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Statistical Validation of Burn Rate Consistency in Sym-Sorted Solid Rocket Motor Boosters for the Gaganyaan Mission

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Abstract*— This paper presents a comprehensive statistical validation of burn rate consistency in sym-sorted SOLID ROCKET MOTOR boosters for the Gaganyaan mission. The study focuses on the critical requirement of thrust balance in paired booster segments, where consistent burn rates are essential for mission success. For this study, segments SYM-SORTED SEGMENT-1 and SYM-SORTED SEGMENT-2 were selected, identified for the Gaganyaan mission, in which critical raw materials such as ammonium perchlorate (AP coarse and fine) and activated copper chromite (ACR) that influence the Agni Grain Burn Rate (AGBR) were sym-sorted to minimize inter-segment variability. The AGBR data were subjected to detailed statistical validation. Descriptive statistics confirmed low variability with %CV < 1%, while skewness and kurtosis values were close to zero, indicating near-normal distribution. Histograms and boxplots showed uniform distribution without extreme outliers. Normality tests further confirmed data normality, validating the use of parametric methods. Variance comparison using the F-test (p = 0.438) showed no significant difference between segments. The two-sample t-test (p = 0.117) revealed no significant difference in mean burn rates, and effect size analysis indicated the difference was practically negligible (Cohen's d = –0.34). Equivalence testing (TOST) confirmed that the mean difference was within the engineering tolerance margin (±0.0125 mm/s). Bland–Altman analysis demonstrated strong agreement, though limits of agreement (–0.0251 to +0.0196) were slightly wider than tolerance, highlighting the effect of raw material dispersion. Control charts showed all data points within 3σ limits, with no trends or special-cause variation, confirming process stability. Overall, the results validate that sym-sorting of critical raw materials effectively minimizes inter-segment burn rate differences and enhances the reliability of SOLID ROCKET MOTOR booster processing for the Gaganyaan mission.

***Index Terms*— AGBR, Burn Rate Consistency, Statistical Validation, Solid Rocket Motor Boosters**

I. INTRODUCTION

The Gaganyaan programme requires extremely reliable propulsion systems, with the SOLID ROCKET MOTOR boosters playing a critical role in mission success. Burn rate is a fundamental ballistic property that governs thrust output in large solid rocket boosters. For dual-segment boosters such as the SOLID ROCKET MOTOR class, thrust balance depends on two segment data processed with similar type of raw materials exhibiting uniform burn rates. Even small deviations in burn rate between segments can lead to thrust mismatch, adversely affecting vehicle performance.

Past experiences have shown that raw material heterogeneity, particularly in ammonium perchlorate (AP) particle size distribution and Activated Copper Chromite (ACR) characteristics, can contribute to variations in mechanical and ballistic properties. To address this, a practice of sym-sorting critical raw materials across two segment data processed with similar type of raw materials was adopted. This study was therefore undertaken to statistically validate whether paired SOLID ROCKET MOTOR segments processed with sym-sorted critical materials demonstrated consistent burn rate performance. The Agni Grain Burn Rate (AGBR) data from sym-sorted segment-1 and sym-sorted segment-2 were analyzed to assess inter-segment consistency.

The equivalence tolerance of ±0.0125 mm/s adopted in this study is based on established internal engineering judgment derived from historical processing experience and thrust balance sensitivity considerations for paired large solid rocket segments. This tolerance represents a practically acceptable variation in burn rate that does not result in adverse thrust mismatch at the mission level. While the detailed derivation of this limit is program-specific, its use here is consistent with prior qualification and acceptance practices employed for large segmented solid motors.

Objectives:

- To assess the uniformity, stability, and equivalence of AGBR between sym-sorted segment-1 and sym-sorted segment-2 using advanced statistical tools.
- To evaluate whether sym-sorting of critical raw materials effectively contributes towards achieving the required level of inter-segment burn rate consistency for the Gaganyaan mission.
- To identify areas where further refinements in raw material characterization could enhance future reliability [5].

