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NASA/ASEE SUMMER FACULTY FELLOWSHIP PROGRAM

MARSHALL SPACE FLIGHT CENTER
THE UNIVERSITY OF ALABAMA

VALIDATION OF THE SPACE SHUTTLE MAIN ENGINE STEADY STATE PERFORMANCE MODEL

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Contract No:	NGT-01-002-099 The University of Alabama

OBJECTIVES

The primary objective of this study was to present methods for validating predictions of Rocketdyne's most current version of the Space Shuttle Main Engine (SSME) Power Balance Model (PBM) with respect to physical relations governing flow systems. This required the development and implementation of postprocessors to check results of PBM computations for satisfaction of conservation relations. A cursory uncertainty analysis of PBM predictions with respect to mass and energy balances was performed. In addition, an effort to identify the empirical relations and physical assumptions within PBM which impact the ability of the model to attain rigorous balance was begun.

BACKGROUND

The SSME Power Balance Model simulates the main stage averaged operating conditions of the space shuttle main engine. It integrates test stand data and flight experience with theoretical flow simulation to predict SSME performance characteristics during ground test and flight operations. The model is composed of four basic subprograms. The power balance subprogram provides quasi-theoretical prediction of nominal and/or off-nominal engine performance characteristics. The data reduction subprogram integrates test data with theoretical simulation to refine efficiencies and other hardware performance parameters used in the prediction of engine operational characteristics. The base balance subprogram calibrates data reduction predictions by adjusting nine performance variables in order to accurately simulate engine operation during a specific time slice. The rated portion of the program uses adjusted engine performance characteristics at a specific time slice as a basis for predicting performance at other operating conditions.

Examination of PBM source code reveals a large number of "hard coded" empiricisms involving flow rates, pressures, and temperatures as a function of overall system performance parameters such as thrust level. These empiricisms do not have a clear physical basis in a flow network analysis. In addition, there are computational inconsistencies between model subprograms. Combined with complex logical sequencing and inadequate documentation, these conditions reduce the level of confidence in the integrity of performance predictions returned by PBM. The object of this effort was to perform fundamental physical analyses on various engine subsystems in order to quantify flow and energy imbalances associated with PBM calculations. The method used to determine subsystem imbalances is described in the next section.

PROCEDURE

In order to check for adherence to fundamental mass and energy conservation principles, the SSME was divided into four subsystems for purposes of analysis. These subsystems are described below.

1. LPFTP - low pressure fuel turbopump system composed of
    - LPFT - low pressure fuel turbine
    - LPFP - low pressure fuel pump

2. LPOTP - low pressure oxygen turbopump system composed of
    - LPOT - low pressure oxygen turbine
    - LPOP - low pressure oxygen pump

3. HPFTP+FPB+HGM - high pressure fuel system composed of
    - HPFT - high pressure fuel turbine
    - HPFP - high pressure fuel pump
    - FPB - fuel preburner
    - HGM - fuel side hot gas manifold

4. HPOTP+OPB+HGM - high pressure oxygen system composed of
    - HPOT - high pressure oxygen turbine
    - HPOP - high pressure oxygen pump
    - OPB - oxygen preburner
    - HGM - oxygen side hot gas manifold
    - HE - heat exchanger
    - POGO - POGO accumulator

For each subsystem, the type material, mass flow rate, pressure, and temperature of each inflow/outflow was identified by position in the PBM output array. A postprocessor named VOLUME was developed to read this information and conduct standard control volume analyses on each subsystem to determine both mass and energy imbalances. VOLUME was constructed to be generic in nature so that the user could easily redefine the subsystem for analysis. This is accomplished by changing the PBM output array locations which are accessed by the VOLUME input file. These locations contain the flow rates, pressures, and temperatures for the subsystem inflows and outflows.

To guarantee the validity of VOLUME computed imbalances, it was necessary to incorporate accurate thermodynamic property relations to establish the specific energy level of each subsystem inflow/outflow. By special permission, the proprietary PROP05 property package developed by Pratt & Whitney was used to provide accurate relations between pressure, temperature, and the other thermodynamic properties for hydrogen, oxygen, steam, and hot gas mixtures. Calls to appropriate PROP05 routines were included within the VOLUME code. Results of mass and energy balance analyses conducted using the VOLUME program are presented in the next section.

