Memorandum M-661

SPACEPLANE FLIGHT SIMULATION;
project definition

June 1992
Prepared by:

B.T.C. Zandbergen

Approved by:

prof.dr.ir. P.G. Bakker

prof. dr.ir. J.A. Mulder

prof.ir K.F. Wakker
Introduction

In this report, a proposal is given for the development of a method allowing for the assessment of current and advanced technology on the mission performance of space launchers. In addition, for background information, a short overview is given on currently proposed launcher concepts (Section 1) and the available assessment method(s) (Section 2).

1. Space launcher concepts and concept options

In view of the limited financial resources available for space exploration, it must be clear that, to allow a significant growth in space exploration, the costs of space transportation must be reduced considerably (at least an order of magnitude). These costs are, generally, divided up into launch and insurance costs. Some typical launch costs are given in Table 1. Today, typical insurance costs are up to 20-25% (the insurance rate) of the insured value of the launcher, including the value of the launcher itself and the launcher operations. The satellite costs are not included in this value.

Table 1: Typical launch costs [1]

<table>
<thead>
<tr>
<th>launcher</th>
<th>launch costs (US $M)</th>
<th>payload/orbit (kg/\text{-})</th>
<th>year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ariane 44L</td>
<td>90-110</td>
<td>4200/GTO (Kourou)</td>
<td>1991</td>
</tr>
<tr>
<td>Commercial Titan</td>
<td>110</td>
<td>4535/GTO (26.4°)</td>
<td>1991</td>
</tr>
<tr>
<td>Scout G-1</td>
<td>10-12</td>
<td>212/LEO (2.9°, 550 km)</td>
<td>1991</td>
</tr>
<tr>
<td>Pegasus</td>
<td>5-10</td>
<td>408/LEO (0.0°, 463 km)</td>
<td>1991</td>
</tr>
<tr>
<td>Delta II (6925)</td>
<td>50</td>
<td>1451/GTO</td>
<td>1990</td>
</tr>
</tbody>
</table>

Hence, reducing the costs associated with space transportation means reducing the launch costs and the insurance costs. Of these, the launch costs, basically, depend on the (forecasted) launcher market, and the launcher hardware costs, which include the costs for development and production of the launcher and the launch facilities, and the launcher operational costs. The latter costs, include the costs for propellants, launch preparation, refurbishment, launch control, and integration. The launcher hardware and operational costs in turn are determined by the level of technology advancement incorporated, the (predicted) life of the launcher and the numbers to be produced. The insurance cost and, more specific, the insurance rate are determined by the reliability of the selected launcher. The common opinion today is that, in order to significantly reduce space transportation
costs, an advanced space launcher or even a range of advanced space launchers has to be developed [2-6].

Current interest [2-18] is basically in two different classes of launch vehicles. The first class consists of conventional 'rocket-propelled' launchers, like e.g. the Japanese H-2, the US National Launch System (NLS) and the European Ariane 5. For a typical example of a conventional launcher, one is referred to Figure 1. The second class is formed by the highly advanced-technology Spaceplane type of launchers, such as HOTOL, Sänger, NASP (X-30) and Star H. Figure 2 gives a typical example of a spaceplane.

Fig. 1: Typical example of a conventional rocket launcher (Ariane 5) [2].

SÄNGER
with CARGUS

SÄNGER
with HORUS

Fig. 2: Typical example of a spaceplane type of launcher (Sänger) [18].
Cost reduction for the class 1 launchers is aimed for by differentiating between manned and unmanned transportation (increased flexibility), attention to modular design (e.g. the family of Ariane launchers), high reliability, ease of manufacturing and safety (REMS), reusability, and reduced dry mass. Typical (normal-growth) technology options are clustering, hybrid rocket engines, reusable boosters, extendable or dual-position nozzles, advanced materials (e.g. fibre reinforced materials) [2-10].

The second class aims at reduced costs through the introduction of aircraft-like features with the aim of fully reusable vehicles with airport launch and landing capability (increased operability), a reduced amount of propellants and an increase of reliability to aviation levels. In order to achieve this goal, the following advanced technologies are envisaged [2-6, 8,11-19]:

. winged launchers
. horizontal take off and landing
. Single-Stage-To-Orbit (SSTO)/Two-Stage-To-Orbit (TSTO)
. airbreathing engines
. advanced rocket engines
. multi-cycle engines
. control configured design
. advanced materials

From this multitude of technologies, many different advanced space launch vehicles can be devised. However, as financial resources are limited and because it is not yet clear which combination of technologies gives the best solution (in terms of cost and availability), studies are needed to guide the development of technology for future Earth-to-orbit launchers. To illustrate the problem, it may be stated that there still is no final answer to the question whether the total costs of a class 2 vehicle will be in excess of the total costs of a class 1 vehicle. For example, the development costs for Ariane 5 are estimated at US $ 5800 million (1991) [8], whereas development costs for winged launchers are estimated at US $ 8400 million (1991) for Hermes [20] and US $ 12000 million for the Sängé first stage (1989) [16].

2. Technology assessment for advanced space launchers

To focus technology development, the impact of technology growth/advancement on launcher hardware costs, launcher operational costs and launch insurance costs has to be studied.

