RELATIVE LIFE-CYCLE-COST ESTIMATION OF FUTURE SPACE TRANSPORTATION SYSTEMS AT CONCEPTUAL DESIGN PHASE

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Abstract

Life-cycle-cost estimation at the conceptual design phase is one of the most essential items to assess the feasibility of various future space transportation systems and to establish the technical scenarios for them. Multidisciplinary optimization involving some subroutines as represented by cost estimation is strongly required to assess the reasonable and feasible future space transportation systems.

"Systems Evaluation and Analysis Tool (SEAT)" is under development in JAXA. This study describes TRANSCOST 7.1 based cost estimation compares with the life-cycle-costs of some rocket based vehicle concepts relatively, and discusses the effectiveness and limitations associated with this estimation.

"TYPE-R" vehicle propelled by thrust controllable liquid rocket engine as RLV has the advantages in the life-cycle-cost reduction and growth in the number of flights. Even if any engine safely shuts down at a certain time during the mission, this vehicle has the potential performance for abort mode operation that the remaining engines can be powered up to full thrust level.

1 Introduction

Recently, there are slightly rising momentum in human space activities all over the world due to SpaceShipOne sub-orbital flight in 2004 autumn. Moreover "vision for space exploration" (VSE) strategy for to the Moon, the Mars and the beyond has been published by NASA in January 2004. In the near/far future new and future space transportation systems to realize the stated missions will make us more attractive.

However, these space launch vehicles are still in a developing process, compared to other ground and air transportation systems. And there are not so many space launch vehicles, not reusable (RLV) but expendable launch vehicles (ELV) all over the world. The flexible, suitable and various space transportation systems are required to achieve the stated activities [1]. From a practical standpoint, the much more development, production and operation costs for the future space transportation systems, the richer experience and more sufficient period are required to achieve more reliable ones with higher performance.

Performance, reliability, operability and life-cycle-cost associated with new space transportation systems are ones of critical issues at the conceptual design phase [2]. Especially, it is said that more than 70 to 85% of a transportation system's life-cycle-cost depends on decisions made at this phase and/or preliminary design one [2-5]. Furthermore, unless the correct concept will be selected at the conceptual design phase, the flawed concept design and selection will not be easily corrected at the latter design phase like preliminary and/or detail design phase [2, 5]. Therefore, it is desirable to support the conceptual design by systems engineering process and it is essential to investigate the mission requirements during this phase. And the adequate databases and design tools are required for new space transportation system concept study.

Recent advances in computer technology and multidisciplinary optimization techniques enable us to realize more flexible design using software. A typical example is the ODIN (Optimal Design Integration System) developed by the NASA in 1970s [4], and it was carried out for SSTO (Single-Stage-to-Orbit) studies [6]. Also, the TRANSYS (Transportation System) developed in Germany, investigated improvement of the performance of the Sanger concept [7]. Some companies have also recently been developing a concept study program [8, 9].

A Systems Evaluation and Analysis Tool (SEAT) [10-12] development for conceptual design studies has been started in Japan Aerospace Exploration Agency (JAXA). Unlike the above-mentioned programs, its main objective is to assist performing relative comparisons of various space transportation system concepts. SEAT evaluates various concepts against the same design goals using same analytical methods and evaluation criteria, allowing the most promising candidates to be selected. Other objectives are to identify required technologies, and to establish quantitative goals for improving present technologies to enable the systems to be realized.

The purpose of this paper is to estimate primarily the life-cycle-costs of rocket engine based vehicles designed conceptually with SEAT. TRANSCOST based Cost estimation as one of some subroutines incorporated into SEAT is focused on and described. And these life-cycle-costs are compared to assess the systems, not absolutely but relatively. Finally, this paper describes the more feasible rocket based launch vehicle from the point of view of life-cycle-costs.

2 Systems Evaluation and Analysis Tool (SEAT)

2.1 Outline of SEAT and Envisioned Mission

Systems Evaluation and Analysis Tool (SEAT) is under development, including the following six subroutines: aerodynamics, propulsion, weight estimation, trajectory, thermal protection system (TPS) design and cost, as shown in Fig.1. And an optimizer controls the mentioned subroutines to iteratively explore the optimized design. Detailed descriptions are here omitted, and please refer to [10-12]. The final goal of this study is to optimize these feasible systems to satisfy the mission to one-ton payload into Low Earth Orbit (LEO) as sample, as shown in Fig.2.

