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ATLAS BASE DRAG STUDY

Report Number GD/C-BTD65-089
21 June 1965

Contract Number NAS3-3232

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FOREWORD

This report evaluates the present method of simulating drag of the Atlas booster stage. Discrepancies between predicted data and flight test data are noted and an alternate method of simulation is presented.

This study was conducted under the provisions of Contract NAS3-3232, to satisfy the requirements of Item 129, of the Centaur Documentation Requirements Plan, Report Number 55-00207E.

SUMMARY

Acceleration data telemetered from Centaur guidance accelerometers was compared with preflight predictions. A consistent pattern was found which justifies:

1. A reduction in drag coefficient at low supersonic velocity
2. Inclusion of an additional base thrust term, both due to base pressure effects.

In the past this base thrust has been considered as a negative drag effect and computed as a function of dynamic pressure. However, test data has shown that this base thrust still exists and is nearly constant even when the density approaches vacuum conditions. Therefore to properly simulate this effect a more realistic simulation is required. A proposed simulation model is presented which will give much better agreement with flight data.

During the investigation another factor was discovered which contributes to the differences between predicted and flight test acceleration. This is the hold-down force exerted by the launcher during the rise beyond 2-inch motion. This force can last up to one second and although the velocity loss is small, the weight change (about 700 pounds propellant) is significant. The proposed changes to trajectory simulation are as follows:

1. Revise C_A versus Mach number
2. Add a base thrust term equal to base thrust at near vacuum multiplied by $(1 - \frac{P}{P_0})$, where $\frac{P}{P_0}$ is the ratio of ambient pressure to sea level pressure. Base thrust at vacuum might be as low as 2500 pounds or as high as 7000 pounds. A probable value of 3400 pounds is suggested. A conservative value of 2500 pounds is recommended for immediate inclusion.
3. Program a hold-down force of 30,000 pounds for one second beyond 2-inch motion. This can best be simulated by adding 30,000 pounds to the launch weight and jettisoning the same weight at one second.

Items 1 and 2 (conservative value) will increase Surveyor mission payload by 25 and 36 pounds respectively (61 pounds total, due to change in base force), and Item 3 will decrease payload 8 pounds. The over-all effect is a payload increase of 53 pounds for a mission to the moon. AC-4 trajectory re-assembly using this technique with the probable value of 3400 pounds base force gives good results, and overwhelming evidence from all previous flights dating back to 1958 indicates that this base force has been the common denominator in the deviations which in the past have been charged to hot engines or low launch weight.

Recommendations are made to incorporate as soon as possible into any and all Atlas flights, base pressure measuring devices of small scale (0 to 1 psi) and high accuracy to verify the results of this study. Based on this study alone it would appear to be good engineering practice to take at least the conservative estimate gain while further test data is accumulated.

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SECTION I

INTRODUCTION

1.1 BACKGROUND

Over the past years there has been much discussion of the drag simulation of the Atlas booster stage. The problem focuses on the base pressure term in the drag build-up. Since the base force is a pressure term, and since all pressure terms are usually considered drag effects, it seemed logical to try to determine a drag coefficient for the base. No difficulty is encountered during the early part of the boost phase, but as the trajectory approaches booster burnout, the dynamic pressure approaches zero due to the atmospheric density. A slight change in trajectory flight path has a pronounced effect on the dynamic pressure at Mach numbers beyond 2. The solution used over the past several years was to take a "typical trajectory" and reference the drag data to that q versus Mach number history. The typical trajectory still being used for Centaur flights is one selected long ago for some "average" Atlas mission. There has also been reluctance to show very high negative values of drag coefficient. However, due to the fact that the base still shows positive pressure at vacuum in all wind tunnel, flight test and theoretical calculations, the drag coefficient required at near vacuum conditions, regardless of Mach number, approaches $-\infty$. This situation points out the obvious deficiency of the method presently used. This study presents an alternate method of simulation which more closely relates predicted data to actual test data.

SECTION II

DERIVATION OF NEW FORCE SIMULATION FROM ANALYSIS OF CENTAUR FLIGHTS

2.1 GENERAL

Acceleration data obtained from the Centaur guidance (Reference 1) was compared with preflight nominal predicted acceleration for AC-2, AC-3, and AC-4 flights. The difference in acceleration is shown typically for the AC-4 flight in Figure 2-1. Data scatter is due to incomplete smoothing. Figure 2-2 shows the acceleration increment after complete smoothing, along with pressure and Mach number scales. The same data was obtained for AC-2 and AC-3 flights; then several schemes for relating these acceleration differences to dynamic pressure, Mach number and/or altitude were tried. The method which gives the best solution was evolved by shifting the time scales horizontally so that a few seconds after liftoff the acceleration matches. This has the effect of eliminating thrust and weight deviations and also tends to get the Mach numbers closer for preflight and test data during the drag rise at transonic speeds. This acceleration difference was then converted to force difference and plotted versus atmospheric pressure ratio.

Figure 2-3 shows the force increment for all three of the Atlas/Centaur flights. All three flights show the same general trend; that is, a dip in force just prior to Mach 1, then a large bulge, peaking near maximum dynamic pressure. As the pressure approaches zero near burnout the increment in force approaches a near constant value. In AC-2 and AC-4, the value is nearly 8000 pounds and in AC-3 it is about 2800 pounds. If a straight line is drawn from the low subsonic part of the curve to the booster burnout end of the curve, the difference in force between the intercepts at $\frac{P}{P_0} = 1$ and $\frac{P}{P_0} = 0$ can be attributed to a base force term which would vary like a conventional rocket engine's thrust with altitude. The remainder of the deviation can be attributed to drag difference; that portion of the deviation below the straight sloping line indicates more drag than assumed and that portion above indicates less drag than assumed.

