NASA Technical Memorandum

NASA TM -86493

SPACE SHUTTLE BOOSTER THRUST IMBALANCE ANALYSIS

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Systems Analysis and Integration Laboratory

January 1985

(NASA-TM-86493) SPACE SHUTTLE BOOSTER THRUST IMBALANCE ANALYSIS (NASA) 35 p HC A03/MF A01 CSCL 22D

N85-21241

Unclas
G3/16 14537

National Aeronautics and Space Administration

George C. Marshall Space Flight Center

TECHNICAL REPORT STANDARD TITLE PAGE

1. REPORT NO. NASA TM-86493

2. GOVERNMENT ACCESSION NO.

3. RECIPIENT'S CATALOG NO.

4. TITLE AND SUBTITLE
Space Shuttle Booster Thrust Imbalance Analysis

5. REPORT DATE January 1985

6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S)
William R. Bailey and Douglas L. Blackwell

8. PERFORMING ORGANIZATION REPORT #

9. PERFORMING ORGANIZATION NAME AND ADDRESS
George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

10. WORK UNIT NO.

11. CONTRACT OR GRANT NO.

12. SPONSORING AGENCY NAME AND ADDRESS
National Aeronautics and Space Administration
Washington, D.C. 20546

13. TYPE OF REPORT & PERIOD COVERED Technical Memorandum

14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES
Prepared by Systems Analysis and Integration Laboratory, Science and Engineering.

16. ABSTRACT

This report presents an analysis of the Shuttle SRM thrust imbalance during the steady-state and tailoff portions of the boost phase of flight. The study includes results from flights STS-1 through STS-13. A statistical analysis of the observed thrust imbalance data is presented. A 3σ thrust imbalance history versus time has been generated from the observed data and is compared to the vehicle design requirements. The effect on Shuttle thrust imbalance from the use of replacement SRM segments is predicted. Comparisons of observed thrust imbalances with respect to predicted imbalances are presented for the two Space Shuttle flights which used replacement aft segments (STS-9 and STS-13).

17. KEY WORDS
Thrust Imbalance on SRB's
Thrust Imbalance from SRM Segment Replacement
Thrust Imbalance from SRM Burn Rate Differences

18. DISTRIBUTION STATEMENT Unclassified-Unlimited

19. SECURITY CLASSIF. (of this report) Unclassified

20. SECURITY CLASSIF. (of this page) Unclassified

21. NO. OF PAGES 35

22. PRICE NTIS

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SPACE SHUTTLE BOOSTER THRUST IMBALANCE ANALYSIS

SUMMARY

An analysis of the Shuttle SRM thrust imbalance during the steady-state and tailoff portions of the boost phase of flight from flights STS-1 through STS-13 has been completed. A statistical analysis of the observed thrust imbalance data for normally processed Space Shuttle boosters (no replacement segments) has been completed. The predicted effect on Space Shuttle booster thrust imbalance from use of replacement SRM segments is shown. The thrust imbalance data observed on the two flights which used replacement SRM segments is compared to the predicted imbalance data.

INTRODUCTION

The Space Shuttle booster consists of two SRMs which provide thrust during the liftoff phase of flight and through the lower atmosphere. The SRMs are mounted on the External Tank in direct opposition as shown on Figure I.1. Thrust differences between the left and right SRMs cause an imbalance in the thrust applied to the vehicle. This imbalance may cause the Shuttle to move in the yaw and roll directions which cause concerns for aeroheating, loads, and vehicle control.

The observed steady-state and tailoff thrust imbalance data generated by the SRMs is available from eleven flights. Nine of the eleven flights used motors which were normally processed. Two of the flights (STS-9 and STS-13) had replacement aft segments. The buildup thrust imbalance data is available for eight flights and will be documented in a separate report on ignition transients. The observed thrust imbalance data from the normally processed Shuttle boosters has been assembled to project the maximum thrust imbalance to be expected from the Shuttle booster. This 3σ thrust imbalance is compared to the vehicle design requirements to assure that the design assumptions were adequate. An assessment is also provided for single segment replacements. First, the effect on Shuttle booster thrust imbalance is shown for only one replacement segment change and no flight effects. This effect is then combined with the 3σ observed thrust imbalance (with no replacement segment) derived from flight data. This combination is compared to vehicle design requirements to show the time periods of concern for Shuttle booster thrust imbalance if the use of a replacement segment is considered for flight.

I. EVALUATION OF FLIGHT STEADY-STATE AND TAILOFF BOOSTER THRUST IMBALANCE EXPERIENCE

A. Discussion

The propellant for the two SRMs for each flight is required to be manufactured from the same batch of raw materials in a "matched-pair" configuration. The "matched-pair" rationale is that when the SRMs are made "perfectly alike" and experience the same environment, then there will be little thrust imbalance between them. In practice, this is not the case. The variations in case diameter, case thickness, mandrel alignment, insulation thickness, propellant burn rate, and propellant burn-out patterns have an effect on thrust imbalance. In addition, the thermal environment experienced by each SRM during casting, transport, stacking, and waiting for launch may be different and can affect the thrust imbalance.

The Shuttle booster thrust imbalance data during the steady-state and tailoff portions of flight is available for analysis from eleven flights. Nine of these flights (STS-1, ..., 8, 11) were normally processed flight sets or manufactured in a matched-pair configuration. Two flights (STS-9 and STS-13) had interchanged aft segments and are not matched-pairs. The STS-10 and STS-12 flights were cancelled.

B. Steady-State and Tailoff Thrust Imbalance Requirements

The thrust imbalance requirements are documented in the SRM CEI Specification [1] and in JSC 07700, Volume 10 [2]. The thrust imbalance requirements are applicable over the propellant mean bulk temperature range of 40 to 90°F. With a maximum propellant mean bulk temperature difference of 1.4°F between the SRMs on a Shuttle vehicle, the thrust imbalance between the two SRMs shall not be greater than the values defined in the following:

1. Steady-State Thrust Imbalance — The maximum, instantaneous, steady-state thrust imbalance is allowed to be 85,000 lb beginning at 1.0 sec and ending at 4.5 sec before the earliest motor web time. The thrust differential transitions to the tailoff imbalance requirement by increasing linearly from 85,000 lb to 268,000 lb during the 4.5 sec time interval.

2. Tailoff Thrust Imbalance — The maximum SRM tailoff thrust imbalance is allowed to be as follows:

Percent Tailoff Time	Maximum Thrust Imbalance (lb)
0	268,000
10	570,000
20	670,000
30	710,000
40	580,000
50	470,000
60	370,000
70	290,000
80	220,000
90	160,000
100	100,000

Tailoff time is defined as the time from the first SRM web time to the last SRM action time. The impulse during tailoff under maximum imbalance conditions is to be $\leq$ 4,500,000 lb-sec.

C. STS-1, ..., 8, 11 Thrust Imbalance Assessment

The Shuttle booster thrust imbalance during steady-state operation and tailoff for the normally processed SRMs on flights STS-1, ..., 8, 11 has been reconstructed from each set of flight data. These imbalances are expected to be representative of future flight imbalances since the STS-9 and STS-13 flights are excluded. The imbalances are calculated as left motor thrust minus right motor thrust.

The normally processed booster thrust imbalances are compared to the imbalance requirements on Figures I.2 through I.10 for flights STS-1, ..., 8, 11, respectively. All of the nine flights were within requirements. The maximum values of thrust imbalance for all flights during the steady-state, transition-to-tailoff, and tailoff regions are tabulated on Table I.1. The tailoff imbalance impulse was within requirements on all flights and is tabulated on Table I.2.

The observed Shuttle booster thrust imbalance data from the nine normally processed SRM flight sets were statistically analyzed to derive an average and to project the 3σ booster thrust imbalance history. These data sets were normalized to the same action time prior to processing to remove the effect of burn time differences. At each time point, an average and standard deviation was calculated based upon the nine samples. The first projection of the 3σ booster thrust imbalance was derived using the K-factor approach to account for possible small sample size ($n = 9$) effects as discussed in Reference 3. A K-factor is used assuming 90 percent confidence of covering 99.73 percent (3σ) of the population of normally processed Shuttle boosters. This 3σ thrust imbalance to be expected from normally processed boosters is compared to the imbalance requirements on Figure I.11. There are multiple small exceedences of the 85,000 lb requirement during steady-state by the 3σ thrust imbalance curve. There are no exceedences in transition or tailoff. The second curve which is designated by $3\ S_x$ shown on Figure I.11 was derived assuming a K-factor of 3.0 to project to a large population size. This curve remains within the requirement limits in all areas. This indicates that as the Shuttle booster population size increases, the projected 3σ imbalance will decrease and the imbalance requirements will be shown adequate. The thrust imbalance between motors will continue to be monitored during the Space Shuttle program.

D. STS-9, 13 Booster Thrust Imbalance Assessment

The STS-9 and STS-13 flights used SRM pairs designated by Thiokol as SRM-9 and SRM-11, respectively. The discovery of severe erosion in the nose cap area of the STS-8A motor nozzle after launch and recovery triggered an extensive nozzle study. All nozzles which had been manufactured for future flight motors were examined for indications of potential anomalies. It was determined by Thiokol that the nozzle contained in the STS-9B (SRM-9B) motor was unacceptable, but the nozzle assigned to the SRM-11A motor was acceptable. A joint decision by MSFC and Thiokol was made to use the SRM-11A nozzle on the STS-9B (SRM-9B) flight motor.

The STS-9 Shuttle vehicle was assembled on the launch pad awaiting launch when the exchange decision was made. A delay in the launch was allowed so a correction could be made to the flight nozzle. The STS-9 launch vehicle was returned to the VAB and disassembled. It was determined that exchanging the complete SRM-9B aft segment with the SRM-11A aft segment could be accomplished more rapidly than replacing only the nozzles. This decision was made to expedite the launch schedule.

Because of the replacement of the SRM-9B aft segment with the SRM-11A aft segment, STS-9 was launched with the first non-matched-pair of motors in the flight program. Since the SRM-11A aft segment was cast with propellant made from a different lot of raw materials than was used for STS-9, the potential for a major Shuttle booster thrust imbalance existed. This potential is due to the uncertainty in predicting large motor burn rates from small motor test data across propellant lots. This uncertainty is known as the scale factor uncertainty. An analysis of the expected Shuttle booster imbalance was requested from Thiokol and verified by MSFC. The Thiokol analysis is documented in Reference 4.

The observed Shuttle booster thrust imbalance during steady-state and tailoff for STS-9 is shown on Figure I.12 with respect to the thrust imbalance requirements. As predicted by Thiokol, the STS-9 booster thrust imbalance slightly exceeded the thrust imbalance requirements, but remained inside the prelaunch, predicted envelope documented in Reference 4 and Waiver RWW-099R1. This waiver was evaluated prior to flight by the system groups at MSFC, JSC, and Rockwell International. The systems evaluation showed that it was acceptable to fly the STS-9 booster with the replacement aft segment.

Due to the cancellations of missions STS-10 and STS-12, the SRM-11 motor set with the STS-9B aft segment was used on the STS-13 flight vehicle. This was the second non-matched-pair of motors in the flight program. During the stacking of STS-13, the STS-9B aft segment was put into the 13B position and the original SRM-11B aft segment was moved to the STS-13A position. The resultant SRM thrust imbalance as observed on the flight of STS-13 was within the thrust imbalance requirements as shown on Figure I.13.

TABLE I.1. STS FLIGHT MAXIMUM THRUST IMBALANCE SUMMARY

	Steady-State[a]		Transition[a]		Tailoff[a]	
	Thrust (10^3 lb)	Time (s)	Thrust (10^3 lb)	Time (s)	Thrust (10^3 lb)	Time (s)
STS-1	49.4	91.0	-50.7	114.5	-36.2	120.5
STS-2	34.4	9.5	34.6	112.0	-156.3	118.2
STS-3	-44.8	106.0	-83.3	111.0	-35.1	120.6
STS-4	-36.2	91.0	-5.1	110.5	-47.0	122.8
STS-5	37.3	107.0	31.6	107.5	183.3	114.5
STS-6	43.8	19.0	-49.2	112.8	-227.6	115.5
STS-7	-33.7	72.5	13.2	105.5	134.4	113.0
STS-8	-40.5	86.5	13.1	106.0	84.0	113.5
STS-9	87.3[b]	87.0	67.1	109.5	132.4	113.5
STS-11	-54.8	105.5	-39.2	107.0	114.3	116.8
STS-13	-76.7	87.5	-79.7	108.5	-283.8	111.0

a. Imbalance is calculated as left minus right.
b. On STS-9, the steady-state maximum thrust imbalance of 85,000 pounds was revised to 87,441 lbs by Waiver RWW-099R1.

TABLE I.2. STS FLIGHT TAILOFF IMBALANCE IMPULSE SUMMARY

	Tailoff Imbalance Impulse[a] (10^6 lb-sec)
STS-1	0.233
STS-2	0.349
STS-3	0.049
STS-4	0.200
STS-5	0.738
STS-6	0.860
STS-7	0.519
STS-8	0.187
STS-9	0.114
STS-11	0.772
STS-13	0.564

a. Maximum tailoff imbalance impulse requirement is 4.5×10^6 lb-sec.

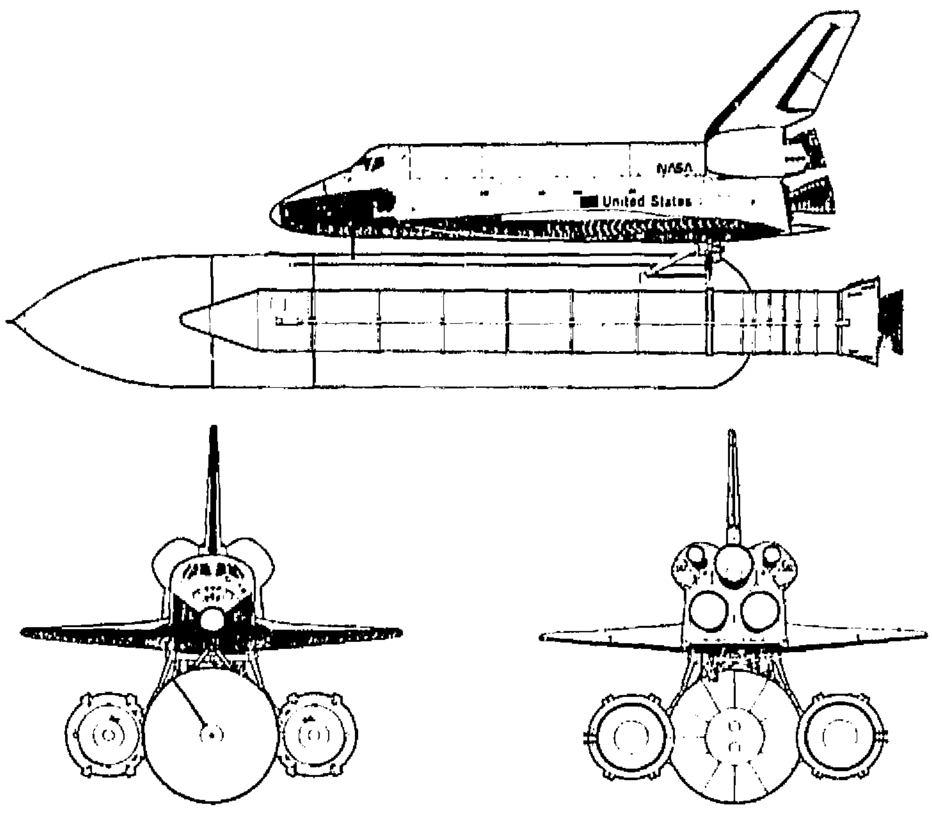

Figure I.1. Shuttle Launch Vehicle.

