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Experimental estimation of the amount of residual slag remaining inside orbital insertion stage solid rocket motor

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Abstract
Several technical reports have raised concerns about the ejection of a significant amount of residual slag from a solid rocket motor (SRM) at the end of combustion, which contributes to the growing space debris problem. The E-31 static firing test have demonstrated a remarkable reduction in residual slag by using advanced propellant with improved aluminum combustion efficiency. E-31 will be adopted for orbital insertion stage for Japan's upcoming flagship solid propellant launcher known as Epsilon S. Experimental findings have validated that in SRMs that selects a propellant that can achieve such high aluminum combustion efficiency, the acceleration sensitivity to aluminum/alumina particles flying inside the combustion chamber drops to a level that cannot be distinguished from the range of variations. Consequently, contrary to the past technical reports, the estimated quantity of residual slag inside the SRM during flight is considered to have a minimal adverse impact on the orbital environment.

1. Introduction

The traditional objective in solid rocket motor (SRM) design has been performance enhancement. Aluminum, with its high reaction energy, is a suitable choice as a metallic fuel, and current composite propellants used in SRMs contain approximately 20% aluminum powder by mass. This aluminum powder undergoes a chemical reaction inside the combustion chamber, converting it into alumina (AL_2O_3). Within the combustion chamber, alumina primarily exists as liquid particles. While most of the high-energy liquid-phase alumina is expelled within the combustion gas flow from the propellant surface to the nozzle outlet, a certain portion becomes trapped in the stagnant flow field surrounding the submerged nozzle and aft-dome regions. This trapped residue is commonly referred to as the "slag pool" in conventional solid rocket boosters employing a submerged nozzle design [1]. The concern arises owing to the expulsion of a fraction of the alumina comprising the slag pool through the nozzle at the end of SRM combustion, potentially leading to the generation of a significant amount of debris [2]. It has been observed by X-ray photography that the trigger for slag expulsion at the end of combustion is the rapid expansion of the gas contained in the slag pool due to the sudden pressure reduction inside the combustion chamber at the end of combustion [6].
From the perspective of sustainable space development and conservation of the space environment, the most effective approach is to minimize debris generation resulting from SRMs. Over several decades, efforts have been devoted to developing solid propellants with high aluminum combustion efficiency to enhance the propulsion performance of solid rockets. Consequently, a reduction in the residual slag within the aft-dome of the SRM has been observed. For instance, a static firing test for M-35 SRM with 15 tons of solid propellant achieved a remarkably low residual slag weight of 31 g [6]. During flight, such residual slag accumulates in the aft-dome owing to the rearward acceleration of the launcher, so the submerged nozzle is positioned between the accumulation site and the exit nozzle throat. As the submerged nozzle presents a relatively substantial barrier to the size of the residual slag, it is speculated that the probability of slag passing through the throat and being discharged into space is minimal with such a small amount of accumulation.
On the other hand, it has been confirmed that the flight direction of the aluminum particles that spring out from the surface of the solid propellant changes depending on the acceleration [4]. Figure 1 illustrates the findings from visualization observations conducted in an experiment where the centrifugal acceleration of 5 G was applied using a spin stand. With a combustion pressure of 5 MPa, the combustion gas was observed to be vertically ejected from the

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combustion surface and directed towards the exhaust orifice. Meanwhile, aluminum particles ejected from the propellant surface were observed to travel in the direction of acceleration. During the flight of the rocket, the thrust generated by the rocket induces high acceleration in the opposite direction to that of the launcher. This acceleration affects the aluminum/alumina particles inside the combustion chamber of SRM, it is highly possible that the amount of residual slag confirmed in the 1G gravity acceleration environment on the ground may differ from the amount of slag accumulated during an actual flight. For instance, Reference [5] reported that firing tests conducted with the SRM positioned vertically and horizontally in a 1G environment on the ground showed an approximately 2.5-fold difference in residual slag quantity.
This study aims to investigate the correlation between slag accumulation and acceleration to predict the amount of slag accumulated during actual flight. Additionally, the amount of slag accumulation during the actual flight of the third stage ‘E-31’ for the next-generation Japanese solid rocket ‘Epsilon S’ was estimated based on the result of E-31 static firing tests.

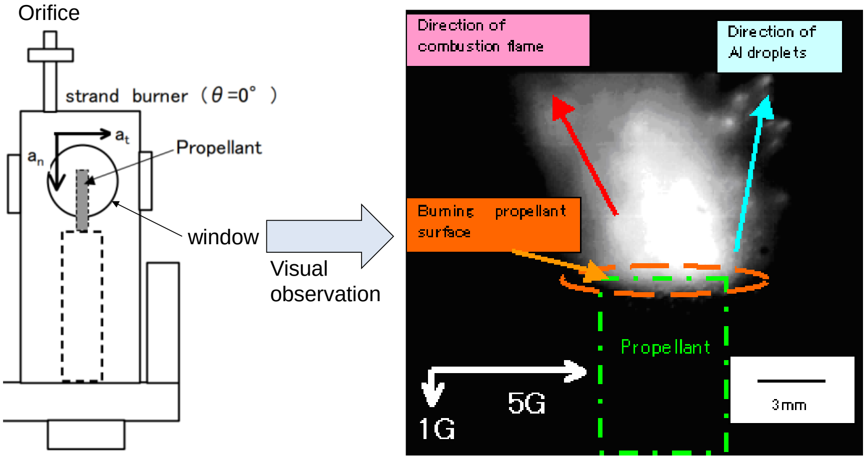

Figure 1: A photograph of flight of aluminum particles in centrifugal acceleration field [4]

