seven years for prototypes and eight for product improvement).
- It appears that the potential market is large enough for a good return on investment. However, this conclusion, unlike the others, cannot be considered robust at this stage.

It is relevant to consider why it is possible to derive such conclusions, which as far as we know are original, using no more than top-level concept engineering. We suggest that this is because the idea of applying to launch vehicles the techniques used for aeroplane concept design went out of fashion some 30 years ago. We expect that most aircraft company design teams, tasked with evaluating second-generation sub-orbital spaceplanes, would arrive at similar conclusions. Much the same applies to the analysis presented in the rest of this paper. One of our aims is to encourage aircraft companies to become more involved in low-cost access to space.

4.0 DEVELOPMENT SEQUENCE

The new space age requires the development of a low-cost orbital infrastructure consisting of space stations, spaceplanes for regular

supply flights to these space stations, reusable heavy lift vehicles (RHLVs) for launching space station modules and large satellites, and space tugs for higher orbits. The sequence in which these vehicles should be developed can readily be derived. The low-cost access provided by an orbital spaceplane is needed before low-cost space stations can be developed. As discussed later, spaceplane technology would enable an RHLV to be developed at reasonable cost. Space tugs depend on RHLVs for launch and on mechanics and spares sent up by spaceplane for service and repair. The second-generation sub-orbital spaceplane, described in the previous section, is the natural predecessor to the first orbital spaceplane. A small first-generation spaceplane with similar basic design features would serve as a useful stepping stone to this second-generation spaceplane.

These considerations lead naturally to the following development sequence, also shown in Fig. 5.

- Small sub-orbital spaceplane
- Second generation sub-orbital spaceplane (described in the previous section)
- Small orbital spaceplane
- Low-cost space station
- Reusable heavy lift vehicle
- Space tug

The second-generation sub-orbital spaceplane was described in the previous section. When considering the remaining vehicles, we have assumed that their basic design features should be selected to provide a competitive business plan. This means keeping development cost and risk to a minimum. Bristol Spaceplanes (BSP) spaceplane projects have been used to provide data for much of the analysis that follows. This is not to suggest that they are necessarily the best designs. They have been used here because they are on the only published spaceplane development sequence that the author is aware of, because design details are available, and because they have indeed been designed to provide a competitive business plan. Two of these spaceplanes, Ascender and Spacecab, have been the subjects of full feasibility studies. The other vehicles on the sequence have been taken only as far as the rough order of magnitude sizing stage. The following sections consider each vehicle in turn.

5.0 SMALL SUB-ORBITAL SPACEPLANE (ASCENDER)

5.1 Ascender leading data

The BSP Ascender is a small sub-orbital spaceplane designed to use existing technology and to pave the way for later vehicles on the sequence. In particular, it is designed as a lead-in to the second-generation sub-orbital spaceplane described earlier, and therefore has many of the same basic design features. However, in the interests of minimising development cost and risk, it has two major differences. First, the jet engines are not large enough for supersonic speed. They are sized for taxiing, ferry flights, aborted landings, diversion to other airfields, and to provide back-up thrust in case of rocket engine failure on take-off. Rocket engines provide most of the thrust for take-off and climb.

Second, the rocket engines use hydrogen peroxide (HTP) as the oxidiser. This is more expensive to purchase than LOX, but history has shown that rocket engines using HTP are simpler to develop than those using LOX. The Ascender rocket engine uses technology developed in the UK before being abandoned in the early 1970s.

Ascender is specifically designed to generate spaceplane revenues at minimum development cost and risk, and thereby to be attractive

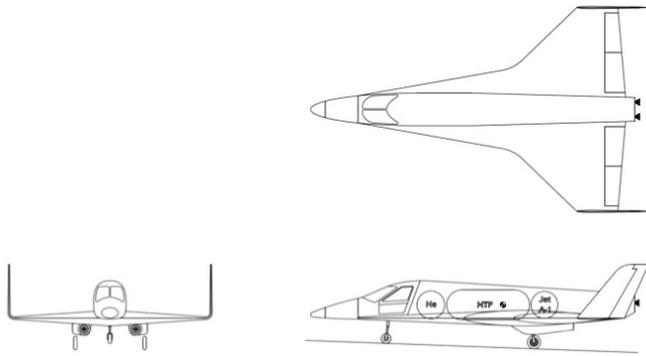


Figure 6. Bristol Spaceplanes (BSP) Ascender layout.

Table 4
Ascender leading data

Span, m	7.6
Length, m	12.9
Jet engines	Two in the 500kg thrust class
Rocket engines	Two in the 2,500kg class
Rocket propellants	HTP and kerosene
Maximum weight, kg	5,500
Empty weight, kg	2,400
Max altitude, km	100

to private-sector investment. A general arrangement is shown in Fig. 6 and leading data in Table 4.

Ascender carries one pilot and one passenger or experiment. The passenger remains strapped in his/her seat during the flight. Ascender has a maximum speed of around Mach 3 on a steep climb and can reach a height of 100km.

5.2 Development cost

A start towards low-cost spaceplane development has been made by SpaceShipOne, shown in Fig. 7, which made its historic first flight to space in 2004. It cost just \$30m to design, build, and fly briefly to space height⁽¹⁾. It is instructive to compare SS1 with the X-15, also shown in Fig. 7, which was the first aeroplane capable of sub-orbital flight. These two aeroplanes have broadly comparable performance, although their aims were different. The X-15 was designed for high-speed research and SS1 as a technology demonstrator for commercial spaceplanes. The X-15 made its first flight in 1959 and its last flight to space height in 1968, 36 years before SS1 became the next fully reusable vehicle to achieve this feat.

The X-15 cost about \$200m to develop, which is approximately \$1.5bn in today’s money — 50 times more than SS1. The X-15 was very advanced for its day whereas SS1 used hardly any new technology. This is a measure of the advances in aeronautical engineering since the X-15 was designed.

SS1 was an aeroplane in engineering essentials. It can be thought of as a small business jet of suitable shape with the jet engines replaced by a rocket motor and fitted with the equipment needed for flight to space and re-entry, i.e., a pressure cabin, reaction controls, and some thermal protection. It did not require a major programme of technology development. The great ingenuity of SS1 was in its concept and project management rather than in its technology.

