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Characterization of Space Shuttle Reusable Rocket Motor Static Test Stand Thrust Measurements

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CHARACTERIZATION OF SPACE SHUTTLE REUSABLE ROCKET MOTOR STATIC TEST STAND THRUST MEASUREMENTS

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ABSTRACT

Space Shuttle Reusable Solid Rocket Motors (RSRM) are static tested at two ATK Thiokol Propulsion facilities in Utah, T-24 and T-97. The newer T-97 static test facility was recently upgraded to allow thrust measurement capability. All previous static test motor thrust measurements have been taken at T-24; data from these tests were used to characterize thrust parameters and requirement limits for flight motors. Validation of the new T-97 thrust measurement system is required prior to use for official RSRM performance assessments.

Since thrust cannot be measured on RSRM flight motors, flight motor measured chamber pressure and a nominal thrust-to-pressure relationship (based on static test motor thrust and pressure measurements) are used to reconstruct flight motor performance. Historical static test and flight motor performance data are used in conjunction with production subscale test data to predict RSRM performance. The predicted motor performance is provided to support Space Shuttle trajectory and system loads analyses. Therefore, an accurate nominal thrust-to-pressure (F/P) relationship is critical for accurate RSRM flight motor performance and Space Shuttle analyses.

Flight Support Motors (FSM) 7, 8, and 9 provided thrust data for the validation of the T-97 thrust measurement system. The T-97 thrust data were analyzed and compared to thrust previously measured at T-24 to verify measured thrust data and identify any test-stand bias. The T-97 F/P data were consistent and within the T-24 static test statistical family expectation. The FSMs 7-9 thrust data met all NASA contract requirements, and the test stand is now verified for future thrust measurements.

The average T-97 F/P value was 0.32 percent lower (statistically significant) than the T-24 population. A correlation between motor average F/P and motor average pressure was identified that can explain 60 percent of the variation in vacuum F/P, and part of the test-stand bias between T-24 and T-97. Many ballistic parameters were analyzed to determine/quantify their contribution to the F/P motor-to-motor variation and to the bias. Normalizing the F/P data to a common average pressure reduced the test stand bias to 0.14 percent.

INTRODUCTION

The Space Shuttle Reusable Solid Rocket Motor (RSRM) is manufactured by ATK Thiokol Propulsion. Each RSRM provides a maximum of approximately 3.5 million pounds of thrust, and burns for approximately two minutes. The nominal RSRM thrust trace is shown in Figure 1.

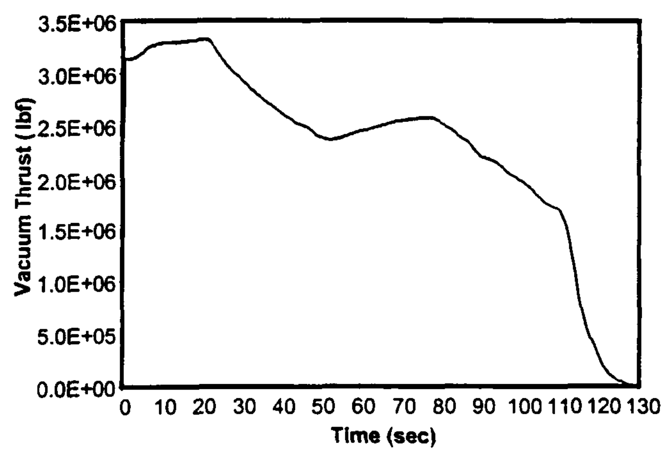

Figure 1. Nominal RSRM Thrust-Time Trace

Full-scale static test stands T-24 and T-97 were constructed to measure thrust on high performance motors (HPM) and RSRMs. The HPM was the precursor to the RSRM; the performance of the two motors is very similar.

Current motor performance predictions and motor performance NASA contract requirements are based on static test motor thrust measured at T-24. The predictions are used for trajectory and system loads analyses conducted by the Space Shuttle performance community (Marshall Space Flight Center, Johnson Space Center/Level II, and Boeing).

T-97 was refurbished and repaired in 1996 to enable thrust measurement. FSMs 7-9 were the first static test motors to have thrust data collected from the T-97 test stand. All previous RSRM and HPM static motor thrust measurements were taken at T-24.

The thrust measured at T-97 was analyzed and compared to thrust measured previously at T-24 to verify the measured thrust data and to identify any test stand bias. If there is a test stand bias, it needs to be established so any static test data anomalies can be properly addressed.

This paper presents the ballistics parameter results from the first three motors that had thrust measured using the T-97 test stand (FSMs 7-9). An overview of the configuration and calibration of the T-97 thrust measurement system is presented. The F/P analyses and results are presented. Also, a significant contributor to T-24 and T-97 F/P bias is presented.

DISCUSSION

HISTORY OF THE TEST STANDS

T-24 was built to enable ATK Thiokol to static test the Space Shuttle solid rocket motors. The T-24 test stand became operational in mid-1977. The T-24 test stand thrust measurements were locked out in 1995 due to a flexure failure.

The T-97 test stand became thrust operational in 1998. The T-97 test stand thrust measuring system had been "locked out" due to a flexure failure that occurred during the original T-97 systems checkout in 1987. In 1996 the decision was made to refurbish and repair the T-97 test stand to enable thrust measurement. T-97 was chosen for future thrust measurements over T-24 because T-97 has a better load test calibrator, a larger data acquisition system, and improved environmental controls. The T-97 test stand configuration is shown in Figure 2.

The most significant difference between the T-24 and T-97 test stands is the T-97 load test applicator/calibrator. The T-97 load applicator has the ability to apply 3.5 million pounds of axial load to the

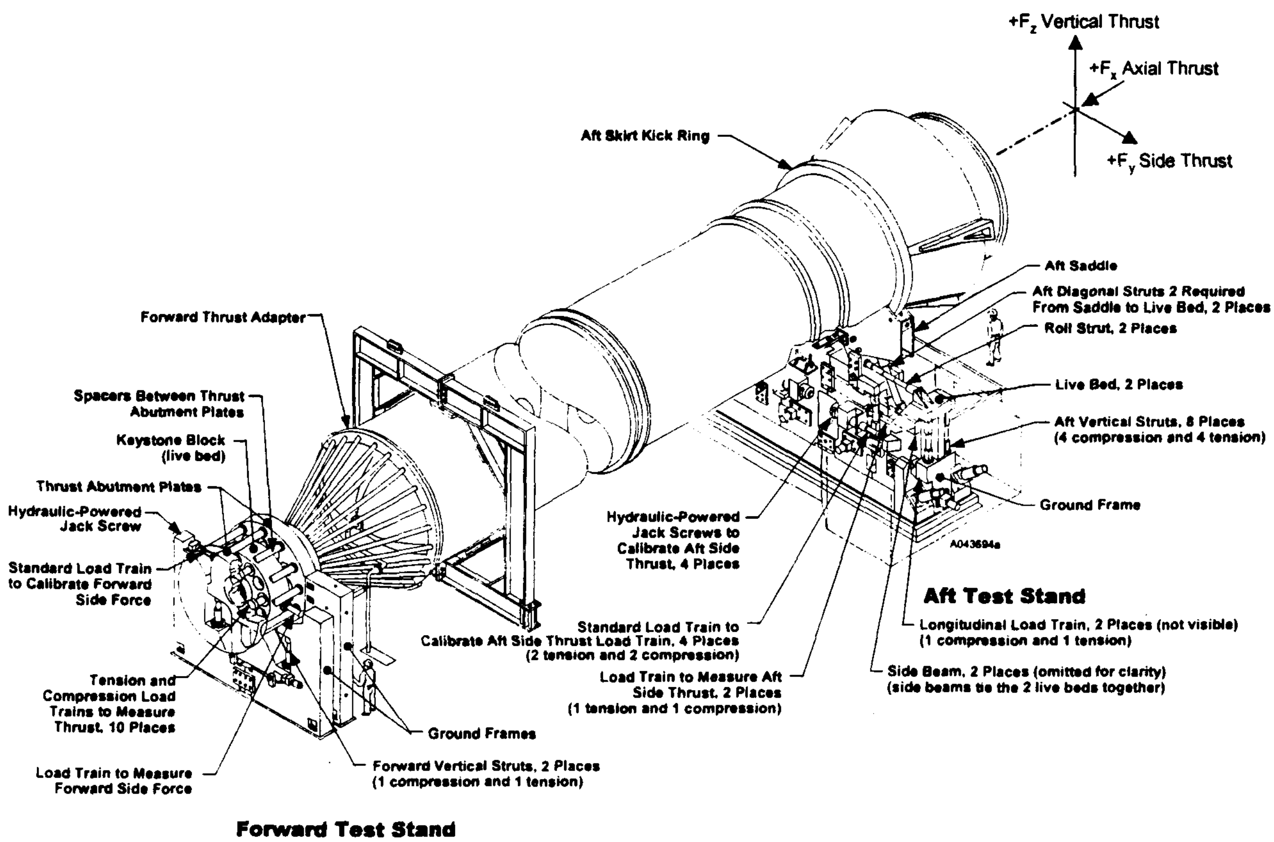

Figure 2. T-97 Static Test Stand

test stand and to measure the applied load with a separate set of thrust measurement load cells. The T-97 test stand load calibration system is traceable to the National Institute of Standards and Technology (NIST). The load application/calibration system at T-24 is capable of applying only 10 percent of full-scale load, and is not traceable to NIST.

T-97 THRUST CHANNEL CONFIGURATION AND SUMMATION

As shown on Figure 2, T-97 has a forward test stand and an aft test stand for motor attachment and thrust measurement. The forward test stand has 22 individual thrust measurement channels (20 axial and two side/lateral). The aft test stand has eight individual thrust measurement channels (four axial, four side/lateral).

The individual thrust measurements are taken from load cells. Each load cell has two identical strain-gage bridges, A and B, which are measurement channels. The axial and side thrust values are calculated by averaging the A and B summations from the axial and lateral load cells, respectively. A and B summations have shown to be within 0.2 percent of each other. There are no vertical axis load cells; this component of thrust is calculated using measured axial thrust and nozzle position data. Total Utah-site thrust is calculated by root-sum-squaring the axial, side and vertical components of thrust.

T-97 TEST STAND CALIBRATION AND ACCURACY

In order to determine the overall test stand accuracy, the T-97 test stand is calibrated by applying a 3.5 million pound load to the test stand. The load is applied by the test stand load applicator and measured by calibrated load cells. Proper calibration of the test stand is verified by agreement of the measured data with the applied load.