2. Investigation of the sensitivity of the SRM installation direction to the amount of accumulated slag

In static firing tests, SRMs are typically placed horizontally on the ground for ease of test preparation. However, in some cases, vertical installation is chosen to emulate flight conditions as possible. As mentioned earlier, gravitational acceleration acts as an external force on the aluminum/alumina particles flying inside the combustion chamber, influencing the process of slag accumulation. In practical SRMs, the propellant shape consists of a cylindrical space extending along the entire axial direction to ensure a wide combustion area. Consequently, the combustion gas is always expelled in the direction of the SRM's central axis. When the SRM is horizontally positioned, the particle velocities possess a component in the direction of gravity due to the effect of gravitational acceleration. Nevertheless, as the combustion gas experiences a load primarily along the central axis, the gravity-induced velocity component is not dominant. Conversely, vertical SRM installation leads to the particles experiencing an external force directed towards the rear of the SRM. In order to confirm the difference caused by the SRM installation orientation, firing tests were conducted with the same SRM design, consisting of three vertical installations and seven horizontal installations, and the quantities of accumulated slag within the combustion chamber were compared. In this test champaign, approximately 200 kg of propellant with relatively high aluminum combustion efficiency was installed and a submerged nozzle was selected. The average amount of residual slag collected was 34.3 g for the vertical installation case and 15.9 g for the horizontal installation case. Thus, the vertically mounted SRM exhibited higher slag accumulation (approximately 2.2 times) compared to the horizontally mounted SRM. This outcome aligns closely with the findings of a similar study presented in Ref. [5], which reported a difference of approximately 2.5 times.
When aluminum particles are ejected from the propellant's burning surface, they undergo oxidation and transform into extremely fine alumina particles while traversing the combustion chamber. The majority of these particles pass through the throat with the main combustion gas stream and are subsequently discharged. However, it is believed that a portion of these particles collides with the submerged nozzle and aft-dome due to their inertial forces. Those colliding with the aft-dome adhere to the roughened surface of the insulation rubber applied to the inner surface of combustion chamber for heat insulation. While most of the particles colliding with the hard carbon-composite part that forms the submerged

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nozzle are expelled through the throat by the influence of the main combustion gas flow, some may jump into the flow stagnation region on the aft-dome side. If a sufficient quantity of particles adheres to the aft-dome insulation rubber, they form agglomerates. The size of the flying particles plays a critical role in this phenomenon. In vertical firing tests, gravitational acceleration amplifies the inertial force of aluminum oxide particles. As the gravity-induced load is sensitive to particle weight, it also depends on particle size. However, the velocity difference between the particles and the flow field generates a viscous force that propels the particles in the throat direction. This viscous force, which acts on the particle surface, is sensitive to the size of the surface area. Assuming the particle to be a sphere with a radius of R, the inertial force is sensitive to R^3, while the viscous force is sensitive to R^2. Consequently, smaller particles experience a relatively greater influence from the viscous force than inertial force. Reducing the size of particles flying inside the combustion chamber becomes an effective method for increasing the relative impact of the viscous force and consequently reducing slag accumulation in the aft-dome. As shown in Figure 2, static firing tests conducted with the SRM positioned horizontally demonstrate a strong correlation between the propellant type and the accumulated slag amount [3]. By analogy, it can be presumed that the "propellant with improved aluminum combustion efficiency," which aids in reducing residual slag, results in significantly smaller flying particle sizes. Consequently, the influence of acceleration is expected to be relatively minor when employing the latest propellant for the orbital insertion stage. In addition, it is presumed that the improvement in combustion efficiency has the effect of suppressing variations in the residual slag weight. In the seven horizontal firing tests presented in this section, the ratio of the maximum weight to the minimum weight of the residual slag was 2.3 times. This figure is an improvement from the three times weight ratio obtained in M-14 family firing tests with old-designed propellant (BP-204J). For the evaluation of the latest SRM E-31, early implementation of the gravitational sensitivity test using the latest propellant is planned. Until the data are updated, the larger value of the variability is applied in the prediction of the residual slag weight in this study.

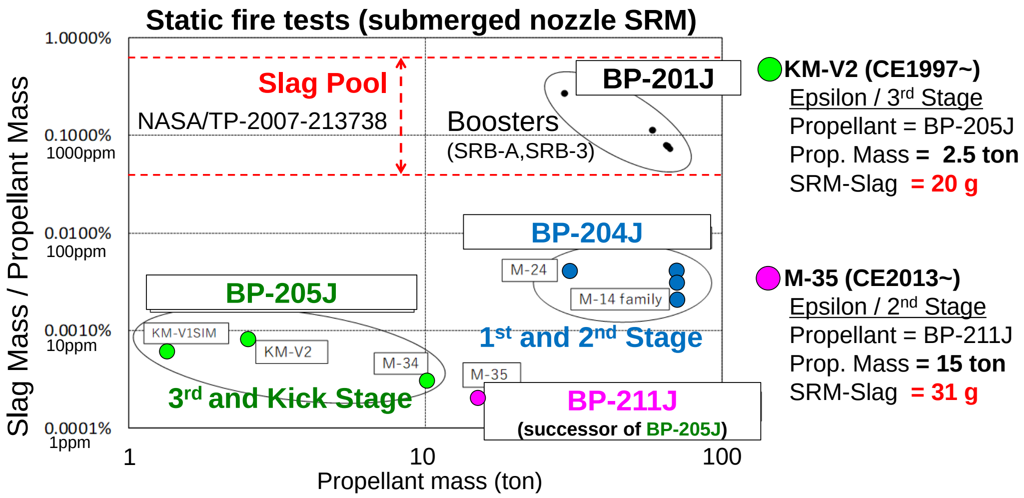

Figure 2: Mass ratio of alumina slag to propellant in major Japanese solid rocket motors [3]

