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Reliability of Future European Launchers with Abort Capability

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Since 1994, the aim of the Future European Space Transportation Investigation Program has been identifying technically feasible and financially affordable reusable or semireusable launcher concepts, with the chief objective of increasing availability and significantly decreasing cost. An overview is given on how consideration of abort modes in reusable and semireusable launchers would fairly increase launcher reliability and lifetime and reduce recurring costs. Results are analyzed of the preliminary reliability assessment of eight different concepts, performed during slice C of the program. This study has proved that probabilistic reliability analyses are also a good decision tool in the early phases of a program where conceptual design will be fixed. It can be used as a comparative argument for concept selection, giving a quantitative idea of the reliability of different conceptual design options, and as a tool to select subsystem design options considered reliable from the beginning.

Introduction

THE goal of early space missions was human access to space. However, the evolution of scientific work and of business needs has led to focusing on taking fuller advantage of work beyond the atmosphere. In recent years, the number of launches has steadily increased, and this tendency is expected to be maintained, making it necessary to envisage two important factors (vehicle availability and lifetime), in combination with a substantial reduction in the recurring cost per flight. As the latter can hardly be achieved in existing space transports, reusable or semireusable launchers were identified as a promising technology: They are not penalized by recurring costs, and launch frequency can be increased, thus amortizing fixed costs. In 1994, the ESA established the Future European Space Transportation Investigation Program (FESTIP) to identify technically sound and cost-effective reusable or semireusable launcher concepts, with the chief objective of increasing availability and significantly decreasing cost, as well as the design of competitive launchers. The goal set for this program is to design a European launcher with 30-year lifetime at 24 launches per year.

The program has focused mainly on the definition of reusable or semireusable launcher concepts enabling a significant cost reduction in transportation, as well as on the assessment of launcher concepts in terms of feasibility and economic viability. It identifies and quantifies technology requirements for the concepts retained. A technology development and verification plan has been established, including flight testing with relevant experimental vehicles, and the program involves research covering the basic technologies that are common to most of the concepts considered.

In the framework of this program, 12 different uncrewed vehicles (grouped within 8 concepts) have been studied, with a nominal mission of launching commercial satellites with a performance equivalent of 7 Mg into equatorial low Earth orbit (LEO) and 2 Mg into polar LEO. The purpose of the study is to select a future reusable launcher for Europe.

Background

FESTIP is structured into three slices, A, B, and C. Slice C features risk assessment as another concept selection factor, together with cost and technology availability. The work was performed in integration with the international system concept team at Daimler Benz Aerospace (DASA) Ottobrunn facilities.

Risk drivers in space projects can be 1) specific environmental conditions, 2) need for high-level performance, 3) low production number, 4) high cost, 5) associated difficulty to test under operating conditions, and 6) limited maintainability during operation.

Objectives of the risk assessment were to follow up on conceptual design of launchers to select the best design option, compare vehicle reliability, and compare assessment results with the requirements that had been established in slice A of the program (see Table 1). In each of the eight concepts retained, the reliability of the best configurations for different systems was also analyzed.

Analysis Method

Even though the preferred method in the aerospace sector for this type of studies is deterministic (failure modes, effects, and criticality analysis), the approach selected for this study was a probabilistic analysis using fault trees.[1] The first step to design a fault tree is to establish its top level event or undesirable consequence whose probability is assessed.

As seen in Table 1, failures in the systems or subsystems can produce undesirable consequences at vehicle system level, which can be serious, such as mission loss or abort, loss of payload, and loss of vehicle, or catastrophic, such as loss of launch pad or even loss of life.

The short time available during slice C of the program only made it possible to assess in detail the probability of loss of vehicle. However, the study also brought forward some qualitative considerations and conclusions on mission loss and abort.

Each of the vehicles studied was the subject of a separate tree. Fault trees were built considering the failures of each vehicle system and subsystem, from the lowest level of detail (system or subsystem failure) up to the highest level achievable (equipment, component, or even item failure where possible).

The level of detail of the analysis depends on several factors. In this case, the most promising concepts were evaluated in detail considering relevant mission phases; the rest of the concepts were evaluated considering only special features of their systems and subsystems. The design detail level achieved at this stage of the program led to considering the design of some systems as basically the same for all concepts. To keep models as simple as possible, these systems were modeled in separate fault trees. Finally, design status and complexity were also taken into account.

To simplify calculations and save time, mission aborts are usually considered successful, that is, no loss of vehicle after mission abort. This simplification can clearly lead to erroneous results. Nevertheless the conclusions of the study take into account this approximation.

