Reentry Capsule for Sample Return from Asteroids in the Planetary Exploration Missions

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Abstract. For carrying sample from the bodies of interplanetary space, a wide range of knowledge of reentry technology is needed. HAYABUSA(MUSES-C) was an asteroid explorer returned to the earth after the 7 years of voyage, and its capsule reenters into the Earth's atmosphere, which was a good example of reentry technology implemented to the flight vehicle. It performed a safe reentry flight and recovery. For the design of the capsule, many considerations were made due to its higher entry velocity and higher aerodynamic heating than those of normal reentry from the low earth orbit. Taking into account the required functions throughout the orbital flight, reentry flight, and descent/recovery phase, the capsule was designed, tested, manufactured and flight demonstrated finally. The paper presents the concept of the design and qualification approach of the small space capsule of the asteroid sample and return mission. And presented are how the reentry flight was performed and a brief overview of the post flight analysis primarily for these design validation purposes and for the better understanding of the flight results.

INTRODUCTION

MUSES-C spacecraft was launched by M-V-5 launch vehicle in May 9, 2003, toward the asteroid 1998SL36. After the launch, the name "Hayabusa" was given to the spacecraft. In September 2005, it approached to the target body, observation through the proximity operations, and several attempts to touchdown and to try to collect sample. Finally it returned to the earth, and performed its reentry flight and recovery in June 13, 2010.

The major objective of the mission is to demonstrate technical issues necessary to conduct an approach and rendezvous to one of the near earth asteroids[1] using a high performance ion-engine system during its cruising flight to and from the asteroid. In touching down to the asteroid, the surface material will be taken by a sampling mechanism and the sample is to be carried by the capsule that directly reenter into the earth's atmosphere along the hyperbolic trajectory with super-orbital speed from the asteroid as presented in Fig.1.
The returning capsule's conceptual design work was initiated in early 90th based on the related technical activities and background both for the aerothermodynamics, thermal protection materials and its responses under heating, descent and recovery subsystems in the several flight lessons at ISAS in the past. The major technical issues are due to hypervelocity atmospheric reentry flight in which the entry velocity is as high as 12 km/sec. Unlike other reentry vehicle, its flight speed is the fastest as ever experienced for the entry into the earth's atmosphere. It will also impose higher heating rate to the thermal protection system. For these reasons, the estimation of the reentry flight environment and the thermal protection material and structure are essential to the design of the capsule. Due to the limitation of the size and weight allocated to the capsule, it has to be accommodated by the various functional parts inside the extremely small capsule, such as a sample canister, parachute and its jettisoning mechanisms, beacon for the localization, power supply subsystem, thermal control, and so on. These various new requirements imposed several technical challenges in the design. An overview of the design of the capsule at the completion of the development is summarized and issued as a collection of technical papers in Ref. 2.

In the flight of Hayabusa spacecraft to and from the targeted asteroid that was named “Itokawa”, many unexpected things happened. It performed the proximity operations, touch-down and trials to collect samples from the surface of the asteroid in 2005 to 06. During these operations, many troublesome affairs happened but finally it recovered the operation on the way back to the Earth, it was suffered by the damages and, as a result, serious limitations for the spacecraft operation in the propulsion subsystems, attitude control subsystems, power/communication subsystems and so on. However it finally returned to the earth in June 2010 after the additional revolution of the Helio-centric orbit. Then the reentry capsule finally took an important part of the mission at its very end.

The capsule came back to the Earth and the final reentry flight of the capsule was conducted in June 13, 2010 at the Woomela prohibited area (WPA) Australia. In the final approach of the spacecraft to the reentry atmospheric flight interface to the landing area, a series of careful trajectory maneuver operations was conducted from safety assurance point of view, and receive the final permission to be issued by the Australian authority. The view of reentry from the ground is shown in Fig.2. After the entry a beacon signal was received at the right time as planned by the final parameter setting made use of the measurement of the deceleration by aerodynamic drag in accordance with the increase of the dynamic pressure.
The capsule position during descent by parachute was localized, then the capsule was found after 30 minutes after the estimated landing, at the place less than one kilometer from the planned landing position. As presented in the previous chapters, the separated parachute cap andforeside heat shield were also found and recovered. After the inspection of the sample canister inside the capsule, dusts from the asteroid were identified and we obtained the extraterrestrial material for the first time from one of the small asteroids. The investigation of the asteroid surface dust is still underway and it will help better understand the evolution of our solar system. As a result Hayabusa mission and the capsule completed its mission.

