Concept Study of Future Space Transportation Systems with SEAT

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Abstract

This paper describes the concept design of five systems that use the rocket, the Turbine-Based Combined Cycle (TBCC), and the Rocket-Based Combined Cycle (RBCC) engine using the concept design tool (SEAT). The concept design is performance to minimize the gross take-off weight. The lightest system concept is the Two-Stage To Orbit (TSTO) using rocket propulsion for both stages. It is clarified that the system using the TBCC engine or the RBCC engine has difficulties for mounting the necessary engines and the second stage. Furthermore, appropriate ascending trajectories depending on the engine type are elucidated.

1. Introduction

When developing a new space transportation system, it is important to investigate the mission requirements during the concept study phase, which necessitates the preparation of adequate databases and concept design tools. Reportedly, 70% of a transportation system's life-cycle cost depends on decisions made during the concept study phase,[1] so this phase is very important.

It is desired to produce a design tool that has flexibility for adaptation to uncertain mission requirements. In addition, the design tool must facilitate concept design within a reasonable time because investigation for suitable transportation system candidates requires comparison among system concepts.

Recent advances in computer technology and multidisciplinary optimization techniques enable us to realize more flexible design using software. A typical example is the Optimal Design Integration System (ODIN) developed by NASA in 1970s,[2] which was used to carry out a Single Stage to Orbit (SSTO) system study.[3] In addition, the TRANsportation SYStem (TRANSYS), developed in Germany, investigated improvement of the performance of the Sanger concept.[4] Some companies have also recently been developing a concept study program.[5, 6]

The Japan Aerospace Exploration Agency (JAXA) started development of a systems evaluation and analysis tool for concept studies from 2004.[7–9] Its main objectives for development are two: to select the most suitable transportation system concept for the mission, and to identify required technologies and to establish quantitative goals for improving present technologies to enable the systems to be realized. This paper focuses on the engine type: rocket propulsion, the Turbine Based Combined Cycle (TBCC) engine, and the Rocket Based Combined Cycle (RBCC) engine. The concept designs of five system concepts that use those engines are then presented.

2. Concept Design Tool (SEAT)

The concept design tool is called SEAT in this paper. Details of its development objectives and the function of SEAT are described in Refs. 7–9. Only the SEAT outline is presented in this paper. Figure 1 shows a conceptual figure of SEAT (the precise data flow is not shown). Seven modules constitute SEAT: aerodynamics, propulsion, weight estimation, Thermal Protection System (TPS) design, trajectory, and cost estimation, and an optimizer that controls the other modules to optimize the design iteratively. Before starting the design process using SEAT, vehicle data must first be prepared off-line, as shown by red blocks in Fig. 1. The designer first enters the three-dimensional external shape of the vehicle using the CATIA computer-aided design tool. These data are then transformed automatically to panel data; the SEAT aerodynamics module then estimates the vehicle's aerodynamic coefficients from the panel data and stores them in a database. Databases of three types of vehicle configurations are prepared as shown in Figs. 2–4.