Twenty-eight calibration test results (conducted before, during and after FSM-7) showed that an average sensitivity bias of –0.5208 percent was present between the test stand measured load and the applied load from the load applicator. The test stand load applicator values are considered the most accurate, as this device is NIST traceable. It was, therefore, decided that FSM-7 and future measured thrust data would be corrected by +0.5208 percent to remove the bias.

Note: The FSMs 7-9 measured thrust data presented in this report have been corrected by the +0.5208 percent.

MEASURED THRUST COMPARED TO NASA CONTRACT REQUIREMENTS

The FSMs 7-9 thrust data met all NASA contract requirements (maximum sea level thrust, average specific impulse, etc.), and the test stand is now verified for future thrust measurements.

MEASURED AND PRESSURE-RECONSTRUCTED THRUST COMPARISON

The pressure-reconstructed thrust is calculated from the measured chamber pressure and a nominal thrust-to-pressure relationship established from a set of T-24 static test motors (Block Model). The current Block Model F/P ratio (3919.1) is based on eight RSRM motors that were static tested at T-24 (Demonstration Motors 8-9, Qualification Motor 6, Production Verification Motor 1, and FSMs 1-4).

Because thrust cannot be measured on flight motors, measured pressure and the Block Model F/P ratio are used to calculate/reconstruct flight motor thrust related parameters. To establish the similarity of measured thrust from T-97 to T-24, FSM 7-9 pressure-reconstructed thrust was compared to measured thrust from T-97.

Thrust that was measured using the T-97 thrust stand correlated well to the thrust that was reconstructed from measured pressure: the average differences for FSMs 7-9 were within 0.50 percent during the steady state portion of the tests. For example, Figure 3 shows the FSM-9 measured thrust compared to the pressure-reconstructed thrust and Figure 4 shows the percent difference between the pressure-reconstructed and measured thrusts. On average, the FSM-9 measured thrust was 0.35 percent less than the pressure-reconstructed thrust during the steady state portion of the test. The FSM-9 differences were similar in shape and magnitude to what was observed on FSM 7-8.

THRUST OVER PRESSURE (F/P) RATIO DATA ANALYSIS

A static motor's thrust trace shape is influenced by many parameters and can be difficult to assess. Propellant mean bulk temperature (PMBT) and burn rate variations in the propellant grain: raw material, mechanical properties, and processing variations all contribute to motor-to-motor trace shape variation.

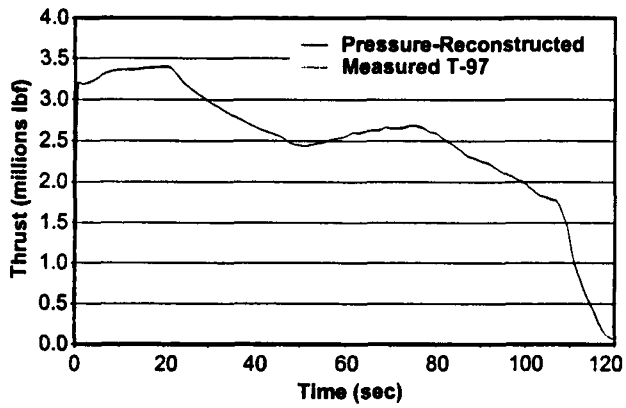

Figure 3. FSM-9 Measured and Pressure Reconstructed Thrust

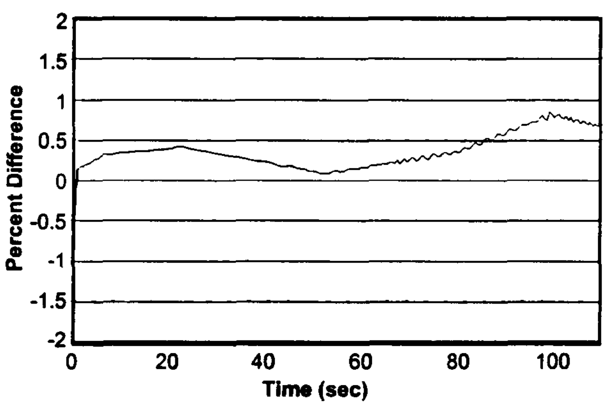

Figure 4. FSM-9 Pressure Reconstructed vs. Measured Thrust Comparison

The best way to analyze thrust data is to compare the motor's measured thrust to the measured pressure. Thrust is directly related to nozzle stagnation pressure and throat area:

$F = C_f \bullet P_{sn} \bullet A_t$, C_f = thrust coefficient
P_{sn} = nozzle stagnation pressure
A_t = nozzle throat area

Assuming a fairly constant C_f and A_t, the thrust is directly related to the nozzle stagnation pressure:

$F = K \bullet P_{sn}$,
$K \approx$ constant (changes slightly due to throat erosion)

Since P_{sn} cannot be measured and any calculated values would contain modeling error, the measured head-end pressure, P_h, is used to calculate and compare F/P ratios. The parameter K changes during motor operation due to the reduction of internal pressure drop (when P_h is used) and nozzle throat erosion, but the value should be similar, motor-to-motor, at specific burn times. All the motors have similar burn times, internal pressure drops, initial nozzle throat areas and nozzle erosion rates. Any variations in these parameters have a minimal effect on the F/P ratio.

F/P CALCULATION METHOD

F/P values for this analysis were calculated using the vacuum thrust and head-end pressure data at delivered conditions. The average F/P ratio for each motor was calculated by dividing the thrust integral by the pressure integral, or the average thrust by the average pressure, from initiation (T-zero) to action time (22.1 psia).

Note: The vacuum thrust data was calculated by adding the measured Utah-site thrust to the product of atmospheric pressure and the area of the nozzle exit plane. Measured Utah site thrust is converted to vacuum thrust for comparison to the NASA contract requirements.

F/P ANALYSIS RESULTS

The FSMs 7-9 T-97 F/P data were compared to the T-24 Block Model test motors, and to five previous Technical Evaluation Motors (TEM) (HPM configuration) that had measured thrust (TEMs 1, 2, 4, 6, and 10). Figure 5 includes individual, average, and statistical F/P data for the above mentioned motors.

Note: The average T-24 F/P values for the five HPMs and eight RSRMs are very close and there is no significant statistical difference between the two populations; the average F/P from the five HPM motors, 3917.2, was 0.05 percent lower than the RSRM T-24 motors.

The individual T-97 F/P average values were consistent and were within the T-24 RSRM and HPM statistical family expectation. The average F/P for the three T-97 motors was 3906.6, 0.32 percent lower than the Block Model value of 3919.1, and 0.30 percent lower than the average F/P of the combined HPM and RSRM T-24 motor populations, 3918.4.

INDIVIDUAL TEST MOTOR CONFIGURATION DIFFERENCES

Unique test-objective changes on each of the 16 static test motors were reviewed for potential influence on F/P. Significant test motor configuration changes included:

- The non-vectored nozzles on the TEMs
- Non-standard nozzle duty cycle on FSM-4
- Asbestos-free insulation on FSM-8

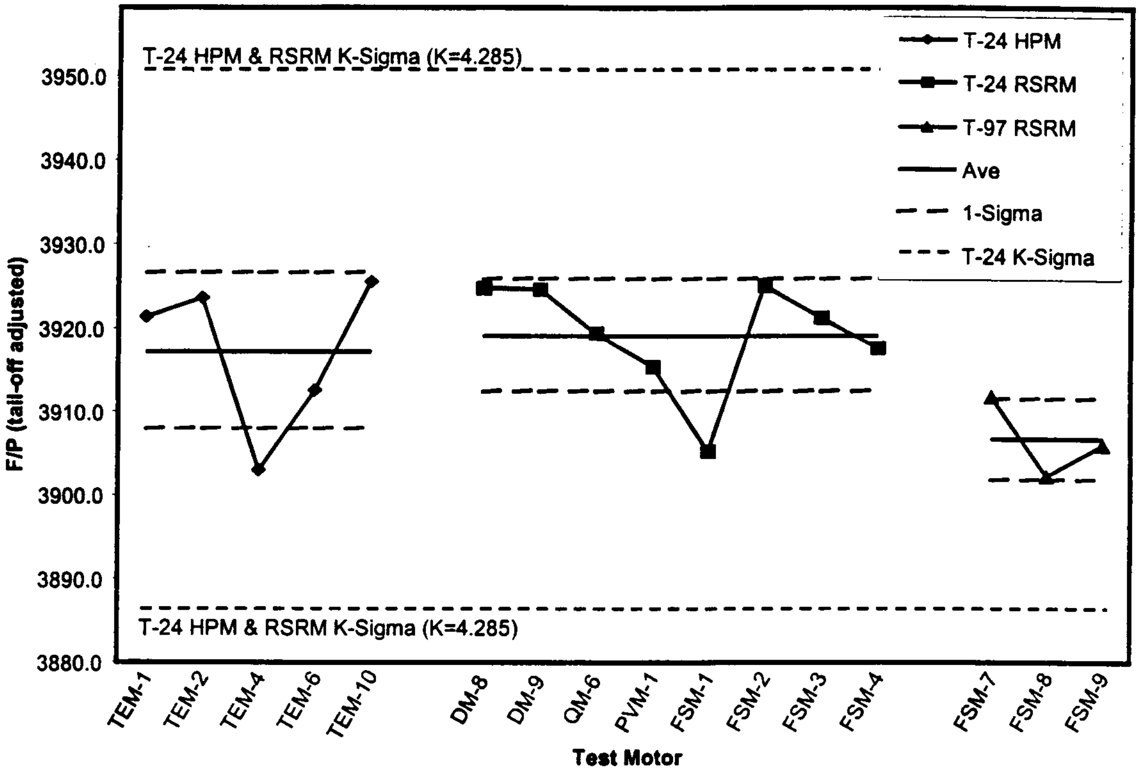

Figure 5. HPM and RSRM Static Test Motor F/P Comparison

- Propellant removal for structural evaluation on FSMs 7-9

None of these changes were determined to have a significant effect on the overall F/P comparison.

The RSRM and HPM configurations had minor differences such as the forward segment propellant grain stress relief regions and case insulation thicknesses. None of these differences have had a significant impact on the F/P ratios.

Potential causes for the lowest F/P values of each set of data (TEM-4, FSM-1, and FSM-8) could not be determined, so these values are considered to be within normal variation.