Once the top level event (which is loss of vehicle) and the level of detail required in the analysis are established, the next step consists in identifying main systems and subsystems. In this study the following system and subsystem distribution, common to all concepts, has been considered: main propulsion (MP) including feeding system, auxiliary propulsion (AP), structures (S), guidance and control (G&C), payload deployment (PD), landing (L), and separation system [for two-stage-to-orbit (TSTO) concepts]. These

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Table 1 FESTIP reliability requirements

Hazard level	Probability	Reference
Catastrophic		
Loss of life on ground	$<1E-07$	SRD[a]
Loss of launch pad	$<1E-04$	Ariane
Serious		
Loss of payload	$<7E-04$	Estimate
Loss of vehicle	$<1E-03$	SRD
Loss of mission	$<3E-02$	SRD

[a]System requirements document.

systems include components featuring failure modes that could lead (directly or in combination with other failures) to loss of vehicle. Failure combinations are gathered in the fault tree of each vehicle.

In the cases where mission phases are taken into account, the main mission phases common to most concepts are ground preparation phase, launch (vertical or horizontal), ascent flight, separation phase (for TSTO vehicles), orbital phase (excepting suborbital vehicles), descent flight, and landing.

Uncrewed vehicles feature almost no redundancy, and most of their elements are in series. Serial systems are represented in fault trees by OR gates. Systems are developed top-down to their main components failure modes or basic event. Some of these basic events do not feature components but systems or parts of systems that are modeled in separate trees to be used in different vehicle trees or even in several parts of a vehicle tree with different data.

Data for the quantification were taken from 1) generic reliability databases such as NPRD-95,[2] tailored as required for applicability; 2) from previous studies performed in the Ariane 4, Ariane 5, or space shuttle programs, tailored to take into account technological differences, mainly by means of expert judgments in different areas; and 3) expert data provided directly by the different companies participating in the FESTIP program. Data correction took into account factors such as mission time for each component in the vehicle, whether the technology necessary for vehicle development is already known and proven or whether it will have to be developed in the future, and the level of technical difficulty entailed.

Other significant data in the quantification included a study performed during slice B, which consisted in the analysis of a variety of engine concepts used in the different vehicles. It evaluated their probability of failure by taking into account the mentioned factors and compared them to one another. For the purpose of risk assessment, as these data would be applied to the entire vehicle, the engine data evaluated were corrected as a function of engine mission time, total number of engines in the vehicle considered, and number of engines required for successful mission or safe abort.

The contribution of structural failures (such as thermal protection failure or bending of flight components) to the overall probability for loss of vehicle was included in a semiqualitative way in the study, considering the safety margins established for the different concepts. Quantification was performed with RiskSpectrum® (PSA professional version 2.13) software.

A brief description of each concept, together with the results of the assessment, is presented, followed by a discussion of the conclusions reached.

Description of Concepts[3–5]

FESTIP Space System Concept 1 (FSSC-1)

The FESTIP Space System Concept 1 (FSSC-1) (Fig. 1) is a single-stage-to-orbit (SSTO) reusable vehicle with vertical takeoff and horizontal landing modes. Its most important features are that it is an all-rocket-propelled vehicle that uses cryogenic propellant [liquid oxygen (LOX)/liquid hydrogen (LH2)], two versions of which are considered, both with staged combustion cycle engines: One has eight 150-bar engines and fixed nozzles (four booster and four sustainer), the other has five 245-bar engines with two-position nozzles. Polar orbit is the design driving mission.

FSSC-3

The FSSC-3 concept (Fig. 2) is a Delta-Clipper-type vehicle, SSTO with vertical takeoff and landing. From the reliability standpoint, main design features are all-rocket-propelled vehicle [four staged combustion cycle engine (SCCE) for ascent with 245-bar combustion chamber pressure and 2060 kN thrust per engine, in addition to six expander cycle engines, developing 150-kN thrust each, used for the orbital maneuver system (OMS) and landing] using cryogenic propellant (LOX/LH2). Some of the rocket engines have to be restarted in descent flight to achieve proper landing position. Mission profile has been considered in the evaluation of this concept.

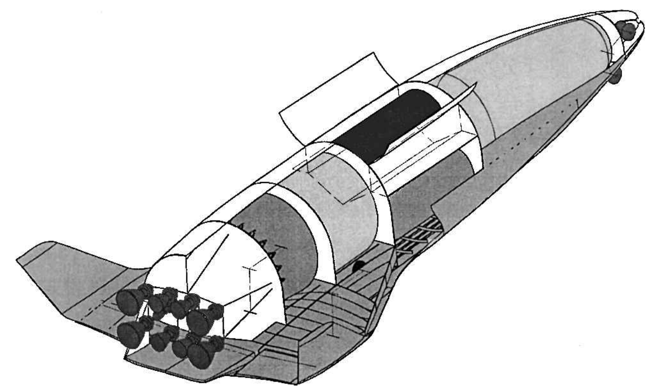

Fig. 1 FSSC-1 concept.