Here in the present paper, an overview of the aerodynamic / aero thermodynamic design of the capsule, the flight results and ongoing post flight analysis are presented in the following Chapters

Figure 2. Hayabusa returned at Woomera in south Australia in June 13, 2010

OVERVIEW OF THE DESIGN OF THE RETURNING CAPSULE

Remarks in Aerodynamics of Hypervelocity Atmospheric Entry Flight

In the design of the reentry capsule for the present purpose, many new design considerations should have been made in aerodynamics, aero thermodynamics, thermal protection system and its responses at very high temperature, flight mechanics, and so on. Because of the entry speed into the earth atmosphere is 12km/sec, also because the resources allocated to the capsule in terms of its weight and envelope were very limited as well. In Table 1, important issues to be thought serious at the stage of starting the design work when the program was approved.
Table 1. Aerothermodynamic Issues to be Thought for the Sample Return Capsule Design

| High Enthalpy Flow Characterization in Super-Orbital Speed (12km/s) |
|-------------------------|-------------------------|
| Entry to the Earth’s atmosphere |
| • Highly Nonequilibrium Flow |
| • Thermal Responses of Ablative Materials under High Heating |
| • Strong Interaction between Shock Layer Flow & Ablation Products |
| • Radiation Heating |
| • Injection Induced Boundary Layer Transition |
| • Leeward Flow Phenomena and Back Face Heating Environment |
| Aerodynamic Characteristics |
| • Static Instability in Rarefied Regime |
| • Transonic Dynamic Instability |
| New Parachute Deployment System, Verification & Its Accommodation |

There would be many causes of uncertainties in prediction, and to reduce these uncertainty was one of the ways in the preliminary aerodynamic design such as geometry trade-off phase, relation among the entry trajectory condition, nose radius, aerodynamic stability and so on as shown in Fig.3. Also considered was to take into account for maximizing the inner envelope for the instrumentation such as parachute, sample canister and avionics. For resolving these issues, following measures were taken on each design issue. Most of these considerations are covered and summarized in Ref. 2.

![Reentry Capsule geometry and Flight & Heating Characteristics](image)

**Figure 3 Reentry Capsule geometry and Flight & Heating Characteristics**

### Radiation Heating

The heating by radiation from highly excited states of the high temperature gas in the shock layer is indispensablel on this mission. For that reason, a numerical radiation estimation code; SPRADIAN(structured package of radiation analysis) is newly developed and used for the radiation analysis by the aid of the flow field solver. The results were compared with the existing and simpler modeling technique such as NEQAIR.

### Interaction Between Outer Flow and Ablation Products

A massive ablation product out of the body surface will affect the shock layer flow greatly. For the charring ablator such as a carbon-phenolic material which is often used for the thermal protection in relatively high heating rate, the reaction at the surface itself is divided into oxidation dominant regime below 3000K of the surface temperature and sublimation dominant
regime for the higher temperature than 3000K. In the latter regime, the surface recession rate increases rapidly with the temperature, a massive flow of ablation product must be taken into consideration in addition to the pyrolysis gassing. Then, a fully thermal and chemical nonequilibrium shock layer flow analysis was made under the condition that there is a carbonaceous ablation product with concerned surface temperature regime.

**Base Flow of the Capsule**

Generally the backward surface heating is far less than that of theforeside, however a careful estimate is needed because of the complexity of the flow and the light-weight design requirement and so on. Since the wake flow phenomenology behind the capsule is so much complicated, it sometimes has difficulties in estimating the heating environment there. The result quantified that the radiation enhancement by ablation products both for the oxidation and sublimation for the present flight environment of the capsule will not be negligible. We had to be careful about the design heat flux setting because of many functioning parts in the surface of the leeward.

**Boundary Layer Transition under Massive Ablation Products**

A possibility of injection-induced boundary layer transition has been pointed out. Since the nature of the transition, even a flow phenomenology is not well understood and some qualitative explanations are being proposed. Ablation products will play as an injectant through the surface will augment the disturbance in the boundary layer, which may result in the earlier transition than that occurs without such an injection of ablation products. A model of the injection-induced turbulence is incorporated to the foreside flow analysis.