RESULTS

Results of flow and energy balance analyses, conducted on the above described subsystems, are summarized in Table 1 for each of seven power level excursions ranging from 65% of engine rated power level (RPL) to 109% RPL. Subsystem imbalances in mass flow rate (DW) and energy flow rate (DE) are displayed. Energy flow rate imbalances are reported in both heat rate units (Btu/s) and power units (hp). A negative sign indicates that more of the flow exited the subsystem than entered, while a positive entry indicates the reverse. A number other than zero reflects a conservation law imbalance which requires reconciliation.

The data in Table 1 indicates a high degree of mass flow balance at all power levels. The worst case mass imbalance, which occurred in the high pressure oxygen subsystem at low RPL, was only a tiny fraction of the overall subsystem flow. Predicted power imbalances were, however, disturbingly large for both high pressure subsystems. Predicted high pressure fuel subsystem imbalances were exceptionally large at all thrust levels as displayed in Table 1. In all cases, the high pressure subsystem imbalances were negative, indicating that more energy exited the system than entered. This is of course a classical First Law violation.

A better indication of the relative magnitudes of the power imbalances is displayed in Figure 1. Each subsystem power imbalance was normalized by the required subsystem pump power. Both high pressure subsystems displayed significant proportional imbalances which decreased with increasing RPL operation and range from over 0.40 at 65% RPL to over 0.25 at 109% RPL.

In order to better determine the sources of power imbalance imposed by PBM predictions within the high pressure subsystems, component energy studies were performed with results displayed in Figures 2 through 4. As shown in Figure 2, significant discrepancy between pump power requirement and turbine delivery was observed at all power levels in the high pressure fuel subsystem. In addition, both preburners were significantly imbalanced as exhibited in Figure 3, with the fuel side imbalance again larger. The combined fuel side turbopump subsystem also displayed a larger proportional imbalance than the oxygen turbopump subsystem as displayed in Figure 4.

Because of the magnitudes of the imbalances on the fuel side, and to better understand the limitations of the study due to property and and modeling restrictions, an uncertainty analysis was performed on both the HPFP and HPFT power predictions. Error bands of approximately +/-3% for the pump and +/-10% for the turbine were estimated. The turbine side uncertainty estimate was larger due to combustion model and real gas mixture uncertainties. Fuel side power levels with uncertainty bands are plotted in Figure 5. The error banded power curves do not overlap which indicates substantial PBM computational bias as opposed to physical data and modeling limitations.

A comparison of PBM subprogram predictions for the high pressure fuel and oxygen subsystems is exhibited in Figure 6. Predictions with significant proportional imbalance were returned by each of the data reduction, base balance, and power balance subprograms as displayed in Figure 6. The theoretical power balance subprogram returned the most imbalanced subsystem predictions in each case, although only marginally larger than data reduction and base balance predictions. In comparing fuel and oxygen side predictions, the turbopump proportional imbalances indicated by the cross-hatched columns were significantly larger on the fuel side than on the oxygen side. This is particularly disturbing since it suggests multiple sources causing the predicted imbalances.

CONCLUSIONS AND RECOMMENDATIONS

Power Balance Model predictions do not satisfy energy conservation requirements adequately. Because of failure to satisfy this fundamental physical requirement, the accuracy of mass flow rate, temperature, and pressure predictions are suspect throughout the engine system.

The following recommendations are made.

1.
Upgrade PBM to adequately account for the flow physics in addition to integrating test and flight data.

2.
Develop an independent data reconciliation model to access the integrity of test data in relation to fundamental flow physics and to reconcile differences prior to PBM data integration.

3.
In order to reduce the uncertainty due to physical property limitations within the model, implement the best available property data into PBM.

4.
Establish benchmark states for hot gas mixture properties in order to reduce prediction uncertainty in high pressure turbopumps and preburners.

