Space Transport Systems for the 21st Century *

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I was recently asked to talk about "Space Transport Systems for the 21st Century" and my problem was to link this with the theme of the forum, namely "Mobility on Earth". I began by suggesting that "space transport" is an extension of "Mobility on Earth". Indeed, even when in space, we remain captives of the Earth's gravitational field, if we exclude the very few space flights that go beyond our planet's sphere of influence.

In addition, ESA's space activities are largely oriented towards our planet: we observe the Earth from space, we communicate on Earth via space, and we return the results of our scientific probing of the Universe to Earth. Moreover, all of our space activities are prepared on Earth, and any funds we spend on space are spent on Earth. We also evolve in and learn about using and exploiting our near-Earth space environment from here on Earth.

Space: a new environment
Contrary to the often expressed view that "there is nothing in space", this near-Earth space environment is of great interest. The following are just a few of its features:

– It is vast, as its volume extends beyond the orbit of the Moon. Within this volume, and once we have surmounted the initial hurdle of reaching low Earth orbit, we can move at will with relative ease; in fact with much greater ease than when we want to move around on the surface of the Earth.
– It has unlimited and unconstrained access to the full power emitted by the Sun.
– It is free from the crushing force of gravity, so that in space we can build gigantic structures that would be unthinkable on Earth.
– Its perfect and infinite vacuum allows contamination-free fabrication processes.
– It is the perfect black-body heat sink and the ideal environment in which to apply the advances of superconductivity.

We can surely find other unique features, but most importantly:

– It is the vantage point from which our planet can be observed in its entirety, from which global correlations become obvious, and the whole Universe can be probed with unlimited clarity. Space offers a new perspective, which can shape mankind's view of itself, its role and its destiny.

Now that I have made my point about how interesting the space environment is, you might also ask whether we, as a species, should appropriate this environment, which is also very hostile to life because of its vacuum, its radiation, and its extreme thermal gradients? Well, it is interesting to observe that nearly every domain on planet Earth is occupied by life, in the form of viruses, bacteria, plants and animals. Today, we humans already occupy a much larger ecological domain than the one naturally suited to us. Indeed, our expansion on this planet has been due not so much to our natural adaptability, but to our intellect and dexterity, which allow us to cloth and protect our bodies from heat or cold, to extend our range through animal-based or mechanical means of transport, and to recreate cosy conditions even in areas naturally hostile to our presence. In fact, we have expanded our living environment through technology, and I would suggest that there is a very direct link between our technological capabilities and the environments that we can penetrate, exploit and eventually occupy.

As far as space is concerned, we are still at the stage of the early pioneers of the Wild West, with early commercial undertakings and the first settlements on the horizon. However, because space completely surrounds the Earth and is accessible from anywhere on our planet, its exploitation and colonisation will not be the act of people from a single continent as was the case for the American West, but will be a task for the whole of humanity.

The key to the new environment: access to space, the expendable rocket launch vehicle
So, if I am convinced that space will become part of daily life on our planet, how come that

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we do not yet have colonies in Earth orbit or on the Moon? What are we waiting for? Well, we are still waiting for the right transportation system, and I will try to outline the scope of the problem.

Although it is deceptively close, the only way we can imagine today of reaching near-Earth space and staying in it is to place ourselves in orbit around Earth. This requires imparting a speed of almost 8 km/s to a body at least 100 km above the surface, for which we currently rely on launchers powered by chemical rocket propulsion. The latter generates the thrust required to accelerate the launch vehicle by ejecting a stream of gaseous matter as fast as possible. The most practical solution with the highest performance is provided by the combustion of hydrogen with oxygen. However, both of the propellants must be carried onboard the launcher (usually in liquid form), unlike a car engine, for instance, which can draw its oxygen from our planet's atmosphere.

As a result, the mass fraction of propellants required onboard such a launcher is much closer to 1 than it is for transport systems on Earth. If we take Europe's state-of-the-art Ariane-5 launcher (Fig. 1) as an example, its total take-off mass is, grosso modo, 735 tons. Of these, 7 tons are the payload to be carried into geostationary transfer orbit (corresponding to about 20 tons into low Earth orbit), 643 tons are the propellants needed, and only 85 tons are made up by the tanks that contain the propellants, the rocket engines to produce the required thrust, the avionics to guide the launcher, and all of the other elements that constitute a complete launch vehicle. This hardware is discarded once the propellants have been ejected, and Ariane-5 is therefore classed as an "expendable launcher". For each launch, a complete new vehicle must be constructed, assembled and launched, at a cost of some 140 million ECU.