Launcher hardware costs are, generally, studied in relation to the required mission performance, i.e. payload mass to orbit. This required performance depends, of course, on the satellite market forecast. In the conceptual design stage, where the basic technology choices are made, mission performance usually is studied using mission performance models, which allow the determination of the payload mass (ratio) of the various concep-
tual launchers. For this, computerized flight trajectory simulation models are used, which take into account the vehicle (architecture, geometry, size, gross mass and dry mass), geophysics (gravity field, atmospherics), aerodynamics, aeroheating, guidance (flight constraints), and propulsion [21-40]. Typical results of conceptual design studies are given in Figure 3.

propellant mass: 347 tons
launch mass: 400 tons

propellant mass: 236 tons
launch mass: 300 tons

a) Rocket powered vehicle        b) Air-breathing vehicle

Fig. 3: Typical results of mission performance calculations (single-stage vehicle, payload mass: 7 tons) [31].

Once the effects of advanced technology on the mission performance of the various conceptual launchers are known, the development and production costs as well as the operational performance and the associated costs, and the reliability aspects can be assessed in detail for the different mission classes. For this, the costs associated with current technology and technology advancement, the production learning factor, the operational performance and the associated costs, the production rate per year and the overall number of vehicles to be produced have to be known. Usually, these data are partly based on historical data and partly on an outlook to the future.

Combining the total costs of launcher development, production, operation and insurance, gives the transportation costs per vehicle, i.e. the Life Cycle Costs (LCC) as well as a technology ranking per vehicle, see e.g. Table 2.
Table 2: Typical technology ranking showing Life-Cycle Cost savings (ΔLCC) versus costs associated with technology development (ΔR); 1976 US dollars [34].

<table>
<thead>
<tr>
<th>Technology program</th>
<th>Δ Technology</th>
<th>ΔR</th>
<th>ΔLCC/ΔR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Miscellaneous structures</td>
<td>ΔW</td>
<td>-7.5</td>
<td>4.5</td>
</tr>
<tr>
<td>Wing and tail structures</td>
<td>ΔW</td>
<td>-13.0</td>
<td>16.4</td>
</tr>
<tr>
<td>Main propulsion-dual mode</td>
<td>Δρ</td>
<td>+50.0</td>
<td></td>
</tr>
<tr>
<td>(A) series</td>
<td>ΔI&lt;sub&gt;sp&lt;/sub&gt;</td>
<td>-7.5</td>
<td>44.3</td>
</tr>
<tr>
<td>(B) parallel</td>
<td>ΔT/W</td>
<td>+30.0</td>
<td>32.8</td>
</tr>
<tr>
<td>Propellant tanks</td>
<td>ΔW</td>
<td>-10.0</td>
<td>9.0</td>
</tr>
<tr>
<td>Thrust structures</td>
<td>ΔW</td>
<td>-8.1</td>
<td>4.5</td>
</tr>
<tr>
<td>Subsystem weights</td>
<td>ΔW</td>
<td>-9.7</td>
<td>4.8</td>
</tr>
<tr>
<td>Subcooled propellants</td>
<td>ΔW</td>
<td>-6.2</td>
<td>17.5</td>
</tr>
<tr>
<td>Thermal protection systems</td>
<td>ΔW</td>
<td>-7.5</td>
<td>10.5</td>
</tr>
<tr>
<td>Main propulsion LOX/LH&lt;sub&gt;2&lt;/sub&gt;</td>
<td>ΔI&lt;sub&gt;sp&lt;/sub&gt;</td>
<td>+2.0</td>
<td>84.0</td>
</tr>
<tr>
<td></td>
<td>ΔW</td>
<td>-2.7</td>
<td></td>
</tr>
<tr>
<td>OMS/RCS propulsion</td>
<td>ΔW</td>
<td>-5.9</td>
<td>26.8</td>
</tr>
</tbody>
</table>

W = weight, ρ = propellant/fuel density, T = thrust, I<sub>sp</sub> = specific impulse

Following identification of the (classes of) vehicles most likely to yield significant improvements in transportation costs, this approach then allows for the identification of important common and possibly even specific technologies needed.

3. Proposal for TUD-LR spaceplane research

Presently, Dutch aerospace industry has a major involvement in the development of components for Europe's next generation launch vehicle: Ariane 5. However, to ensure work on future space launchers, TNO-PML, Stork Product Engineering BV (SPE) and NLR, supported by the Netherlands agency for aerospace programs (NIVR) [41], started in 1988 a joint project aiming at the development of key technology for future airbreathing space launchers [42]. In 1992, plans have been initiated by NIVR to increase the budget from about 0.7 Mfl to 2-3 Mfl and to also include Fokker Space & Systems BV (FSS) in
the project. Since then, FSS has indicated that they are very interested in joining the project team and talks on a redefinition of the work are making good progress.