5.
Perform an energy sensitivity analysis for all subsystems to estimate the consequences of First Law violation.

Table 1. Power Level Excursions

POWER BALANCE # 1 109% RPL

THRUST = 109.000% RPL

SUBSYSTEM	DW(LB/S)	DE(BTU/S)	DE(HP)
LPFTP	0.002	192.431	272.258
LPOTP	0.000	55.949	79.159
HPFTP+FPB+HGM	-0.002	-13635.504	-19292.000
HPOTP+OPB+HE+POGO+HGM	0.002	-5349.570	-7568.762

POWER BALANCE # 2 104% RPL

THRUST = 104.000% RPL

SUBSYSTEM	DW(LB/S)	DE(BTU/S)	DE(HP)
LPFTP	0.004	231.743	327.878
LPOTP	0.000	68.043	96.270
HPFTP+FPB+HGM	-0.002	-12798.664	-18108.012
HPOTP+OPB+HE+POGO+HGM	0.002	-5009.715	-7087.922

POWER BALANCE # 3 100% RPL

THRUST = 100.000% RPL

SUBSYSTEM	DW(LB/S)	DE(BTU/S)	DE(HP)
LPFTP	0.003	199.509	282.272
LPOTP	0.000	62.402	88.289
HPFTP+FPB+HGM	-0.002	-12121.408	-17149.918
HPOTP+OPB+HE+POGO+HGM	0.014	-4694.590	-6642.074

POWER BALANCE # 4 90% RPL

THRUST = 90.000% RPL

SUBSYSTEM	DW(LB/S)	DE(BTU/S)	DE(HP)
LPFTP	0.002	146.214	206.869
LPOTP	0.000	53.746	76.042
HPFTP+FPB+HGM	-0.001	-10727.629	-15177.836
HPOTP+OPB+HE+POGO+HGM	0.035	-4092.676	-5790.465

POWER BALANCE # 5 80% RPL

THRUST = 80.000% RPL

SUBSYSTEM	DW(LB/S)	DE(BTU/S)	DE(HP)
LPFTP	0.002	83.443	118.058
LPOTP	0.000	42.848	60.622
HPFTP+FPB+HGM	0.000	-9450.035	-13370.250
HPOTP+OPB+HE+POGO+HGM	0.053	-3517.473	-4976.645

POWER BALANCE # 6 70% RPL

THRUST = 70.000% RPL

SUBSYSTEM	DW(LB/S)	DE(BTU/S)	DE(HP)
LPFTP	0.002	49.171	69.569
LPOTP	0.000	25.512	36.095
HPFTP+FPB+HGM	-0.001	-8352.645	-11817.621
HPOTP+OPB+HE+POGO+HGM	0.070	-2941.273	-4161.418

POWER BALANCE # 7 65% RPL

THRUST = 65.000% RPL

SUBSYSTEM	DW(LB/S)	DE(BTU/S)	DE(HP)
LPFTP	0.001	33.004	46.696
LPOTP	0.000	20.258	28.661
HPFTP+FPB+HGM	0.000	-7815.320	-11057.395
HPOTP+OPB+HE+POGO+HGM	0.082	-2680.719	-3792.776