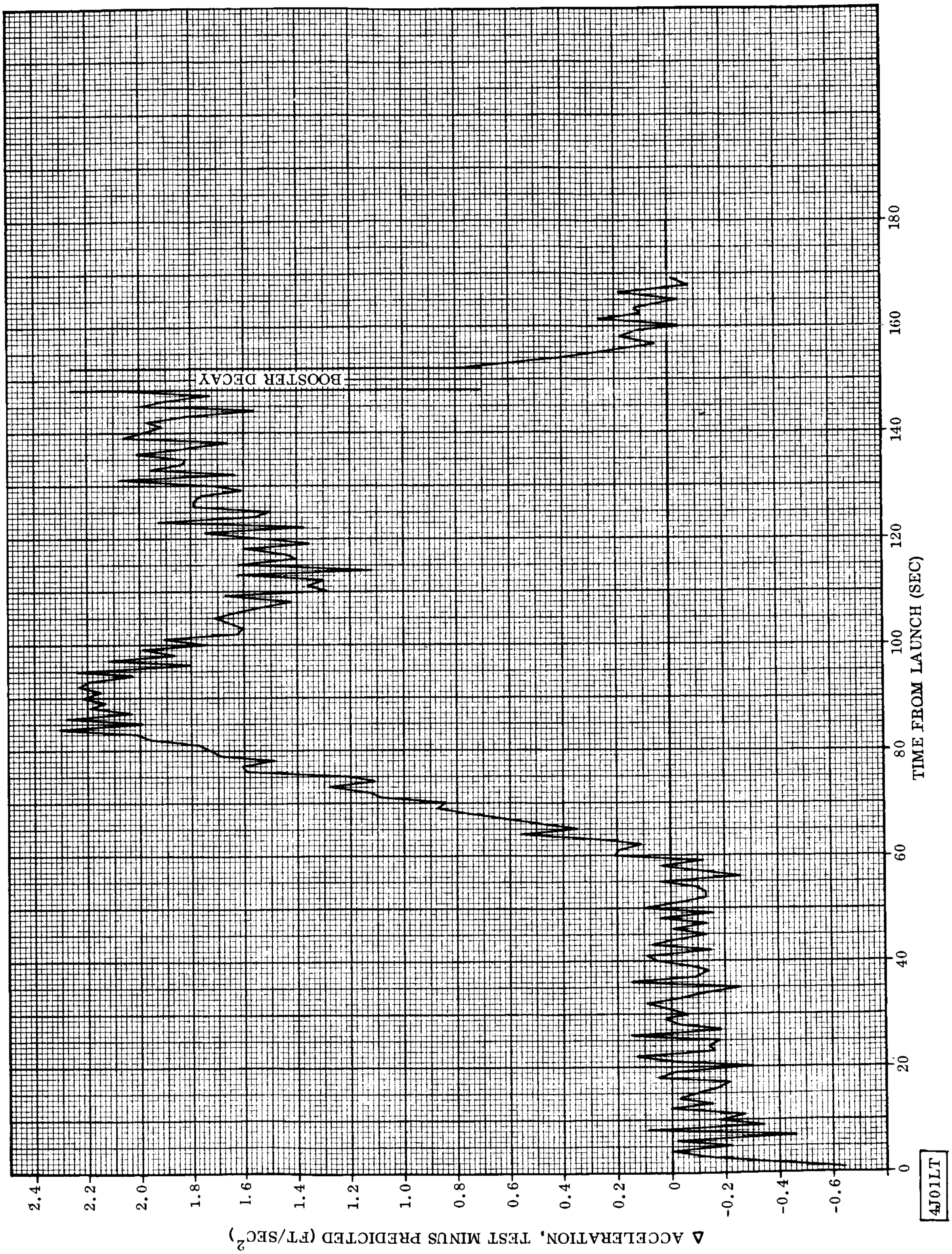

Figure 2-1. AC-4 Axial Acceleration Increment between Test and Predicted

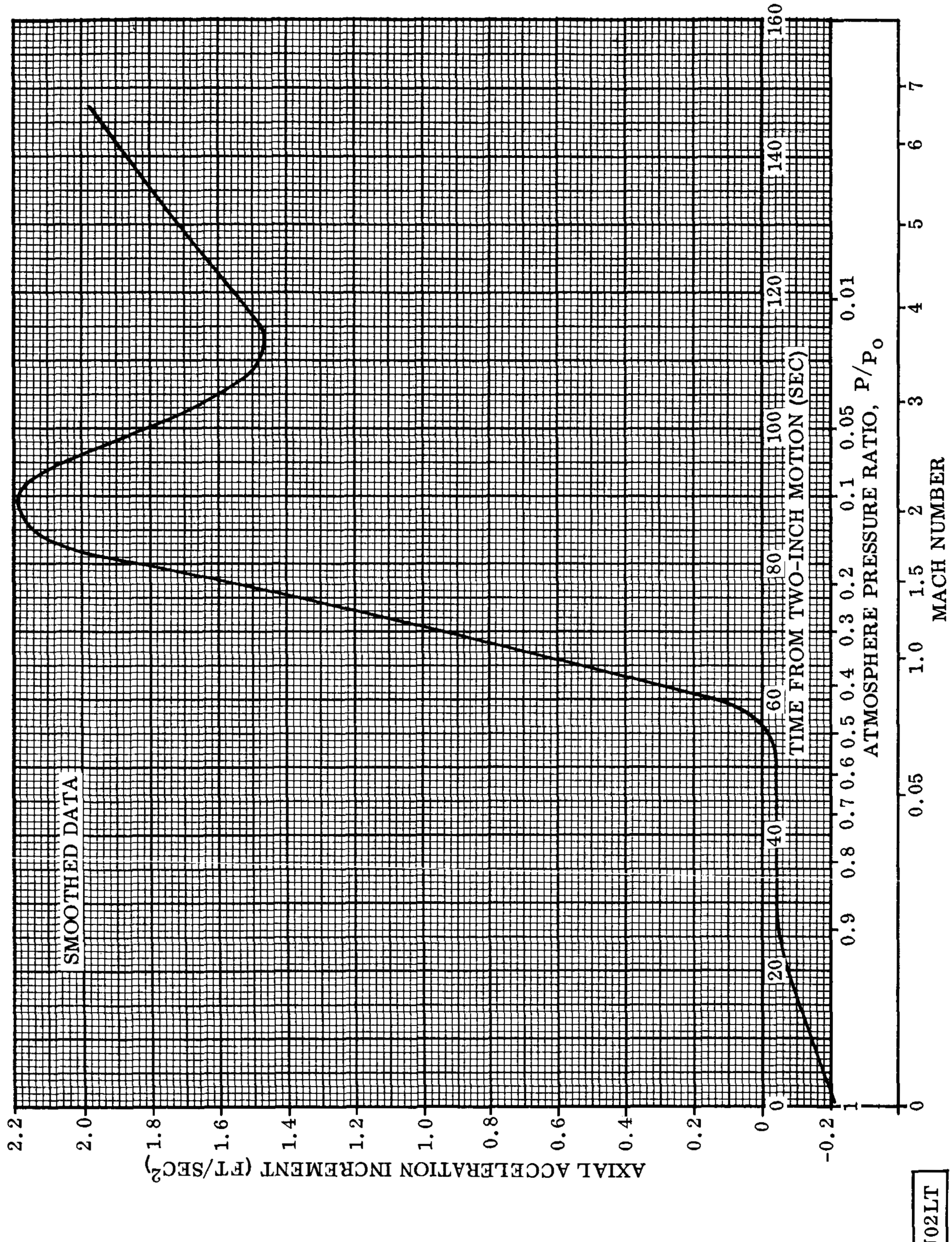

Figure 2-2. AC-4 Axial Acceleration Increment versus Time, Atmospheric Pressure and Mach Number