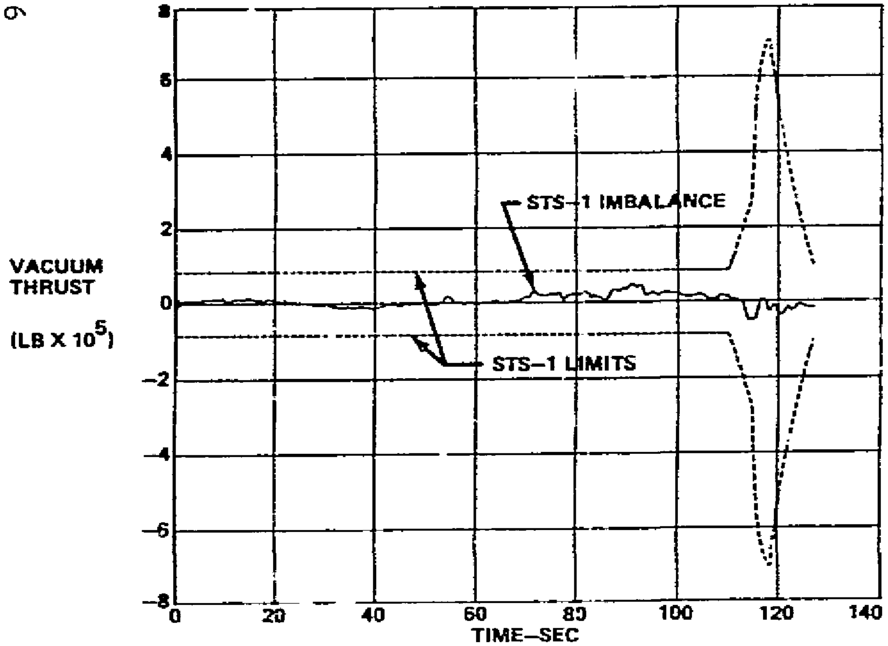

FIGURE I.2 COMPARISON OF STS−1 THRUST IMBALANCE TO REQUIREMENTS

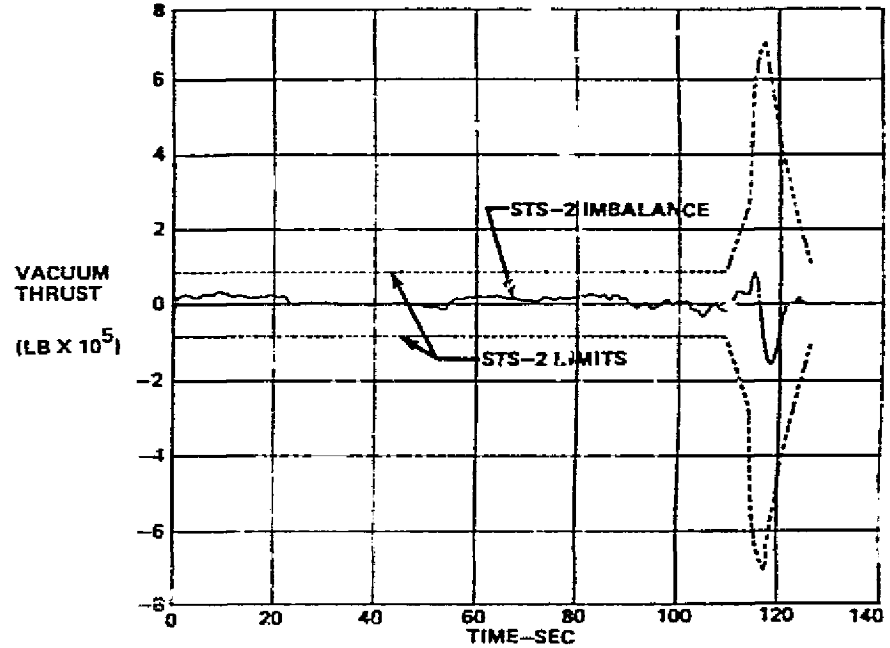

FIGURE I.3 COMPARISON OF STS−2 THRUST IMBALANCE TO REQUIREMENTS

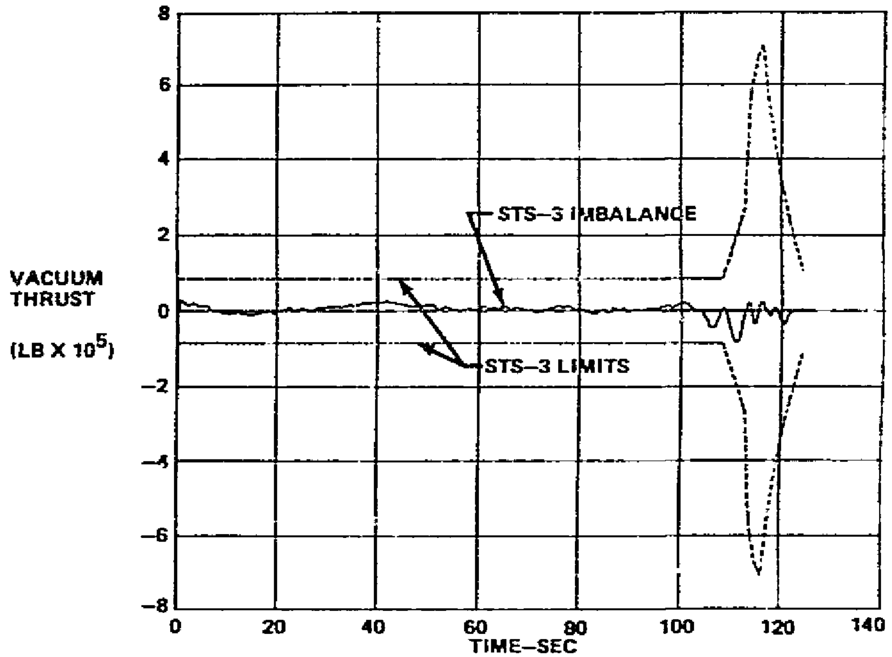

FIGURE I.4 COMPARISON OF STS−3 THRUST IMBALANCE TO REQUIREMENTS

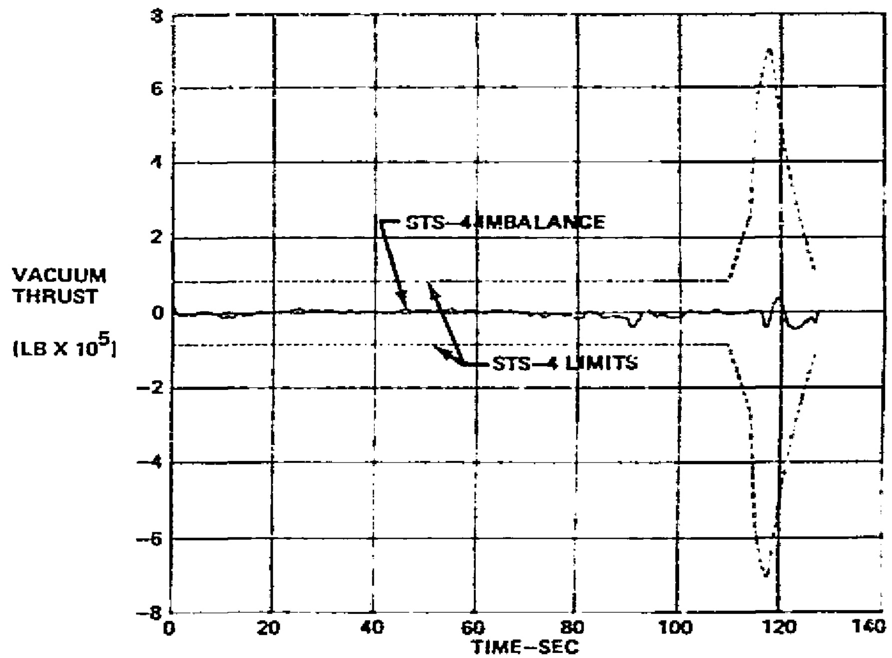

FIGURE I.5 COMPARISON OF STS−4 THRUST IMBALANCE TO REQUIREMENTS

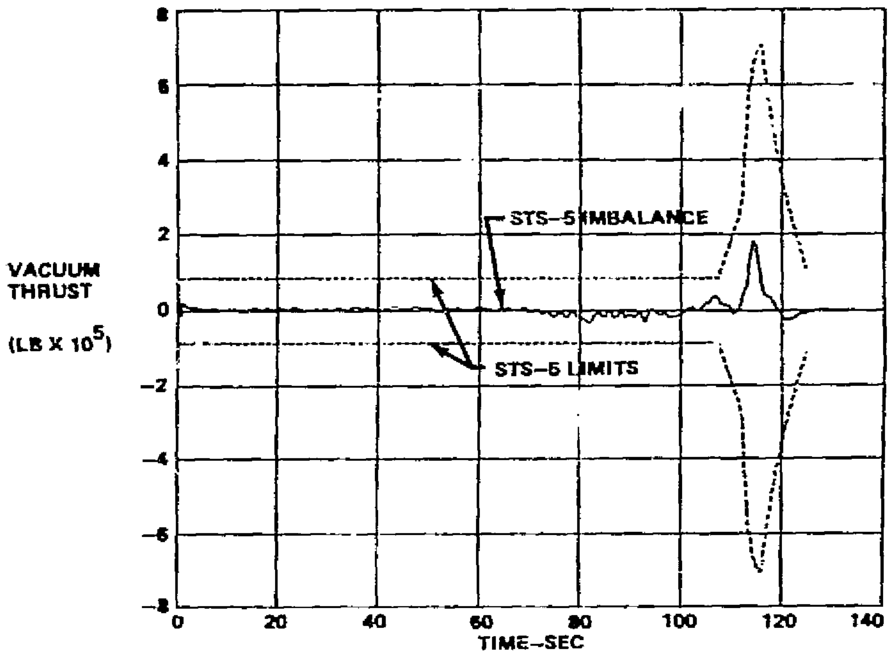

FIGURE I.6 COMPARISON OF STS-5 IMBALANCE TO REQUIREMENTS

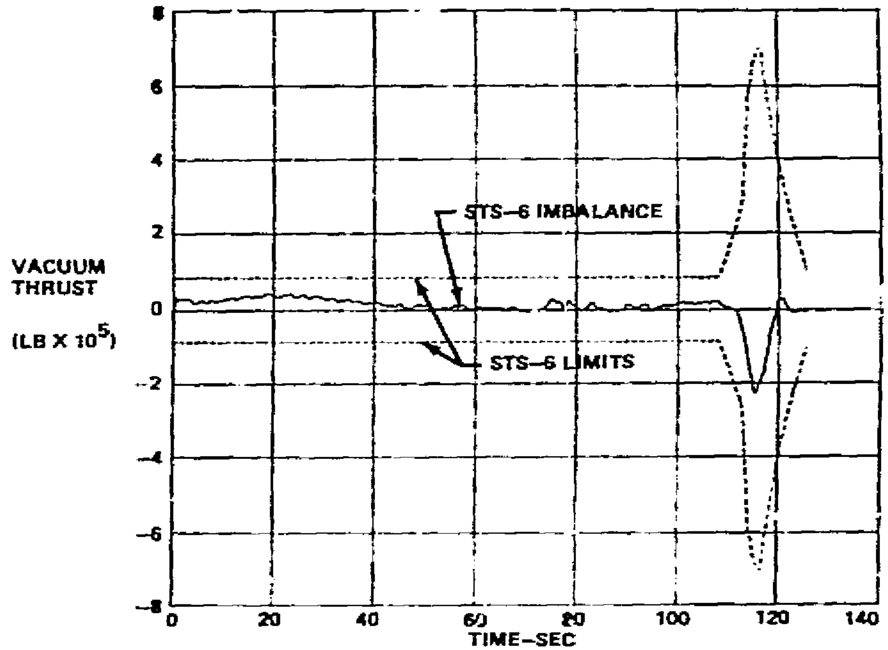

FIGURE I.7 COMPARISON OF STS-6 THRUST IMBALANCE TO REQUIREMENTS

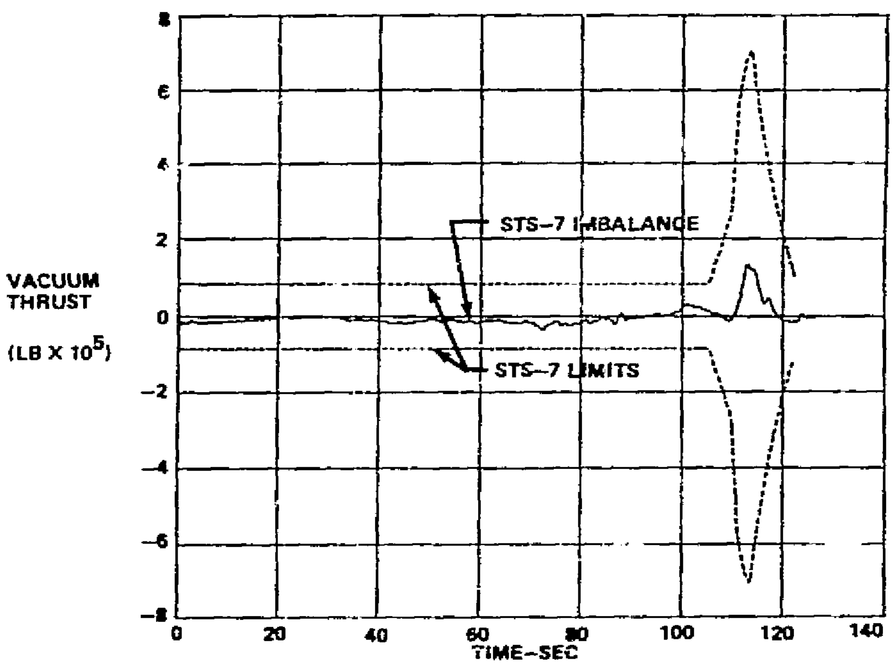

FIGURE I.8 COMPARISON OF STS-7 THRUST IMBALANCE TO REQUIREMENTS

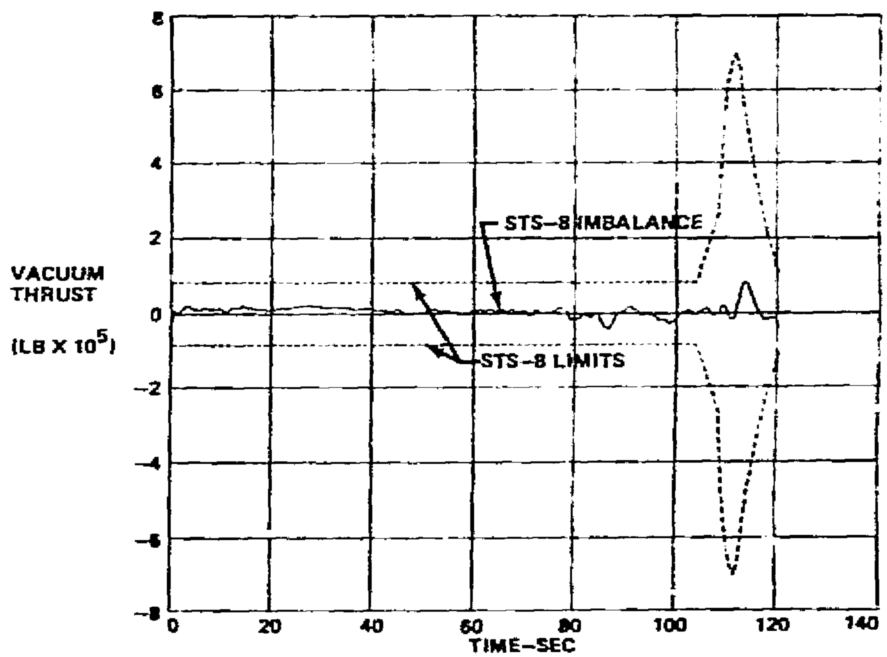

FIGURE I.9 COMPARISON OF STS-8 THRUST IMBALANCE TO REQUIREMENTS

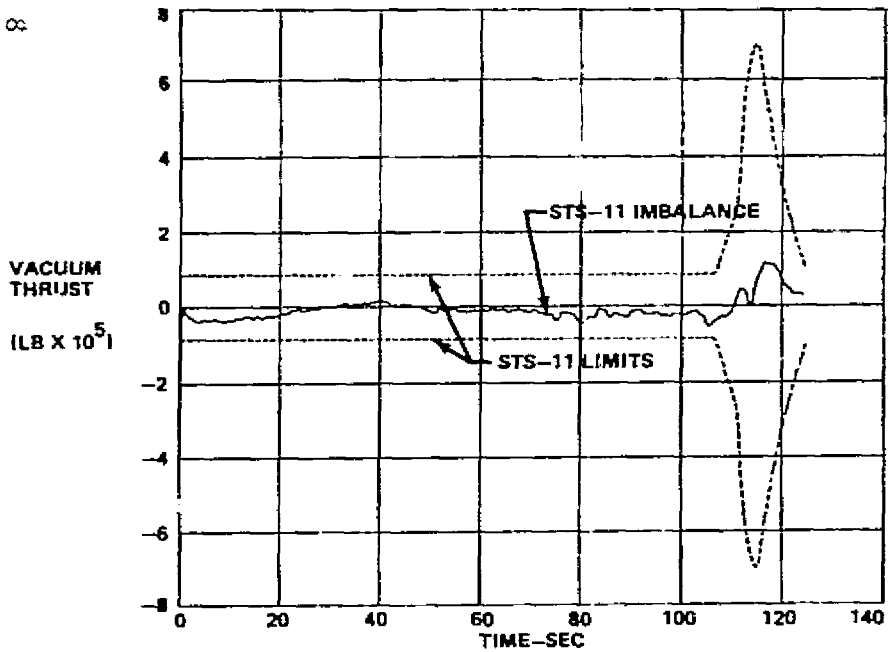

FIGURE I.10 COMPARISON OF STS–11 THRUST IMBALANCE TO REQUIREMENTS

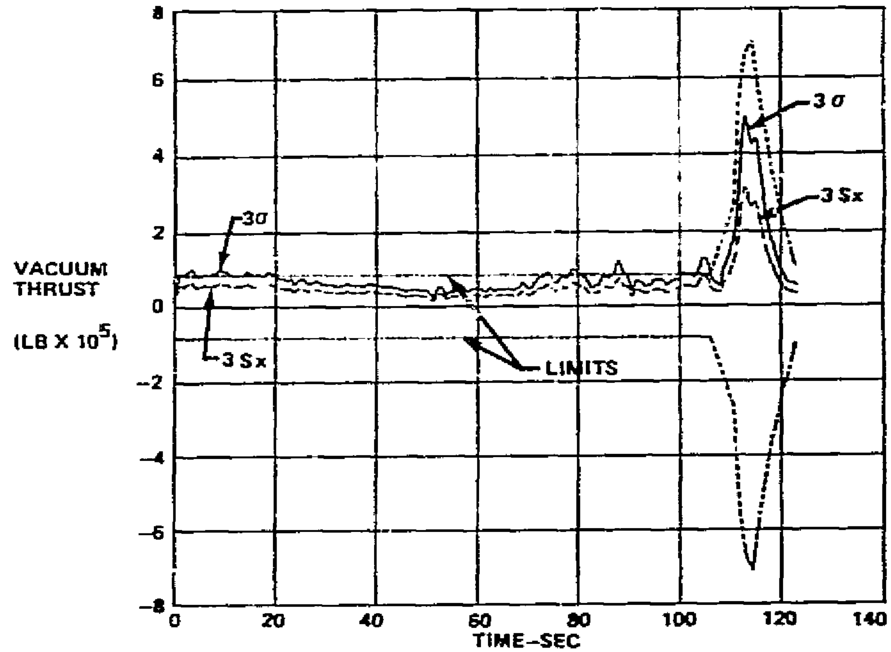

FIGURE I.11 COMPARISON OF MAXIMUM THRUST IMBALANCE CURVES TO REQUIREMENTS

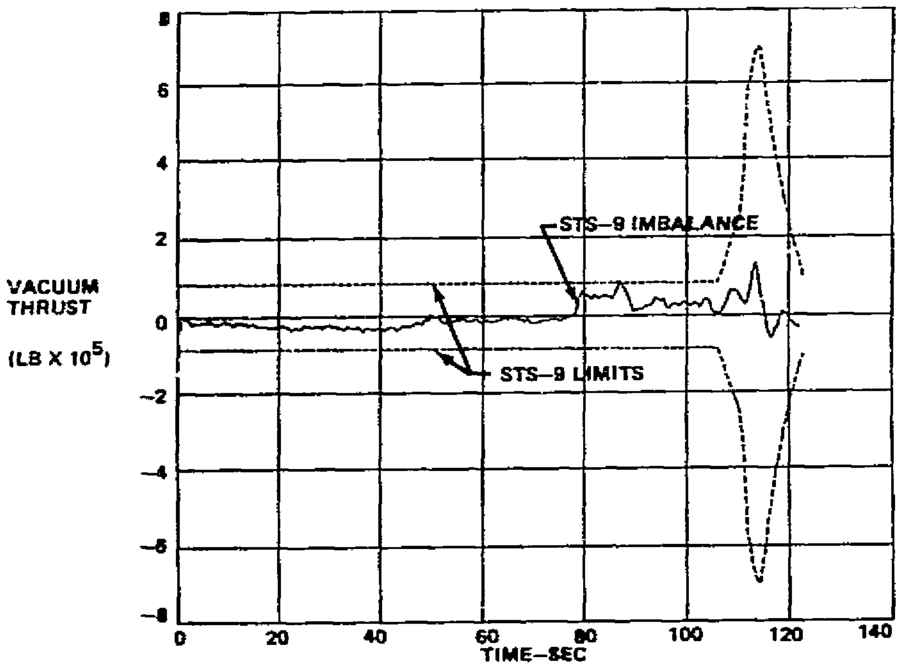

FIGURE I.12 COMPARISON OF STS–9 THRUST IMBALANCE TO REQUIREMENTS

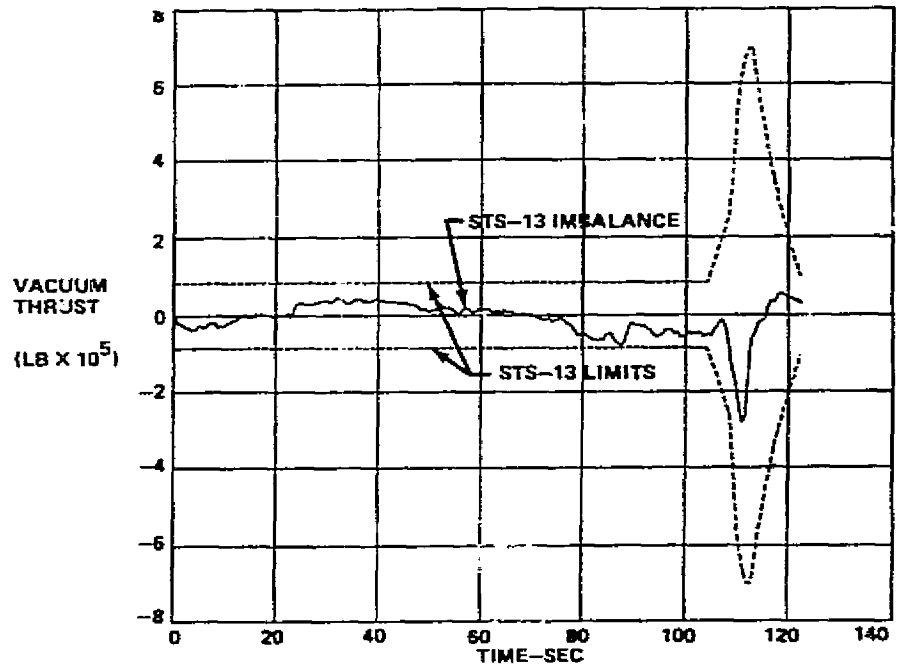

FIGURE I.13 COMPARISON OF STS–13 THRUST IMBALANCE TO REQUIREMENTS

II. EFFECT OF SEGMENT REPLACEMENT ON STEADY-STATE AND TAILOFF BOOSTER THRUST IMBALANCE

A. Discussion

Following the experience with STS-9 and STS-13, it is evident that as the Space Shuttle program progresses through its schedule, there may be further considerations of changes that necessitate a motor segment replacement. The replacement segment will not be manufactured from the same lot of raw materials and the booster will not be a "matched-pair" configuration. There is a good likelihood that significant booster thrust imbalance may occur between the SRMs due to the differences in segment burn rates. A study of the effect of replacement segment burn rate differences on imbalance would be useful in determining acceptability or risks in evaluating the proposed changes. The SRM ignition portion of flight is not addressed individually, as single segment replacements should have little effect on ignition prior to a head pressure value of $\sim$560 psia or $\sim$0.23 sec. The behavior of the motor performance during this time region is dominated by flame spreading and not by burn rate. This time period encompasses the period of peak ignition thrust imbalance which occurs at $\sim$0.16 sec. After $\sim$560 psia, the ignition characteristics are influenced by motor burn rate similar to steady-state, but without the effects from propellant web burnout. This study evaluates the booster thrust imbalance during steady-state and tailoff caused only by burn rate differences from a single segment replacement.

There are two sources of booster thrust imbalance. One source is the difference in segment burn rates between a replacement segment and the paired motor segment. The second source is the normal motor-to-motor difference which is analyzed from previous flight experience in Section I. If a segment is replaced there are two types of possible replacement segment burn rate differences. The first type of burn rate difference can occur because the mismatch in propellant raw materials can cause a mismatch in propellant burn rate scale-up factor. The scale-up factor is the ratio of the large motor burn rate to the 5 in. CP small motor burn rate. The $\pm 3\sigma$ uncertainty in the first type (scale-up factors for the burn rates of large motors from different lots of materials) is approximately $\pm$2.7 percent or about $\pm$10 mills in burn rate. This uncertainty is based upon SRM test/flight scale factor data gathered through STS-13. The second type of burn rate difference results from the miss in 5 in. CP target burn rate if a segment must be cast out of the usual time sequence. In this case, the scale-up factor is assumed to be identical to the paired motor. This time delay may result from such things as a casting facility incident, a handling incident, the loss of a casting pit, or the loss of a casting mandrel. The effect on 5 in. CP burn rates from the time interval between casting dates of SRM segments is documented by Thiokol in Reference 5. The 3σ burn rate differences may be as much as $\pm$4 mills for time intervals between casting of up to 15 days. From 16 to 80 days, the 3σ burn rate differences may be $\pm$6 mills. The effect of time delay is approximately one half of the scale factor effect.

B. Booster Thrust Imbalance from Segment Replacement Burn Rate Differences

There are four casting segments in each SRM. These are the forward (FWD), forward center (FWD CNTR), aft center (AFT CNTR), and aft segments. Replacement of each of these segments may be contemplated during the Shuttle program.

The burning of the propellant in each segment contributes differently to the total thrust of the SRM. The replacement of each segment must be evaluated for its own effect on booster thrust imbalance.

Sixteen distinct cases were generated to provide visibility of the effect each segment contributes to booster thrust imbalance. These cases were generated at burn rate increments of ±5 and ±10 mills using the SRIBM model. This model is the MSFC-EL24 SRM propulsion performance prediction program as described in Reference 6. The basic performance ground rules were as follows:

1) The performance predictions are based upon the HPM test/flight experience at a primary burn rate of 0.368 ips and an Isp of 268.0 sec.

2) Variations in segments are not reflected in propellant weight. The propellant weight is fixed at 1,108,704 lbs.

3) Each segment changeout is singular.

4) All cases have constant weight overboard.

A booster thrust differential history was generated for each of the 16 segment replacement cases assuming the paired SRM to have the nominal thrust-time trace. The thrust-time comparison and thrust-time differential comparison to the thrust imbalance requirements is shown for each case as follows:

Segment	Segment Burn Rate Change (Mills)	Figures
