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# Thrust Imbalance of the Space Shuttle Solid Rocket Motors

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**In earlier papers, the authors presented a theoretical Monte Carlo analysis of thrust imbalance for the pair of large solid rocket motors (SRM's) firing in parallel during the launch of the Space Shuttle. The present paper gives further evidence of the validity of the analysis. Test results from the Space Shuttle program and comparisons of these with the Monte Carlo analysis are presented. The test results are examined in three phases: 1) pairs of SRM's selected from static tests of the four developmental motors, 2) pairs of SRM's selected from static tests of the three quality assurance motors, and 3) the first flight-test results. Possible inaccuracies in evaluation of thrust imbalance due to flight-test instrumentation are discussed. General agreement of theory and test results is shown which supports the present Monte Carlo prediction of thrust imbalance for future Space Shuttle SRM pairs.**

## Introduction

THE ability to predict thrust imbalance between pairs of solid rocket motors (SRM's) firing in parallel, as on the Titan IIIC and Space Shuttle launch vehicles, is essential for successful propulsion system and vehicle integration. The knowledge of the thrust imbalance vs time is of particular interest for the Space Shuttle because the capability of the vehicle control system to correct for thrust imbalance is time dependent. Hence, not only are the maximum value of thrust imbalance and when it occurs important, but the thrust imbalance vs time must be evaluated during the entire time period the motors are operating. The authors have applied the Monte Carlo method of statistical analysis to both the Titan IIIC and Space Shuttle SRM's.[1] It should be noted that though thrust imbalance during the motor ignition period is important, it is not included in the present analysis. The ignition period thrust imbalance was not included because of the lack of statistical data for required input variables to currently available internal ballistic ignition models which might be used with the Monte Carlo analysis. For the motor operating period after ignition, sets of approximately 40 significant variables are selected using a random sampling technique and the imbalance is calculated for a large number of SRM pairs using a simplified, but comprehensive, model of the internal ballistics. The model's treatment of burning surface geometry allows for variations in ovality and misalignment of the casting mandrels and motor cases as well as for those arising from differences in the basic size dimensions and propellant properties.

The original analysis[1] gave comparisons of resultant thrust imbalance for the Titan IIIC calculated from 1) the theoretical thrust-time traces of 130 randomly selected pairs of SRM's and 2) those obtained from flight-test data for 20 pairs. The comparison shows that the theory underpredicts the standard deviation in maximum thrust imbalance by 20% when the maximum imbalances are determined without regard to the time at which they occur. The range in thrust imbalance of Space-Shuttle-type SRM pairs was then determined using applicable tolerances and variabilities and a correction factor (1.2) based on the Titan IIIC analysis. A subsequent analysis[2] included the effect of asymmetric temperature gradients within the solid propellant grain of the Space Shuttle.

Reference 2 upgraded the Space Shuttle imbalance analysis using approximate final design parameters and gave a complete prediction of the thrust imbalance vs time envelope (range) including the effect of the anticipated range of temperature gradients. The correction factor (1.2) was not used in the latter Space Shuttle prediction because it is strictly applicable only to the maximum thrust imbalance calculated without regard to when it occurs. The thrust imbalance vs time envelopes, e.g., those in Ref. 2, are based on statistical analysis of thrust imbalance at specific times. Reference 2 does not present the comparable theoretical envelope for the Titan IIIC shown now in Fig. 1.

Superimposed on the theoretical plot in Fig. 1 is the comparable result from flight tests of 21 Titan IIIC pairs. Both results in Fig. 1 are based upon assumed normal distributions of thrust imbalance at specific times and on confidence coefficients for two-sided tolerance limits which give 90% probability that at least 99.7% of the total

