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Conceptual Study of Japan's Future Solid Rocket System

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A new space transportation system with an expendable solid-fuel booster and a reusable liquid-fuel orbiter is under consideration as part of activities in JAXA to construct a fully reusable space transportation system in the future. This paper shows this new system's conceptual study results, the system specifications, the new technology to be applied, the requirements to the subsystems, and the prospects.

Key Words: Solid Motor, Reusable, Integrated Propulsion System, Flight Abort, Active Cooling

Nomenclature

ACS	:	active cooling system
GH2	:	gas hydrogen
GOX	:	gas oxygen
HTPB	:	hydroxyl-terminated polybutadiene
LEO	:	low earth orbit
RCS	:	rocket control system
TPS	:	thermal protection system
TVC	:	thrust vector control

1. Introduction

The necessity and significance of reusable launch vehicles, cost-effective, eco-friendly and reliable, have long been recognized; however, no practical use of such systems except the Space Shuttle had been achieved until Falcon 9's recent success. There are two main reasons for obstacles to this: one is that recurring cost of reusable vehicles is too high as the Space Shuttle proved, and the other is that reusable vehicles involve many technical difficulties, especially of re-entry and landing, such as aerodynamic heating during re-entry phase, vehicle control in landing, mass increase in development, and safety management in a complicated flight sequence.

To overcome these obstacles, we are considering a new space transportation system with an expendable solid booster and a reusable liquid-fuel orbiter.

To reduce the recurring cost, an advanced version of the automatic inspection system developed for our solid rocket motor is to be applied to soundness analyses between the flights of reusable launch vehicles. To tackle the technical difficulties of re-entry, challenging technologies are applied to the upper stage. Those include lightweight and heat-tolerant materials and structures, an active-cooling system sharing hydrogen with the liquid propulsion system, and an advanced guidance and control system. Whereas our existing solid motor technology with the high reliability is applied to the booster so as to minimize the development risk and the number of changes in each stage's specifications in the development phase. More specifically, we aim to overcome the difficulties in the system integration of stages by concentrating its development on the orbiter elements. Having developed various types of solid motors since the first small solid motor in 1954, JAXA/ISAS have accumulated efficient development methods. The application of our legacies to the new system is expected to be quite beneficial.

This new system itself is not the final objective but part of the activities to construct a fully reusable space transportation system in the future. Another team in JAXA is also considering the development of a reusable booster, and the combination of both results will contribute to the realization of a fully reusable space transportation.

2. System Concept

The system concept for the system and subsystem designs is described in Table 1.

Table 1. System concept.

Mission	1. An alternative to satellite missions in middle or long term (several months to a year) 2. Transportation of payloads necessary to return to the earth
Launch Capacity	Payload mass: 1.5 tons to LEO
Reusability	Booster: expendable Orbiter: reusable
Key Technologies	1. Inspection technology between flights 2. Automatic flight abort system 3. Re-entry technology (TPS, ACS) 4. Propellant utilization system 5. Landing technology (Attitude control, Image recognition)

Two missions are set in this concept to make the most of superiorities in reusability. One is an inexpensive alternative to conventional satellite missions that have been performed by expendable launch systems. The other is a mission in which payload return is necessary and cannot be achieved by the

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expendable. As the minimum required performance for such missions, the payload mass is set to 1500 kg for LEO.

Basically, we do not apply any challenging technology to the booster. The requirements of the booster are inexpensiveness, high reliability, and design stability. The booster is used one time and then disposed of in contrast to the orbiter.

Based on such system concept, the operation concept is also set as in Fig. 1. The orbiter has a payload bay which mounts payload inside and also works as 3rd stage. The payload is not separated from the orbiter but returns with the orbiter. The technologies to realize this operation concept are included in Table 1, and the details are explained in the next session.

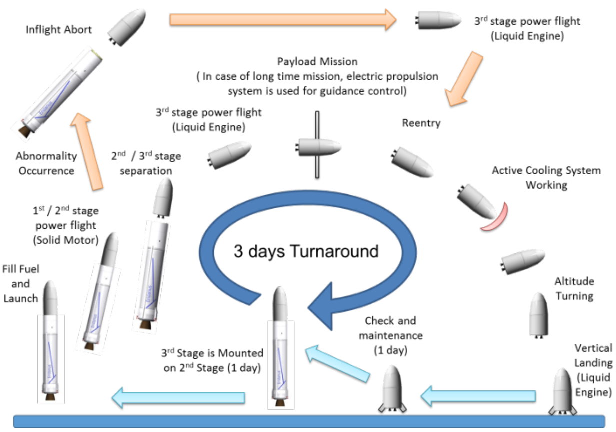

Fig. 1. Operation concept.