3. Investigation of sensitivity of acceleration to amount of accumulated slag

A test campaign was conducted using the centrifugal force generated by rotating the test stand to evaluate the effect of axial acceleration on the particles flying inside the combustion chamber.

3.1 Small spin stand test

To assess the impact of axial acceleration on particles flying inside the combustion chamber, a test campaign was conducted using centrifugal force generated by rotating a small SRM on a spin stand.

For comparative evaluation of the combustibility of aluminum near the combustion surface under accelerated conditions, combustion tests were performed on a small SRM installed on a spin stand with centrifugal acceleration. The distance from the combustion surface to the nozzle was deliberately kept short to specifically evaluate the effect of acceleration on aluminum particles in proximity to the combustion surface. The test motors were positioned at each end of the spin stand, applying horizontal and vertical centrifugal acceleration to the propellant's combustion surface.

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Acceleration perpendicular to the propellant burning surface pushes aluminum particles against the propellant surface. This setup allowed for a relative assessment of the influence of gas viscous forces on particle flight under different acceleration conditions for the tested propellants. In this test, the propellant for the booster and the propellant for the orbital insertion stage were used for comparative evaluation.

In the test, a small SRM containing 65 g of propellant (Figures 3 and 4) was used. By adjusting the setting angle of the small SRM, acceleration distribution in perpendicular and tangential directions to the combustion surface could be controlled. The throat diameter was 3mm, and the combustion pressure was 6.5 MPa. Accelerations in the perpendicular direction were set at 10G and 20G, while the tangential acceleration was fixed at 12G. After the firing test, the remaining slag in the receiver portion was collected and weighed. Figure 5 presents the results of comparing propellants for booster (BP-201J) and for orbital insertion stage (BP-205J, BP-211J) under the several acceleration conditions. The slag rate presented in Figure 5 represents the ratio of collected slag to the initially charged 65 g of propellant. It was observed that the booster propellant, which exhibited a significant amount of residual slag in the static firing test (as shown in Figure 2), also displayed a high residual slag rate in the small-scale spin stand test, indicating high sensitivity to acceleration magnitude. Conversely, the propellant “BP-211J” for the orbital insertion stage exhibited minimal residual slag and low sensitivity to acceleration magnitude.

In order to improve the aluminum combustion efficiency, maximizing the aluminum evaporation efficiency for each particle is desirable. A high surface-area-to-volume ratio is desirable and a smaller particle size may be advantageous. As previously mentioned, smaller particles are less sensitive to acceleration but more influenced by viscous forces, resulting in reduced residual slag. This correlation between aluminum combustion efficiency and residual slag quantity is supported by the obtained results.