**Ablative Thermal Protection and its Characterization of Thermal Responses**

The selection and evaluation of the heat shield material are ones of the most important issues in the design of the capsule. The present mission offers a considerably high heating load up to 15MW/m² for about 30 seconds, then a charring ablator is to be a unique solution. A carbon-phenolic material is chosen and there are many possibilities in fabric layout and manufacturing processes. Starting with the preliminary evaluation and screening for choosing the fabric-resin arrangement by arc-heating test, basically a cloth-layered carbon-phenolic ablator was selected. In the evaluation process, a careful inspection was made to characterize both the thermo-chemical reactions and the mechanical durability of the ablator such as pyrolysis, surface recession by both oxidation and sublimation, spallation, delamination, and so on. Besides these heating test-based evaluation, a numerical simulation model to simulate the thermal responses was made and refined for the present application.

The flow enthalpy of heating facility such as arc-heaters is far less than that in the real flight, and the numerical-simulation-based correlating studies is necessary to bridge from the test results to that at the flight condition. On this context, modeling of the thermal responses of the ablator is essential to predict the ablator behavior in the flight environment. At the surface of the heated material, many effects are taken into account, such as air mixture of incoming flow, composition of pyrolysis gas, and products of the surface reaction by oxidation and sublimation. The angle of fabric layers against the surface is one of the important parameters taking into
account the in-depth thermal conductivity and avoiding delamination due to out-gassing. The refinement of these parameters was conducted primarily by heating-test basis.

Aerodynamics and Flight Mechanics of the Capsule

Since the reentry capsule is flown by totally passive aerodynamic stability, the flight characteristics are to be carefully investigated both statically and dynamically, throughout the entire reentry flight and descending flight followed by the parachute deployment. Due to the nature of the aerodynamics of the disk-shaped body used here, it inherently has a dynamic instability in pitching motions in the transonic flight regime. In addition, it was pointed out that the static pitching instability may occur in the rarefied gas regime[3].

This trend would be critical to the attitude motion at initial entry. The static stability is primarily examined by a conventional wind tunnel test or by a simple estimation technique, however, the dynamic stability is difficult to know generally. Fig.4 illustrates the methodology to establish the aerodynamic database of MUSES-C reentry capsule. Above-mentioned important characteristics were needed to careful and intense considerations in relation to the reentry flight mechanics and following parachute opening.

![Figure 4. Methodology for Constructing Aerodynamic Database](image)

Descent Subsystem and Subsonic Parachuting

The descent sub-system of the capsule has several special features. These are to cope with the difficulty in an arrangement of the descent subsystems inside the small capsule, such as light-weight cross parachute with radar reflector, torus-shaped packing, drogue concept, newly developed parachute ejection devices, and so on. Due to the pitching motion instability from low supersonic to subsonic speed, supersonic parachuting could have been a solution. The characterization of this instability showed and resulted no tumbling may occur by this instability. Therefore, a subsonic parachuting was chosen. In addition, for the sake of simplicity, we employed the design in which jettisoned parachute cover plays a roll of drogue chute. The sequence of parachute deployment and foreside heat shield separation is illustrated in Fig.5. We employed that the foreside heat shield is to jettison, in order to avoid heating from the hot heat shield to the sample container inside the instrument module. Making use of the ballooning flight test opportunities at ISAS, two drop-tests for supersonic descending flight of the capsule were conducted for the demonstration of both transonic attitude instability and parachute opening.
HAYABUSA REENTRY FLIGHT AND RESULTS

Reentry Flight and Recovery Operation Overview

The spacecraft came back to the Earth and the final reentry flight of the capsule was performed in June 13, 2010, at the Woomela Prohibited Area (WPA) Australia. In the final approach of the spacecraft to the reentry atmospheric flight interface to the landing area, a series of careful trajectory maneuver operations was conducted from ground-safety-assurance point of view, and the final permission was issued by the Australian authority.

Figure 6 shows the final trajectory foot-print and 4-sigma error ellipse of capsule's landing position which was estimated in the planning phase before the final trajectory correction maneuver. This estimation was made based on the GRAM-99[4] atmosphere model and the initial condition, whose position and velocity of capsule at 200km in altitude, estimated according to the orbital determination before the final trajectory correction maneuver. Thus, its initial condition used in this estimation includes the error of the orbital determination and the trajectory correction maneuver. The altitude of the parachute deployment was set to 10 km in the planning phase. The solid ellipse in Fig.6 shows the 4-sigma dispersion ellipse of landing position of the capsule. Its ellipse was expected to extend to 150km in the east-west direction and 100km in the north-south direction due to the uncertainty of the orbital determination and the wind profile. The dash dot line shows the WPA boundary. We had to define the target landing position to set the 4-sigma error ellipse of the landing position into WPA.