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II. METHODOLOGY

A multi-faceted statistical approach was employed to evaluate the inter-segment consistency of AGBR [1]. The analysis utilized 43 paired AGBR measurements from the sym-sorted segment-1 and sym-sorted segment-2 solid rocket motor booster segments. Normalized AGBR values were obtained by dividing each individual measurement by the combined mean of all samples from both sym-sorted segments. This approach preserves relative variability and inter-segment differences while preventing disclosure of absolute burn rate magnitudes. Methods included:

- Descriptive statistics (mean, standard deviation, coefficient of variation, skewness, kurtosis).
- Graphical methods (histograms, box plots).
- Normality testing using the Anderson–Darling test.
- A two-sample t-test to compare mean burn rates.
- Effect size quantification using Cohen's d [4].
- Equivalence testing with the Two One-Sided Tests (TOST) procedure (±0.0125 mm/s equivalence margin).
- Homogeneity of variance assessed using the F-test.
- Process stability checked using an X-bar control chart.
- Agreement assessment performed through Bland–Altman analysis [3].

III. RESULTS AND DISCUSSION

3.1 Descriptive Statistics

The foundational step of the statistical analysis involved a detailed examination of the descriptive statistics for the Agni Grain Burn Rate (AGBR) data obtained from the sym-sorted segment-1 and sym-sorted segment-2. This initial characterization is critical for understanding the central tendency, dispersion, and underlying distribution shape of the data, which informs the selection and validity of all subsequent inferential statistical tests.

The results, summarized comprehensively in Table 1, reveal a high degree of similarity between the two segments. The mean burn rate for the sym-sorted segment-1 was calculated to be **0.999 mm/s**, while the sym-sorted segment-2 exhibited a mean of **1.001 mm/s**. The observed difference of merely **-0.0028 mm/s** is numerically minimal, providing the first strong indication of successful process control and effective sym-sorting.

Beyond the means, the analysis of dispersion metrics is equally crucial for thrust balance, as it reflects the consistency of the burn rate throughout the combustion duration. The standard deviations were found to be **0.008 mm/s** for sym-sorted segment-1 and **0.009 mm/s** for sym-sorted segment-2. A more insightful metric for comparing variability across datasets with different means is the Coefficient of Variation (%CV), which is the ratio of the standard deviation to the mean, expressed as a percentage. Both segments demonstrated exceptionally low %CV values of **0.77%** and **0.86%** respectively. In high-precision propulsion system manufacturing, a %CV of less than 1% is widely considered an indicator of an exceptionally stable and well-controlled process. This low variability is a direct testament to the effectiveness of the enhanced Quality Assurance Plan (QAP) and the raw material sym-sorting protocol.

Further analysis of the distribution shape was conducted using skewness and kurtosis. Skewness measures the asymmetry of the data distribution. The values of **0.10** for sym-sorted segment-1 and **-0.15** for sym-sorted segment-2 are very close to zero, indicating that both distributions are highly symmetrical and not skewed to the left or right. Kurtosis measures the "tailedness" of the distribution compared to a normal distribution. The values of **-0.28** (platykurtic) for sym-sorted segment-1 and **0.42** (leptokurtic) for sym-sorted segment-2 are both within the range typically considered to represent a mesokurtic distribution (kurtosis ≈ 0). These near-zero values for both skewness and kurtosis provide strong preliminary evidence that the AGBR data for both segments follow an approximately normal distribution.

Overall, the AGBR values for sym-sorted segment-1 and sym-sorted segment-2 exhibited closely aligned means, with low dispersion. Coefficients of variation were <1%, indicating stable process performance. Skewness and kurtosis were near zero, consistent with approximate normality. This sets a strong precedent for the more advanced inferential statistical tests that follow.

Table 1. Comprehensive Descriptive statistics for AGBR data

Variable	Mean	SD	Min	Median
Segment-1	0.999	0.008	0.983	0.998
Segment-2	1.001	0.009	0.977	1.002

Max	Range	IQR	Skewness	Kurtosis
1.015	0.032	0.010	0.1	-0.28
1.018	0.042	0.012	-0.15	0.42

3.2 Graphical analysis

Visual representation of the data provided critical insights into distribution characteristics and inter-segment comparability. Histograms for both sym-sorted segment-1 and sym-sorted segment-2 revealed approximately bell-shaped distributions, providing initial visual confirmation of normality. The box plot analysis demonstrated remarkable alignment between the two segments, with nearly identical medians and interquartile ranges. A single outlier was identified in the sym-sorted segment-2 dataset but was retained for analysis after verification confirmed it as a genuine process measurement whose exclusion would not alter the statistical conclusions [2].

