JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 40, No. 2, March–April 2003

Comparative Assessment of Rocket-Propelled Single-Stage-to-Orbit Concepts

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A variety of reusable launch vehicle concepts has been designed and analyzed within the scope of the Future European Space Transportation Investigations Program systems study, which has been performed under a contract of the ESA by a joint European industry team. The designs under consideration included reusable two-stage-to-orbit configurations as well as several reusable single-stage-to-orbit vehicles with cryogenic rocket propulsion. All concepts were based on unified requirements, standards, technology assumptions, and design tools. To verify the consistency of the design process and to ensure the compatibility of the achieved results, as well as to identify the relative merits and inherent characteristics of the different basic vehicle concepts, a comparative technical assessment was performed among the various designs themselves as well as in relation to analogous configurations from other programs found in the open literature. Whereas the performance relations between the designs generated under common ground rules were found to be plausible, discrepancies in comparison to other programs could be traced to differences in requirements, technology assumptions, and design approaches. The results of associated considerations with respect to the main vehicle characteristics and related performance parameters are presented.

Introduction

COMPLEMENTARY to the individual design activities on reusable launch vehicle concepts carried out in the Future European Space Transportation Investigations Program (FESTIP) systems study, qualitative plausibility considerations, as well as quantitative data cross checks using analytical relationships, were performed for all FESTIP single-stage-to-orbit (SSTO) systems. The aim was to validate the coherence of the design process for the different configurations, which were created using unified design tools and based on common design standards, consistent technology assumptions, and identical mission requirements.

This comparative evaluation concerned the designs for two versions of a wing–body vertical takeoff/horizontal lander (VTHL), a vertical takeoff/vertical lander (VTVL) with nose first reentry, a sled launched wing–body horizontal takeoff/horizontal lander (HTHL), and a lifting-body VTHL.

In addition, comparisons with analogous external concepts generated in other programs were performed, as far as relevant information could be obtained. The depth of the comparisons performed reflects the level of detail that was available or could be extracted from the accessible information sources for the different externally generated concepts. The focus of the analyses was placed on fundamental performance and technology characteristics, whereas operational and economic aspects, such as safety and maintainability, as well as development, acquisition, and operations cost, were not included, due to a lack of data, and respectively dissimilar assessment approaches and ground rules in the different programs.

A winged VTHL in-house design performed by NASA, two concepts generated in the Russian Oryol reusable launch vehicle (RLV) program, the original three competing X-33/RLV industry proposals, and a VTVL vehicle studied in an in-house activity at Aerospatiale Espace et Defense were identified as relevant comparable concepts originated by outside sources. Results generated for the SSTO concepts within the Oryol program were obtained through an information exchange organized between FESTIP and Oryol in the form of two missions of Russian experts to the FESTIP design team.

Received 13 June 2002; accepted for publication 30 October 2002.

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Criteria for the selection of the external concepts were compatibility with the FESTIP ground rules with respect to mission requirements and performance, general configuration, and design characteristics such as size and gross mass, technology assumptions, propellant combination, and propulsion concept. Other relevant aspects concerned the level of design maturity and the availability of the pertinent main system data and the possibility to derive them from accessible information. An effort was undertaken to harmonize the data, in case contradictions were discovered between different data sources. Whenever there were notable differences in vehicle size between otherwise similar designs, scaling effects were taken into account. It should be noted that all concepts used for the evaluation were defined at a conceptual design level, which implies a higher level of uncertainty than that of more detailed analyses at the preliminary design stage. SSTO concepts in general exhibit strong design sensitivities and high associated risks, and performance degradations, which can typically be expected to occur during subsequent design iterations with increased fidelity, can seriously impair or even completely negate the practical feasibility of these concepts, especially if projected technology goals cannot be achieved. This is even more of a concern when operability margins required for the robust and efficient operations of reusable concepts are taken into account.

A concrete example of these effects is the lifting-body concept eventually selected for the suborbital X-33 and intended for the full-scale Venturestar RLV. A failure of a geometrically complex composite hydrogen tank during a ground test illustrated the high design risk associated with advanced technologies having low technology readiness levels. At the same time, higher fidelity analyses during the preliminary design phase of the operational RLV had necessitated significant configuration and technology changes, as well as an increase of the liftoff mass by 27% over the conceptual design results by 50% over the initial estimates.[1] As a consequence, NASA eventually decided to terminate the X-33 program[2] and to abandon the SSTO approach as a candidate for a next-generation shuttle successor.

