GEORGE C. MARSHALL SPACE FLIGHT CENTER

MTP-AERO-62-37

ERROR ANALYSIS OF PROPULSION SYSTEM PARAMETER EVALUATION FOR SATURN SA-1

By

C. R. Fulmer

(U) ABSTRACT

This report presents an analysis of the probable errors in the propulsion system parameter evaluation from flight simulation for SA-1. The types of error contributors considered are: trajectory parameter errors, liftoff weight errors, atmospheric measurement errors, and axial drag force coefficient errors. A solution for the axial drag force coefficient and an estimated error margin is obtained based on the results of the SA-1 test flight.

The value chosen for liftoff weight and the average values of the propulsion parameters which will produce a trajectory which matches the SA-1 observed trajectory are given below.

Average Vehicle Performance Parameters

Parameter	Unit	Quantity
Liftoff	Weight, lb	929,560
Average Sea Level Thrust	lb	1,333,300 ± 1,500
Average Total Flow Rate	lb/sec	5,240 ± 4
Average Sea Level Specific Impulse	sec	254.4 ± 0.4

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FLIGHT EVALUATION BRANCH
AEROBALLISTICS DIVISION

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DEFINITION OF TERMS

Propulsion Parameters	Thrust, flow rate, and specific impulse
Trajectory Parameters	Slant distance, earth-fixed velocity, and longitudinal acceleration (on-board or external measurement)
Adjustments	Shifts in levels of thrust and flow rate and changes in specific impulse and axial drag force coefficient required to simulate the actual trajectory
Flight Reconstruction	A computer program which uses a few high quality propulsion system measurements with a preflight prediction program to produce the propulsion parameters.
Flight Simulation	A computer program with a differential correction procedure used to obtain adjustments to the propulsion parameter inputs which will produce a trajectory which matches the actual vehicle trajectory with a resultant simulation of the overall propulsion system performance.
Flow Rate	Total mass loss rate
Profile	The functional variation of an input parameter with respect to time of flight.

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SUMMARY

Probable errors in the propulsion system parameter evaluation as obtained from flight simulation are given. The types of error contributors considered are: trajectory parameter errors, liftoff weight errors, atmospheric measurement errors, and axial drag force coefficient errors. A solution for the axial force coefficient and an estimated error margin is obtained based on the result of the SA-1 test flight. Errors in vehicle thrust, flow rate, and specific impulse resulting from the root-sum-square of all the error contributors are given versus liftoff weight.

1.0 INTRODUCTION

Functional performance of the propulsion system for Saturn SA-1 was determined from the 267 telemetered propulsion and associated subsystems measurements. The major transients evidenced in these measurements were unaltered in any analyses of the vehicle performance.

Some of the high quality propulsion system measurements, such as turbine speed, were introduced into the preflight prediction program to achieve an analytical reconstruction of the remainder of the propulsion measurements. The results of this flight reconstruction were compared with the inflight measurements to validate both the measurements and the reconstruction program.

Performance of the individual engines, as well as those subsystems associated with the propulsion system, was established from telemetry and/or the flight reconstruction program.

Thrust and flow rate, from telemetry or the flight reconstruction program, were used with an assumed liftoff weight as inputs to the flight simulation program (all other inputs, including aerodynamic force coefficients, were the values predicted for SA-1). The levels of the thrust and flow rate are adjusted until the trajectory from this program matches the actual vehicle trajectory within specified limits. The results from this trajectory match are a flight simulation of the vehicle performance only. The distribution of these adjustments upon the individual engines can be obtained only in an arbitrary manner. The distribution, in this particular case, was assumed proportional to the thrust and flow rate for the engine considered. Individual engine performance evaluation is given in References 1 and 2.

Vehicle performance from the flight simulation program is a result of all the forces and moments acting along the vehicle longitudinal axis. Therefore, some basic differences between vehicle and individual engine performance must be expected. The inboard and outboard engines are canted at three and six degrees, respectively, with the vehicle longitudinal axis, and the outboard engines are gimballed according to commands from the control system. These two factors cause the thrust and specific impulse from the vehicle to average about 0.4% lower than the corresponding values for the individual engines. Turbine exhaust thrust and buoyancy forces must be considered in the flight simulation program, but only the turbine exhaust thrust contributes to the vehicle performance.

Propulsion parameter adjustments are only as accurate as the basic input for the trajectory computation program. Some of the sources of inaccuracy in the adjustments are:

Trajectory parameter error
Liftoff weight assumption
Atmospheric measurement error
Axial drag force coefficient error.

Inaccuracies in the adjustments resulting from trajectory parameter and atmospheric measurement errors are small. Vehicle specific impulse is virtually free of the assumption for liftoff weight, but thrust and flow rate adjustments are highly correlated with the liftoff weight assumption. All three adjustments are highly correlated with errors in the axial drag force coefficient.

2.0 TRAJECTORY PARAMETER ERRORS

Trajectory parameters used in the flight simulation program to obtain the adjustments to the propulsion parameters were:

Trajectory Parameters

Parameter	Derived From
Slant Distance from Launch Pad to Vehicle	External Tracking
Earth-fixed Velocity	External Tracking
Longitudinal Acceleration	On-board Measurements and External Tracking

An estimate of the errors in the measurement of the trajectory parameters is shown below:

Trajectory Parameter	Error	% Value at IECO
Slant Distance, m	± 10	± 0.019
Earth-fixed Velocity, m/s	± 0.2	± 0.013
Longitudinal Acceleration, m/s^2	± 0.1	± 0.239

The error given for longitudinal acceleration is the error associated with the on-board measurement. The error in the acceleration from external tracking is probably larger during the first 15-30 sec of flight but much better during the last half of the powered flight. Longitudinal acceleration is the only trajectory parameter which is indicative of the instantaneous vehicle performance.

The errors resulting in the adjustments from these trajectory parameter errors are:

Vehicle Propulsion Parameter Adjustments

Adjustment	Units	Error	% of Total
Thrust	lb	± 75	0.006
Flow Rate	lb/sec	± 0.6	0.011
Specific Impulse	sec	± 0.04	0.017

The percentage figures of this table clearly show that position and velocity have the largest influence on the adjustments.

3.0 ADJUSTMENTS AS A FUNCTION OF LIFTOFF WEIGHT

No mechanical or electrical system was designed to weigh the loaded Saturn vehicle at the launch site. Methods have been designed to estimate the amount of propellants loaded. These estimates with an estimate of the weight of the empty vehicle provide an accuracy of about ± 0.5% for the liftoff weight determination.

The variation of the adjustments with liftoff weight was obtained by merely using different assumptions for liftoff weight in the flight simulation program. It was found that even with a variation of $\pm$ 2% in liftoff weight, adjustments could be obtained which would match the trajectory parameters within the limits specified in paragraph 2.0.

Figure 1 shows the percent deviation in average vehicle thrust, flow rate, and specific impulse resulting from a given percentage deviation in liftoff weight. There is virtually no variation of vehicle specific impulse with liftoff weight which clearly indicates that specific impulse is the propulsion parameter determined best from the flight simulation program.