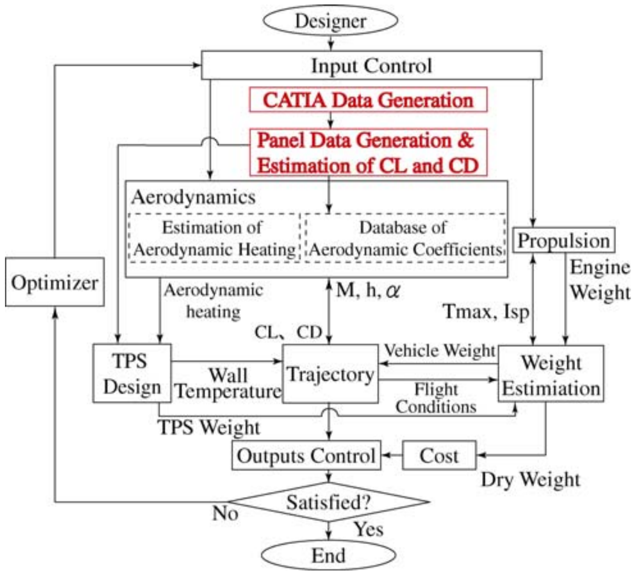

Fig.1. Conceptual Figure of SEAT (Systems Evaluation and Analysis Tool)

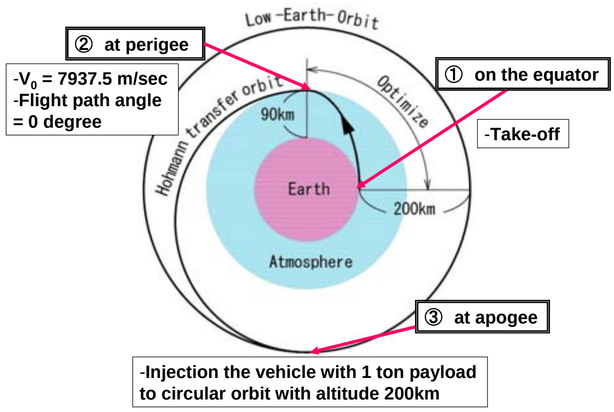

Fig.2. Envisioned Mission to Low Earth Orbit

The relevant vehicle is launched from the equator on the Earth, and reaches a circular 0-degree inclination 200 km altitude orbit. The trajectories are then constrained within the vertical plane. The atmosphere exists below 90 km altitude, and the vehicle will be thrown into the perigee of the Hohmann transfer orbit at the exit of the atmosphere, as shown in Fig.2. The fuel used on the Hohmann transfer is not taken into account. As flight conditions at the perigee on the Hohmann transfer orbit, inertial velocity and flight path angle are set as 7937.5 m/s and 0 degrees respectively. The performance index is launch weight for all cases.

2.2 TRANSCOST based Cost Estimation

Life-cycle-cost is especially one of the key objective functions at the conceptual design phase. Because, it is said that more than 70 to 85% of a transportation system's life-cycle-cost depends on decisions made at this phase and/or preliminary design one [2-5]. Furthermore, generally speaking, cost affects the concrete mid/long-term technological scenarios. The reasonable and feasible life-cycle-costs are strongly required to realize the future space transportation systems for JAXA 2025 visions and missions [1].

In this study, cost estimation model is fundamentally based on TRANSCOST 7.1 [12] and is developed and incorporated into SEAT. TRANSCOST 7.1 is a statistical, analytical and top-down model for cost estimation and economical optimization of launch vehicles. This model is based on the past various vehicles involving the airplanes, fighters and launch vehicles and various propulsion systems all over the world, from 1963 to 2002.

The following sections describe the basic principle, how to use this cost estimation model and which technical factors can be effective and ignored to compare with relatively. The life-cycle-cost indicates the summation of the development, production and operation costs.