This is still a high price for putting a few tons of payload into Earth orbit, but it was even more expensive in the past. As a result, incursions into space remain the preserve of an elite of astronauts and scientists and of high-value satellites and probes; today's commercial applications of space are primarily still those that deal in the flow of information and not of material goods.

How come expendable launchers are not cheaper? It is mainly because they are complicated machines that must work under very high stress levels and meet very exacting safety requirements. As a result, the margin between success and failure is very narrow and launchers still fail from time to time, often for seemingly trivial reasons or due to minor oversights.

If we now look to commercial aviation, a large aircraft such as an Airbus 340 costs about as much to purchase as an Ariane-5 launcher. However, the aircraft is capable of logging many thousands of flying hours with extraordinary safety. Its fuel load represents only 30% of its take-off mass and is an easy to handle petroleum product. Its dry mass is a comfortable 50% of the take-off mass, and its engines can run for thousands of hours without a major rebuild.

Clearly, today there is no technical or operational commonality between an aircraft and a rocket launcher. It is therefore hardly surprising that their markets and their marketing logic have so little in common.

Figure 1. Lift-off of the second Ariane-5 test flight from the ELA-3 launch complex at the Guiana Space Centre on 30 October 1997

The future imperative for access to space: reduce the cost!

The question now then is whether aviation and space, which today seemingly have so little in common, could or should come together more closely in the future. There are two trends that might lead to a possible convergence in the longer term: one is the desire to reduce the cost of access to space, and the other is the search for higher speeds in aviation in order to reduce journey times.

As regards the need for reducing the cost of access to space, the main argument of its proponents is that, with the present cost of launching with expendable launchers, applications of space will never blossom beyond those of today and that space will remain a restricted market. If, however, the cost of access to space could be lowered by a factor of 10, or 100 or 1000, then many more uses of space - most of them still to be discovered or invented - might become possible and the market revenue from commercial space activities might reach what now seem impossible orders of magnitude.

In fact, however, the situation is not that clear-cut between the claimed presently excessive high costs and the as much claimed need for so much lower costs in the future. In reality, space is already a very profitable and dynamic market, as evidenced by the recent boom in communications satellites for network applications. In such applications, which will generate turnovers of many billions of dollars, the launch costs represent a very minor element. Nevertheless, there has been fierce competition between the launch providers to win these launch orders, with success dependent on competitive pricing. Even a slight cost advantage is therefore already very important, but we will not have to wait for the hoped for orders of magnitude cost reductions before seeing impressively large space markets.

At ESA, therefore, we are pursuing all promising options for cost reduction. Presently, our two main approaches are firstly to improve what we have to the best of our ability, and secondly to look into novel solutions within a reasonable technology horizon.

Our “improvement activities” are focussed on nurturing our current operational expendable launcher, Ariane-5. We already have an approved Ariane-5 Evolution programme running, and we are proposing an Ariane-5 performance-improvement programme known as “Ariane-5 Plus”. Both programmes are aimed at keeping pace with the evolving market needs and reducing the cost per kilogramme of payload put into orbit.

These Ariane-5 improvements, whilst important to maintain a competitive edge in the current and near-term launcher market, will not change the present launch costs by a large factor. Today’s expendable launchers have effectively reached a technology plateau in terms of technical implementation and cost per flight. Novel solutions are required if we are to reduce the cost of access to space by an order of magnitude or more and I will now briefly review some of the possibilities, before outlining what ESA has been and will be doing in this context.

Reusable launchers with rocket propulsion

The first option that comes to mind is that of reusing a launcher instead of discarding it after one mission. In the traditional view, such a vehicle would accelerate to orbital velocity, eject its payload, re-enter the atmosphere at orbital speed (28 000 km/h, or about Mach 25), dissipate its kinetic energy in working against drag, and land near the launch base, where it would then be prepared for its next flight. Such a single-stage reusable launcher must therefore carry sufficient propellant to achieve orbital speed with rocket propulsion, and must be resilient enough to survive a full re-entry from Mach 25 intact. In short, structures and engines that are expended today must instead survive a controlled re-entry and remain healthy enough to be reused many times.