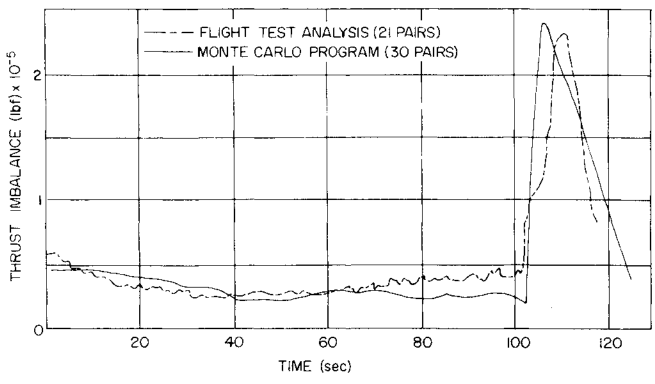


**Fig. 1 Comparison of Monte Carlo tolerance limits for 30 pairs of Titan IIIC SRM's with flight-test analysis for 21 pairs.**

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population will lie within the resultant thrust imbalance vs time envelopes.[3,4] The comparison demonstrates generally excellent agreement between the Monte Carlo method and the flight performance data and lends validity to the statistical approach. The purpose of this article is to further corroborate the Monte Carlo analysis by comparison of results from the Space Shuttle program, which include the four development SRM's (DM-1-DM-4), the three qualification motors (QM-1-QM-3), and finally, the SRM's (STS-1A and STS-1B) on the first flight-test vehicle (STS-1). Verification of the analysis should give credibility to the present prediction of performance for future Space Shuttle SRM pairs.

## Thrust Imbalance from Static Test Data

The primary objective here is to assess the possible thrust imbalance of Space Shuttle SRM pairs from static test data. This analysis is based on data obtained from static firings of the four Space Shuttle DM's and the three QM's. The thrust imbalance is evaluated by pairing motors from the seven individual static test motors.

It should be emphasized at this point that DM-1 and DM-2 were one of a kind motors; that is, there were differences in the two motors due to manufacturing, processing, and minor design modifications. The development motors 3 and 4 and the qualification motors 1 and 2 were constructed as two motor pairs. Qualification motor 3 had by design a nominal 1% increase in burn rate to provide the burn rate required to compensate for generally lower propellant bulk temperatures for Space Shuttle missions launched from the Western Test Range. With the exception of the slight increase in burn rate for QM-3, variations which do exist between the last five motors should be indicative of what is present in final production motors.

In order to increase the statistical sample size, various pair combinations of the seven test motors are evaluated. The thrust imbalance is evaluated for each pair of motors by comparing measured thrust-time characteristics of each motor. The imbalance vs time is computed by taking differences in measured thrust at specific times after initiation of ignition. The thrust-time characteristics for individual motors are modified for differences in test conditions and for any known differences in the as-built characteristics of the motors.

The method used to correct the data is general and summarized below. A detailed description of the method can be found in Ref. 5. Thrust vs time data for the second SRM of a pair is corrected to the conditions of the first SRM by application of correction factors to both the measured thrust and time values of the second SRM. These factors are determined from standard ballistic equations for thrust, burning rate, and quasisteady state equilibrium chamber pressure. The analysis allows for changes in any or all of the following single-valued parameters as required by differences in test conditions and SRM's: burning rate coefficient, propellant density, average propellant characteristic velocity as determined from ballistic test motor firing or thermochemical calculations, average coefficient of thrust, initial throat area, ignition time, and propellant bulk temperature. In addition, changes in the burning surface area as a function of time are permitted to allow for possible design modifications in propellant configuration between SRM's of a pair. It is assumed that the nominal value of the burning rate exponent does not change between pairs. It is unlikely that such a change would be made intentionally and thus the nominal value (as opposed to random value) should be the same between SRM's of a pair.

In the analysis scheme, when a correction is made, all variation in the parameter being corrected is eliminated so that not even random variation is permitted. In practice, in spite of close attention to obtaining matched pairs, random variations in virtually all parameters will occur between SRM's of a pair. Therefore the present treatment of the