3. Key Technologies

3.1. Inspection technology between flights

As mentioned above, it is essential to reduce the recurring cost in the operation between flights of reusable launch vehicles. Accordingly, we will advance the inspection technology introduced to our Epsilon Launch Vehicle and apply it to the new system. Epsilon's inspection devices[1)] such as ROSE (Responsive Operation Support Equipment), MOC (Miniature Ordnance circuit Checker), and LCS (Launch Control System) can be applied easily in principle. However, to effectively utilize these devices in the new system, we need to build a failure pattern database in advance to distinguish nominal patterns and failure patterns in functions of components and subsystems. Not having enough data especially for TPS, ACS and landing system, we should acquire sufficient data through development tests on these subsystems.

3.2. Autonomous check system for flight abort

Flight abort is a new demand for reusable vehicles. To achieve it, we need to ensure not only the soundness of each component and subsystem but also the soundness of the system. It means to detect the possibility of abnormal modes caused by environments and failure modes due to complex events or chain events. These modes can not be identified by the soundness of each device alone. For example, if a worse-than-expected weather condition, together with surrounding structures, makes gusts stronger than design criteria, any system with properly functioning measuring and controlling devices could not fly a nominal flight route. Early-stage detection would switch the system to a flight abort mode, enabling the orbiter to return and the payload and the main body to be used again.

The evaluation of the soundness of the system requires quantitative and systematic analyses, which are superior to the conventional hazard analysis. One promising method for such analyses is the use of FTLA (Functional Time Line Analysis), which evaluates system functions chronologically, and FN 2 C (Functional N 2 Chart: Function correlation diagram), which evaluates the relationship between functions, enabling us to detect hazards in the system and evaluate each hazard condition quantitatively usign simulation. This method can set quantitative conditions of hazards, allowing for monitoring the soundness of the system in real time. Combining with Monte Carlo simulations, this method achieves a higher order of quantitative system reliability evaluation which could not be realized by conventional evaluation methods.[2)]

3.3. Re-entry technology

One of the technical difficulties in the reusable orbiter is to protect the body from aerodynamic heating at the time of reentry. To address this issue, we need to install TPS on board. The Space Shuttle used C/C composite materials, porous ceramic tiles, flexible heat insulating materials, etc. as materials for TPS. Recently, these technologies have advanced into Si/C composite materials with better oxidation properties than those of C/C composite materials, heat-resistant ceramic tiles that can withstand higher temperatures, and advanced surface-reinforced flexible insulation materials.[3)] Although these materials display remarkable performances in an extreme environment exceeding 1500 °C, they have difficulties in establishing a manufacturing process to maintain product quality, and tend to be more expensive. In addition, as demonstrated by the Space Shuttle, parts subjected to high thermal load even below the temperature limit require inspection during turnaround, thus boosting recurring cost.

Therefore, we apply Active Cooling Technology, which is being studied along with materials for TPS. Specifically, the thermal load on TPS materials is reduced through lowering surface temperature of TPS by film cooling with liquid hydrogen.[4) 5)] This will also decrease the risk of damage to TPS and inspection cost during turnaround, and enable a system design to take advantage of reusability. Clarifying functional requirements of TPS through flight analyses, we will select materials for each part and set the amount of cooling fluid. And also the active cooling of this type has not been proven so much generally, so accuracy of performance estimation is difficult in the present. Experiments and numerical analyses with some models are required for the future.

3.4. Propellant utilization technology

This system is compact and therefore its outfit design and mass control are directly affected by increased components. Nevertheless, reusable vehicles need many functions, such as propellant, control, reentry, and landing. Sharing propellants with the main engine is considered as one way to perform many functions with as few components as possible.[6] Figure 2 shows the system configuration diagram of the orbiter. In the first stage of study, priority is given to performance (specific impulse) of propellant, so liquid hydrogen and liquid oxygen are selected. Ordinary spacecraft have individual propulsion system such as hydrazine for posture control, while this system takes out GH2 and GOX from the propellant of the main engine to use these combustion gases as a gas jet for RCS. For ignition of GH2 and GOX, catalytic systems and laser systems are being studied. The application of catalyst systems is desirable from the viewpoint of safety, but decision will be made in consideration of necessary electric power and components' mass.