Forward	+5	II.1, II.2
Forward	-5	II.3, II.4
Forward	+10	II.5, II.6
Forward	-10	II.7 II.8
Forward Center	+5	II.[illegible], II.10
Forward Center	-5	II.11, II.12
Forward Center	+10	II.13, II.14
Forward Center	-10	II.15, II.16
Aft Center	+5	II.17, II.18
Aft Center	-5	II.19, II.20
Aft Center	+10	II.21, II.22
Aft Center	-10	II.23, II.24
Aft	+5	II.25, II.26
Aft	-5	II.27, II.28
Aft	+10	II.29, II.30
Aft	-10	II.31, II.32

Generalized results of this case study which excludes flight-to-flight imbalance experience are as follows:

1) A ±5 mill burning rate difference in any segment does not violate the thrust imbalance requirements.

2) A +10 mill burning rate difference in the aft segment violates the steady-state thrust imbalance requirements by 6,000 lb and 33,000 lb at 105.5 and 108.5 sec, respectively. This is the only case which violates requirements.

3) A -10 mill burning rate difference in the aft segment is near the thrust imbalance requirements.

4) The aft segment burning rate difference has the most effect in the steady-state/tailoff interface when one segment has burned out.

5) Center segment burning rate differences have the most effect in the region of tailoff.

6) Forward segment burning rate differences have the most effect in the first twenty seconds of burn and affect the tailoff period of burn.

C. Comparison of STS-9/13 Flight Thrust Imbalance Experience to the Segment Replacement Predictions

The post-flight reconstructions and evaluations of STS-9 and STS-13 have been completed. The evaluations show that the average SRM burn rates of STS-9 were 0.3661 and 0.3668 ips at 60°F for the left and right motors, respectively. The average SRM burn rates of STS-13 were 0.3712 ips and 0.3703 ips at 60°F for the left and right motors, respectively. The STS-13 burn rates are an average of ∿1.2 percent greater than STS-9 burn rates.

The STS-9/13 burn rate evaluation indicates that the original STS-13B aft segment placed on the STS-9B flight motor would have a burn rate higher than the other segments. Thus, the STS-9 booster thrust imbalance should be approximated by the replacement aft segment +5 or +10 mill cases. The thrust imbalance observed on STS-9 is compared to the +5 and +10 mill burn rate cases for a replacement aft segment on Figure II.33. Conversely, the STS-9B replacement aft segment on the STS-13B flight motor would have a burn rate lower than the other segments. Thus, the STS-13 thrust differential would be approximated by the replacement aft segment -5 or -10 mill cases. The thrust imbalance observed on STS-13 is compared to the -5 and -10 mill burn rate cases on Figure II.34. These comparisons show the following:

1) The general trend of the STS-9 and STS-13 flight thrust imbalance data is similar to the predicted thrust imbalance histories based upon the replacement segment data derived in Section II.B. Both flight data sets exhibit a shift at about 75 to 80 sec which indicates a crossover of thrust magnitude between motors.

2) The predictions of the flight thrust imbalance is only a fair match of the STS-9 and STS-13 flight experience. The STS-9 flight thrust imbalance data matches the predictions better than STS-13. The thrust mismatch of STS-13 indicates that the other sources of booster thrust imbalance were more influential on STS-13 than STS-9.

D. Segment Replacement Total Thrust Imbalance

The estimate of the total booster thrust imbalance likely to be encountered in flight with a replacement segment is derived from combination of the two sources. The thrust imbalance generated from the expected segment replacement burn rate change is combined in an RSS approach with the projected flight thrust imbalance resulting from normally processed motors. The normal flight thrust imbalance data from STS-1, ..., 8, 11 provides the projected 3σ (small sample size) and $3\ S_x$ flight thrust imbalance histories. These histories account for the unknown sources of imbalance seen on normal flights as derived in Section I.C. The replacement segment thrust imbalance histories are provided by the analyses of Section II.B. These are combined with the 3σ and $3\ S_x$ projections and are compared to the imbalance requirements on Figures II.35 through II.50. Some comments are offered as follows:

1) The forward segment replacement cases have exceedances on all 3σ cases. These are designated as RSS 3σ on the figures. The +10 mill cases have serious exceedances for the 3σ and the $3\ S_x$ cases in the steady-state/tailoff transition regions. The other $3\ S_x$ cases designated by RSS $3\ S_x$ have only minor exceedances.

2) The forward center segment replacement cases have exceedances on all 3σ cases. The +10 mill cases have exceedances in the transition region but these are not as large as the forward segment exceedances. The other $3\ S_x$ cases have no exceedances.

3) The aft center segment replacement cases have exceedances on all 3σ cases. The +10 mill 3σ case has slight exceedances during tailoff. The $3\ S_x$ cases have no exceedances.

4) All of the aft segment replacement cases have exceedances similar to STS-9. The +10 and -10 mill cases are excessive in the steady-state/transition region.

5) The 3σ cases always exceed the requirements because the 3σ normal flight imbalance already exceeds requirements in the first 20 sec and several other time periods.

The tailoff thrust imbalance from these cases is summarized on Table II.1.

TABLE II.1. SEGMENT REPLACEMENT TAILOFF IMBALANCE IMPULSE SUMMARY

Case	3σ Imbalance Impulse (10^6 lb-sec)	$3\ S_x$ Imbalance Impulse (10^6 lb-sec)
Forward +5 mills	3.49	2.36
Forward -5 mills	3.14	2.04
Forward +10 mills	4.60[a]	3.54
Forward -10 mills	3.18	2.10
Forward Center +5 mills	3.58	2.56
Forward Center -5 mills	3.25	2.20
Forward Center +10 mills	4.70[a]	3.85
Forward Center -10 mills	3.44	2.47
Aft Center +5 mills	3.48	2.48
Aft Center -5 mills	3.21	2.14
Aft Center +10 mills	4.50[a]	3.68
Aft Center -10 mills	3.33	2.31
Aft +5 mills	3.15	2.01
Aft -5 mills	3.12	2.01
Aft +10 mills	3.10	1.98
Aft -10 mills	3.20	2.13

a. Equals or exceeds the requirement of 4.5×10^6 lb-sec.