Currently, no major SSTO study or effort is underway, and the programs mentioned before are not being pursued further. The basic concept of single stage configurations is, however, still regarded as an attractive long-term goal for advanced RLVs if the required advanced technologies can be matured to a sufficient level. Therefore, the objective of this paper is to compare the fundamental characteristics and analyze the relative merits of different SSTO concepts, rather than to perform detailed individual design investigations.

Requirements, Design Assumptions and Concepts

In FESTIP, initially a set of common requirements, design standards, and assumptions was defined, which was then consistently applied to all vehicle concepts. On the programmatic side, the main target dates chosen were a technology readiness date of 2005, an initial operational capability by 2015, and a reduction factor of three for the specific launch cost in comparison to present expendable launch vehicles, such as Ariane 5.

For the performance to be achieved by the different concepts, the uncrewed delivery of 7 Mg to a circular near-equatorial orbit with 250-km altitude and 5-deg inclination and the uncrewed delivery of 2 Mg to a circular near polar orbit with 250-km altitude and 98-deg inclination were specified as the two design reference missions. Based on these requirements, the following SSTO FESTIP system study concepts (FSSC) with cryogenic rocket propulsion were defined and analyzed: 1) the winged VTHL FSSC-1 with 150-bar chamber pressure staged combustion rocket engines, 2) the winged VTHL FSSC-1a with 244-bar chamber pressure staged combustion rocket engines, 3) the nose first reentry VTVL FSSC-3 with 244-bar chamber pressure staged combustion rocket engines, 4) the sled-launched winged HTHL FSSC-4 with 244-bar chamber pressure staged combustion rocket engines, and 5) the lifting-body VTHL FSSC-5 with 150-bar chamber pressure gas generator linear aerospike rocket engines.

For the outside SSTO design efforts with comparable layouts, the design reference missions were as follows: 1) The NASA VTHL study required 20 Mg uncrewed to an elliptical transfer orbit with 93-km perigee, 185-km apogee, and 28.5-deg inclination. 2) The Oryol program required 10 Mg uncrewed as well as crewed to a circular orbit with 250-km altitude and 51.6-deg inclination. 3) The X-33/RLV program required 20 Mg uncrewed to a circular orbit with 185-km altitude and 28.5-deg inclination as well as 10 Mg uncrewed to a circular orbit with 445-km altitude and 51.6-deg inclination. 4) The Aerospatiale Espace et Defense VTVL study required 10 Mg uncrewed to a circular orbit with 200-km altitude and 28.5-deg inclination.

As can be seen, the most notable discrepancy in payload requirements existed between the FESTIP vehicles and the American designs by NASA, as well as the X-33/RLV contenders. However, for all FESTIP SSTO designs the polar mission performance demand turned out to be the design driver, which consequently led to a substantial overfulfillment of the near equatorial requirement, making the United States and FESTIP designs more comparable in terms of payload capability.

Comparison of FESTIP SSTO Concepts

To validate the consistency of the results achieved in the analyses of the different SSTO concepts studied within FESTIP, the designs were first compared among themselves by means of plausibility considerations regarding their relative performance parameters and design characteristics.

Figure 1 shows a size comparison of the different designs, and their key data and technologies are compiled in Table 1. A cross check of the main engine parameters of sea level and vacuum specific impulse and thrust-to-weight ratio showed the linear aerospike engine defined for the lifting body concept FSSC-5 to be inferior in relation to the staged combustion engine with 244-bar chamber pressure and two-position bell nozzle from a performance point of view and as having no significant advantage over the staged combustion engine with 150-bar chamber pressure and fixed bell nozzle in a booster/sustainer combination.

Potential benefits of the aerospike engine were, however, seen in the synergy of also being able to use it for the orbital maneuvering system, as well as the possibility to eliminate the need for a separate engine base plate and engine actuators through the differential throttling of engine modules for thrust vector control. The detailed impact of the need for engine out capability on the feasibility of this feature, however, was not fully explored. The less demanding gas generator cycle was also regarded as a factor lowering the technology development risk.