F/P STATISTICAL ANALYSIS

An analysis of variance showed that the T-97 F/P population was significantly different (-0.32 percent bias) from the T-24 population, at a 95 percent confidence level. A correlation, however, was identified which questions the validity of the bias (discussed below). Future thrust data from T-97 will continue to be assessed to determine/characterize any bias between the T-24 and T-97 measurements.

ANALYSIS OF TEST STAND F/P BIAS

The thrust measured at T-97 was analyzed and compared to thrust measured previously at T-24 to characterize the statistically significant -0.32 percent bias between the two test stands.

F/P DATA ANALYSIS AND TRACE SHAPE

At every time step, an instantaneous F/P ratio can be calculated by dividing the measured thrust by the measured head-end pressure. The T-24 static test motor F/P traces are shown in Figure 6. The F/P traces of the three T-97 motors, FSMs 7-9, are compared to the T-24 motor population minimum and maximum values in Figure 7. The T-97 F/P traces are consistently lower but have a similar shape. The F/P traces were reviewed at various time ranges. No anomalies were found.

F/P CORRELATION WITH AVERAGE PRESSURE

The average F/P values for the T-97 motors, FSMs 7-9, are shown in Figure 8 with the T-24 HPMs and RSRMs.

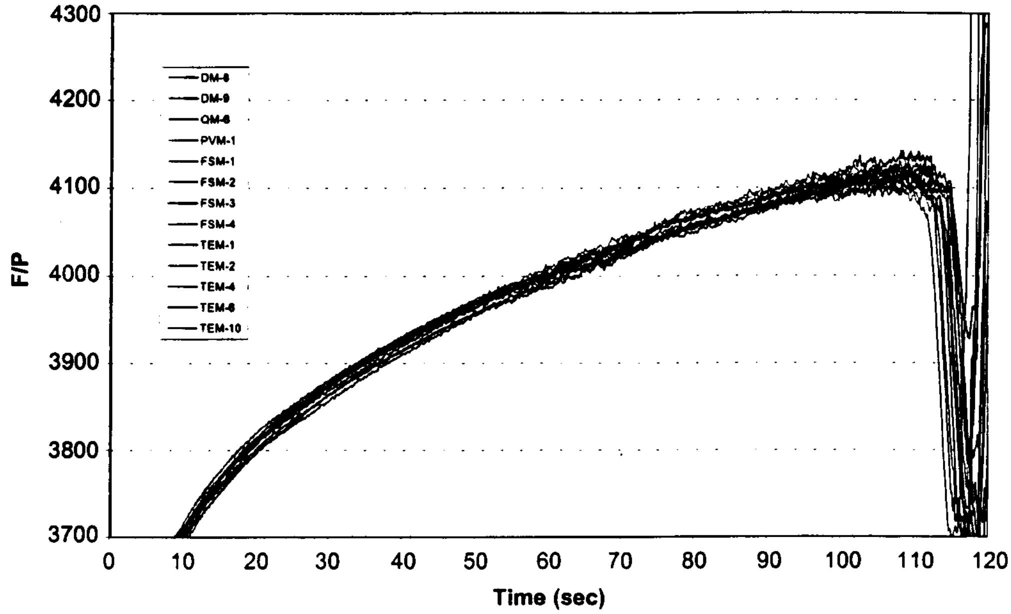

Figure 6. F/P Traces of T-24 Static Test Motors

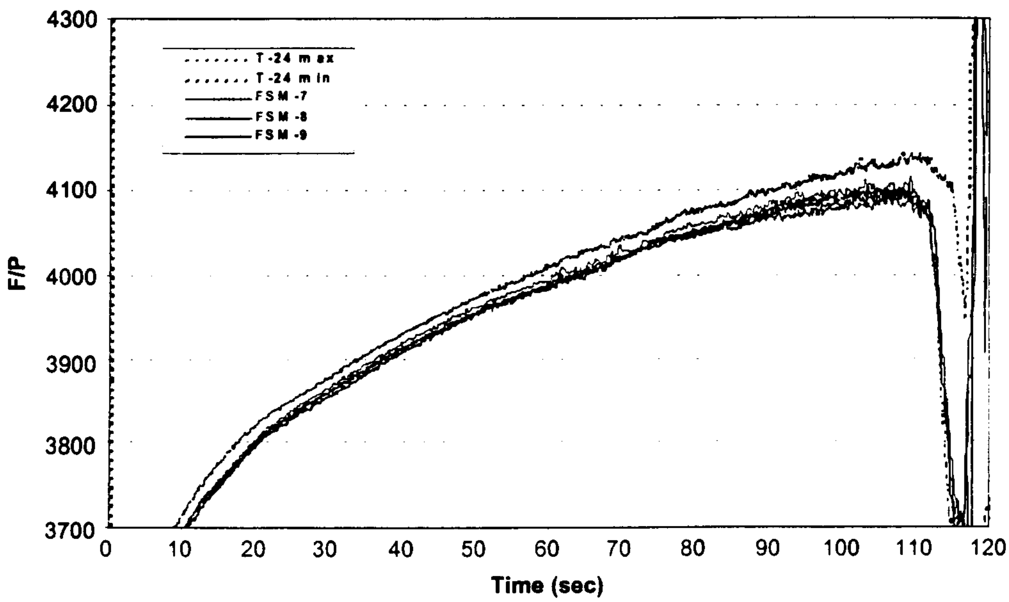

Figure 7. F/P Traces of T-97 Static Test Motors

As mentioned earlier, the F/P values for the three T-97 motors were statistically significantly lower than the T-24 motors, indicating a -0.32 percent bias (see Figure 5). However, a correlation was identified between vacuum thrust F/P and motor average pressure, shown in Figure 9. A correlation coefficient (r^2) of 0.6 signifies that 60 percent of the variation in F/P can be explained by the average pressure variation. The action time, used for average pressure calculations, is defined as the interval of time that begins at ignition (T-0) and ends when the head-end chamber pressure has decayed to a value of 22.1 psia.

Whether there is a test-stand bias is questionable since all the T-97 motors had high average pressure values (all points are on the right side of Figure 9). Higher propellant burn rates and the improved thermal conditioning of T-97, which resulted in higher PMBT than at T-24, were contributors to the higher average pressures on the T-97 motors. Without the T-97 motors, however, this correlation still exists for the T-24 HPM and RSRM static motor populations ($r^2 = 0.57$ and 0.54, respectively).

The correlation between F/P and motor average pressure does not exist for Utah thrust F/P values (see Figure 10). Also, the motor population F/P variation (standard deviation) for Utah thrust is less than that for vacuum thrust (see Figures 8 and 11). The increased variation of vacuum thrust F/P values and the correlation of vacuum thrust F/P values with average pressure indicate that the Utah-thrust to vacuum-thrust conversion calculations may have errors.

STATISTICAL ANALYSIS OF UTAH SITE THRUST F/P

An analysis of variance was conducted on the Utah thrust F/P values to simultaneously assess the effects of motor type (RSRM vs. HPM) and test stand (T-24 vs. T-97). Results indicated no significant difference between motor types, but the F/P bias between the test stands (7.05 or 0.20 percent) was statistically significant at a 95 percent confidence level. Even though the difference between the two test stands was still statistically significant, the 0.20 percent bias was less than the 0.32 percent bias for vacuum thrust F/P values.

EXPLANATION OF F/P CORRELATION WITH AVERAGE PRESSURE

The measured Utah thrust is converted to vacuum thrust by the following equation:

$$F_V = F_{ut} + P_a \bullet A_e,$$

P_a = ambient pressure, A_e = nozzle exit plane area

The average F/P correlation with average pressure occurs when extra thrust (from ambient pressure) is added in the conversion of Utah thrust to vacuum