Because of the relatively small budget available (2-3 Mfl) compared to e.g. the United States, Japan, Germany and France, an early and careful analysis of the required technology, thereby allowing for 1) identification and selection of key technolog(y)/(ies) and 2) spreading of investments. For this, advanced space launcher technology assessment studies are required. Such an approach also agrees well with the opinion of ESA [3,42], being that a future launcher program should start with a study phase:

'in which all possible future transportation concepts would be defined and compared. The results would then be used to identify the common, or even specific, enabling (i.e. key) technologies'.

To allow independent assessment of advanced space launcher technology by Dutch aerospace industry, an assessment method should be available. So far, however, no evidence exists that such a method is available for Dutch industry. Therefore, it is deemed necessary to also set up a (national) program to acquire relevant expertise in this field and to develop a general advanced (spaceplane) technology assessment method. Delft University of Technology, Faculty of Aerospace Engineering (TUD-LR) is of the opinion that TUD-LR can contribute significantly to such a national program.

In anticipation of the creation of this national program, TUD-LR has set up a project group (March 1992), including the disciplinary groups/sections: Aerodynamics/High Speed Aerodynamics (HSA), Aerospace Design and Flight Mechanics/Space Technology (ST) and Stability and Control (S&A). The aim of this project group is to develop a computerized flight simulation model, which can be used for the analysis of the flight trajectory and of the (real time) flight behaviour, thereby taking into account the vehicle characteristics (architecture, geometry, size, gross mass, payload mass and dry mass), geophysics, aerodynamics, aeroheating and propulsion.

The planned duration of the project is 5 years; the project will consist of 3 phases:

1. Exploratory phase
   The duration of phase 1 is 15 months. The major objectives are 1) to perform initial studies to establish a baseline for the proposed simulation model with special attention to innovative aspects, 2) to establish organization and control, and 3) to generate a final project proposal.

2. Prototype phase
   The duration of the prototype phase is 30 months. In this phase, detailed design and development of the flight simulation model will take place based on the specifications derived from phase 1.
3. Final phase

During this phase (21 months) the results of phase 2 are consolidated. Also specific attention will be given to the validation of the model.

A schedule of the project is given in Figure 4.

Fig. 4: Project schedule

The project group consists of staff members of the faculty, as well as graduate and undergraduate students. At present, the total manpower involved is about 2 manyear/year. It is planned that the level of manpower will increase in 1993 to about 4 manyear/year.

The project group is headed by a management group, which is responsible for project control, configuration control, documentation, external contacts, and finance and contracts. In addition, a technical manager is appointed, who is responsible for the overall design of the flight simulation software. He is assisted by a technical group, where at least the following disciplines are represented 1) aerodynamics and aeroheating, 2) flight mechanics, 3) propulsion, 4) guidance and control 5) aerospace design and 6) geophysics. To coordinate the work, the technical group and the technical manager will convene on a monthly bases.

At present, it is assumed that reporting on the project status to the management group will be done on a three-monthly basis, whereas financial reporting will be done on a yearly basis.
REFERENCES

1. Wilson, A. (ed.)

2. Feustel-Buechli, et al

3. Branscome, D.R. and Reese, T.G.


5. Gunn, C.R.

6. Koelle, H.H.

7. Kolcum, E.H.
   Delta Clipper partners set goal for single-stage-to-orbit vehicle, Aviation Week &

8. Johnson, C. and Lieberherr, J.F.

9. Dargies, E. and Lo. R.E.

10. Westphal, W and Behle, E.

11. Conchie, P.J.
    A horizontal take-off and landing satellite launcher or aerospace plane (HOTOL),
12. DeMeis, R.
   An Orient Express to capture the market, Aerospace America, September 1987.


    The personnel launch system, Aerospace America, November 1990.

15. Peebles, C.

    63-72, 1989.

17. Jones, R.A. and Donaldson, C. du P.
    From Earth to orbit in a single stage, Aerospace America, August 1987.

18. Eggers, A.J. et al
    Hypersonic aircraft technology and applications, Astronautics & Aeronautics, June
    1970.

19. Johnston, P.J. et al
    Fitting aerodynamics and propulsion into the puzzle, Aerospace America, September
    1987.

20. Selding, P.B. de

    Potential directions for a second generation shuttle, Acta Astronautica, Vol.17, pp

22. Sakata, K. et al
    Hypersonic turbomachinery-based air-breathing engines for the Earth-to-orbit vehicle.

23. Swales, A.W.

24. Eldred, C.H. and Talay, T.A.
    Prospects for advanced rocket-powered launch vehicles, Acta Astronautica, Vol. 17,
25. Dorrington, G.E.


27. Kramer, P.A. and Buhler, R.D.

28. Manski, D.

29. Wilhite, A.W.

30. Ashford, D.M.

31. Bouillot, J.C. et al

32. Froning, H.D. jr.

33. Arend, H.

34. Arrington, J.P.

35. Schoettle, U.M.
36. Martin J.A.

37. Wilhite, A.W.

38. Wilhite, A.W. et al

39. Eldred, C.H. and Talay, T.A.

40. Martin, J.A.

41. An.

42. Wolf, W.B. de, Troost, G.K. and Korting, P.A.O.G.
Application of ramjet engines for Mach 2 to 7 flight, proposal for a joint NLR-SPETNO study (in Dutch), version 7, april 1988.

43. An.