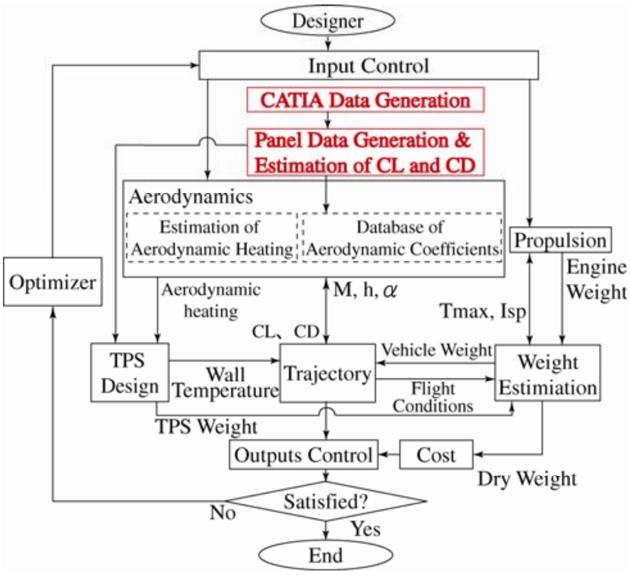


Figure 1: SEAT Concept

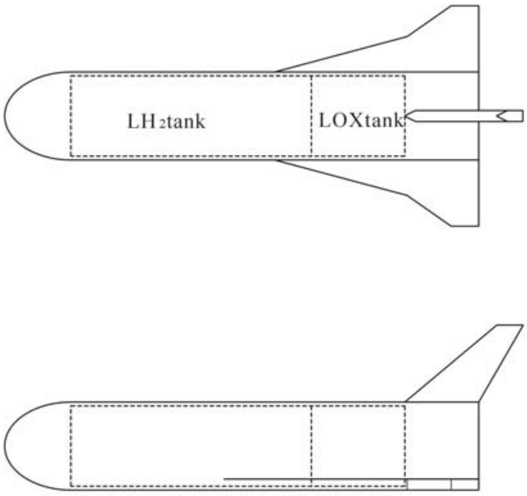


Figure 2: Rocket-Mounted Vehicle

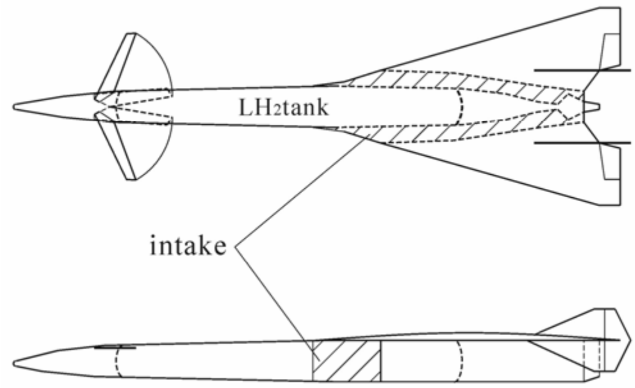


Figure 3: TBCC Engine-Mounted Vehicle

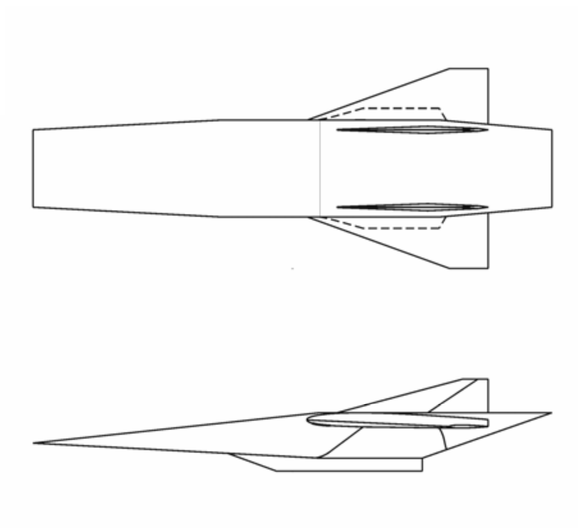


Figure 4: RBCC Engine-Mounted Vehicle

The SEAT can flexibly design various fully reusable or partially reusable system concepts. The propulsion module can estimate the thrust and specific impulse of liquid and solid rockets, the TBCC engine, and the RBCC engine. Details of the rocket and the TBCC engine are described in Refs. 7–9. This paper describes only a summary of the RBCC engine; its details are presented in Ref. 10.

Use of the air-breathing engine in a high-speed region is effective for increasing the kinetic energy of the vehicle. The ramjet is superior in the specific impulse in supersonic and hypersonic regions. The ramjet engine and the rocket engine are combined in the RBCC engine. Figure 5 shows a schematic diagram of the operating conditions and Table 1 shows the operating modes of the RBCC engine in the present study.