2.2.1 Cost Estimation Relationship

The statistical and analytical models are introduced to estimate the cost of vehicles and/or propulsions. Basic formula is written as the cost estimation relationship (CER):

$$C = a \cdot M^{x} \cdot \prod_{i=1}^{3} f_i \qquad (1)$$

With C = cost in Man-Year (MYr), a = system-specific constant value, M = mass in kg, x = system-specific cost-to-mass sensitivity factor and f_i = technical assessment and/or correction factors that depends on the technical quality, vehicle and/or propulsion type and learning factor for mass production and so on, as shown in Table 1. These coefficients, a and x, are statistically derived from the actual costs as mentioned.

Table 1 Technical factors' list

Technical factors	Section	Remarks
f_0	2.2.3	System engineering/integration
f_1	2.2.4	Development standard
f_2	2.2.4	Technical quality
f_3	2.2.4	Team experience
f_4	2.2.5	Cost reduction
f_6	2.2.3	Cost growth about schedule
f_7	2.2.3	Cost about growth contractors
f_8	2.2.3	Productivity for each country

2.2.2 Man-Year Value

MYr effort is used as cost value in this study. This MYr value is defined as the ratio of the relevant total project costs to the number of fully accounting people or the ratio of the total annual net turnover (excluding subcontracts) of the technical personnel (excluding administration and management) for specific company. MYr is introduced, because firm cost data which is valid internationally, independent from the time, periods and the different currencies and independent from the annual changes due to inflations and the other factors such as currency conversion rate fluctuations.

However, finally in this study, the absolute MYr value can be ignored, because the relative comparisons are performed to assess the feasible and reasonable vehicles based on the same criteria

2.2.3 System Engineering Factors

System engineering factors, f_0, and f_6 to f_8 are introduced to improve accuracy of estimation.

The system engineering factor f_0 depends on the vehicle stage number. The factor f_6 depends on development schedule delay, f_7 on the contract number and f_8 on the country productivity. Each criterion is in detail listed in the handbook of TRANSCOST 7.1 [12].

In this study, these stated factors excluding f_0 can be ignored for relative comparison, because f_6 and f_7 can be assumed, and f_8 is set up as same value due to the country status.

2.2.4 Development Cost

Development cost estimation is fundamentally based on the equation (2) as follow:

$$C_{DEV} = a \cdot M^{x} \cdot \prod_{i=1}^{3} f_i \qquad (2)$$

Especially, three technical factors are introduced to estimate the development cost as follow: development standard factor, f_1, technical quality factor, f_2, and team experience factor, f_3.

At first, technical quality factor f_2 depends on the kinds of the vehicle and propulsion system, for example, the net mass fraction of the vehicle, the number of firing test for qualification and acceptance, and furthermore the designated reliability.

Secondly, there is a certain level of correlation between the development standard factor f_1 and team experience factor f_3. Each criterion for f_1 and f_3 is listed in the handbook of TRANSCOST 7.1 [12]. If a team had gone through a successful project, f_1 and f_3 would be concurrently lower than 1.0 with this type of project. Here, f_1 x f_3 indicates that the team with superior or related experience can reduce the development cost with same type of project.

However, the almost same development project is not usually executed successively, because the successful development project will be shifted to the production phase or the project with no success will be cancelled in general [15]. If a team with superior experience, $0.7<f_3<0.8$, will face to the minor or major modification, $0.4<f_1<0.6$, the state of the art, $0.9<f_1<1.0$, and the quite new technical challenging project, $1.3<f_1<1.4$, finally f_1 x f_3 changes from 0.3 to 1.2 gradually as shown in Fig.3.