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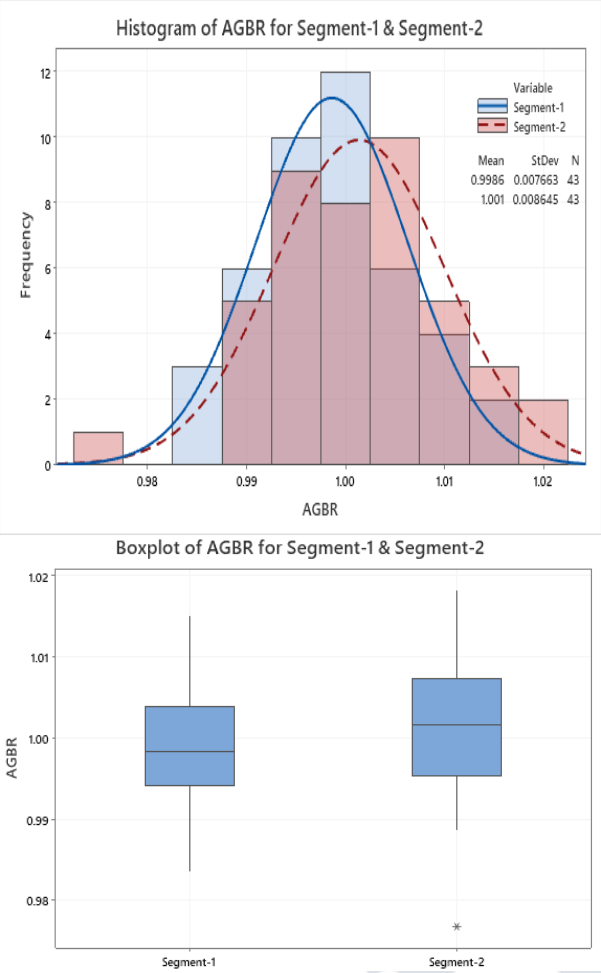


Figure 1. Histogram and Boxplot of SYM-SORTED SEGMENT-1 and SYM-SORTED SEGMENT-2 AGBR values

3.3 Normality Test

Formal normality testing was conducted using Anderson-Darling test. The Anderson–Darling test assesses whether sample data follow a normal distribution by comparing the cumulative distribution of data to that of a theoretical normal model. This method yielded p-value significantly above the 0.05 threshold ($p > 0.05$), providing statistical evidence that the AGBR data for both segments follow a normal distribution [1]. This validation of the normality assumption is crucial as it justifies the application of parametric statistical methods—including t-tests, F-tests, and equivalence testing—in subsequent analysis phases. The combination of graphical evidence and formal statistical tests confirms that the data meets the fundamental assumptions required for robust inferential analysis. Parametric tests were therefore valid.