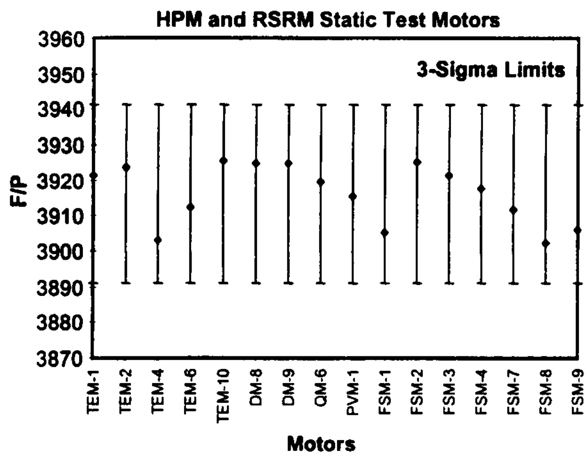

Figure 8. Average F_V/P

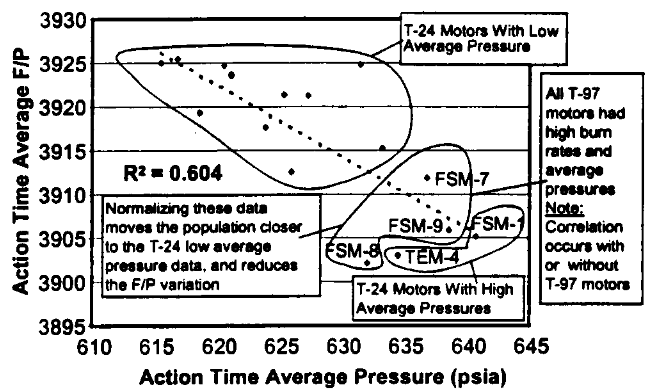

Figure 9. F_V/P vs. Average Pressure

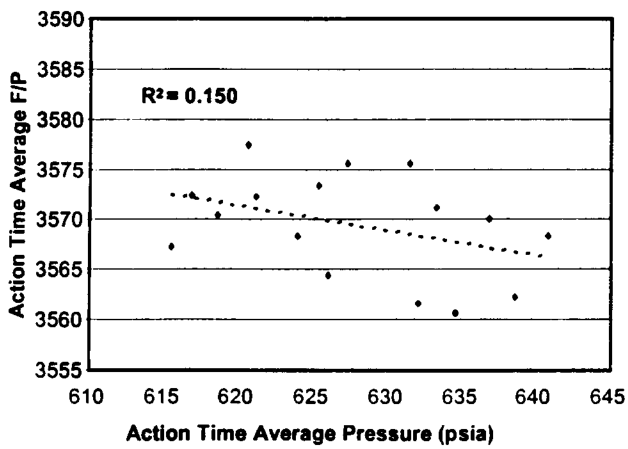

Figure 10. F_{ut}/P vs. Average Pressure

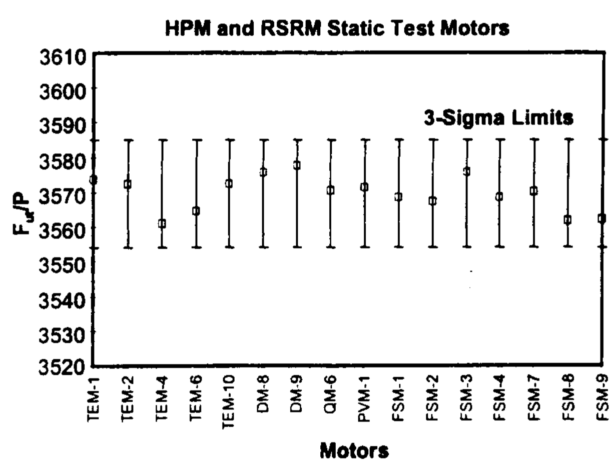

Figure 11. Average F_{ut}/P

thrust. Slower burning motors with lower average pressures and longer action times have a larger quantity of thrust added during the conversion to vacuum thrust than do motors with high burn rates, higher average pressures and shorter action times. Yet, the pressure integral in the denominator of the F/P ratio does not change. The vacuum thrust and Utah thrust F/P relationships with action time are shown in Figures 12 and 13, respectively. The figures show a correlation between vacuum thrust F/P and action time ($R^2 = 0.565$, Figure 12) and no correlation between Utah thrust F/P and action time ($R^2 = 0.123$, Figure 13). Notice the increased influence of the vacuum thrust conversion on slower burning motors (right side of Figure 11).

EVALUATION OF MOTOR PARAMETER CONTRIBUTIONS TO F/P

The following parameters were evaluated to quantify their contribution to the variation of the calculated vacuum thrust and F_v/P ratios, and help explain the correlation:

1. Ignition Transient
2. Ambiant Pressure
3. Exit Plane Erosion
4. Radial Growth of Aft Exit Cone
5. Nozzle Stagnation Pressure
6. Nozzle Flow Separation Adjustment
7. FSM-8 Non-asbestos Insulation
8. PMBT
9. Pressure Integral

Except for PMBT, which influences burn rate and average pressure, the effects from all the parameters were minimal and did not provide a cause for the correlation.

CONCLUSION OF TEST STAND F/P BIAS ANALYSIS

In general, the vacuum F/P correlation was found to be dependent on the action time or the average pressure but no specific cause was identified. If the correlation is correct, then any bias in the thrust measurement between the two thrust stands could be reduced from the current 0.32 percent. Additional T-97 thrust data from motors with low average pressures would be needed to calculate an accurate bias. These motors would have to be targeted at propellant lower burn rates, as much as 0.005 in/sec less than the current 0.368 in/sec target burn rate.

F/P NORMALIZED TO A COMMON MOTOR AVERAGE PRESSURE

In the absence of additional data from T-97 motors with low average pressures, a preliminary analysis was conducted to correct the F/P data to a common motor average pressure of 625 psia. All of the F/P values were adjusted using the following equation derived from HPM and RSRM T-24 motors:

$$F_v/P_{\text{at 625 psia}} = F_v/P - 0.7482 \bullet (625 - P_{ave})$$

The normalized F/P values for HPM and RSRM T-24 motors averaged 3917.0 and 3920.2, respectively. For the T-97 motors, the normalized F/P values averaged 3914.7. The variation for all the motors was similar to the Utah thrust F/P variation (compare Figures 11 and 14).

An analysis of variance was conducted on the normalized F/P values to simultaneously assess the affects of motor type (RSRM vs. HPM) and test stand (T-24 vs. T-97). The results indicated that the F/P bias

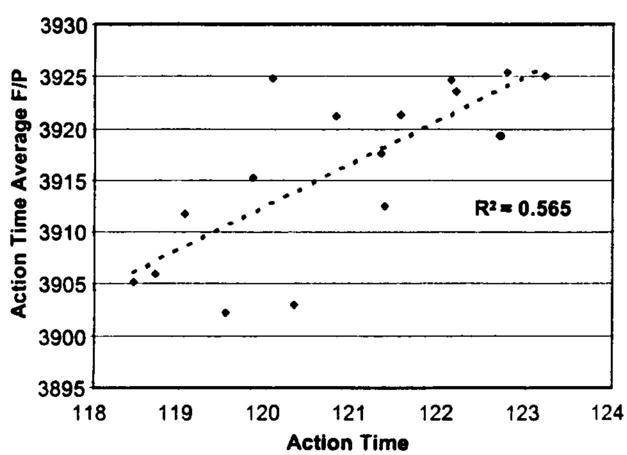

Figure 12. F_v/P vs. Action Time

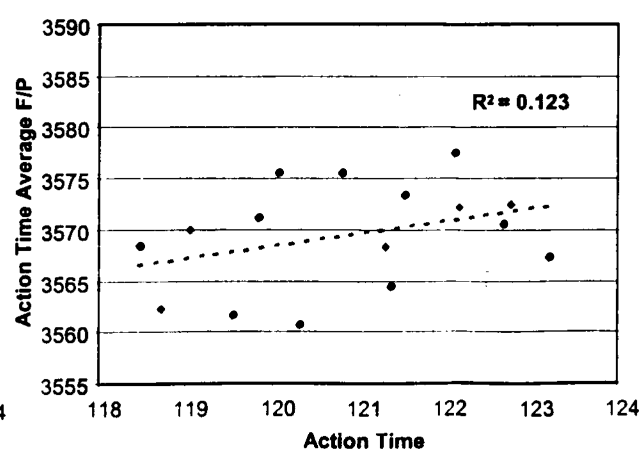

Figure 13. F_{ut}/P vs. Action Time

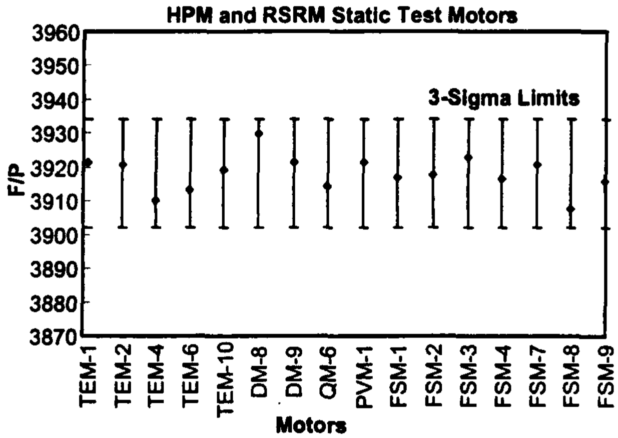

Figure 14. Average F_{UT}/P Normalized to 625 PSIA

between motor types (HPM minus RSRM) of -3.2 or -0.08 percent is not statistically significant at any reasonable confidence level. The test stand F/P bias (T-24 minus T-97) of +5.5 or +0.14 percent is only borderline statistically significant at an 85 percent confidence level.

These results still indicate the possibility of a bias between T-24 and T-97, but there is not enough evidence yet to state this conclusively. As previously stated, additional T-97 thrust data from motors with low average pressures are needed to provide a better comparison with the nominal T-24 historical data and calculate an accurate bias.

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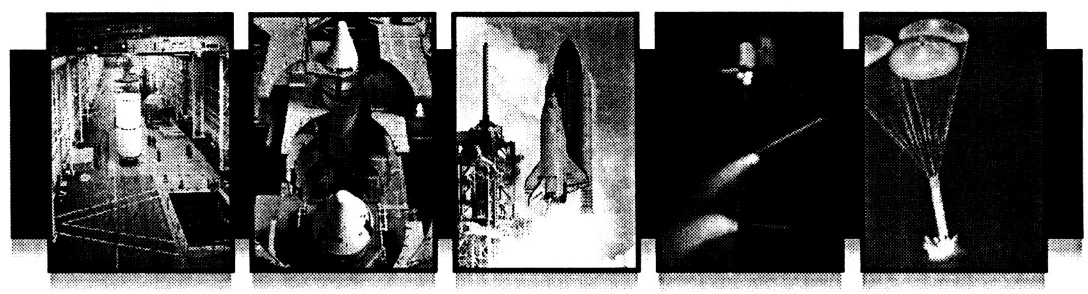


Presented by:

Laurent Gruet & Mart Cook

RSRM Ballistics and Grain Design

January 6, 2003

020750ppt

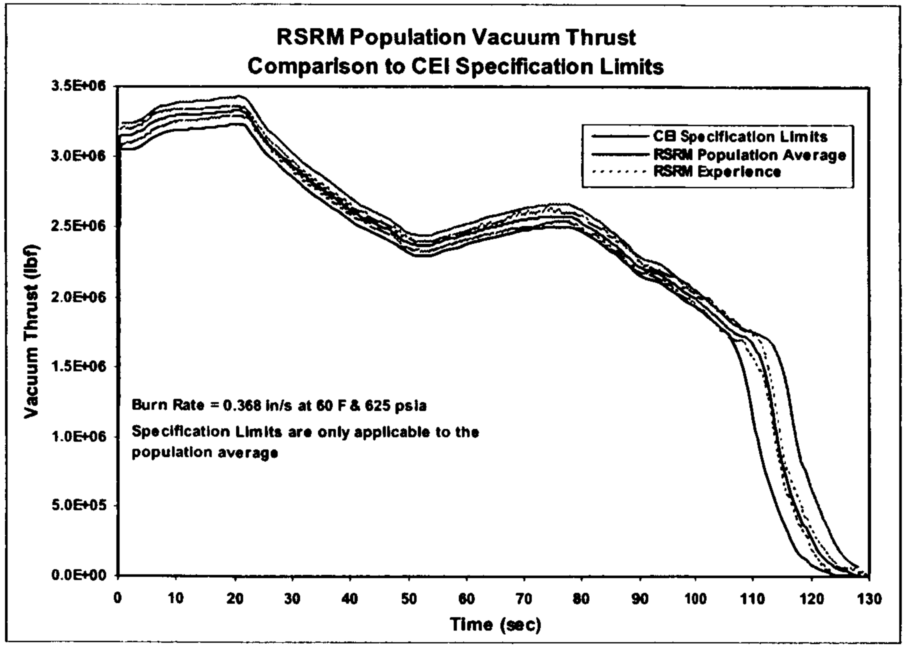
ATK ALLIANT TECHSYSTEMS

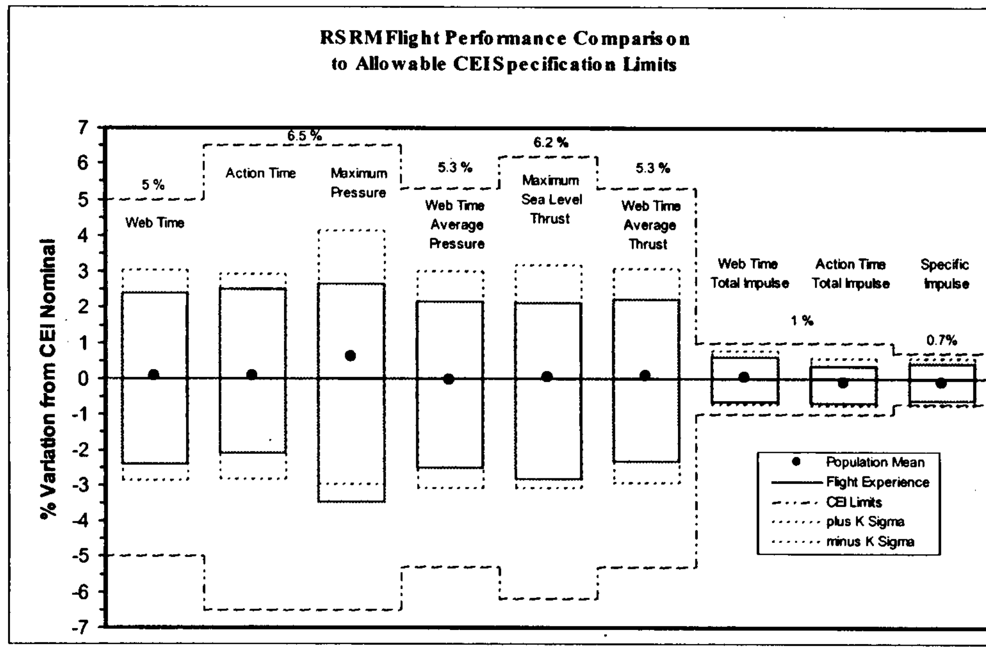
ATK THIOKOL PROPULSION

Introduction/Background

- **Reusable Solid Rocket Motor (RSRM)**
  - RSRMs are manufactured by ATK Thiokol Propulsion to launch Space Shuttles into orbit
- **RSRM static tests**
  - RSRMs are static tested at two ATK Thiokol test facilities: T-24 and T-97
  - Newer T-97 facility was recently upgraded to allow thrust measurement capability
    - All previous static test thrust measurements taken at T-24
- **RSRM nominal thrust**
  - Thrust measured at T-24 was used to characterize and certify RSRM performance
    - Validation of T-97 thrust measurement system is required for official use
  - RSRM nominal thrust and NASA contract limits are based on an average thrust/pressure ratio (F/P) from eight RSRM motors static tested at T-24
    - Nominal performance is used in conjunction with subscale test data to predict RSRM flight motor performance in support of pre-launch trajectory and system loads analyses
    - RSRM nominal F/P ratio is also used to reconstruct flight motor thrust from measured pressure (thrust cannot be measured on flight motors)

RSRM Nominal Thrust and Requirements

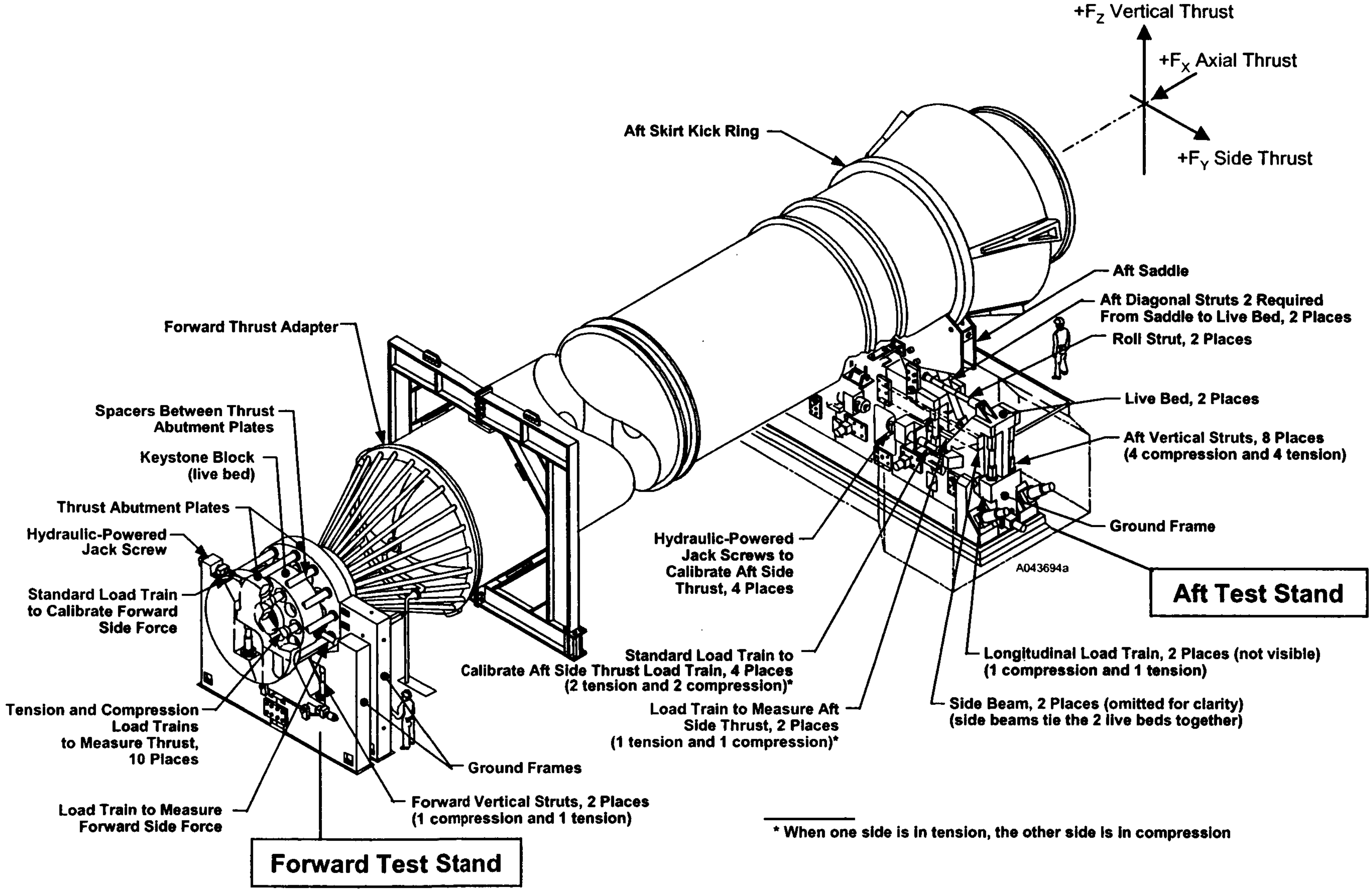




T-97 Test Stand Configuration

- **T-97 refurbishment**
  - T-97 was refurbished and repaired in 1996 to enable thrust measurement
    - The T-24 test stand thrust measurements were locked out in 1995
      - Flexure failure from stress corrosion cracking and hydrogen embrittlement
    - T-97 is expected to be more accurate than T-24
      - T-97 has full-scale load applicator/calibrator, traceable to NIST
      - T-97 has 100% (3.5 Mlbf) full-scale load application/calibration capability vs. T-24's 10% calibration capability
- **Thrust measurement system configuration**
  - T-97 has a forward test stand and an aft test stand for motor attachment and thrust measurement
    - The forward test stand has 22 thrust channels (20 axial, two side)
    - The aft test stand has eight thrust channels (four axial, four side)
    - Each load cell has two, duplicate gages (A-side gages and B-side gages)
      - Comparison of the A and B measurements provides confidence in measurement
      - Total measurements are the mean of the two measurements

T-97 Thrust Measurement System



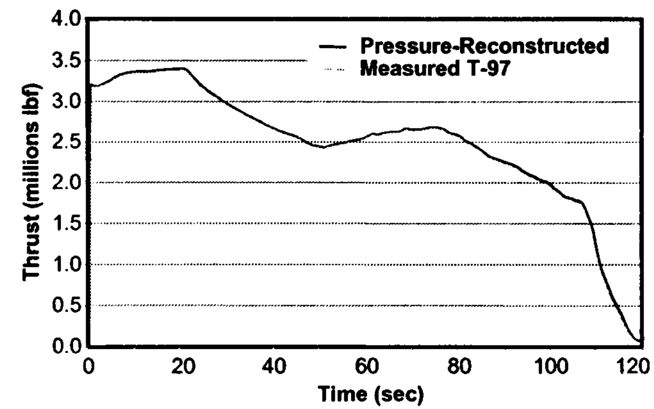
* When one side is in tension, the other side is in compression

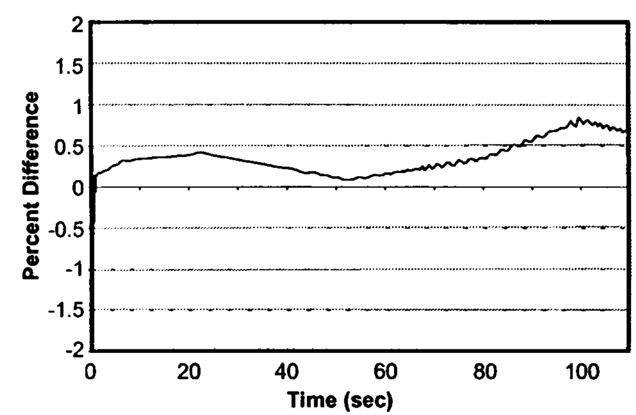
T-97 Assessment

- **Characterization of T-97 thrust measurement system**
  - Characterization of the T-97 test stand thrust measurement system consisted of:
    - Test stand calibration
    - Measured thrust compared to contract requirements
    - Measured thrust compared to pressure-reconstructed thrust (based on T-24 data)
    - Assessment of thrust-to-pressure relationship (F/P ratio) (T-97 compared to T-24)
- **Test stand calibration**
  - 28 calibration tests showed an average sensitivity bias of –0.5208% between measured and applied load
    - Calibration system is NIST traceable
    - All measured thrust data is corrected +0.5208%
- **Measured thrust compared to contract requirements**
  - Measured thrust data from three Flight Support Motors (FSMs 7-9), tested at T-97, met all applicable contract performance limits for measured-thrust parameters
  - The FSM 7-9 data are sufficient to show that the T-97 thrust stand is now verified for thrust measurements