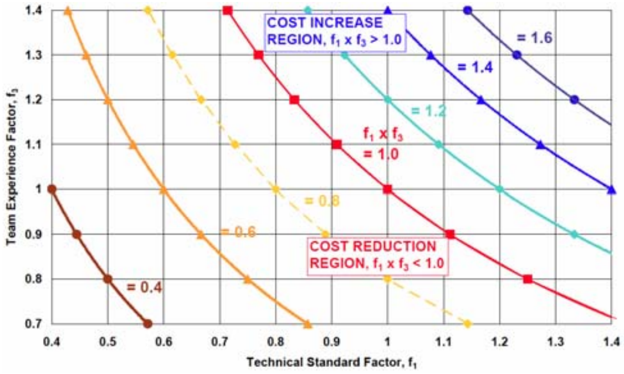

Fig.3: Correlation between f_1 and f_3 factors

On the other hand, sometimes after a project completion any members of a team will switch positions with the experts or rookies keeping or enhancing the team experience for next project. The usual long-term project for aerospace development makes the stated personnel reshuffle. The f_3 depends on the team members' quality. If a partially different team or a team without superior experience will face to next one, f_3 is usually slightly higher than 1.0, and if some sophisticated members are involved in a team, f_3 keeps the same level or is the slightly lower than 1.0.

Consequently, from the stated point of view, it is not possible in Japan that significant cost reduction by f_1 x f_3 will be achieved, because not sophisticated experiences but the successive team conditions are substantially required. Finally, total development cost for each vehicle type is shown in equation (3):

$$C_{DEV} = C_{DEV-V} + C_{DEV-E} + C_{DEV-B} \qquad (3)$$

With C_{DEV-V}, C_{DEV-E} and C_{DEV-B} are the vehicle, engine and booster development costs, respectively. In this study, the effect of the stated technical factors excluding the technical quality factor f_2 can be ignored. Because there are not sufficient sophisticated experiences on the stated vehicle types' development in Japan, excluding 1st and 2nd stage for TYPE-BR like H-

IIA. Furthermore, relative comparison can be performed.

2.2.5 Production Cost

Production cost estimation is also same as the development cost, but another technical factor is introduced to estimate the production cost as shown in equation (4):

$$C_{PRO} = a \cdot M^{x} \cdot f_4 \cdot n \quad (4)$$

With n = production number and f_4 = cost reduction factor. Here, cost reduction factor f_4 as a function of the learning factor p and production number n is shown as follow. Learning factor p is fundamentally defined, based on simple economical principle. The more production number n increases, the less cost reduction factor number f_4 decreases. That is, it indicates the cost reduction.

In this study, cost reduction factors f_4 can be considered for RLV and clustered propulsion systems mounted on the TYPE-R vehicle. Furthermore, so many propulsion systems mounted on these vehicles will be produced and it is easy to see the effect of the cost reduction factor. Finally, total production cost for each vehicle type is shown in equation (5):

$$C_{PRO} = C_{PRO-V} + C_{PRO-E} + C_{PRO-B} \quad (5)$$

With C_{PRO-V}, C_{PRO-E} and C_{PRO-B} are the vehicle, engine and booster production costs, respectively.

2.2.6 Direct Operation Cost

Some operation costs including direct, indirect operation costs, business charge and insurance costs are discussed and listed in the handbook of TRANSCOST 7.1 [12]. In this study, the feasible and reasonable space transportation systems will be assessed based on the life-cycle-cost including not development and production costs but operation cost. Therefore, the direct operation costs (DOC) about the ground, propellant, mission and recovery operations are focused on. Some formulas about the stated DOC are listed in the handbook of TRANSCOST 7.1 [12]. Finally, total operation cost for each vehicle type is shown in equation (6):

$$C_{OPR} = C_{PLO} + C_{PROP} + C_{M} + C_{REC} \quad (6)$$

With C_{PLO}, C_{PROP}, C_M and C_{REC} are the ground operation cost, propellant cost, launch, flight and mission operation cost and recovery operation cost, respectively. Especially, the launch per annum, LpA, is incorporated into each formula for direct operation cost. It is the one of the cost drivers for cost per flight to assess the life-cycle-cost.

2.2.7 Life-Cycle-Cost

As stated, the development, production and operation costs of the vehicle and propulsion are calculated by the stated formulas. Finally, the equation (7) is introduced to assess the life-cycle-cost for each launch vehicle.

$$C_{LCC} = C_{DEV} + C_{PRO} + C_{OPR} \quad (7)$$

With C_{LCC} is defined as the life-cycle-cost in this study.

2.3 Space Transportation System Candidates

SSTO type vehicle is selected and focused on as RLV in this study. The “TYPE-R” vehicle, as shown in Fig.4, propelled by liquid rocket engines is focused to estimate the different objective functions as follow: the former one is to minimize the vehicle weight at the nominal thrust operation, the latter one to do the summation of development and production costs at the throttling thrust operation.