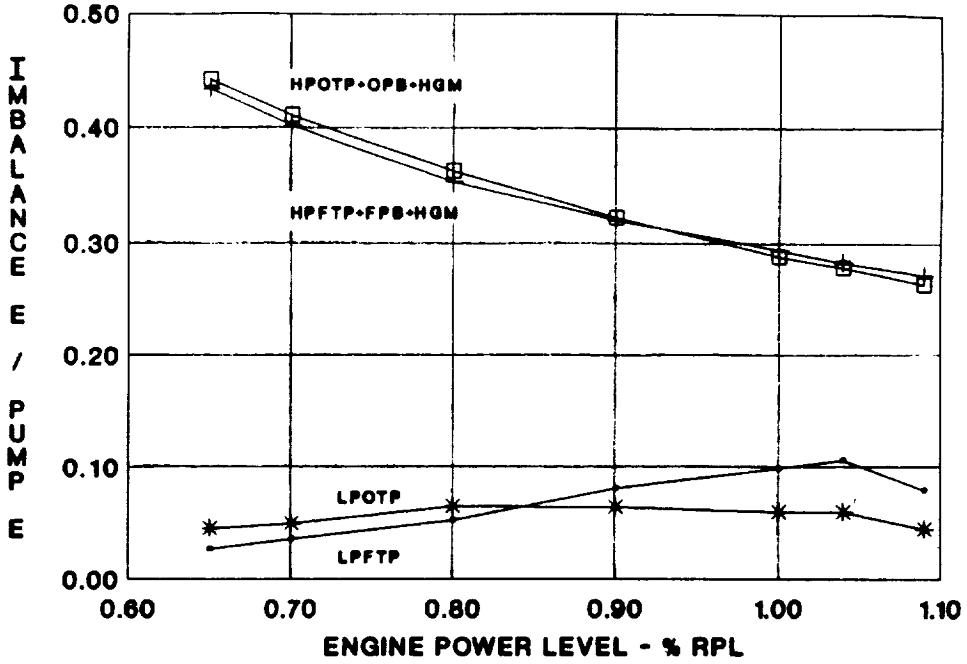

FIGURE 1. SYSTEM PROPORTIONAL IMBALANCE

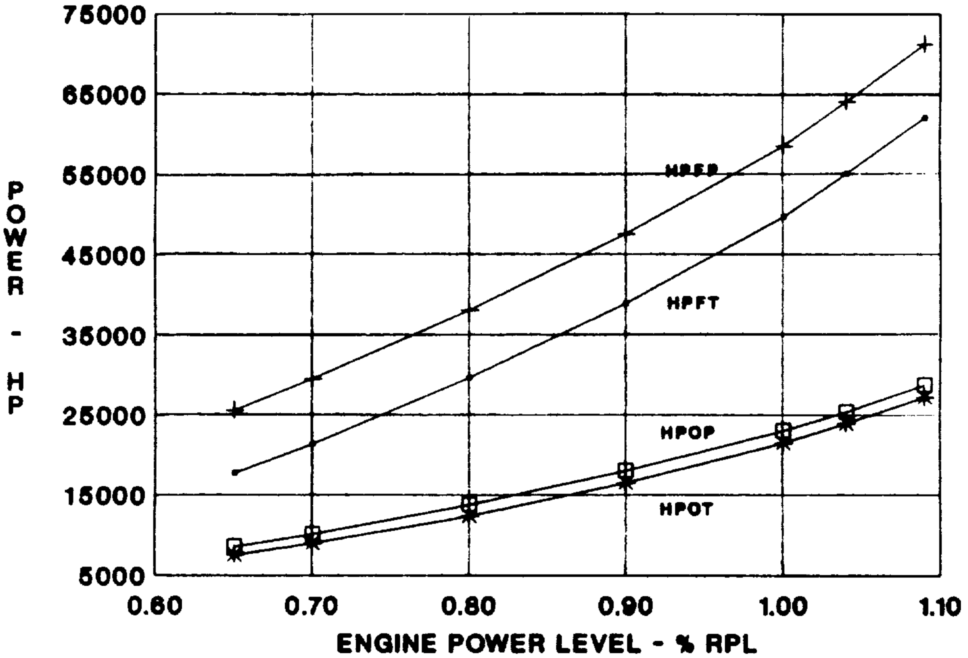

FIGURE 2. HIGH PRESSURE SYSTEM POWER

