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SPACE SHUTTLE MAIN ENGINE PERFORMANCE ANALYSIS

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I. BACKGROUND

For a number of years, NASA has relied primarily upon periodically updated versions of Rocketdyne's Power Balance Model (PBM) to provide Space Shuttle Main Engine (SSME) steady-state performance prediction. A recent computational study (1) indicated that PBM predictions do not satisfy fundamental energy conservation principles. More recently, SSME test results provided by the Technology Test Bed (TTB) program have indicated significant discrepancies between PBM flow and temperature predictions and TTB observations (2). Results of these investigations have diminished confidence in the predictions provided by PBM, and motivated the development of new computational tools for supporting SSME performance analysis.

A multivariate least squares regression algorithm was developed and implemented during this effort in order to efficiently characterize TTB data. This procedure, called the "gains model", was used to approximate the variation of SSME performance parameters such as flow rate, pressure, temperature, speed, and assorted hardware characteristics in terms of six assumed independent influences. These six influences were engine power level, mixture ratio, fuel inlet pressure and temperature, and oxidizer inlet pressure and temperature. A BFGS optimization algorithm (3) provided the base procedure for determining regression coefficients for both linear and full quadratic approximations of parameter variation. Statistical information relative to data deviation from regression derived relations was also computed.

A new strategy for integrating test data with theoretical performance prediction was also investigated. The current integration procedure employed by PBM treats test data as pristine and adjusts hardware characteristics in a heuristic manner to achieve engine balance. Within PBM, this integration procedure is called "data reduction". By contrast, the new data integration procedure, termed "reconciliation", uses mathematical optimization techniques, and requires both measurement and balance uncertainty estimates. The reconciler attempts to select operational parameters that minimize the difference between theoretical prediction and observation. Selected values are further constrained to fall within measurement uncertainty limits and to satisfy fundamental physical relations (mass conservation, energy conservation, pressure drop relations, etc.) within uncertainty estimates for all SSME subsystems. The parameter selection problem described above is a traditional nonlinear programming problem. The reconciler employs a mixed penalty method to determine optimum values of SSME operating parameters associated with this problem formulation.

The new data reconciliation procedure was used to analyze performance characteristics of two SSME subsystems, the high pressure fuel turbopump and fuel preburner subsystem (HPFTP), and the high pressure oxidizer turbopump and oxidizer preburner subsystem (HPOTP). Reconciliation results for these subsystems were compared to data from TTB test sequence 25 and to PBM data reduction analysis predictions. Typical comparison results are presented in the next section of this report.

II. ANALYSIS RESULTS

Gains model regression analyses were performed using HPFTP data from TTB-25, a 205 second duration SSME firing. Data from 59 time slices were used to obtain both linear and quadratic fits to operating parameter variation. Results for three such parameters are plotted relative to data slice start time in Figures 1 through 3. Multivariate linear fits provided excellent agreement with both high pressure fuel turbine flow and discharge temperature data as exhibited in Figures 1 and 2. For these parameters, the standard deviation of data from functional fit was 0.23 lb/sec and 3.81 degrees Rankine respectively. A multivariate quadratic fit accurately (σ=0.0018 mru) described fuel preburner O_2/H_2 mixture ratio as shown in Figure 3. The gains model used in this study was uniformly efficient and reliable in identifying performance influences for all test data examined.

Comparisons of TTB-25 test data, PBM reduction analysis predictions, and reconciliation analysis results are presented in Figures 4 through 6. Regarding high pressure oxidizer turbine flow, alarming differences, both in magnitude and trend, exist between PBM prediction and TTB-25 data as displayed in Figure 4. Reconciliation results for HPOT flow are seen to agree well with TTB-25 data. Large differences, on the order of 100-160 degrees R, are observed between PBM prediction and TTB-25 data for the oxygen preburner combustion temperature, as displayed in Figure 5. Reconciliation analysis results are seen to lie between test data and PBM predictions, approximately 60-100 degrees greater than PBM predictions. TTB-25 data for high pressure oxidizer turbine temperature drop are significantly greater than both PBM and reconciliation predictions as displayed in Figure 6. In general, the reconciliation procedure appears to provide a reasonable integration of flow thermo-physics and test data. In addition, it provides a logical scheme for indicating test data integrity.

III. RECOMMENDATIONS

1. Gains model regression fits should be extended to a larger range of engine operating conditions and/or multiple engine tests to determine range and order limitations.
2. The gains model should be expanded to support decisions regarding the health and operation of the SSME.
3. Development of the reconciliation strategy should be continued.
4. Assumptions underlying PBM predictions should be evaluated.

IV. REFERENCES

1. Santi, L. M., "Validation of the Space Shuttle Main Engine Steady State Performance Model," NASA Contractors Report CR-18404-XLI, October, 1990.
2 "Technology Test Bed Program - Engine 3001 - with Instrumented Turbopumps - First Test Series Test Report," NASA report TTB-DEV-EP93-001, January 15, 1993.
3. Fletcher, R., "A New Approach to Variable Metric Algorithms," Comput. J., Vol. 13, 1970, pp. 317-322.