The two kinds of main engine are respectively installed on this TYPE-R; Japanese liquid rocket engine LE-7 and Russian liquid rocket engine RD-0120. The former one is the first staged combustion cycle, main booster and liquid hydrogen/oxygen rocket engine in Japan developed with reference to Space Shuttle Main Engine (SSME). And this main engine LE-7 is installed on H-II first stage and has only thrust full level operation. Now this advanced engine LE-7A is mounted on the current H-IIA.

The latter one has the features as follow: the same staged combustion cycle, liquid hydrogen/oxygen reusable rocket engine, is driven by single-shaft high-pressure turbopump and the capability for power level adjustable from 0.68 to full level [16, 17]. The RD-0120 had been installed on the Russian Space Shuttle "Energia" core stage. However, original RD-0120 engines have been mothballed.

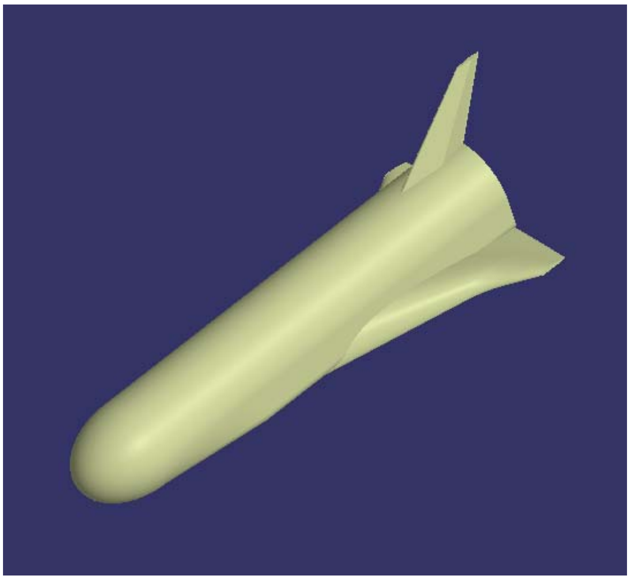

Fig.4. TYPE-R Vehicle (SSTO/VTHL: Vertical Takeoff and Horizontal Landing)

3 Results and Discussions

3.1 Objective Functions

In this study the objective functions are to minimize the total vehicle weight and/or the development and production costs. Finally, from the point of the view of life-cycle-cost, the advantages and disadvantages are extracted and discussed to achieve the envisioned mission as shown in Fig.2. Moreover, the possibilities for the reusability and abort mode operation are discussed in response to the results in this study.

Here three vehicles as follow are designed with SEAT and investigated to compare with the cost allocation and life-cycle-cost; LE-7 based TYPE-R is 'LE-7', RD-0120 based TYPE-R is 'RD-0120W' and cost per flight minimized RD-0120 based TYPE-R is 'RD-0120C', respectively. The main specifications of these vehicles are listed in Table 1 and they are relative values and are used in the following sections. Especially, 'RD-0120C' can achieve the mission at the nominal thrust level that can maximize the number of flights.

Table 2 TYPE-R Relative Specifications

TYPE-R	LE-7	RD-0120W	RD-0120C
Total mass	1.000	0.945	1.155
Vehicle mass	1.000	1.118	1.302
Length	1.000	0.975	1.040
Volume	1.000	0.925	1.126
Engine(s)	10.30	9.73	11.14
Nominal thrust level	1.00	1.00	0.68
Flight(s)	1 or 5	5	50

3.2 Relative Comparisons of Life-Cycle-Cost

3.2.1 Design for Reusable Launch Vehicle

At first, the relative life-cycle-cost (LCC) estimation for LE-7 based TYPE-R vehicle is performed to understand the advantages of the reusability. LCC, 'C_{LCC}', indicates the total cost that sums up the development, production and operation costs for all flights. Here, this vehicle is given 5LpA mission. These case studies, Case-1 to 4, are categorized as reusable and/or expendable vehicle and/or engine and listed in Table 3 to achieve the stated mission. Case-4 is the baseline for 5LpA mission. The following relative comparisons with Case-4 are performed.