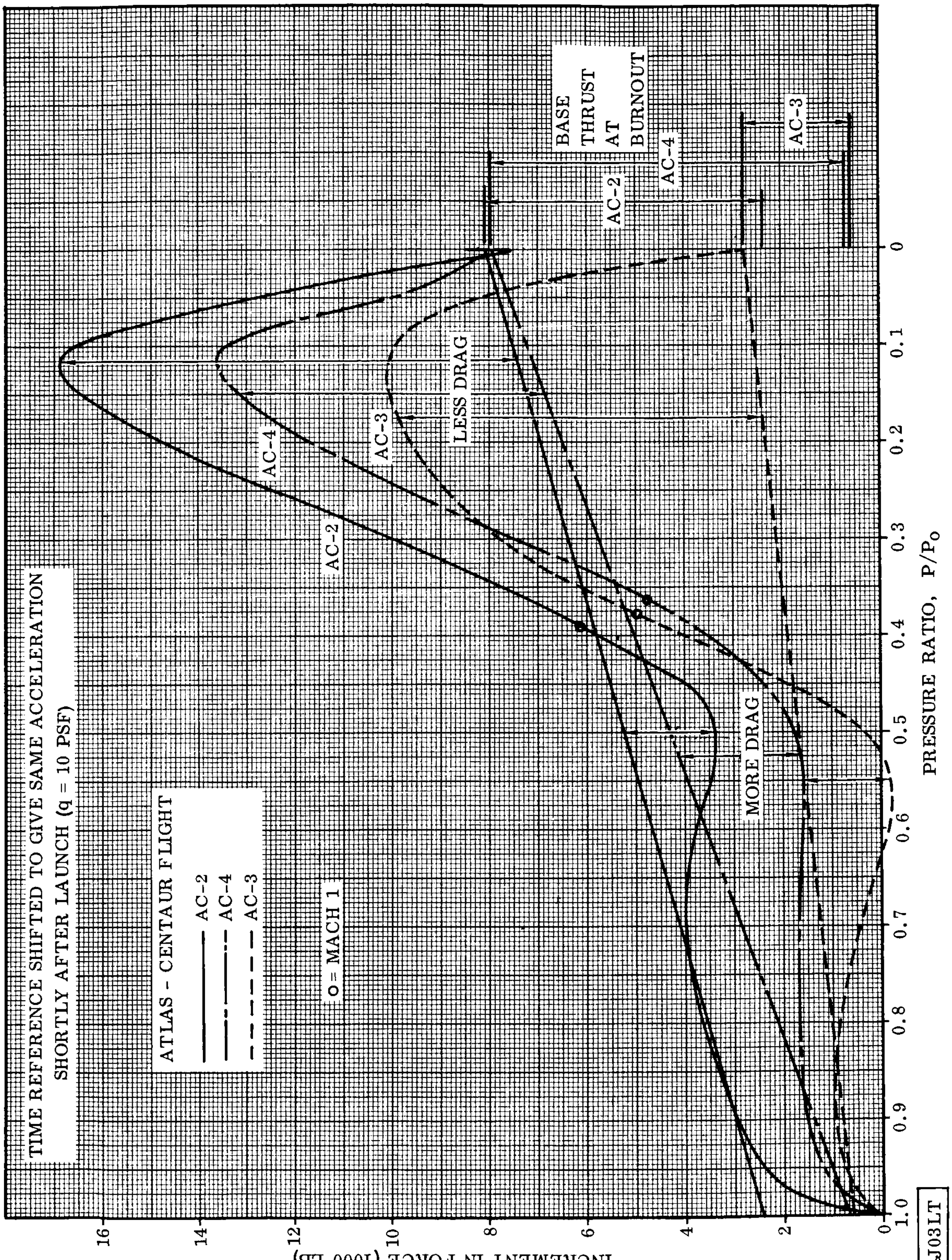

Figure 2-3. Comparison of Flight Data with Predicted Data; Force Increment versus Pressure Ratio

2.2 NEW q-DEPENDENT DRAG

Figure 2-4 shows the results of computing this drag increment in coefficient form. The increment in drag coefficient was added or subtracted from the predicted drag coefficient and a very good agreement for the three flights was obtained, if points with a dynamic pressure of less than 10 are ignored. The ignored points are those which would indicate a very high drag coefficient at Mach numbers below 0.15 where drag based on q contributes little anyway. Using these computed drag points a curve was faired that gives a slightly higher drag coefficient subsonically, a lower peak C_D, a definitely sharper drop beyond the peak through the low supersonic region and finally approaches a constant hypersonic value. This curve was compared with the drag coefficient of the vehicle less base and the difference is shown in Figure 2-5. The solid line shows the newly predicted base drag which is q dependent. It has the same static value, nearly the same peak value at sonic speeds but does rise earlier and drops off sharper. Between Mach 2 and 3 it approaches a constant negative value which is not really too critical as the value of q approaches zero. The finalized q-dependent drag coefficient is shown in Figure 2-6.

2.3 NEW ALTITUDE-DEPENDENT BASE THRUST

The difference in intercepts shown in Figure 2-3 then is treated as a base thrust term varying from zero at sea level to full value at vacuum by the relation $(1 - \frac{P}{P_0})$. Rigorous theoretical proof is lacking for this assumption but it looks like the best emperical fit to the data. The base force term can also be treated as a pressure acting over the base area. Since the base area is about 11,300 square inches a very small pressure exerts a fairly large force. A search through all previous Atlas flight test data was made in an attempt to define this pressure more accurately. The results of this search, which are discussed in Section III, show that a pressure of at least 0.20 psi has been substantiated in previous Atlas test flights, and it could be considerably higher. From the Centaur flight data, indications are that the base thrust could be as low as 2500 pounds or as high as 7000 pounds. A probable value of 3400 pounds is