The linear aerospike nozzle concept represented, however, a major unknown, for which performance and mass data could not be determined with the same accuracy and confidence at the conceptual design stage in FESTIP as for conventional rocket engines, due to the lack of experimental data and operational experience.

Tables 2 and 3 contain the comparisons of the main vehicle mass and performance parameters for the two FESTIP design reference missions with near-equatorial and near-polar inclination, respectively. With regard to the payload fraction into the near-equatorial low Earth orbit, the lifting-body concept FSSC-5 shows the highest value, followed by the HTHL sled-launched concept FSSC-4, the ballistic FSSC-3 system, and the FSSC-1 variants, with FSSC-1a having the lowest payload fraction.

For the near-polar orbit, which was the dimensioning mission driving the design for all SSTOs, the payload fractions of the majority of all systems are almost identical, with the FSSC-1 baseline showing the only major deviation. This indicates that the tradeoffs between the different launch and landing modes do not lead to significant differences in launch mass for a given mission and technology level. The relative differences of the performance into the two design orbits for the various concepts are due to different sensitivities resulting from the individual vehicle characteristics and layouts.

The variations in the dry mass fraction between the concepts are more significant. As could be expected, the unwinged VTVL concept FSSC-3 with circular fuselage cross section has the lowest dry mass fraction of all concepts because it trades vehicle structure mass in the form of minimum aerodynamic surfaces against additional propellant required for the powered landing. It is followed by

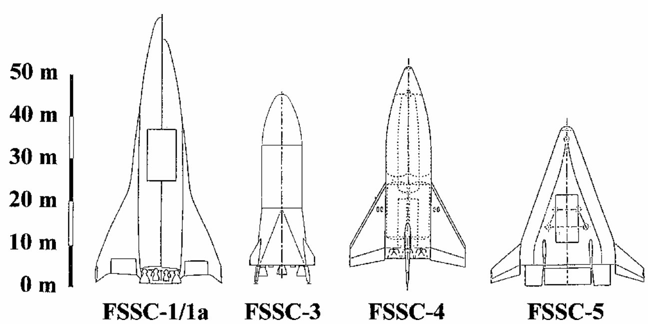

Fig. 1 FESTIP SSTO configurations.

Table 1 Comparison of key data and characteristics for the FESTIP SSTO concepts

Parameter	FSSC-1	FSSC-1a	FSSC-3	FSSC-4	FSSC-5
Configuration	Wing-body VTHL	Wing-body VTHL	Nose-first reentry VTVL	Sled launch HTHL	Lifting-body VTHL
Engine cycle	Staged combustion	Staged combustion	Staged combustion	Staged combustion	Gas generator
Chamber pressure, bar	150	244	244	244	150
Engine nozzle type	Fixed bell	Two-position bell	Two-position bell	Two-position bell	Linear aerospike
Sea level specific impulse, s	363	379	386	379	347
Vacuum specific impulse, s	450	459	453	459	455
Installed sea-level thrust, kN	12,356.4	9,489.7	8,240.0	5,376.0	9,179.2
Engine sea-level thrust/weight	65.1/50.1[a]	55.4	56.2	55.4	56.0
Liftoff acceleration, *g*	1.4	1.4	1.24	0.91	1.3
Oxygen tank design	Nonintegral	Nonintegral	Integral	Nonintegral	Integral
Hydrogen tank design	Integral/nonintegral[b]	Integral/nonintegral[b]	Integral	Nonintegral	Integral

[a]Booster/sustainer engines. [b]Front/aft tanks.

Table 2 Comparison of the FESTIP SSTO concepts for the near-equatorial orbit

Parameter	FSSC-1	FSSC-1a	FSSC-3	FSSC-4	FSSC-5
Payload mass, Mg	16.6	12.3	12.5	12.5	14.7
Dry mass, Mg	97.8	78.8	58.6	65.5	68.1
Main propellant mass, Mg	779.4	595.0	589.5 + 8.6[a]	539.4	634.5
Launch mass, Mg	900.0	691.2	679.9	625.6	720.0
Payload fraction, %	1.84	1.78	1.84	2.00	2.04
Dry mass fraction, %	10.8	11.4	8.6	10.5	9.5
Main propellant mass fraction, %	86.6	86.1	87.1 + 1.3[a]	86.2	87.2
Trajectory average specific impulse, s	437	448	445	452	440
Ideal velocity increment, m/s	8627	8651	8804 + 496[a]	216 + 8568[b]	8856
Ascent gravity loss, m/s	992	1015	946	949	1165
Ascent drag loss, m/s	196	200	182	36 + 301[b]	261

[a]Ascent plus descent/landing. [b]Sled launch ground run plus ascent.