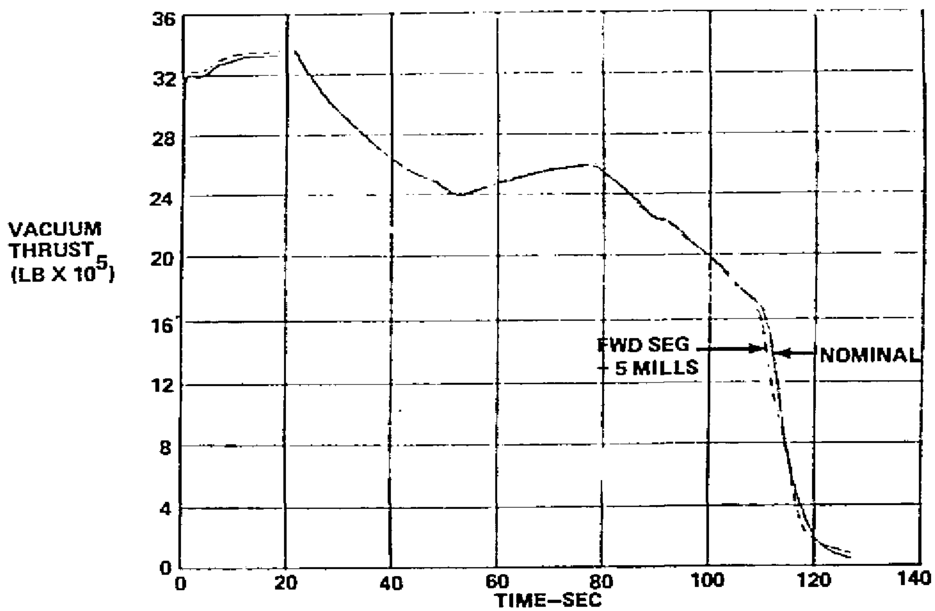

FIGURE II.1 COMPARISON OF NOMINAL AND FORWARD SEGMENT REPLACEMENT WITH 5 MILL BURN RATE INCREASE

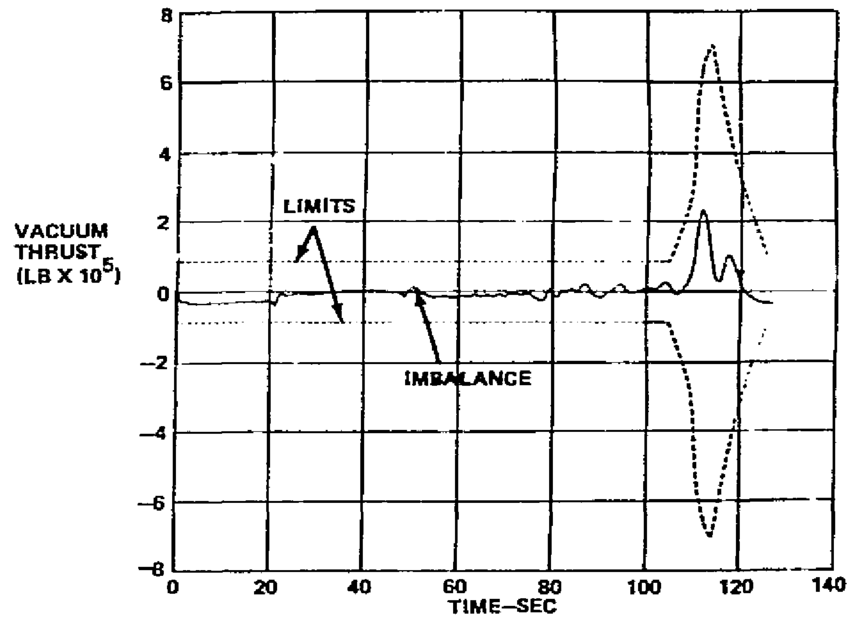

FIGURE II.2 THRUST IMBALANCE FROM FORWARD SEGMENT REPLACEMENT WITH +5 MILL BURN RATE VS. REQUIREMENT

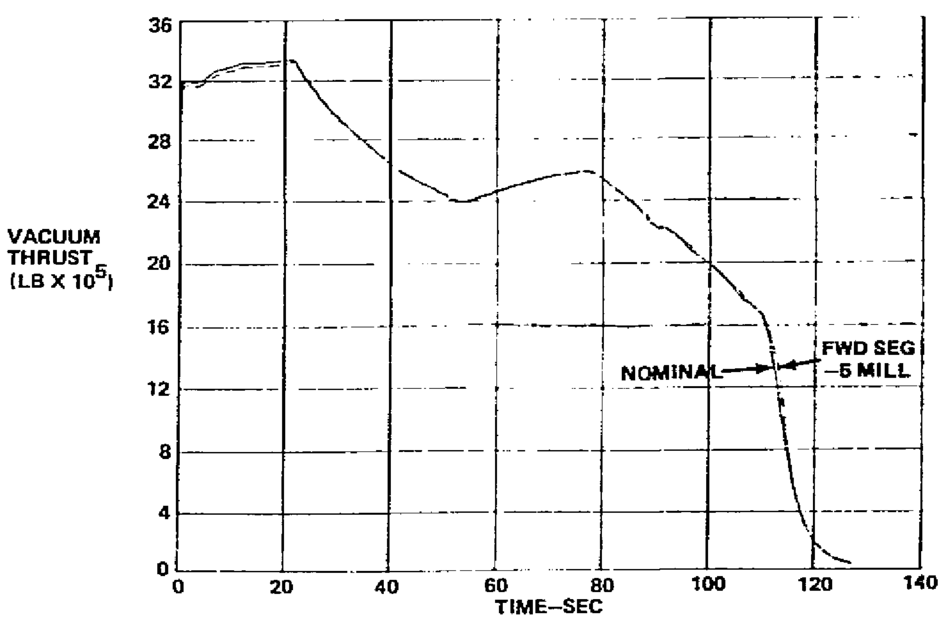

FIGURE II.3 COMPARISON OF NOMINAL AND FORWARD SEGMENT REPLACEMENT WITH 5 MILL BURN RATE DECREASE

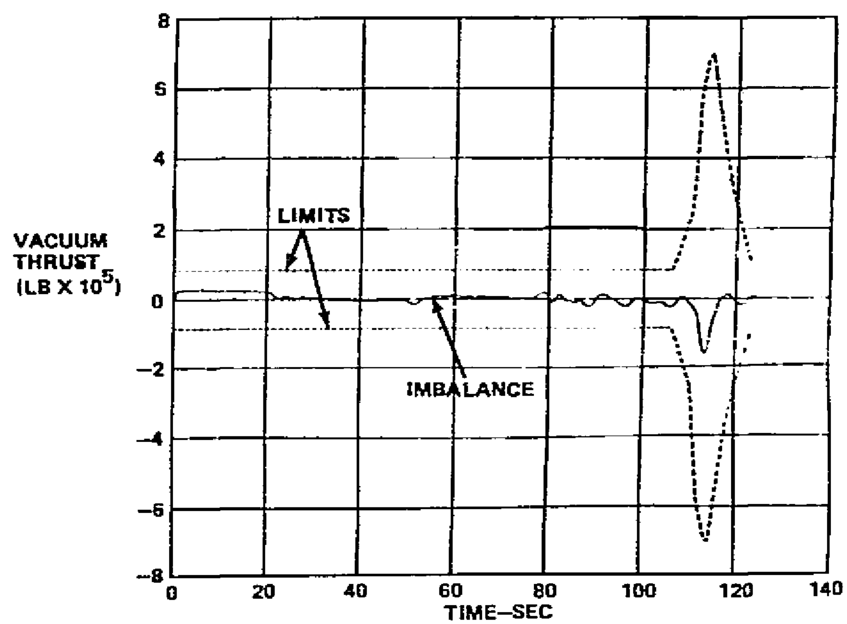

FIGURE II.4 THRUST IMBALANCE FROM FORWARD SEGMENT REPLACEMENT WITH −5 MILL BURN RATE VS. REQUIREMENT

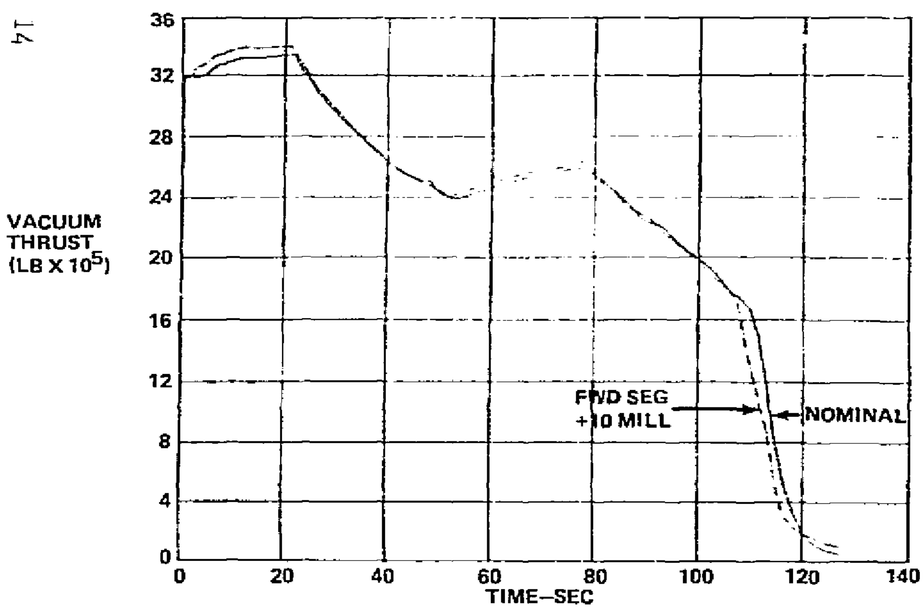

FIGURE II.5 COMPARISON OF NOMINAL AND FORWARD SEGMENT REPLACEMENT WITH 10 MILL BURN RATE INCREASE

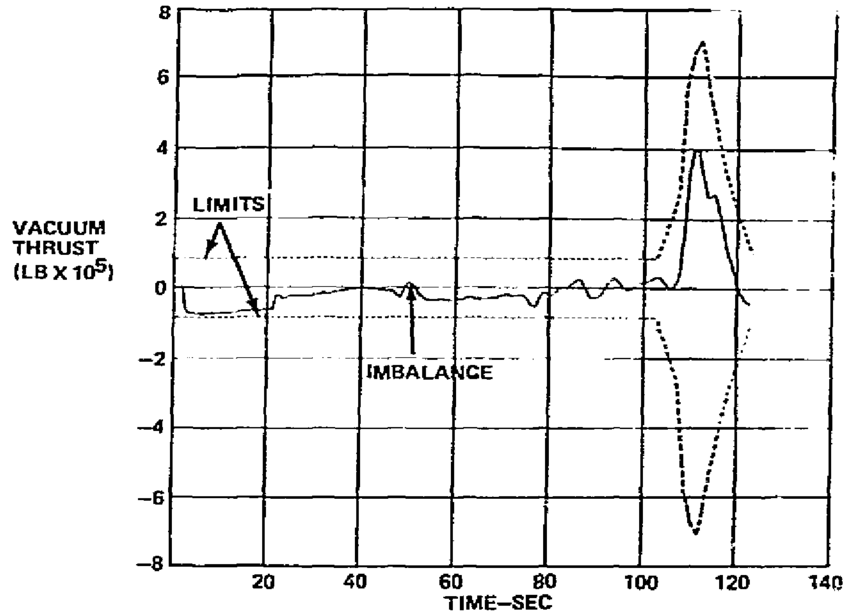

FIGURE II.6 THRUST IMBALANCE FROM FORWARD SEGMENT REPLACEMENT WITH +10 MILL BURN RATE VS. REQUIREMENT

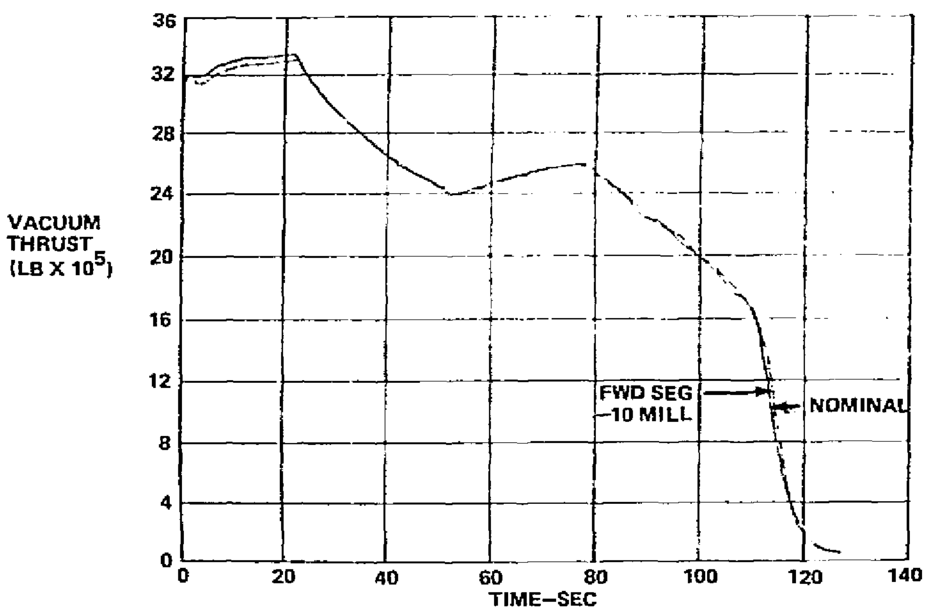

FIGURE II.7 COMPARISON OF NOMINAL AND FORWARD SEGMENT REPLACEMENT WITH 10 MILL BURN RATE DECREASE

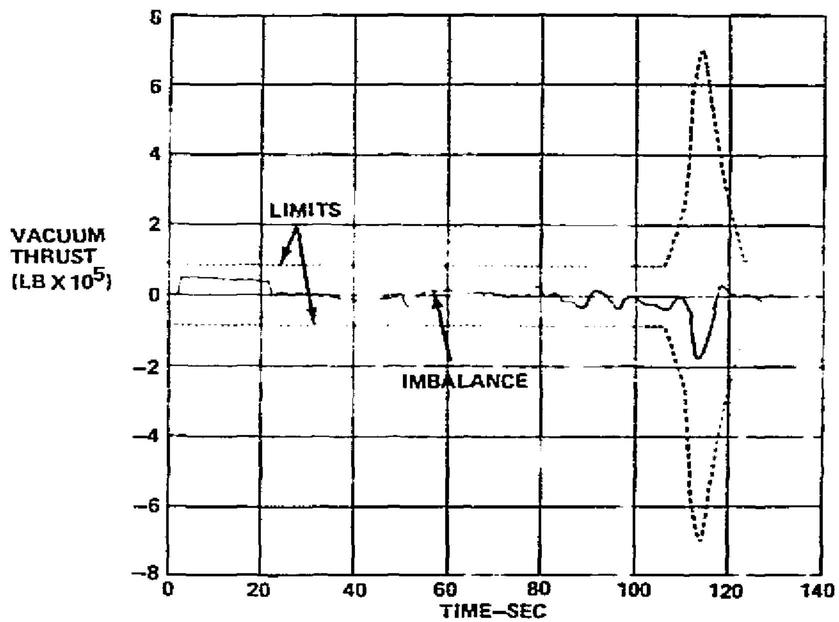

FIGURE II.8 THRUST IMBALANCE FROM FORWARD SEGMENT REPLACEMENT WITH –10 MILL BURN RATE VS. REQUIREMENT

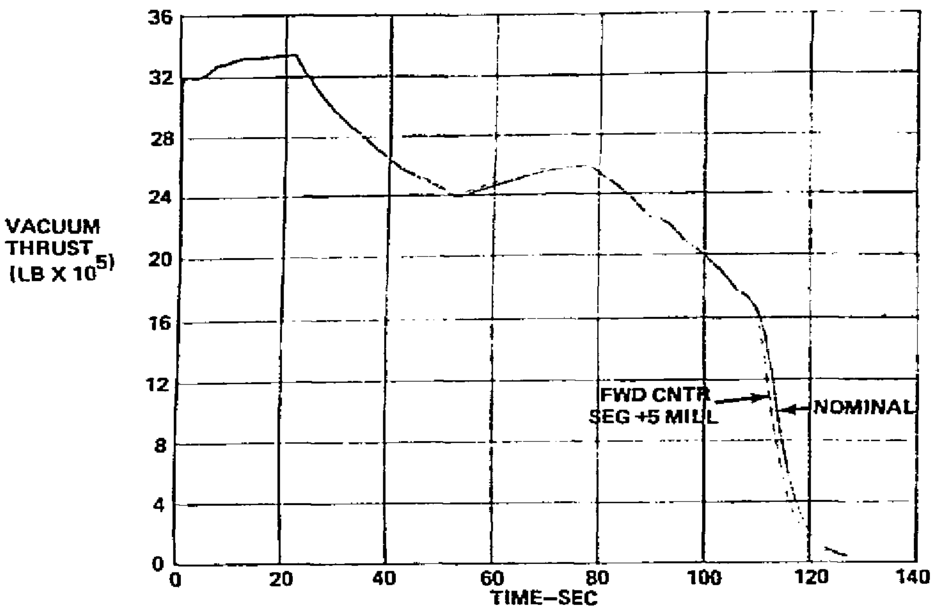

FIGURE II.9 COMPARISON OF NOMINAL AND FORWARD CENTER SEGMENT REPLACEMENT WITH 5 MILL BURN RATE INCREASE

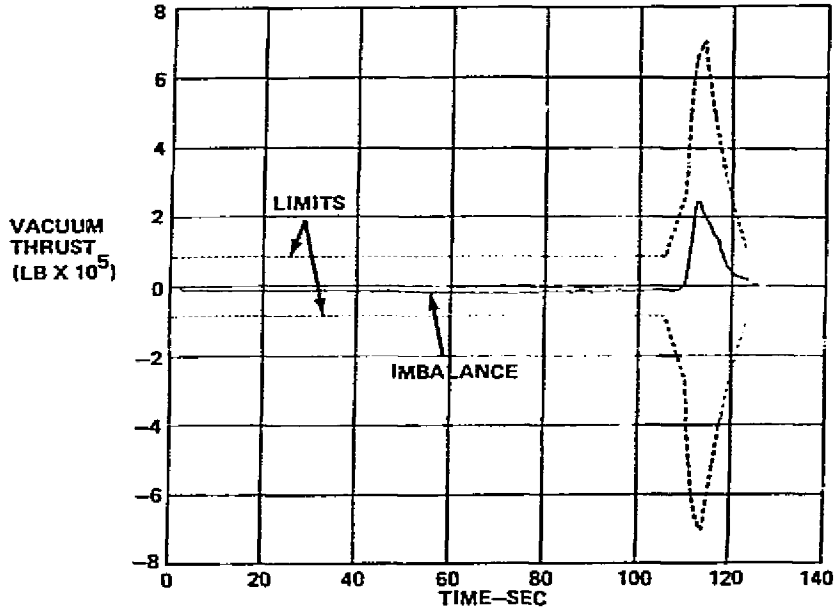

FIGURE II.10 THRUST IMBALANCE FROM FORWARD CENTER SEGMENT REPLACEMENT WITH +5 MILL BURN RATE VS. REQUIREMENT

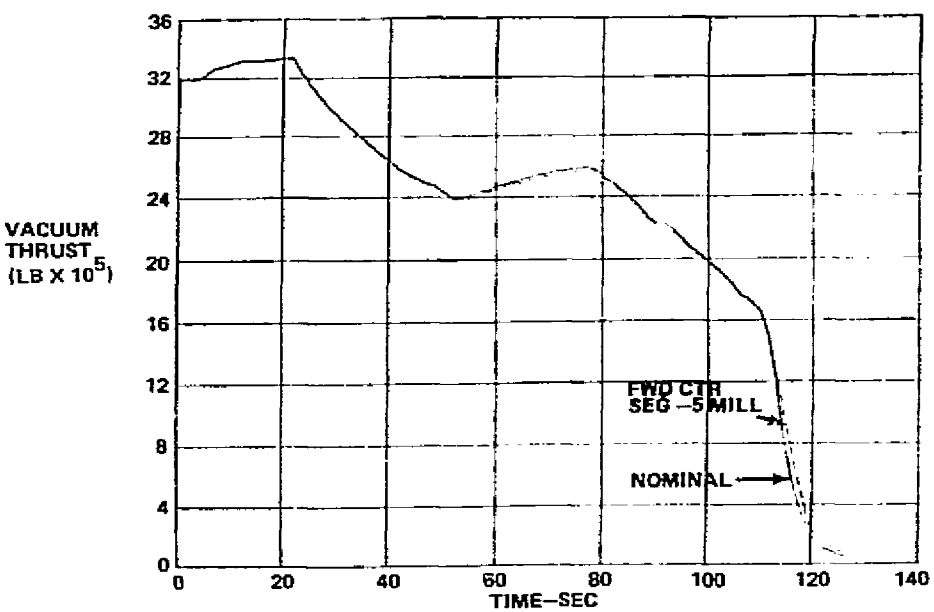

FIGURE II.11 COMPARISON OF NOMINAL AND FORWARD CENTER SEGMENT REPLACEMENT WITH 5 MILL BURN RATE DECREASE

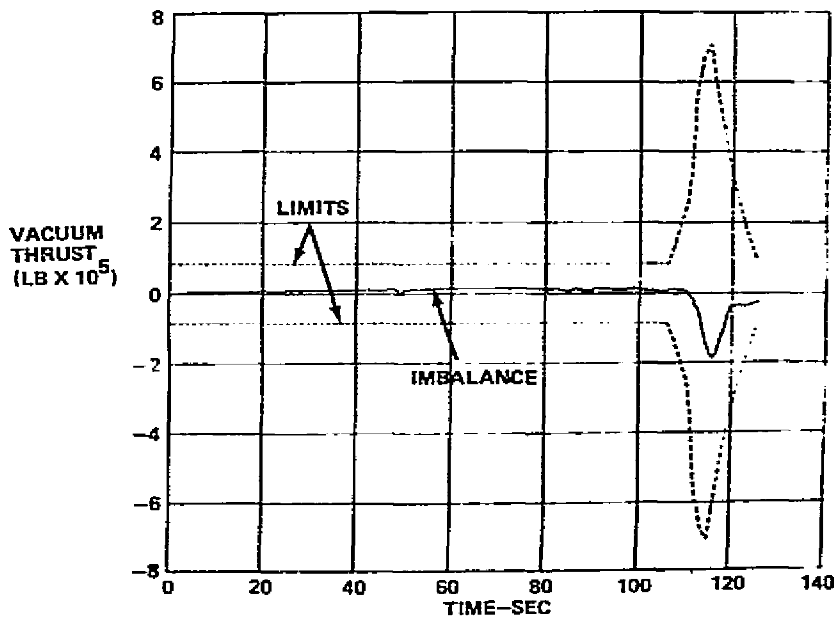