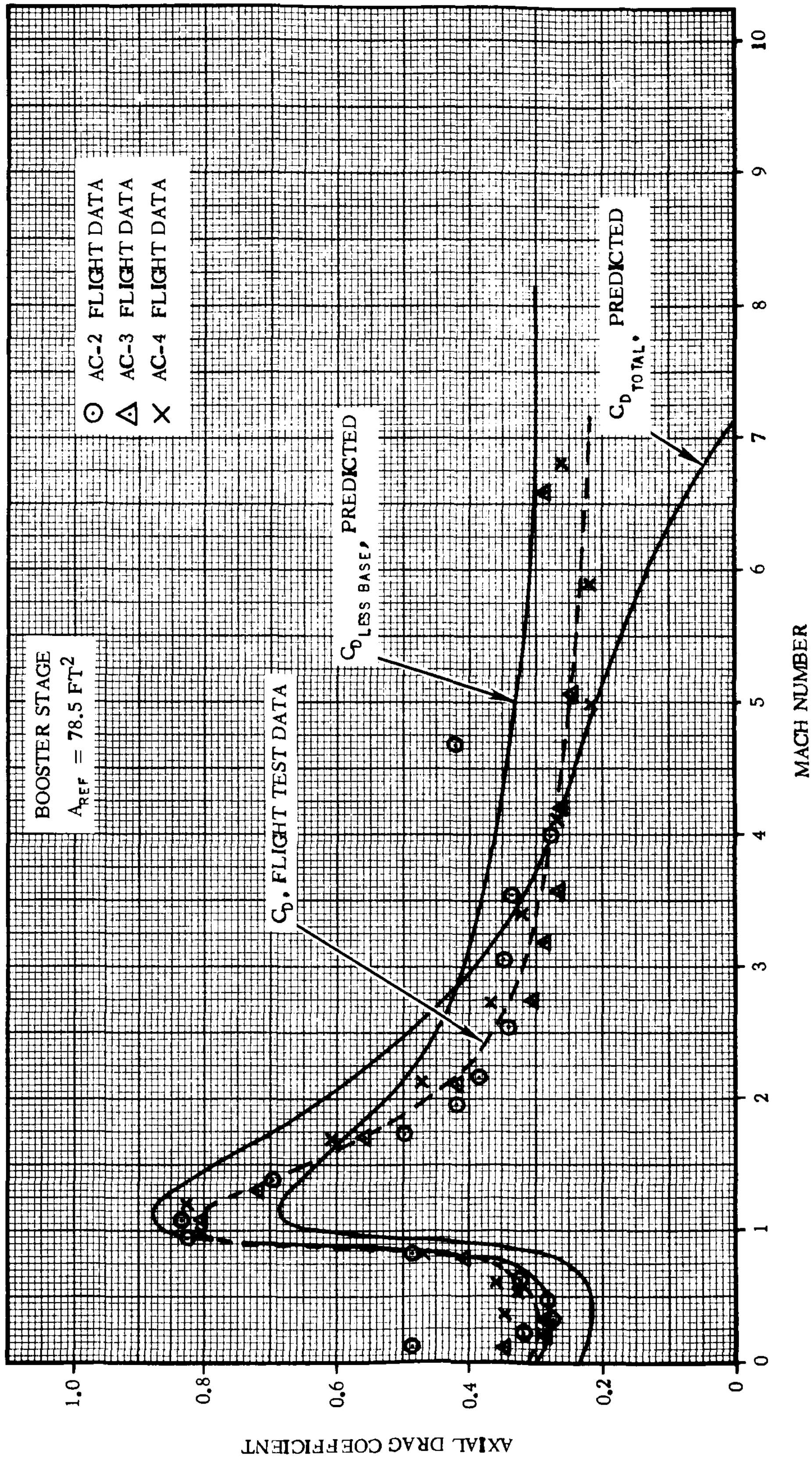

Figure 2-4. Correlation of Test with Predicted Drag

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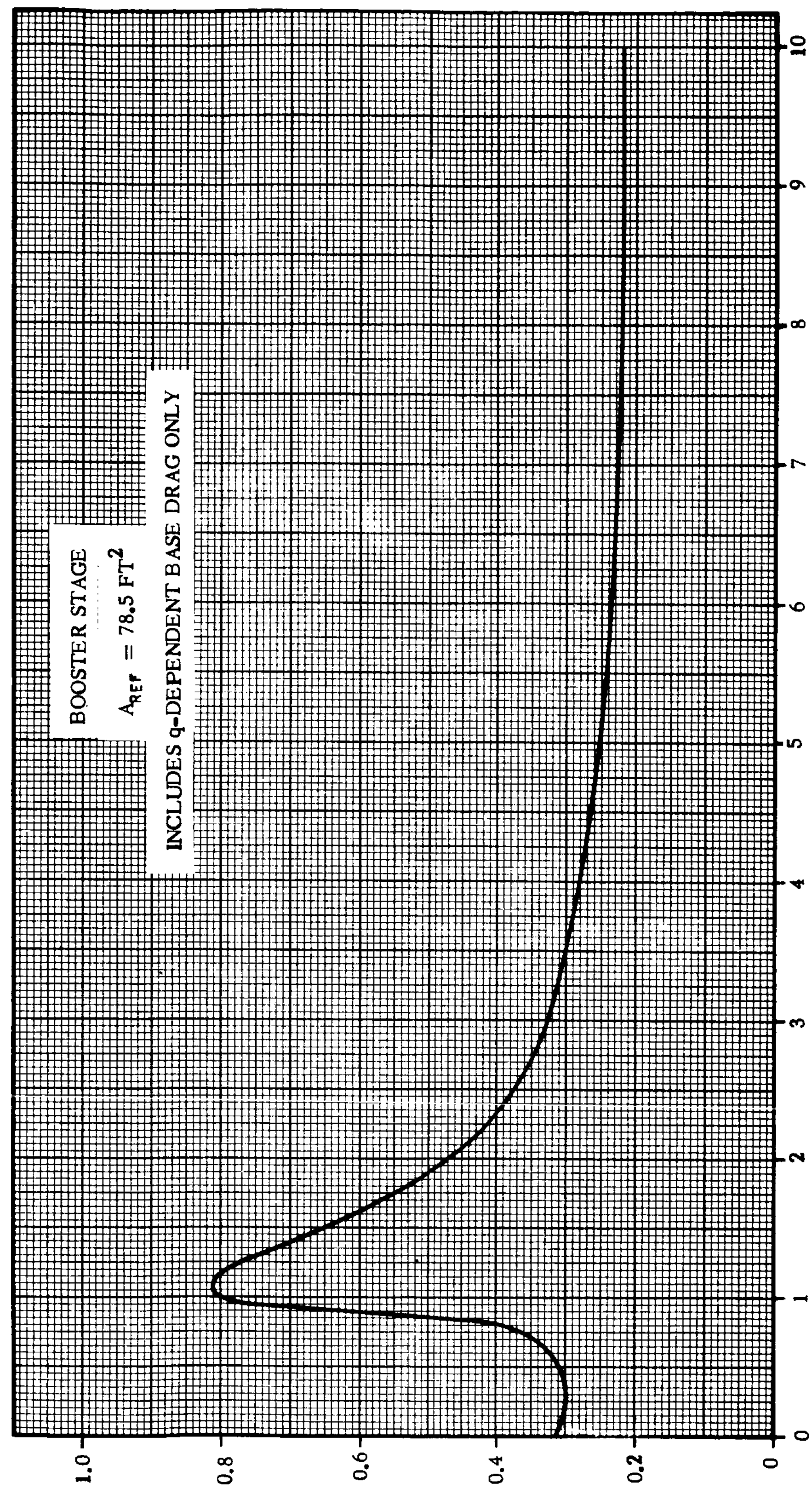

Figure 2-5. Axial Drag Coefficient versus Mach Number

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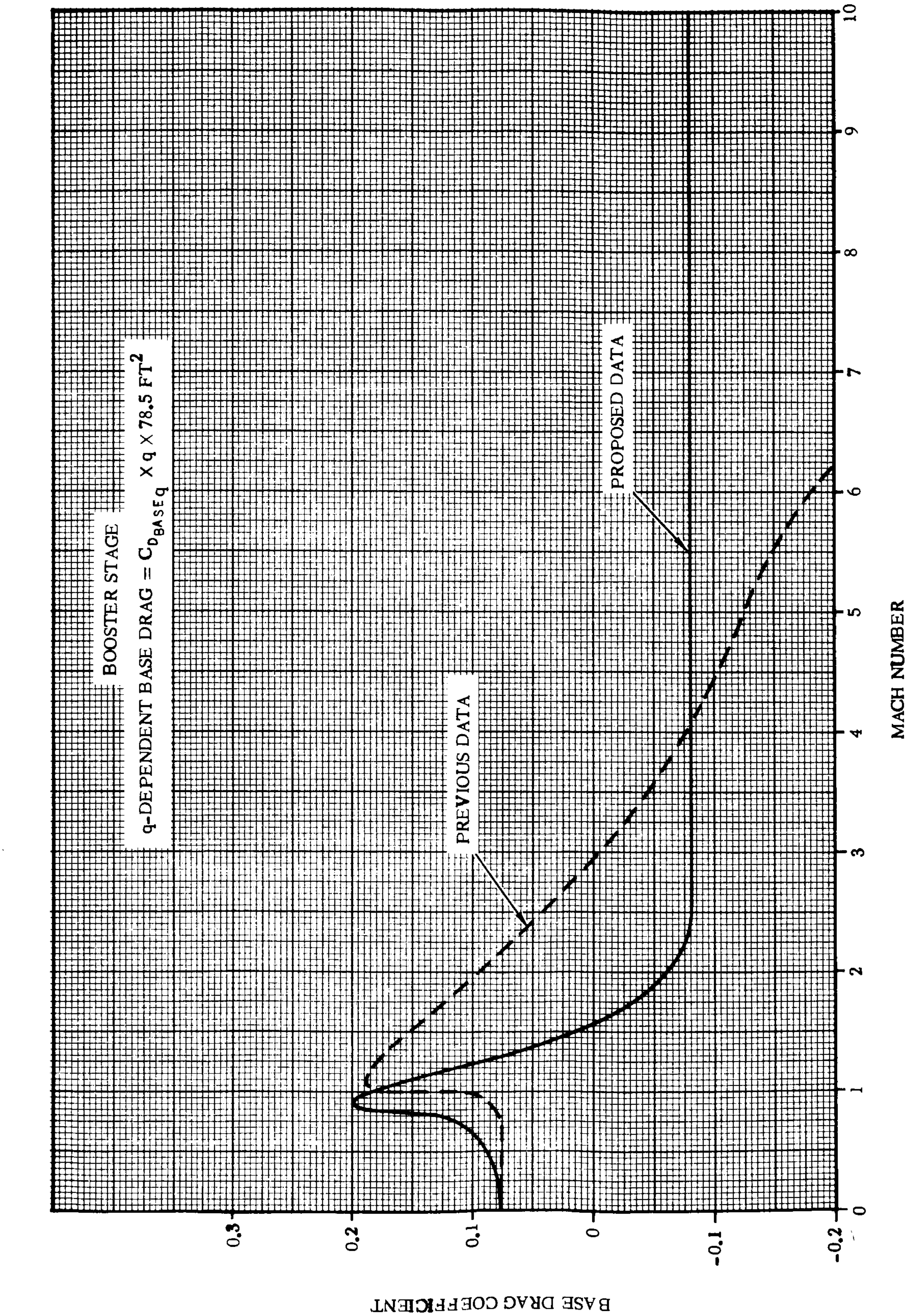

Figure 2-6. q-Dependent Base Drag Coefficient

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suggested (base pressure = 0.30 psia). A conservative value of 2500 pounds is recommended for immediate inclusion in Atlas boosted flights.

2.4 HOLD-DOWN FORCE

During the base drag investigation, study of the acceleration at liftoff revealed another factor which should be simulated better. That is the hold-down force existing beyond 2-inch motion. This hold-down force is that force beyond the initial release and is caused by the kick struts restraining the pitching moment produced by crosswinds, engine differences, etc. This force can last up to one second beyond 2-inch motion with oscillating hold-down forces nearly equal to the thrust minus weight difference as shown in Figure 2-7. Although the velocity loss is small during this period it is equivalent to the loss of as much as 700 pounds of propellant. To simulate this force, a programmed hold-down can be included by simply increasing the launch weight 30,000 pounds and jettisoning this weight one second beyond 2-inch motion.