Table 3 Comparison of the FESTIP SSTO concepts for the near-polar orbit

Parameter	FSSC-1	FSSC-1a	FSSC-3	FSSC-4	FSSC-5
Payload mass, Mg	2.0	2.0	2.0	2.1	2.4
Dry mass, Mg	97.8	78.8	58.6	65.5	68.1
Main propellant mass, Mg	794.0	605.5	600.0 + 8.6[a]	539.4	634.5
Launch mass, Mg	900.0	691.2	679.9	614.7	708.7
Payload fraction, %	0.22	0.29	0.29	0.34	0.34
Dry mass fraction, %	10.8	11.4	8.6	10.7	9.6
Main propellant mass fraction, %	88.2	87.6	88.2 + 1.3[a]	87.8	88.6
Trajectory average specific impulse, s	437	449	446	452	441
Ideal velocity increment, m/s	9169	9195	9366 + 496[a]	216 + 9093[b]	9403
Ascent gravity loss, m/s	987	1003	958	941	1157
Ascent drag loss, m/s	192	201	176	36 + 290[b]	263

[a]Ascent plus descent/landing. [b]Sled launch ground run plus ascent.

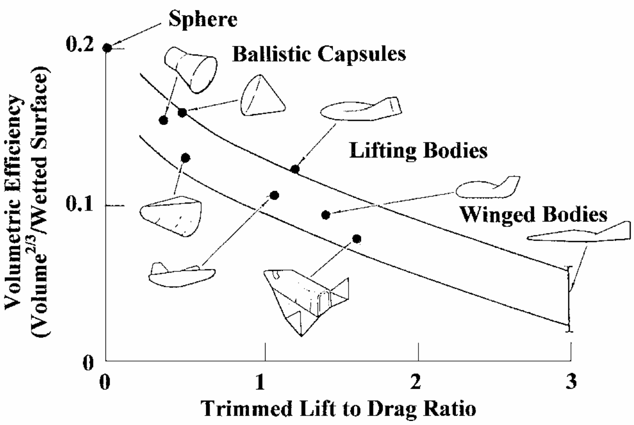

Fig. 2 Comparison of typical configurations for reentry vehicles.[3]

the FSSC-5 lifting body, which was aimed at reducing the aerodynamic surface area required for the return glide and landing through its specific body shape. The HTHL concept FSSC-4 is next, which indicates that the mass savings achieved by the reduction of the number of engines due to the lower acceleration level required for the horizontal takeoff outweigh the increase in wing structure mass necessitated by the significantly higher wing loading caused by the aerodynamic lifting takeoff and ascent. The winged VTHL FSSC-1 and FSSC-la variants exhibit the highest dry mass fractions, with the smaller vehicle having a higher value, partly due to scaling effects, which drive up relative dry mass with diminishing vehicle size.

The relations with respect to the dry mass ratios exhibited by the different principal vehicle layouts such as ballistic, lifting-body, and wing–body configurations are in good agreement with the volumetric and resulting structural efficiencies to be expected from the basic body shapes as illustrated in Fig. 2 for reentry vehicles.[3]

As a conclusion, the fundamental mass and performance relationships between the different FESTIP SSTO concepts were found to be plausible and justified, and they validated the consistency of the design process.

Comparison of VTHL SSTO Concepts

As mentioned, the different FESTIP concepts were also compared with applicable results from outside studies, as far as information was available. The comparability of the concepts analyzed in the different studies taken into consideration was constrained by differing assumptions and requirements, but some general conclusions could be drawn. For the VTHL concepts, the following SSTO RLV studies with cryogenic rocket propulsion were identified as relevant and evaluated with respect to mission requirements, design characteristics, technology assumptions, and performance in comparison to the FESTIP designs: 1) the NASA wing–body design, 2) the Oryol program V6 wing–body design, 3) the X-33/RLV program wing–body design by Rockwell International Corp., and 4) the X-33/RLV program lifting-body design by Lockheed Martin Advanced Development Co. (Venturestar).