The liftoff weight of the Saturn vehicle consists primarily of the dry vehicle, water ballast in the upper stages, fuel and oxidizer on-board at liftoff, lubricants, coolants, pressurizing agents, and ice accumulation. The deviation between actual and predicted liftoff weight is distributed among these.

Liftoff Comparison

Parameter	Unit	Actual	Predicted	Act.-Pred.
Liftoff*	Weight, lbs	928,725	926,229	2,496
Water Ballast	Weight, lbs	191,525	191,525	0
Fuel at Liftoff	Weight, lbs	187,548	190,275	-2,727
Oxidizer at Liftoff	Weight, lbs	429,887	426,049	3,838
Dry Vehicle	Weight, lbs	118,110	116,110	2,000
Gox, GN2 Hydraulic Oil	Weight, lbs	1,655	2,270	-615

* Ice accumulation of about 1,000 lbs not included.

Inboard engine cutoff (IECO) for SA-1 was given by the fuel level switch in fuel tank #2. This imposes some limitations on the distribution of the liftoff weight deviations.

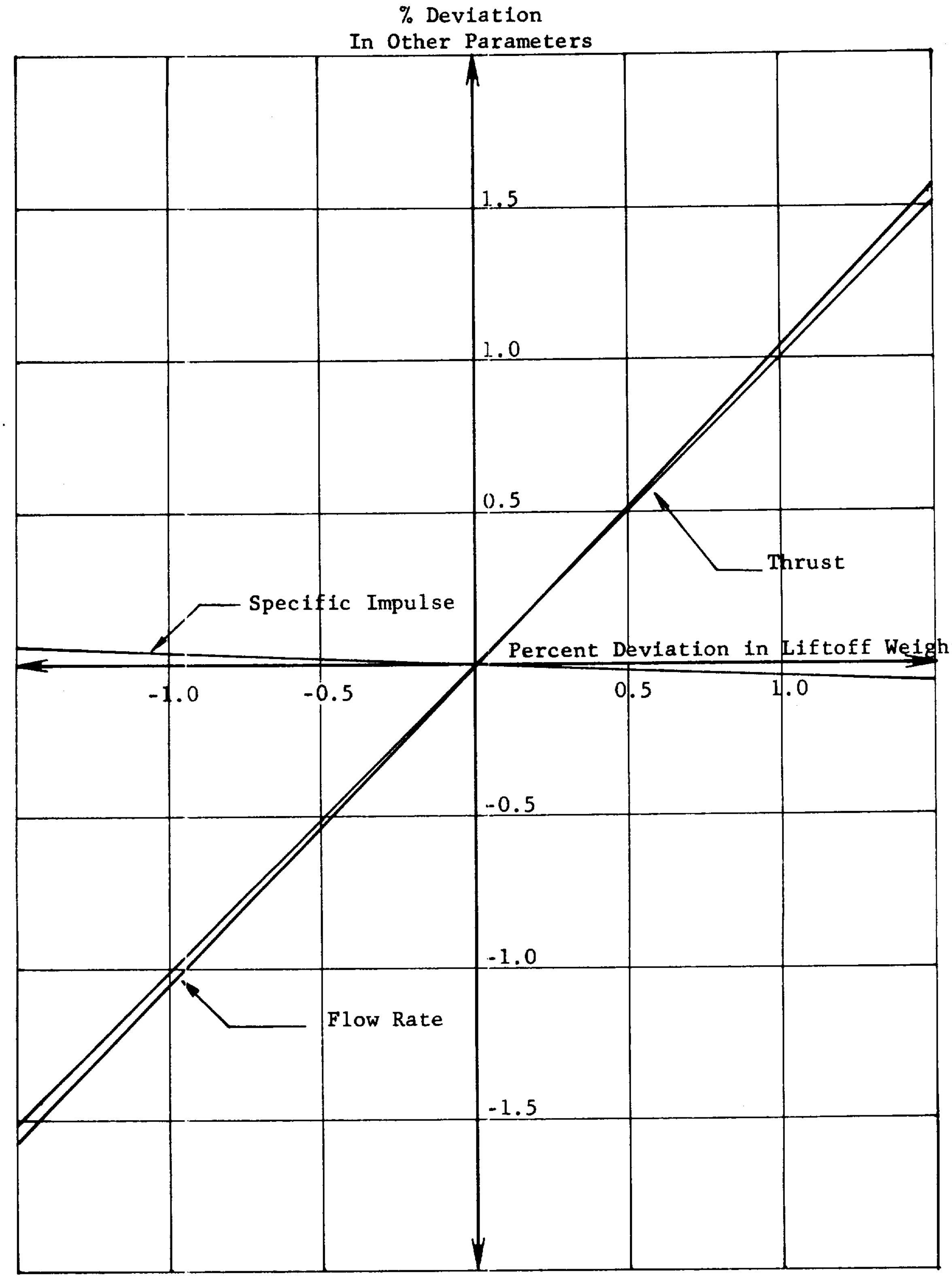


Fig. 1 ADJUSTMENT VS LIFTOFF WEIGHT DEVIATIONS

4.0 LIMITATIONS ON LIFTOFF WEIGHT DISTRIBUTION IMPOSED BY FUEL LEVEL CUTOFF

A study was made to determine the effects of fuel level cutoff signal on the distribution of the liftoff weight deviations. Several basic assumptions, tabulated below, were made for this study.

1. Time between liftoff and cutoff signal is constant.
2. Total propellant flow rate to each engine is constant.
3. Vehicle liftoff weight remains constant.
4. The height of the fuel level cutoff probe in the tank is invariant.

Vehicle liftoff weight and total propellant flow rate are the adjusted values taken from the flight simulation method and are thus considered invariant. The time between liftoff and cutoff can be determined very accurately from several telemetered measurements. The primary variable, with these assumptions, is the fuel tanking weight.

From the assumptions above, several things can be immediately deduced. Only a fuel tanking weight change affects the individual fuel and LOX flow rates and the mixture ratio. The LOX level at cutoff will not be constant, but the vehicle weight at cutoff will be constant.

Several variations were made in fuel tanking weight, LOX tanking weight and dry missile weight to develop characteristic curves for various engine parameters. The fuel and LOX flow rates as a function of fuel tanking weight change are shown in Figure 2. They both vary linearly with fuel tanking weight change due to the fixed cutoff time and fuel cutoff level. They vary in opposite directions due to the constant total propellant flow rate restriction. Figure 2 also shows mixture ratio as a function of fuel tanking weight change. The variation of LOX level at cutoff as a function of fuel or LOX tanking weight change is plotted in Figure 3.

Once the total liftoff weight deviation has been determined the fuel tanking weight deviation can be obtained from the total flow rate derived in the flight simulation program and the fuel level at cutoff. Also, if the error in the dry vehicle and water ballast weight is known, the LOX tanking weight deviation can be obtained.

The fuel level cutoff probes were 24.1 in from the bottom and 19.5 in from the tank center line in fuel tanks #2 and #4. The LOX level cutoff probes were 29.25 in from the bottom and 22.0 in from the tank center line in tanks #2 and #4. A sufficient excess of LOX was loaded so that cutoff would be given by the fuel probes.