There are two assumptions as follow: 5LpA is assumed to bring about breakthrough here and actually current H-IIA launcher has a good track in 3LpA. Moreover, LE-7 engine does not have a good track in reusability due to only installation on the expendable launch vehicle, H-II launcher. On the other hand, the four times engine firing duration as the mission duty cycle, 4MDC, had already been achieved to pass the qualification test. Consequently, LE-7 engine is assumed to achieve 5LpA here.

As shown in Table 3, Case-1 shows the only one vehicle with the same engine systems can fly five times. It is fully reusable launch vehicle system. As well, there is an assumption that LE-7 can be used for five flights. Case-2 shows the only one vehicle can fly five times, but these engine systems must be exchanged for new ones after the return. This is the partially reusable launch vehicle system.

Case-3 shows the five vehicles can fly each one time with the same engine systems. It is easy to understand more expensive operation costs, because they are removed and reinstalled on the next vehicle at each flight. Case-3 shows the only one vehicle with the same engine systems can fly only one time, but the other four vehicles are prepared for the next missions. They are like the expendable launch vehicle systems. Therefore, Case-4 is the baseline concept to clarify the advantage over the current launch vehicle systems.

Table 3 Various Operation Cases

Case	TYPE-R vehicle Flights	TYPE-R vehicle quantity	LE-7 engine Flights	LE-7 engine quantity
1	5	1	5	10.3
2	5	1	1	51.5
3	1	5	5	10.3
4	1	5	1	51.5

3.2.2 Advantages of Reusable Launch Vehicle

The bar chart as shown in Fig.5 shows the cost allocation as follow: C_{DEV_VEH} and C_{DEV_ENG} are development costs for vehicle and engine, C_{PRO_VEH} and C_{PRO_ENG} are production ones for them and C_{OPR} is operation one, respectively. And cost per flight, CpF, is the ratio of LCC to the number of flights.

Fig.5 shows that about 15% LCC and CpF reduction can be achieved at Case-1 and 2. However, the engine mass production has little effect on LCC reduction in comparison with the Case-1 and 2 or Case-3 and 4. On the other hand, the reusable launch vehicle has to be noted to achieve the remarkable LCC reduction. Furthermore, its size and mass have to be minimized to reduce research and development costs, because its mass has a considerable impact on the cost increase and decrease.

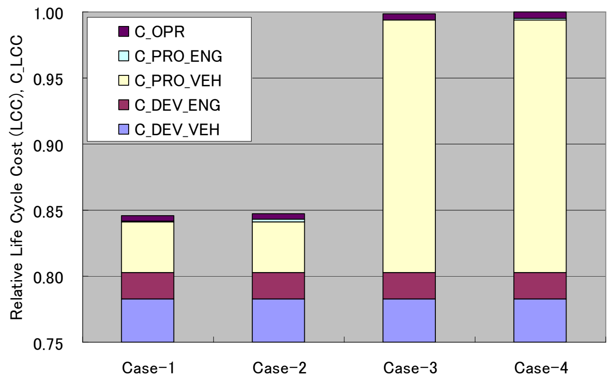

Fig.5. Relative Life-cycle-cost Comparison of LE-7 based TYPE-R Case Studies (5LpA)

3.2.3 Design for Thrust Controllable Engine based Reusable Launch Vehicle

LE-7 based TYPE-R vehicle is designed with SEAT and discussed in the mentioned section; however, LE-7 is not reusable liquid rocket engine. In this section, the thrust level controllable liquid rocket engine 'RD-0120' is focused to investigate the feasibility of reusable launch vehicle. Because RD-0120 engine has a good track in the wide thrust level operation. The relationship between the number of flights and thrust level was obtained [16, 17].

Here, the baseline TYPE-R vehicle with LE-7 is redesigned with exchanging LE-7 for RD-0120 and minimizing the total weight. Moreover it is redesigned with minimizing the cost per flight, CpF, that is the ratio of development and production costs of RD-0120 based TYPE-R vehicle to the number of flights. The former vehicle is 'RD-0120W' and the latter one 'RD-0120C'. The main specifications designed with SEAT are listed in Table 2.