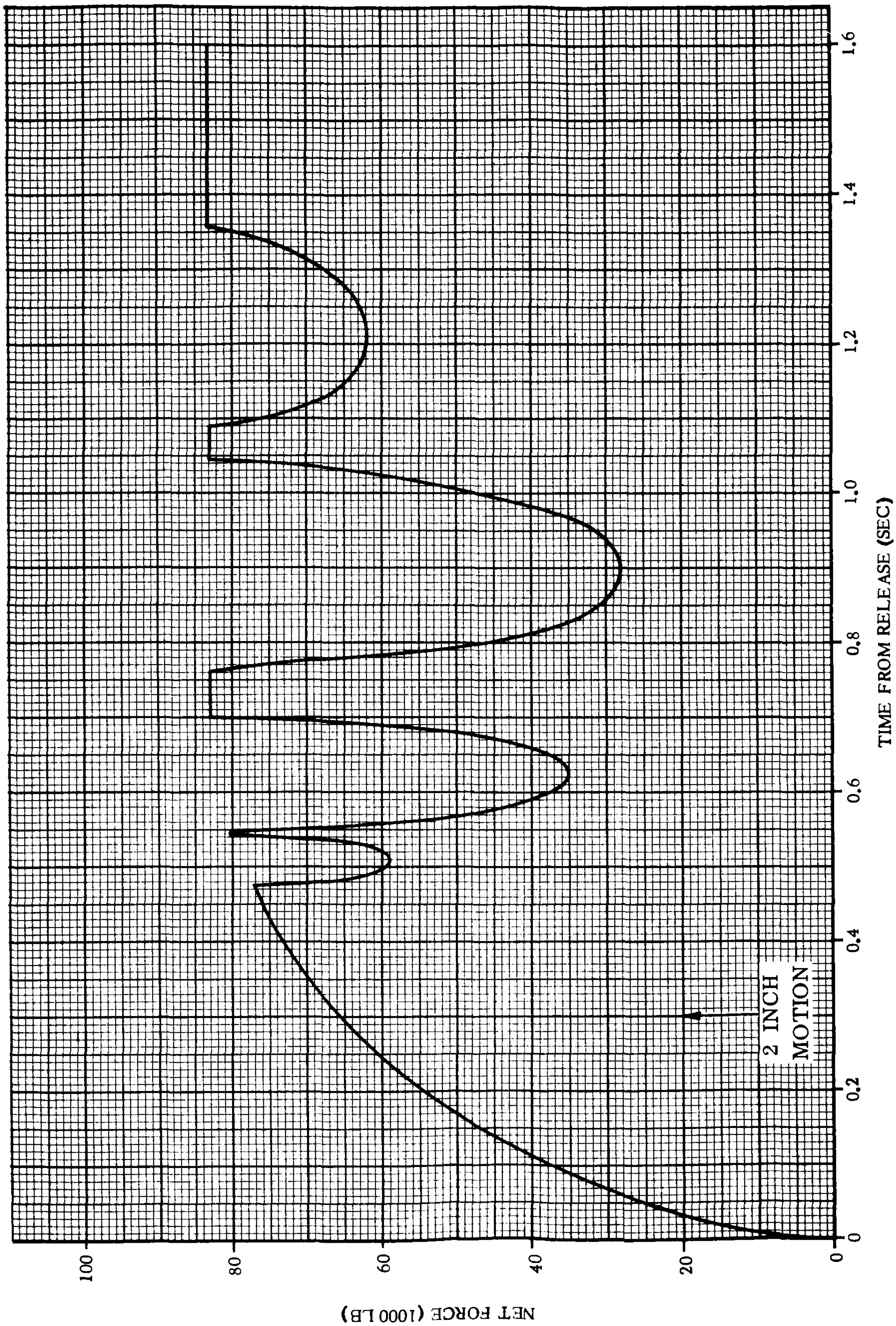

Figure 2-7. Typical Net Force at Liftoff

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SECTION III

ANALYSIS OF ATLAS B, C, D AND SLV FLIGHTS

A search was conducted of all post flight test evaluation reports (Reference 2) to determine

1. What information had been obtained on the Atlas base pressure
2. General trends in the acceleration deviation from nominal
3. Drag correlation methods used
4. On which flights the drag was evaluated.

3.1 BASE AND ENGINE COMPARTMENT PRESSURE MEASUREMENTS

Base pressure measurements were conducted early in the tests, not to determine base force, but to provide information to solve the base heating problem which existed at that time. The pressure measuring devices were either of 15 psi range with a resulting 5% accuracy deviation of 0.75 psi or a 7.5 psi gage, which still did not have the accuracy required. Measurements were made inside the engine compartment so they do not represent the base itself. Measurements were made on some later Atlas flights which show that through the transonic region the base pressure deviates from the compartment pressure due to delay in flow through the engine boots. Here again the absolute value cannot be obtained with good accuracy. In cases where high positive values of engine compartment pressure were obtained, apologies were made for the fact that the curve did not go to zero and data was considered qualitative only. Actually a smooth curve showing the pressure going exponentially from about 15 psi to some low value was all that was being sought. A buildup in engine compartment pressure would mean a hot gas flow in, a condition which was to be avoided.

During all the hundreds of Atlas flights, actual high accuracy absolute pressure measurements of the base pressure were never obtained. However an attempt was made to determine the base pressure from that data available. Taking the data as shown in Table 3-1, assuming that zero scale is accurate, the engine compartment pressure on flights ranged from -0.30 to +0.80 psia.

TABLE 3-1. ATLAS ENGINE COMPARTMENT PRESSURE TEST MEASUREMENTS

Vehicle	Engine Compartment Pressure (psia)			
	Launch		Booster Burnout	
4B	14.85	(14.7)	+0.30	(+0.15)
5B	14.7	(14.7)	+0.30	(+0.30)
6B	14.7	---	Failed	---
8B	*		-0.30	
9B	*		+0.75	
12B	*		-0.30	
3C	*		0	
4C	13.9	(14.7)	0	(+0.80)
5C	*		+0.30	
7C	*		+0.30	
8C	*		+0.15	
11C	*		+0.30	
5D	*		+0.20	
11D	*		+0.20	
14D	*		+0.15	
15D	*		+0.20	
17D	*		+0.80	
18D	*		0	
119D	14.9	(14.7)	+0.75	(+0.55)
7101	14.25	(14.7)	+0.30	(+0.75)
7102	14.4	(14.7)	0	(+0.30)
7103	14.55	(14.7)	+0.05	(+0.20)
4F	*		+0.20	
5F	*		+0.50	
8F	*		-0.10	
16F	**		+0.15	

* Pressure gage scale = 7.5 psi maximum

** Pressure gage scale = 5 psi maximum

() Numbers in brackets indicate pressure if data is adjusted to give 14.7 psi at sea level.

The mean of the 25 values as shown by the distribution in Figure 3-1 is about +0.21 psi. If the measurements, where both sea level and burnout pressure were determined, are corrected so that sea level values are 14.7 psia, then the mean value of these seven tests is about 0.43 psia at burnout. If these seven values are averaged with the 25 unmodified values, the mean is then about 0.26 psia. The seven modified values are shown in dashed lines and the best estimate value of engine compartment pressure is noted as 0.26 psia. From looking at differential pressures across the base heat shield an additional 0.04 psi might be reasonable, giving a total base pressure of +0.30 psi. This value of +0.30 psia appears to be consistent with results obtained from the Centaur flights and with the wind tunnel tests conducted at Arnold Engineering Development Center. Figure 3-2 shows a curve reproduced from this tunnel data (Reference 3) which also shows the increment between base pressure and ambient pressure approaching 0.3 psi with jets on at high altitude.