The X-15 was a well-managed project that was built more or less to time and cost and which performed as advertised. It was built by a large company (North American Aviation, Inc) under government contract and supervision whereas SS1 was built under experimental workshop conditions by a small company using private funding.

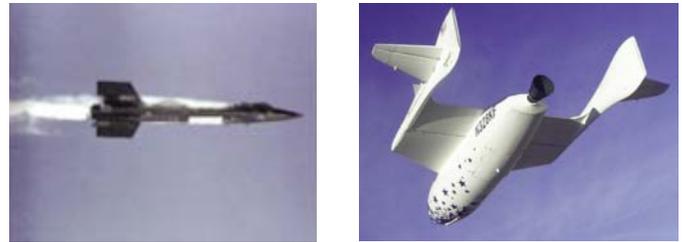


Figure 7. X-15 (left) and SpaceShipOne (SS1) — the only fully reusable spacefaring vehicles to date. There was a 36-year gap between the last flight of the X-15 and the first flight to space of SS1.

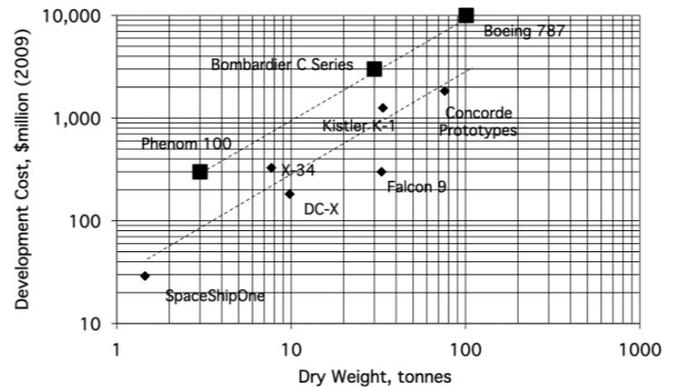


Figure 8. Development cost comparisons. The upper trend line is for airliners and business jets. The lower line is for reusable launch vehicle demonstrators built in experimental workshops (SpaceShipOne, X-34, DC-X), and for semi-reusable launchers (Falcon 9, Kistler K-1). An advanced aeroplane prototype (Concorde) is also shown.

This and advances in technology explain the big cost difference between the X-15 and SS1.

SS1 was a technology demonstrator. SS2, mentioned earlier, is the operational development which Virgin Galactic are planning to use for carrying passengers on brief flights to space.

To provide preliminary estimates of development cost, this paper uses a chart showing the development cost and dry weight of a variety of aerospace projects, as shown in Fig. 8.

There are two trend lines in Fig. 8. The lower one shows prototype, experimental, or demonstrator reusable launch vehicles built under experimental workshop conditions, including SS1. The Concorde prototypes are also shown, which were built using production tooling. The forthcoming semi-reusable SpaceX Falcon 9 and Kistler K-1 are also shown. Although the development of the latter project is now on hold, its development cost is well established. The higher trend line shows the development cost to full certification of business jets and airliners. (Only three vehicles are shown. This is largely because manufacturers now seem to be coy about releasing figures. However, this trend line is adequate for present purposes.)

A useful rule of thumb is that the cost to full certification of a new aeroplane is approximately ten times that of a prototype. On this basis, the trend line for fully certificated spaceplanes would be about ten times higher than that for prototypes. This is higher than for airliners, which is to be expected because of greater complexity. To reduce clutter, this trend line is not shown in Fig. 8.

These trend lines are used here to derive first approximations of the cost of developing spaceplanes, and will be used later for other space vehicles. The results must of course be used with the caution due to such preliminary methods.

The BSP Ascender sub-orbital spaceplane has a dry mass of 2.4t and, according to the lower trend line, should cost some \$60 million to develop to the prototype stage. This is quite close to BSP's internal bottom-up estimate, based on a feasibility study part-funded by the UK Department for Trade and Industry⁽¹²⁾.

5.3 Markets

Small sub-orbital spaceplanes can be used for a variety of purposes, in addition to carrying passengers on space experience flights. These include:

- Microgravity research
- High altitude photography
- Meteorological research
- Space science
- Astronaut training
- Testing satellite equipment
- Testing systems for more advanced high-speed aeroplanes
- Carrying rocket upper stages to launch very small satellites

Thus, a small sub-orbital spaceplane like Ascender would be useful in its own right, as well as paving the way for more advanced spaceplanes.

6.0 SMALL (FIRST GENERATION) ORBITAL SPACEPLANE (SPACECAB)

6.1 Spacecab leading data

The small sub-orbital spaceplane described in the previous section will build up the market for low-cost spaceflight and start to mature spaceplane technology and operations. The subsequent second-generation vehicle, described earlier in Section 3, will continue this process and thereby pave the way for an orbital spaceplane, for which the market will be far larger. It can be used for:

- Launching satellites
- Transporting crew and supplies to space stations
- Sending up mechanics for satellite maintenance and repair and for assembling space station modules
- Government HSF missions
- Transporting passengers to and from space hotels. (Visits of several days duration to orbiting space hotels will be more attractive than the brief flights possible with sub-orbital spaceplanes).

In recent years, there have been few published studies of small fully reusable orbital spaceplanes. One exception is the BSP Spacecab project. It has design features aimed at achieving fully reusable orbital operations soon and at minimum development cost and risk. It is therefore a candidate to be the first orbital spaceplane. Spacecab can be used to provide safe and economical transport to and from the International Space Station (ISS), which is an urgent requirement.

Spacecab is in effect an updated version of the 1960s European Aerospace Transporter concept⁽¹³⁾, designed to minimise development cost by using now-existing technology. In conceptual terms, the lower stage is like an enlarged Quarter Concorde and the upper stage like an enlarged and advanced Ascender.