A size comparison of the different winged VTHL concepts is shown in Fig. 3 and of the lifting body VTHL concepts in Fig. 4, and Table 4 summarizes the main data of the vehicles. For FSSC-1, first a comparison with assumptions and results concerning the NASA design of a winged VTHL–SSTO with purely cryogenic rocket engines[4–7] was performed, based on fundamental qualitative considerations, as well as quantitative analytical evaluations. Both concepts are wing–body designs with circular tank cross sections and delta wings with winglets, as shown in Fig. 3. The NASA technology assumptions of advanced subsystems and an improved thermal protection system in comparison to the space shuttle, aluminum–lithium oxygen tanks, graphite composite materials for primary structures and the hydrogen tank, and cryogenic rocket engines based on the space shuttle main engine (SSME), but with reduced performance for better operational characteristics, are also generally closely comparable to those of FSSC-1. Table 4 contains the main characteristic data of both systems.

The specific impulse performance of the propulsion systems is almost identical, and both employ a staged combustion cycle. The NASA concept, however, relies on seven identical SSME derived engines with a nominal chamber pressure of 200 bar, whereas the FSSC-1 uses four booster and four sustainer engines with a chamber pressure of 150 bar each, but with different expansion ratios and a variable propellant mixture ratio, which has been optimized for maximum performance in conjunction with the ascent trajectory. This

Table 4 Comparison of key data for VTHL SSTO concepts

Parameter	FSSC-1	NASA	Oryol V6	Rockwell	FSSC-5	Venturestar
Configuration	Wing–body	Wing–body	Wing–body	Wing–body	Lifting body	Lifting body
Target orbit altitude, km	250	93/185[a]	250	185	250	185
Target orbit inclination, deg	5	28.5	51.6	28.5	5	28.5
Length, m	62.2	55.0	58.0	64.9	37.2	38.7
Wing span, m	29.4	28.6	32.0	31.4	35.6	41.6
Engine cycle	Staged combustion	Staged combustion	Staged combustion	Staged combustion	Gas generator	Gas generator
Engine nozzle type	Fixed bell	Fixed bell	Fixed bell	Fixed bell	Linear aerospike	Linear aerospike
Number of engines	8	7	8	6	7	7
Oxygen tank design	Nonintegral	Integral	N/A	Integral	Integral	Integral
Hydrogen tank design	Integral/nonintegral[b]	Integral	N/A	Integral	Integral	Integral
Launch mass, Mg	900.0	937.3	930.0	997.9	720.0	1179.4
Dry mass, Mg	97.8	93.4	95.0	93.4	68.1	94.3
Maximum payload, Mg	16.6	20.4	10 + 3 Crew	19.0	14.7	23.6
Dry mass fraction, %	10.8	10.0	10.2	9.4	9.5	8.0
Payload fraction, %	1.84	2.18	1.08	1.9	2.04	2.0

[a]Perigee/apogee. [b]Front/aft tanks.

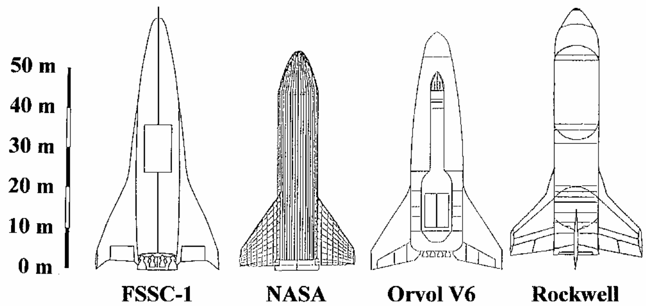

Fig. 3 Winged SSTO concepts.

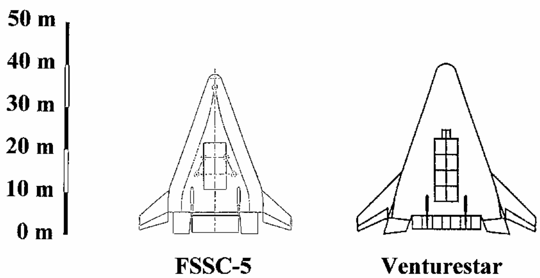

Fig. 4 Lifting-body SSTO concepts.

approach allows the achievement of the same trajectory average specific impulse as the NASA concept with a more conservative propulsion technology level and more benign engine operating conditions.

