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Cost Estimation of the NAL Spaceplane (Modeling of a Vehicle Fleet Life-Cycle)

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COST ESTIMATION OF THE NAL SPACEPLANE (MODELING OF A VEHICLE FLEET LIFE-CYCLE)

(NAL スペースプレーンのコストエンジニアリング - 機体のライフサイクルに関するモデリング)

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Abstract

Reusable Launch Vehicles (RLVs) are seen as one step toward inexpensive space transportation. The Japanese Government considers a Two-Stage-To-Orbit Vehicle, called NAL Spaceplane, as a potential future RLV. The system has a total launch mass of 193 Mg and the orbiter's payload capability is 8 Mg for LEO (300km) launched from Christmas Island. This study examining the economical performance of the NAL Spaceplane concept. To obtain relevant information, a multi-vehicle space carrier fleet cost model, called TRASIM, is used. For comparison and verification of the results, the Space Shuttle, which is the only existing partially reusable launch vehicle in operation, is simulated in parallel. For the NAL Spaceplane scenario it is assumed that development phase is 12 years while operation phase is 50 years. As one result, the Total Cost per Flight (CpF) for the NAL Spaceplane is calculated to $40 million (2001), while the Total CpF for the Space Shuttle is about $480 million (2001).

KEYWORDS: Cost Estimation, TRASIM, Life-Cycle Cost, NAL Spaceplane, Space Shuttle

Introduction

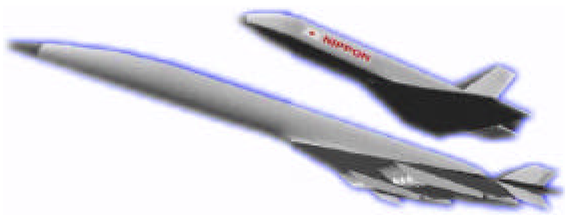

Figure 1: NAL Spaceplane (NAL)

It is believed that the only potential means for further significant reduction of the recurrent launch cost is to make the launcher partially or completely reusable and to greatly increase its reliability, while preserving its operability. Potential reduction in RLV long-term production costs is attributed to vehicle refurbishment and reuse after each flight, rather than replacement. RLVs are designed for quick-turnaround operations that will allow for a higher volume and launch rate, resulting in economies of scale. Some assets of RLVs are low operating costs for high launch rates, high reliability, and satisfactory ecological compatibility. The known disadvantages of RLVs are high development costs and high operating costs for low launch rates.

The NAL Spaceplane is under consideration as a future fully Reusable Launch Vehicle that Japan aims to develop and realize. The Two-Stage-To-Orbit Vehicle is composed of a hypersonic booster plane and a winged orbiter, as shown in Figure 1. The booster is powered by LH2 airbreathing engines, called ATREX, which are under development in the Institute of Space and Astronautical Science (ISAS) of Japan as shown in Figure 2.

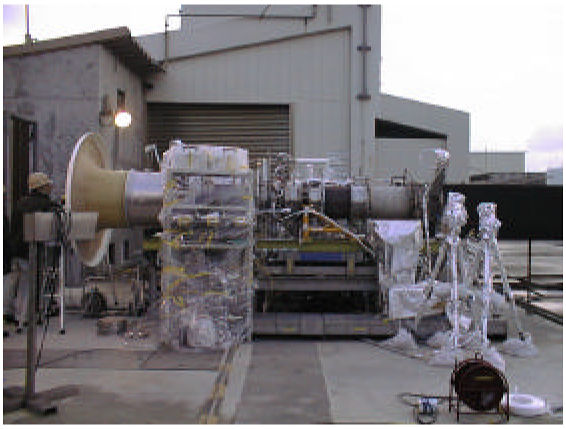

Figure 2: Experimental Turbo-Ramjet Engine at Noshiro Testing Center

The orbiter has a LOX/LH2 rocket engine. The booster carrying the orbiter on the body, takes off horizontally at the launch site and accelerates with the ATREX engines. After performance limit of the ATREX engines about Mach 6, the orbiter will be separated as shown in Figure 3. The booster flies back to the launch site, while the orbiter continues its ascent to the orbit with the rocket engine. After the satellite is separated, the orbiter reenters in the atmosphere and returns to the launch site.