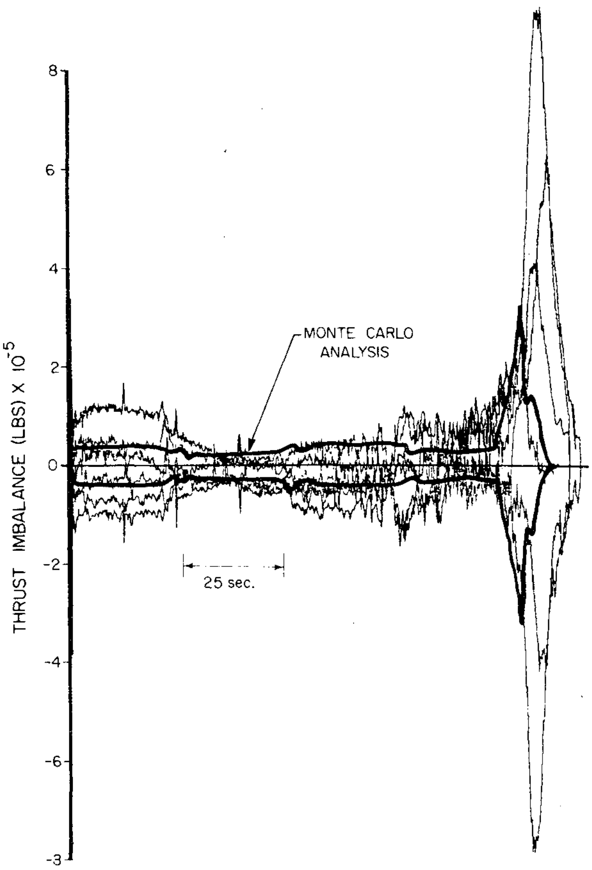


**Fig. 2 Corrected thrust imbalance vs time for six pairs of Space Shuttle SRM's based on static test data for the four development SRM's.**

particular parameters involved is not, in general, conservative with respect to the effect of these parameters on the analysis. Whether or not the overall analysis is conservative with respect to tolerance limits will depend on both the planned and random differences between the SRM's that are not accounted for in the analysis in addition to inaccuracies introduced by the assumptions made. The analysis does provide, however, a practical method for obtaining a first approximation, based on static test results, for the thrust imbalance characteristics to be expected in the flight vehicle.

### Development Motors

This evaluation of thrust imbalance is based only on the six possible combinations formed from the four DM's. In computing the thrust imbalance for the six pairs of Space Shuttle SRM's, corrections are made only in the following variables: burning rate coefficient, initial throat diameter, initial propellant bulk temperature, and ignition interval. Corrections to the other variables, propellant density, characteristic exhaust velocity, and burning surface area, are not included because there is insufficient data to justify within pair differences for these parameters.

The ignition interval correction is, except for one pair, calculated based on the ratio of the times required for each motor in a pair to reach 1.5 million pounds of thrust. In view of the substantial differences in the amount of igniter propellant among the first three DM's, this approach serves to eliminate some of the nonrandom variation in the ignition transient. It is important to realize that this correction accounts for only gross effects of planned igniter modifications. Differences in the shapes of main motor thrust-time traces produced by igniter changes are not corrected for in this analysis. Thus the corrected thrust imbalance during ignition may be higher than it would be if the same igniter were used in

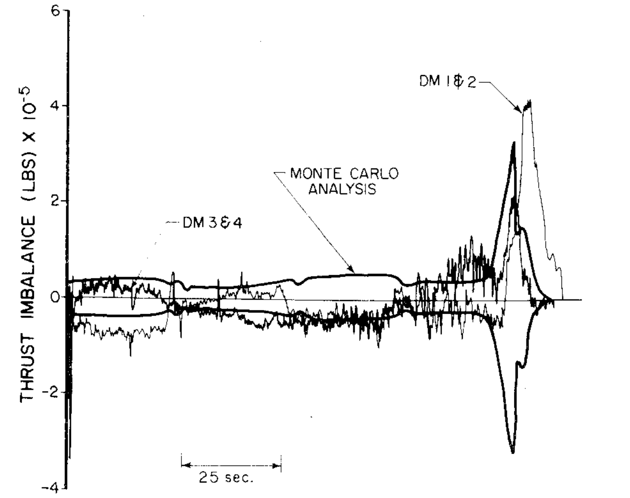


Fig. 3 Corrected thrust imbalance vs time for two pairs of Space Shuttle SRM's selected from the DM's.