As a result of a higher ideal velocity requirement caused by a lower liftoff acceleration in conjunction with a higher orbital inclination, the NASA concept requires a slightly higher propellant mass fraction than FSSC-1. Together with a payload mass fraction, which is also higher than that of FSSC-1, this results in a significantly lower dry mass fraction in relation to FSSC-1. The achievability of this lower dry mass fraction is partly dependent on there being only one integral oxygen and hydrogen tank each in the NASA concept,[8] whereas FSSC-1 incorporates one nonintegral oxygen tank and two separate hydrogen tanks, of which only the front one is integral, whereas the aft one is nonintegral.

The different tank designs and arrangement of the NASA concept, together with the blunter forebody, yielding a higher volumetric efficiency of the forward tank, and the generally more compact proportions of the vehicle enable a better utilization of the available inboard volume when compared with the aerodynamically more refined and slender FSSC-1. Another factor reducing the NASA vehicle size is the probable use of subcooled oxygen and hydrogen, as was applied to a previous NASA SSTO concept,[9] which allows the increase of propellant density and the decrease of the required tank volumes and associated masses. These influences are the cause of the smaller overall dimensions of the NASA concept as compared to FSSC-1, in spite of the higher propellant and launch masses of the NASA design.

When these differences in the vehicle layout are taken into consideration, the technology assumptions of the FSSC-1 concept appear to be somewhat more conservative than those of the NASA SSTO, despite a lower dry mass margin of FSSC-1.

No specific information concerning the stability and controllability of the NASA concept was given, but it was stated that the forward location of the oxygen tank and of the payload bay in the intertank section helped to bring the center of gravity forward and balance the vehicle.[10] No further quantitative data regarding the tank arrangement of the NASA concept and the resulting consequences for the location and travel of the center of gravity were available for analysis. The same applies for the aerodynamic vehicle properties and the associated lifting return glide flight performance in connection with the higher wing loading of the NASA concept as a result of the smaller exposed wing area.

In general, the results available for the NASA SSTO VTHL concept support and confirm the validity of the findings and design solutions of FSSC-1, which generally appear to reflect a lower technology risk approach.

Within the framework of an information exchange with the Russian Oryol program for advanced RLVs, the results achieved for FSSC-1 were also discussed with Oryol program representatives in comparison to those of an analogous design in Oryol. A major difference between FSSC-1 and the corresponding Oryol concept is the layout of the latter as a crewed system with a dedicated cockpit, which imposes design requirements and constraints not accounted for in FESTIP and drives up the dry mass fraction in relation to FSSC-1.

The structural technology level of FSSC-1 was assessed to lie between the corresponding medium- and long-term technology targets defined for Oryol, whereas the main propulsion thrust to weight ratio corresponded to the respective Oryol long-term technology level.

The engine thrust-to-weight ratios of FSSC-1 and FSSC-1a as stated in Table 1 are, on the other hand, notably below the corresponding value of 75 postulated for the RS-2100 staged combustion rocket engine incorporated in the Rockwell International Corp. concept,[11] so that the FESTIP propulsion technology level assumptions appear to lie between the respective expectations of the United States and Russia. Generally, the FSSC-1 baseline is well comparable in terms of overall size and capability with the analogous designs performed by the Oryol program and Rockwell International Corp. and, with the exception of the Russian assumptions for rocket propulsion, incorporates slightly more conservative technology expectations than both of those concepts.

Note that both the Oryol and the Rockwell International Corp. designs have wings with sweptback trailing edges, which bring the center of pressure further back than in FSSC-1 and could also have helped to solve difficulties encountered with the longitudinal stability of FSSC-1. For the two VTHL X-33/RLV contenders, the data were compiled using sources publicly available for the Rockwell International Corp. concept[11] and for the Lockheed Martin Advanced Development Co. Venturestar concept.[12] The status of the Venturestar data used for the evaluation corresponds to the critical design review at the end of October 1997, which represented a significant increase of takeoff mass, as well as a decrease of payload capability in comparison to earlier, more optimistic projections.