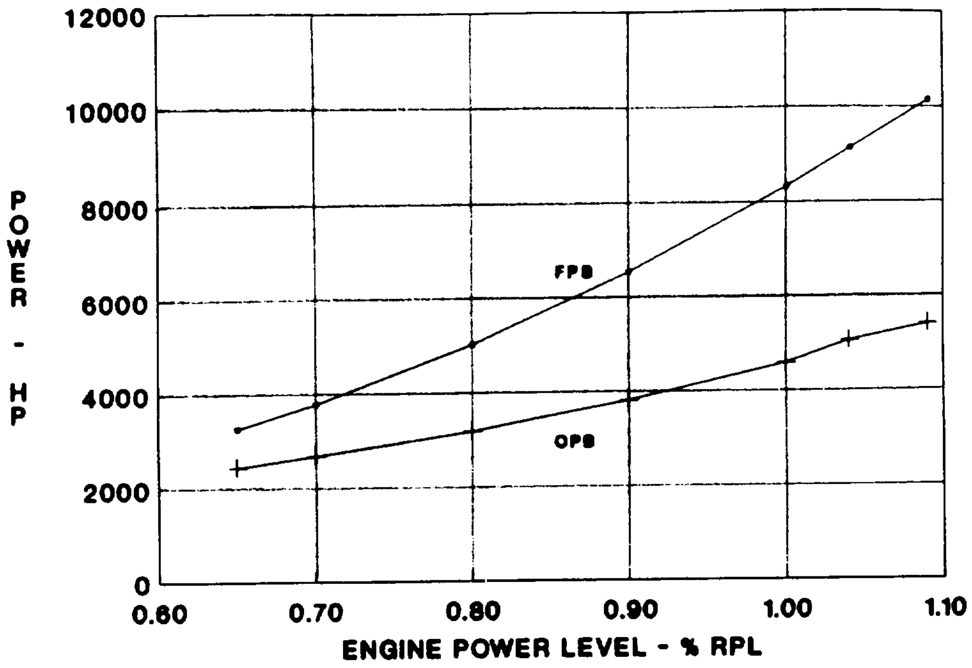

FIGURE 3. PREBURNER POWER IMBALANCE

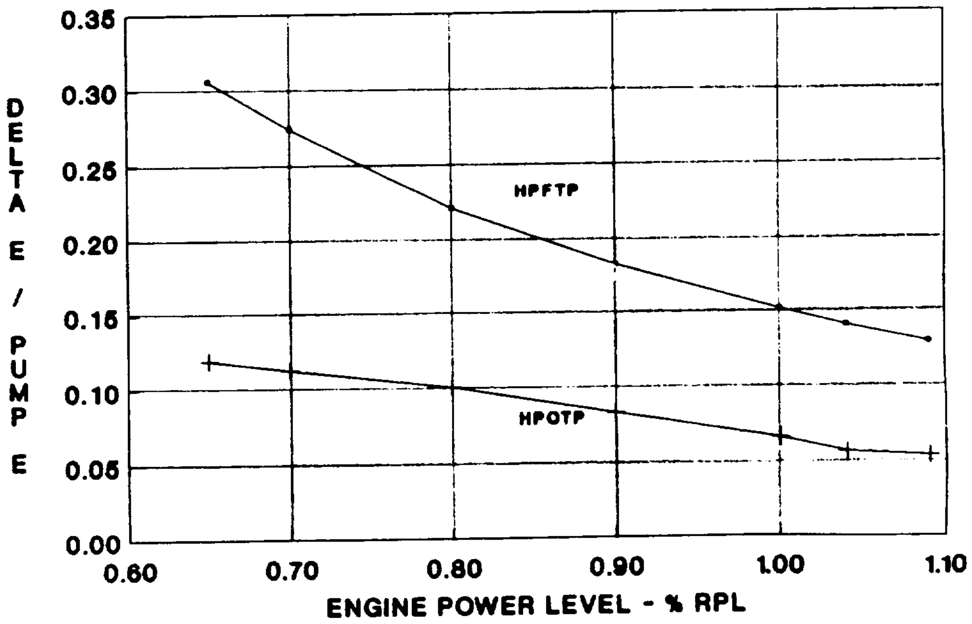

FIGURE 4. TURBOPUMP PROPORTIONAL IMBALANCE