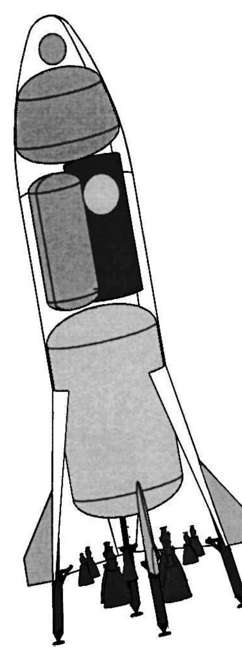

Fig. 2 FSSC-3 concept.

FSSC-4

The main design features of the FSSC-4 concept (Fig. 3) are that it is a SSTO, all-rocket-propelled vehicle (three SCCE with 245-bar chamber pressure), using cryogenic propellant (LOX/LH2). It features sled-launched horizontal takeoff and horizontal landing modes (passive sled, running on skids). Mission profile is not considered in the study.

FSSC-5

The FSSC-5 concept (Fig. 4) is a lifting-body-type vehicle. Its design has changed since the beginning of FESTIP, especially with respect to the propulsion system: In earlier program phases (slices A and B), propulsion was performed by rocket linear-aerospike engines; that was changed to typical SCCE in slice C. Current FSSC-5 features are as follows: 1) SSTO vehicle, with vertical takeoff and horizontal landing modes; 2) all rocket propelled (slice C version features seven SCCE with 245-bar chamber and separate OMS); and 3) uses cryogenic propellants (LOX/LH2) and features multilobe nonaxisymmetric tanks.

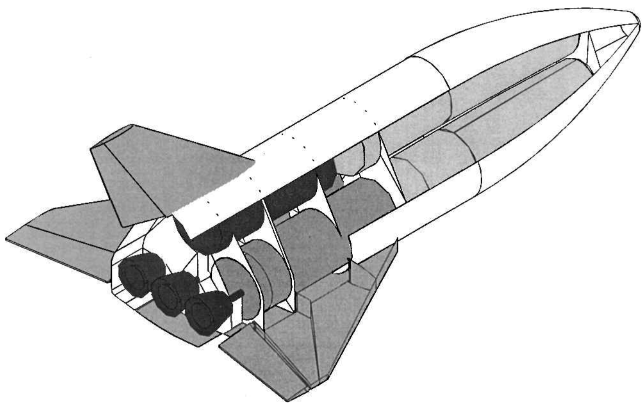

Fig. 3 FSSC-4 concept.

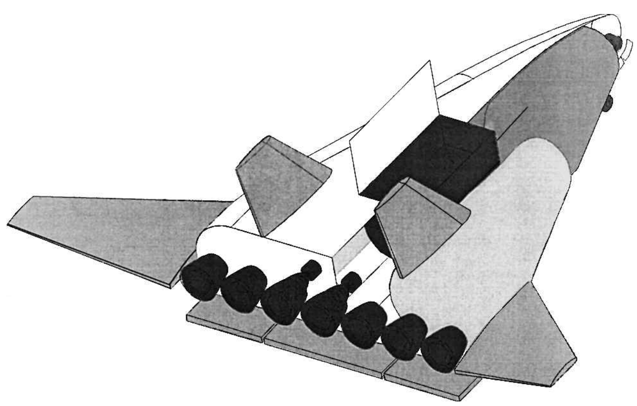

Fig. 4 FSSC-5 concept.

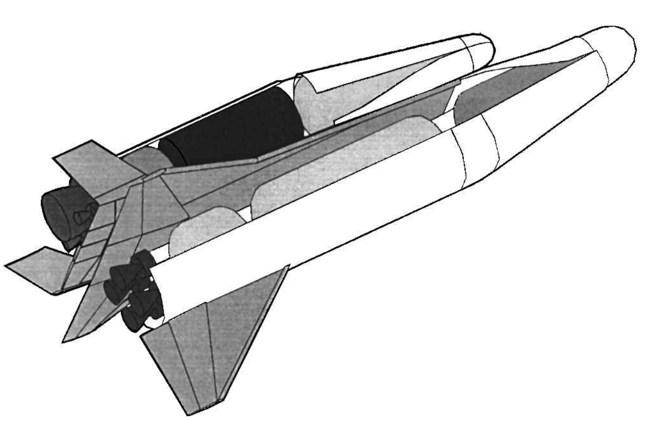

Fig. 5 FSSC-9 concept.