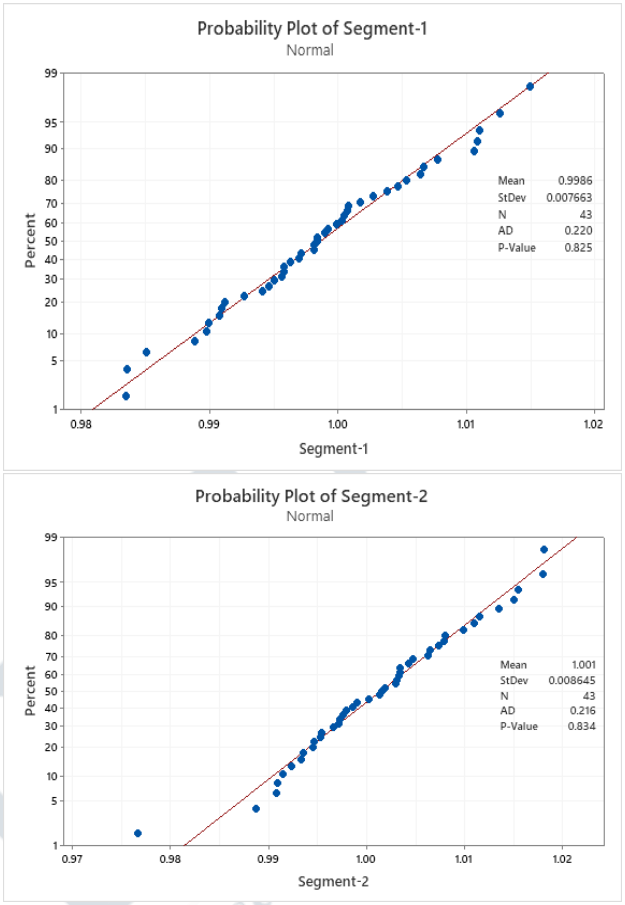


Figure 2. Probability plot of sym-sorted segment-1 and sym-sorted segment-2 AGBR values by A-D test

3.4 Two-Sample t-Test

A two-sample t-test was conducted to determine if there was a statistically significant difference between the mean burn rates of sym-sorted segment-1 and sym-sorted segment-2. The test was performed under the following hypotheses:

Null Hypothesis (H_0): $\mu_1 = \mu_2$ (No difference in mean burn rates)

Alternative Hypothesis (H_1): $\mu_1 \neq \mu_2$ (Significant difference in mean burn rates)

The analysis revealed a mean difference of **-0.00279 mm/s** with a 95% confidence interval ranging from **-0.00630 to +0.00071 mm/s**. The resulting p-value of **0.117** substantially exceeds the common significance level of 0.05.

Since the p-value > 0.05, we fail to reject the null hypothesis. This indicates that there is **no statistically significant difference** in the mean burn rates between the sym-sorted segment-1 and sym-sorted segment-2. The confidence interval, which contains zero, further supports this conclusion by showing that the observed difference is consistent with random variation rather than a systematic bias between segments.

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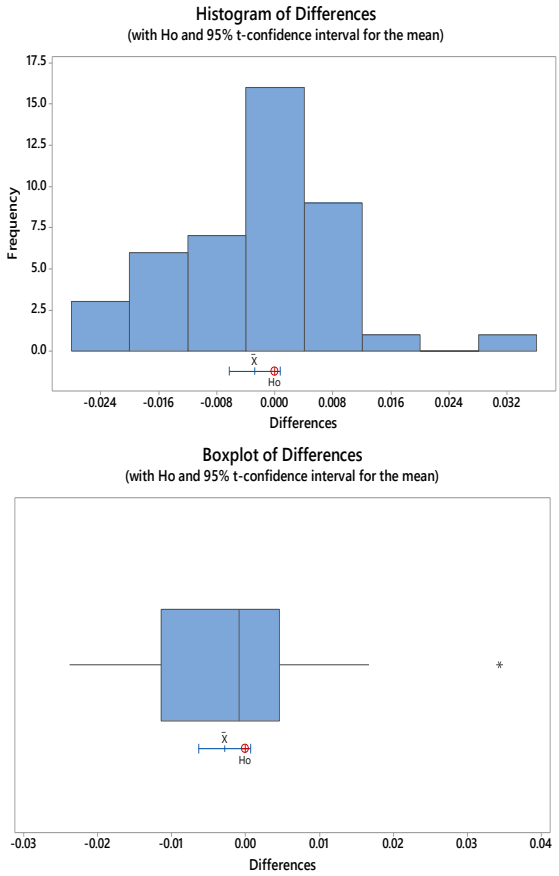


Figure 3. Graphical summary for the two-sample t-test comparing sym-sorted segment-1 and sym-sorted segment-2 AGBR values

3.5 Assessment of Variance Homogeneity

The consistency of thrust profiles throughout the burn duration requires not only similar mean burn rates but also comparable variability between segments. An F-test for equality of variances was conducted to verify this critical aspect.

The sample variances were calculated as **0.000064 (mm/s)² for sym-sorted segment-1** and **0.000081 (mm/s)² for sym-sorted segment-2**. The F-test yielded an F-statistic of **0.790** with a p-value of **0.438**.