This degradation indicated substantial design uncertainties and sensitivities, for example with respect to the efficiency of composite structures and the performance of the aerospike engine. Also note that the data given for the Venturestar[12] yield a dry mass ratio that is lower than that for the Delta Clipper VTVL.[13] Because of the trade of lower dry mass for higher propellant mass of ballistic systems outlined earlier, the opposite should be expected, especially when considering the more complex tank shapes required for the lifting body as opposed to the circular tank cross sections feasible for the other two RLV layouts. This low dry mass ratio is once again likely, at least partly, related to the use of subcooled propellants, as well as the implementation of a composite oxygen tank,[14] as opposed to the aluminum–lithium baseline foreseen for the other RLV contenders. Therefore, the Venturestar was assessed to be an extremely ambitious design, as is also illustrated by the further concept evolution mentioned earlier and evidenced in the high thrust-to-weight ratio of 80 postulated for the RS-2200 engines[12] in comparison to the corresponding value of 56 established for the FSSC-5 propulsion in Table 1. Because the Venturestar project served as the initial basis for the FSSC-5 design, and the available literature documenting the parallel progress of the American activities was evaluated and used as input for the further refinement of the concept during the design process, the FSSC-5 lifting body is generally comparable with the original Venturestar design with respect to specific design features. A launch mass increase analogous to that of the Venturestar was experienced in the design cycles of this vehicle as well. When its smaller size and resulting scaling effects are taken into account, as well as the different design reference missions and associated propulsion performance requirements and the uncertainties related to the aerospike engine, FSSC-5 was found to be generally comparable to the Venturestar with respect to relative performance and slightly more conservative concerning the structural technology assumptions. In general, the FESTIP VTHL SSTO design parameters appear plausible and justified in comparison with other independent vehicle studies based on compatible assumptions and specifications.

Comparison of VTVL SSTO Concepts

Analogous to the VTHL designs, the following VTVL SSTO RLV studies with pure cryogenic rocket propulsion and nose-first reentry were identified as relevant and evaluated with respect to mission requirements, design characteristics, technology assumptions, and performance in comparison to the respective FESTIP design: 1) the Oryol program V7 design, 2) the X-33/RLV program design by McDonnell Douglas Aerospace (Delta Clipper), and 3) the Aerospatiale Espace et Defense design. Figure 5 shows the size comparison of the different VTVL concepts, and the main data of the vehicles are compiled in Table 5, having once again been extracted from different open sources for the Delta Clipper[13] and the Aerospatiale Espace et Defense design.[15] The data for the Oryol vehicle were obtained in the FESTIP/Oryol information exchange mentioned earlier. Note that some limited information of an updated version for the Aerospatiale Espace et Defense concept[16] concerning a redesign of the oxygen tank as an internal tank and an increase of the number of rocket engines to nine, together with an increase of the launch mass to 1200 Mg for a payload of 10 Mg, was identified, but could not be applied for a comparison of all relevant main parameters because no further data were available for this revised design.

FSSC-3 is smaller than most of the other VTVL designs with nose-first reentry concerning the geometric size as well as the launch mass and, taking scaling effects into account, appears more ambitious than, especially, the V7 and Aerospatiale Espace et Defense concepts with regard to the dry mass fraction. This is remarkable because a composite oxygen tank is foreseen for the Aerospatiale Espace et Defense concept, which represents a more advanced technological concept than the corresponding metallic design of FSSC-3. Because a detailed mass breakdown was not available for the Aerospatiale Espace et Defense design, no further comparisons could be performed.

When the difference in launch mass and the associated scaling effects are examined, a higher dry mass fraction might have been expected for FSSC-3 in comparison to the Delta Clipper; however, the opposite is the case. Recall that the Delta Clipper exhibits a higher dry mass fraction than the Venturestar lifting body, which indicates that the structural technology assumptions of the American RLV contenders were not homogenous. From a plausibility point of view, therefore, the Delta Clipper has to be considered relatively more conservative in this respect, also when taking a correlation to the Rockwell International Corp. VTHL design into account. When compared on a payload mass to dry mass basis, FSSC-3 and Delta Clipper are rather close. Because the Delta Clipper was also foreseen to use the RS-2100 engines intended for the Rockwell International Corp. VTHL, and the FSSC-3 rocket engine assumptions correspond basically to those of FSSC-1a, the respective remarks made for the VTHL systems apply accordingly. The main engine thrust-to-weight ratio of 85 for the Aerospatiale Espace et Defense concept[15] is significantly higher than that of 56.2 specified for FSSC-3 in Table 1, so that the FESTIP rocket engine technology assumptions again appear to be moderately conservative.