The capsule passed 200km altitude in 13:51(UT) and the luminescence of HAYABUSA mother ship and the capsule was observed from the ground stations. In 5 minutes after the reentry, the parachute was deployment at about 5km altitude and the beacon signal was transmitted as scheduled. All of the station acquired the beacon signal. The headquarters of the recovery team analyzed the information from the stations and localized result in real time using the position analysis system. The capsule was landed near the predicted landing position at 14:09(UT). The final prediction was made with initial condition estimated from orbital determination data which was delivered at 0:00(UT) 13, June, before reentry operation and modified atmospheric model which takes account of National Center Environmental Prediction’s (NCEP) [5] atmospheric forecast data which delivered 0:00(UT) in 13, June.
In the final decision for parameter setting, the altitude of the parachute deployment is 5 km by setting on-board G-trigger and delay timer. According to the final prediction, the capsule reenters from the west-northwest direction and changes the descending course to northerly direction due to the jet stream. After the parachute deployment at 5km altitude, capsule with a parachute moves to the west direction at about 3km due to the eastward wind near the ground surface. The discrepancy between the actual recovery position and the final predicated landing position was less than 1km as shown in Fig.7. The reentry and descending trajectory prediction contributed to the recovery operation greatly. The jettisoned heat shields and parachute cover were found and recovered also very near to the predicted positions.

**Figure 6. Nominal reentry trajectory and 4-sigma error ellipse of the landing position**

**Figure 7. Planned and resulted trajectory and important locations** (Actual recovered position of the instrument module is designated by X)
Reconstruction of Reentry Trajectory

Reentry trajectory was reconstructed made use of most reliable data acquired in the reentry operation for a post flight analysis. The most reliable initial condition, which is a set of time, position and velocity of capsule at altitude 200km, is listed in Table 2. That is based on the final orbital determination carried out at the position nearest to the Earth. Table 2 also shows the dispersion (1-sigma) in addition to nominal value. The most reliable atmosphere model including the wind profile was made to take in consideration most recent NCEP forecast data which was delivered 12:00(UT) in 13. June. Figure 8 is wind profile comparison between the nominal data and dispersion of GRAM99 statistical database and NCEP forecast data. In the present reconstruction, the head shield jettison was made at the altitude of 5.5 km determined by onboard 5G trigger and 244 second delay timer. The parachute deployed in 1 second after the head shield jettison.

Table 2. Initial condition of reentry trajectory reconstruction

|                      | Final orbital determination data | Shift value for reconstruction |
|----------------------|----------------------------------|--------------------------------|
|                      | Nominal                          | Dispersional                   |
| Time                 | 12:00:12.16 (UT)                 | 0.091 s (sec)                  | --                             |
| Altitude             | 200 km                           | 13 m                           | --                             |
| Latitude             | -27 37 608 (deg)                 | 0.0026 (deg)                   | +0.00015 deg (-13 m)           |
| Longitude            | 126 4 599 (deg)                  | 0.0069 (deg)                   | +0.0045 deg (+14.6 m)          |
| Velocity             | 11 451.87 (m/s)                  | 0.01631 (m/s)                  | --                             |
| Azimuth              | 117 1867 (deg)                   | 0.003454 (deg)                 | --                             |
| Path angle           | -12 61093 (deg)                  | 0.004513 (deg)                 | --                             |

Figure 8. Wind profile comparison with GRAM-99 and NCEP forecast data delivered 12:00(UT) in 13. June 2010

For the reconstruction of the reentry trajectory, the descent trajectory of the capsule was calculated according to the above conditions at first. Next, the initial position is shifted from the final orbital determination data to match the calculated landing point with the actual recover position. The shifted value of initial condition from final orbital determination is 0.00029 deg in latitude and 0.0045 deg in longitude. These values are within 1-sigma dispersion. The reentry trajectory reconstructed from shifted initial condition is expected to be reasonable reentry trajectory.
The trajectory reconstructed by above mentioned procedure is shown in Fig. 9. For showing the agreement between the predicted, real-time-estimated and resulted/reconstructed trajectory, these three trajectories are presented in Fig. 7. The real-time-estimated trajectory is that by using the data taken by two ground-tracking stations located at "Vivian" and "Cattle Bore". The agreement of the landing point of sample container for example is less than 1km, which was far better than the preflight prediction taken into account various causes of the uncertainty.