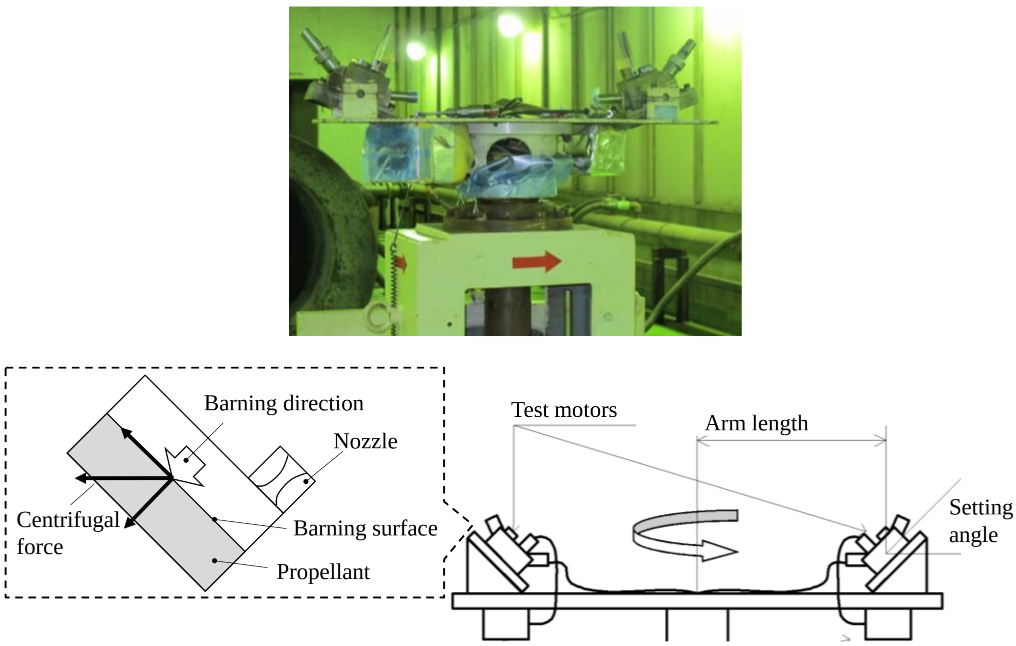

Figure 3: Schematic diagram of a small spin test stand

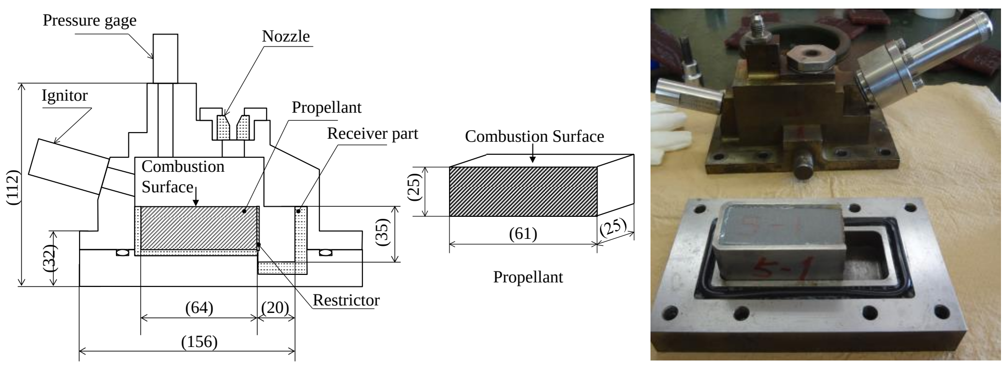

Figure 4: Small size test motor

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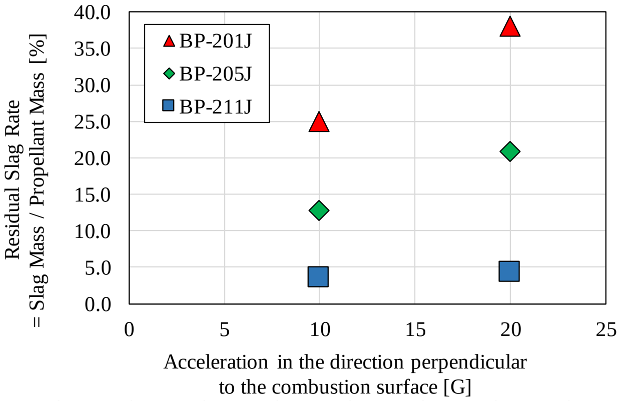

Figure 5: Acceleration sensitivity test results for residual slag rate and residual slag example

3.2 Large spin stand test

In order to conduct a more practical evaluation, firing tests were conducted using a slightly larger SRM (Figure 6). This small SRM has a propellant capacity of approximately 4.6 kg. This SRM adopted a grain shape with a central axis hole, resembling a practical SRM. Moreover, the combustion pressure was designed to set at 4 MPa, which aligned with the average combustion pressure of the third-stage SRM for the Epsilon S rocket. To assess the sensitivity of residual slag quantity to acceleration, a submerged nozzle that extended deep into the combustion chamber and a dedicated component for capturing residual slag were incorporated. The residual slag-capturing part was equipped with insulation rubber, replicating the practical configuration. Additionally, a carbon/carbon composite material was used for the SRM throat. Axial acceleration induced by centrifugal force was set at 4G, representing the average acceleration during the actual flight, and 6G, representing the assumed maximum acceleration, in addition to the standard 1G condition. Figure 7 illustrates the installation of small SRMs at both ends of the spin table, with a 1m arm length. Table 1 provides the corresponding number of rotations required to achieve each axial acceleration.

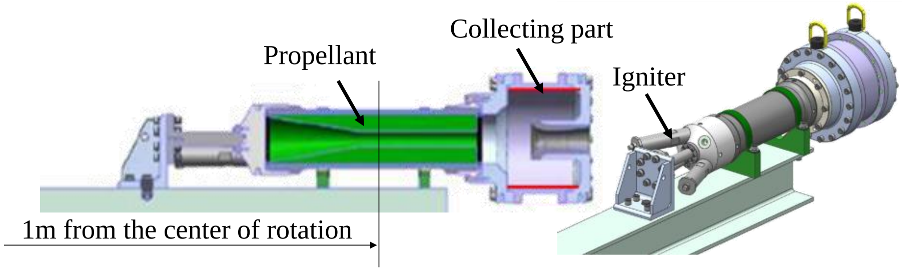

Figure 6: Test equipment

Figure 7: Large spin test stand

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Table 1: Number of rotations for each axial acceleration

Arm (m)	rpm	ω (rad/s)	$r\omega^2$ (G)
1 m	30	3.142	1.0
1 m	60	6.283	4.0
1 m	73	7.645	6.0

Figure 8 shows the progress of the firing test. Initially, the spin table's rotation count gradually increased until reaching the desired value, which was then maintained by fixing the applied current. The firing test sequence commenced at -10s, and at 0s, the ignition signal was sent to both SRMs. Combustion of the SRMs persisted for approximately 4 seconds, followed by rotation for approximately 1 minute after burnout. Subsequently, the rotation count gradually decreased until coming to a complete stop. A total of six small SRMs were fired during the test campaign. Four of them utilized the latest propellant for the orbital insertion stage, known as "BP-402H," while the remaining two employed ISP-DT-24, a propellant currently under development that further enhances aluminum combustion efficiency. Figure 9 presents the combustion pressure results for each SRM.