This is a very difficult technical problem, the implications of which are nevertheless being investigated world-wide. The most advanced work is being done in the USA, in the form of the Reusable Launch Vehicle (RLV) programme, which includes the X33 as an Advanced Technology Demonstrator to determine whether or not the technologies needed to build a cost-effective operational RLV are available.

Air-breathing propulsion for reusable launchers

Rocket propulsion requires such high propellant mass fractions that a more performant technology needs to be found. The most obvious option is to use atmospheric oxygen for propulsion into orbit, instead of carrying the oxygen inside the launcher. Since the launcher’s

Figure 2. An ESA Future Launching System (FLS) studied, by Aerospatiale leading a team of European companies, in the early 1980s. The reusable first stage would fly back to the launch base, whilst the second stage would be expendable (courtesy of Aerospatiale)

task is to achieve its terminal speed in vacuum, some form of rocket propulsion will always be required and the air-breathing propulsion option would help to achieve the highest possible speed in the atmosphere, before exiting it with rocket propulsion.

However, orbital speed is a very high target compared with present aircraft speeds. Millions of us fly at Mach 0.9 in commercial jets, thousands fly at Mach 2 when in Concorde, and just a select few get to fly at Mach 3.5+ in the world's fastest military aircraft. These speeds are minimal compared with the Mach 25 that must be achieved to stay in orbit. Limiting the contribution of air-breathing propulsion to only the lower Mach numbers as is possible today is therefore not really helpful in making a reusable launcher more feasible.

Novel air-breathing propulsion systems able to reach speeds in the Mach 6 to 12+ range must therefore be defined and developed. Assuming that these efforts meet with success, one can imagine that these systems might also find application in global high-speed aviation.

Atmospheric oxygen collection for reusable launchers

Another possible solution is that of collecting the oxygen required for the rocket-ascent propulsion directly from the atmosphere. This would allow the launcher to take off with reduced weight, loaded only with liquid hydrogen, and then to extract the oxygen that it needs from the Earth's atmosphere. Once the required amount has been collected, the launcher would switch over to rocket propulsion and accelerate to orbital speed.

Staging for reusable launchers

All of today's launchers have several stages, allowing them to jettison structural mass as soon as the propellant that it contains has been consumed and the thrust from its engines exploited. The launcher then becomes lighter and the remaining rocket engines have a smaller mass to accelerate. Staging is currently the most efficient means of accessing space with rocket propulsion and it might therefore be of interest to apply staging in reusable launchers also.

For example, the first stage could be a rocket propulsion stage that accelerates the second (upper) stage to about Mach 6. The second stage then fires its engines until orbital velocity, while the first stage dives back into the atmosphere, decelerates to subsonic speed and flies back on turbojets to its launch base, where it can be reused. This approach introduces some additional operational complexity, but the problem of reuse is simplified.

We can also imagine a scenario in which the first stage reaches orbital altitude, but its velocity is short of orbital, and so it ejects its upper stage with payload and immediately re-enters the atmosphere to land again at its launch base after having made one circuit around the Earth, or at a base down range of the launch site.

With staging, we are also free to implement expendable or reusable second stages. When the second stage is expended, we are relieved of the problem of re-entry and we can have a more robust second stage with a higher payload capability than if it were reusable.

Many technical solutions and combinations thereof can be visualised and are possible. However, the fundamental question is, and will remain, will the chosen technology or system be able to reduce the cost of access to space by one or two orders of magnitude?

Staging also opens up options for implementing air-breathing propulsion for space launching in an elegant manner. For example, a TSTO (two stage to orbit) launcher of which the first stage is air-breathing allows one to separate the air-breathing and the rocket-propulsion cycles. Also, the high-speed propulsion system developed for the air-breathing first stage could well be of interest to the global aviation community.

ESA's approach to lowering launch costs in the longer term

I would like to turn now specifically to what has been done so far in ESA on launcher reusability, and our plans for the future. Reusable launchers are feasible technically, but it is has yet to be proved that they are economic. For many years, we have had a very small level of study activity on reusable launchers. In the early 1980s, we concluded that only partial reusability would make economic sense in the foreseeable future (Fig. 2). We also concluded at that time that the next generation of European launcher, Ariane-5 – the development programme for which began in the mid-1980s – should be expendable but optimised for cost efficiency.