A general arrangement is shown in Fig. 9 and leading data in Table 5. Spacecab has a payload in the one tonne class and has two piloted stages so that existing technology can be used. (The required technology for two-stage vehicles was available in the 1970s when

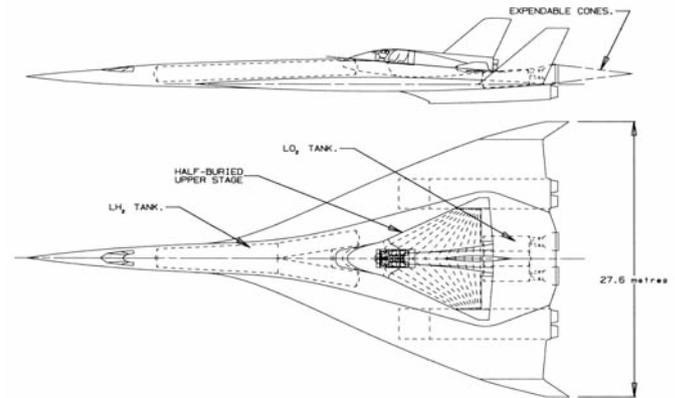


Figure 9. The Bristol Spaceplanes Spacecab Small Orbital Spaceplane.

Table 5
Spacecab leading data

	Carrier Aeroplane	Orbiter
Span, m	28	12.2
Length, m	54	16.3
Jet engines	Four in the 20,000kg thrust class	None
Rocket engines	Two in the 100,000kg class	Six in the 7,000kg class
Max speed with jet engines	Mach 2	N/A
Separation speed	Mach 4	N/A
Rocket propellants	LOX/kerosene	LOX/LH ₂
Take-off weight, kg	181,000	41,000
Empty weight, kg	71,200	6,507
Payload, kg	41,000 (Orbiter)	750 (to LEO)

the Space Shuttle was designed, and probably even in the 1960s when numerous studies were carried out.)

Single-stage-to-orbit vehicles are clearly preferable in the long term. However, using the best available rocket engines, they require a propellant mass fraction of about 87%, which is beyond the present limits for a practical and robust design. The propellant mass fraction can be reduced by using advanced air-breathing engines, but these require new technology and a long development programme. We therefore suggest that two-stage vehicles be developed first in order to lower launch costs, build up the new markets, and mature the technology. A single-stage vehicle can then be developed when the market is ready to pay for it. (This conclusion does not apply to sub-orbital vehicles because, as discussed earlier in Section 3.2.1, single-stage vehicles are feasible with today's technology because they need a smaller propellant mass fraction). The technology availability for two-stage vehicles is discussed further in Ref. 5).

The Spacecab Carrier Aeroplane stage accelerates to Mach 2 using jet engines. Rocket engines then take over for acceleration to Mach 4. During the rocket phase, Spacecab pulls up into a climb so that separation can take place at a height where air and thermal loads are low enough to be readily manageable. After separation, the Carrier Aeroplane re-enters and flies back to base and the Orbiter carries on to low earth orbit (LEO).

Spacecab was the subject of a feasibility study funded by the European Space Agency in 1993/4⁽¹⁴⁾. The main conclusions were that new technology was not needed for an operational prototype and that development cost to initial operations would be equivalent to the cost of just two or three Shuttle flights. This study was broadly endorsed by an independent review commissioned by the then UK Minister for Space, Ian Taylor, MP⁽¹⁵⁾.

6.2 Spacecab development cost

The dry mass of the Spacecab lower stage (carrier aeroplane) is 71 tonnes and that of the upper stage (orbiter) is 7 tonnes. From the lower trend line in Fig. 8, the development cost of Spacecab prototypes should be around \$2,000m for the carrier aeroplane and \$200m for the orbiter, making a total of about \$2.5bn in round numbers. This may seem like a low figure for a vehicle of comparable size to Concorde and with a maximum speed (carrier aeroplane) twice as fast. However, there are two reasons why development costs can be that low. First, Spacecab should be able to enter service when developed as far only as the prototype stage because, even then, it should be far safer than ELVs. As discussed earlier, this is about ten times less expensive than development to full certification. (Total Concorde development cost was about ten times greater than that of the prototypes.)

Second, as with Quarter Concorde, the Spacecab Carrier Aeroplane has to maintain its maximum speed for a very short time—just long enough for the Orbiter to separate—whereas Concorde had to do so for more than two hours. This means that high aerodynamic efficiency is not needed and that the high fuel consumption of rocket engines can be tolerated during the Carrier Aeroplane boost phase. This removes the need for advanced engine intakes and for a thin wing of complex shape.

6.3 Timescale and operating cost

The development timescale for Spacecab starting from now should be comparable to that for Quarter Concorde—seven years for prototypes and eight to mature the design, given adequate priority. However, if Quarter Concorde were developed first, many of the advances in technical and operational maturity could be applied to Spacecab, and the timescale might be somewhat shortened.

As soon as a vehicle like Spacecab enters service, the potential for low-cost access to space will become highly visible. It will be able to undercut ELVs of comparable payload, because of lower marginal cost per flight. It will encourage the development of new markets, especially space tourism, that require the cost and safety of spaceplanes. This will encourage investment to enlarge and mature the designs, which will lead to lower costs, which will lead in turn to larger markets—and so on down a virtuous cost spiral until the lower cost limit is reached for vehicles using mature developments of existing technology. As shown later in Section 11.2, the cost per seat in an enlarged and mature development of Spacecab is in the region of \$10,000.

The first orbital spaceplane will enable the aviation approach to be applied to space stations, RHLVs, and space tugs, as described in the following three sections.

7.0 SPACE STATION

As soon as a small orbital spaceplane like Spacecab becomes operational, the design requirements of space stations can be relaxed. Regular supply flights will be routinely affordable, as will flights to carry repair crew to fix failures that cannot wait until the next supply flight. Perhaps more importantly, operators will be able to plan to rescue crews reliably in case of emergency. The exceptional factors that make present space stations so expensive will then no longer apply.

Given these relaxed requirements and that, as discussed earlier in Section 2.3.2, a space station is inherently simpler than an airliner, it is almost certainly conservative to use the upper trend line from Fig. 8 for a preliminary estimate of development cost.