FIGURE II.12 THRUST IMBALANCE FROM FORWARD CENTER SEGMENT REPLACEMENT WITH −5 MILL BURN RATE VS. REQUIREMENT

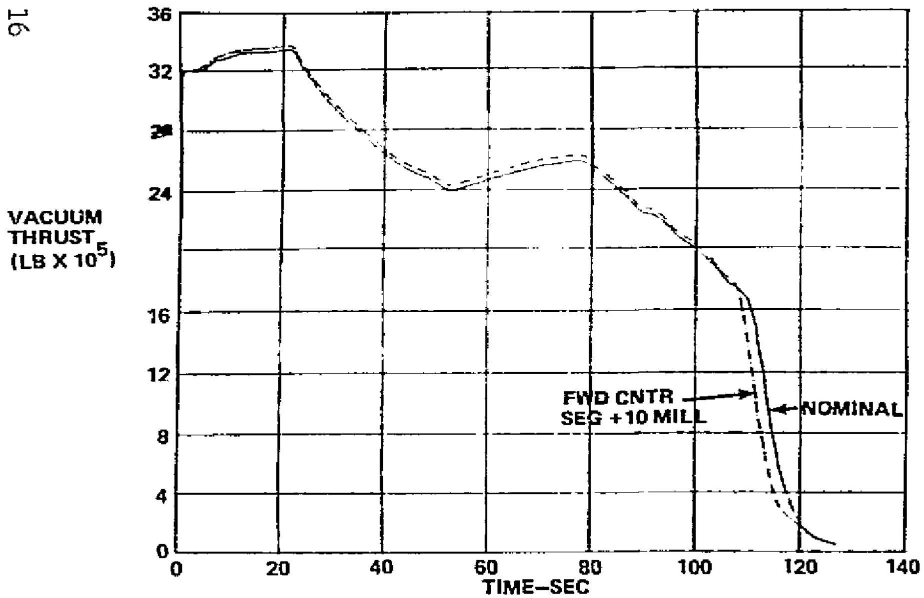

FIGURE II.13 COMPARISON OF NOMINAL AND FORWARD CENTER SEGMENT REPLACEMENT WITH 10 MILL BURN RATE INCREASE

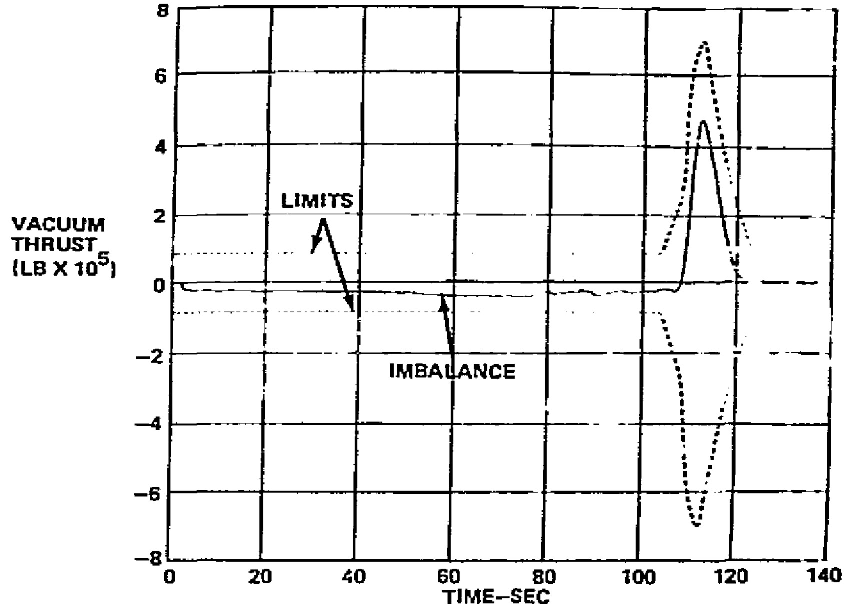

FIGURE II.14 THRUST IMBALANCE FROM FORWARD CENTER SEGMENT REPLACEMENT WITH +10 MILL BURN RATE VS. REQUIREMENT

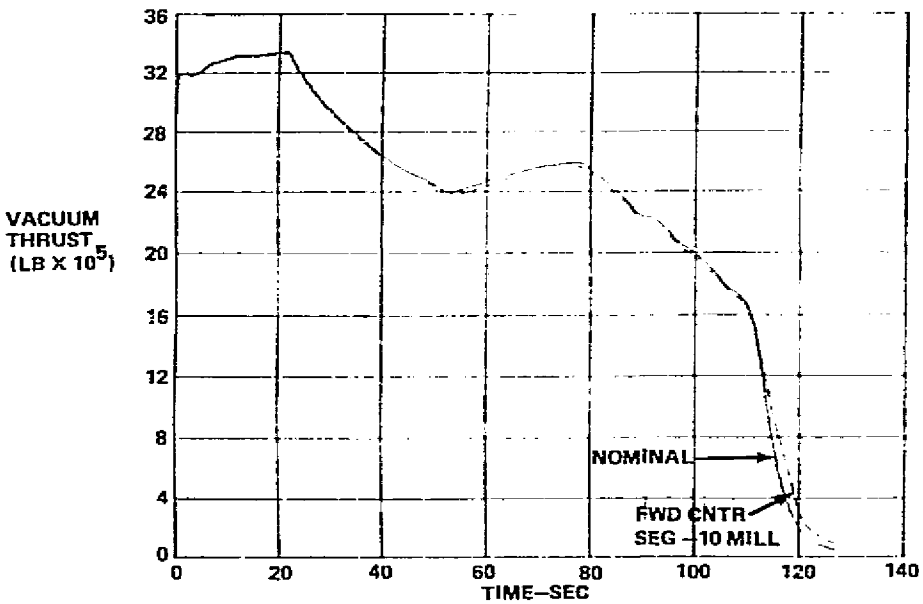

FIGURE II.15 COMPARISON OF NOMINAL AND FORWARD CENTER SEGMENT REPLACEMENT WITH 10 MILL BURN RATE DECREASE

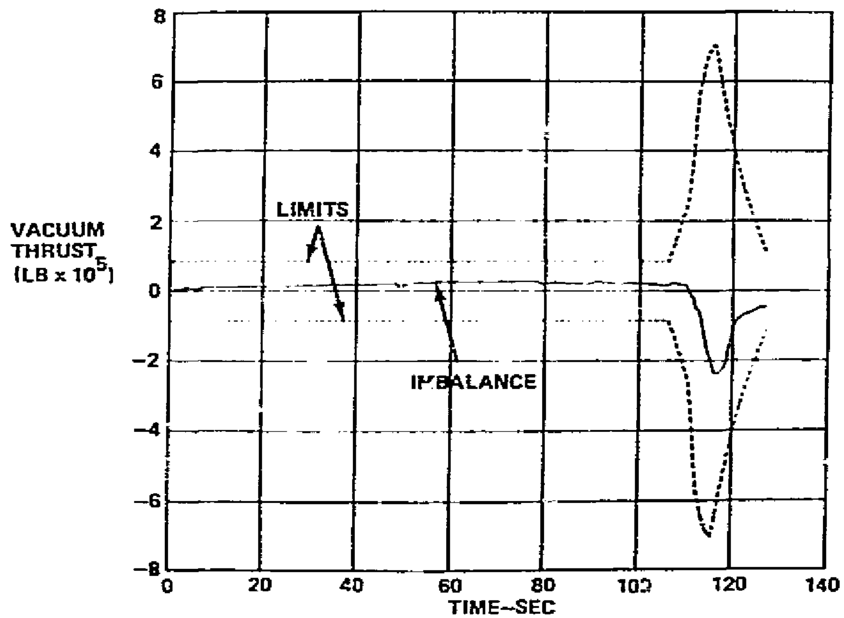

FIGURE II.16 THRUST IMBALANCE FROM FORWARD CENTER SEGMENT REPLACEMENT WITH –10 MILL BURN RATE VS. REQUIREMENT

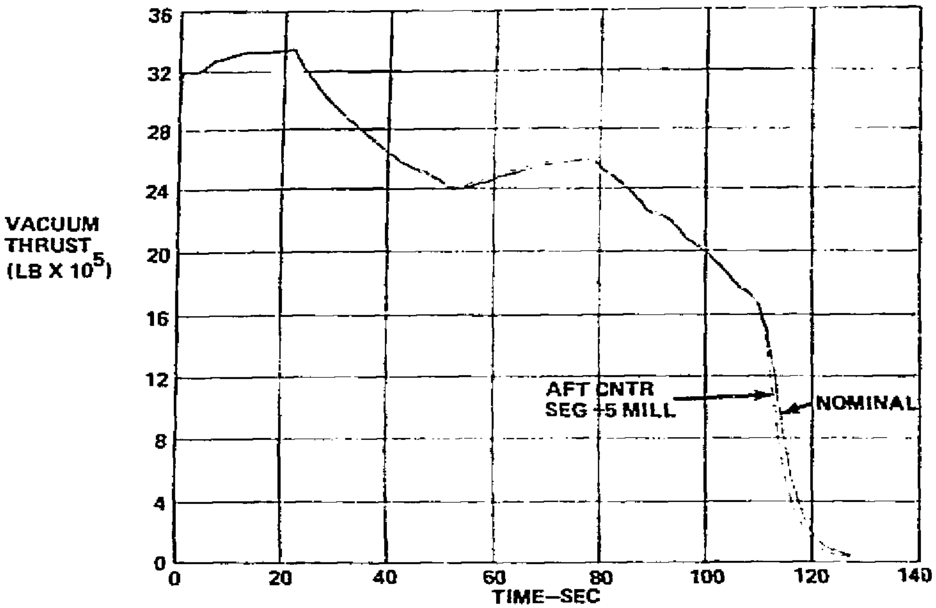

FIGURE II.17 COMPARISON OF NOMINAL AND AFT CENTER SEGMENT REPLACEMENT WITH 5 MILL BURN RATE INCREASE

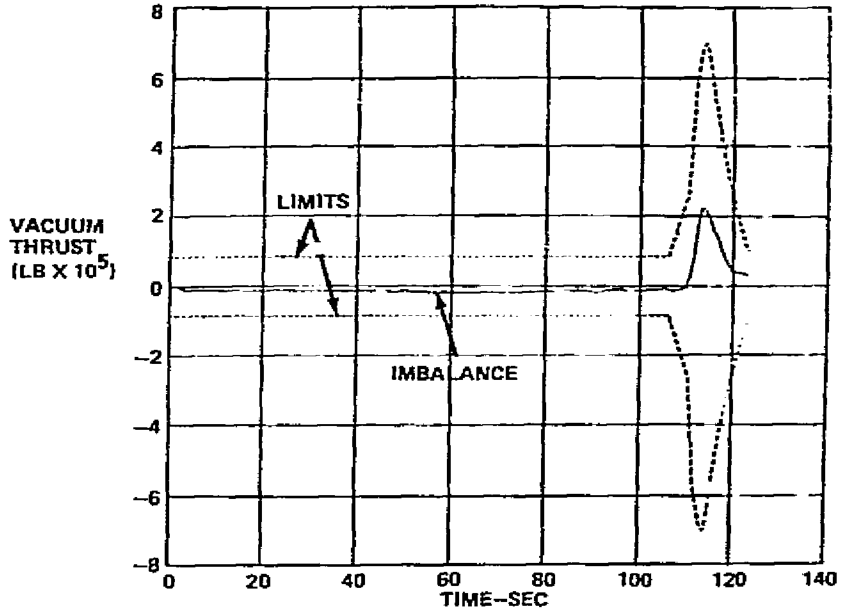

FIGURE II.18 THRUST IMBALANCE FROM AFT CENTER SEGMENT REPLACEMENT WITH +5 MILL BURN RATE VS. REQUIREMENT

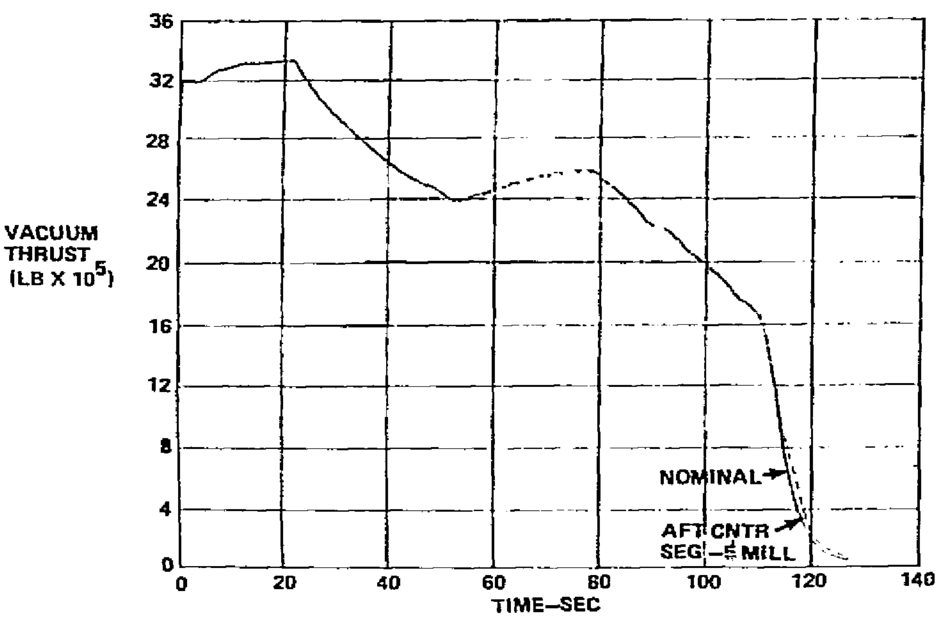

FIGURE II.19 COMPARISON OF NOMINAL AND AFT CENTER SEGMENT REPLACEMENT WITH 5 MILL BURN RATE DECREASE

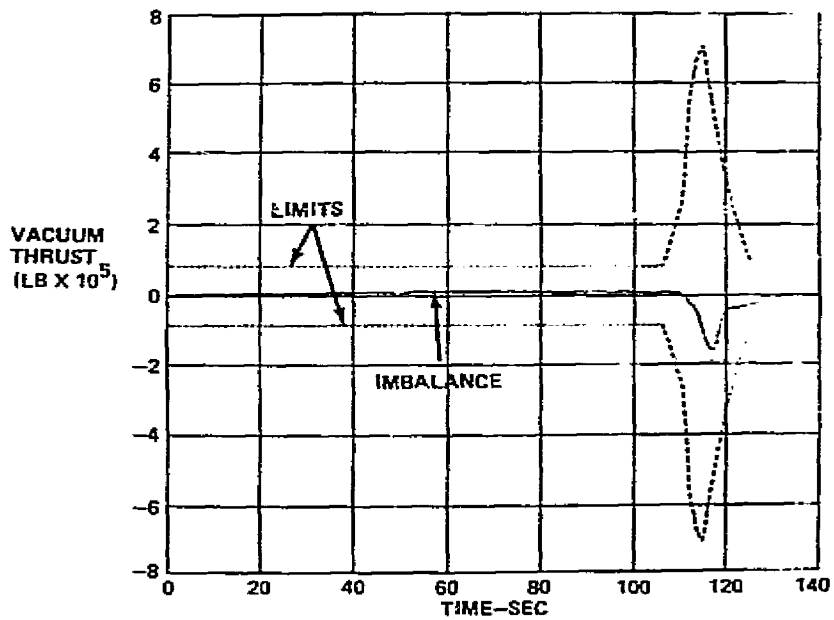

FIGURE II.20 THRUST IMBALANCE FROM AFT CENTER SEGMENT REPLACEMENT WITH –5 MILL BURN RATE VS. REQUIREMENT

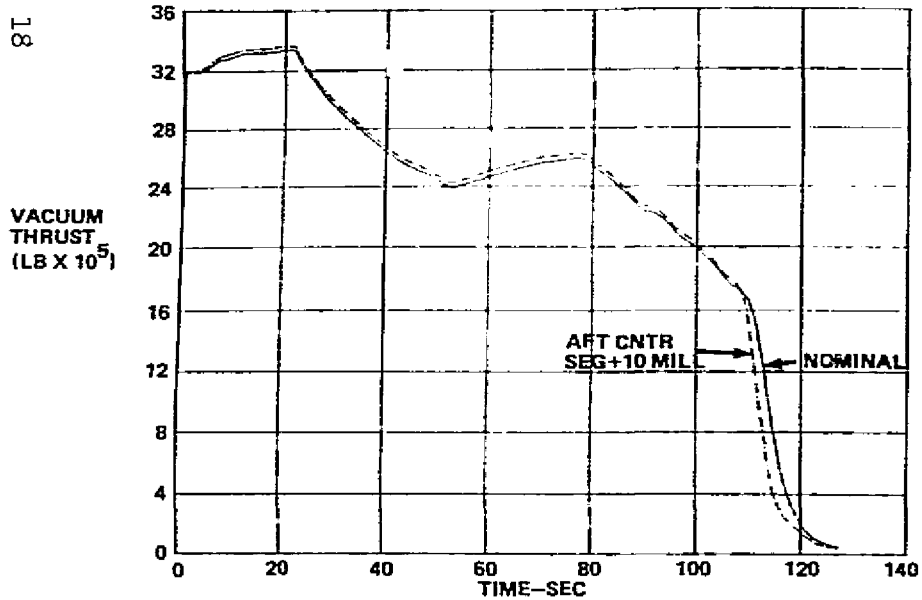

FIGURE II.21 COMPARISON OF NOMINAL AND AFT CENTER SEGMENT REPLACEMENT WITH 10 MILL BURN RATE INCREASE

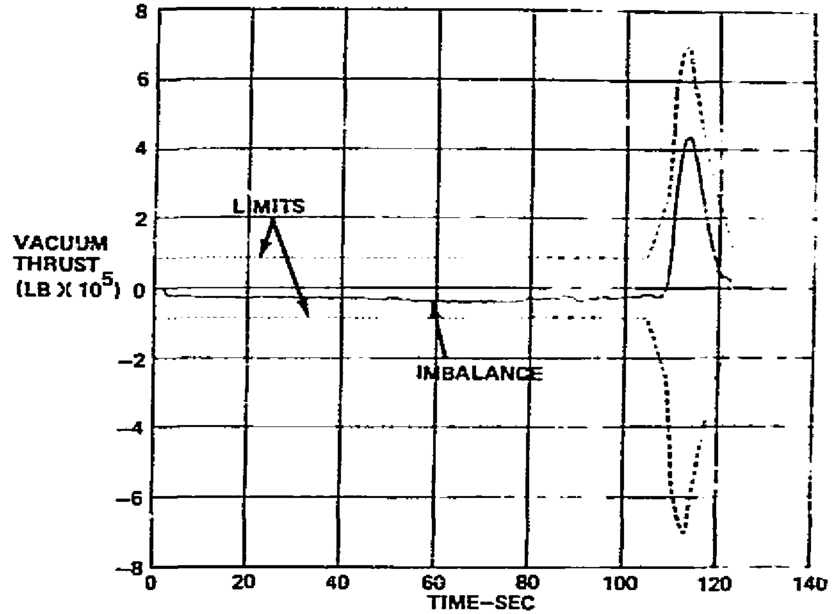

FIGURE II.22 THRUST IMBALANCE FROM AFT CENTER SEGMENT REPLACEMENT WITH +10 MILL BURN RATE VS. REQUIREMENT

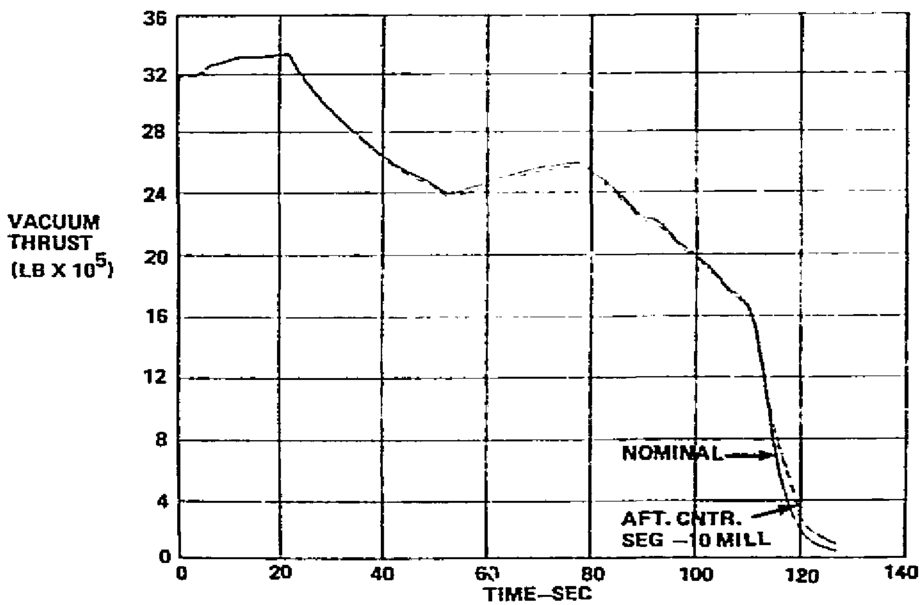

FIGURE II.23 COMPARISON OF NOMINAL AND AFT CENTER SEGMENT REPLACEMENT WITH 10 MILL BURN RATE DECREASE