In the late-1980s and early 1990s, we investigated whether the Ariane-5 architecture would be suitable for reusability, by replacing the two solid boosters with reusable liquid-propellant boosters. We concluded, however, that this approach would not be cost-effective in practice (Fig. 3).

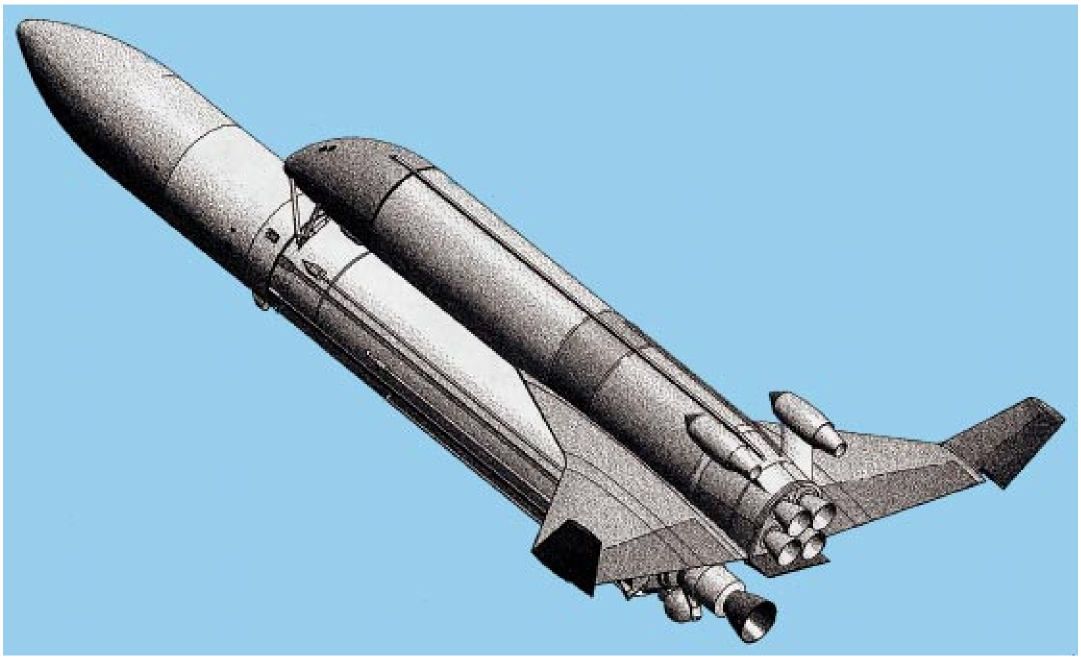


Figure 3. An ESA Reusable Rocket Launcher (RRL), studied by Aerospatiale in the early 1990s, with a reusable first stage powered by the Russian RD170 liquid oxygen/kerosene engine (courtesy of Aerospatiale)

At around the same time, the USA was undertaking the National Aerospace Plane (NASP) programme, and we tried to understand whether the air-breathing approach proposed for NASP was credible. We found this not to be an option for Europe (Fig. 4). On this same occasion, we also brought the United Kingdom's Hotol and Germany's Sänger proponents together in order to assess the respective merits of these two approaches. It turned out that neither was optimum, as the respective launcher architectures had been selected somewhat prematurely without having explored all possible alternatives.

We also knew that answers regarding the true potential of reusability will never be obtained from endless theoretical studies, but will come from practical work on mastering the new technologies needed. Therefore, in parallel with these study activities, we have proposed, at each Council Meeting at Ministerial Level since the meeting in Rome in January 1985, the implementation of a dedicated programme to explore whether the technological performance levels needed for launcher reusability could be achieved. This finally led to the investigative programme FESTIP (Future European Space Transportation Investigations Programme) coming into effect in February 1994.