(Note: Fuel Tanking Weight is Primary Variable)

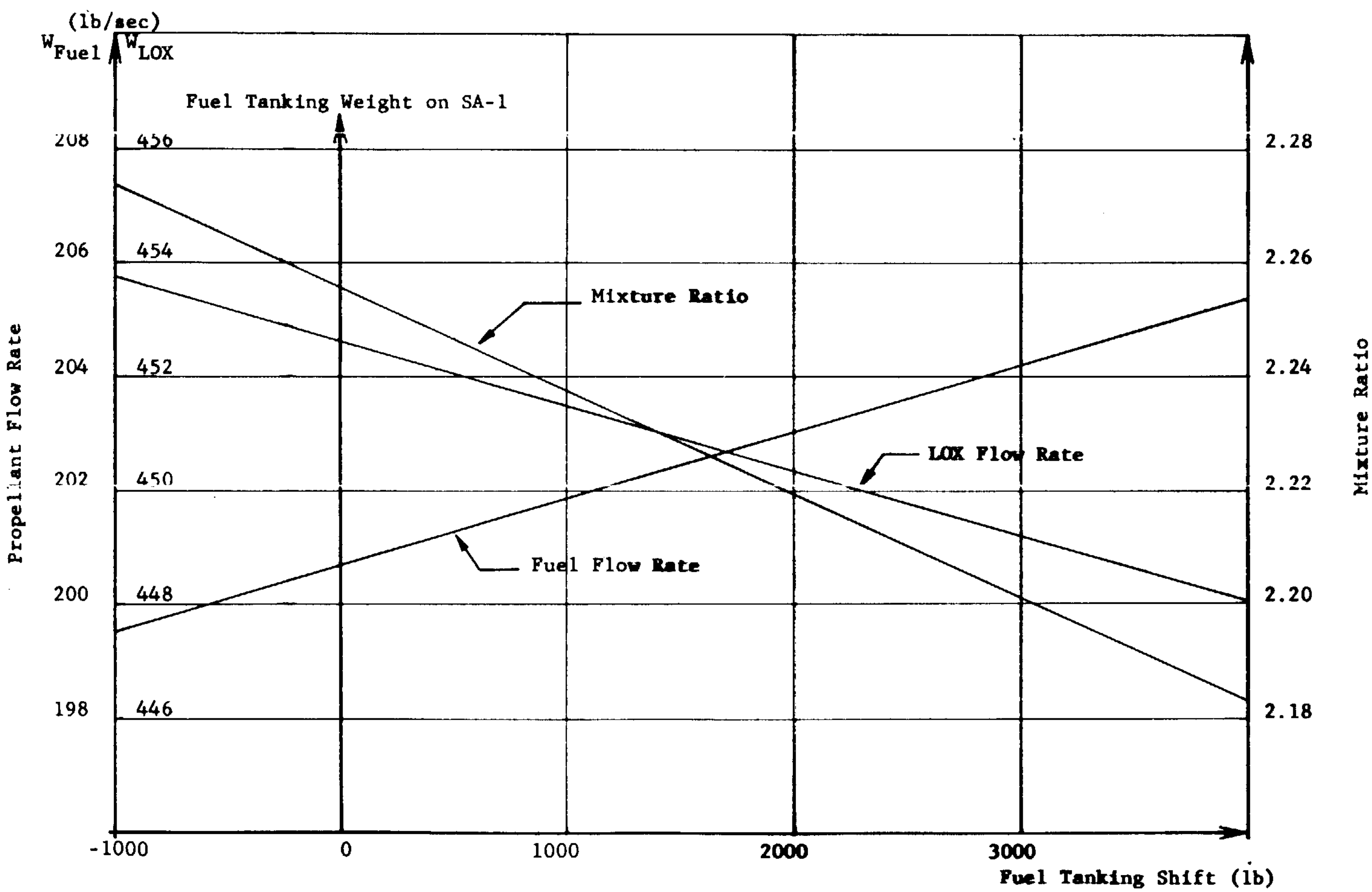


Fig. 2 MIXTURE RATIO AND PROPELLANT FLOW RATE VS FUEL TANKING SHIFT

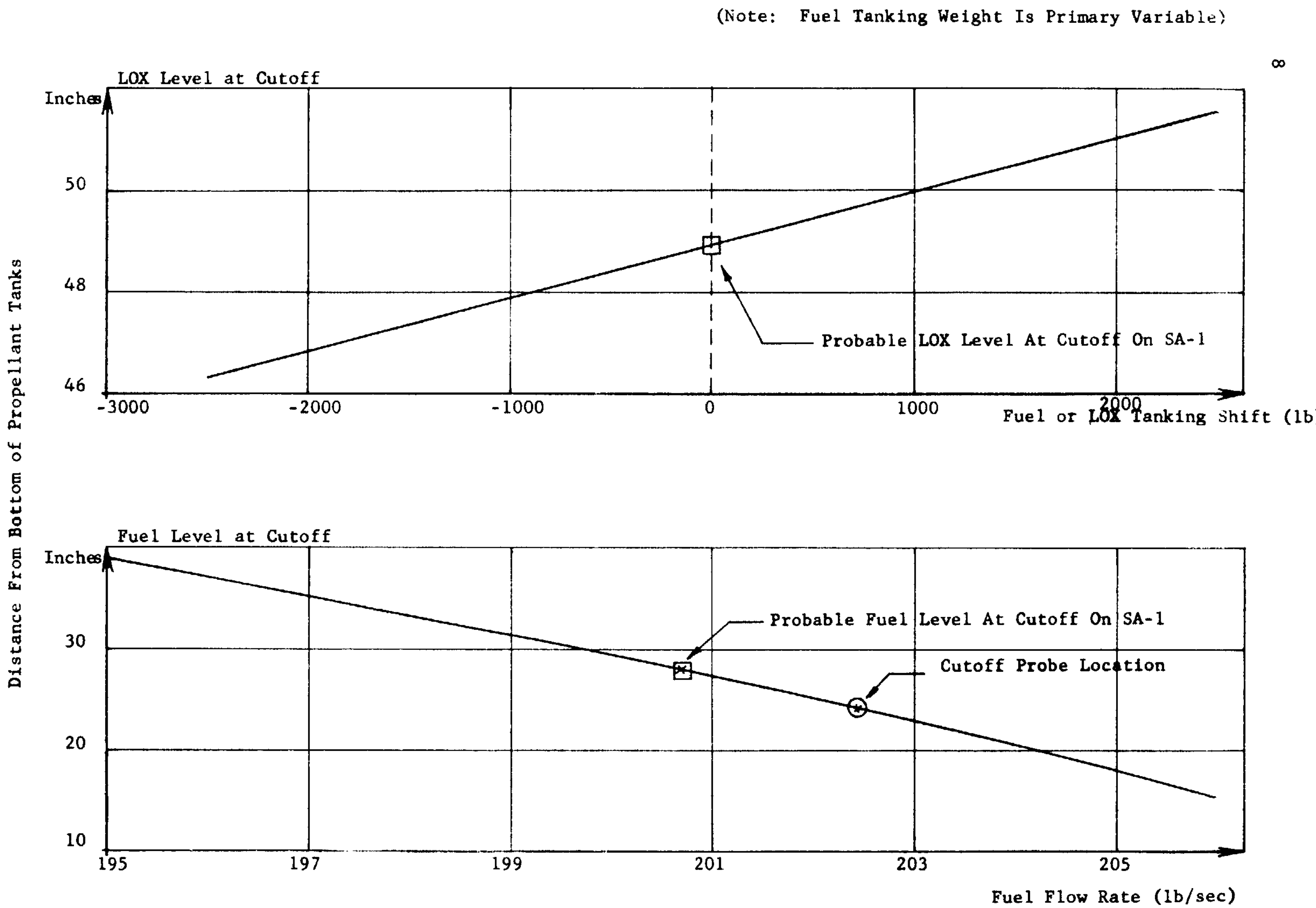


Fig. 3 LOX LEVEL AT CUTOFF VS PROPELLANT TANKING SHIFT AND FUEL LEVEL AT CUTOFF VS FUEL FLOW RATE

The measurement for the cutoff signal given by the probe in fuel tank #2 was telemetered on a commutated channel with a resultant accuracy of only $\pm$ 0.1 sec. Also, sloshing with an amplitude of about 2-4 in was experienced in both the LOX and fuel tanks for SA-1. Both of these factors place a degree of uncertainty about the actual fuel level in the tank when cutoff was given. The first three assumptions made earlier were combined with an invariant tanking weight to show how the fuel level at cutoff varies with average fuel flow rate. This is shown in the lower portion of Figure 3. The location of the fuel probe and the probable fuel level at cutoff are also shown on this plot.

The fuel level cutoff does not contribute directly to the results from the flight simulation. It does aid in the distribution of the liftoff weight deviations and provides at least some guide lines for the fuel flow rate.

5.0 ATMOSPHERIC MEASUREMENT ERRORS