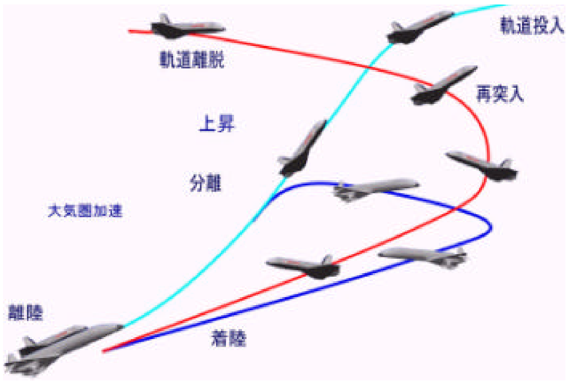

Figure 3: Flight Profile (NAL)

It is assumed that the NAL Spaceplane is unmanned and orbiter's payload capability should be 8 Mg for LEO when launched from Christmas Island.[1]

For a better understanding of the economical performance of the NAL Spaceplane the life-cycle simulation is also run for the Space Shuttle which is shown in Figure 4.

Figure 4: Space Shuttle (NASA)

System Realization

In addition to the technical feasibility of a vehicle concept, the probability of realization the vehicle under real world political and financial conditions must be analyzed. Table 1 and Figure 5 show a first approach to a representative life-cycle scenario for the NAL Spaceplane.

It is assumed that the period from Preliminary Phase (Pre-phase A) to Production Phase (Phase D) can be accomplished within 12 years. The Operation Phase (Phase E) is assumed to be 50 years and would be completed by a 1/2 year Abolition Phase (Phase F).

Table 1: Proposal for System Realization

Phase of Realization		Duration	Financing	Responsible
Pre-phase A (preliminary)	Idea definition and market analysis	1/4 year	Institutional funding	Individual
Phase A (concept)	Tentative selection of candidate vehicle concepts	1 year	Company sponsored study Public sponsored study	Individual
	Conceptual design and system analysis	1 year	Private funding Institutional funding Public Agency Contract	Consulting company
Phase B (definition)	Preliminary design and system specifications	2 years	Commercial investor Public investor	Space agency
	Assessment of political and legal restrictions	1 year	Public investor	Consulting company Space agency
	Insurance concept	1/2 year	Commercial investor	Consulting company
	Business plan	1 year	Commercial investor	Potential Investor
	Advanced development on high risk items	2 years	Commercial investor	Public agencies
Phase C (development)	Primary development includes testing of prototype	4 years	Commercial investor Joint enterprise of companies Joint enterprise of public organization	Established aircraft industry
	System certification	2 years	Commercial investor	International organization Military organization
Phase D (production)	Production of operational vehicles	3 years	Commercial investor	Established aircraft industry New company
	Construction of ground support equipment infrastructure	1 year	Joint venture investors with government participation	Established aircraft industry New company
Phase E (operation)	Establishment of operating company	1/2 year	Commercial investor	Operating company
	Establishment of marketing and training infrastructure	1 year	Commercial investor	Operating company
	Operating vehicle fleet	50 years	Commercial investor	Operating company
Phase F (abolition)	System phase out and replacement	1/2 year	Commercial investor	Operating company

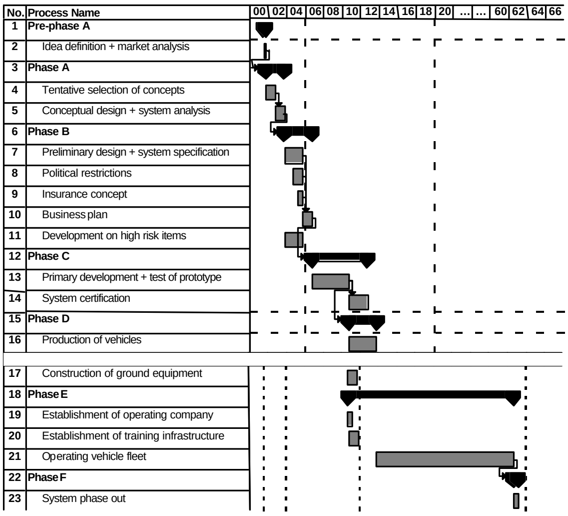

Figure 5: Proposal for Master Bar Chart

Cost Engineering

For assessment of a vehicle's success it is important to estimate realistic launch cost. This is done by calculation of life-cycle costs for a simulated scenario. The life-cycle costs include development cost, vehicle production cost, operating cost, and abolition cost:[2;3]

- **Development Cost:** development costs are non-recurring. They include the testing as well as the fabrication rigs and tools cost since, normally, at least a prototype unit is included in a development program requiring the tools and rigs.