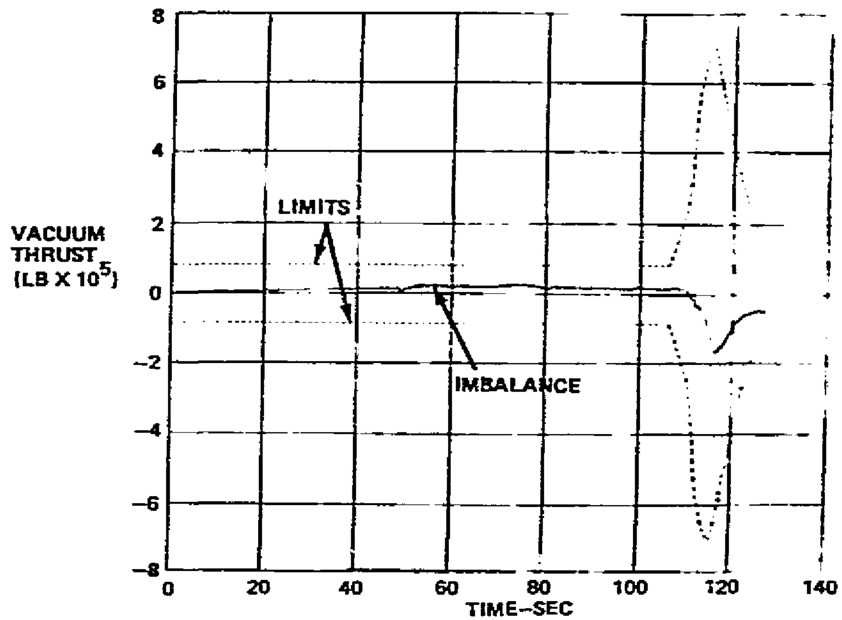

FIGURE II.24 THRUST IMBALANCE FROM AFT CENTER SEGMENT REPLACEMENT WITH –10 MILL BURN RATE VS REQUIREMENT

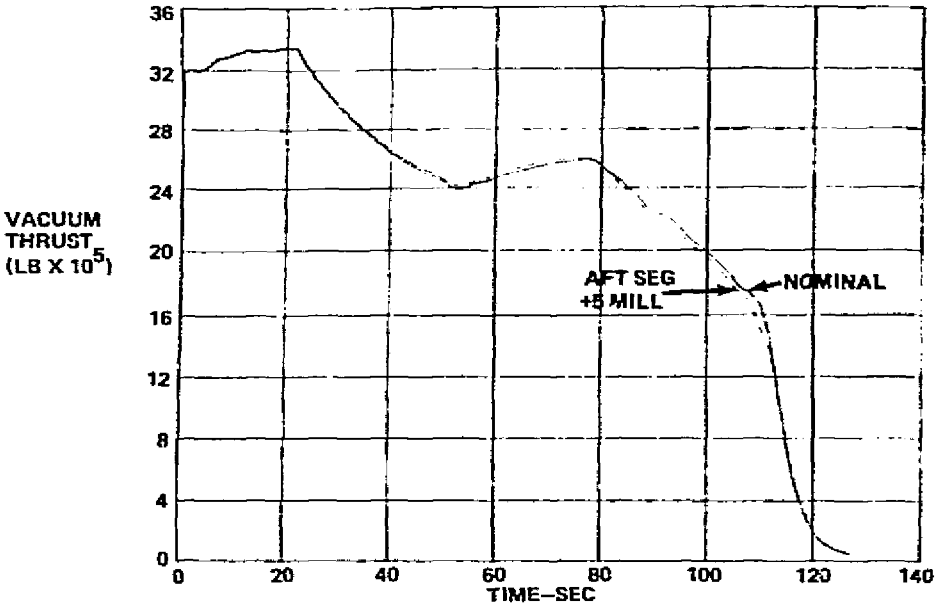

FIGURE II.25 COMAPRISON OF NOMINAL AND AFT SEGMENT REPLACEMENT WITH 5 MILL BURN RATE DECREASE

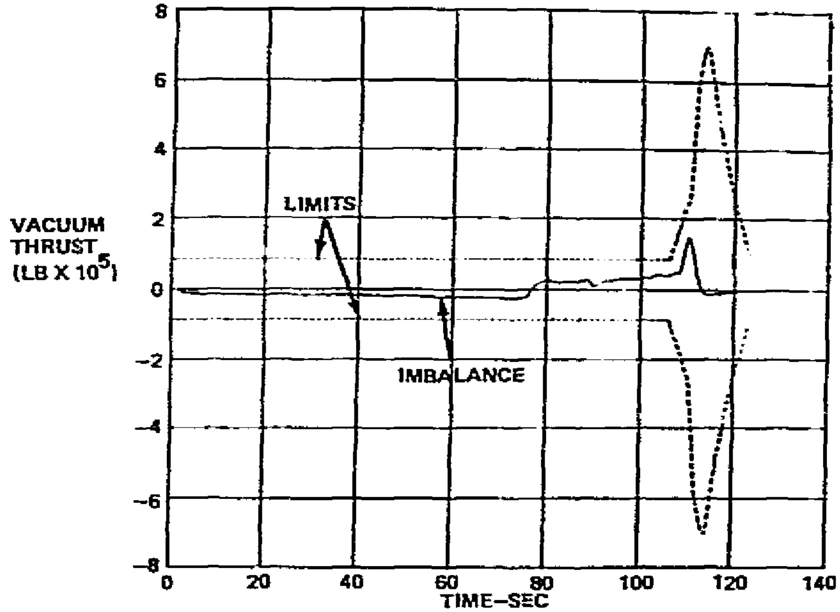

FIGURE II.26 THRUST IMBALANCE FROM AFT SEGMENT REPLACEMENT WITH +5 MILL BURN RATE VS. REQUIREMENT

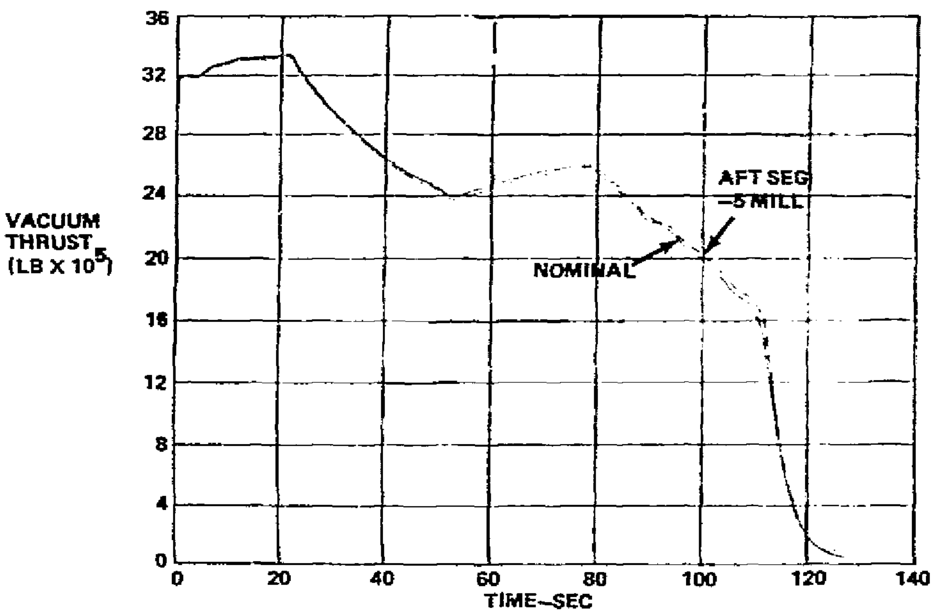

FIGURE II.27 COMPARISON OF NOMINAL AND AFT SEGMENT REPLACEMENT WITH 5 MILL BURN RATE DECREASE

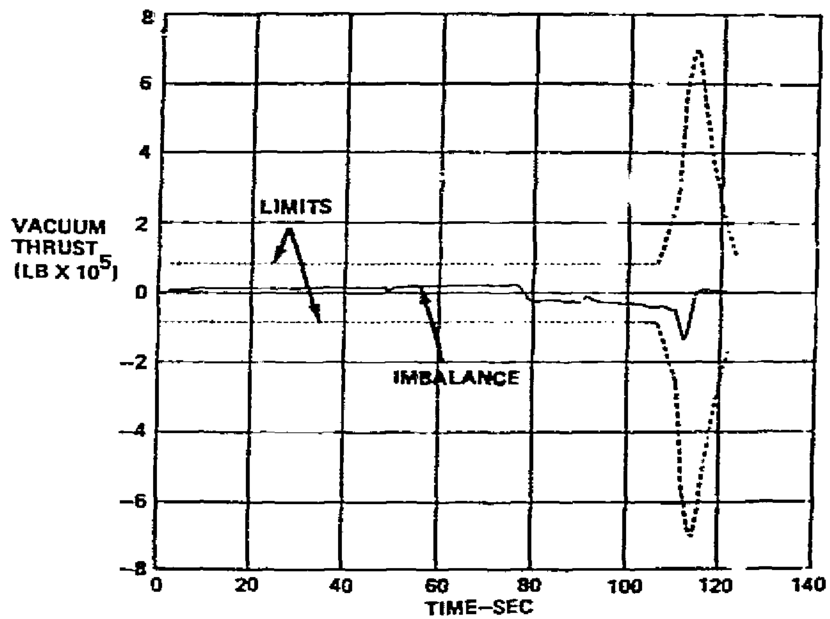

FIGURE II.28 THRUST IMBALANCE FROM AFT SEGMENT REPLACEMENT WITH –5 MILL BURN RATE VS. REQUIREMENT

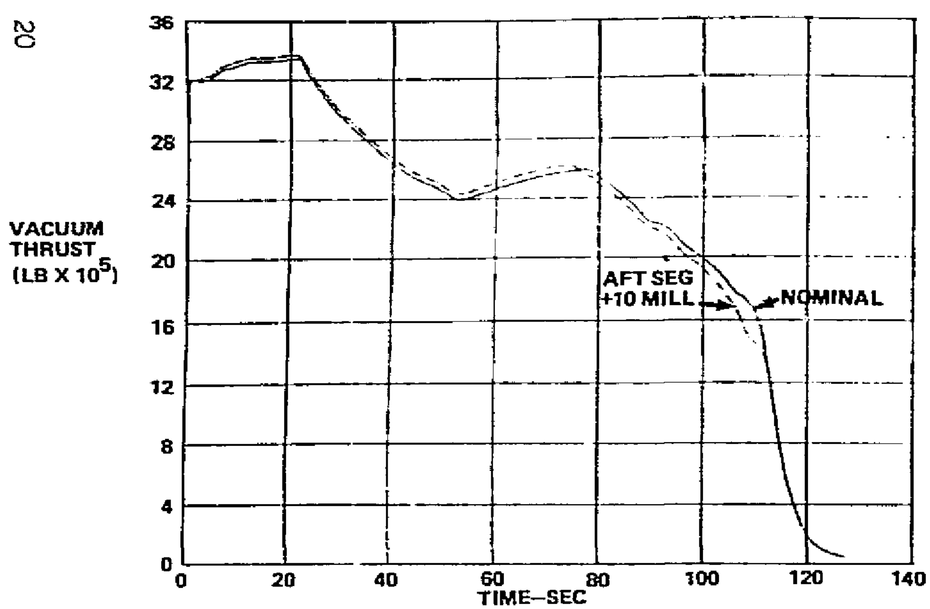

FIGURE II.29 COMPARISON OF NOMINAL AND AFT SEGMENT REPLACEMENT WITH 10 MILL BURN RATE INCREASE

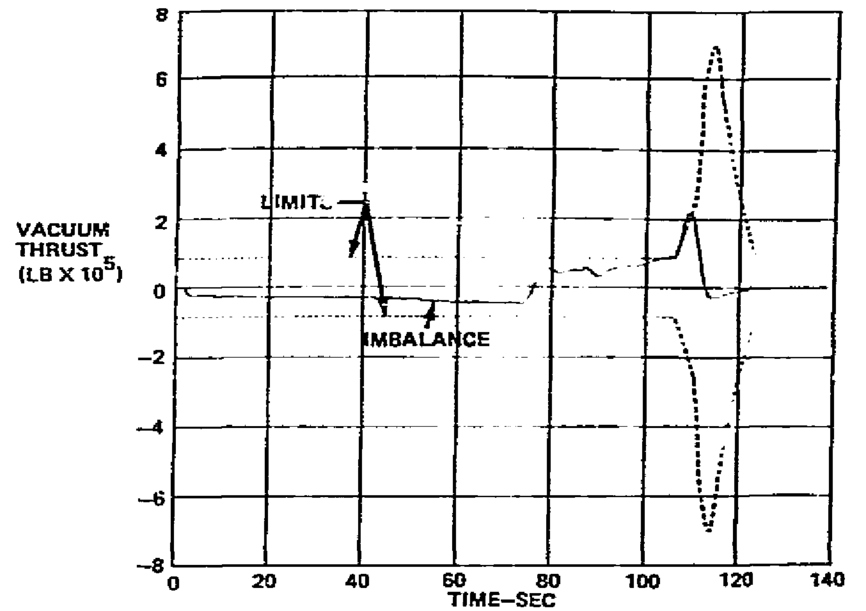

FIGURE II.30 THRUST IMBALANCE FROM AFT SEGMENT REPLACEMENT WITH +10 MILL BURN RATE VS. REQUIREMENT

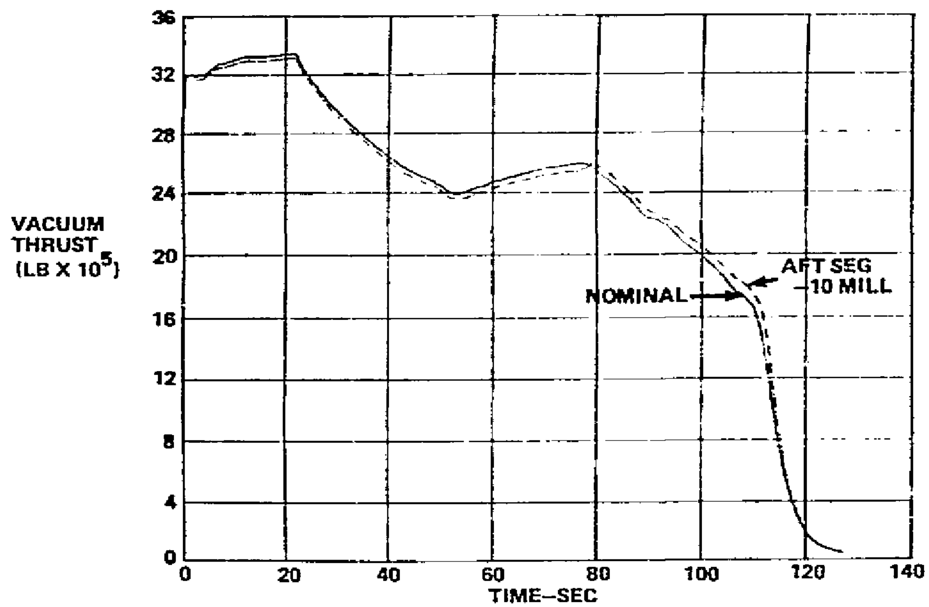

FIGURE II.31 COMPARISON OF NOMINAL AND AFT SEGMENT REPLACEMENT WITH 10 MILL BURN RATE DECREASE

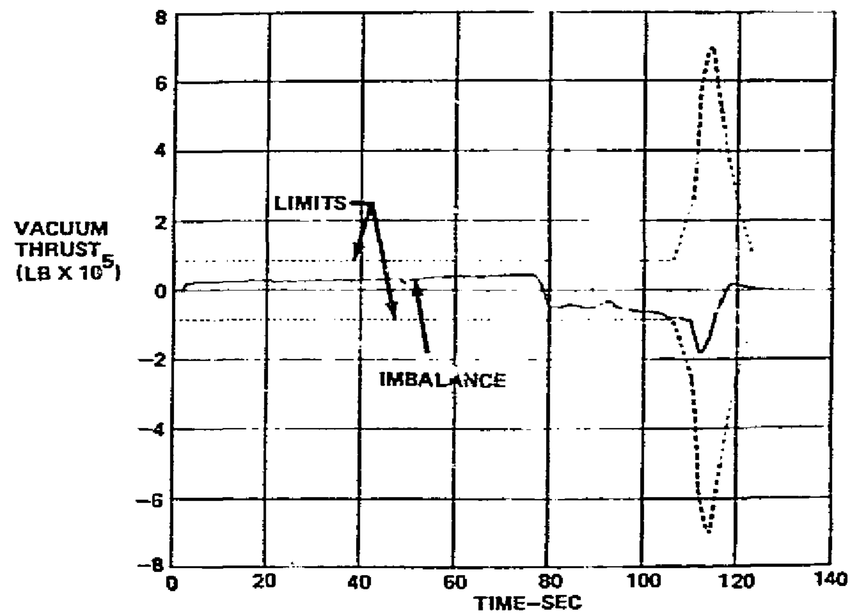

FIGURE II.32 THRUST IMBALANCE FROM AFT SEGMENT REPLACEMENT WITH –10 MILL BURN RATE VS. REQUIREMENT

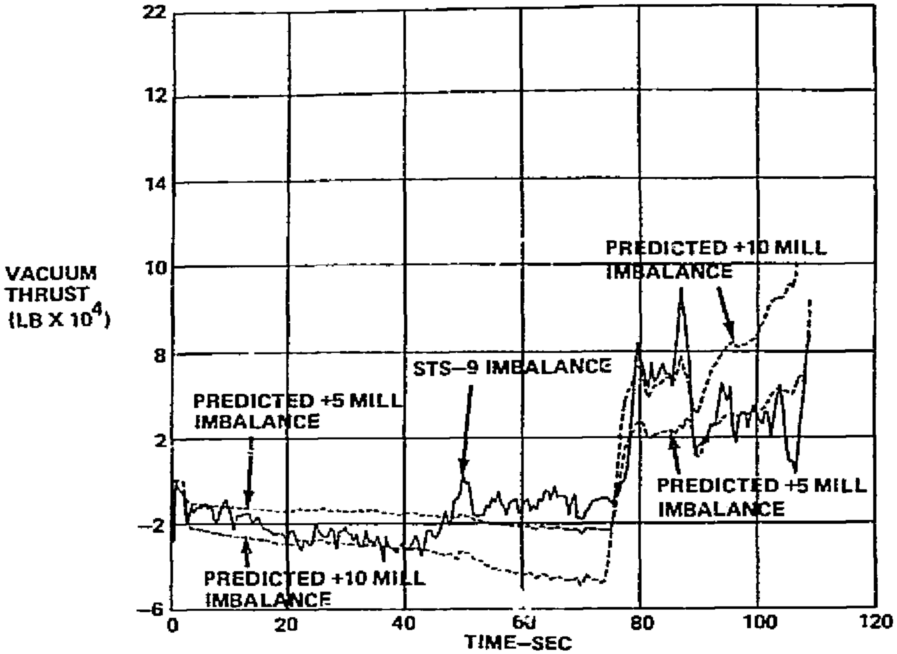

FIGURE II.33 COMPARISON OF STS-9 FLIGHT THRUST IMBALANCE TO PREDICTED THRUST IMBLANCE

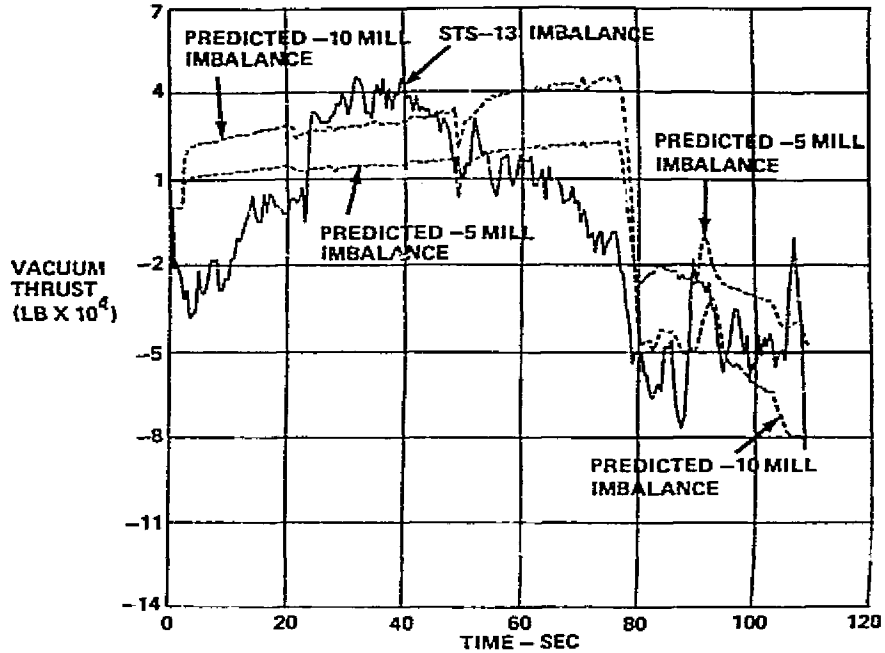

FIGURE II.34 COMPARISON OF STS-13 FLIGHT THRUST IMBALANCE TO PREDICTED THRUST IMBLANCE

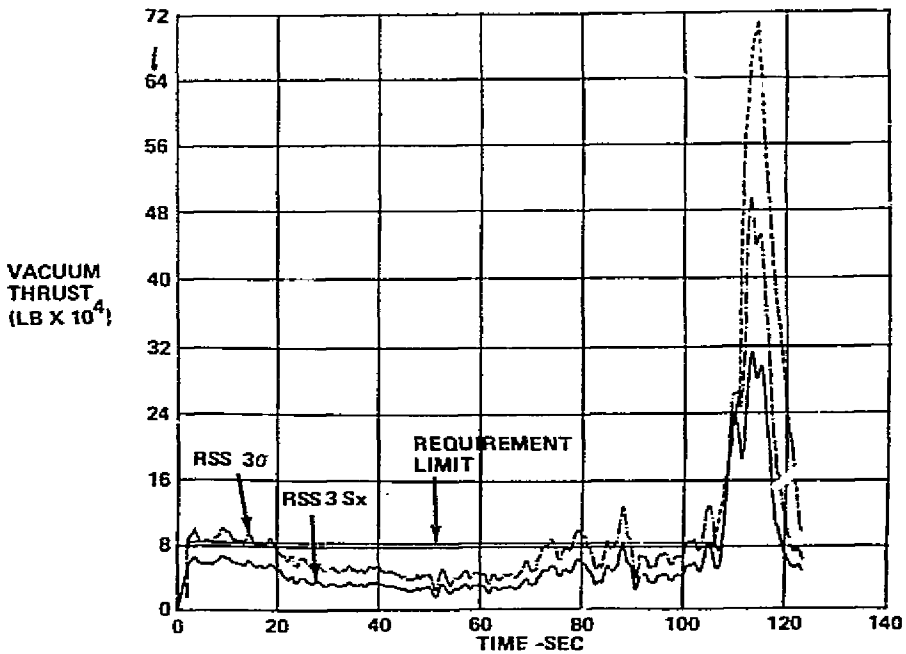

FIGURE II.35 TOTAL THRUST IMBALANCE FROM FORWARD SEGMENT REPLACEMENT WITH A +5 MILL BURN RATE