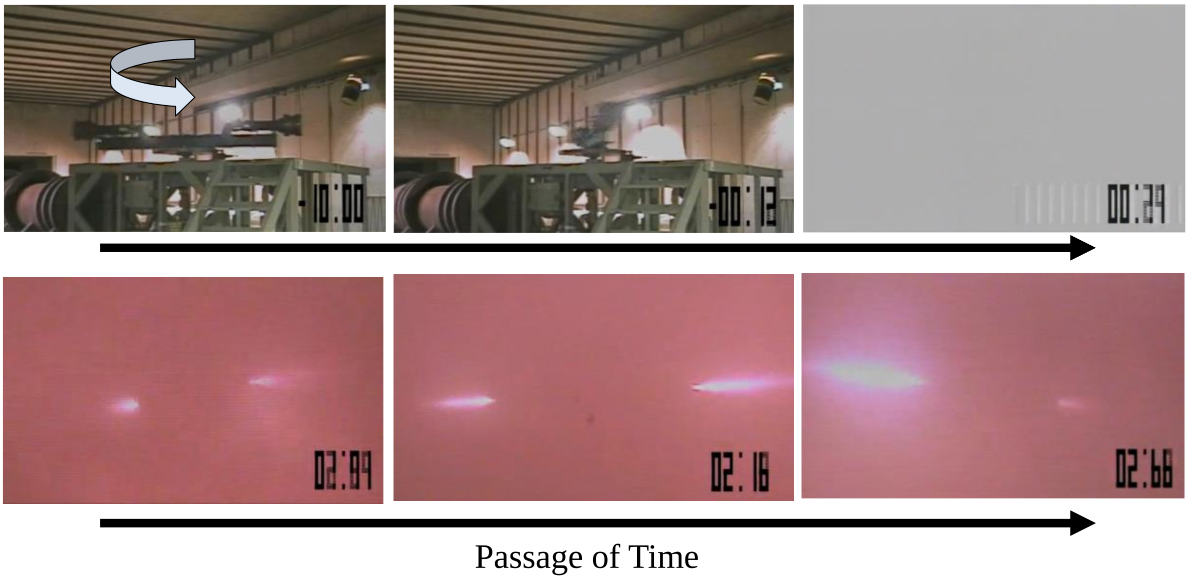

Figure 8: Firing test under spin condition

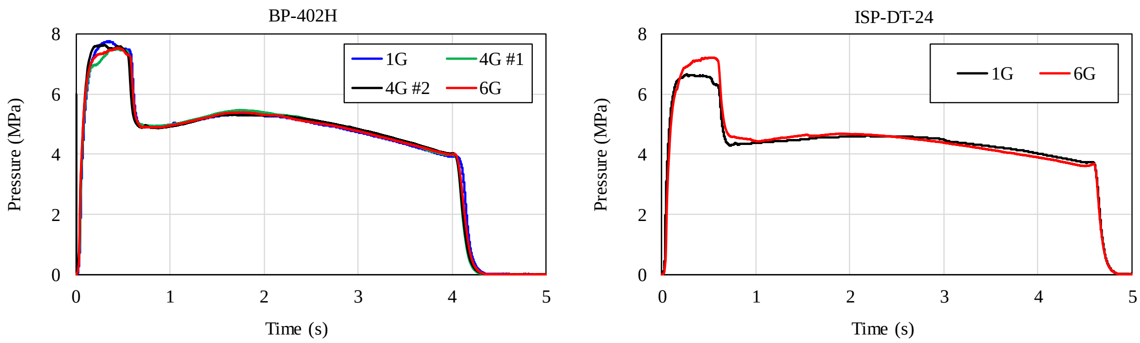

Figure 9: Combustion pressure results (left: BP-204H, right: ISP-DT-24)

The accumulation of residual slag is depicted in Figure 10, and the corresponding collected weight results are listed in Table 2. For BP-402H, the test results exhibited no significant sensitivity to acceleration, as they all fell within the range observed under the 4G conditions. Conversely, in the case of ISP-DT-24, a reduction in residue amount compared to BP-402H was observed. This indicates that ISP-DT-24, which enhances aluminum combustion efficiency, is less sensitive to acceleration than BP-402H.

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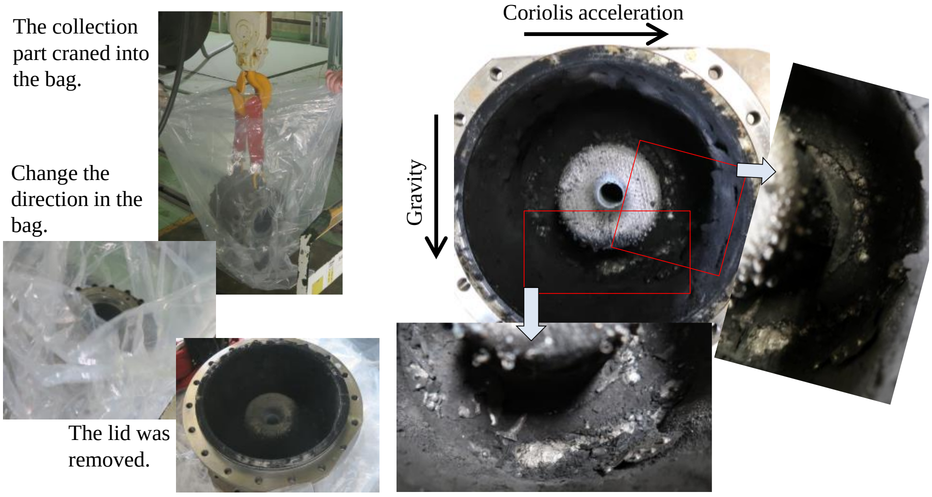