FIGURE 1. HPFT FLOW FROM TTB-25

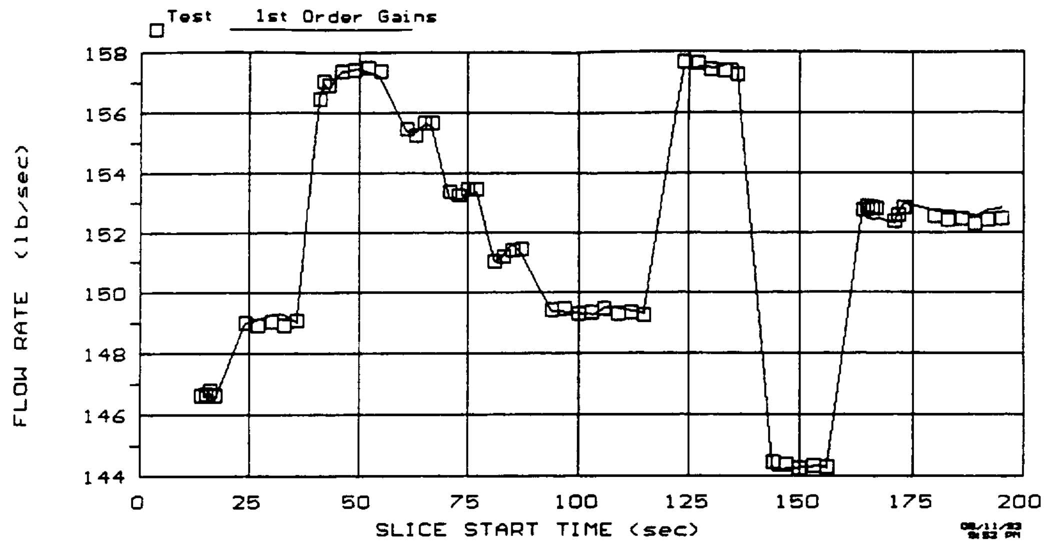

FIGURE 2. HPFT DISCHARGE TEMPERATURE - AVG FROM TTB-25

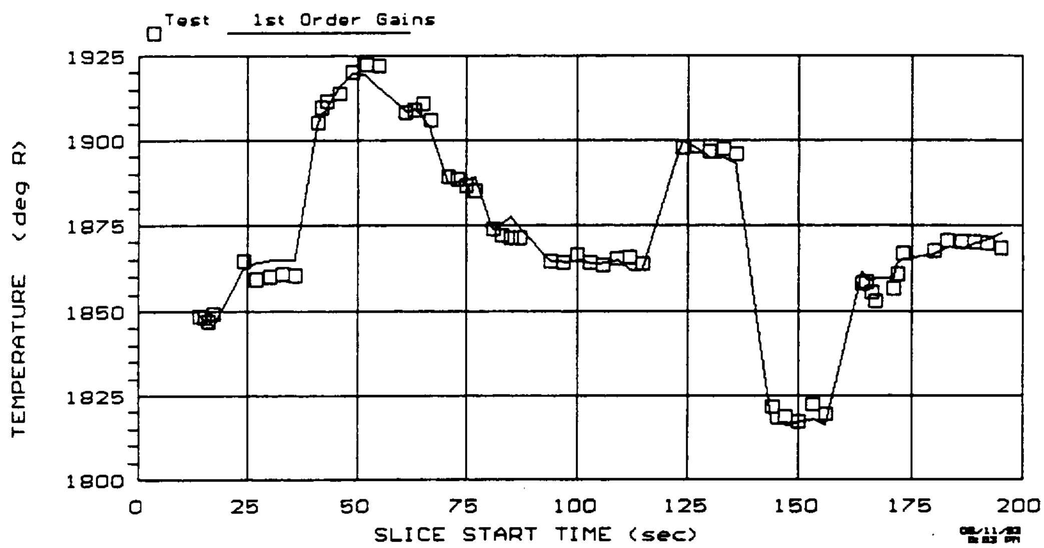

FIGURE 3. FPB MIXTURE RATIO FROM TTB-25