3.2 ATLAS ACCELERATION DEVIATIONS FROM NOMINAL

The test evaluation data was then studied to obtain trends in how closely the vehicle acceleration compared to predicted nominal. Here we get the greatest clue that the existing simulation is in error. As shown in Table 3-2, out of 110 Atlas D and SLV flights, 89 had a steeper acceleration history between launch and BECO than predicted. Of these flights, 62 had an acceleration difference of more than 0.2 g at BECO and 40 had more than 0.3g. Approximately nominal performance was obtained in 11.8% of the flights and only 7.2% show lower than a nominal acceleration history. This has been interpreted by others to mean that the engines were all high thrust or the vehicles were all underweight. This report proposes the conclusion that the base force was the common denominator in producing this consistent acceleration increase in the booster phase of Atlas as it approaches BECO.

Strangely, those few cases where the acceleration was close to nominal were chosen for extraction of drag coefficient data, and not so strangely, agreement of predicted data with test data was always good.

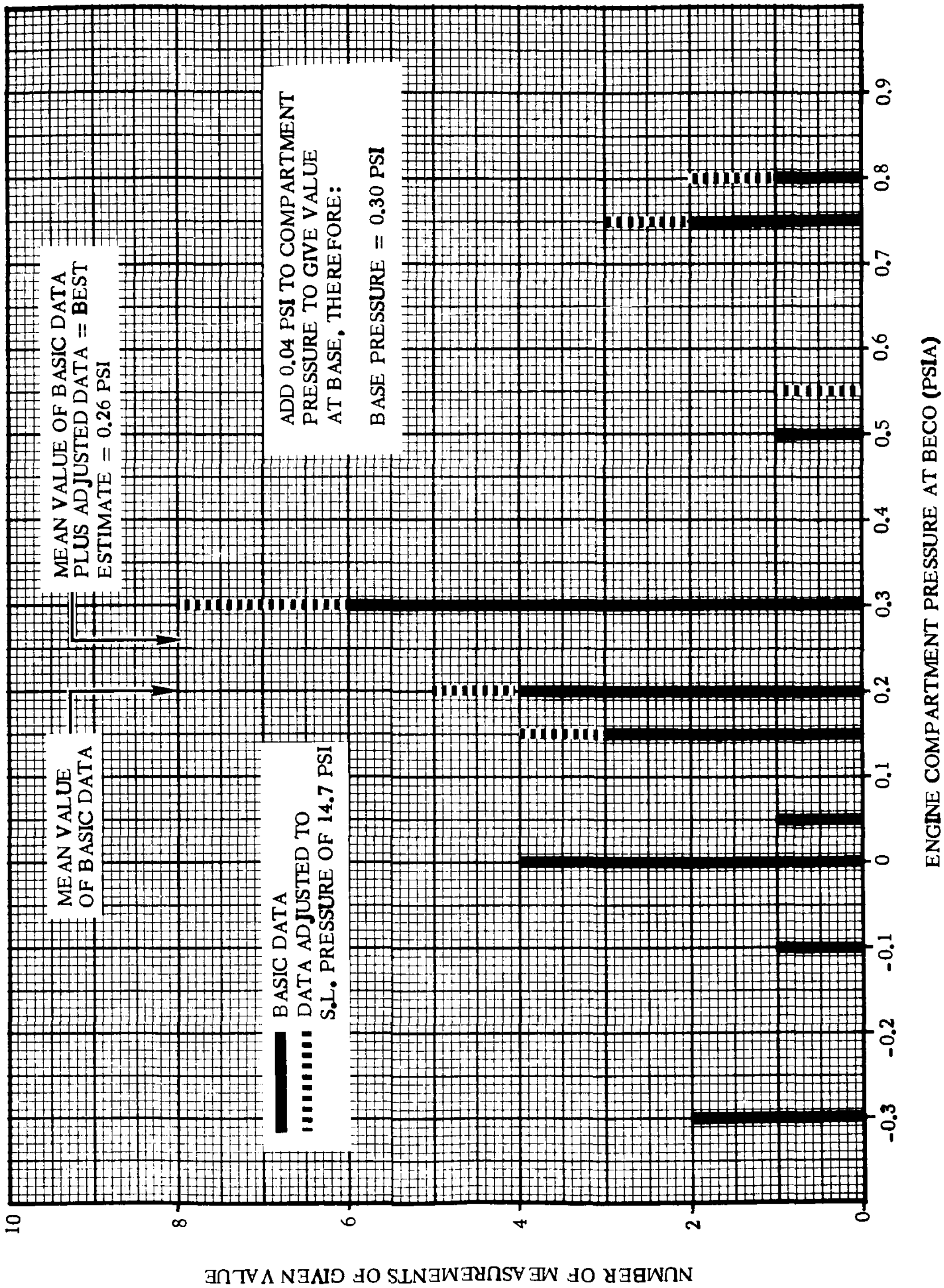

Figure 3-1. Base Pressure Measurements

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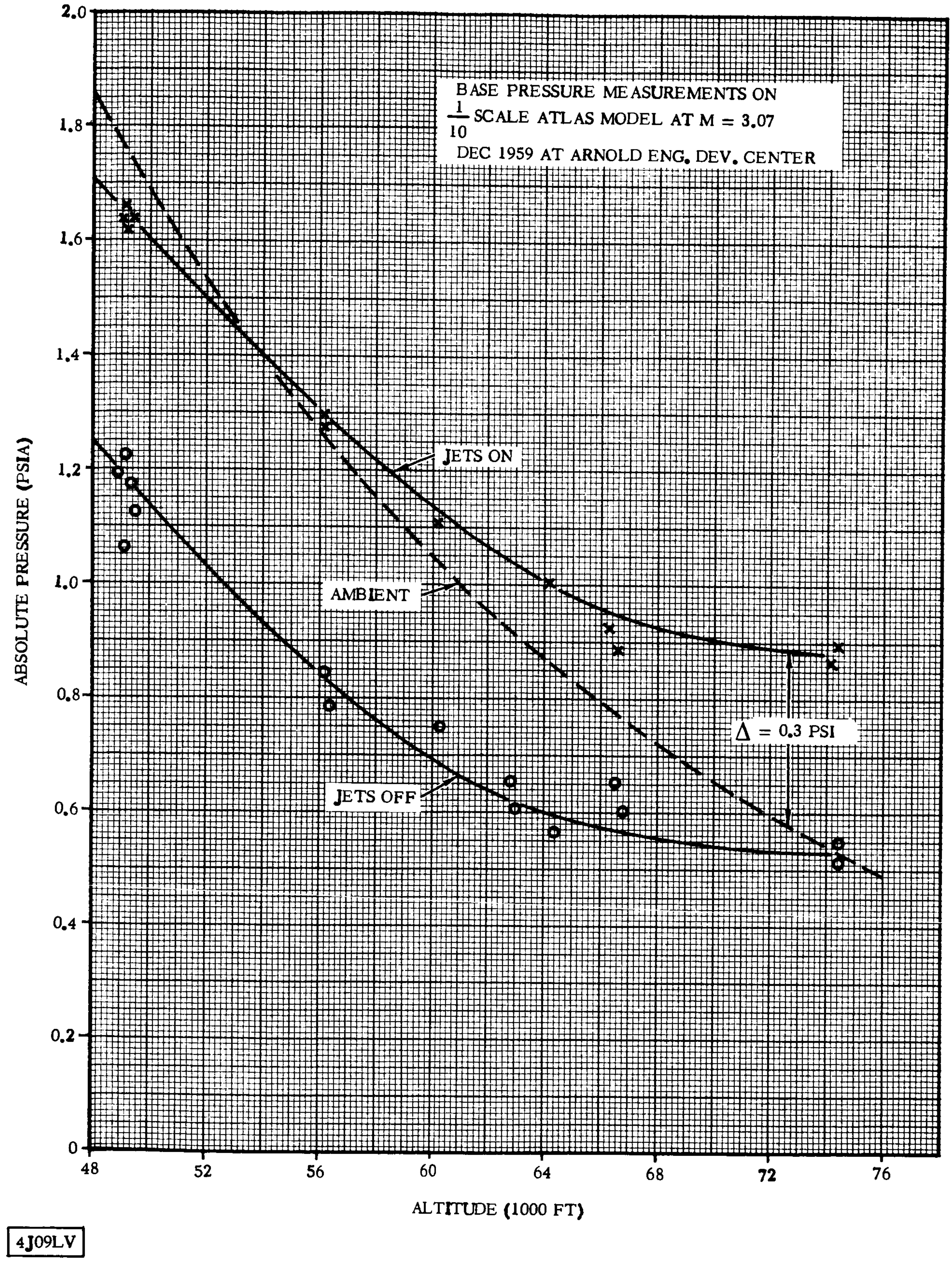