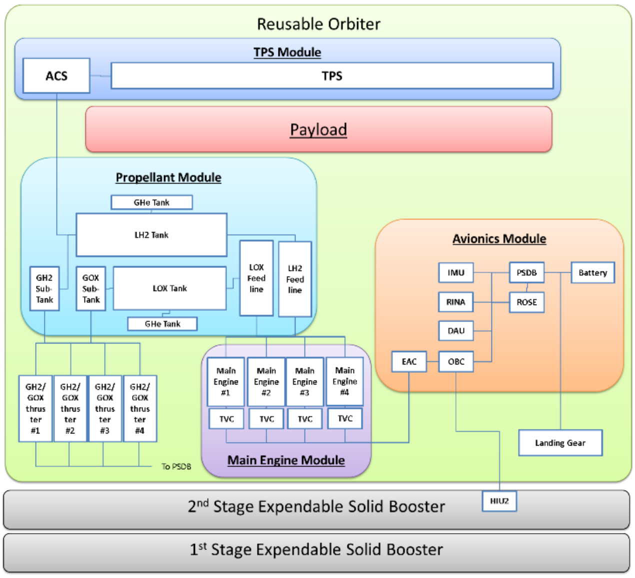

Fig. 2. System configuration diagram of the reusable orbiter.

Furthermore, liquid hydrogen used for the active cooling described in Section 3.3. is also supplied from the propellant of the main engine. In the flight sequence, active cooling is activated only in the reentry phase, during which the main engine is shut down. However, hazard control is required to prevent a situation that the orbiter can not be reentered because the propellant has been exhausted by the main engine Therefore, we are considering a design of TPS that allows the orbiter without active cooling to reenter at least one time (in this case, reusability should be ruled out). This design philosophy, named Reusable Coating, is a concept that originally expendable subsystems can be reused by adding functions to them, and in a certain case, the capability of such subsystems is fully utilized. This is an epoch-making method in the development of a reusable space transportation system, that enable us to achieve both safety and reusability while ensuring technical continuity and cost-effective development.

3.5. Landing technology

Recently, automatic driving techniques using computer image recognition has advanced rapidly, and is expected to become available in real life any time soon. Similarly, in the field of spacecraft, the technology of autonomous landing on the moon with image verification cameras and altitude and velocity detection radars is being developed under the project named SLIM (Smart Lander for Investigating Moon).[7] An image recognition technology like this is applied to the reusable orbiter along with an autonomous landing system using positioning satellites and radars. As for the landing on the ground, there are horizontal and vertical landing; horizontal landing needs the orbiter to have wings, which in turn becomes structure mass in the ascending phase and demands more strict requirements of this compact system design. So, we think that our best bet is vertical landing which uses the orbiter's legs and reverse thrust generated by the main engine injection. This landing method is similar to that of SLIM; therefore, its landing impact absorption system can be applied to the orbiter.

In order to control the landing using injection of the main engine, the orbiter re-entering with the nose cone downward should be turned around by approximately 180 degrees after deceleration. Such acrobatic attitude control requires to specify the orbiter's dynamics including aerodynamics and propellant sloshing, and set proper specifications and arrangement of thrusters. Analysis technologies using simulation for these phenomena are also advancing.[8][9] By linking with these technologies, we will be able to apply a high reliability design method that allows for the high-precision risk evaluation in the early development phase to minimize the development risk.

4. System Design

To set the specifications of each subsystem, sizing calculation and flight analysis were performed based on the past rocket specifications and the configuration of this system. Table 2 shows the system specifications. Figure 3 shows the flight analysis results in the ascending phase. This analysis has been performed with OPT3D, JAXA's launcher flight analysis tool.

Table 2. System specifications.

Orbiter		
	inert mass	1,607 [kg]
	propellant mass	LH2: 868 [kg], LOX: 4,222 [kg]
	mass fraction	0.76
	ΔV	3,644 [m/s]
	propulsion system	LH2/LOX Engine
2nd Stage Booster		
	inert mass	2059 [kg]
	propellant mass	14,990 [kg]
	mass fraction	0.88
	ΔV	2,509 [m/s]
	propulsion system	Solid HTPB
1st Stage Booster		
	inert mass	9205 [kg]
	propellant mass	65960 [kg]
	mass fraction	0.88
	ΔV	2,944 [m/s]
	propulsion system	Solid HTPB
Total	mass (wet)	101,011 [kg]
	ΔV	9097 [m/s]

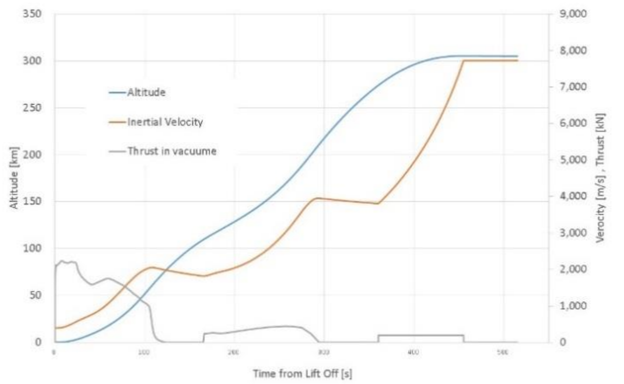

Fig. 3. Flight analysis results in the ascending phase.

5. Subsystem Specifications

The subsystem specifications were set based on the system concept review results shown in Sections 2 and 4.