The parachute deployment position of reconstructed trajectory was almost identical to the first determined capsule position by two stations. After deploying parachute, the capsule (now it is a sample container suspended by parachute as shown in Fig. 5 in the previous section) moved from east to west according to reconstructed trajectory. That movement also agrees with the tracking results. Then it was confirmed that the reconstructed data is valid. Figure 6 shows relation between altitude, velocity and downrange and acceleration and stagnation heat flux time history. The stagnation heat flux is estimated by the Tauber’s equation[6].

**Figure 9. Reconstructed trajectory about relation between altitude, velocity and downrange and acceleration, stagnation heat flux time history**

**INSPECTION OF THE RECOVERED CAPSULE AND IN-FLIGHT SURFACE TEMPERATURE MEAUREMENT**

The recovered parts of the reentry capsule were looking all very soundly worked as presented in Fig. 10. No serious damages were observed, and no hazardous and anomalous things were observed both in the heat shields, parachute and sample container. The surface of the foreside heat shield looks very smooth, and in the rear side heat shield, there remained the surface coating for the in-orbit thermal control, which may tell smaller heat input than expected.
Figure 10. Recovered parts of the Capsule and X-ray Cross section image of theforeside heat shield

By inspection, the surface of the foreside region was very smooth and no hazardous damage and / or delaminations were observed, which means preflight evaluation of the surface recession and out-gassing of pyrolysis gas were properly made. Also no major change in shape and color of internal surface of the heat shield and exterior surface of the instrument container, which tells us the validity of the thermal design of the capsule system during reentry flight were properly made. Then the parachute and payload container was kept in the proper temperature, then, as a result, the samples in the sample canister was estimated and kept in good condition. In addition, in the special parts such as the gaps and junctions of neighboring heat shield, holes for venting, cable penetration, and so on, flight result shows that all looks very soundly worked out.

A non-intrusive technique such as X-ray CT-scanning has been applied as much as possible, in order not for unnecessary destruction of the recovered items. The linear absorption coefficient (LAC) of the X-ray is strong function of the density and the element composition of the material. Though the element well-correlated to the ablator density in advance by using arc heated test piece with a given density. Although there are many causes of difficulties in conducting non-destructive investigation of the internal properties, the correlation between the heating test pieces and recovered items were made. By adjusting the beam power and the band width, we could successfully obtained the LAC distribution map in the regions of char layer, pyrolysis layer, and virgin layer over the heat shield. This result is used for the correlation between thermal response analysis as presented in the following sections. The right hand side of the Fig. 7 shows an example of raw X ray image of the fore-body heat shield.

On the surface of the rear side heat shield, there remained the thermal control film adhered to the surface of the heat shield for the in-orbit thermal-control purposes. It may mean that the rear-surface heating was smaller than expected. Many of studies and discussions were made in the design phase on these phenomena in rear-side. Considerably large heat flux (10% of that at stagnation point) was assumed as previously described. The recovered rear-side heat shield shows us that the maximum temperature will be about 400 °C from the decomposition of the polyimide film. As a result, the design heat flux has much margin and that is the case. As the flow phenomenology in the wake region is so much complicated, we have to be more careful about the next estimation and design on this context.

In addition to these inspections, the surface radiation measurement during reentry was carried out. In order to study the radiation and resulted heating environment and in order to know the surface temperature of the capsule, the radiation observation was made both from the ground and the airborne measurement system [7][8]. As a result, the radiation temperature is fixed
by taking account of optical conversion efficiencies. The temperature profile based on the blackbody radiation from the capsule surface has been estimated based on this measurement and the results will be presented in the following sections.

POST FLIGHT ANALYSIS OF THE THERMAL RESPONSES OF THE HEATSHIELD

In order to make better understanding of the flight results, the thermal response of ablative TPS of the capsule is calculated along the most probable reentry trajectory by using the integrated analysis method [9]. In the present study, several physical models hitherto proposed to predict the ablation phenomena are tested for the purpose of comparison. The calculated results are compared with the flight data obtained at the present time.

In the present study, the thermal response of ablative TPS of the capsule is calculated by using the several physical models related to the ablation phenomena. Calculation conditions used in this study are summarized in Table 3. Four cases are considered for the purpose of comparison: In case 1, we consider the conventional surface reaction model that was used to calculate the heating environments over the Stardust entry capsule. The effect of nitridation reaction is considered in case 2. In case 3, the effect of the enhanced probability value due to surface roughness[13] is considered both for atomic oxygen and atomic nitrogen. The effect of turbulence due to the pyrolysis gas[14] is included in case 4.