Figure 10: The accumulation of residual slag (1G, BP-204H)

Table 2: Weight of residual slag collected under acceleration condition

Case	Acceleration			BP-402H		ISP-DT-24
	Axis	Coriolis (Max.)	Overall			
1	1.0 G	11.3G	11.3 G	39.4 g	-	34.6 g
2	4.0 G	22.5 G	22.9 G	42.1 g	38.8 g	-
3	6.0 G	27.4 G	28.1 G	40.2 g	-	32.6 g

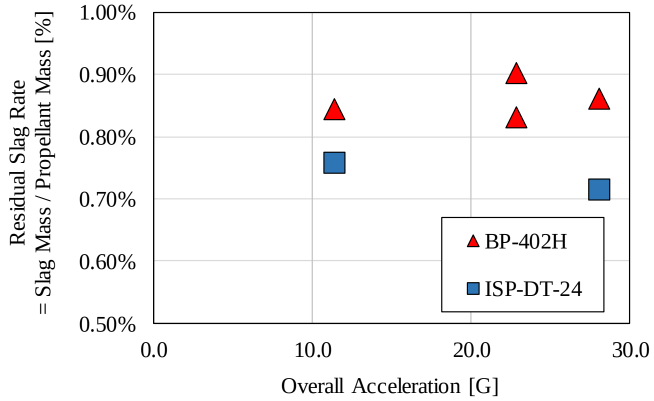

Figure 11: Overall acceleration sensitivity test results for residual slag rate

Table 2 presents the estimated maximum Coriolis accelerations. The particle velocities used for calculations assumed that the microparticles reached the same velocity as the gas flow. In this test, the rotation generated both centrifugal and Coriolis forces in the flying particles. As the resulting slag amount is influenced by both forces, the evaluation focuses on the overall sensitivity to acceleration rather than pure centrifugal acceleration. Considering the overall acceleration, Case 3 exhibited approximately 2.4 times the acceleration of Case 1. However, as presented in Figure 11, no significant increase in accumulated residual slag rate for BP-402H was observed. This suggests that the sensitivity to acceleration is sufficiently low and falls within the expected range of variability.

4. E-31firering test results and flight prediction

In June 2023, JAXA conducted a firing test on the third-stage SRM of Japan's next-generation solid rocket, Epsilon S. The propellant used for this SRM 'E-31' was the latest version for the orbital insertion stage, called BP-402H, with a quantity of 5.1 tons. In the shortest possible time after the end of combustion, the interior of the motor was examined, as shown in Figure 13. From this figure, it can be confirmed that there is no accumulation of large slag inside the SRM.

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The collection process is depicted in Figure 14, while Figure 15 displays all the collected slags. The amount of slag obtained from inside the E-31 SRM was 5 g, accounting for a weight fraction of 0.0001% relative to the initial propellant quantity. Figure 14 presents the updated database that incorporates this result.
Based on the firing test results, the residual slag weight during flight was predicted as follows:

1) Considering the variation observed in the M-14 result shown in Figure 16, the E-31 firing test results were considered three times. Using the formula, the estimated weight is 5 g × 3.
2) Additionally, a factor of 2.2 was introduced to account for the sensitivity caused by the SRM installation direction in firing tests with Japanese propellant. That figure is wrapped up in the 2.5 times reported from another research institute. Until the sensitivity data is updated with BP-402H, it is estimated with stricter factor. Thus, the estimated weight becomes 5 g × 3 × 2.5.
3) As BP-402H does not exhibit a clear sensitivity to acceleration, no further adjustment was made to prediction of in-flight result. Hence, the estimated weight is 5 g × 3 × 2.5 × 1.

Consequently, the estimated residual slag weight during flight amounts to 37.5 g.

Length	2.8 m
Outer diameter	1.8 m
Propellant weight	5.1 ton

Figure 12: Image of the E-31 firing test situation.