Especially, the nominal thrust level for 'RD-0120C' is 0.68, because it can maximize the number of flights, 50LpA [16, 17], as listed in Table 2. 'RD-0120C' is designed to avoid the weight growth with the engine units' increase in comparison with 'RD-0120W' and to increase the flight time at the nominal thrust level, 0.68. Therefore, the increase in the flight time for 'RD-0120C' leads to the total mass, especially propellant mass, and the vehicle size.

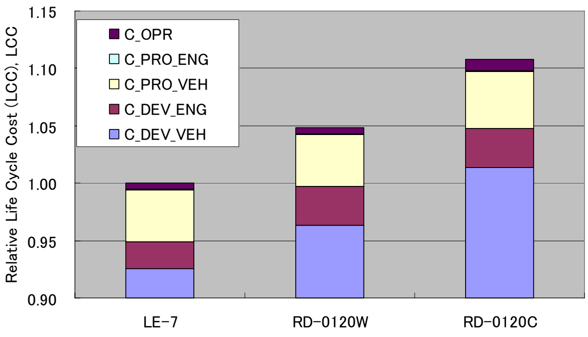

Fig.6. Relative Comparison of Life-Cycle-Cost

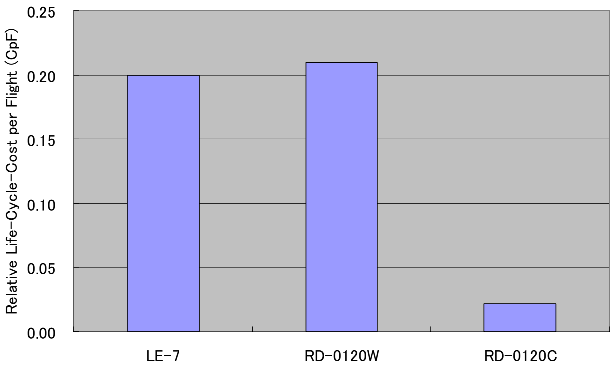

Fig.7. Relative Life-Cycle-Cost per Flight

3.2.4 Advantages of Thrust Controllable Engine based Reusable Launch Vehicle

The bar chart as shown in Fig.6 shows the relative life-cycle-cost and cost allocation such as development, production and operation costs. Here LE-7 based TYPE-R is the baseline and these relative LCC comparisons are performed. The increase in relative life-cycle-cost for 'RD-0120W' and 'RD-0120C' are 5% and 11%, respectively, in comparison with 'LE-7'. It is easy to see gradual increase in the relative life-cycle-cost and each cost due to the vehicle mass and size increase.

As mentioned section, relative life-cycle-cost is occupied by the development cost for vehicle and engine in each vehicle system. Here, the cost per flight, CpF, indicates the ratio of the life-cycle-costs to the number of flights as shown in Fig.7. The CpF for 'RD-0120C' is drastically cut down to one of tenth of CpF for 'LE-7' and 'RD-0120W'.

The results describe that TYPE-R vehicle propelled by RD-0120 as RLV has the advantages to reduce the life-cycle-cost per flight drastically and to increase the number of flights. Furthermore, even if any engine safely shuts down at a certain time during the mission, this vehicle has the potential performance for abort operation, because the remaining engines can be powered up to full thrust level.

4 Conclusions and Future Works

The purpose of this paper is to estimate primarily the life-cycle-costs of rocket engine based vehicles designed conceptually with SEAT. TRANSCOST based life-cycle-costs cost estimation are performed to assess the feasibility of the candidates for the space transportation systems, not absolutely but relatively. The following results and conclusions are attained in this study.

1) Engine mass production does not contribute to the drastic life-cycle-cost reduction. The life-cycle-cost per flight for the vehicle with thrust controllable engines can be drastically cut down to about one of tenth one for the vehicle with only full thrust level operation engine.
2) Fully reusable launch vehicle system is one of the most effective candidates for the space transportation systems from the point of the view of life-cycle-cost reduction. However, there are so many technical issues to overcome.
3) The life-cycle-cost per flight can be reduced when the engine system can be accomplished as follow: the trust level can be controlled, the loading on the engine can be reduced by thrust level control operation and the engine system can be reusable.
4) The vehicle with the thrust controllable liquid rocket engine has the potential ability to be shifted to the abort operation and to enhance the performance to achieve the mission as follow: the remaining engines can be throttled up to full thrust level, even if any engine safely shuts down at a certain time during the mission.

