AIM

Association for Information and Image Management

1100 Wayne Avenue, Suite 1100
Silver Spring, Maryland 20910
301/587-8202

Centimeter

Inches

MANUFACTURED TO AIM STANDARDS
BY APPLIED IMAGE, INC.

1 of 1

Aerodynamic, Structural, and Trajectory Analysis of Astrid-1 Vehicle

L. S. Glover
A. P. Iwaskiw
M. A. Oursler
L. L. Perini
E. D. Schaefer

February 10, 1994

DISCLAIMER

Work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract number W-7405-ENG-48.

This document was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor the University of California nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial products, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or the University of California, and shall not be used for advertising or product endorsement purposes.

The Johns Hopkins University
Applied Physics Laboratory
Laurel, Maryland 20723-6099

AL-94-S020
Attachment 1

**AERODYNAMIC, STRUCTURAL, AND
TRAJECTORY ANALYSIS OF ASTRID-1 VEHICLE**

THE JOHNS HOPKINS UNIVERSITY
THE APPLIED PHYSICS LABORATORY

L.S. Glover, A.P. Iwaskiw, M.A. Oursler, L.L. Perini, and E.D. Schaefer

February 10, 1994

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

MASTER

INTRODUCTION

The Johns Hopkins University/Applied Physics Laboratory, JHU/APL, in support of Lawrence Livermore National Laboratory, LLNL, is conducting aerodynamic, trajectory, and structural analysis of the Advanced Single Stage Technology Rapid Insertion Demonstration (ASTRID) vehicle, being launched out of Vandenberg Air Force Base (VAFB) in February 1994.

The resulting analysis documented herein is for the purpose of (1) developing results to be used in generating Flight Plan Approval, FPA, and Operational Approval, OA, for the ASTRID-1 launch, Reference 1, and (2) documentation of analysis in fulfillment of the tasks assigned to The Johns Hopkins University/The Applied Physics Laboratory, JHU/APL, under contract to Lawrence Livermore National Laboratory, LLNL.

The launch is designated ASTRID-1 and is the first in a series of three that will be launched out of Vandenberg Air Force Base, VAFB. Launch dates for the next two flights have not been identified, but they are scheduled for the 1994-1995 time frame.

The primary goal of the ASTRID-1 flight is to test the LLNL light weight thrust on demand bi-propellant pumped divert propulsion system, Reference 2. The system is employed as the main thrusters for the ASTRID-1 vehicle and uses hydrazine as the mono-propellant.

The major conclusions are:

- 1) The vehicle is very stable throughout flight (stability margin = 17 to 24 inches).
- 2) The aerodynamic frequency and the roll rate are such that pitch-roll interactions will be small.
- 3) The high stability margin combined with the high launcher elevation angle makes the vehicle flight path highly sensitive to perturbations during the initial phase of flight, i.e., during the first second of flight after leaving the rail.
- 4) The major impact dispersions for the test flight are due to winds. The wind impact dispersions are 90% dictated by the low altitude, 0 to 1000 ft., wind conditions.
- 5) In order to minimize wind dispersions, head wind conditions are favored for the launch as November VAFB mean tail winds result in land impacts. The ballistic wind methodology can be employed to assess the impact points of winds at the launch site.

- 6) The stress analysis indicates that the vehicle is designed with sufficient strength to endure the proposed flight.
- 7) Structural and aerodynamic frequencies are separated sufficiently to preclude resonance phenomena.