Atmospheric measurements are part of the basic inputs required for flight simulation. Each of the measurements do contain some error. The error profiles for pressure and temperature are shown in Figure 4. The error in the wind measurement is $\pm$ 5 m/s. These estimates of the error in the measurements were provided by Aerophysics and Astrophysics Branch, Aeroballistics Division. The wind error curve used in the flight simulation was an oscillation with an amplitude of $\pm$ 5 m/s and a period of about 5 km in altitude.

The errors resulting in the adjustments from these measurement errors are:

Vehicle Propulsion Parameter Adjustments

Adjustments	Units	Error	% of Total
Thrust	lb	1150	0.086
Flow Rate	lb/sec	2.8	0.053
Specific Impulse	sec	0.34	0.134

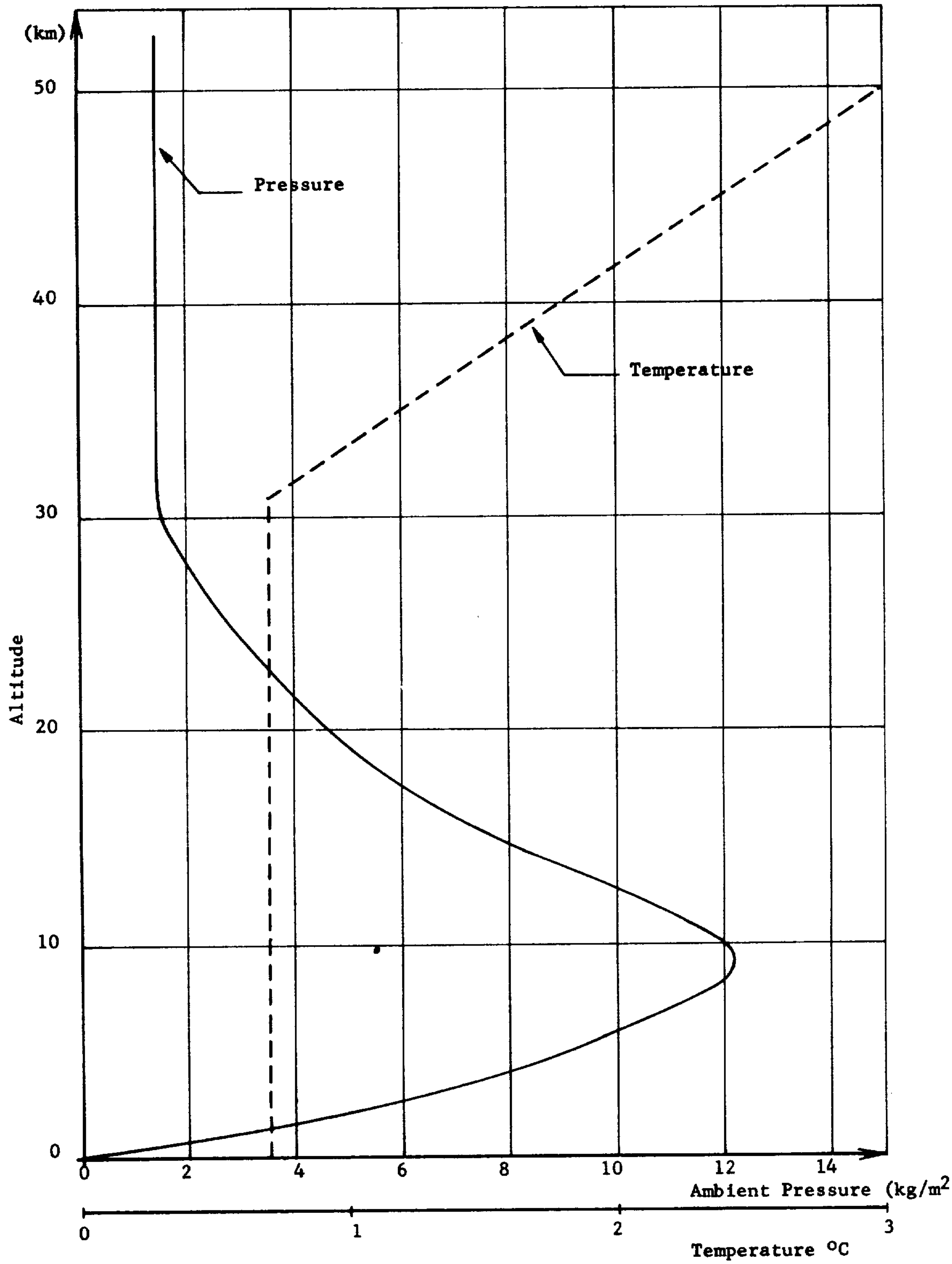


Fig. 4 AMBIENT PRESSURE AND TEMPERATURE MEASUREMENT ERRORS

Errors in the atmospheric measurement also produce errors in the calculation of the axial drag force coefficient (see Par. 6.2).

6.0 ERRORS IN SOLUTION RESULTING FROM ERRORS IN AXIAL DRAG FORCE

The Saturn vehicle has a representative cross sectional area of about 33.5 square meters. This large area and the fact that the vehicle remains in the denser part (ambient pressure 10.8 kg/m^2 at IECO) of the atmosphere throughout most of the powered flight indicate that the aerodynamic force will have a large influence on the trajectory simulation.