- **Production Cost:** production costs are recurring. They include the prototype manufacturing as well as the follow-on production.

- **Operating Cost:** operating costs are recurring. They include management, pre-launch operations, launch operations, mission control, propellants and ground transportation.

- **Abolition Cost:** abolition costs are non-recurring. During the abolition phase the vehicles and ground facilities are scrapped, the employees are dismissed, and licenses are sold. In general, the abolition costs are the balance between the expenses and the proceeds which is compensated by the Variable Direct Operating Cost (DOC_{var}) of one launch.

However, development and abolition costs are normally covered by contract of a governmental agency. Therefore, they are not included in the launch costs estimates of this study.

TRASIM Model

The TRASIM model is a tool for the analysis of the entire life-cycle of a fleet of space transportation systems on an annual basis. It can consider transportation activities between 9 transportation nodes of 5 different space transportation systems consisting of up to 3 stages with 5 payload categories each employed in 8 different mission modes. The output of performance and cost data requires a minimum of 38 tables. Applying this model since 1989 has led to refinements which have been incorporated into the current version.[4;5]

Structure

As shown in Figure 6, four data files are the inputs to the system simulation program module which creates two output data files. Additionally one data file is needed for the economic evaluation program module which creates one additional output data file, but is not used for the simulation in this study.

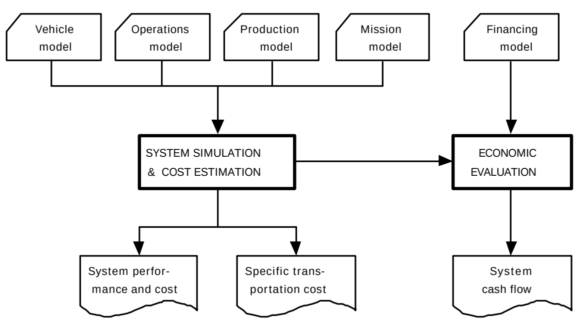

Figure 6: Data Flow Diagram (Koelle, Johenning)

Input Parameters

Appendix A shows the necessary input parameters for the Space Transportation Simulation Model including used equations[4;6] and an estimation of the sensitivity concerning the specific transportation costs. (Appendix A can be ordered from the author.)

Results

Note: For comparison of the results, some input values for the Space Shuttle have to be changed due to simulation limitations. The corresponding outputs are put in parentheses.

As shown in Table 2, the total development cost for the NAL Spaceplane is currently calculated to be about $24 billion (2001), which may be an acceptable value for such a fully reusable launch vehicle.

The NAL Spaceplanes' development cost for the engines represent the largest subsystem cost share with 61% for the Turbo-Ramjet Engine (Booster) and 46% for the Liquid Rocket Engine (Orbiter).

Table 2: Comparison of Development Costs in FY 2001

Subsystem	NAL Spaceplane		Space Shuttle			Unit
	Booster Stage 1	Orbiter Stage 2	SRB Stage 1	ET Stage 2	Orbiter Stage 3	
Cold Structure	920	239	1257	28	1450	M$
Hot Structure	296	185	0	0	368	M$
LH2 Tanks	1411	453	0	660	0	M$
LOX Tanks	0	175	0	256	0	M$
Equipment	2333	1516	0	0	7772	M$
Engines	7971	2184	0	0	4932	M$
Recovery	82	40	0	0	210	M$
Interstage	0	0	0	0	0	M$
Total	**13 013**	**4792**	**1257**	**944**	**(14 732)**	**M$**
Tooling	267	36	159	292	107	M$
Engineering and Integration	5182		(8314)			M$
Ground Facility (First Unit)	1075		1075			M$
Total Development Cost	**24 365**		**26 880**			**M$**

The first unit production cost for the NAL Spaceplane is estimated to be about $1,7 billion (2001), nearly half of the cost compared to the Space Shuttle as shown in Table 3. This results mainly in the simplicity of the NAL orbiter.