The ESA Columbus module of the ISS weighs 10t empty but depends on ISS for services. If we assume that a free-flying derivative would weigh 20t, the development cost from Fig. 8 is \$2bn. This is almost certainly on the high side given that Columbus itself, which is most definitely not a product of the new space age, cost about that amount and that SpaceX and Bigelow Aerospace are

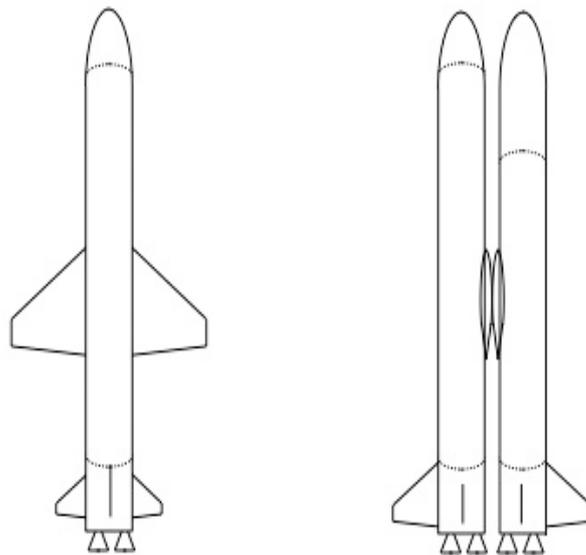


Figure 10. Reusable Heavy Lift Vehicle (RHLV) twin concept.

developing useful HSF capsules or stations for a small fraction of that sum. (We were unable to obtain cost figures from either company, but it is clear that they are talking in terms of hundreds rather than thousands of millions of dollars.)

For present purposes, we will use a figure of \$2bn for the development cost of a small space station. This is clearly an approximate estimate but is almost certainly conservative.

8.0 REUSABLE HEAVY LIFT VEHICLE

Some large satellites, space station modules, and other spacecraft will be too large for carriage in spaceplanes that take-off from conventional runways, even when broken down into modules that are assembled in orbit. There will therefore continue to be a requirement for heavy lift vehicles that take off vertically.

One attractive layout is the so-called twin configuration, Fig. 10, in which two similar vehicles are coupled together, one as booster and the other as orbiter. During the boost phase, all engines are used and the orbiter engines use propellant transferred from the booster. The booster therefore uses its propellant first. It then separates from the orbiter, which starts the subsequent acceleration to orbit with full tanks. Spaceplane technology would be directly relevant to the recovery systems.

Compared with conventional two-stage vehicles, there are some cost savings due to stage commonality, and reliability gains through starting all engines before take-off. On the other hand, the separation velocity is less than for an optimised two-stage vehicle, which results in a lower payload for a given launch weight.

If the tankage were similar in size to that of Ariane 5, the payload to LEO would be in the range of 10 to 20t. If the tankage of Ares 5 were used, the payload would be more than 100t. These configurations would provide fully reusable transport for heavy payloads to and from LEO and their launch cost would start to come down the learning curve for RLVs shown in Fig. 2.

Other configurations are possible. In the 1960s, several of the Apollo major contractors considered that reusable derivatives of the massive Saturn 5 were desirable and feasible⁽¹⁶⁻¹⁸⁾. A variety of recovery systems were studied, including wings and parachutes. If Saturn had not been abandoned in the early 1970s, it seems likely that it would have been developed on these lines.

Starting now, the development cost of an RHLV would be high because of the combination of large size and lack of familiarity with the technologies and operational techniques needed for re-entry, fly back, landing, and rapid turn-around. However, spaceplanes will introduce precisely such familiarity and it would then be practicable to develop an RHLV at modest cost in an experimental workshop. The engines, most of the systems, and perhaps even tankage and structure, could be readily adapted from those of existing ELV designs.

To provide a preliminary estimate of the development cost of a twin configuration, the lower trend line in Fig. 8 can be used. To be consistent with the size of space tugs described later, a payload to LEO of 50t has been assumed. The inert mass of each stage is then about 100t. Using the lower trend line in Fig. 8 results in a prototype development cost of three billion dollars. To allow for the fact that the two stages are not identical, it should be conservative to assume a total development cost of \$4bn.

These costs can be compared with those of the SpaceX series of launchers. The small Falcon 1 was developed from scratch for approximately \$100m. The total development cost of Falcon 1, the larger Falcon 9 (some ten tonnes to LEO), and the seven-seat Dragon cargo and astronaut carrier (to be launched by Falcon 9) has been quoted as about \$300m⁽¹⁹⁾, although it is not clear if this includes full man rating. These costs are well below the trend line in Fig. 8, which indicates the possibility of developing an RHLV for less than the \$4bn estimated above.

9.0 SPACE TUGS

The orbital spaceplane, low-cost space station, and RHLV described above will provide regular, reliable, and economical access to LEO. The aviation approach can then be extended to space tugs for geostationary orbits (GEO), the essential requirements for this approach being reusability and reasonable utilisation. These tugs will spend their working lives in space. They will be launched by the RHLV and refuelled and serviced in LEO. They can use propulsion systems developed for spaceplanes, and other systems developed for low-cost space stations.

An initial mass of 50t has been assumed for the purposes of a preliminary cost estimate. We have assumed the use of LOX/LH₂, rather than storable propellants, to maximise the payload. To reduce the velocity requirements, aero-braking is used to slow down the Tug for insertion into LEO on return to earth.

Technologies that will need to be refined include storing hydrogen fuel in orbit and aero braking. The longer that the hydrogen can be stored, the more flexible can be the operations for transporting the fuel from earth to LEO (using the RHLV). Precise navigation will be required to ensure accurate aero-braking.

Preliminary sizing estimates for the Tug are shown in Appendix 2. The outbound payload is in the five tonne class, assuming a small return payload. If a higher return payload is required, the outgoing payload is reduced. These payload masses are gross in that they include any accommodation or services needed for the useful load itself.

Given that the Tug uses many components from the low-cost orbital infrastructure and that no new technology is required, it is almost certainly conservative to use the upper trend line in Fig. 8 for a preliminary estimate of development cost. With an inert mass of eight tonnes, the development cost of the Tug works out at \$900m. Again, this is no more than a first preliminary estimate but, at this stage, we are looking for conservative approximations rather than precision.

This cost will no doubt seem low to those used to the present way of developing space projects. We are suggesting that it is achievable by the combination of ready access to LEO, familiarity with all the technologies, reusability, reasonable flight rates, and the ability to rescue astronauts reliably at any stage of a mission. The engineering standards required for space tugs should then be similar to those of aeroplanes.