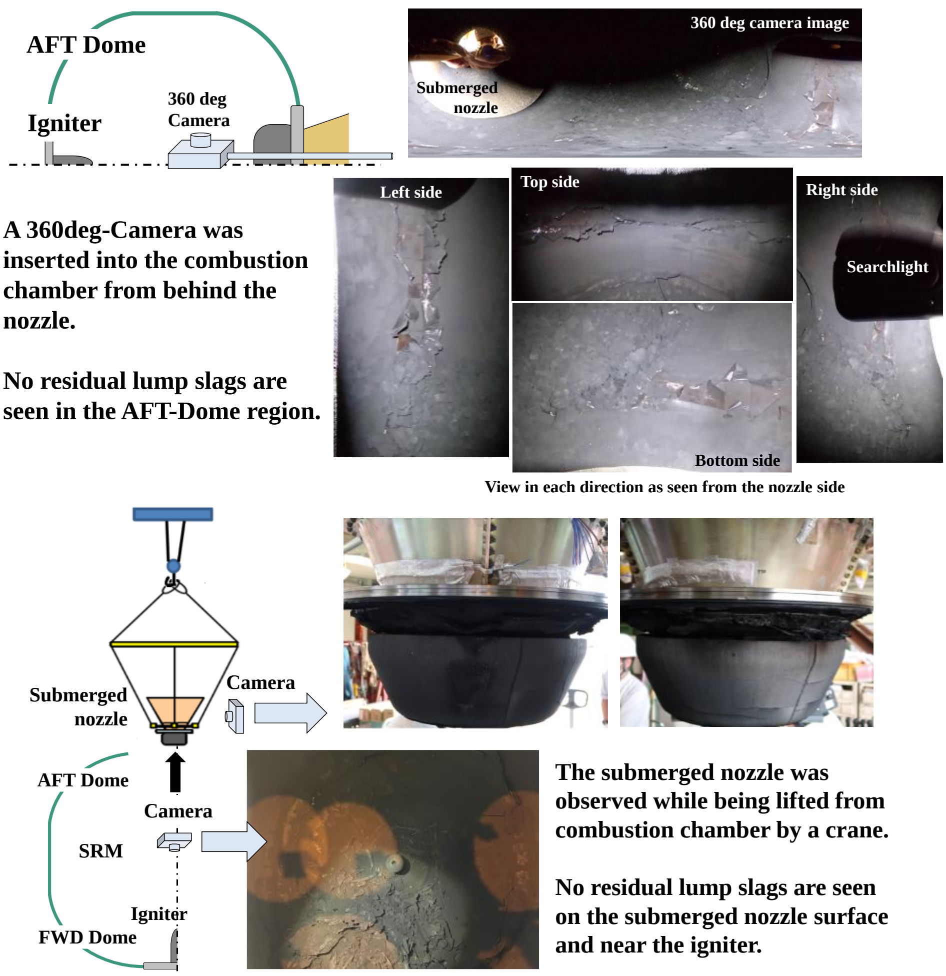

Figure 13: Image of the inside of E-31 after the firing test.

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Figure 14: Collecting work of residual slag inside E-31 motor case.

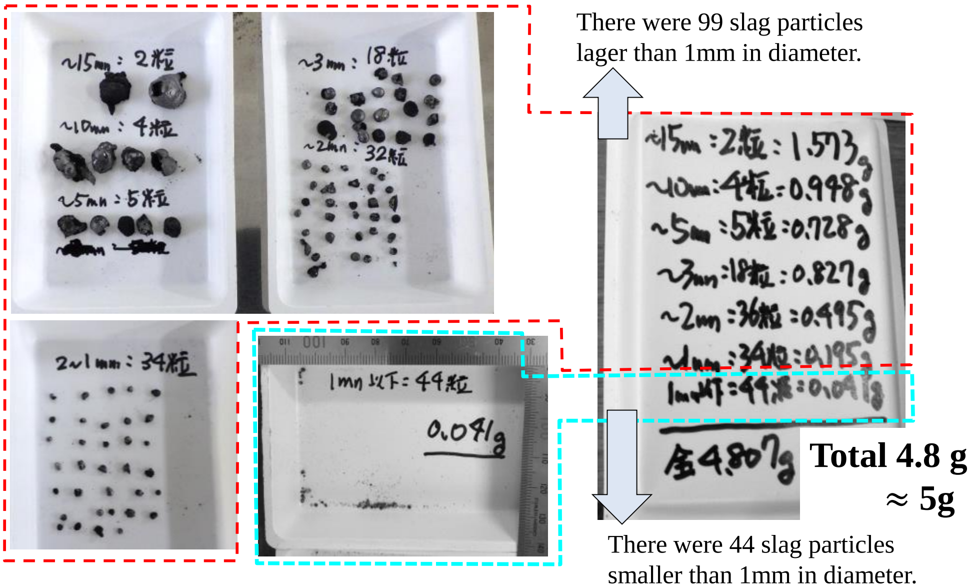

Figure 15: All of the collected slags

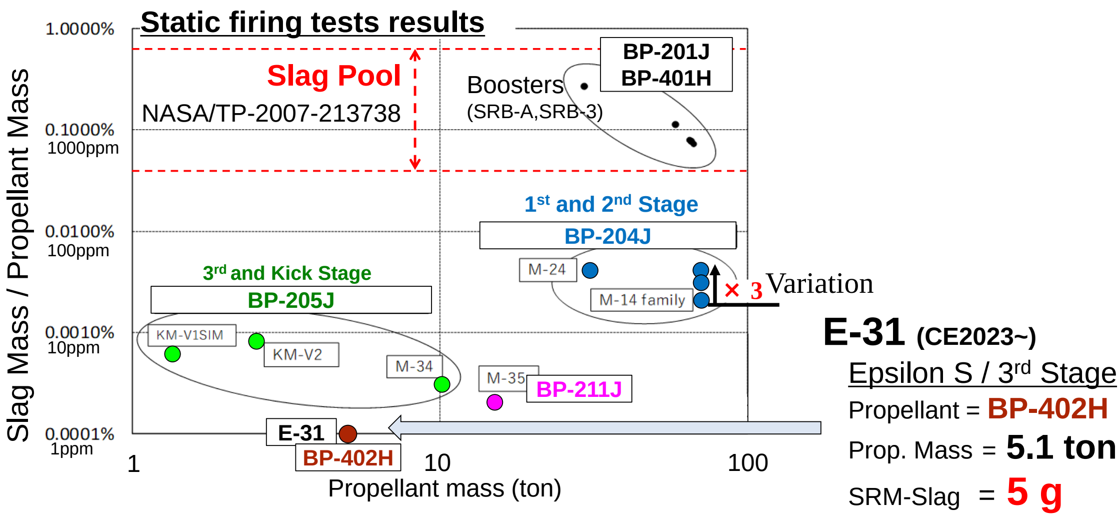

Figure 16: Updated mass ratio of alumina slag to propellant in major Japanese solid rocket motors.