Figure 3-2. Wind Tunnel Test Data

TABLE 3-2. ATLAS BOOSTER ACCELERATION, TEST VERSUS PREDICTED (SERIES D AND SLV VEHICLES WITH DATA AVAILABLE)

Vehicle of Atlas D or SLV Series	Acceleration Increment Shortly after Liftoff $A_{T_1} - A_{P_1} = A_1$ (g's)	Acceleration Increment Shortly before BECO $A_{T_2} - A_{P_2} = A_2$ (g's)	Acceleration Slope $A_2 - A_1$ (g's)
8	0	0.40	0.40
10	0	-0.10	-0.10
11	0	0.10	0.10
13	-0.05	0.05	0.10
14	0	0	0
15	0	0.30	0.30
17	0.05	0.05	0
18	0	0	0
20	0	-0.15	-0.15
21	-0.05	0	0.05
22	0	-0.40	-0.40
26	0.05	-0.30	-0.35
27	0	0	0
28	0	0	0
29	-0.05	-0.40	-0.35
31	0	0	0
32	0	0.30	0.30
42	0	0.25	0.25
43	0	0.10	0.10
44	0	0.35	0.35
45	0	0.40	0.40
49	0	0.15	0.15
53	0	0.60	0.60
54	0.05	1.10	1.05
55	0.05	0.70	0.65
56	0.05	0.80	0.75
62	0	0.20	0.20
63	0.10	0.10	0
64	-0.10	0	0.10
66	0.05	0.60	0.55
67	0	0	0
70	0	0.80	0.80
71	0	0.20	0.20
75	0.05	0.20	0.15
76	0	0.20	0.20
79	-0.05	0.05	0.10

TABLE 3-2. ATLAS BOOSTER ACCELERATION, TEST VERSUS PREDICTED (SERIES D AND SLV VEHICLES WITH DATA AVAILABLE) (Continued)

Vehicle of Atlas D or SLV Series	Acceleration Increment Shortly after Liftoff $A_{T_1} - A_{P_1} = A_1$ (g's)	Acceleration Increment Shortly before BECO $A_{T_2} - A_{P_2} = A_2$ (g's)	Acceleration Slope $A_2 - A_1$ (g's)
80	-0.05	0.20	0.25
82	0.05	0.60	0.58
83	0	0.45	0.45
84	0	0	0
87	0	0.35	0.35
88	-0.10	0.30	0.40
93	0	0.20	0.20
95	0.05	0.20	0.15
97	0.05	0.40	0.35
99	0	0	0
101	-0.10	0.35	0.45
105	0	0.20	0.20
107	-0.10	0	0.10
108	0	0.25	0.25
109	-0.05	0.20	0.25
110	-0.05	0.15	0.20
111	0.07	0.32	0.25
112	0	0.30	0.30
113	0	0 (Checked drag here)	0
114	0	0.20	0.20
115	0	0.40	0.40
117	-0.05	0.25	0.30
118	0	0.40	0.40
119	0	0.15	0.15
120	0.07	0.40	0.33
121	-0.05	0.25	0.30
123	0	0.20	0.20
124	-0.-2	0.30	0.32
126 (AC-2)	0.02	0.17	0.15
127	-0.05	-0.20	-0.15
128	0.05	0.40	0.35
129	0.20	0.65	0.40
130	0	0	0
132	0	0.50	0.50
134	-0.05	0.30	0.35
135 (AC-3)	0	0.30	0.30

TABLE 3-2. ATLAS BOOSTER ACCELERATION, TEST VERSUS PREDICTED (SERIES D AND SLV VEHICLES WITH DATA AVAILABLE) (Continued)

Vehicle of Atlas D or SLV Series	Acceleration Increment Shortly after Liftoff $A_{T_1} - A_{P_1} = A_1$ (g's)	Acceleration Increment Shortly before BECO $A_{T_2} - A_{P_2} = A_2$ (g's)	Acceleration Slope $A_2 - A_1$ (g's)
137	0	0.30	0.30
140	0.07	0.40	0.33
141	0.25	0.85	0.60
142	0	0.20	0.20
145	-0.10	0	0.10
146 (AC-4)	0	0.10	0.10
159	0.05	0.35	0.30
160	0	0	0
161	0.05	0.10	0.05
172	-0.10	0.15	0.25
179	-0.05	0.05	0.10
188	0	0.20	0.20
193	0	0.30	0.30
195	-0.10	0	0.10
196	0	-0.20	-0.20
199	-0.10	0	0.10
201	0.05	0.50	0.45
212	0.05	0.50	0.45
215	0.05	0.50	0.45
216	0	0.20	0.20
224	0.05	0.50	0.45
227	0	0.10	0.10
250	-0.10	0.20	-0.30
263	0	0.20	0.20
285	0	0.30	0.30
288	0	0.10	0.10
289	-0.05	0.05	0.10
296	0	0.10	0.10
350	0.02	0.30	0.28
351	0	0.20	0.20
352	-0.05	0.15	0.20
353	-0.05	0.15	0.20
7101	0	0	0
7102	-0.05	0.15	0.20
7103	0.05	0.20	0.15
7105	0	0.10	0.10
7106	-0.05	0.10	0.15
7107	0	0	0

SECTION IV

CONCLUSIONS

The proposed changes to the Atlas booster trajectory simulation are as follows:

1. Revise C_A versus Mach number.
2. Add a base thrust term equal to base thrust at near vacuum multiplied by $(1 - \frac{P}{P_0})$, where $\frac{P}{P_0}$ is the ratio of ambient pressure to sea level pressure. Base thrust at vacuum might be as low as 2500 pounds or as high as 7000 pounds. A probable value of 3400 pounds is suggested. A conservative value of 2500 pounds is recommended for immediate inclusion.
3. Program a hold-down force of 30,000 pounds for one second beyond 2-inch motion. This can best be simulated by adding 30,000 pounds to the launch weight and jettisoning the same weight at one second.

The results of these changes are as follows:

1. Revision of q-dependent drag increases Surveyor mission payload by 25 pounds.
2. Addition of a base thrust term increases Surveyor mission payload by 36 pounds based on conservative base force of 2500 pounds, or 49 pounds based on the probable base force of 3400 pounds.
3. Addition of hold-down force decreases Surveyor mission payload by 8 pounds.

The over-all effect of these three changes based on the conservative value is 53 pounds more payload to the moon. Using the 3400 pounds probable value gives a payload increase of 66 pounds to the moon.

The total base force acting during booster phase is shown in Figure 4-1 for the case of a 3400 pounds base force. For comparison, the force using previous drag simulation technique is shown.

AC-4 re-assembly using this proposed simulation with the probable value of 3400 pounds gives very good agreement as shown in Figure 4-2.