6.1 DRAG FORCE

The ratio of the drag force to the local thrust force is shown as a percentage in the upper portion of Figure 5. The peak ratio of drag to local thrust force during power flight is about 12% which occurs at maximum dynamic pressure. The drag force averages about 4% of the local thrust force during the powered flight and produces an "effective reduction" in vehicle specific impulse (see lower portion of Fig. 5). The peak "effective reduction" is about 33 sec which again occurs at maximum dynamic pressure. The average reduction in vehicle specific impulse is about 10 sec or 4% of the total vehicle specific impulse.

Drag forces are computed from axial drag force coefficients, dynamic pressure, and the representative cross sectional area. The predicted axial drag force coefficient, shown as dashed line in Fig. 6, is principally determined from wind tunnel tests. The estimated accuracy of this axial force coefficient determination is unknown prior to Mach 1.2, -10% from Mach 1.2 to Mach 4.0, and $\pm$ 10% after Mach 4.0. This axial drag force coefficient and the estimate of accuracy were obtained from Aerodynamics Analysis Branch, Aeroballistics Division.

6.2 AXIAL DRAG FORCE COEFFICIENT FROM FLIGHT TEST DATA

The axial drag force coefficient can be obtained from the following equation

$$Cx = \frac{1}{qA} \; FJ1 + FE1 + FB1 - B1 - \frac{M}{qA} \; AL$$

where:

Cx is axial drag force coefficient
q is dynamic pressure
A is representative cross sectional area
FJ1 is thrust forces along vehicle's longitudinal axis