Table 1: RBCC Engine Operation Mode

Mach	Mode	Remarks
~3.5	Ejector jet	
~7.0	Ramjet	DP≧30 kPa
	Rocket	other
~15	Scramjet	Static Pressure≧250 Pa
	Rocket	other
15~	Rocket	

In the ejector-jet mode, the rocket exhaust mixed with the breathed air and the pressure of the mixture increased in the divergent section. Fuel is injected to the mixture and the combustion gas is choked at the engine exit. In the ramjet mode, recovery of the breathed air produces thrust. Fuel is injected and the combustion gas is choked at the exit. In the scramjet mode, the rocket component operates as an injector of pre-combustion fuel. A variable throat is presumed at the exit of the downstream combustor. The starting position of the pseudo-shock is at the entrance of the divergent section. The mixture ratio, O/F, and the combustion chamber pressure are, respectively, 7 and 7.0 MPa in the ejector-jet and the rocket modes. In the ramjet mode, they are, respectively, 3 and 0.2 MPa. In the scramjet mode, they are, respectively, 5 and 7 MPa.

Conditions of the air and the combustion gas are calculated using the one-dimensional flow model. Pressure on the external nozzle is calculated using the Prandtl-Meyer function. Gases in the engine duct are assumed to be in the equilibrium conditions, and the gas in the external nozzle is in a frozen condition. The amount of the breathed air is calculated using a simple model of the interaction between the rocket exhaust and the air.[11]

(a) Inlet

The inlet has fixed geometry and a ramp compression system. The swept angle is 70 deg. Total pressure loss is neglected in the inlet for simplification when the air is subsonic. The kinetic energy efficiency is 0.98 in supersonic and hypersonic conditions.

(b) Divergent section

In the ejector-jet and the ramjet modes, the breathed air and the rocket exhaust flow in the divergent section at supersonic speeds. The gases pass through the pseudo-shock and are mutually mixed with no reaction; the mixture reacts with the injected fuel in the downstream combustor. In the scramjet mode, the rocket exhaust and the air react in the upstream combustor. Then the combustion gas expands in the divergent section.

(c) Downstream combustor and the choking condition

In the ejector-jet and the ramjet modes, fuel is injected to the mixture in the downstream combustor. The combustion gas is choked at the throat in the downstream combustor. The throat area is variable.

Fig. 6 shows the thrust and specific impulse of the RBCC.