The p-value > 0.05 indicates no statistically significant difference in variances between the two segments. This confirms that the **variability in burn rates is statistically indistinguishable** between sym-sorted segment-1 and sym-sorted segment-2. For thrust balance assurance, this finding is equally important as the mean comparison, as it ensures consistent performance throughout the entire burn duration, not just on average.

3.6 Effect Size

While the t-test assessed statistical significance, Cohen's d was calculated to determine the practical significance of the observed mean difference. Cohen's d is a standardized method of effect size. Unlike *p-values*, which only say if a difference is "statistically significant," Cohen's d tells us if the difference is **small, medium, or large in practical terms**. To assess the practical significance of the observed difference—beyond statistical significance indicated by the p-value—Cohen's d was calculated. This metric standardizes the mean difference between the groups using the pooled standard deviation S_p providing a scale-independent measure of effect magnitude:

$$d = \frac{Mean_1 - Mean_2}{S_p}$$

The calculation resulted in Cohen's d = -0.34 [4]. According to conventional interpretation guidelines (where |d| < 0.2 represents a negligible effect, 0.2-0.5 small, 0.5-0.8 medium, and >0.8 large), this value falls within the **small effect size** range. This confirms that the mean difference of -0.0028 mm/s is practically negligible in an engineering context.

The small effect size confirms that the observed mean difference of -0.0028 mm/s is not statistically significant and, more importantly, is **practically negligible in engineering terms**. This reinforces that the minor numerical difference between segments lacks operational significance for thrust balance performance.

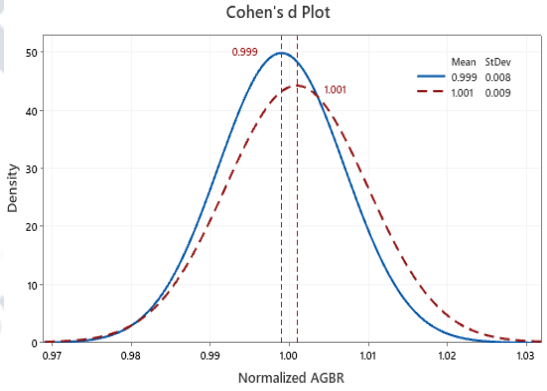


Figure 4. Effect size plot using cohen's d

3.7 3.7 Equivalence Testing (TOST)

While traditional hypothesis testing can only indicate whether a difference exists, equivalence testing actively demonstrates practical equivalence. The Two One-Sided Tests (TOST) procedure was employed with an equivalence margin of **±0.0125 mm/s**, derived from engineering tolerance requirements.

TOST (Two One-Sided Tests) is the standard method to test **statistical equivalence**. To evaluate whether the burn rates of sym-sorted segment-1 and sym-sorted segment-2 can be considered practically identical, the Two One-Sided Tests (TOST) procedure was employed. Unlike conventional t-tests, the two-sample t-test can only reject or fail to reject the hypothesis of a difference, but it cannot confirm sameness. TOST directly tests equivalence within a predefined equivalence margin (±0.1 mm/s, based on engineering tolerance).

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The analysis revealed that the 95% confidence interval for the mean difference of **-0.00279** mm/s (**-0.00572 to +0.00014 mm/s**) fell entirely within the pre-defined equivalence bounds (±0.0125 mm/s). Both one-sided tests yielded p-values < **0.001**. sym-sorted segment-1 and sym-sorted segment-2 are statistically equivalent.

This statistically confirms that the mean burn rates of sym-sorted segment-1 and sym-sorted segment-2 are **practically equivalent** within the engineering tolerance limits [6]. Unlike the t-test which failed to find a difference, TOST positively establishes that any difference is too small to be of practical concern for mission performance.