10.0 THE NEW SPACE AGE

The orbital spaceplanes, space stations, RHLVs, and space tugs provide the basic vehicles needed for the low-cost use of near-earth space. The RHLV would be used to launch large satellites and space station modules, and the spaceplane for routine supply and maintenance flights. Space tugs would be used for higher orbits. The pivotal development needed for this low-cost infrastructure is the orbital spaceplane, as the other vehicles depend on it for low-cost access or for technology.

This idea of a complete orbital infrastructure is by no means new. The rocket pioneer von Braun and others carried out realistic studies in the early 1950s [20]. NASA came close to achieving it thirty-five years ago with the X-15, Skylab space station and Saturn heavy lift vehicle—but did not close the gap by developing an orbital successor to the X-15 or a reusable development of Saturn 5, as discussed earlier.

When spaceplanes enter service, access to orbit will become routine. Space will lose its ‘exceptionalism’, which, following the heady pioneering days, is nowadays due almost entirely to very high launch cost. This is due in turn to the continuing exclusive use of throwaway launchers. No other form of commercial transport uses expendable vehicles.

Space tourism is likely to become the largest commercial user of this low-cost orbital infrastructure [e.g., 5] and could provide much of the funding needed for maturing the technology. Pilot schemes for manufacture in orbit and space solar power generation for use on earth will become affordable, and transportation cost will no longer be a barrier to subsequent commercial exploitation.

The result will be low-cost access to orbit of benefit to all commercial and scientific users of space. The term ‘new space age’ (or just ‘new space’) is becoming recognised as a suitable name for this radically improved space scenario.

As mentioned earlier, but worth repeating, this new infrastructure will be based on aviation standards of engineering and operations, and will reduce costs and encourage the development of new markets. These new markets will encourage investment to mature the designs, which will lead to lower costs, which will lead to larger markets—and so on down a virtuous cost spiral on the lines of the learning curve for RLVs shown earlier in Fig. 2.

The analysis behind Fig. 2 is adequate to show broad trends but provides only an approximate idea of the lower limit. To explore this further, the next section considers a mature second-generation spaceplane developed after Spacecab and estimates its operating cost after a long production run and continuous product improvement.

11.0 LARGE (SECOND GENERATION) ORBITAL SPACEPLANE (SPACEBUS)

11.1 Spacebus leading data

Spacebus, Fig. 11, is an enlarged development of Spacecab. It is designed such that a prototype could be built a few years after Spacecab without requiring a significant programme of enabling technology. It therefore retains the use of two stages. It weighs about twice as much as Concorde, which is probably close to the practicable upper limit for spaceplanes using existing runways. Both stages are piloted and take-off and land horizontally. The carrier aeroplane accelerates to Mach 4 using turbofanjets of new design but using existing technology. Rocket engines are then used to accelerate to Mach 6 and to climb to the edge of space where air and thermal loads are low. The orbiter then separates and accelerates to orbit.

Spacebus is designed to carry 50 people or equivalent cargo. Leading data are shown in Table 6. The basic design features of Spacebus were derived using a similar process to that described earlier in Section 3.2 for Quarter Concorde and are summarised in

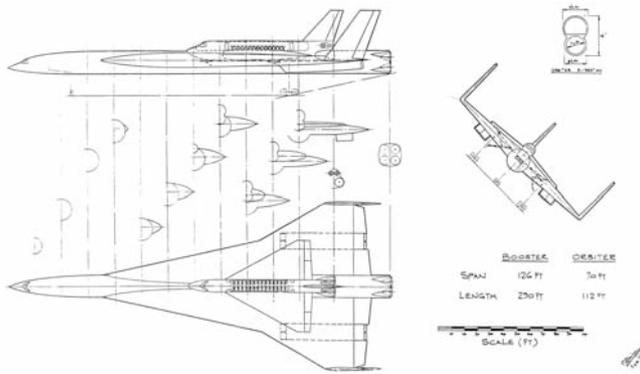


Figure 11. The Bristol Spaceplanes Spacebus Concept.

Table 6
Spacebus leading data

	Carrier aeroplane	Orbiter
Span, m	38	21
Length, m	88	34
Max speed with jet engines	Mach 4	N/A
Separation speed	Mach 6	N/A
Rocket propellants	LOX/kerosene	LOX/LH ₂
Take-off weight, tonnes	400	90
Empty weight, tonnes	113	16
Payload, tonnes	90 (upper stage)	5

Fig. 12. Clearly, the optimum design depends on the requirements set. We have assumed that Spacebus should be designed for the best return to investor or taxpayer, rather than for technical elegance or maximum efficiency. This means giving priority to early revenues, to minimising development cost and risk, and to accessing large new markets.

11.2 Spacebus cost per flight

The cost per flight of Spacebus will be reduced as it progresses down its various learning curves. Eventually, after a long production run, its cost per flight should approach the lower limit possible with mature development of more or less existing technology. Given a fleet of a few dozen vehicles, each making several flights per day to space, airliner cost estimating relationships can be used to assess the likely direct operating cost.

Appendix 3 shows an estimate of Spacebus cost per seat based on scaling the costs of a Boeing 747. The resulting cost, rounded up, is eight thousand dollars. To this must be added indirect costs and profits, which would bring the total up to about ten thousand dollars, which is consistent with Fig. 2.

Preliminary estimates (e.g., 5) show that the total cost of a few days in a space hotel will be about twice the cost of getting there. Thus the cost of visit to space, when all systems are mature, should be in the region of \$20,000. This cost is affordable by middle-income people prepared to save, and so orbital space tourism has the potential to become a big business as soon as mature spaceplanes become available, as discussed later in Section 11.4.