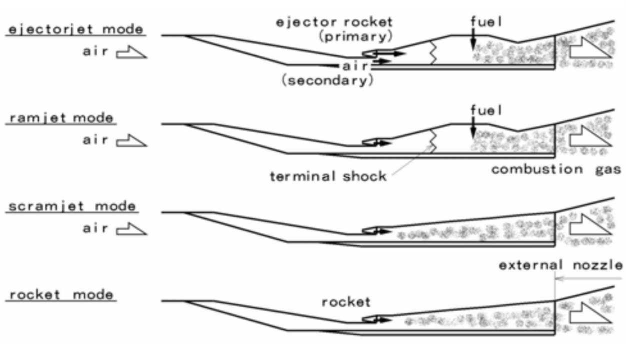


Figure 5: Conceptual Diagram of the RBCC engine

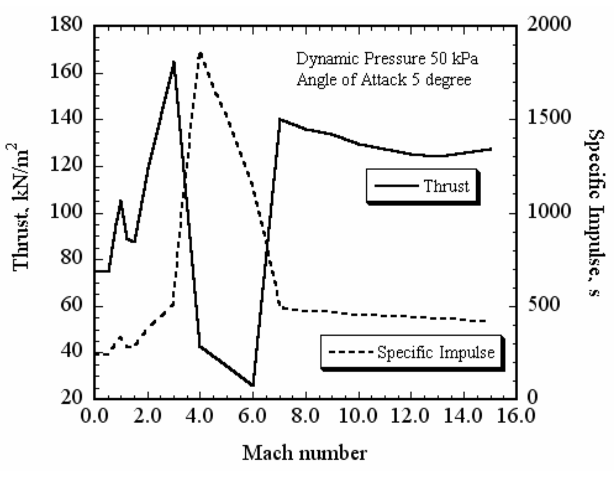


Figure 6: RBCC performance

3. Concept Design

The five system concepts shown in Table 2 are designed in this paper to compare space transportation systems that mount three typical types of engines. Each concept includes the stage number and engine type.

Table 2: Selected Concepts

Name	Stage type	First-stage engine	Second-stage engine
Type-R	Single	Rocket	-
Type-S	Single	RBCC	-
Type-RR	Two	Rocket	Rocket
Type-TR	Two	TBCC	Rocket
Type-SR	Two	RBCC	Rocket

The mission is designed such that the vehicle takes off from a launch site at the Equator to carry a one-ton payload to a circular 0-deg inclination 200 km altitude orbit. Atmosphere exists below 90 km altitude; the vehicle will be thrown into the perigee of the Hohmann transfer orbit at the exit of the atmosphere. The SEAT performs concept design minimizing the gross take-off weight (GTOW) and deals with the vehicle motion from take-off to the perigee. The SEAT does not design the vehicle configuration and engine, the vehicle is scaled up or down while maintaining a reference configuration.

3.1 Problem Formulation

The vehicle motion is constrained within the vertical plane. It is modeled as a point of mass. The Earth is modeled as a rotating sphere. The state expressing vehicle motion is the distance from center of the Earth to the center of gravity r, inertial velocity V, inertial path angle γ, and fuel mass m_{fuel}; the control includes the angle of attack α and thrust throttle CT. Details of equations of motion are described in Ref. 7. Altitude and Earth-relative velocity at take-off are, respectively, 0 m and 170 m/s. For designing the Type-R and the Type-RR vehicles, the inertial velocity and the inertial path angle at the take-off are the design variables to be optimized. These relations are expressed as the following equation.

$$\gamma = \cos^{-1}\left((V^2+(\omega R_0)^2-V_R^2)/(2VR_0\omega)\right) \quad \textbf{(1)}$$

Therein, ω is the angular velocity of the Earth; R_0 is the Earth radius (=6378.142 m), and V_R represents the relative velocity (=170 m/s).

For designing the Type-S, the Type-TR, and the Type-SR vehicles, the path angle at take-off is prescribed as 1 deg. As flight conditions at the apogee, the altitude, the inertial velocity, and inertial flight path angle are set respectively as 90.0 km, 7937.5 m/s, and 0 deg. The fuel used on the Hohmann transfer is not considered in calculations.

For the combined configuration of second stage systems, the lift coefficient is represented as that of the first stage; the drag coefficient is applied summing up the first and second stage.

A typical Japanese rocket engine, LE-7, is selected as the rocket propulsion engine. A pre-cooled turbo ramjet engine using liquid-hydrogen coolant is selected as the TBCC engine. The RBCC engine is described in chapter 2.

The vehicle weight is estimated by HASA.[12] The TPS for the first stage of the two stage systems is not taken into account. The propellant tank is non-integral.

The performance index is GTOW.

This concept design has four constraints. The first constraint is that angle of attack is constrained from -10 deg to 15 deg for the rocket and the TBCC engine mounted vehicle, and from 0 deg to 15 deg for the RBCC engine mounted vehicle. The second is that dynamic pressure is held under the maximum dynamic pressure of 50 kPa. The third is inclusion of necessary fuel within the fuel tank. The last is to have a sufficient base area to mount all the rocket engines. This constraint is expressed as follows.

$$r_{\mathrm{LE7}}^2\pi\times N_{\mathrm{LE7}} \leqq r_{\mathrm{fus}}^2\pi \quad \textbf{(2)}$$

In that expression, r_{LE7} represents the radius of the required area for mounting LE-7 (=1.5 m), N_{LE7} is the number of LE-7, and r_{fus} denotes the radius of the fuselage.