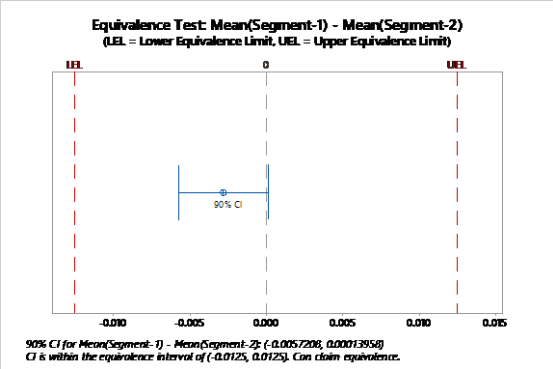


Figure 5. TOST equivalence testing results showing mean difference within ±0.0125 mm/s tolerance

3.8 Process Stability Analysis using Control Charts

Process stability was evaluated using an Individuals (I) control chart. Since the subgroup size is one for AGBR measurements, the X-bar chart is equivalent to an I-chart, where individual observations are plotted against control limits calculated from the moving range.

The control limits were established at ±3σ using the average moving range method. All 43 individual data points from both sym-sorted segment-1 and sym-sorted segment-2 fell within the control limits. The chart exhibited random patterns with no discernible trends, cycles, or shifts in the process mean.

The absence of out-of-control signals indicates that the propellant processing operation was in a **state of statistical control**. This demonstrates that the manufacturing process was stable, predictable, and free from special-cause variations during the production of both segments. Process stability is a fundamental prerequisite for meaningful capability analysis and ensures that the statistical comparisons between segments are valid.

Overall, the data points fell within ±3σ limits. No trends, cycles or special-cause variations were observed. The process was stable and under control.

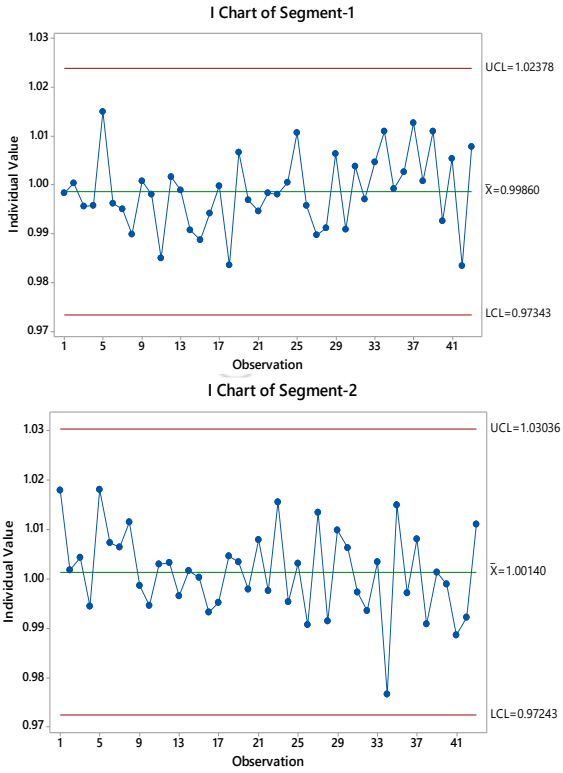


Figure 6. Individuals (I) chart with subgroup size = 1 for sym-sorted segment-1 and sym-sorted segment-2 data

3.9 Agreement Analysis using Bland–Altman plot

The Bland-Altman analysis was employed to assess the agreement between paired AGBR measurements from sym-sorted segment-1 and sym-sorted segment-2. This method plots the difference between paired measurements against their mean, providing a visual assessment of measurement agreement. It helps check whether

i) there is a **systematic bias** (average difference),

ii) differences are within **acceptable limits of agreement (LOA)**.

Bland–Altman analysis performed on normalized AGBR data yielded a mean bias of −0.0028, indicating that Sym-Sort Segment-1 burns marginally slower than Sym-Sort Segment-2 by approximately 0.27%. The 95% limits of agreement (LoA) were (−0.0251, +0.0196), reflecting the combined effect of systematic offset and random batch-to-batch variability. Although the lower limit slightly exceeds the predefined equivalence band, the narrow bias and absence of proportional error confirm strong agreement between the paired segments.

The near-zero mean bias confirms the absence of significant systematic error between segments [3]. Although the LOA range is slightly wider than the engineering tolerance band (±0.0125 mm/s), the random scatter of points across the measurement range indicates no proportional bias. The observed spread primarily reflects residual intra-batch raw material dispersion rather than consistent inter-segment differences, reinforcing that the sym-sorting methodology

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effectively minimizes systematic variation between two segment data processed with similar type of raw materials.