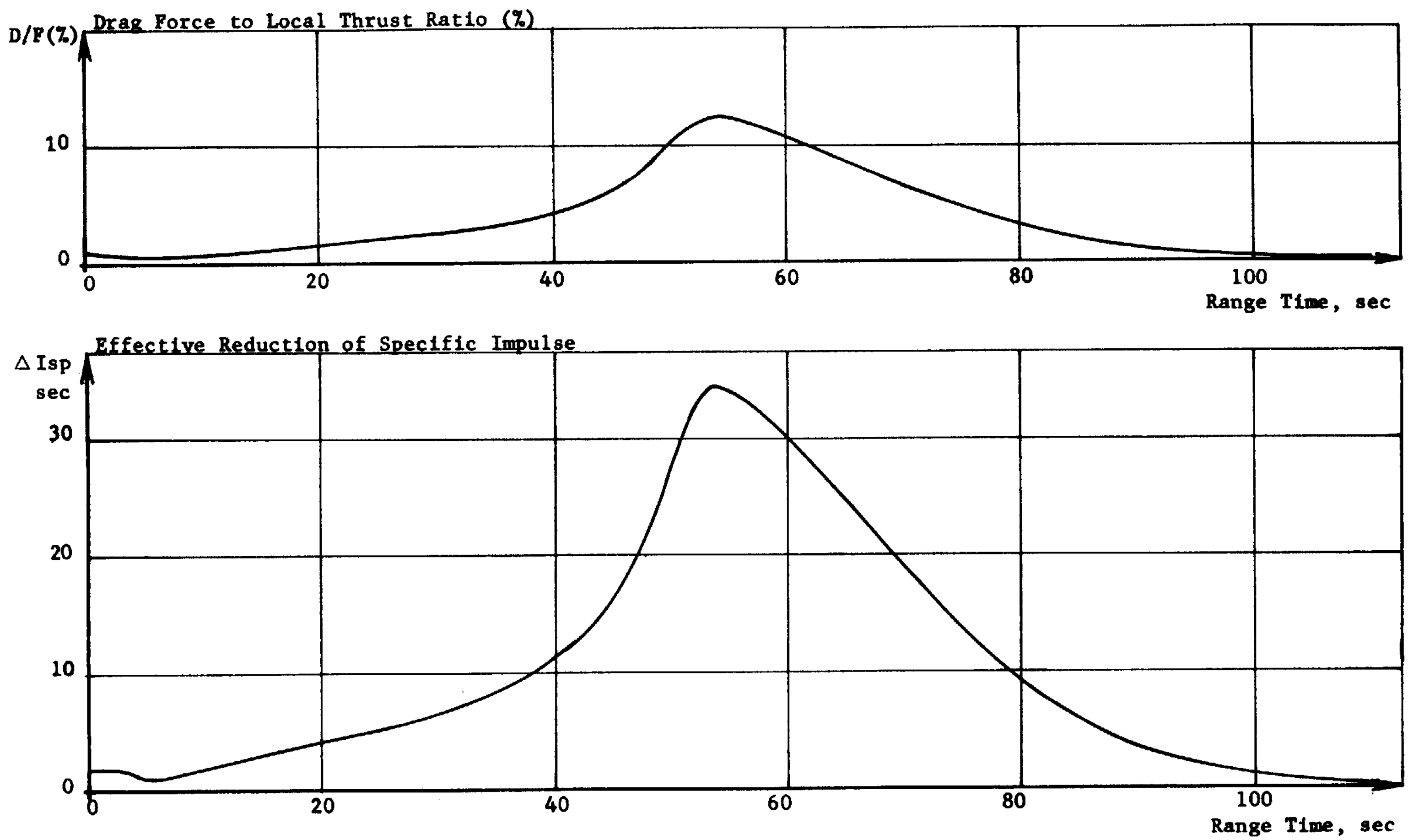


Fig. 5 DRAG FORCE TO LOCAL THRUST RATIO AND EFFECTIVE REDUCTION IN SPECIFIC IMPULSE

Note: The error margin cannot be estimated prior to Mach 0.4 or after Mach 4.0

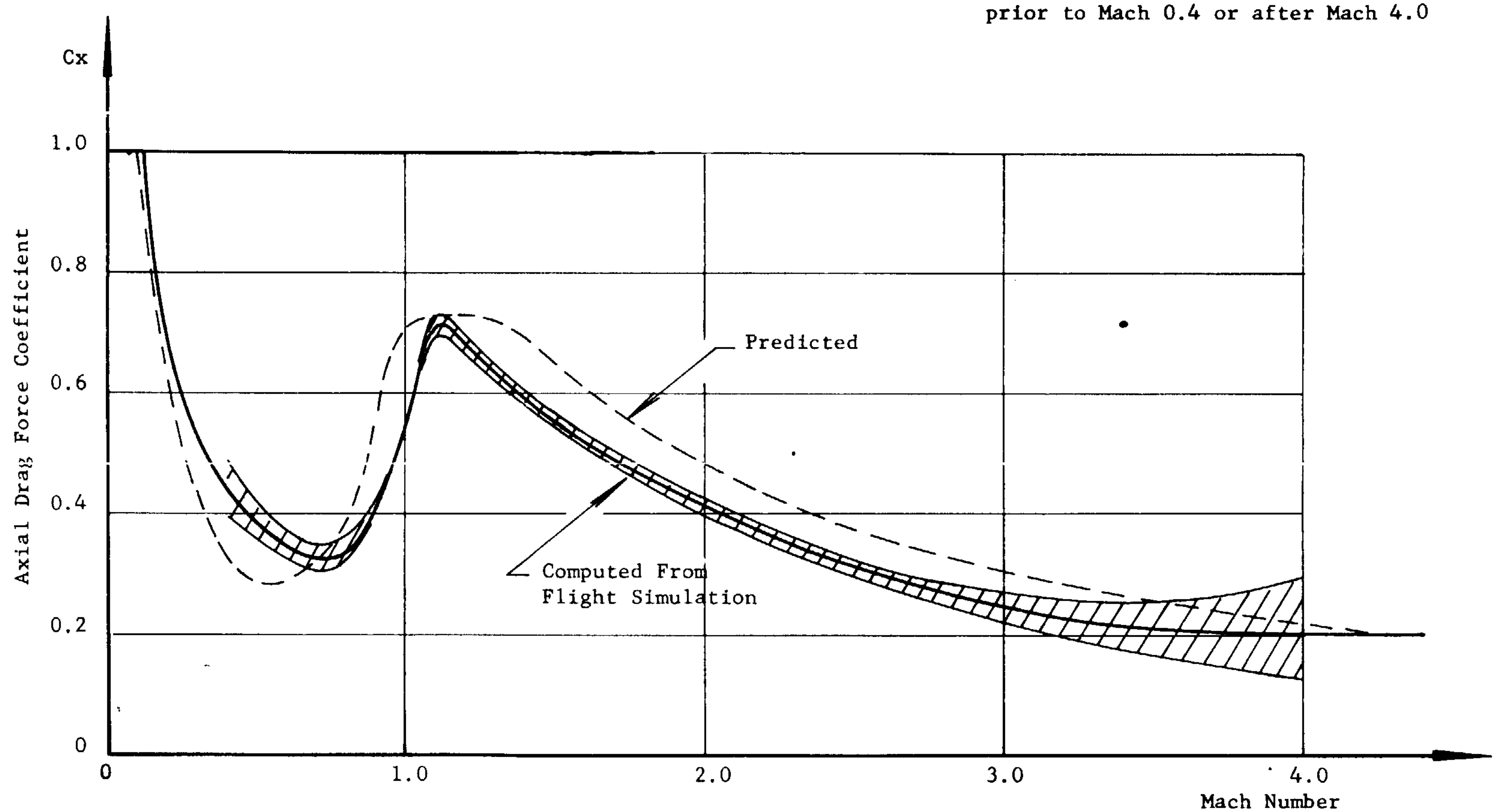
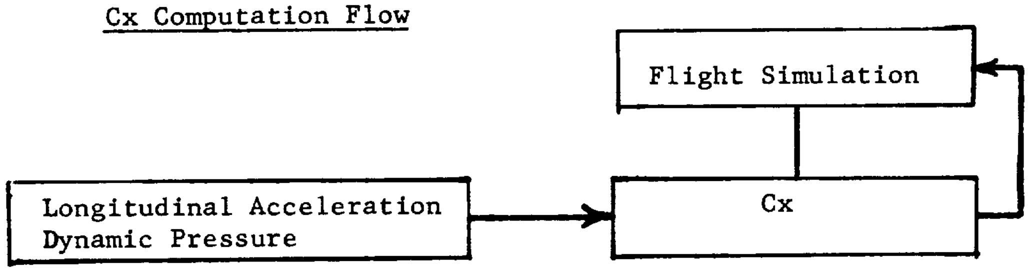


Fig. 6 AXIAL DRAG FORCE COEFFICIENT

FE1 is turbine exhaust forces along vehicle's longitudinal axis
FB1 is buoyancy forces along vehicle's longitudinal axis
B1 is influence of jet suction forces
B1 (0-40)m = 4500-75 h; where h = altitude in meters
B1 (above 40 meters) = $\frac{1500}{1 + 1000\ M^4}$; where M = Mach Number
AL is acceleration along vehicle's longitudinal axis
M is instantaneous mass

Thrust forces and instantaneous mass are obtained from flight simulation; buoyancy force, turbine exhaust thrust and jet suction effect, all of which are small compared to the total thrust, are the predicted values; all other values are obtained from on-board or external measurements. The buoyancy forces are predicted from the vehicle contour. An error in any of these terms will produce corresponding errors in Cx. Thrust forces, mass, and longitudinal acceleration (particularly in the early part of the powered flight) are the terms which largely determine Cx, but they also contain the largest errors. The errors in thrust forces and instantaneous mass are greatly reduced through flight simulation. An abbreviated flow diagram of the Cx computation is shown below:

Cx Computation Flow



This is an iterative procedure which is dependent on the outputs from the flight simulation program and the longitudinal acceleration and dynamic pressure measurements. The largest single error contributor is longitudinal acceleration. On-board measurement accuracy is only $\pm$ 0.1 m/s^2 during any part of the powered flight. The relative error of this measurement is naturally larger in the early part of the flight with a resultant larger relative error in the Cx computation. Only random errors in longitudinal acceleration are permissible since bias or even systematic errors over any sustained period of time could be eliminated through the velocity and position matches.

A "psuedo-random" error curve for the longitudinal acceleration was established to illustrate its effect on the Cx computation. The error curve assumed was an oscillation with an amplitude of $\pm$ 0.1 m/s^2 and a period of 10 sec. This error curve was added to the measured longitudinal acceleration and Cx computed from both accelerations.

The Cx computed from the measured longitudinal acceleration is shown as the solid line in Figure 6. The average of the oscillations which occur when Cx is computed from the acceleration with error curve added is shown as the shaded area in this same figure. The maximum or minimum axial drag force coefficient represented by these shaded areas cannot occur for a sustained time period (less than 10 sec maximum).

Errors in the measurement of atmospheric pressure, temperature, and wind cause errors in dynamic pressure which would cause errors in the computation of Cx. However, the errors resulting in Cx from the measurement errors given in paragraph 5.0 are negligible.

The computation for Cx is virtually independent of the assumption for liftoff weight whenever flight simulation results for the thrust and flow rate are used. Thrust and flow rate errors from all other sources must also be included to obtain the total error in the Cx computation. These also are included in the shaded area shown in Figure 6.

The approach used in determining Cx has some serious limitations, especially if only one flight is considered. The functional variation of an input parameter with respect to time of flight is defined as the input parameter profile. Any deviation between the profile used for input and the actual profile experienced by the vehicle for any one or all of the input parameters will be translated into an error in Cx determination. The profiles for the parameters which were measured during flight were not altered in any of the preceeding analyses. A deviation in these profiles would probably be a function of the sensing element, the telemetering system, and the data reduction. Only sensing elements which have been tested in previous development programs are being used for the Saturn program. This fact combined with adjustments obtained from the flight simulation program minimize the error from input parameter profile deviations. Several near normal flights are required before a high degree of confidence in the profiles for the input parameters could be developed. The equations of motion used in the flight simulation program are those presently considered to represent best the motion of the Saturn vehicle. The Cx curve and the associated error margins shown in Figure 6 should be considered as the results for SA-1 and the first step in evolving the Cx curve for the Block I C-I Saturn vehicles. Revisions of this curve will be made when required.