The design variables are summarized in Table 3. The SEAT determines these design variables minimizing GTOW subject to all constraints and initial and final conditions.

Table 3: Design Variables

Items	Type-R	Type-S	Type-RR	Type-TR	Type-SR
α, deg	○	○	○	○	○
CT	○	○	○	○	○
Flight time, s	○	○	○	○	○
Number of engines	○	○	○	○	○
Reference area, m^2	○	○	○	○	○
Flight path angle at take-off, deg	○	×	○	×	×
Separation condition	×	×	○	○	○

○, Yes ×, No

3.2 Results

Design results are summarized in Table 4 and are shown in Figs. 7–9.

The best value of GTOW is obtained using Type-RR, which uses rocket propulsion in both stages. The Type-RR does not present the difficulty for mounting all required engines, and it is the most realistic system concept. Although the vertical tail of the first stage might interact to the second stage at the separation, it might be solved by changing from a single vertical tail to a double one.

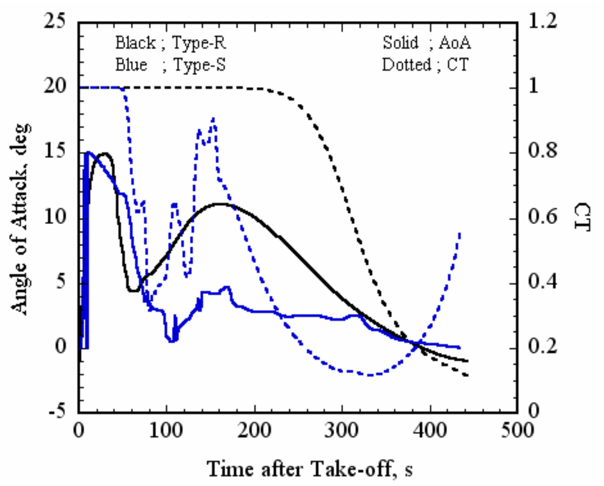
For the concept design for the Type-S, the optimal solution was not obtained. The result shown in Table 4 was achieved by reducing the estimated structure weight by half, so it uses only reference values. To realize the Type-S, the structure weight must be reduced by half, which might be very difficult.

For Type-TR and Type-SR, which use air-breathing engines, two common technological opportunities were addressed. One is that the number of required engines is too great to load on the first stage. From the resultant vehicle size and the configurations of Figs. 3 and 4, the first stage of the Type-TR and of the Type-SR can mount only 16.5 and 3.0 respectively. On the other hand, the respective first stages of Type-TR and of the Type-SR required 47.7 and 18.0 from the result. The other opportunity is the location of the second stage at the combined style. For the Type-TR, the shock wave from the nose of the first stage might interact with the second stage. For the Type-SR, the pitch-up moment generated by the forebody might become strong. Although the second stage is located at the rear of the first stage to avoid interaction with the vertical tail of the first stage, this style might decrease the stability. The suitable location and size of the second stage must be taken into account in future work.