Measured and Pressure-Reconstructed Thrust

- **Measured thrust compared to pressure-reconstructed thrust**
  - To establish similarity of thrust measured from T-97 and T-24, FSMs 7-9 measured thrust was compared to pressure-reconstructed thrust
    - Pressure-reconstructed thrust was calculated from nominal T-24 RSRM F/P relationship
  - T-97 measured thrust correlated well to the pressure-reconstructed thrust
    - The average differences were within 0.50% during the steady state
    - As shown to the right, FSM-9 measured thrust averaged 0.35% less than the pressure-reconstructed thrust during steady state





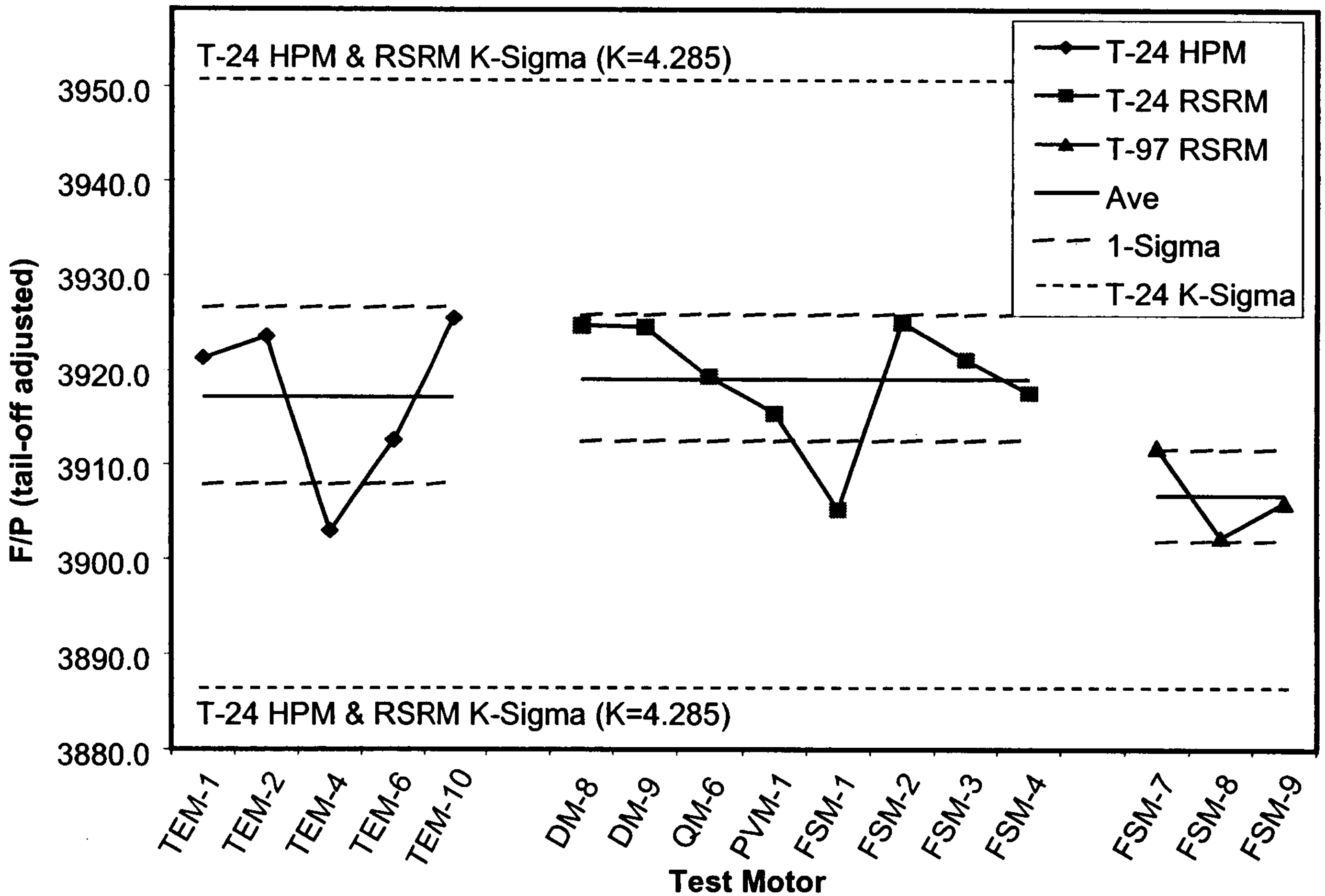
Thrust Over Pressure (F/P) Evaluation

- **Assessment of F/P ratio**
  - Thrust is directly related to nozzle stagnation pressure

    $F = C_f \bullet P_{sn} \bullet A_t$, C_f = thrust coefficient, A_t = nozzle throat area (C_f & A_t are fairly constant values)

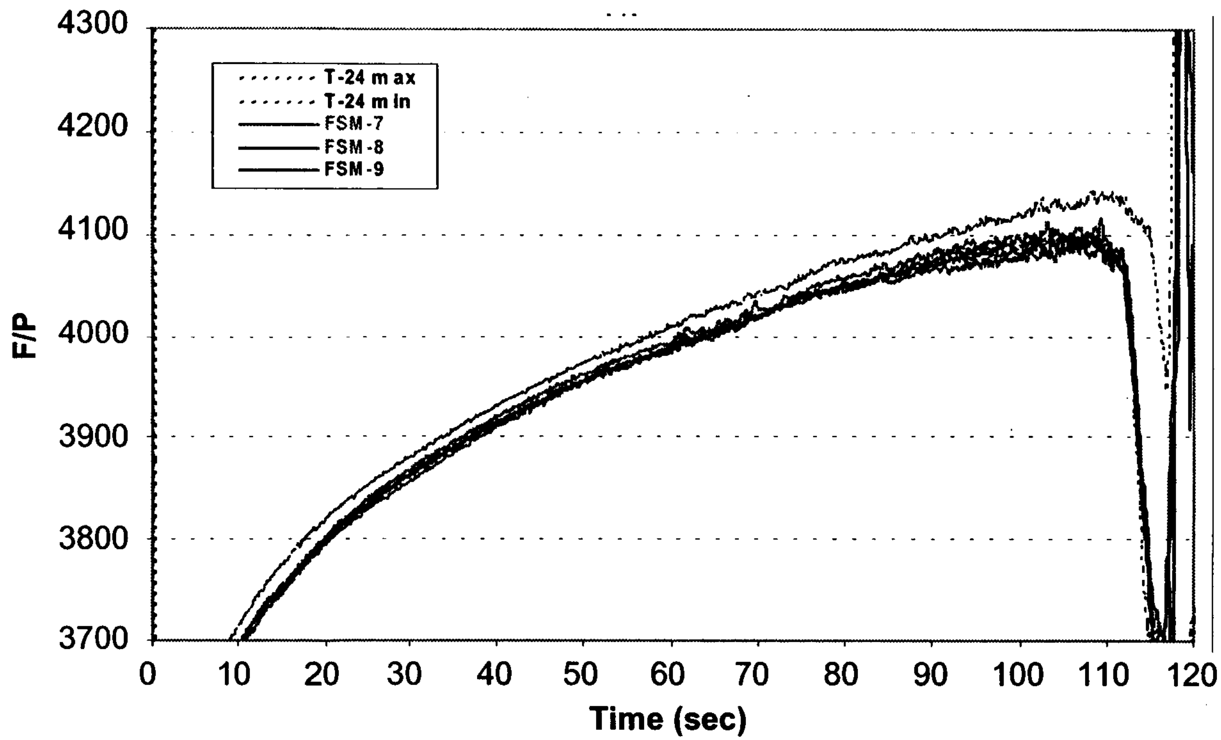
    - $F/P = F_{integral}/P_{integral}$
    - All full-scale motors have similar burn times, internal pressure drop, initial throat areas, and nozzle erosion rates
    - Variations in these parameters have a minimal effect on F/P ratio
  - The individual T-97 F/P average values were consistent and were within the T-24 RSRM and High Performance Motor (HPM) statistical family expectation
    - HPMs were the precursor to the RSRM; the performance of the two motors is very similar
    - The T-97 average F/P was 3906.6
      - 0.32% lower than the T-24 RSRM average of 3,919.1
      - 0.30% lower than the average F/P of the combined HPM/RSRM T-24 motor populations of 3,918.4
  - The -0.32% bias is within expectation, but is statistically significant at a 95% confidence level