The adjustment errors in the propulsion parameters correspond to the combination of all the contributors to errors in Cx are:

Vehicle Propulsion Parameter Adjustments

Adjustments	Unit	Error	% of Total
Thrust	lb	193	0.014
Flow Rate	lb/sec	1.34	0.026
Specific Impulse	sec	0.10	0.04

7.0 CONCLUSIONS

The contributors to errors in the adjustments can be combined as a function of liftoff weight. The resultant adjustment errors from the three error contributors and the root-sum-square combination are shown in the table below.

Adjustment/ Error Source	Units	Trajectory Parameters	Atmospheric Measurement	Cx	Root-sum-square
Thrust	lb	75	1150	193	1168
Flow Rate	lb/sec	0.59	2.80	1.34	3.16
Specific Impulse	sec	0.04	0.34	0.10	0.36

Figures 7, 8, and 9 illustrate the variation of the three propulsion parameters with liftoff weight. The shaded areas in each of these plots is the root-sum-square of the errors in adjustments from the three error sources.

The value chosen for liftoff weight and the average values for the propulsion parameters which will produce a trajectory which matches the observed trajectory for SA-1 are given on the following page.

Average Vehicle Performance Parameters

Parameter	Unit	Quantity
Liftoff	Weight, lb	929,560
Average Sea Level Thrust	lb	1,333,300 $\pm$ 1,500
Average Total Flow Rate	lb/sec	5,240 $\pm$ 4
Average Sea Level Specific Impulse	sec	254.4 $\pm$ 0.4

If any other value of liftoff weight is chosen, the propulsion parameters which will produce the trajectory match can be obtained from Figures 7, 8, and 9.