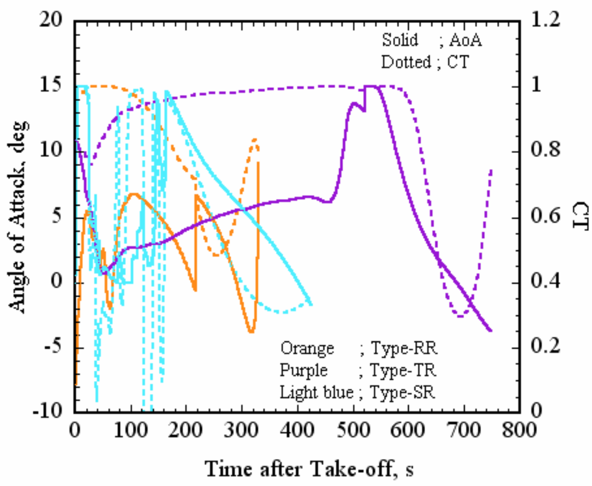
Table 4: Concept Design Results

Items		Type-R	Type-S	Type-RR	Type-TR	Type-SR
W_{TO} (1st/2nd), Mg		991.0	864.9	298.2 (261.3/36.9)	635.3 (491.6/143.8)	414.7 (317.0/97.7)
Empty weight, Mg		133.3	84.6	45.5/18.7	400.2/35.6	87.4/28.2
Length, m		52.0	59.1	34.0/17.8	84.0/27.4	48.7/24.0
Reference Area, m^2		1008.0	999.1	430.7/118.4	1217.4/278.9	679.7/215.4
Number of Engines		10.3	19.9	4.3/1.1	47.7/2.8	18.0/2.1
Separating conditions	Altitude, km	-	-	73.6	33.0	35.5
	Mach number	-	-	15.5	5.7	7.5
	Earth-relative path angle, deg	-	-	3.7	7.6	6.9

Results of the Type-S vehicle were obtained from a reference.