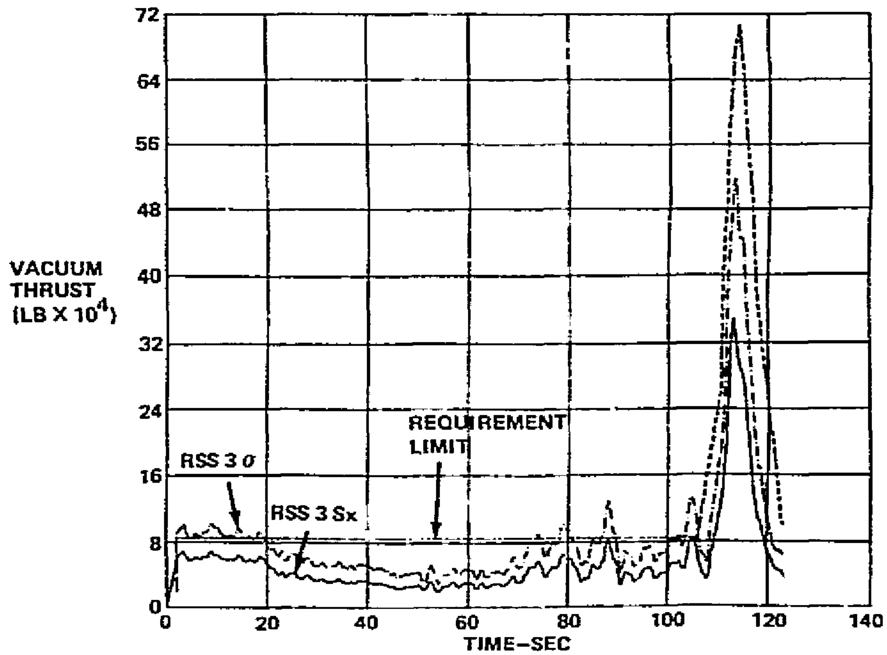

FIGURE II.36 TOTAL THRUST IMBALANCE FROM FORWARD SEGMENT REPLACEMENT WITH A -5 MILL BURN RATE

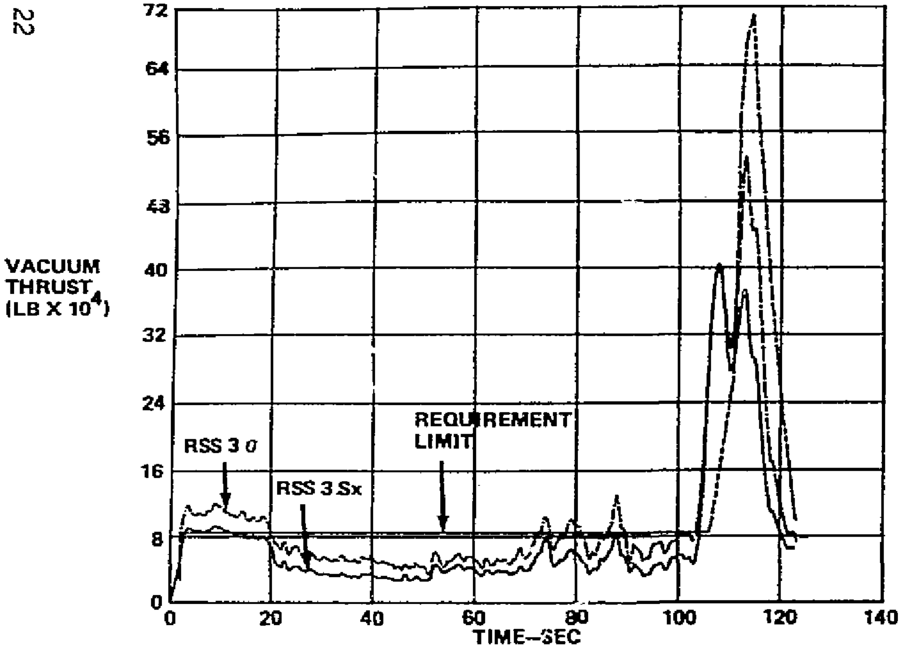

FIGURE II.37 TOTAL THRUST IMBALANCE FROM FORWARD SEGMENT REPLACEMENT WITH A +10 MILL BURN RATE

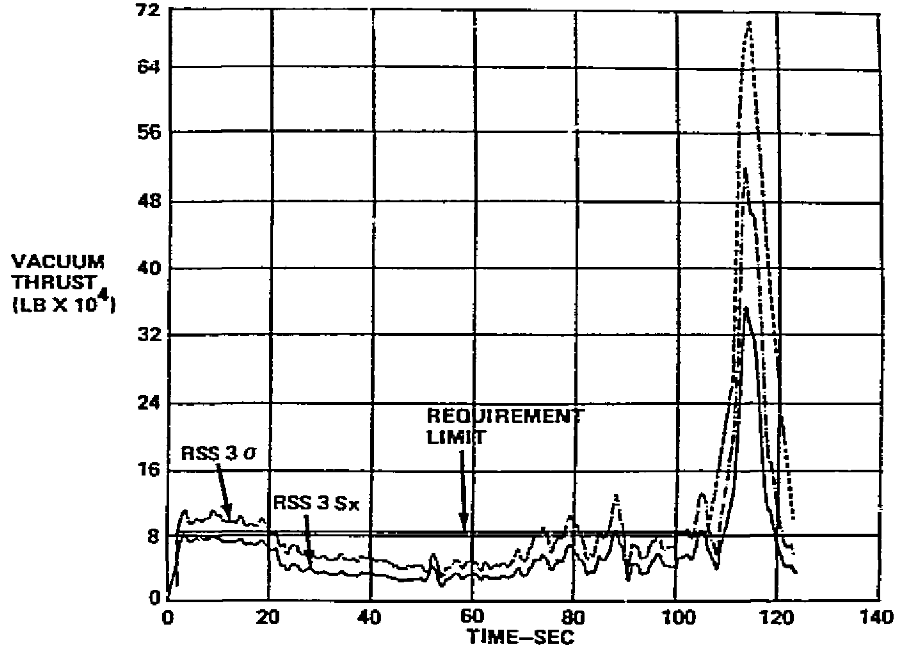

FIGURE II.38 TOTAL THRUST IMBALANCE FROM FORWARD SEGMENT REPLACEMENT WITH A −10 MILL BURN RATE

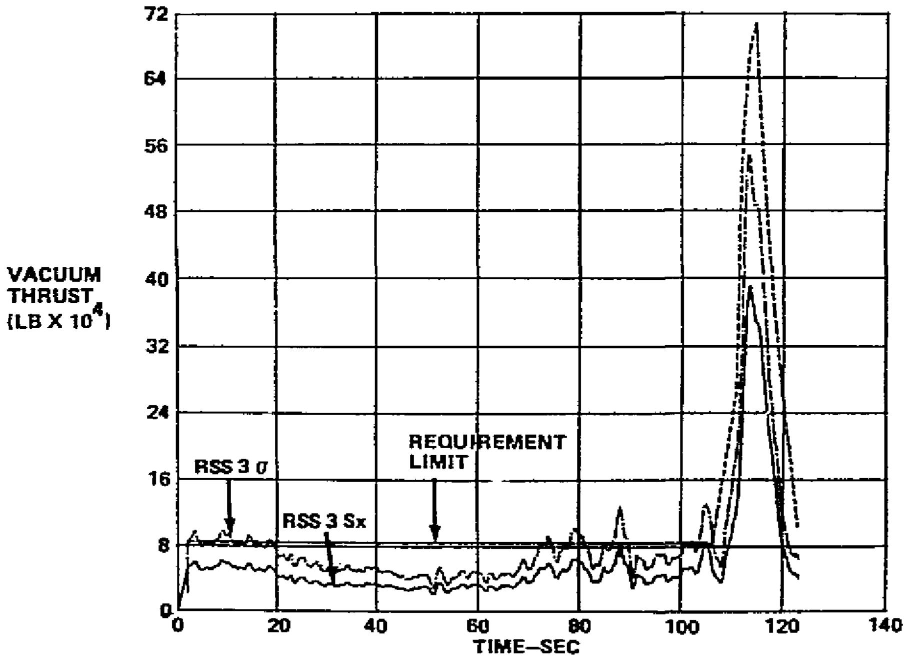

FIGURE II.39 TOTAL THRUST IMBALANCE FROM FORWARD CENTER SEGMENT REPLACEMENT WITH A +5 MILL BURN RATE

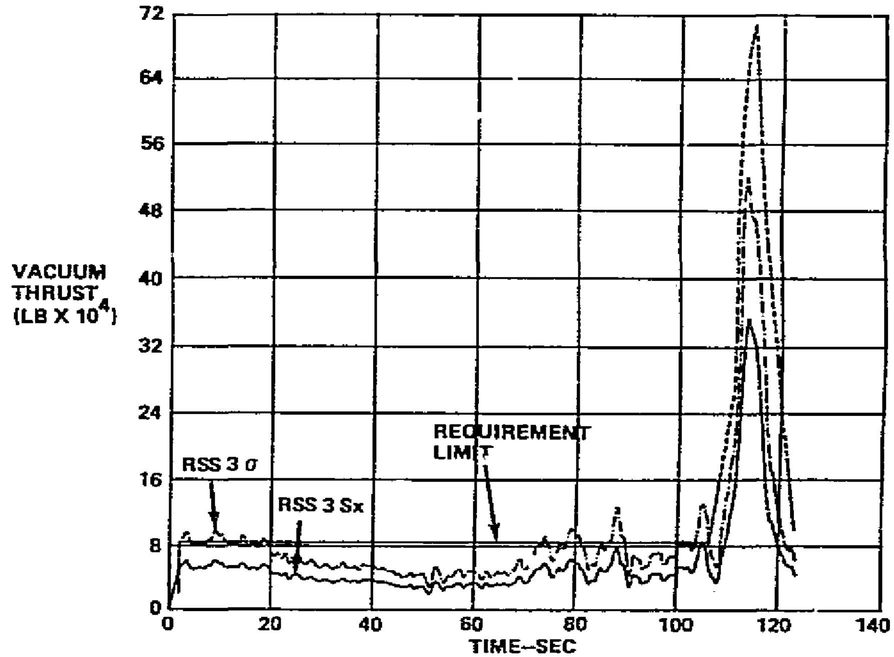

FIGURE II.40 TOTAL THRUST IMBALANCE FROM FORWARD CENTER SEGMENT REPLACEMENT WITH A −5 MILL BURN RATE

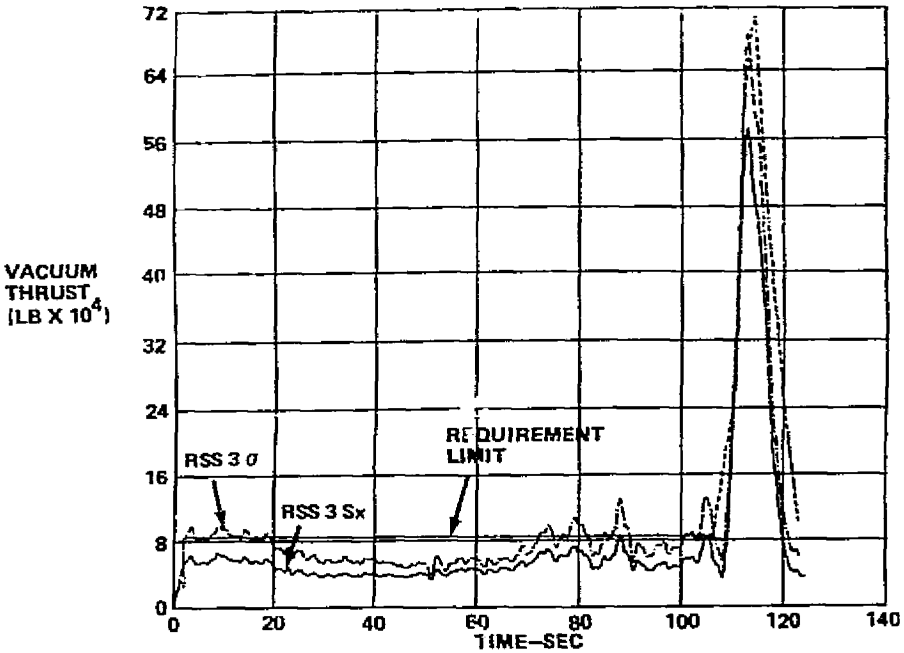

FIGURE II.41 TOTAL THRUST IMBALANCE FROM FORWARD CENTER SEGMENT REPLACEMENT WITH A +10 MILL BURN RATE

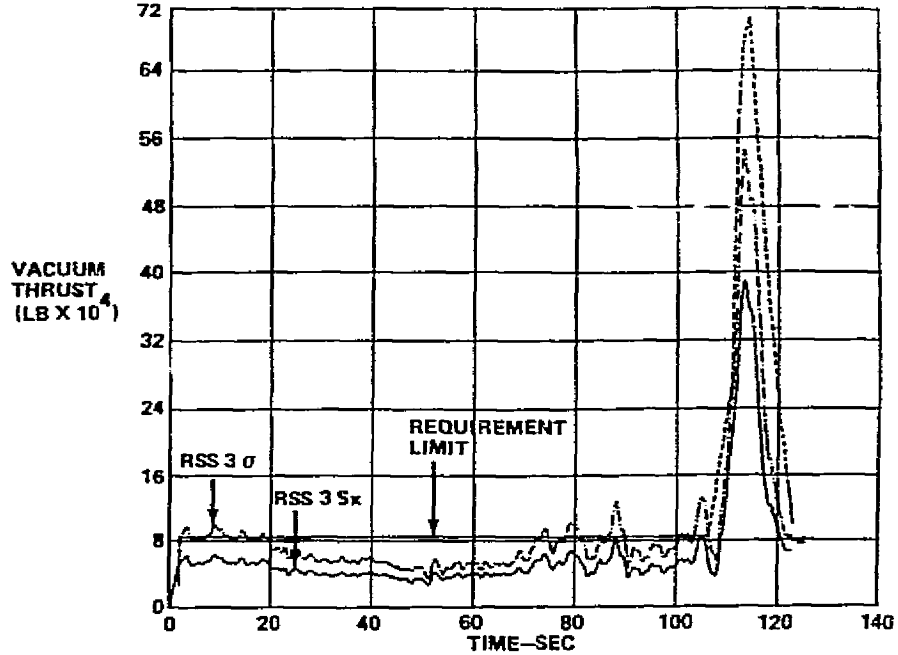

FIGURE II.42 TOTAL THRUST IMBALANCE FROM FORWARD CENTER SEGMENT REPLACEMENT WITH A –10 MILL BURN RATE

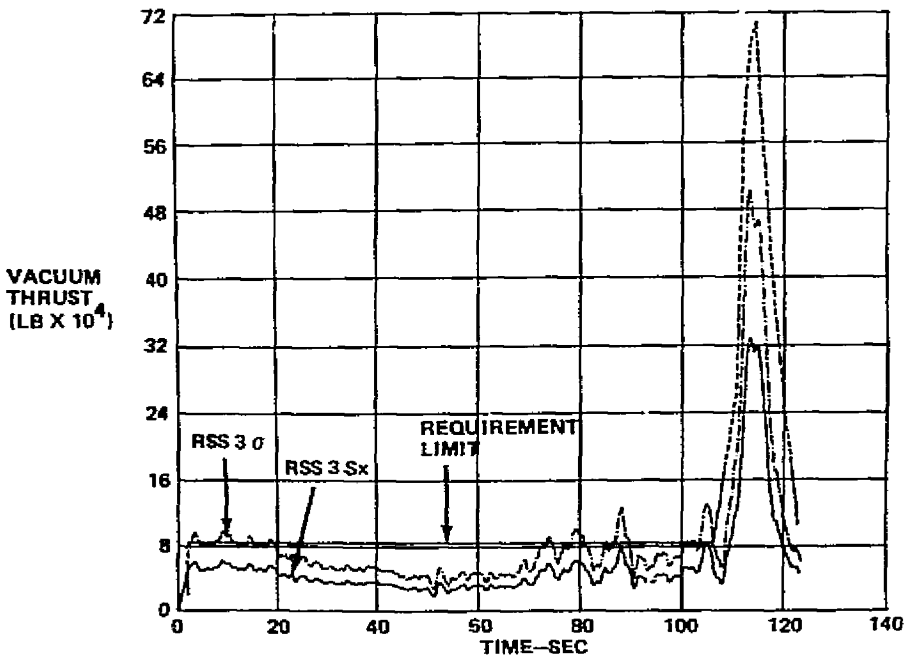

FIGURE II.43 TOTAL THRUST IMBALANCE FROM AFT CENTER SEGMENT REPLACEMENT WITH A +5 MILL BURN RATE

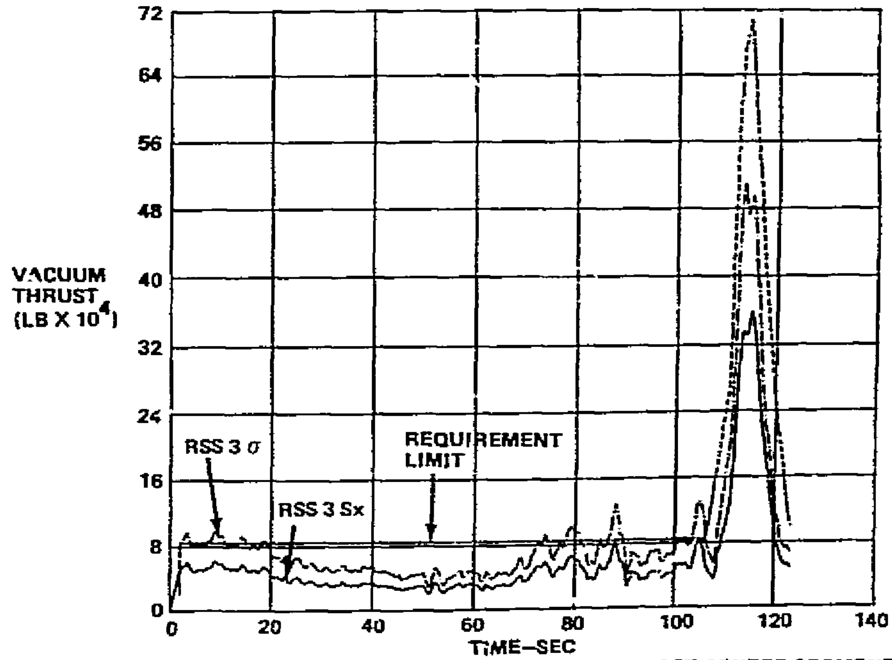

FIGURE II.44 TOTAL THRUST IMBALANCE FROM AFT CENTER SEGMENT REPLACEMENT WITH A –5 MILL BURN RATE

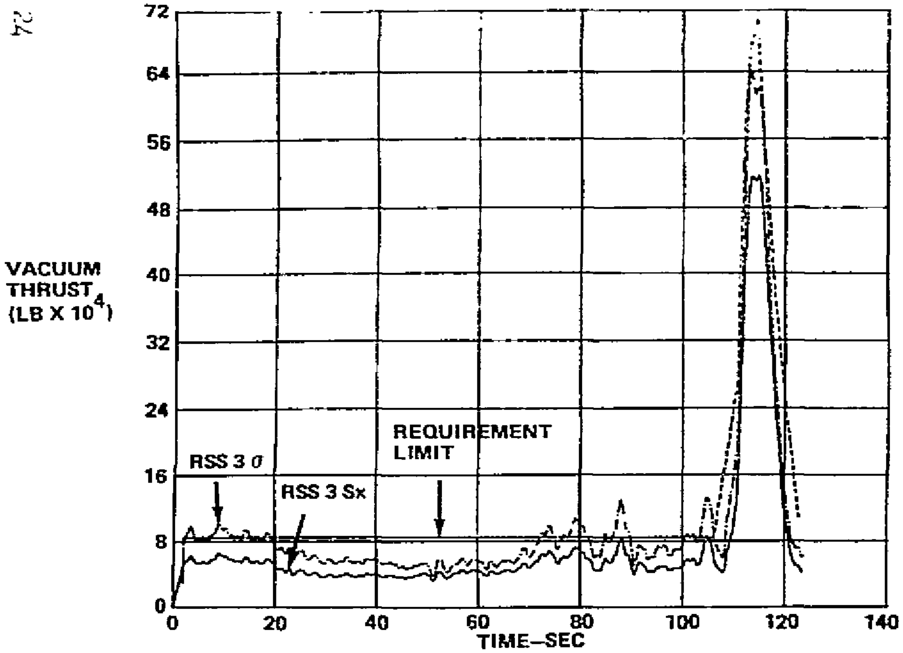

FIGURE II.45 TOTAL THRUST IMBALANCE FROM AFT CENTER SEGMENT REPLACEMENT WITH A +10 MILL BURN RATE

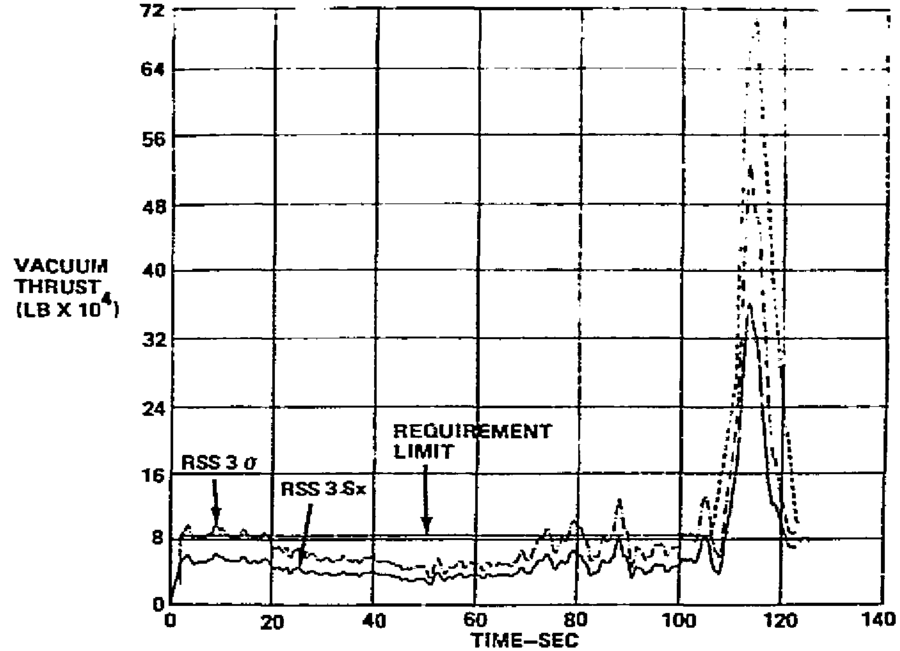

FIGURE II.46 TOTAL THRUST IMBALANCE FROM AFT CENTER SEGMENT REPLACEMENT WITH A –10 MILL BURN RATE

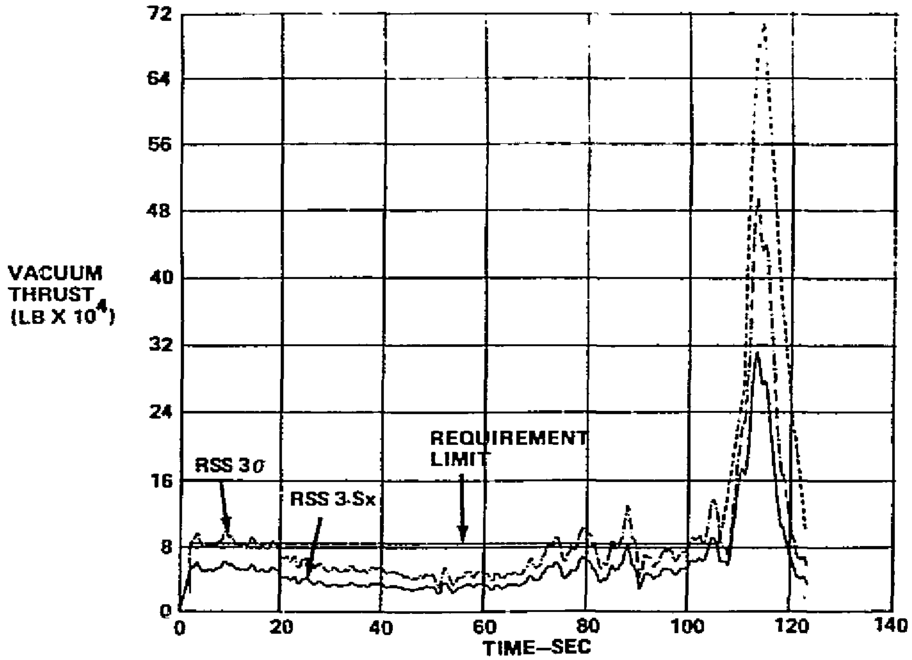

FIGURE II.47 TOTAL THRUST IMBALANCE FROM AFT SEGMENT REPLACEMENT WITH A +5 MILL BURN RATE