A very reasonable question is why these costs are so much lower than those of the Shuttle Orbiter, which itself is fully reusable. The basic cause is that the complete Space Shuttle vehicle is not reusable — the Orbiter is launched using an expendable propellant tank and recyclable (not reusable) solid rocket boosters. Section 2.3.3 described in general terms the cost penalties arising from expend-

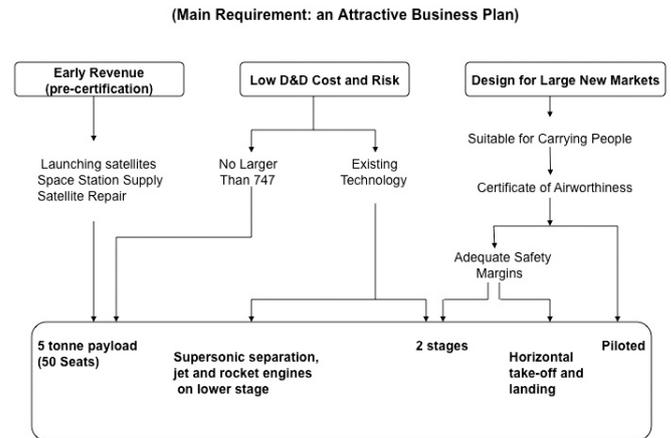


Figure 12. Spacebus design logic. The basic design features have been selected to give a high return to investor or taxpayer.

ability. Applying the conclusions from this section to the particular case of the Shuttle leads to two main reasons for its high cost per flight. First, the total cost per flight of the complete Shuttle is so high, because of the use of non-reusable components, that the number of flights remains too low for the Orbiter to even approach airliner standards of maturity.

Second, the safety of the Shuttle crew depends on large complex non-reusable components, which are inherently unsafe by conventional aviation standards. Indeed, the two fatal accidents were caused by the non-reusable components failing in a manner that damaged the Orbiter.

Another reason is that each flight has a different payload that requires close integration with the Orbiter.

This technical immaturity, concern for safety, and non-standard payloads, result in the number of people involved in flight preparation being measured in thousands, compared with the ten or so for an airliner.

Spacebus is fully reusable and therefore not subject to these limitations.

11.3 Spacebus development cost

The dry mass of the Spacebus lower stage (carrier aeroplane) is 113t and the upper stage (orbiter) is 16t. From the lower trend line in Fig. 8, the development cost of Spacebus prototypes would be about \$3,000m for the carrier aeroplane and \$500m for the orbiter, making a total of \$3,500m.

The cost of development to full certification and design maturity might be expected to be about ten times greater, at around \$35bn.

11.4 Spacebus markets

Achieving the low operating cost estimated above depends on obtaining the funding to mature the design, and this in turn depends on large new markets. As with Quarter Concorde, the largest market is likely to be carrying passengers, in this case to and from space hotels. Repeating the approach used for Quarter Concorde, we assume for a conservative preliminary estimate of market size that the world’s industrialised population is 1bn people and that 1% of these would be prepared to pay \$20,000 for a visit to a space hotel. The initial market then works out at \$200bn. This should be large enough to provide the funding for maturing the technology with a good return on investment, but the margin of error of these preliminary estimates is such that this conclusion cannot be considered robust.

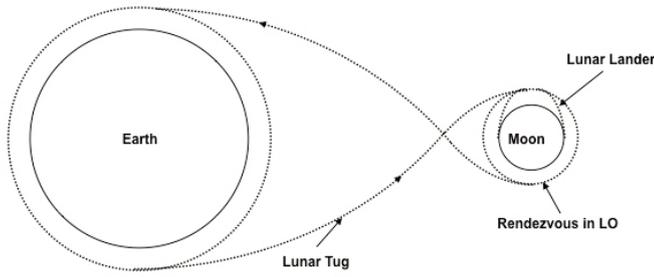


Figure 13. Lunar exploration architecture (not to scale).

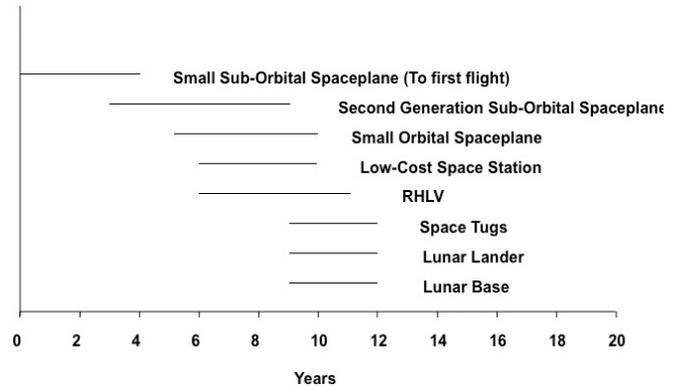


Figure 14. Development timescales for a lunar base using the aviation approach.

12.0 TO THE MOON

It is relevant to consider whether the development of the low-cost infrastructure can save money on missions at present being planned. To explore this question, we have carried out a preliminary sizing and cost estimate of a simple lunar base. The architecture that we have assumed is summarised in Fig. 13.

A Lunar Tug is used for transportation between LEO and lunar orbit (LO). The velocity requirements are quite close to those for geostationary orbits. More velocity is needed from LEO to a lunar transfer orbit than for a geostationary transfer orbit (GTO) but less for insertion into lunar orbit than into a GEO one, and these two differences nearly cancel out. The GEO Space Tug can therefore readily be adapted to serve as a Lunar Tug for transport between LEO and LO.

A Lunar Lander is used to transport payloads from LO to and from the lunar surface. Early payloads would be the modules for a lunar base and the astronauts to assemble them. The Lunar Lander is assembled in LO from modules sent there by the Lunar Tug. It is refuelled in LO with propellant modules also transported by the Lunar Tug. Subsequent payloads are transferred from Tug to Lander in LO.

A simple early lunar base would probably have a mass in the region of 20 tonnes and would consist of an accommodation module derived from space stations, together with external stores and equipment. Several missions would be needed to transport the base and supplies from Earth to the Moon.

Preliminary sizing estimates for the Lunar Lander are shown in Appendix 2. The inert mass is 2.3t. Using the upper trend line in Fig. 8 for a preliminary estimate indicates a development cost of \$250m.

We are not claiming that these concepts and sizes for the RHLV, Tug, and the Lunar Lander are in any way optimised. There is scope for ingenuity in maximising commonality between these vehicles by means of a modular approach, and for optimising the logistics, which we have not investigated. We have done just sufficient rough order of magnitude sizing to enable a preliminary but conservative estimate of development costs.