Table 3: Comparison of Production Costs (First Unit) in FY 2001

Subsystem	NAL Spaceplane		Space Shuttle			Unit
	Booster Stage 1	Orbiter Stage 2	SRB Stage 1	ET Stage 2	Orbiter Stage 3	
Cold Structure	210	65	114	4	1929	M$
Hot Structure	71	9	0	0	235	M$
LH2 Tanks	26	9	0	58	0	M$
LOX Tanks	0	5	0	21	0	M$
Equipment	153	108	0	0	353	M$
Engines	920	54	0	0	201	M$
Recovery	70	22	0	0	44	M$
Interstage	0	0	0	0	0	M$
Total	**1450**	**272**	**114**	**83**	**2762**	**M$**
Total Production Cost (First Unit)	**1722**		**2959**			**M$**

Table 4 shows that in this 50 year program scenario totally 11 NAL Spaceplanes have to be built and 2 vehicles are left at the end of the operation phase.

The model calculates the number of cumulative flights of each vehicle up to the year when retired. The number of reuses is different for individual subsystems which are replaced after reaching their respective design life time, but the total vehicle is decommissioned after a given number of years in the inventory (here: 20 years resulting in 280 reuses for the NAL Spaceplane's cold structure). An ambitious goal from today's viewpoint, but small in comparison to present aircraft cold structures which have 30 000 flights or more before they are sold for scrap.

Table 4: Inventory and Operational Data of NAL Spaceplane

Year	Procurement	Withdrawals	Losses	Inventory	Turnaround-Time
[-]	[-]	[-]	[-]	[-]	[days]
1	3	0	0	3	90,3
2	0	0	0	3	90,3
3	0	0	0	3	45,2
4	0	0	0	3	45,2
5	0	0	0	3	45,2
6	0	0	1	2	30,1
7	0	0	0	2	30,1
8	0	0	0	2	30,1
9	0	0	0	2	30,1
10	1	0	0	3	45,2
11	0	0	0	3	30,1
12	0	0	0	3	30,1
13	0	0	0	3	30,1
14	0	0	1	2	20,1
15	1	0	0	3	30,1
16	0	0	0	3	30,1
17	0	0	0	3	30,1
18	0	0	0	3	30,1
19	0	0	0	3	30,1
20	1	0	0	4	30,1
21	0	1	0	3	22,6
22	0	0	0	3	22,6
23	0	0	0	3	22,6
24	0	0	0	3	22,6
25	1	0	0	4	30,1
26	0	0	1	3	22,6
27	0	0	0	3	22,6
28	0	0	0	3	22,6
29	0	0	0	3	22,6
30	1	0	0	4	30,1
31	0	0	0	4	30,1
32	0	0	0	4	30,1
33	0	0	0	4	30,1
34	0	0	0	4	30,1
35	1	1	0	4	30,1
36	0	0	0	4	30,1
37	0	0	0	4	30,1
38	0	0	0	4	30,1
39	0	0	0	4	30,1
40	1	1	0	4	30,1
41	0	0	0	4	30,1
42	0	0	0	4	30,1
43	0	0	0	4	30,1
44	0	0	0	4	30,1
45	1	1	0	4	30,1
46	0	0	0	4	30,1
47	0	0	1	3	22,6
48	0	0	0	3	22,6
49	0	0	0	3	22,6
50	0	1	0	2	15,1
Total	**11**	**5**	**4**	**-**	**-**

Figure 7 shows the annual launch rates assumed. The annual launch rate can be increased over the time due to learning effects during the operation phase. Those effects are mainly achieved by maintenance and refurbishment improvements).