T-24 and T-97 F/P Comparison



Analysis of T-24/T-97 F/P Bias

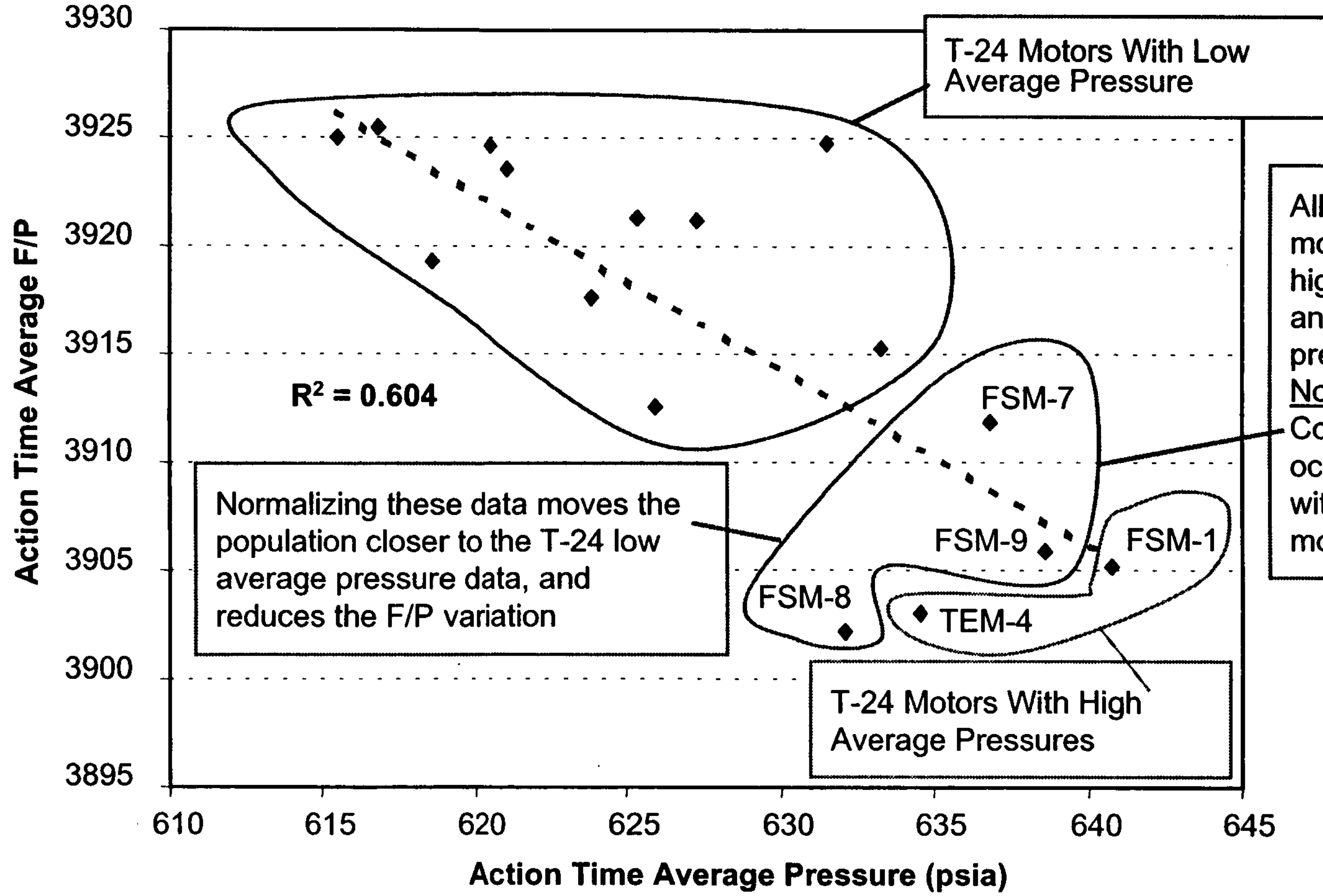
- **Assessment of F/P trace shape**
  - F/P trace shapes of T-97 motors are similar to T-24 motor population
    - The F/P traces were consistently lower than most of the T-24 F/P traces; however, no anomalies were found



Assessment of Vacuum Thrust and Utah Site Thrust

- **Vacuum thrust**
  - Measured Utah site thrust is converted to vacuum thrust for comparison to the NASA requirements
    - RSRM vacuum thrust is provided to the Space Transportation System (Space Shuttle) performance community for trajectory and system loads analyses
  - When investigating the T-24/T-97 bias, a correlation (R^2=0.6) was identified between motor average F_v/P and motor average pressure
    - The correlation signifies that 60% of the variation in F_v/P can be explained by the average pressure variation
  - This correlation questions the validity of the -0.32% bias
    - The bias is confounded by the high-average pressure grouping of the T-97 motors
      - The T-24 RSRM motors had lower average pressures and longer action times than the T-97 motors
    - This correlation exists with or without the T-97 motor population

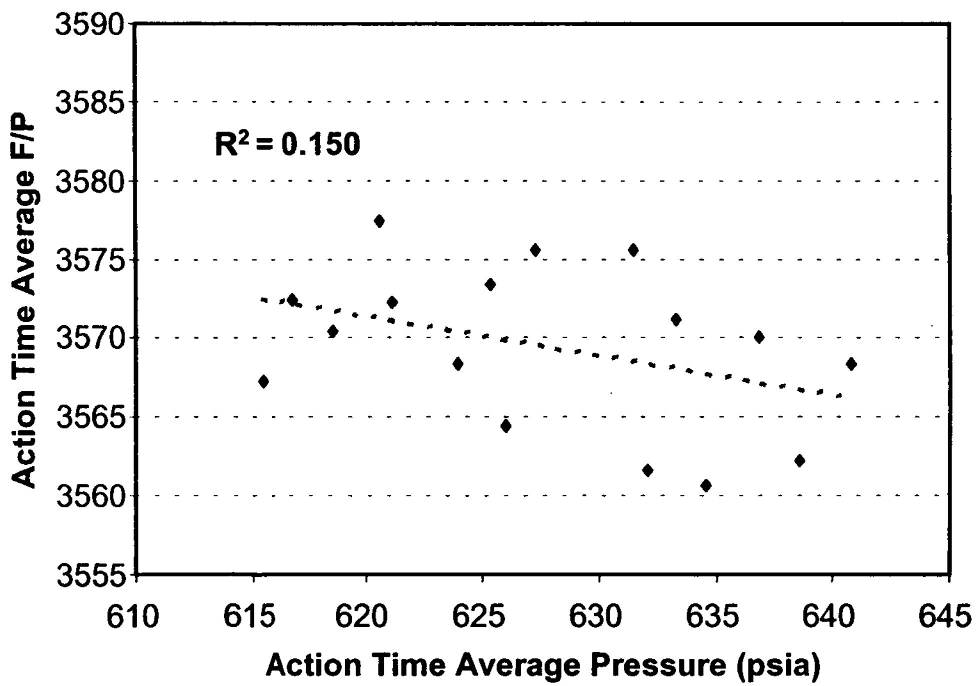
F_v/P Correlation With Average Pressure



All T-97 motors had high burn rates and average pressures
Note: Correlation occurs with or without T-97 motors

F_{ut}/P Comparison With Average Pressure

- **Utah site thrust**
  - No correlation with average pressure
  - F_{ut}/P motor-to-motor variation is 50% lower than F_v/P
    - This suggests that there are errors in the conversion of measured thrust-to-vacuum thrust
  - -0.20% difference between T-97 and T-24 motor F_{ut}/P values is still statistically significant



Assessment of F/P Variation and F/P Correlation

- **Evaluation of motor parameter contributions to F/P variation**
  - The following parameters were evaluated to help explain the correlation:
    - Ignition, ambient pressure, exit plane erosion, nozzle throat erosion, nozzle flow separation, PMBT, pressure integral, total impulse, etc.
    - None of these parameters provided a cause for the correlation
- **Explanation of F/P correlation with P_{ave}**
  - The correlation most likely occurs as a result of the conversion from measured Utah thrust to vacuum thrust

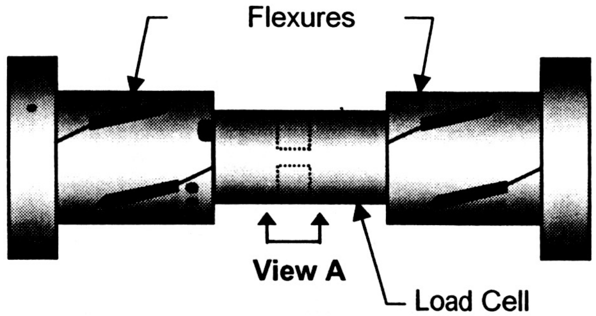
    $F_v = F_{ut} + P_a \bullet A_e$, P_a = ambient pressure, A_e = exit plane area
    - Cause of correlation attributed to additional thrust from ambient pressure
    - Slower burning motors have:
      - Lower average pressures
      - Longer action times and more "additional" thrust integral
    - All motors have similar total pressure integral, the denominator of F/P
  - There may be large motor, external effects (aft exit cone entrainment) that are not accounted for in the Utah Site-to-Vacuum thrust conversion

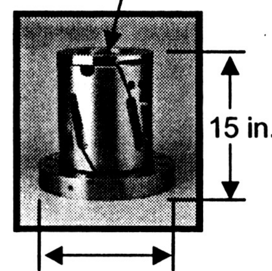
F/P Evaluation Conclusions

- **F/P normalized to common average pressure**
  - F/P data was corrected/normalized to a common motor average pressure of 625 psia
    - The normalized test stand bias (T-24 minus T-97) was reduced to 0.14%
      - Borderline statistically significant at an 85% confidence level
    - This still indicated the possibility of a bias between T-24 and T-97, but there is not enough evidence yet to state this conclusively
- **Conclusion/summary**
  - Additional T-97 thrust data from motors with low average pressures are needed to calculate an accurate bias
    - These motors need to be targeted at lower burn rates; as much as 0.005 in./sec less than the current 0.368 in./sec target burn rate
  - Future thrust data from T-97 will continue to be assessed to determine/characterize any bias between the T-24 and T-97 measurements
  - Vacuum thrust conversion may be inaccurate
    - There may be large motor, external effects (aft exit cone entrainment) that are not accounted for in the Utah Site-to-Vacuum thrust conversion

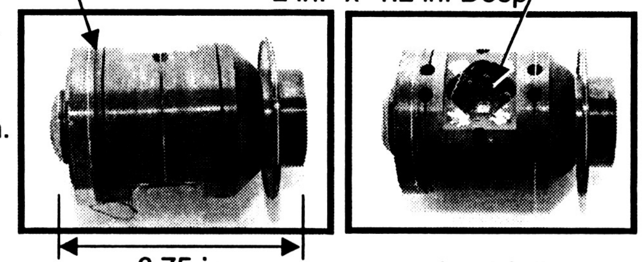
Test Stand Characterization Supporting Charts