FESTIP was initially approved for a first slice of three years (1994-1996) to cover concept definition and technology work. For the concept definition work, we set ourselves the goal of being prepared for a decision on the

Figure 4. An ESA Winged Launcher Configuration (WLC) studied, by DASA leading a team of European companies, in the late 1980s. It has a supersonic combustion ramjet air-breathing propulsion system (courtesy of British Aerospace)

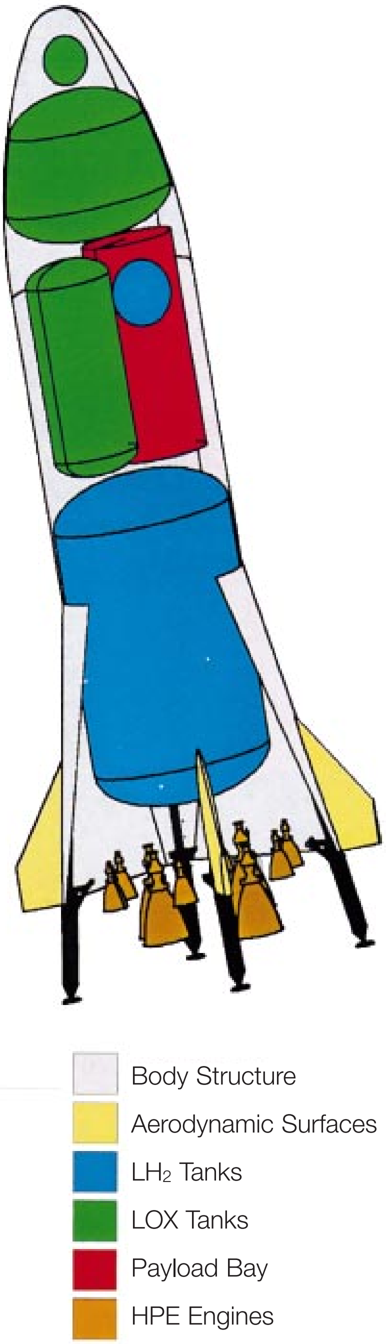
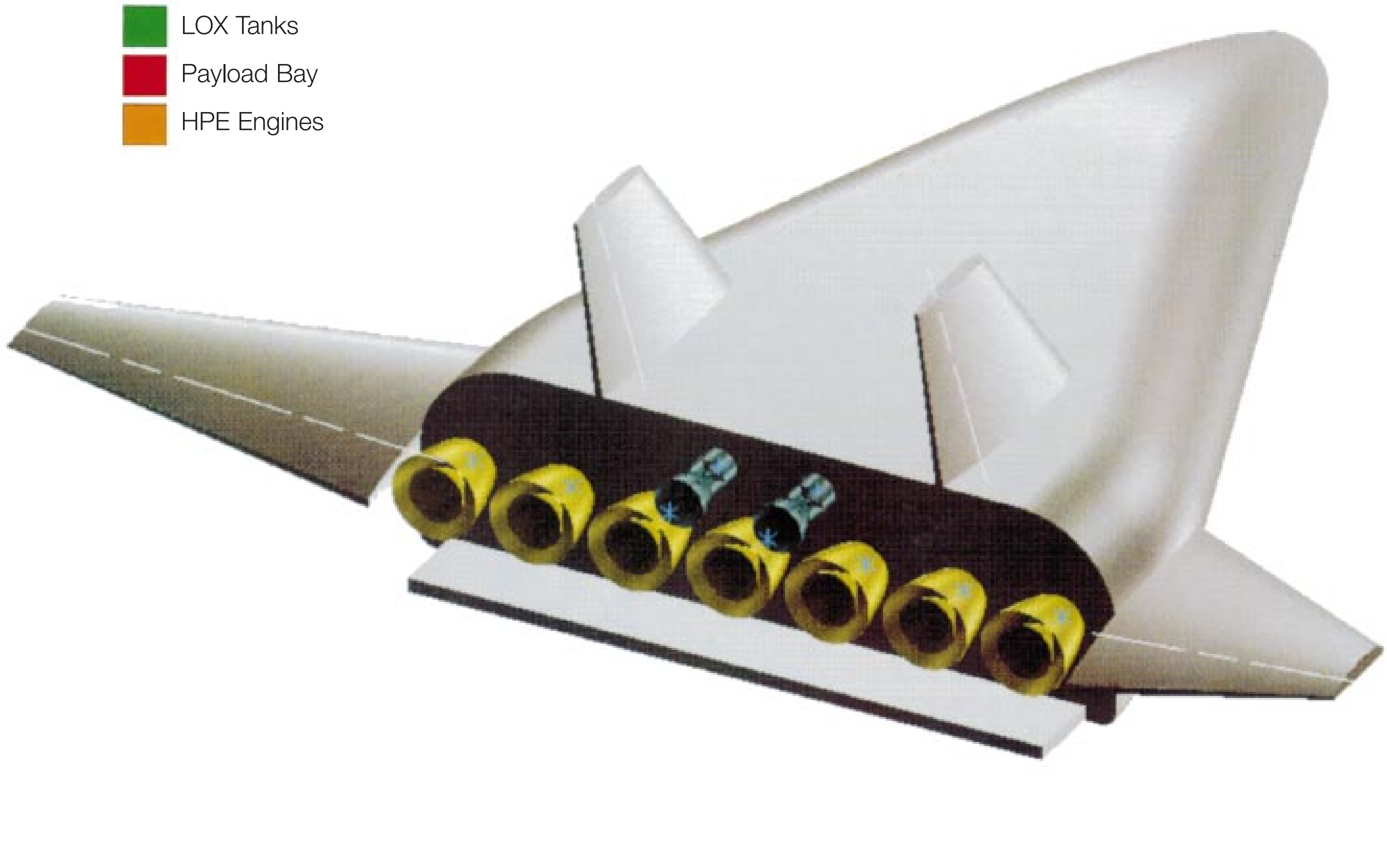