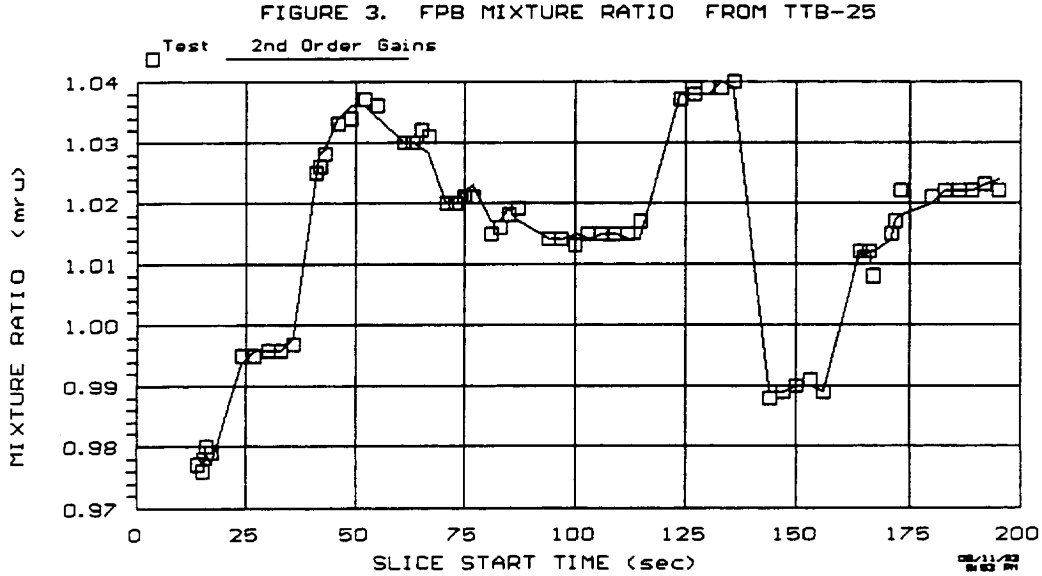

FIGURE 4. HPOT FLOW FROM TTB-25

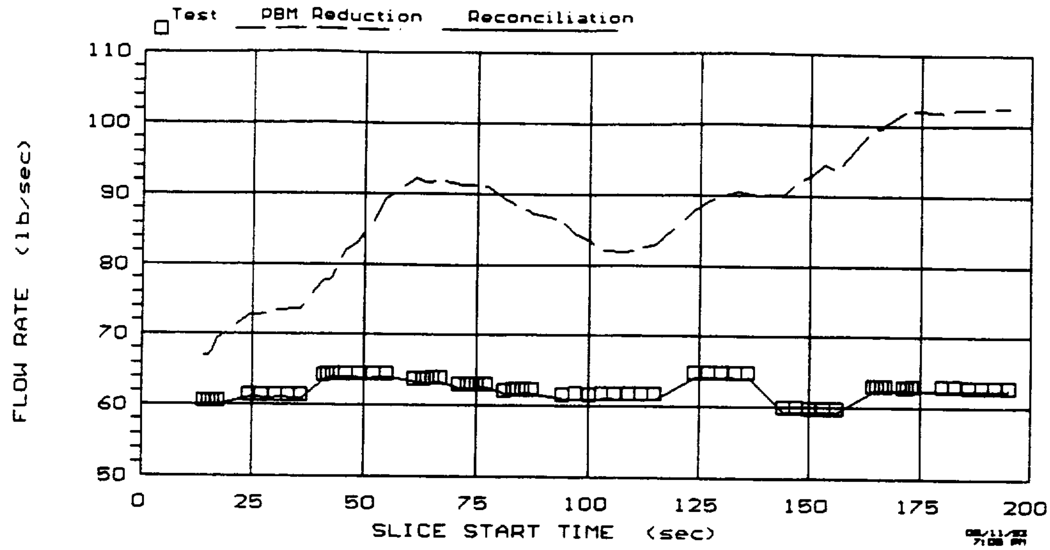

FIGURE 5. OPB COMBUSTION TEMPERATURE FROM TTB-25

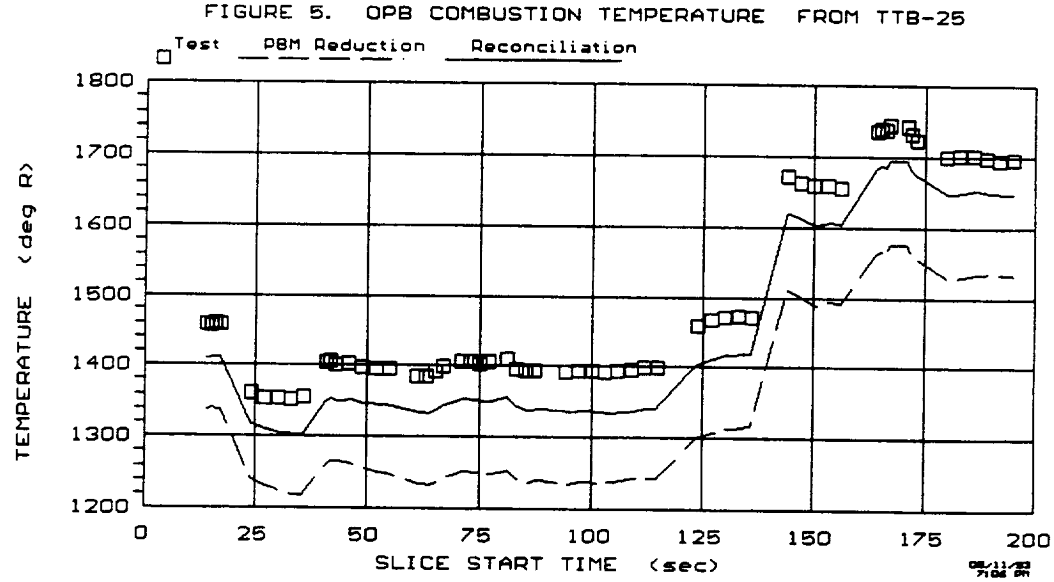

FIGURE 6. HPOT TEMPERATURE DROP FROM TTB-25