FSSC-9

The FSSC-9 concept (Fig. 5) is a TSTO vehicle with vertical takeoff and horizontal landing modes. It is rocket propelled: four SCCE with 245-bar chambers and fixed nozzles in the booster and one SCCE with 245-bar chamber and extensible nozzle in the orbiter. In addition, the booster has two turboengines (hydrogen feed) for descent and landing. Cryogenic propellants (LOX/LH2) with cross feeding are used, and stage separation occurs at Mach 9.4.

FSSC-12

As was the case for the FSSC-9 concept, the FSSC-12 concept (Fig. 6) is a TSTO vehicle, but with horizontal takeoff and horizontal landing modes. It is booster propelled by airbreathing engines (eight turbojets) and orbiter propelled by rocket engines (three SSCE with 245-bar chamber and extensible nozzle) with cryogenic propellants (cross feeding of LH2 and LOX). Stage separation occurs at Mach 4.0. The airbreathing engines in this concept are adapted from well-known conventional aircraft engines, which has a positive impact on reliability.

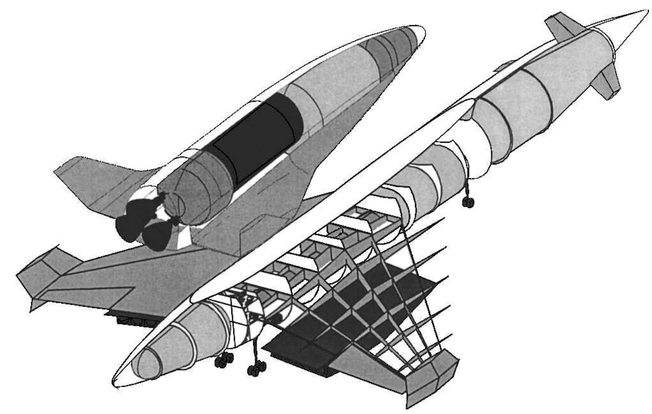

Fig. 6 FSSC-12 concept.

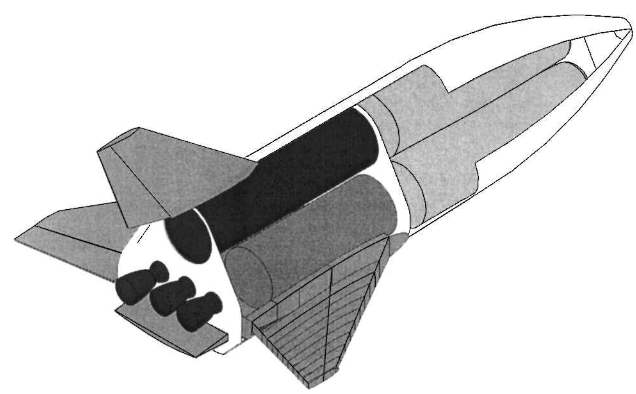

Fig. 7 FSSC-15 concept.

This vehicle has some special mission features. The first part of the coupled ascent, up to Mach 1.3, where rocket engines start after cross feeding, is performed only with the airbreathing engines of the first stage. Aerodynamic surfaces are not fully redundant for only 15 s of the ascent phase, and the FSSC-12 concept has complex separation maneuvers.

FSSC-15

The FSSC-15 (Fig. 7) refers to a family of reusable SSTO vehicles with horizontal takeoff and landing modes, derived from the FSSC-4 concept. Two members of the family have been studied in this case: the FSSC-15 once around the Earth (OAE) and the suborbital hopper (SOH) featuring state-of-the-art technology.

The configuration of the FSSC-15 concept is identical to that of FSSC-4. The difference between both concepts lies in the mission, which in this case is suborbital, single-stage, OAE with no orbital phase, just the performance of an exoatmospheric arc (OAE version) and suborbital single-stage transatlantic range (SOH version). The two FSSC-15 concept versions are all-rocket-propelled vehicles: three SCCE with 245-bar chamber pressure and extensible nozzle (in OAE version) and three Vulcain 2 engines (in SOH version). Both versions use cryogenic propellants (LOX/LH2).

FSSC-16

The FSSC-16 concept also represents a family of TSTO concepts. Two versions of the FSSC-16 concept have been studied: a fully reusable (FR) version derived from the FSSC-9 concept and an advanced semireusable (ASR) version (Fig. 8) whose first stage is the same as in the FR version, whereas the second stage is Ariane 5 without solid boosters.