5.1. Inspection system between flights

In the inter-flight inspection system, the automatic inspection function mainly checks the following points in one single day:

· Damage to the outside of the orbiter (especially TPS)
· Degradation and damage of tanks and piping
· Functions of valves and separation mechanisms (before / after filling propellant)
· Functions of avionics equipment

5.2. Flight abort system

For the flight abort system, we set mainly three scenarios at launch site and during the booster flight and consider functions necessary for each scenario. These scenarios will later be supplemented with the above-mentioned FTLA.

5.2.1. Scenario A; booster anomaly

It is a case that an anomalous solid booster (abnormal combustion, combustion gas leak, etc.) prevents steady flight. Considering this system philosophy, we believe there is a extremely low possibility of this scenario; however, we have set this scenario because of its high criticality. The specifications required for the abort system are as follows:

· Booster health monitoring (motor case, nozzle, avionics system)
· Anomaly judgment by health monitor information of F-ROSE (Flight ROSE)
· Switching to flight abort mode (orbiter/booster separation, booster tumbling, orbiter main engine ignition)

5.2.2. Scenario B; Orbiter anomaly (emergency)

It is a case that immediate response is required soon after any anomaly is detected in the orbiter. Switching to the flight abort mode during booster power flight, including in the case of Scenario A, involves the risk of collision of the booster and the orbiter, so it is preferable that the orbiter should be separated after the completion of the booster burning. Therefore, we apply to this scenario the case where the risk of the collision by flight abort during booster burning is outweighed by the one of the orbiter's failure to return from a high altitude. Such case arises when TPS suffers critical damage or control equipment fails. In this scenario, the specifications required for the abort system are as follows:

· Orbiter health monitoring (propulsion system, tank, PBS, avionics system)
· Anomaly judgment by health monitor information of F-ROSE
· Switching to flight abort mode (orbiter/booster separation, booster tumbling, orbiter main engine ignition)

5.2.3. Scenario C; Orbiter anomaly (not emergency)

It is a case that the sequence should be continued until nominal orbiter separation even when any anomaly is detected in the orbiter. For example, it is conceivable that an anomaly occurs in the propulsion system of the orbiter. The required specifications are as follows:

· Orbiter health monitoring (propulsion system, avionics system)
· Anomaly judgment by health monitor information (of enhanced ROSE)
· Switching to flight abort mode (reentry without igniting the orbiter main engine after planned orbiter separation)

5.3. TPS and Integrated propellant system

The TPS specification requirements are set as shown in Table 3 based on past research[10] results and the design philosophy mentioned in Section 2. The amount of fluid required for ACS and the distribution of the propellant of the Orbiter are set as in Table 4.

Table 3. TPS specifications.

	without ACS	with ACS
Maximum Wall Temperature	1800 [K]	1500 [K]
Maximum Heat Flax	600 [kW/m2]	1000 [kW/m2]
Operating Time	300 [s]	300 [s] (in a flight)
Reusability	No	Yes (100 times)

Table 4. Propellant distributions.

	LH2 [kg]	LOX [kg]
Main engine for accent phase	691	3799
Main engine for re-entry phase and landing phase	62	338
RCS	15	85
ACS	100	0

5.4. Re-entry and landing system

Based on the past research results, we set up the operations in the reentry and landing phase as follows:

A) Turn around the orbiter using RCS by approximately 180 degrees on Earth orbit (at an altitude of 300 km), then ignite the main engine to move the orbiter to the reentry orbit.
B) Turn around its direction again before the orbiter descents to an altitude of 120 km, and activate ACS after the orbiter reenters into the atmosphere.
C) Decelerate the orbiter to the transonic range using aerobraking before it descends to an altitude of 5 km.
D) After deceleration, turn around the orbiter once again into

an upright position before it reaches to an altitude of 1 km.

E) Perform posture control by the main propulsion system and RCS below an altitude of 1 km, and then conduct guidance control using image recognition to land the orbiter at the destination.

However, considering the concept of Reusable Coating, we allow the orbiter one-time parachute landing at an acceleration of up to 10 G if Phase E fails. In this case, the reuse of the orbiter is ruled out.

6. Conclusion

We conducted a system review of a new launch vehicle with a reusable orbiter and an expendable booster, which will play a part of the fully reusable space transportation system. By assuming a mission to make the most of the advantages of reusable vehicles, we identified some technologies and subsystems to be needed for realizing its operation, and incorporated them into the system configuration. Based on this system configuration, we conducted a primary sizing calculation to set the system specifications. Then, we examined and provisionally set the subsystem specifications.

From now on, using the specifications of the subsystems, we will draw up development plans for the subsystems and thenintegrate them into the system to make a development plan of the whole system. Subsequently, we will proceed to the next step of building a prototype.

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