The Bland–Altman analysis indicates a small negative mean bias, suggesting that Sym-Sorted Segment-1 exhibits marginally lower burn rate compared to Sym-Sorted Segment-2. This bias is consistent and limited in magnitude, reflecting a systematic but practically insignificant shift. The limits of agreement are wider than the equivalence tolerance, particularly on the negative side, which is attributable to inherent batch-to-batch dispersion rather than systematic process drift. It is important to note that limits of agreement represent statistical variability and are not acceptance criteria. Engineering acceptance is governed by predefined equivalence bounds, within which the observed mean difference comfortably resides.

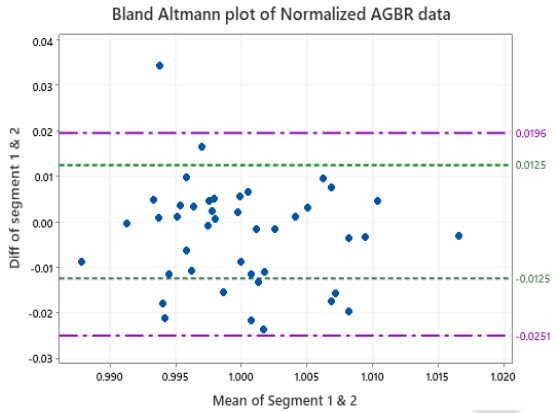


Figure 7. Bland–Altman plot comparing sym-sorted segment-1 and sym-sorted segment-2 paired AGBR data

IV. CONCLUSIONS

This study presents a comprehensive statistical validation of burn rate consistency achieved through the sym-sorting of critical raw materials in SOLID ROCKET MOTOR booster segments for the Gaganyaan mission. The multi-faceted analysis of AGBR data from the sym-sorted segment-1 and sym-sorted segment-2 leads to the following definitive conclusions:

A) Process Characterization: The initial data assessment via **descriptive statistics** confirmed exceptionally low variability, with %**CV values below 1%**, indicating a highly stable and precise manufacturing process. The near-zero values for **skewness and kurtosis** suggested normally distributed data, a critical assumption for subsequent parametric tests. This was visually supported by **Normality test**, **histograms** and **box plots**, which showed significant distributional overlap and no significant outliers affecting the analysis.

B) Statistical Equivalence: The core inferential analysis robustly confirmed the absence of meaningful differences between the segments. The **two-sample t-test** found no statistically significant difference in mean burn rates ($p = 0.117$). This was reinforced by the **F-test**, which confirmed homogeneity of variances ($p = 0.438$), meaning the segments exhibit statistically indistinguishable variability—a crucial factor for consistent thrust profiles over time. The **effect size** (Cohen's $d = -0.34$) quantified the mean difference as "small" and practically negligible. Most importantly, the **Equivalence Testing (TOST)** proactively demonstrated that the mean difference lies entirely within the strict engineering tolerance margin of ±0.0125 mm/s, affirming the segments are practically equivalent for mission purposes.

C) Process Stability and Agreement: The **Individuals control chart (I-chart)** verified that the manufacturing process was in a state of statistical control, with all data points within limits and no special-cause variation [1]. The **Bland-Altman analysis** provided a final layer of validation, showing a near-zero mean bias and a random scatter of differences, confirming strong agreement between the segments without any proportional bias [3]. In summary, the consolidated evidence from descriptive, inferential, and equivalence statistics unequivocally validates that the sym-sorting protocol has successfully minimized inter-segment burn rate differences. This provides high confidence in the thrust balance of the SOLID ROCKET MOTOR boosters for the Gaganyaan mission. The primary opportunity for future improvement lies in addressing the residual intra-batch dispersion of raw materials, as indicated by the process spread. While occasional variability extended beyond strict tolerance limits, this highlights the importance of further refining raw material characterization (particle morphology, friability, surface area, catalyst site density, and thermal stability) to minimize dispersion effects [5]. Future work will focus on refining raw material characterization to further narrow intra-batch dispersion and sustain reliability in human-rated missions.

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