The FSSC-16 design (Fig. 8) features 1) vertical takeoff and horizontal landing modes for the booster in the ASR version and for both stages in the FR version, 2) replacement of expendable Ariane 5 solid boosters by a reusable fly-back booster in the ASR version, and 3) stage separation at Mach ≈ 4 in the FR version and Mach >6 in the ASR version. The propulsion system for both concept versions is the same on the booster side: five SCCE with 150-bar chamber

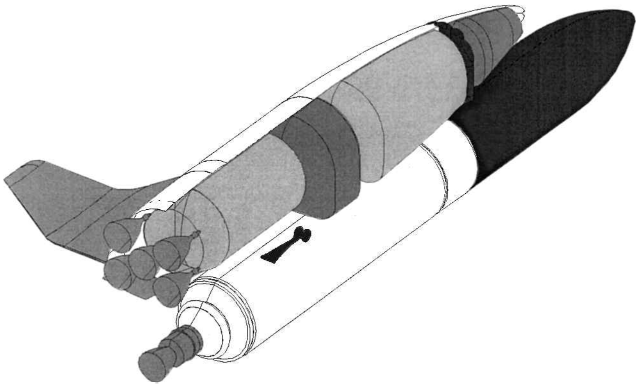

Fig. 8 FSSC-16 concept (ASR version).

pressure and four turboengines for fly-back booster. The FR orbiter features two SCCE with 150-bar chambers. There is cross feeding in the FR version, but both concept versions use cryogenic propellants (LOX/LH2).

Assessment Results

The assessment results obtained with each concept just described follow. These results correspond to the probability of loss of vehicle, due to the contribution of each system or mission phase, for each concept studied. These contributions were obtained by quantifying the subsystem or mission phase fault trees; they are not always comparable from one vehicle to another because they correspond to the probability of loss for different vehicle designs.

To enable some type of comparison, however, even though slice B and slice C concepts were not analyzed with the same level of detail in the reliability assessment, both types of concepts were submitted to a sensitivity analysis to enable appropriate comparison of all results at the end of slice C. This sensitivity analysis showed higher conservatism (≈30%) in the less detailed study (with no mission profile) than in the detailed one.

FSSC-1

Usually, the features that will make a difference between the concepts, from the reliability standpoint, are the propulsion system and the mission profile. SSCE feature technology that is not currently available in Europe, and this, together with high pressure in the chamber, increases difficulty from the reliability point of view. The mission profile was not considered in this study.

Figure 9 shows the contribution to failure of the different systems making up this vehicle. In the case of the 150-bar engine, the highest contributions to vehicle loss probability correspond, respectively, to the propulsion system (featuring SCCE with high chamber pressure) and to high-performance turbopumps. The rest of the systems have a much lower contribution, even considering a much longer operation period. The FSSC-1 concept has a relatively high abort capability, mainly due to one-engine-out capability.

As regards the FSSC-1 concept featuring 245-bar engines (Fig. 10), failure distribution is similar, but with a higher failure probability of main propulsion. Results of both concepts are compared in Fig. 11.

FSSC-3

Figure 12 shows failure distribution for the FSSC-3 concept. The most dangerous phase of the FSSC-3 mission is propelled ascent flight up to the main engine cutoff (MECO) with MP system operation, which is responsible in most cases for catastrophic failures, contributing 71% of the total probability of loss of vehicle. As with the FSSC-1 concept, the FSSC-3 concept has abort capability, mostly due to engine-out capability in the propulsion system. The phase that ranks second for loss-of-vehicle probability is descent (21%), which is long and complex due to vertical landing. It is an important phase because the vehicle has to perform numerous maneuvers before landing, using auxiliary propulsion.

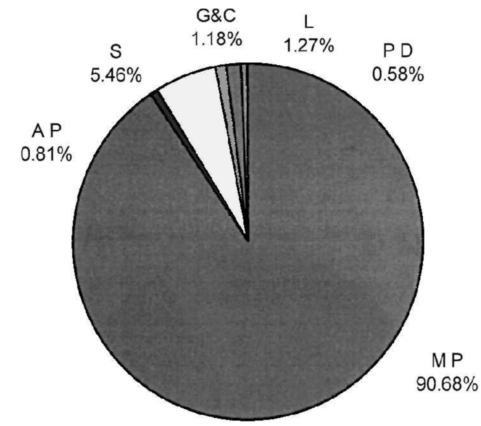

Fig. 9 Failure distribution for the FSSC-1 (150-bar) concept.