Thrust Load Trains

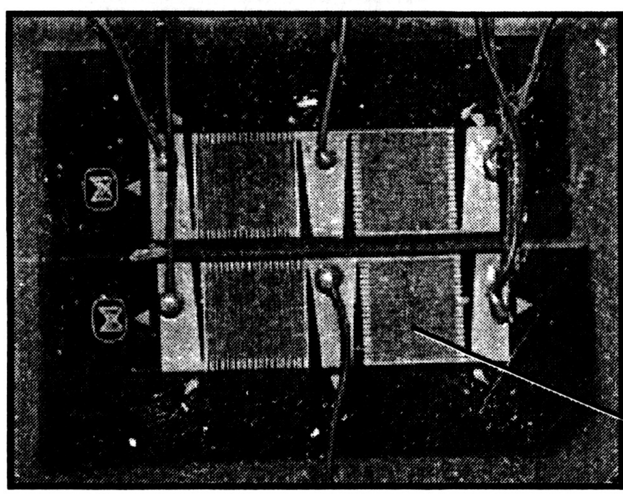




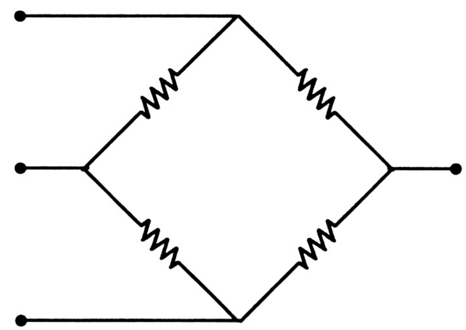
Flexure



Load Cell — **Load Cell (threaded ends removed)**



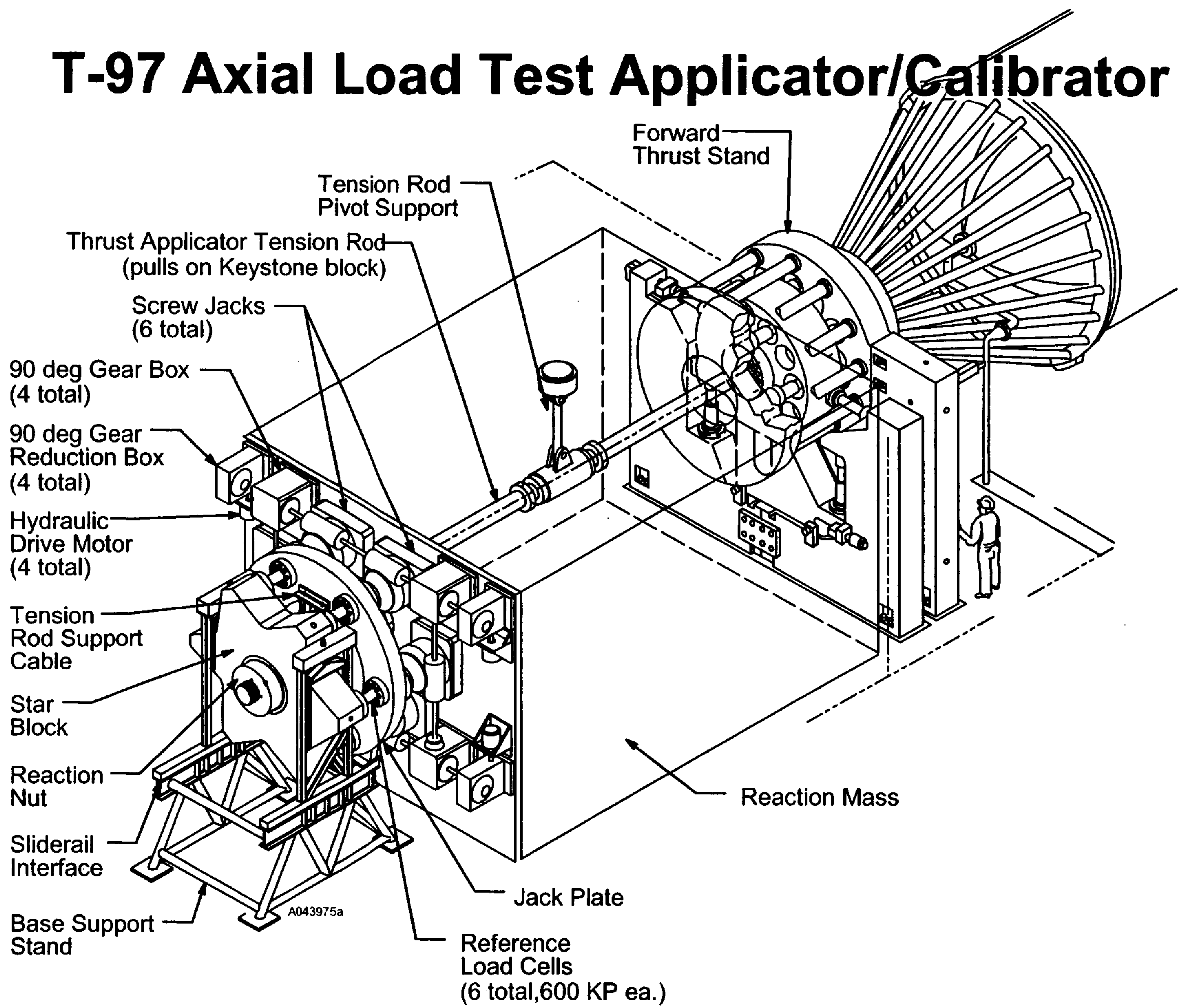
View A: "A" Strain Gage Bridge



Strain Gage Wheatstone Bridge Schematic
- Gage compensates for side and bending loads, and temperature effects, to measure axial load
- Identical for "A" and "B" gages

- Tension and compression load trains are identical
- "A" and "B" gages are duplicates
- View shown is typical for flexurized load trains

T-97 Axial Load Test Applicator/Calibrator

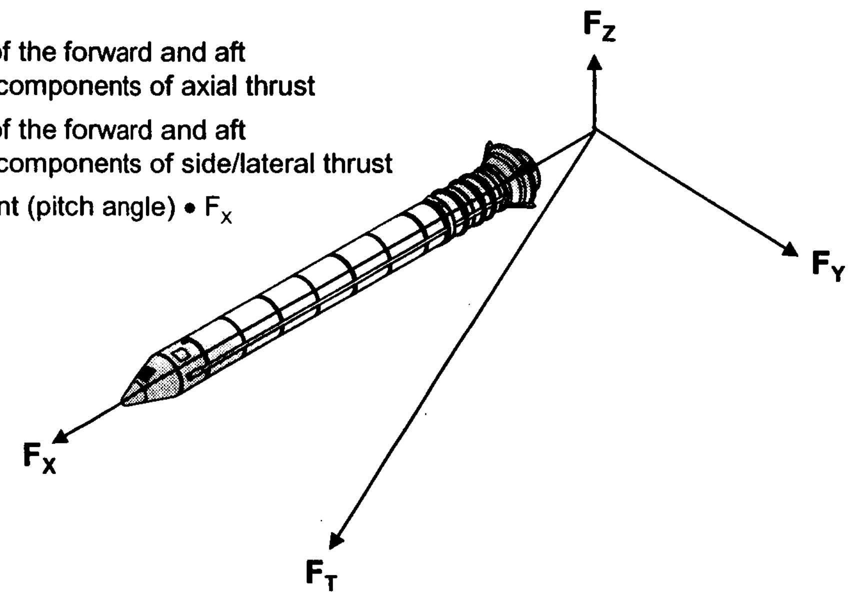


Test Stand Thrust Summing

Where: F_X = sum of the forward and aft test stand components of axial thrust

F_Y = sum of the forward and aft test stand components of side/lateral thrust

F_Z = tangent (pitch angle) • F_X



F_T = total Utah site measured thrust

F_T = root sum squaring the axial, side, and vertical components of thrust

$$F_T = \sqrt{F_X^2 + F_Y^2 + F_Z^2}$$

Vacuum thrust (F_V) is calculated by adding the ambient pressure effects to total thrust (F_T)

$F_V = F_T$ + (ambient pressure) (area of the nozzle exit plane)

Summary of Average Thrust/Pressure (F/P) Ratios

Motor/Test Stand Group	Motor	PMBT (°F)	Average Pressure (psia)	Average Tail-off Adjusted Thrust (lbf)	Action Time (sec)	Average Tail-off Adjusted F/P (lbf/sec)
Current Block Model/RSRM T-24 derived F/P (effective RSRM-71)						3919.1
HPMs at T-24	TEM-1	71	625.3	2452128	121.53	3921.3
	TEM-2	67	621.1	2437078	122.18	3923.6
	TEM-4	80	634.6	2476692	120.32	3903.0
	TEM-6	69	626.0	2449110	121.36	3912.6
	TEM-10	69	616.8	2421253	122.77	3925.4
	Ave T-24 HPM	71.2	624.8	2447252	121.63	3917.2
	1-sigma T-24 HPM					9.3 (3907.9 - 3926.5)
RSRMs at T-24	DM-8	76	631.5	2478434	120.06	3924.8
	DM-9	64	620.6	2435441	122.11	3924.6
	QM-6	70	618.6	2424475	122.68	3919.3
	PVM-1	79	633.3	2479508	119.84	3915.3
	FSM-1	82	640.8	2502427	118.46	3905.1
	FSM-2	69	615.5	2415712	123.21	3925.0
	FSM-3	78	627.3	2459760	120.79	3921.2
	FSM-4	62	623.9	2444150	121.31	3917.6
	Ave T-24 RSRM	72.5	626.4	2454988	121.06	3919.1
	1-sigma T-24 RSRM					6.7 (3912.4 - 3925.8)
	2-sigma T-24 RSRM					13.4 (3905.7 - 3932.5)
	3-sigma T-24 RSRM					20.1 (3899.0 - 3939.2)
	K-sigma T-24 RSRM (4.971)					33.3 (3885.8 - 3952.4)

Summary of Average Thrust/Pressure (F/P) Ratios (cont)

Motor/Test Stand Group	Motor	PMBT (°F)	Average Pressure (psia)	Average Tail-off Adjusted Thrust (lbf)	Action Time (sec)	Average Tail-off Adjusted F/P (lbf/sec)
HPMs and RSRMs at T-24	Ave T-24 HPM & RSRM					3918.4
	1-sigma T-24 HPM & RSRM					7.5 (3910.9 - 3925.9)
	2-sigma T-24 HPM & RSRM					15.0 (3903.4 - 3933.4)
	3-sigma T-24 HPM & RSRM					22.5 (3896.9 - 3940.9)
	K-sigma T-24 HPM & RSRM (4.285)					32.1 (3886.3 - 3950.5)
RSRMs at T-97	FSM-7	75	636.8	2491202	119.06	3911.8
	FSM-8	78	632.1	2466574	119.53	3902.2
	FSM-9	77	638.6	2494320	118.71	3905.9
	Ave T-97	76.7	635.8	2484032	119.10	3906.6
	1-sigma T-97					4.9 (3901.8 - 3911.5)
RSRMs at T-24 and T-97	Ave T-24 and T-97 RSRM					3915.7
	1-sigma T-24 & T-97 RSRM					8.4 (3907.3 - 3924.1)
HPMs and RSRMs at T-24 and T-97	Ave T-24 and T-97 HPM & RSRM					3916.2
	1-sigma T-24 & T-97 HPM & RSRM					8.4 (3907.8 - 3924.6)