Figure 5a. An ESA Single-Stage-to-Orbit Reusable Rocket Launcher studied in the context of FESTIP, by DASA leading a team of European companies, and designed for vertical take-off and landing

possible development of a first-generation reusable launcher in 2005. We wanted to establish which reusable-launcher concepts might be feasible with the technologies that could be developed by then. We first concluded that air-breathing propulsion could only be envisaged to the extent that its technology was not too ambitious with respect to the overall state of the art in aviation. We then defined single- (Fig. 5) and two-stage (Fig. 6) to orbit reusable rocket launchers, which are either fully reused or their main parts at least are recovered for reuse. We concluded that recurrent launch costs could be reduced by a factor of 3 with respect to expendable launchers, but at the price of a significant investment in advanced technologies, mainly in the field of materials, structures and reusable rocket propulsion.

The FESTIP first slice was supplemented by the 1997-1998 extension, which will conclude the investigative work. Beyond 1998, ESA proposes the execution of a dedicated Future Launchers Technologies Programme (FLTP), which will draw upon the full competence of the European launcher industry. One important feature of the FLTP will be our proposal to design, build and fly a European Experimental Test Vehicle (Fig. 7), which will provide European industry with its first hands-on experience in practical launcher stage reuse operations. The large jumps in technology and gaps in experience between Ariane and any first-generation reusable launcher make such a learning phase a prerequisite. Only when we have learned the basics of reuse, will we truly

Figure 5b. An ESA Single-Stage-to-Orbit Reusable Rocket Launcher studied in the context of FESTIP, by DASA leading a team of European companies, and designed as a lifting body for vertical take-off and horizontal landing