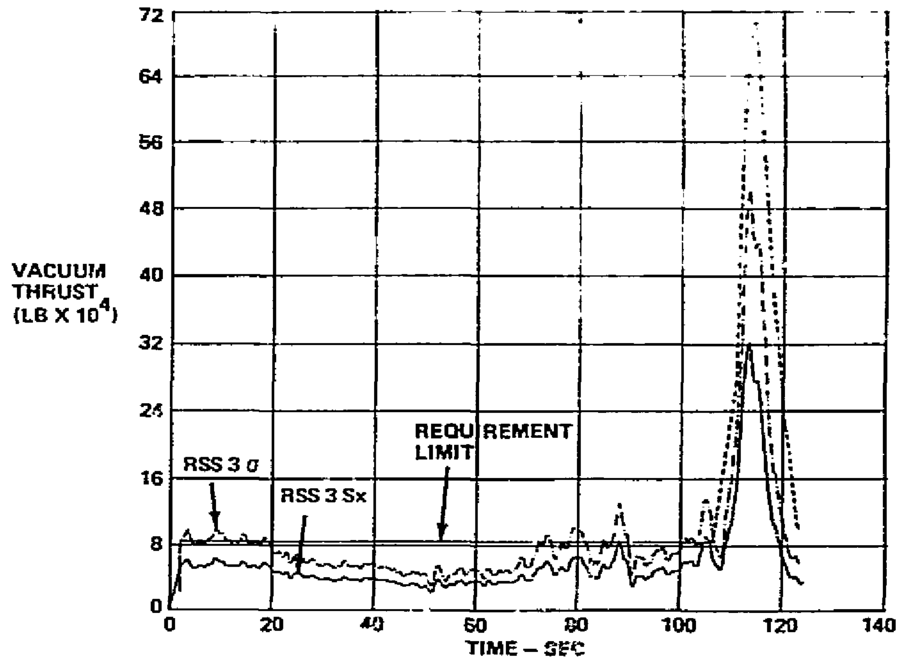

FIGURE II.48 TOTAL THRUST IMBALANCE FROM AFT SEGMENT REPLACEMENT WITH A –5 MILL BURN RATE

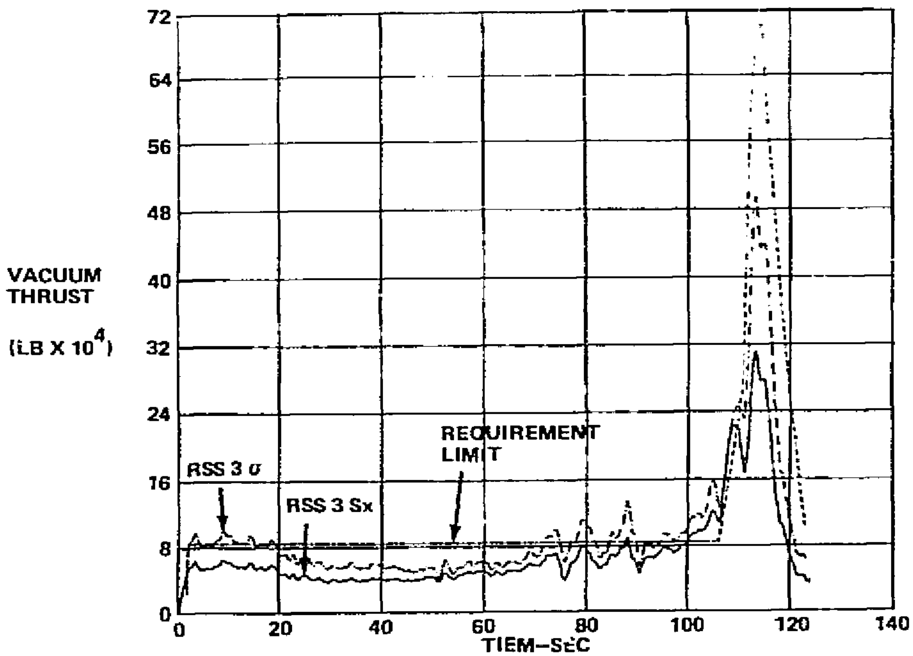

FIGURE II.49 TOTAL THRUST IMBALANCE FROM AFT SEGMENT REPLACEMENT WITH A +10 MILL BURN RATE

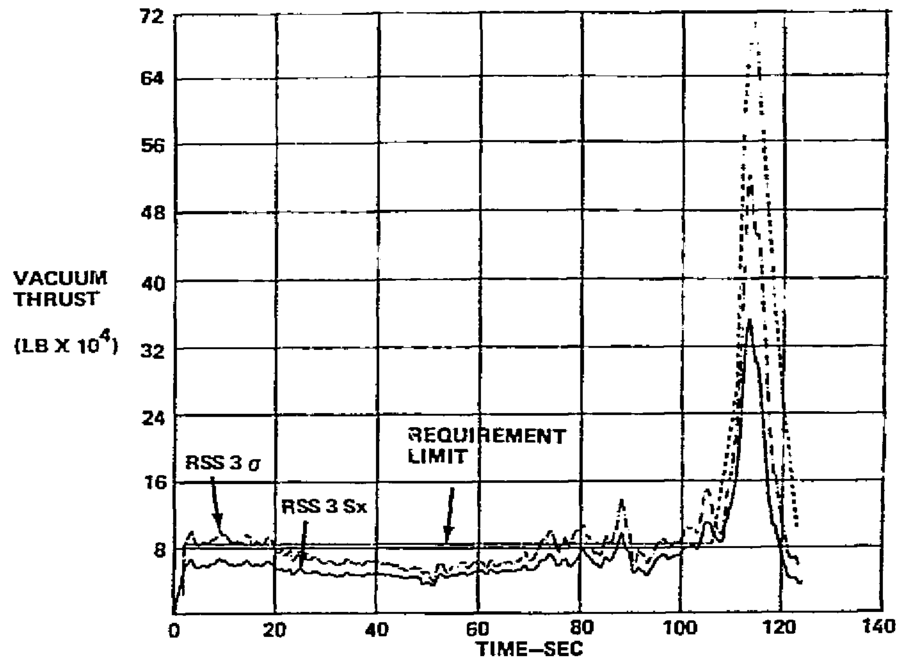

FIGURE II.50 TOTAL THRUST IMBALANCE FROM AFT SEGMENT REPLACEMENT WITH A –10 MILL BURN RATE

III. CONCLUSIONS

The measured flight thrust imbalance data has been statistically analyzed and used to project the 3σ booster thrust imbalance time history. Because of the small sample size, the 3σ imbalance projection exceeds the allowable. The 3 S emains within the allowable which indicates that as the population sample size increases, the imbalance requirements will be shown adequate.

The replacement of an SRM segment should be approached with care. There is a good possiblity of exceeding the thrust imbalance limits during flight. Because of each segment's contribution to the thrust, the exceedances occur in different places. Exceedances in different intervals of flight may be acceptable as demonstrated in the STS-9/13 preflight analyses. A system assessment of flight worthiness should be made on a per flight basis prior to accepting or rejecting the possibility of a segment replacement.

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APPROVAL

SPACE SHUTTLE BOOSTER THRUST IMBALANCE ANALYSIS

By William R. Bailey and Douglas L. Blackwell

The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

G. D. HOPSON
Director, Systems Analysis and
Integration Laboratory

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