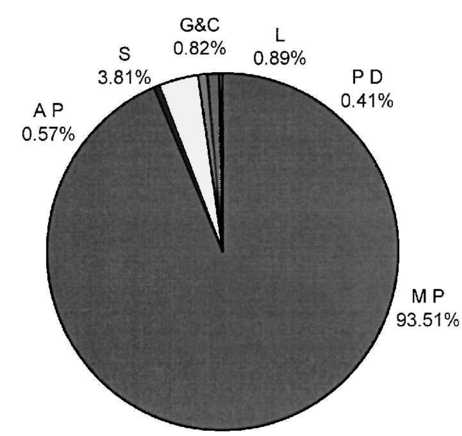

Fig. 10 Failure distribution for the FSSC-1 (245-bar) concept.

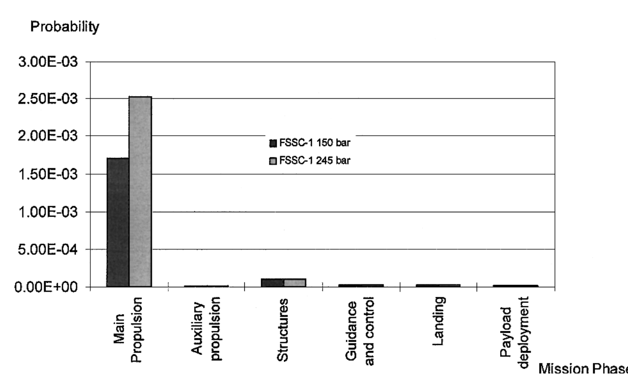

Fig. 11 Comparison of results obtained with FSSC-1 150- and 245-bar concepts.

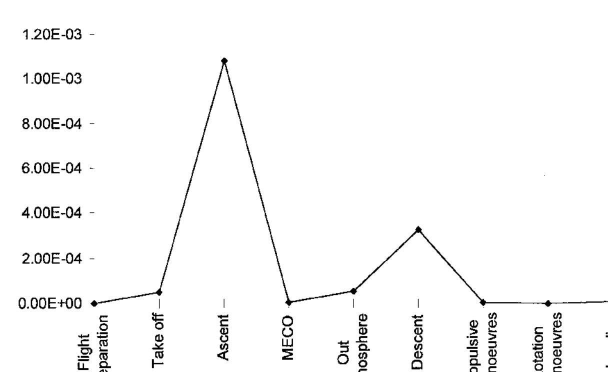

Fig. 12 Failure distribution for the FSSC-3 concept.

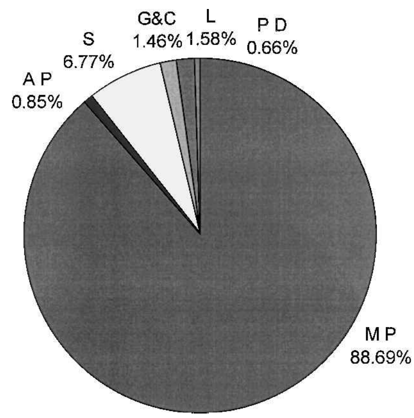

Fig. 13 Failure distribution for the FSSC-4 concept.

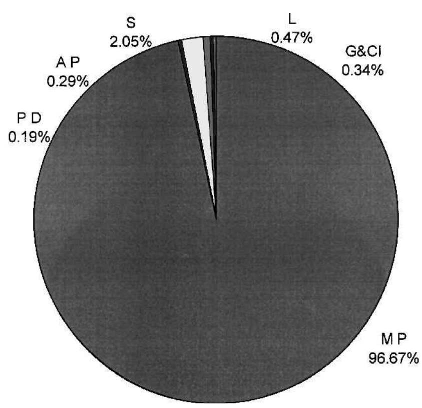

Fig. 14 Failure distribution for the FSSC-5 concept.

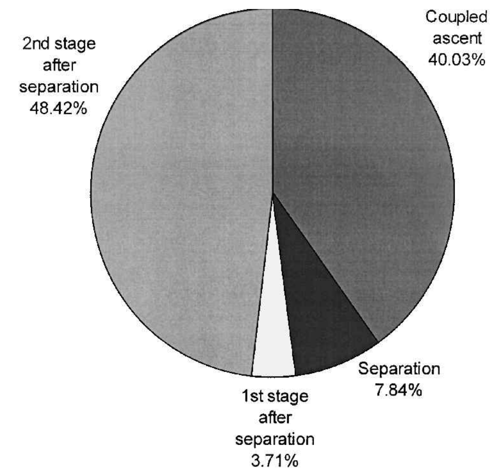

Fig. 15 Failure distribution for the FSSC-9 concept.