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5. Conclusion

The expected residual slag weight for the E-31 flight was remarkably low, totaling 37.5 g. These residual slags are likely to accumulate in the stagnant gas flow region of the aft-dome, persisting during the powered flight due to acceleration. Positioned between the slag and throat, the submerged nozzle acts as a substantial barrier against the slag. Consequently, the likelihood of slag passing through the throat and being discharged after combustion is considered to be minimal (Figure 17). This represents a significant improvement over the historical issue of SRMs dispersing substantial amounts of slag into orbit, as highlighted in some literatures. Thus, Japan's efforts to enhance propellant performance have effectively minimized residual slag while advancing the prospects of sustainable space development. Gravitational effects and residual slag weight variation in the static firing tests applied in this study were obtained with former-designed propellant. Therefore, the estimated residual slag weight during E-31 flight may be updated to a smaller value with updating these data. Achieving more accurate predictions is important for correctly estimating the impact on orbit, and continuing further research is extremely significant.

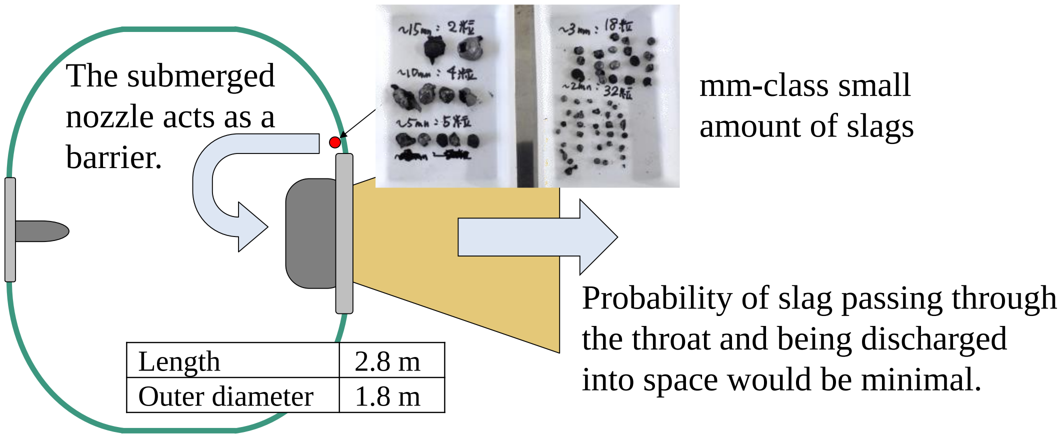

Figure 17: Positional relationship between slag accumulation region and submerged nozzle

6. Note

Ongoing research in Japan focuses on understanding the nature of SRM slag, which has been recognized as a potential source of space debris. An illustrative study involved analyzing the properties of slag collected from the combustion chamber. Consistent with previous findings [3][6], X-ray examinations revealed the existence of numerous voids within these particles. Some slag particles were exceptionally delicate, collapsing effortlessly during the investigation. The findings of this study will be elaborated upon in the near future.

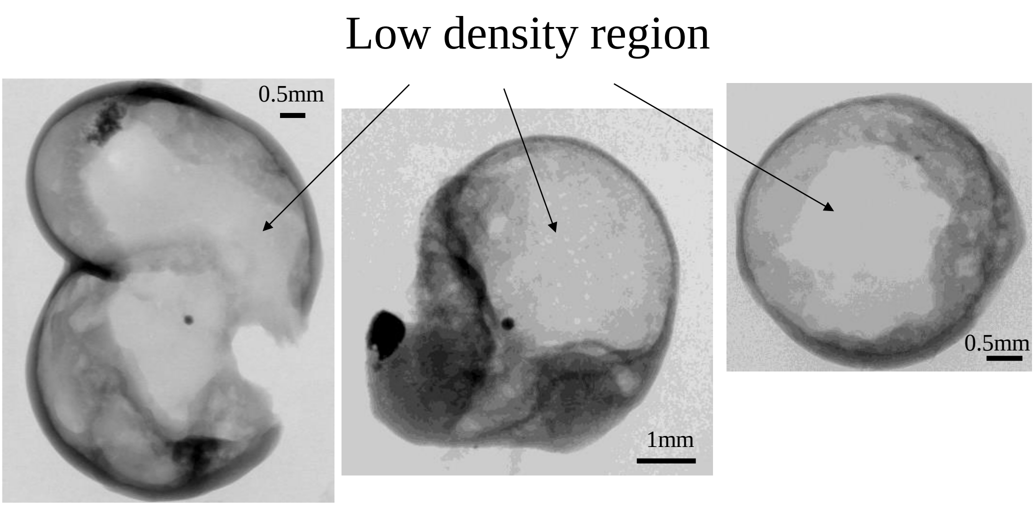

Figure 18: Results of X-ray computed tomography observations of slag particles

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