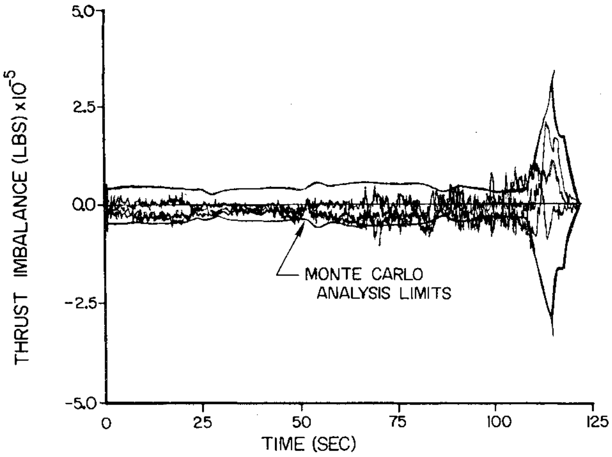


Fig. 4 Corrected thrust imbalance vs time for three pairs of Space Shuttle SRM's (QM-1-QM-3).

both SRM's. In the case of the pair consisting of DM-3 and DM-4, no corrections were made for ignition differences, the assumption being that variations in the ignition transients were random.

As noted above, the correction method removes all random variation between the motors when correcting for design or condition changes. One significant design change was not considered in this analysis: the increase of the insulation thickness in DM-3 and DM-4 over that in DM-1 and DM-2. This correction was not made owing to the impracticality of determining the actual burning area of the SRM's near motor burnout. Because of the insulation difference, the most significant thrust imbalances between motors are DM-1 vs DM-2 and DM-3 vs DM-4.

Figure 2 is a plot of the imbalance of all six pairs with the higher numbered motor corrected to the lower numbered motor in a pair and with the results of the Monte Carlo analysis superimposed. Figure 3 is a plot of the imbalance when DM-2 is corrected to the conditions of DM-1 and when DM-4 is corrected to the conditions of DM-3, again with the Monte Carlo analysis superimposed.

Examination of Fig. 2 shows that even the results of the corrected data are well outside those results predicted by the Monte Carlo analysis of the Space Shuttle SRM's. There are several reasons for these gross discrepancies, the first of which is the previously mentioned insulation changes. This first discrepancy results in a built-in thrust imbalance at tailoff which is much more than when motors having the same insulation design are compared as in Fig. 3.

The second discrepancy is in burn time between the predicted results and the actual firings. A time-wise displacement occurs in the peak imbalance for those pairs which include DM-1 and/or DM-2 because the burn time used in comparing the motors of a pair is that of the longer burning motor. However, DM-3 and DM-4 are built most nearly like the final flight motors and their burnout occurred very near that predicted, as shown in Fig. 3.

A third discrepancy occurs between approximately 80 s and 110 s of burn (Fig. 2), possibly owing to a relatively small burning instability in the SRM's in this region.[6] The only other significant discrepancy in thrust imbalance occurs between the end of the ignition transient and approximately 30 s of burn. There is no ready explanation for this discrepancy; however, it is less pronounced for DM-3 and DM-4.

The maximum thrust imbalance limits excluding the ignition transient, as assessed by a Monte Carlo analysis of the Space Shuttle SRM's, calculated without regard to propellant temperature gradients and without regard for the time at which the maximum imbalance occurs is ±405,500 lbf.[2] The limit as assessed from the worst case for the six pairs studied, DM-1 and corrected DM-3, is 926,000 lbf. However, because of insulation differences, which lead to uncorrected discrepancies in geometry between these two motors, this is not a good assessment of thrust imbalance to be expected in production pairs. The two pairs of motors which are built most nearly alike, DM-1 and DM-2 and the pair DM-3 and DM-4, have maximum thrust imbalances of 419,000 and 246,000 lbf, respectively. The first value is 103% of the limit while the second value is only 61% of the limit. Because DM-3 and DM-4 were built as a matched motor pair, it is reasonable to bias estimates of flight-test imbalance toward the results obtained from this particular pair of motors.

### Qualification Motors

The method for evaluating the thrust imbalance using the qualification static test firings is the same as for the demonstration motors. However, the only corrections needed for the qualification motors are in burning rate and initial propellant bulk temperature.