(a) Type-R and Type-S



(b) Type-RR, Type-TR, and Type-SR

Figure 7: Time Histories of Control

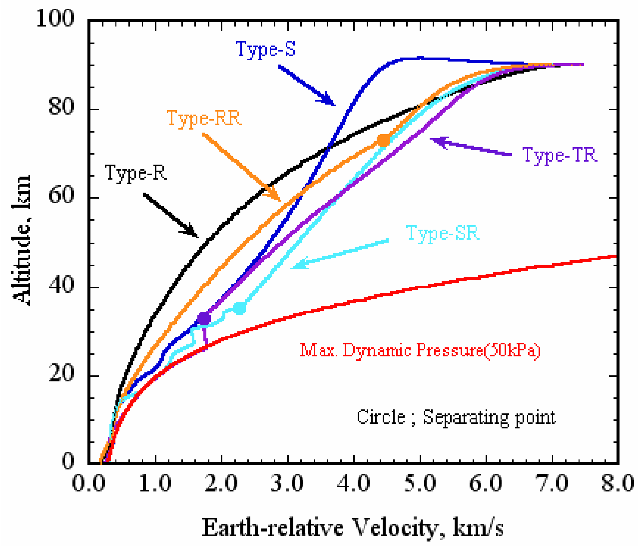


Figure 8: H-V Diagram

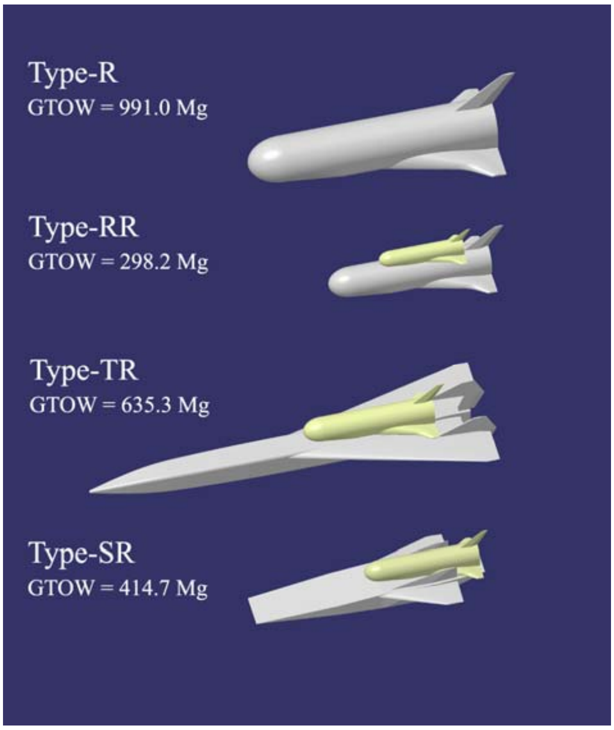


Figure 9: Comparison of Four Systems

Optimal ascent trajectories were discovered for the respective systems. In the Type-RR case, the first stage obtains only potential energy; the second stage then accelerates to orbital speed effectively in the thin atmosphere. However, under the separation conditions of the Type-RR, the first stage vehicle might need thermal protection for flyback. In the Type-TR case, the combined system takes off horizontally, then climbs in a low dynamic pressure region until achieving supersonic flight. This flight strategy is also typical for the Type-SR. Subsequently, the combined system ascends at maximum dynamic pressure. For effective acceleration, the second stage must fly with a high flight angle at separation to ascend into the thin atmosphere. For this reason, the combined system flies into a low dynamic pressure region again immediately before separation to avoid the penalty associated with pulling up at high velocity. In the Type-SR case, some types of engine operation mode were discovered. Achieving supersonic flight, the combined system ascends at maximum dynamic pressure or at high dynamic pressure to Mach 5 to use the ramjet mode. The RBCC engine was operated by an ejector jet until Mach 3.5 and by ramjet mode to Mach 7. Subsequently, the RBCC engine was operated by the scramjet mode until the second-stage separation, and the combined system flies at the low dynamic pressure region during the scramjet mode operation.

Except for the Type-SR, the supported fuel tanks were able to accommodate the fuel load. For the Type-SR, the fuselage was treated as the fuel tank, which is not realistic. Redesigning the location and configuration of the fuel tank and of the vehicle configuration are necessary in future work.

4. Conclusions

The five system concepts, which were combinations of the three types of engine and of the stage number, are considered in this paper. These systems were designed using the SEAT concept design tool. From results of this study, we can draw the following conclusions.

1) The lightest GTWO system concept is the TSTO, which uses rocket propulsion for both stages. The system has a sufficient base area to mount all required engines; it is also the most realistic concept.

2) For the other TSTO concept using air-breathing engines, the TBCC and the RBCC, two common problems are addressed: the required engines are too numerous to mount on the vehicle, and the difficulty loading the second stage.

3) Results clarified that the ascent trajectories mutually differ depending on the type of the first-stage engine.

References

[1] Hammond, W. E. Design methodologies for Space Transportation Systems, AIAA Education Series, AIAA, Virginia, 2001, Chap. 1.

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

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

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

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

[6] 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*, AIAA 2004-4316, AIAA, New York, 2004.

[7] Suzuki, H. and Minami, Y. Development of Optimal Design Tool for Future Space Transportation Systems, *AIAA International Space Planes and Hypersonic Systems and Technologies*, AIAA 2005-3292, AIAA, Capua, Italy, 2005.

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

[9] Kobayashi, H. and Suzuki, H. Simultaneous Optimal Design of Hypersonic Turbojet Engine and Trajectory with SEAT, *14th AIAA/AHI International Space Planes and Hypersonic Systems and Technologies*, AIAA 2006-8051, AIAA, Canberra, Australia, 2006.

[10] Kanda, T., Tani, K., and Kudo, K. Conceptual Study of a Rocket-Ramjet Combined-Cycle Engine for an Aerospace Plane, *Journal of Propulsion and Power*, pages 301-309, Vol. 23, No. 2, 2007.

[11] Aoki, S., Lee, J., Masuya, G., Kanda, T., Kudo, K., and Murakami, A. Experimental Investigation of an Ejector-jet, *Journal of Propulsion and Power*, to be published.

[12] Harloff, G. J., and Berkowitz, B. M. HASA – Hypersonic Aerospace Sizing Analysis for the Preliminary Design of Aerospace Vehicles, NASA CR-182226, 1988.

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