13.0 TIMESCALES

Figure 14 shows a tentative set of timescales for developing operational prototypes of the vehicles needed for a simple lunar base, as described above. The bars represent the times between go-ahead and first operational use. The timescales shown are a compromise between a high-priority programme, in which the vehicles are developed in parallel, and a lower-risk programme in which they are developed in series. Development times for later vehicles are assumed to shorten as familiarity with the aviation approach becomes more widespread and as systems developed for earlier vehicles become available for later ones. Spacebus is not shown because it is not essential for the first lunar base.

Table 7
Development cost of vehicles for a simple lunar base

Vehicle	Design Status	Development Cost (\$ million)
Ascender	Feasibility study	60
Quarter Concorde	Concept sketch	
	ROM Sizing	500
Spacecab	Feasibility study	2,500
Space Station	ROM Sizing	2,000
RHLV	ROM Sizing	4,000
Tug	ROM Sizing	700
Lunar Lander	ROM sizing	250
Lunar Base	ROM sizing	2,000
<i>Total, \$ million</i>		<i>12,010</i>

Early missions use these operational prototype vehicles, as even these should be safer and less expensive to develop than expendable designs. These prototypes can then be improved towards airliner standards of maturity through a programme of continuous product improvement, probably largely paid for by commercial applications.

On this basis, a simple lunar base could be operational within 12 years from the start of a revised programme of lunar exploration based on the aviation approach. If this started immediately, the date of the first lunar base would not be much later than the present target NASA date of 2020. Achieving a date that soon requires that orbital spaceplane development be given priority in the near future.

It is likely to be several years before the private sector alone will be able to find the funding for an orbital spaceplane. The major unknown at present is the size of the demand for space tourism, which will directly affect the funding available for development and hence the timing. Coming close to the 2020 target therefore requires governments to give priority soon to spaceplane development, and this is discussed later in Section 15.

14.0 THE COST OF A LUNAR BASE USING THE AVIATION APPROACH

The previous sections have presented approximate but conservative estimates of the development costs of the vehicles needed for an early lunar base. These are summarised in Table 7. A lunar base has been added with a notional inert mass of twenty tonnes and a development cost of \$2bn. Again, these are no more than first preliminary estimates but, at this stage, we are looking for conservative approximations rather than precision. Also shown is the present

design status of the various vehicles in the table, ranging from full feasibility study to concept sketch and rough order of magnitude sizing.

On this basis, the total cost of developing the vehicles needed for an early lunar base is \$12bn in round numbers.

These costs are only for developing operational prototypes. To this has to be added the cost of the operations needed to set up an early lunar base. A preliminary guide to the cost of these operations can be provided by the Apollo programme. Budget appropriations for each year of the Apollo programme^(21,22) show that the cost of operations is at most 30% of the development cost and probably significantly less. It is difficult to be more precise without going into more detail because it is not obvious from the numbers readily available where development stopped and operations began.

Reusability should lower the cost of operations compared with development, so it should be conservative to use the above 30% figure, giving a grand total for setting up a lunar base of \$16bn. The average annual cost is around \$1.3bn, which is readily affordable by NASA and ESA. Indeed, it is considerably less than the present budget for human spaceflight.

We are certainly not claiming that the \$16bn figure is accurate. But we are claiming that it should be an upper limit, given an efficient programme.

15.0 PUBLIC-PRIVATE PARTNERSHIP

NASA and other space agencies are planning a new exploration of the Moon, and NASA has started developing the large Ares 1 and Ares 5 expendable launchers. The latter is broadly comparable to the massive Saturn 5 used in the US lunar programme of the 1960s and early 1970s. The cost of this programme, which includes a lunar base, is estimated to be between \$105bn dollars (NASA) and \$230bn (General Accounting Office)^(23,24). History suggests that the latter is more likely to be accurate.

Thus the total cost of a lunar base using the aviation approach, according to the estimates presented in this paper, is approximately one fourteenth of the GAO figure, or, say, one tenth for the sake of a more cautious claim and a round number.

This difference is so great that, even allowing for the conjectural assumptions used to derive this result, it is safe to conclude that the aviation approach should greatly reduce the cost of a lunar base.

We suggest that the best way to achieve a more accurate cost estimate is for space agencies to engage industry in the idea of a public-private partnership to develop spaceplanes, to bring in the aviation approach, and to explore the moon. Government would carry the political and marketing risks and the private sector the programme risks. Government agencies would thereby fund the development of vehicles with maturity adequate for the next round of human spaceflight missions. They would save money on present programmes alone because of the lower costs when spaceplanes are used. The private sector would then fund a programme of product improvement towards airliner maturity, paid for by profits from commercial operations, especially tourism.

A public-private partnership on these lines might involve replacing Ares 1, which is designed for transporting crew, with a spaceplane like Spacebus, and evolving the design of Ares 5 into a fully reusable launcher—either a twin configuration or using concepts from the 1960s studies of reusable developments of Saturn 5.

16.0 DISCUSSION

SpaceShipOne has demonstrated the possibility of low-cost sub-orbital human spaceflight in the near future. Allowing for inflation, it cost some 50 times less to develop than the X-15 of the 1960s, which had comparable performance. This paper has shown that second-generation successors to SpaceShipOne will have a cost per

seat of less than \$2,000, given a high enough demand to fund a programme of maturing the technology. Thus, small spaceplanes using SpaceShipOne as an exemplar will enable passengers to experience spaceflight at an affordable cost, by bringing in the aviation approach of reusability and a high number of flights per year. They will also transform sub-orbital space science.

This paper has presented a development strategy for progressively extending this aviation approach to near-Earth spaceflight. There is a realistic prospect that the cost of science in space could thereby approach that in Antarctica and that visits to space hotels could become affordable by middle-income people prepared to save. Given the funding, this could be approached in about 15 years — seven for prototype vehicles and eight to mature the technology. The pivotal development is the first orbital spaceplane.

The paper has shown that, while it may seem paradoxical at first sight, it is precisely because spaceplanes are inherently so much safer and less expensive to fly than man-rated expendable launchers that they can cost less to develop. Operational prototypes can be built in experimental workshops and their marginal cost per flight is not a barrier to adequate testing. The same should apply to heavy lift vehicles and space tugs, given reusability and a reasonable number of missions per year.