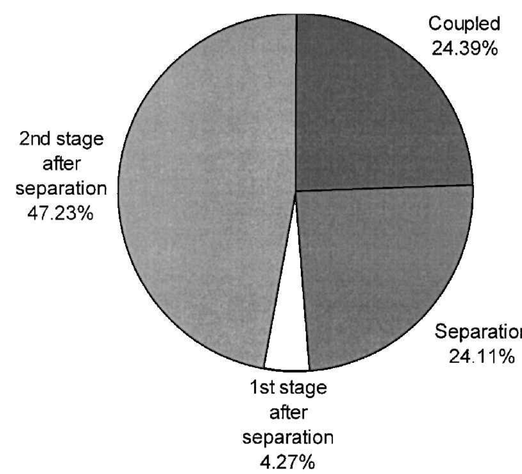

Fig. 16 Failure distribution for the FSSC-12 concept.

FSSC-4

Failure distribution for the FSSC-4 concept (Fig. 13) shows that MP is, as in the other cases, the most important contributor to loss of vehicle. The special takeoff mode could also be a source of failures and was taken into account in a simplified way in the construction of the model. The rest of the contributions to the final figure more or less follow the same logic as in the preceding cases.

FSSC-5

The high contribution of the MP system to loss of vehicle (Fig. 14) is the result of having seven engines with just a single-engine-out capability. The only other distinctive result is the contribution of structural failures to the overall probability of loss of vehicle, which is higher than in other concepts, because of the tank shape (multilobe) that is the only one that can be adapted to the lifting body vehicle.

Slice B version of the concept (aerospike engines) was also assessed for comparative purposes. Results show a significant increase in loss-of-vehicle probability due to the high uncertainty associated with the use of aerospike engines.

FSSC-9

The significant differences with respect to other vehicles are that the FSSC-9 is a two-stage concept, its separation phase occurs at Mach 9.4, and it has practically no abort capability. Landing cannot take place before separation, when the two stages are coupled. After separation, the second stage only has a single engine for MP, and any failure that could produce loss of the engine at that point would directly lead to loss of the vehicle.

Failure distribution for this concept (Fig. 15) shows that the most critical phase is ascent, particularly second-stage ascent after separation, because of the special design features just mentioned. It also results in high loss-of-vehicle probability with respect to the other concepts. The separation phase, even though it is short, contributes significantly to failure.

FSSC-12

Failure distribution for the FSSC-12 concept (Fig. 16) shows a lower contribution of propulsion during the first phase of the ascent due to the use of almost redundant airbreathing (aircraft-derived) engines, as well as low contribution of the first stage after separation for the same reason. However, separation at Mach 4.0 has been identified as one of the most critical phases for this concept due to high integration of both stages.

FSSC-15

The failure distribution corresponding to both concept versions (OAE and SOH) are shown in Fig. 17. Results for both FSSC-15 concept versions differ from those of the FSSC-4 due to shorter mission time and the absence of auxiliary propulsion (which is not needed because there is no orbital phase). Lower probabilities in the SOH version are due to the use of state-of-the-art engine technology (Vulcain 2), which make an important difference in the final results of the study, and to shorter mission time. Both concept versions profit from horizontal takeoff and landing modes.

FSSC-16

The failure probability obtained with the ASR version of the concept (Fig. 18) is influenced by Ariane 5 reliability. Reliability requirements are not as high for Ariane 5 (concept of expendable solid boosters) as for the FESTIP concepts. As regards the FR version of the concept, the loss-of-vehicle probability is much lower (Fig. 18) and in line with that of other vehicles. As was the case for the FSSC-9 concept, the long ascent time and the type of propulsion system (second stage) is again the main contributor to the probability of loss of vehicle.

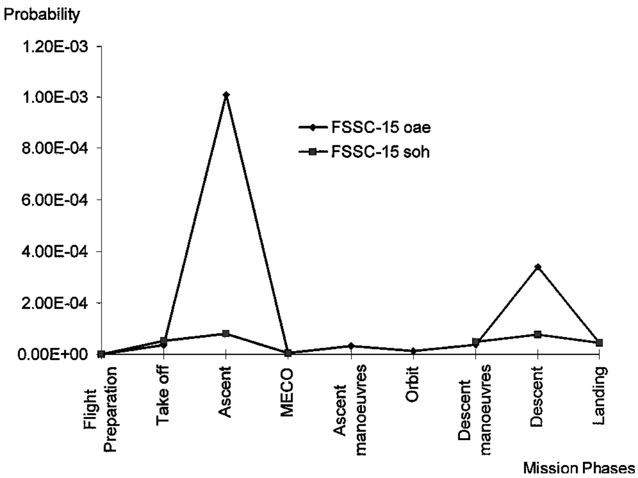

Fig. 17 Failure distribution for FSSC-15 concept versions.