Figure 4 shows the thrust imbalance vs time results for the three motor pairs formed by grouping the three QM's, two at a time. The theoretical limits obtained from the Monte Carlo analysis[1] are superimposed on the corrected imbalance vs time results in Fig. 4. As seen in Fig. 4, the thrust imbalance calculated using combinations of the three qualification motors is reasonably well contained within the predicted Monte Carlo analysis envelope. In particular, the maximum thrust imbalance and the time at which it occurs shows very good agreement with the Monte Carlo prediction.

There are some discrepancies between the QM test data and the Monte Carlo analysis. The most obvious difference occurs between 90 and 105 s. This discrepancy can again possibly be attributed to the slight burning rate instability described in Ref. 6. It should be noted that the Titan IIIC data presented in Fig. 1 exhibit this same tendency right before motor tailoff. However, this trace characteristic does not provide firm evidence for instability. Another possible explanation for this discrepancy is that there are significant variations which exist but which are not accounted for in the present model immediately before tailoff as the propellant grain burns out. Variations in insulation thickness, for example, would be difficult to model but could cause an increase in thrust imbalance due to either premature or delayed burnout of the propellant grain. Notice that the rather large differences between DM test data and Monte Carlo analysis which occurred in the early, 0-30-s, portion of the thrust imbalance vs time curve is not seen in the QM data. This is most likely a result of the fact that the motors were manufactured in pairs. Hence one would expect lower thrust imbalance since the nonrandom variables are eliminated or at least their variability is reduced owing to consistent processing and manufacturing details. Another, and possibly very significant, factor during the early time period of the thrust imbalance trace is that the igniters used for QM firings were also manufactured as pairs. Therefore the resultant main motor thrust imbalance near the ignition phase should be reduced.

### First Flight Test

In order to assess the actual thrust imbalance of the Space Shuttle during flight, it is necessary to reduce the thrust of each SRM from the head-end pressure data obtained from telemetry or tape records on board each booster. This is accomplished by first establishing the relation between the head-end chamber pressure through the frictionless one-dimensional momentum equation for a constant cross-sectional area port modified empirically for a tapered port as discussed in Ref. 7. Thrust was then calculated as the product of the ideal thrust coefficient, aft-end stagnation pressure, nozzle throat cross-sectional area, and a constant thrust loss coefficient based upon the static test results.

In order to verify the accuracy of the analysis, a comparison was made between the thrust imbalance computed from head-end pressure measurements and that deduced directly from thrust measurements during the DM-1 and DM-2 static tests, considering these development SRM's to be a pair. The results are shown in Fig. 5, which is a plot of the thrust imbalance vs time obtained by the two methods. The general agreement of the two traces is judged sufficient to provide confidence in this procedure for deducing thrust and thrust imbalance between pairs of SRM flight motors.

Several features of the instrumentation system design and certain aspects of its operation during the first flight test raised questions about the accuracy with which a thrust imbalance analysis could be made. Recording of flight instrumentation began 30 s before liftoff. The prefiring data revealed that all SRM pressure measurements contained a significant amount of noise. The noise amplitude was between 8 and 12 psi, peak to peak.

During the static test program chamber pressure was measured within an overall instrumentation system accuracy of ±0.5% of full scale or ±5 psi out of 1000 psi. The comparable flight accuracy was ±2.0% or ±20 psi out of 1000 psi. The same type of transducer was used in both the static and flight tests. Another significant factor is that an eight-bit word was used to digitize the full-scale range of the chamber pressure flight measurement which resulted in a "minimum bit size" of approximately 4 psi. The minimum bit size in the static test program was 0.25 psi.

The reduced accuracy of the flight-test data can produce errors in the analysis of individual SRM's. At this time there is no evidence of biases existing which would make one motor more susceptible to instrumentation error and therefore introduce an additional erroneous imbalance between motors. Still, the determination of thrust and hence thrust imbalance is subject to an additional random instrumentation system error which has not been accounted for.