**Table 3. Calculation Conditions**

| Case | Oxidation | Nitridation | Sublimation | Boundary layer | Notes |
|------|-----------|-------------|-------------|----------------|-------|
| 1    | A         | N/A         | E           | Laminar        | Conventional surface reaction set |
| 2    | A         | C           | E           | Laminar        | Case 1 + nitridation |
| 3    | B         | D           | E           | Laminar        | Fully rough surface for O & N |
| 4    | A         | N/A         | E           | Turbulent      | Case 1 + injection-induced turbulence |

Figure 11 shows the temporal variations of surface temperature at the stagnation point. As shown in this figure, the temperature begins to increase at 40s after the passage of altitude of 200 km. A maximum temperature value of about 3,200 K is then obtained at 70 s of flight time for the cases 1, 2 and 4. After that time, the surface temperature decreases due to the radiative cooling effect. As shown in this figure, there are no significant differences in surface temperature between the cases 1 and 2. The effect of nitridation reaction on surface temperature is believed to be small because the rate of nitridation given by Symbol C is smaller than the rate of oxidation given by Symbol A by a factor of 100.
Figure 11. Comparison of surface temperature variations at the stagnation point between the calculation and the measurements

Figure 11 also shows the surface temperature data estimated from the black body spectrum obtained by both the ground observation[7] and the airborne observation presented in the previous section[8]. As shown in this figure, the temperature value estimated from the airborne observation data is about 2,500K at 60s of flight time, and the maximum value of 3,300K is obtained at 70s. After that, the temperature decreases down to about 2,700K at 85s, although the temperature values are characterized by very strong scattering after the peak heating point. On the other hand, the surface temperature is estimated to be about 2,700K at 80s from the ground observation result. By comparing these estimated surface temperatures with the present calculated results, it is found that the calculation for the cases 1, 2 and 4 duplicates well the temperature data obtained by the airborne observation, although the calculated peak temperatures slightly underestimate the measurement at 70s of flight time.

Based on the X-ray image of the capsule as presented in the previous sections, the char depth and the thickness of remained virgin layer of the ablative TPS are measured, and the results are also shown in Figs. 12(a) and 12(b). By comparing the flight results and the calculated results, it is found that the density distributions calculated for the cases 1 and 2 reproduce the flight data moderately both at the stagnation point and the downstream region. Especially in the downstream region, the calculated thickness of char layer overestimates the flight data when we consider the effect of turbulence due to the pyrolysis gas, while it underestimates the flight data when the effect of surface roughness of ablative TPS is taken into account.
(a) Stagnation point

(b) Downstream region (s=0.2m)

**Figure 12.** Comparison of char depth and thickness of remained virgin layer between the calculations and the flight data

**CONCLUDING REMARKS**

A flight opportunity of an asteroid sample return mission offered us many new study topics in high speed aero- and aero thermodynamics, thermal protection systems, descent subsystems and in the design of the whole capsule system. For these technical issues, an approach to being ready for the flight and the flight results are summarized in the present paper. One of the major achievements is that the capsule performed the reentry flight from the asteroid, and recovered totally as planned. As a result, it would be understood that the design and verification processes were satisfactorily made in terms of the high enthalpy flow characteristics around the capsule with emphasis on the radiation heating, interaction between outer-flow and ablation-product, and so on. A characterization of the ablative heat shield durable to the high heating condition was also one of the major and new design issues, and it is also satisfactorily performed. The post flight analysis is still going on in many aspects, however the present paper highlighted the relation between the design and flight results. On this context, issues such as how much design margin we should have for the heat shield, was one of the key design issues. Also observed were the conservative design for the rear side heat shield. These topics will need further studies for more accuracy and a lighter vehicle construction. The flight result of landing point dispersion was very small, which means that the aerodynamic characteristics, entry initial conditions, atmosphere modeling and so on were sufficiently accurate and appropriate. From aerodynamic and flight mechanical point of view, however, the flight results tells less, because only few onboard measurements for the motion analysis were done because of the limited resources due to its small capsule size. No serious discrepancy is foreseen between the prediction and the results on this flight mechanics such as attitude motion of the capsule, but we have to know that the design credibility has not yet been perfectly proved. These issues will be passed to the next ventures. Based on the success of the Hayabusa mission’s final reentry and recovery, many follow-on missions toward other asteroids and bodies in the planetary space. The exercises and lessons learned in this Hayabusa capsule studies and flight demonstration contributed greatly toward these next ventures.
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