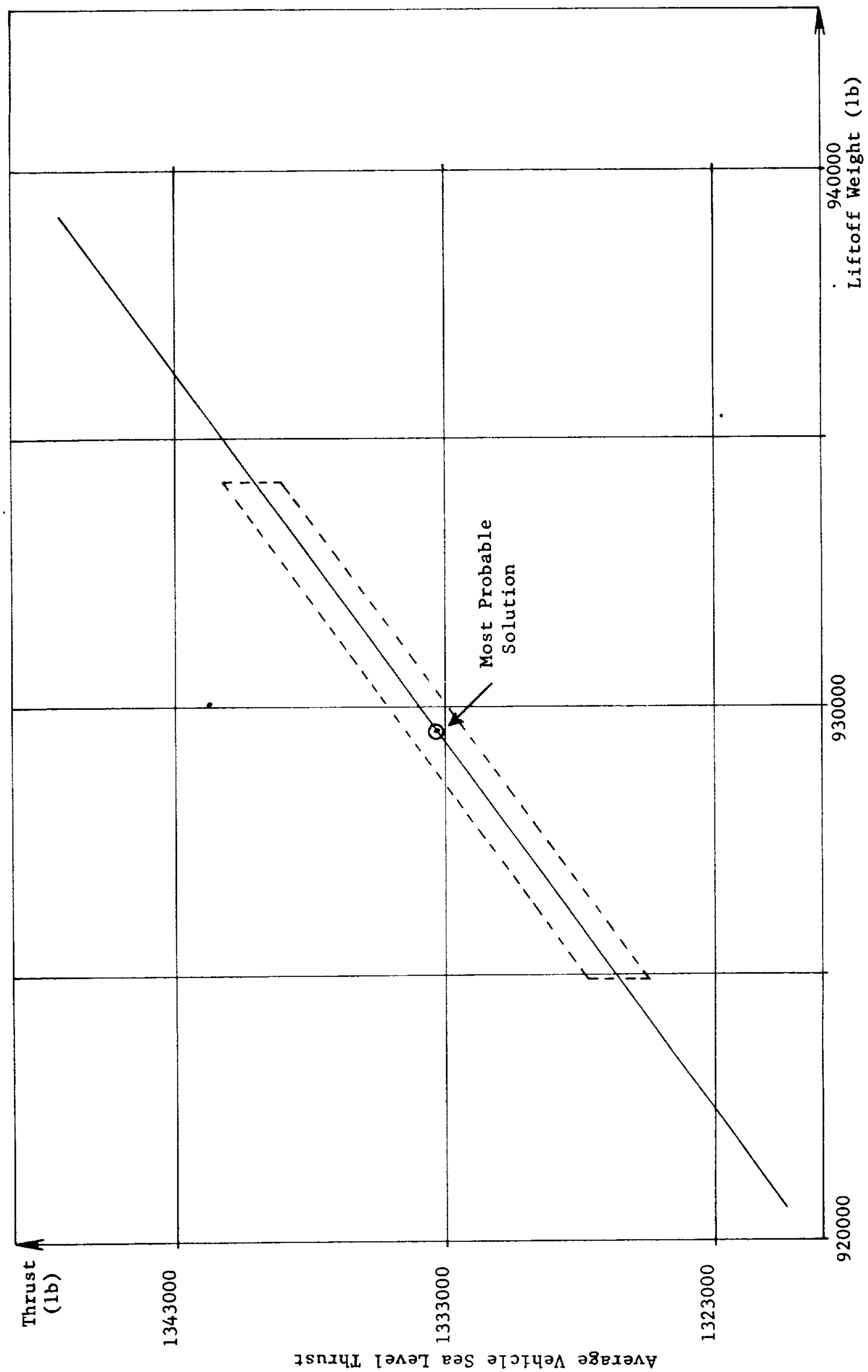


Fig. 7 AVERAGE VEHICLE SEA LEVEL THRUST VS LIFTOFF WEIGHT

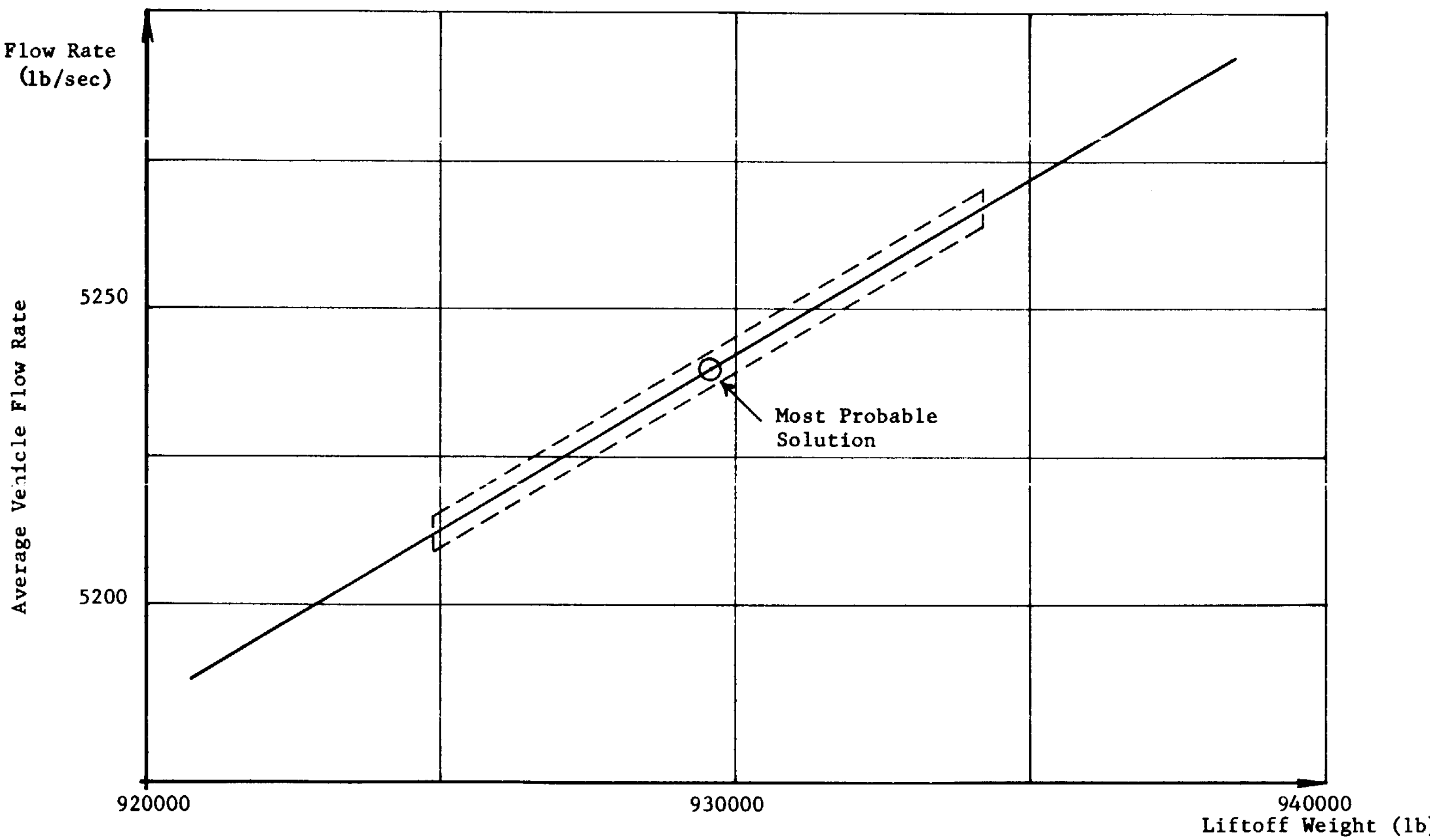


Fig. 8 AVERAGE VEHICLE FLOW RATE VS LIFTOFF WEIGHT

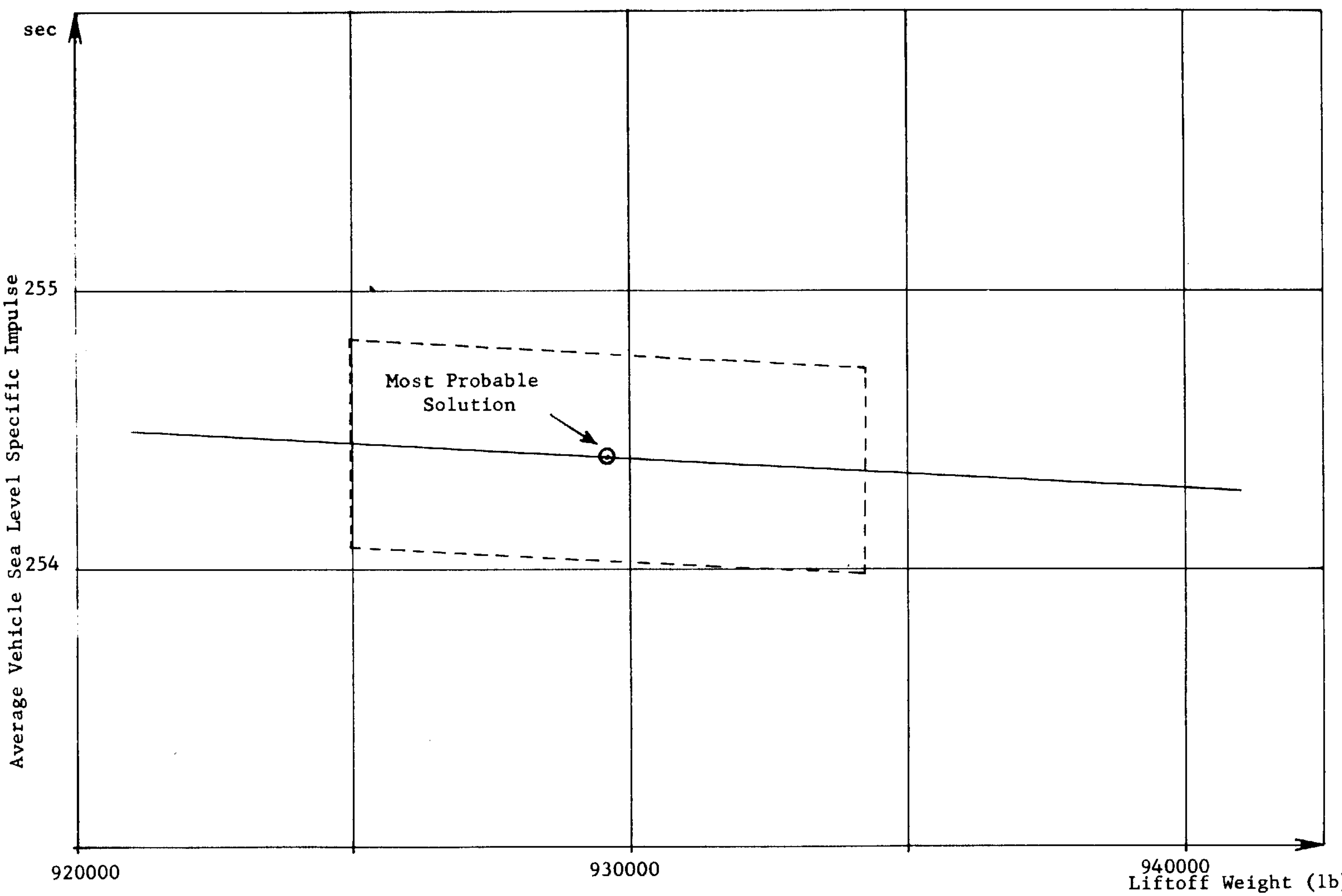


Fig. 9 AVERAGE SEA LEVEL SPECIFIC IMPULSE VS LIFTOFF WEIGHT

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2. Flight Performance Evaluation Unit, Propulsion and Vehicle Engineering Division, Evaluation of Flight Test Propulsion Systems and Associated Systems Saturn Vehicle SA-1, MTP-P&VE-P-62-1, March 9, 1962, Confidential.

APPROVAL MTP-AERO-62-37

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The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

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E. D. GEISSLER
Director, Aeroballistics Division

ERROR ANALYSIS OF PROPULSION SYSTEM
PARAMETER EVALUATION FOR SATURN SA-1

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M-SAT
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