Space agencies would save money on presently planned programmes alone by giving priority to spaceplane development. As an example, the paper has presented an approximate but conservative estimate showing that the cost of an early lunar base using the aviation approach would be about ten times less than that of present plans that use expendable launchers. Timescales need not be greatly affected. Such cost reductions would enable more space exploration missions to be carried out using existing budget streams.

The best way ahead is for space agencies to engage with industry in the idea of a public-private partnership for developing orbital spaceplanes and follow-on vehicles.

The cost estimates presented in this paper are inevitably based on some conjectural assumptions. However, they are conservative and they do show that the potential of spaceplanes to reduce the cost of space exploration is so great that further investigation is needed urgently.

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A1 OPERATING COST OF QUARTER CONCORDE WHEN MATURE

	Regional airliner	Quarter Concorde
Leading data		
All up weight, tonnes	55	46
Seats	100	22
Utilisation		
Hours per flight	1	1*
Fights per day (average)	5	5
Flights per year	1,825	1,825
Fuel consumption per flight, tonnes		
Jet fuel (kerosene)	5	7
LOX		12
Rocket fuel (kerosene)		5
Cost data		
First Cost, \$m	50	100*2
Insurance, % first cost per year	1.5	1.5
Depreciation, % first cost per year	10	10
Kerosene cost per tonne	462	462
LOX cost per tonne	110	110
Maintenance cost, % first cost per day	0.012	0.012
Annual costs, \$m		
Depreciation	5.00	10.00
Insurance	0.75	1.50
Cost per flight, \$		
Depreciation	2,740	5,479
Insurance	411	822
Jet fuel (kerosene)	2,287	4,745
Liquid oxygen		1,320
Rocket fuel (kerosene)		2,310
(Total propellant)	(2,287)	(8,375)
Maintenance	1,200	2,400
Crew	2,700	2,700
Total direct operating cost	9,338	18,265
Cost per seat, \$	93	830

Notes

1. Mature sub-orbital spaceplanes will make several flights per day of about one hour duration. For the sake of comparison, the region airliner is assumed to have similar utilisation.
2. The spaceplane is assumed to cost twice as much because of greater complexity and smaller production run.

A2 PRELIMINARY SIZING OF SPACE TUG AND LUNAR LANDER

	GEO Tug	Lunar lander
Basic data		
Launch mass, tonnes	50 in LEO	15 in LO
Specific impulse, sec	450	450
Inert/gross mass	0.15	0.15
Delta V requirements, m/sec		
	2,600 LEO to GTO	2,300 LO to surface
	1,600 GTO to GEO	
	4,200	2,300
Mass ratio (outbound)	2.59	1.68
Propellant mass, tonnes	30.69	6.09
Mass after outbound burn	19.31 in GEO	8.91 on Moon
Inert mass	7.50	2.25
Disposable mass	11.81 in GEO	6.66 on Moon
Of which, payload	5.00	5.00
Mass before second burn	14.31 in GEO	3.91 on Moon
Delta V requirements, m/sec		
	1,600 GEO to ETO	2,300 surface to LO
	2,600 ETO to LEO	
	-2,000 aero braking	
Margin	250	
	2,450	2,300
Mass ratio (return)	1.74	1.68
Propellant	6.09	1.59
Mass after return burn	8.21 in LEO	2.3 in LO
Inert mass	7.50	2.3
Return payload, tonnes	0.71	0.07

A3 COST COMPARISON BETWEEN SPACEBUS AND BOEING 747

	747	Spacebus Carrier Aeroplane	Spacebus Orbiter	Spacebus Total
Technical data				
Wing span, m	65	38	21	
Length, m	71	88	34	
Wing area, sq m	525			
Passenger seats	420		50	50
Fuel mass, tonnes				
Liquid oxygen		75	56	131
Liquid hydrogen		17	13	30
Kerosene	170	80		
Total	137	172	69	241
Empty mass, tonnes	184	112	15	127
Take-off mass, tonnes	396	312	88	400
Cost data				
Complexity factor	1	2.5	5	
Fuel unit cost, \$/kg				
Liquid oxygen	0.11			
Liquid hydrogen	2.80			
Kerosene	0.46			
First cost, \$m	250	380	102	
Flights per day	1	2	1	
Annual costs, \$m				
Amortisation	25.00	38.04	10.19	
Insurance	3.75	5.71	1.53	

Costs per flight, \$

Fuel	78,200	92,650	41,326	133,976
Amortisation	68,493	52,114	27,918	80,033
Insurance	10,274	7,817	4,188	12,005
Crew	28,000	28,000	28,000	56,000
Maintenance	25,000	38,043	10,190	48,234
Landing fees, navigation	25,000	25,000	25,000	50,000
Total	234,967	243,625	136,622	380,247
Cost per seat, \$	559			7,605

Notes

1. The main assumption is that Spacebus has been developed to airliner standards of maturity, i.e., life, maintainability, and turn-around time. It is then reasonable to use airliner cost estimating relationships to assess its likely cost. The above table starts with 747 costs, taken from various sources, and uses simple scaling rules to estimate the equivalent costs of Spacebus.
2. In the above table, complexity factor is a measure of relative production cost per unit mass. Thus, the Spacebus Orbiter is assumed to cost five times as much per kg empty mass as the 747. This, and several other, assumptions could be significantly in error without greatly affecting the total, which is dominated by the cost of fuel.
3. The cost per kg of liquid hydrogen assumes a higher production rate than at present. Even so, it is roughly ten times more expensive than kerosene.
4. First costs have been scaled by empty weight and 'complexity factor'.
5. The 747 is assumed to make one 12-hour flight per day, as is the Spacebus Orbiter. The Spacebus Carrier Aeroplane has a flight time of one to two hours and is assumed to make two flights per day.
6. Annual amortisation is 10% of first cost, and annual insurance is 1.5% of first cost.
7. Crew costs are assumed the same for all vehicles. The shorter flight time of Spacebus is assumed to balance higher salaries for spacefaring pilots and cabin staff.
8. Maintenance costs are scaled in proportion to first cost.