Each SRM has three parallel pressure channels. Each measurement is multiplexed at one sample per second (sps) and at 320 sps. The flight thrust imbalance reported here is based on the earliest available data which were telemetered at 1 sps. An apparent time shift of approximately 1 s between motors was evident on the one sps data. The time shift is attributed to instrumentation inaccuracy combined with low data sampling rates. Thrust imbalance during ignition is not evaluated in this analysis since the one sps rate is much too low to define the ignition pressure transient. This omission does not restrict the treatment presented here since, for

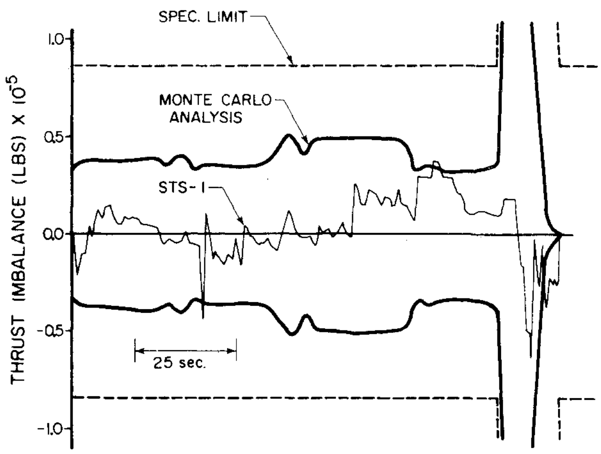


**Fig. 6 Comparison of thrust imbalance for STS-1 with the Monte Carlo and design specification envelopes assuming a 1-s time shift in telemetered data.**

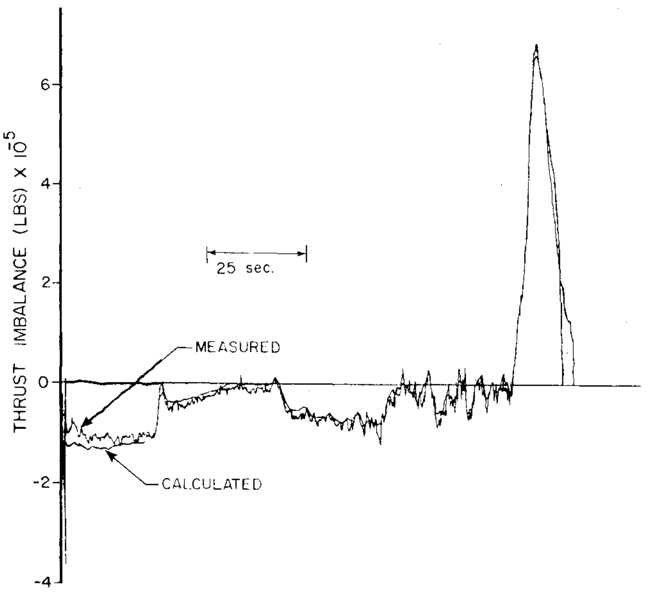


**Fig. 5 Uncorrected thrust imbalance vs time for DM-1 and DM-2 obtained directly from thrust measurements and calculated from head-end pressure measurements.**

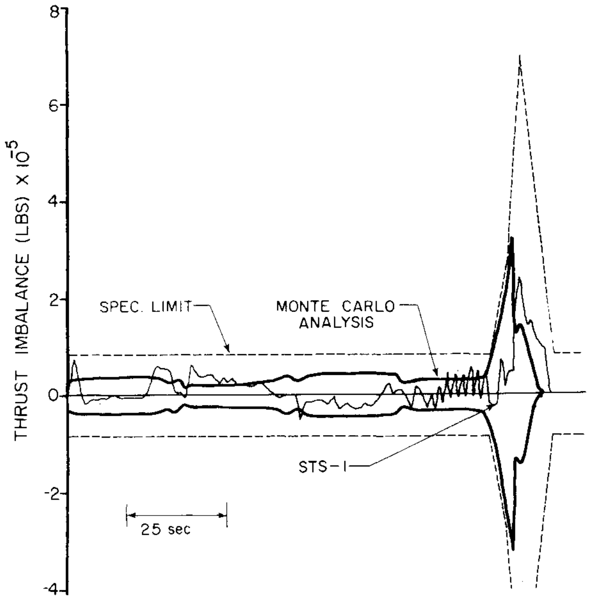


**Fig. 7 Comparison of thrust imbalance for STS-1 with the Monte Carlo and design specification envelopes without a time shift in telemetered data.**

reasons previously discussed, the Monte Carlo method was used only for steady-state and tailoff thrust imbalance. Subsequent analysis using the higher sampling rate data provide additional accuracy but it is not likely that the thrust imbalance during steady-state and tailoff will show any major changes.