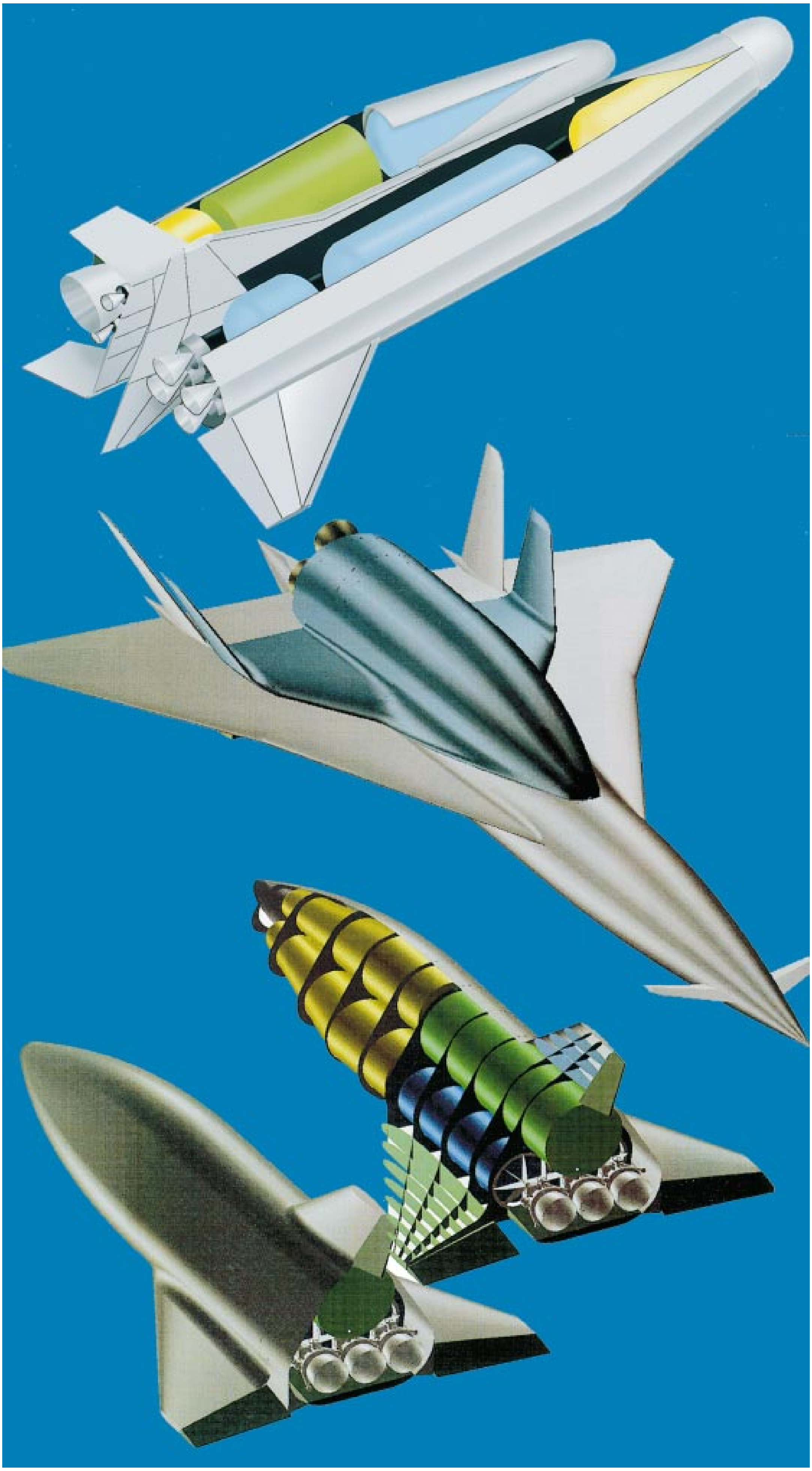


Figure 6a. An ESA Two-Stage-to-Orbit Reusable Rocket Launcher studied in the context of FESTIP, by DASA leading a team of European companies, and designed for vertical take-off and horizontal landing

Figure 6b. An ESA Two-Stage-to-Orbit Reusable Rocket Launcher studied in the context of FESTIP, by DASA leading a team of European companies, and designed for horizontal take-off and landing, with the first stage propelled to Mach 4 by air-breathing propulsion

Figure 6c. An ESA Sub-Orbital Reusable Rocket Launcher studied in the context of FESTIP, by DASA leading a team of European companies, and designed for horizontal take-off and landing. The sub-orbital stage would attain orbital altitude (but not reach orbital velocity) and eject its payload equipped with an upper stage. The reusable Sub-Orbital Launcher would then land down range and be transported back to the launch site for its next flight