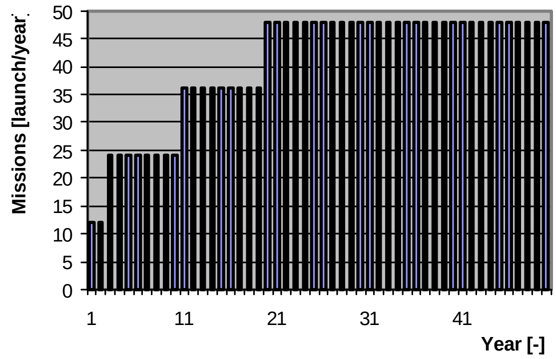

Figure 7: Annual Launch Rate of NAL Spaceplane

Figure 8 shows the resulting inventory in any year of the program, which is a function of procurement, withdrawals, and losses of vehicles. The inventory is of particular importance for determining ground support facilities and equipment. It appears reasonable to start out with 3 vehicles and combine this with an production rate of one new vehicle every 5 years periodically in such a way that the transportation market can be satisfied at plausible operational conditions. The inventories are reduced towards the end of the program by cutting the production during the last decade. There should be at least a fleet out of 3 vehicles in operation to avoid delays in the case of an unforeseen vehicle loss.

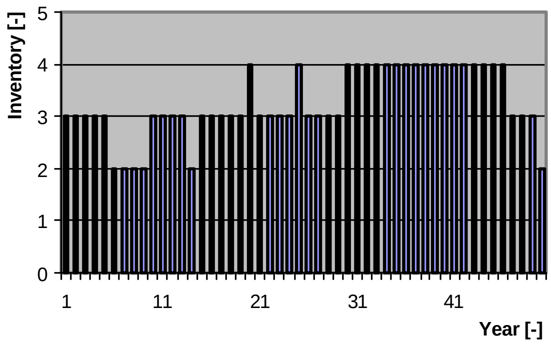

Figure 8: Inventory of NAL Spaceplane

Turnaround times between two consecutive flights are resulting from calculations dividing the number of flights by the number of vehicles in the inventory. These are available turn-around times which do not have to be used up. As indicated in Figure 9, during the first years of operation 90 days are available for turn-around time, while decreasing to 15 days in the last year because of optimized maintenance due to learning effects. Additionally, to avoid delays, the available turn-around time is modeled in average about 30 days so that there is a margin concerning to the minimum turn-around time. Regarding ground operations activities of RLVs a Boeing Study indicated that a winged Two-Stage Vehicle (and therefore the NAL Spaceplane) requires a 9 day minimum turn-around time.[7]

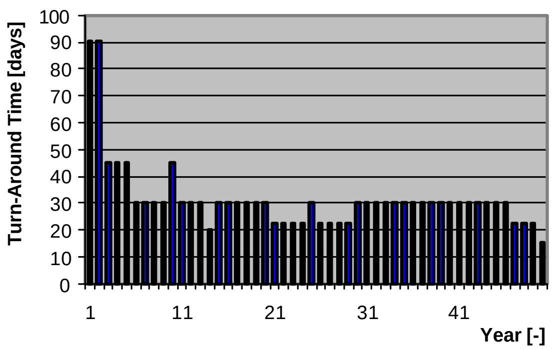

Figure 9: Available Turn-Around Time of NAL Spaceplane

As shown in Figure 10 the Total Cost per Flight (CpF) for the NAL Spaceplane is calculated to $40 million (2001) in average, while the Total CpF for the Space Shuttle is about $480 million (2001). The initial high launch cost of $81 million (2001) for the first operating year decreases to only $33 million (2001) in the last operating year due to learning effects of production and operations of the NAL Spaceplane fleet.

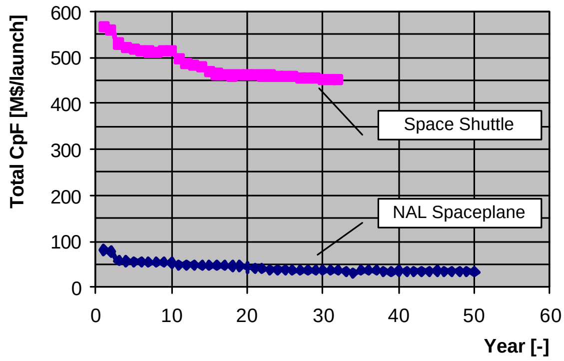

Figure 10: Total Cost per Flight

Discussion

For a better understanding of the sensitivity of the input parameters made in this study, the main Operating Cost items as shown in Figure 11 are discussed. Operating Cost is the sum of Variable Direct Operating Cost, Fix Direct Operating Cost, and Indirect Operating Cost:

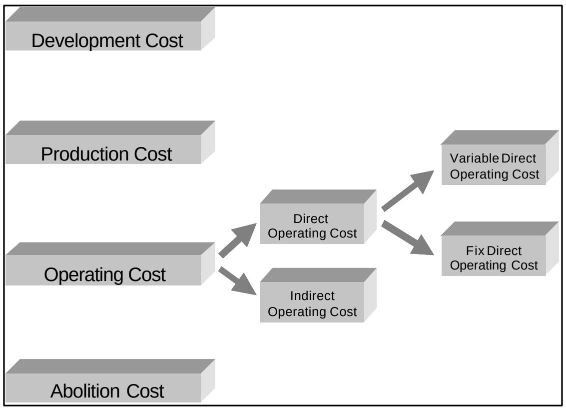

Figure 11: Overview of Operating Costs

Variable direct operating cost (DOC_{var}) are all those costs which are dependent on the vehicle's utilization. For example, two launches instead of one means twice the propellant cost.

Fix direct operating cost (DOC_{fix}) are all those costs, which are independent of the vehicle's utilization. In order to determine total operating cost per launch, DOC_{fix} is distributed over all launches of the fleet during life-cycle. For example, due to changing regulations during the fleet life-cycle the vehicle has to be equipped with new safety facilities.
Indirect operating cost (IOC) comprises all those costs that are not directly related to the launch operations. For example, the marketing cost can be the same for different models of vehicles.

Variable Direct Operating Cost

Pre-Launch Ground Operating Cost

Pre-launch ground operating cost includes ground transportation, vehicle assembly, maintenance, fueling, and launch preparations. It is strongly influenced by vehicle size, launch mode (vertical or horizontal), and launch rate. Maintenance includes checks, repairs, and replacement of single-use items between two consecutive flights (called on-line activity).

Launch and Mission Operating Cost

Launch and mission operating cost includes the communication system and the personnel and software used by the mission control center. It depends on vehicle complexity, crew size, and stay time.
Space Shuttle launch and mission operating cost include payload and experiment operations which are not considered to be part of the transportation business. Therefore, about 7% of the Space Shuttle Total Cost per Flight have to be deducted for comparison of the specific transportation cost with the NAL Spaceplane.[3]

Propellant Cost

The propellant cost depends on the quantity, type, and boil-off-losses.

Launch Site User Fee Cost

Launch site administration, facilities maintenance, range stations, and safety provisions make up the launch site user fee cost. Government controlled and financed launch sites require from commercial launch operators usually a user fee. For example, the US Department of Transportation (DoT) charges a fee of $5,5 per kg for LEO payload.

Public Damage Insurance Cost

There is normally a governmental requirement for a launch service provider to take insurance against public damage. For a $100 million (2000) coverage for damage caused by pieces of a launch vehicle falling down to ground insurance cost are typically about $0,1 million (2000).[3] Governmental launches are exempted from this requirement.

Premature Loss Charge Cost

There is a small chance that a catastrophic failure leads to a premature vehicle loss. This risk must be covered by an insurance or by a reserve fund contribution (self-insurance). Space Shuttle's statistical vehicle loss rate of less than 0,01 (1 out of 100 flights) is the lowest of all space launch vehicles to date. For comparison the statistical loss rate of civil aircraft is 0,000 001 (1 out of 1 million flights). The NAL Spaceplane should reach a loss rate less than 0,001 (1 out of 1000 flights), which can be seen as a good compromise between the cost for insurance (lower loss rate causes lower insurance cost) and the costs for life-cycle (lower loss rate causes higher effort in development, production, and operation).

Surcharge for Mission Abort Cost

The failure to deliver the payload causes a free re-launch. However, the complete cost of an aborted flight can be up to a factor 3 higher than of a regular mission, taking into account the indirect cost resulting from the necessary investigations and service interruption. For Two

Stage Vehicles, the assumed abort rate is 0,04 (1 out of 25 flights). For comparison the abort rate for civil aircraft is 0,0003 (1 out of 3000 flights).

Vehicle Amortization Cost

Vehicle amortization cost is based on the vehicle, turbo-ramjet engine and rocket engine production cost and the number of reuses.