The telemetered measurements reflected interruptions of data to various degrees on all chamber pressure channels. This is evident since the instrumentation system is designed to output the last value of pressure sampled until a new value is sampled. If a measurement is interrupted for any reason, a constant output results until the interruption ceases. The data show several instances where this occurs. To calculate the thrust imbalance, the least interrupted measurement channel was selected for each motor and each interrupted interval is completed with interpolated data which give the proper pressure trace shape during that interval and match the measured data at each end of the interval.

The final result for the flight test based on the data taken at 1-s intervals and assuming a 1-s time shift between measurements is given in Fig. 6. The Monte Carlo analysis and design specification envelopes are shown superimposed on the flight-test data in Fig. 6. The maximum thrust imbalance is −63,700 lbf and occurs at 117 s. Secondary peak imbalances of −44,100 and +37,800 lbf occur at 33.1 and 93.0 s, respectively. In computing the imbalance, the thrust of the right-hand (with respect to the pilot) SRM is subtracted from that of the left-hand motor so that a negative imbalance indicates the SRM on the right has the greater thrust.

It is notable that the thrust imbalance vs time lies almost entirely within the envelope predicted by the Monte Carlo analysis as well as meeting the design specifications limits. Figure 7 shows the thrust imbalance vs time assuming no time shift in the pressure measurements between the two SRM's. Even with this assumption, believed to be ultraconservative, the results lie generally within the Monte Carlo prediction envelope.§

The low level of tailoff thrust imbalance was verified by other sources. During all but the latter part of tailoff, SRM nozzle gimballing provides most of the vehicle flight control authority. During the early part of tailoff, the gimbal actuator position measurements on both motors indicated very low yaw angles. Gimballing of the Space Shuttle Main Engines (SSME's) provides dominant vehicle attitude control late in SRM tailoff and during separation. The three SSME's yaw commands did not exceed the noise level during the time of SSME control. Finally, after the mission astronauts Young and Crippen said they were prepared for thrust imbalance during the tailoff, but it never occurred.[8]

## Concluding Remarks

This paper demonstrates the ability to predict on a statistical basis the thrust imbalance between a pair of SRM's firing in parallel. Comparing the evaluation of thrust imbalance for Titan IIIC motor pairs to flight-test data shows that the method is capable of establishing thrust imbalance limits for a relatively large population of motor pairs.

Static test data from individual motors can be used to create fictitious motor pairs for substantiation of the statistical analysis provided all nonrandom motor to motor variations are established and appropriate corrections made. The simplified internal ballistic model utilized in this paper for computing thrust from head-end pressure measurements gives excellent agreement with measured thrust data.

Flight-test data from the first Space Shuttle test flight show the thrust imbalance to be generally well within the envelopes predicted by the statistical analysis and that required by the design specifications. Considering the possible variations which could exist between motors, the thrust imbalance results for the first flight test are quite remarkable. In fact, the differences in thrust between motors as shown in Fig. 6 are for the most part within that corresponding to the noise level amplitude (approximately 8-12 psi) of the instrumentation system as indicated by the preflight measurements. The extremely low thrust imbalance indicates that a high degree of quality control was maintained throughout the processing and manufacturing of the motors for STS-1.

The Monte Carlo analysis assumed variability between motors based on data obtained primarily from the Titan IIIC program with modifications made to account for known improvements in the manufacturing and processing operations which were to be used in the Space Shuttle program. The variations between motors used in the Monte Carlo analysis are not believed to be overly conservative even though the first flight test might indicate that they were. Considering the results obtained from pairing the static test motors and the fact that full-scale production has not yet begun, the capability to maintain the low thrust imbalance level of STS-1 has not been definitely verified.

§The tape record of the 320 sps data aboard the recovered boosters later substantiated both the time shift and the thrust imbalance evaluation using the one sps data.

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