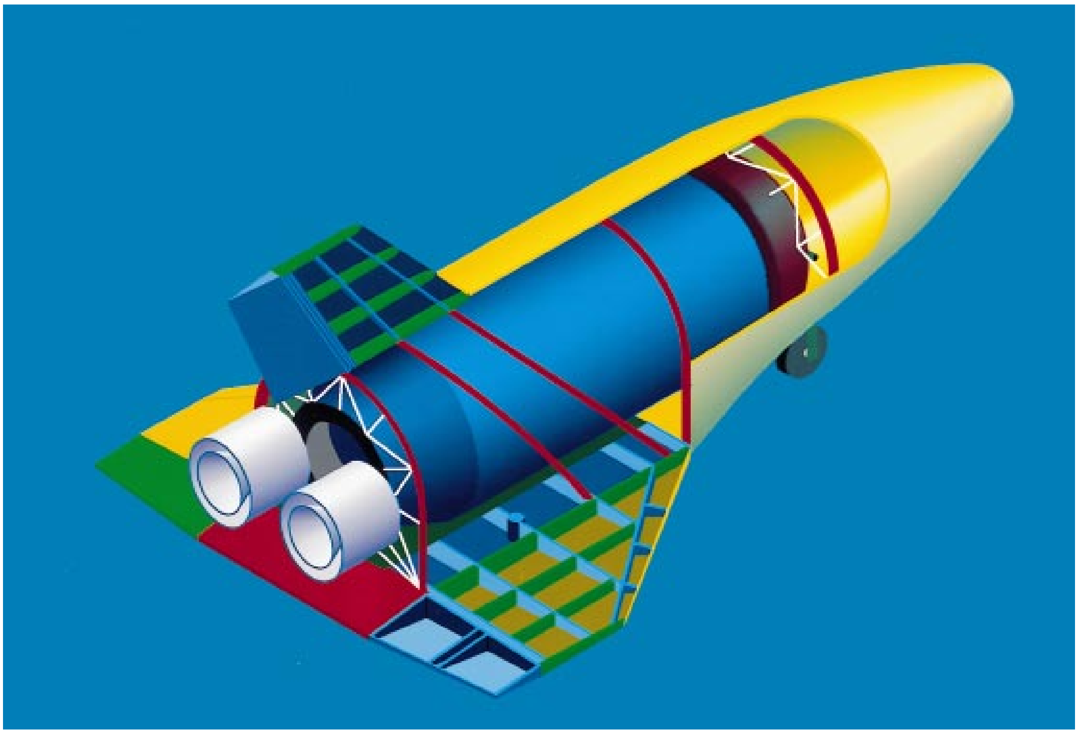


Figure 7. The European Experimental Test Vehicle (EXTV) studied in the context of FESTIP, by DASA leading a team of European companies. The version shown is designed for vertical take-off and horizontal landing

be ready to decide whether or not to apply that knowledge to operational developments.

The long term: synergy between access to space and global aviation?

It is likely that launcher reusability developments will also significantly influence the way in which global aviation is viewed in the future. Work on the so-called "high-speed commercial transport", which aims to reduce the travel times for global flights by a straightforward extrapolation of subsonic aviation, has been in progress for some considerable time. However, supersonic cruising flight poses rapidly increasing thermal problems as the speed increases, and the sonic-boom problem still makes approval of supersonic flight over populated land masses unlikely.

The alternative that could emerge thanks to reusable launchers is that of reaching an antipodean point on Earth in one hop through space, referred to as a "boost glide". It relies on the fact that one could fully load a reusable launcher with propellant and have it reach orbital velocity, or load less propellant but more payload and have it hop halfway around the planet. To be fully effective, such a form of global travel would call for chemical propulsion with higher performance than pure rocket propulsion, but propulsive performance levels less than those already achieved by today's turbojets for subsonic transport would already be more than adequate.

Finally, since we seem to be performance-limited by chemical propulsion, are there alternatives? In fact, the only other possible near-term solution for reaction propulsion is that of nuclear thermal propulsion, in which a fission reactor (gigawatt class) is used to heat the working fluid. Although such a solution might be of use on the Moon, for instance, and would be ideal for rapid planetary-transfer missions, it seems unlikely that Europe would undertake such a development in earnest in the near term unless there were very compelling reasons for doing so.

Conclusion

I would like to conclude with a statement of faith. Within our present technology horizon, we know along which lines we must proceed in order to make access to space cheaper, more flexible and safer than it is today. The progress that can be expected is significant enough for the work to be undertaken. Since a successful outcome is likely, but not yet certain and therefore not commercially attractive, we will still be dependent on dedicated short-term funding from far-sighted Governments in order to make progress. I believe that the proposed ESA Future Launchers Technologies Programme (FLTP) is a step in the right direction in this respect and will contribute to unleashing the true potential of space, to the long-term benefit of Europe, its citizens and its Industry.