Since production cannot be switched on and off according to program requirements, there are only two options: 1. For a relatively low launch rate all vehicles and spares required for the planned operational period are produced in an optimum time period and put into storage until they are needed. 2. For a relatively high launch rate a continuous production activity is maintained which means the scheduled introduction of new vehicles into the program as assumed for the NAL Spaceplane fleet.

Transportation and Recovery Cost

Due to bad weather conditions the Space Shuttle Orbiter cannot land on the launch area. The Orbiter ferry transportation by a modified B747 from Edwards AFB in California to KSC in Florida costs about $3,7 million (2001).[3] Also the NAL Spaceplane can cause transportation costs due to bad weather conditions, aborted launches, or emergency landings.

Refurbishment and Spares Cost

Refurbishment means that reusable vehicles have to be taken out of the regular service after a number of flights to undergo a detailed inspection and exchange of components before wear-out (called off-line activity). The Space Shuttle Orbiter is an exception since it requires refurbishment after each flight due to the technologies employed.

In case of the Space Shuttle the Refurbishment and Spares cost reaches an extraordinary share of the Total Cost per Flight. This is due to the very high refurbishment effort for Solid Rocket Boosters (SRBs) and Orbiter. It can be assumed that this will be much lower for the NAL Spaceplane. The NAL Spaceplane Orbiter can be expected to have a refurbishment after at least 25 flights (in particular: engines and thermal protection systems).

The vehicle system refurbishment cost per flight is about 2% of the Production Cost for the Space Shuttle Orbiter, 0,3% of the Production Cost for the NAL Orbiter, and 0,02% of the Production Cost for the NAL Booster.

The rocket engines refurbishment cost per flight for the SSME has been up to 11% of the Production Cost. However, rocket engine designs with a much reduced number of parts and a more rugged construction can reduce the refurbishment effort to few percentage per flight. It is also effective with respect to lifetime to overdesign the engine and to use only some 90% of the design thrust level.

In general, the higher the refurbishment factor, the lower is the number of lifetime flights for a cost-optimized operation.

Fix Direct Operating Cost

Development Amortization Cost

In case of a commercial project, the development amortization cost is linearly distributed over all launches of the fleet's vehicles.

Financing Cost

In case of a commercial project, the financing cost is caused by a loan to finance the development cost and the first operating unit at the beginning of the operation phase.

Product Improvement Cost

Increasing the reliability, maintenance, and security causes the product improvement cost.

Launch Site Support Cost

Commercial launch service companies have to pay a certain fixed fee per year for use of the infrastructure. Launches of national spacecraft are not charged with any site and range cost. For comparison the Space Shuttle launch site Kennedy Space Center (KSC) required an annual budget of about $308 million (2001).[3]

Indirect Operating Cost

Administration Cost

A space launch system operator needs a certain staff for administration, system management, customer relations, spares storage, and marketing causing cost for travel, office equipment, exhibits, publications, etc.

Conclusion

The NAL Spaceplane concept is a technology driver for future Reusable Launch Vehicles and has potential to increase the market of space transportation and exploration. It can be much better designed and operated than the Space Shuttle. However, it will be difficult to convince government or private financing companies to fund such an enterprise.
The NAL Spaceplane may be built if there would be a significant demand for launches of communication satellites. The space transportation system should be compatible to serve other new markets such as space station resupply and flights for space tourists. This is an important issue because Reusable Launch Vehicles cannot only be profitably operated by serving the satellite market due to low annual launch rates expected.
It should be mentioned that currently a 7,0 Mg payload to LEO launched by the Soyuz U has a user cost of about $30 to $50 million (2001).[8] Therefore, the expendable launchers are competing with Reusable Launch Vehicles. However, the low cost potential for expendable launchers is nearly consumed and thus, hopefully, the reusable launchers will be the winner in the long run.

List of Abbreviations

AFB	[-]	Air Force Base
CpF	[M$/launch]	Cost per Flight
DOC	[M$/launch]	Direct Operating Cost
FY	[-]	Fiscal Year
IOC	[M$/launch]	Indirect Operating Cost
KSC	[-]	Kennedy Space Center
LEO	[-]	Low Earth Orbit
Mg	[-]	Mega grams
M$	[-]	Million US dollars
NAL	[-]	National Aerospace Lab.
RLV	[-]	Reusable Launch Vehicle
SSME	[-]	Space Shuttle Main Engine

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