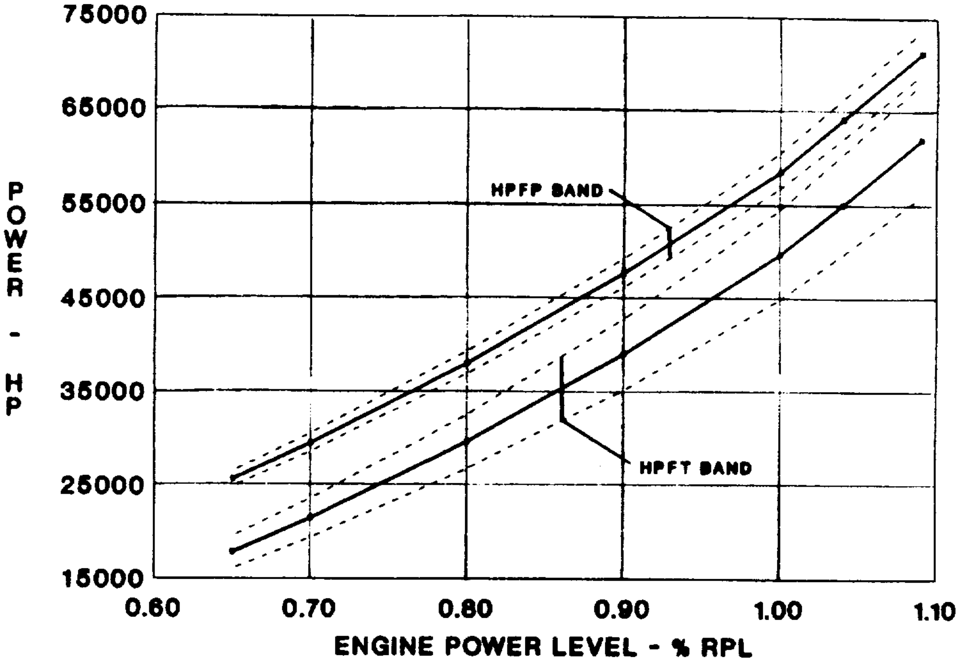

FIGURE 5. HPFTP SYSTEM UNCERTAINTY

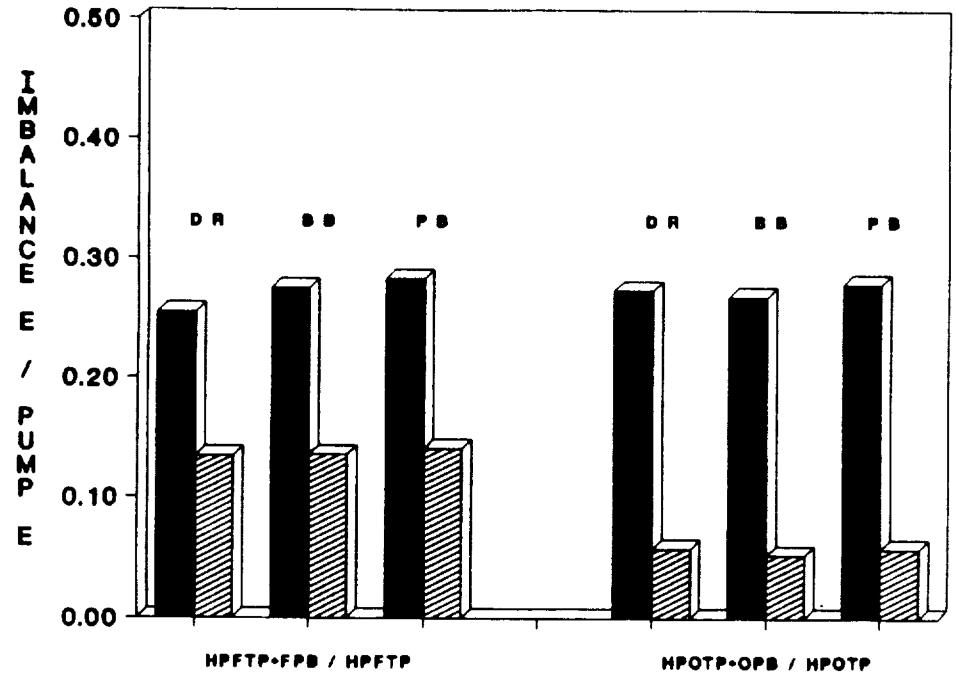

FIGURE 6. PBM90A EVALUATION AT 104% RPL