Development scenarios for the future space transportation systems can be appropriately proposed by this life-cycle-cost estimation incorporated into SEAT. Especially, it can be clarified which fundamental technologies are considerably required to realize new space transportation system.

It is significantly necessary to estimate the life-cycle-cost for future space transportation systems successively and/or as occasion may demands. Moreover, to estimate the re-entry vehicle for return to the Earth, the thermal protection system has to be taken into account for in order to realize the reusable launch vehicle as Future works.

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References

[1] JAXA, "JAXA 2025 Vision & missions", http://www.jaxa.jp/about/vision_missions/long_term/index_e.html

[2] Christenson R L, Whitley M R and Knight K C. *Comprehensive Design Reliability Activities for Aerospace Propulsion Systems*. NASA/TP-2000-209902, 2000

[3] Hammond W E. *Design methodologies for Space Transportation Systems* AIAA Education Series, AIAA, Chaps. 1. 2001

[4] Glatt C R and Hague D S. *ODIN Optimal Design Integration System*. NASA CR-2492, 1975

[5] Blair J C, Ryan R S, Schutzenhofer L A, Humpheries W R. *Launch Vehicle Design Process: Characterization, Technical Integration, and Lessons Learned*. NASA/TP-2001-210992, 2001

[6] Henry B Z and Decker J P. Future Earth to Orbit Transportation Systems/Technology Implications. *Aeronaut. Astronaut*, Vol. 14, No. 9, pp. 18-29, 1976

[7] Wolf D M. TRANSYS-Space Transportation System Preliminary Design Software. *Journal of Spacecraft and Rockets*, Vol. 31, No. 6, pp. 1067-1071, 1994

[8] Bowcutt K G. A Perspective on the Future of Aerospace Vehicle Design. *AIAA International Space Planes and Hypersonic Systems and Technologies*, Norfolk, AIAA 2003-6957, 2003.

[9] Baker M L, Munson M J, Hoppus G W and Alston K Y. Weapon System Optimization in the Integrated Hypersonic Aeromechanics Tool (IHAT). *AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference*, New York, AIAA 2004-4316, 2004

[10] Suzuki H and Minami Y. Development of Optimal Design Tool for Future Space Transportation Systems. *13th AIAA/CIRA International Space Planes and Hypersonic System and Technologies Conference.* Capua Italy, AIAA 2005-3292, 2005

[11] Suzuki H, Hirotani T, Kobayashi H and Takasaki K. Optimal Design for Future Space Transportation Systems Using Airbreathing Engines. *17th Int. Symp. on Airbreathing Engines.* Munich, ISABE-2005-1204, 2005

[12] Koelle D E. *Handbook of Cost Engineering for Space Transportation Systems with TRANSCOST 7.1*. TCS-TransCostSystems, 2003

[13] Kuratani N, Suzuki H, Goehlich R. Multidisciplinary Optimization of Space Transportation Systems *56th International Aeronautical Congress 2005*, Fukuoka Japan, IAC-05-D.1.3.04, 2005

[14] Shirouzu M, Inouye Y, Watanabe S, Shigemi M, Ueno M and Yamamoto Y. Overview of the Aero- and Aero-thermodynamic Research in HOPE-X and Related Activities in Japan. *34th AIAA Fluid Dynamics Conference and Exhibit*. Portland, AIAA-2004-2426, 2004

[15] Ballhaus W. Success and Challenges in Transforming National Security Space, Reno, AIAA-2005-2, 2005

[16] Spies J, RLV HOPPER: CONSOLIDATED SYSTEM CONCEPT, *53rd International Astronautical Congress*, Houston, Texas, IAC-02-V.4.02, 2002.

[17] Rachuk V, Orlov V, Plis A, Gontcharov N and Fanciullo T J. The Low Risk Development of a Fuel Rich Preburner Tripropellant Engine using the RD-0120. *AIAA Space Technology Conference*, Huntsville, AIAA 94-9465, 1994