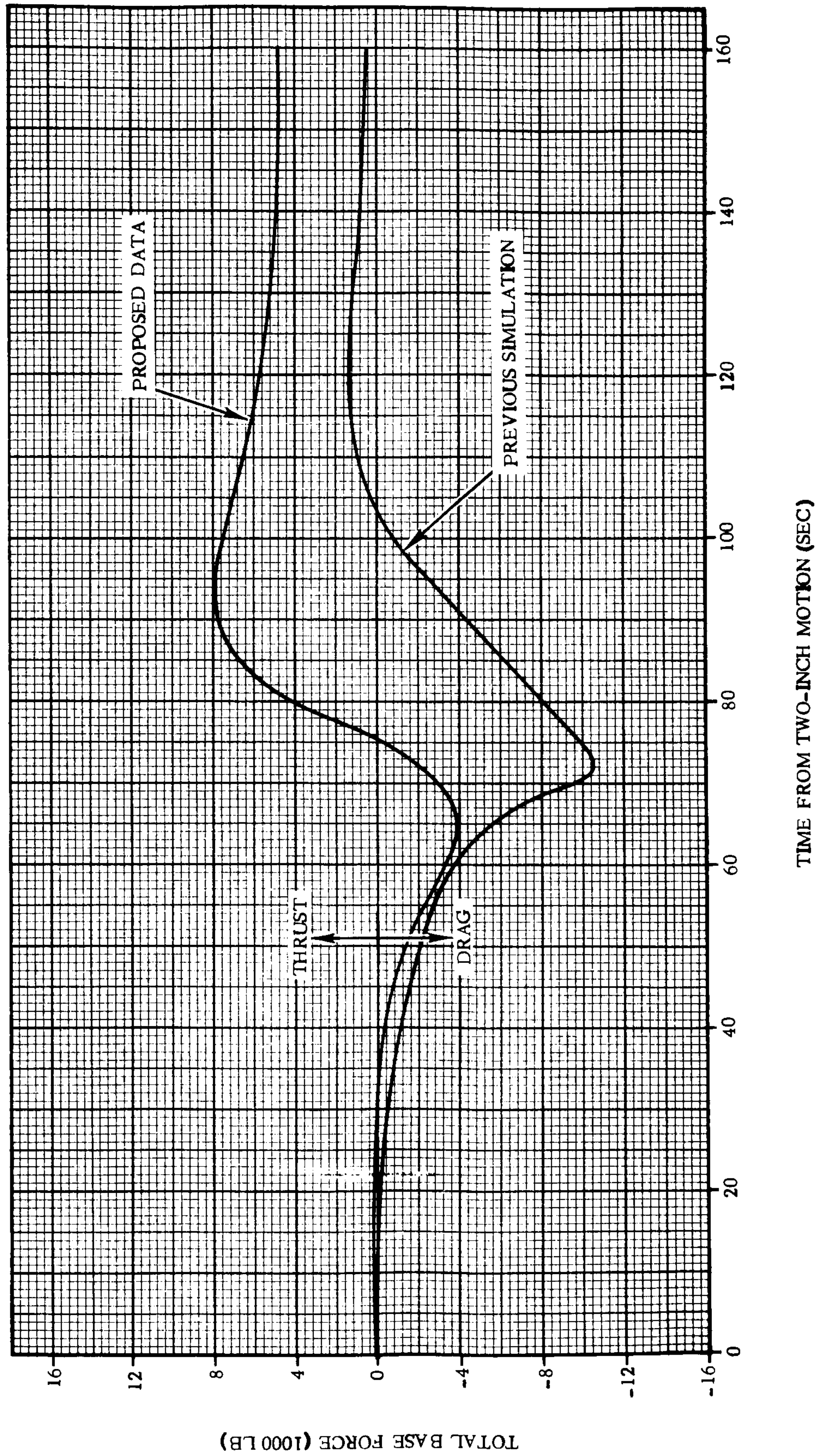

Figure 4-1. Total Base Force, Proposed versus Previous Simulation

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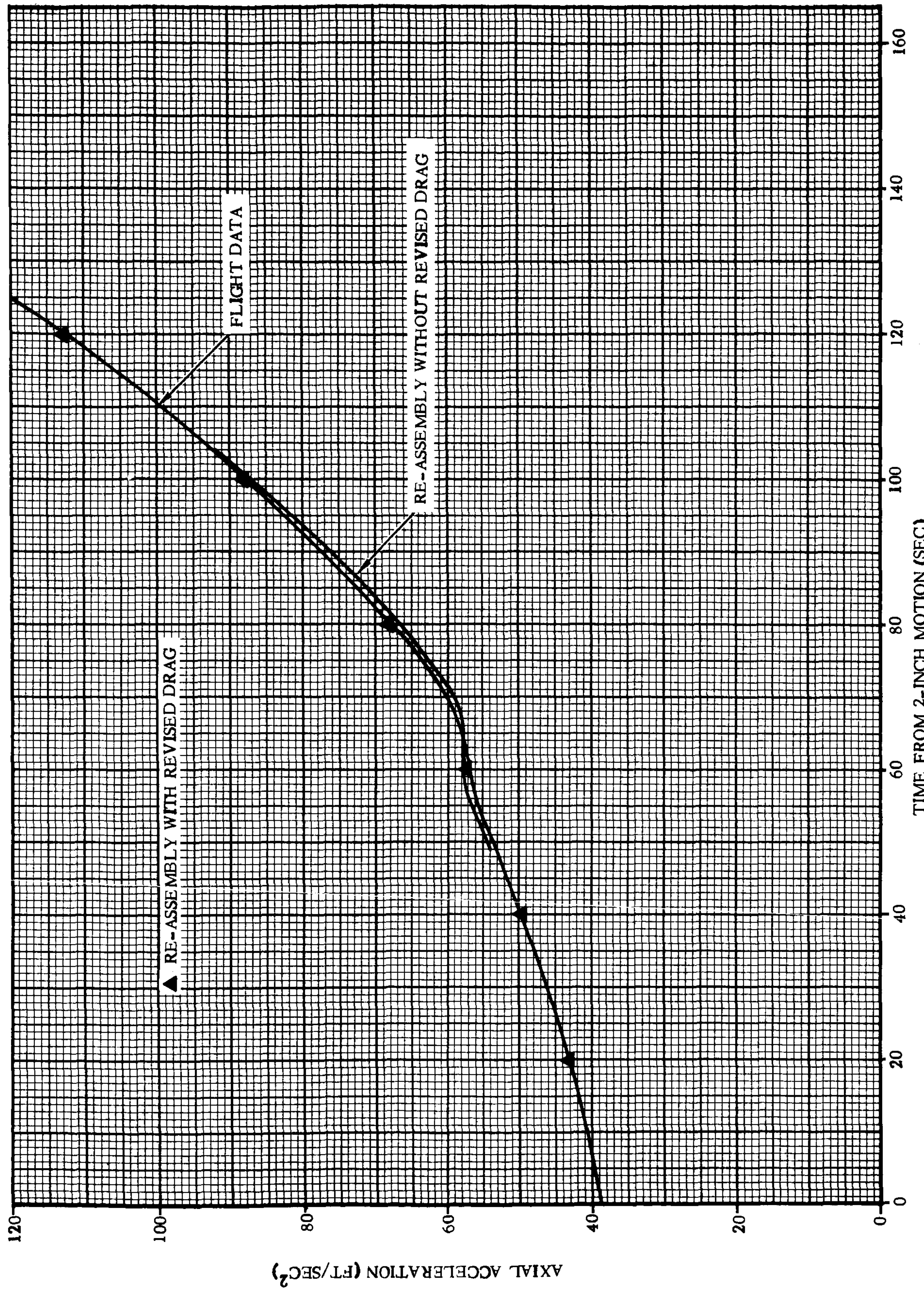

Figure 4-2. AC-4 Re-Assembly Results, Axial Acceleration versus Time

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SECTION V

RECOMMENDATIONS

The following recommendations are made:

1. Incorporate as soon as possible into any and/or all Atlas flights, base pressure measuring devices of small scale (0 to 1 psi) and high accuracy.
2. Change the present trajectory simulation technique to include the base thrust term and hold-down force.
3. Use revised drag coefficient data and conservative value of base force of 2500 pounds in all Atlas booster simulations.
4. Increase base force if warranted by later test data.

SECTION VI

REFERENCES

1. Atlas/Centaur Guidance Test Data for AC-2, AC-3, and AC-4, (Unpublished).

2. Atlas B, C, D, E, F and SLV Test Flight Evaluation Reports, too numerous to list.

3. An Investigation of Recirculation at the Base of a 1/10 Scale Atlas XSM-65 Missile Model at M = 3.07 and at Several Altitudes, dated December 1959, by Arnold Engineering Development Center.