Note that the Delta Clipper, which was the first VTVL concept to include a nose-first reentry and essentially inspired all other configurations based on this approach, was also the first one to incorporate small fins for the enhancement of aerodynamic stability and control in later design versions. This feature, along with a flattened afterbody underside, was also identified as being necessary for FSSC-3 and confirms the validity of the design and analysis process.

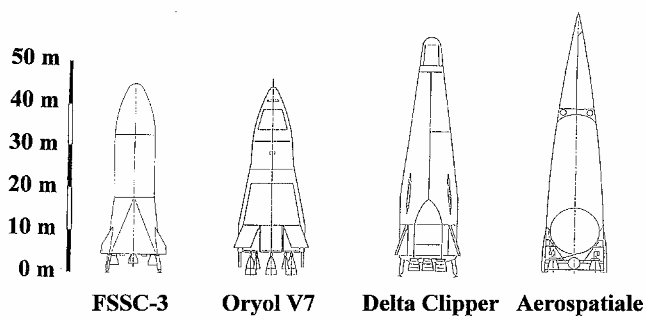

Fig. 5 Ballistic SSTO concepts.

Table 5 Comparison of key data for VTVL SSTO concepts

Parameter	FSSC-3	Oryol V7	Delta clipper	Aerospatiale
Target orbit altitude, km	250	250	185	200
Target orbit inclination, deg	5	51.6	28.5	28.5
Length, m	45.0	42.5	56.4	63.0
Base width, m	11.0	15.7	14.8	12.6
Engine cycle	Staged combustion	Staged combustion	Staged combustion	Staged combustion
Engine nozzle type	Two-position bell	Two-position bell	Fixed bell	"Ventilated" bell
Number of engines	4	8	8	8
Oxygen tank design	Integral	N/A	Integral	Nonintegral
Hydrogen tank design	Integral	N/A	Integral	Integral
Launch mass, Mg	679.9	1045.0	1088.6	1180.0
Dry mass, Mg	58.6	96.7	99.3	112.0
Maximum payload, Mg	12.5	10.0	20.4	12.3
Dry mass fraction, %	8.6	9.3	9.1	9.5
Payload fraction, %	1.84	0.96	1.87	1.04

In conclusion, FSSC-3 appears to be more optimistic with respect to the dry mass fraction in relation to comparable designs, which is partly attributable to apparent inconsistencies in the technology assumptions, for example of the American RLV studies. These discrepancies also make it difficult to assess which benefits originate from the incorporation of specific technologies, especially in the areas of structures and propulsion, and which ones are inherent in the different basic system architectures for the American designs. FSSC-3 is, on the other hand, well in line with the other FESTIP SSTO concepts concerning the basic technology assumptions and is, therefore, regarded to represent a consistent design.

Conclusions

Qualitative plausibility analyses and quantitative data comparisons for different SSTO concepts studied in the FESTIP were performed among the concepts themselves as well as in comparison to other similar independent designs. The relations concerning the relative dry mass ratios of the different vehicle layouts as ballistic, lifting-body, and wing–body configurations were found to be in good agreement with the volumetric and resulting structural efficiencies to be expected from the fundamental body shapes. The basic mass and performance relationships between the different SSTO concepts were therefore found to be plausible and validated the consistency of the design procedure.

The findings and conclusions of the FESTIP and the Russian Oryol program on different SSTO designs were found to be in good overall agreement.

In comparing the Western European designs with the X-33/RLV program contenders, it was found that apparent inconsistencies in the technology assumptions of the different American proposals across the contractors caused notable differences to the results generated by the joint European effort. These discrepancies resulted from different degrees of optimism in the design assumptions of the originating companies and made it difficult to assess which benefits stemmed from the incorporation of specific technologies and which were inherent to the basic system architectures. Because of the lack of available information, considerations of the potential effects of differences in the operational and safety approaches and the accommodation of off-nominal operating conditions, such as abort cases, could also not be included.

In summary, the design results for the various Western European single-stage concepts appear consistent and justified, and they validate the coherence of the design process when compared among themselves. Furthermore, they are well in line with other independent design studies based on compatible assumptions and specifications, which also confirmed the general design approach applied in the FESTIP.

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