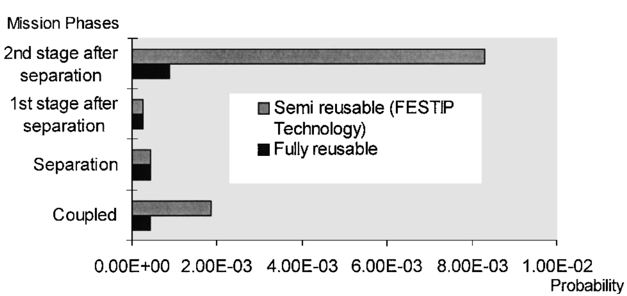

Fig. 18 Comparison of FSSC-16 FR and ASR results.

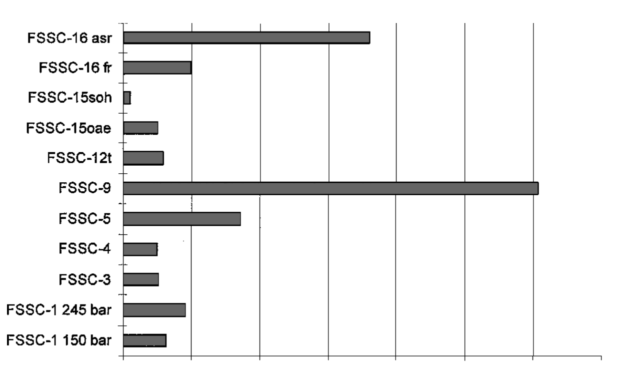

Fig. 19 Comparison of vehicle concepts under study (loss-of-vehicle probability).

Global Assessment Results

Figure 19 compares the probabilities of loss of vehicle of all of the described concepts. Uncrewed launchers have almost no redundancy. That means that practically any failure can produce loss of vehicle. However, study results show that loss-of-vehicle probability drops dramatically with a certain level of redundancy (even if it is just enough to allow the vehicle to turn back to Earth after one single failure). For example, the MP system of most vehicles features one-engine-out capability, which means that in case of failure of one engine the vehicle cannot continue with the mission but can perform safe landing. Most concepts have a loss-of-vehicle probability of approximately $1.5E-3$, which is 50% higher than the FESTIP requirement (compare with Table 1).

As can be seen in Fig. 19, the highest deviation from reliability requirement corresponds to the FSSC-9 concept, which has no abort capability in regard to highly significant failure: that of MP. It has no engine-out capability (its orbiter is propelled by just one main engine), and any engine failure will immediately lead to loss of vehicle. Although featuring similarities to the FSSC-9 in design, the FSSC-12 concept has a significantly lower loss-of-vehicle probability because of its high abort capability. Other reasons for the improved result are as follows. 1) Even though it is a TSTO concept, the FSSC-12 can abort the mission before staging (something that is not possible in other TSTO concepts). 2) The concept design features a high-redundancy level in the first stage, for example, engine-out capability in airbreathing propulsion and redundant control surfaces. 3) It has some redundancy in the second stage (such as engine-out capability in MP).

Deviations from the required value obtained with the other concepts studied are not so pronounced and can be explained. For example, the semireusable FSSC-16 ASR concept should not be compared with FR vehicles. The FSSC-5 concept design involves an unusual shape making control difficult and is combined with a very powerful propulsion system (eight high-pressure SCCE). The SOH version of the FSSC-15 concept obtained the lowest failure probability, as a result of fewer uncertainties due to state-of-the-art technology and to the shortest mission time.

The high uncertainty in results is due to new technologies employed in the concepts and to the estimates required by less detailed designs at this stage of the program. Results are still very useful for comparison purposes because uncertainties are almost the same for all concepts envisaged, and the results obtained give a fair indication of design weak points in each system.

Conclusions

As indicated earlier, one of the main objectives of FESTIP was to design competitive launchers. Two important factors for competitiveness are vehicle availability and lifetime. This reliability assessment study has proved that probabilistic reliability analyses are a good decision-making tool even at the early design stage in a program where conceptual design can be corrected. It can be used as a comparative argument for concept selection, giving a quantitative reliability estimate of different conceptual design options, as well as for the selection of subsystem design options established as having a reliable design from the onset.

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