ASTRID-1 is a single stage liquid propellant rocket. There are no ejectables during the flight. The vehicle configuration is sketched in Figure 1. The vehicle dry weight is 8.20 kg (18.081 lbs). The take-off propellant weight will be dependent on the thrust level measured by a load cell at ignition. The vehicle will be loaded with 14.76 kg (25.931 lbs) of propellant and for a 80 lb thrust the launch propellant weight will be 7.60 kg (16.785 lbs) whereas for a 90 lb thrust level the launch propellant weight will be 9.0 kg (19.845 lbs). The propellant loads are selected on the criteria that burnout occurs 2 to 3 seconds prior to apogee. The appropriate launch propellant load is attained by burning off propellant on the rail prior to release for take-off. The 90 lb sea level thrust is the nominal case, whereas the 80 lb sea level thrust represents the lower thrust value acceptable for launch. The lower value has been employed for the baseline trajectory analysis as a conservative bound for range safety. Hydrazine, N_2H_4 , has a density of 1.004 Mg/m^3 (8.323 lb/gal) and the fuel load is 7.6 l (2.01 gallons). Hydrazine is considered a hazard group III liquid propellant, Reference 3. The propellant load is selected to provide a burn-out time approximately 2.77 seconds prior to apogee.

The vehicle is to be launched from a 18.29 m (60 ft) long rail at a 80° elevation angle with a launch azimuth of 245° from true north. The ASTRID-1 has four fins , that are to be canted at 1° , in order to attain a 23.5 rad/sec (3.74 rev/s) roll rate to reduce dispersions. No guidance is employed on the ASTRID-1.

For the atmospheric model we have employed the VAFB Reference Atmosphere, Ref. 4, used by 30 SPW/SEYO for flight analysis and the properties (temperature, pressure, density, and sound speed as a function of altitude) are listed in Table 1.

LAUNCH TOWER

The ASTRID-1 rocket is stabilized by fins. Its low acceleration at launch requires that it be rail guided until the fins become aerodynamically effective. The launch tower and guide rail are 18.3 m (60 feet) long. The tower is a commercial triangular guyed radio tower, Reference 5. The guide rail is clamped to one of the legs of the tower. The tower and rail are shown in Figure 2 and are installed at a 10° ($\pm 1.0^\circ$) angle from the vertical, i.e., initial elevation angle, $\gamma_0 = 80^\circ$. The launch is to be from launch complex LF-08 at VAFB with the following geodetic coordinates, Reference 6, based on the World Geodetic System of 1984 (WGS 84):

Latitude	34.8506°
Longitude	-120.5975°
Geodetic height	2.0 m (6.57 ft)

The tower is oriented on LF-08 Launch Site to produce a $245^\circ (\pm 5^\circ)$ launch azimuth from true north so that the control van will be located behind the 90 degree line, References 7 and 8.

PROPULSION

Propulsion parameters were received from LLNL, References 9 and 10, and are listed in Table 2. There are four nozzles each developing 116.72 N (26.241 lbs) of vacuum thrust at a flow rate of 0.05278 kg/s (0.1164 lb/s). The nozzles are tilted such that the thrust vector for each nozzle goes through the center-of-gravity (cg) at the fully loaded weight. The nozzle centerline, at the base, is located 1.79" radially from the ASTRID longitudinal axis and, for a fully loaded cg location of 0.931 m (36.65") from the nose [body length = 1.869 m (73.582")], this gives a nozzle cant angle of 2.78° . The four motors develop a total baseline vacuum thrust of $F_{vac} = 466.88$ N (104.963 lbs) and, for the 2.78° cant angle, this yields an axial thrust of 466.32 N (104.84 lbs). The vacuum thrust level, F_{vac} , and propellant flow rate were maintained constant for the analysis, with the delivered thrust being evaluated from,

$$F_{del} = F_{vac} - p_0 A_e,$$

where p_0 is the ambient pressure and A_e is the nozzle exit area. The total baseline sea level thrust for the 4 nozzles is 355.84 N (80.00 lbs).

Figure 3 shows a rear view of the ASTRID-1 configuration. The six-degree-of-freedom, 6DOF, trajectory program used in the analysis employs a body reference axes system where the x axis is positive out of the figure along the body longitudinal axis, the z axis is positive up and the y axis is positive to the right. This is in contrast to the LLNL coordinate system where the x axis is positive into the figure. The nozzles are in a cross configuration at launch with the north nozzle designated No. 1 and the sequence increasing in a clockwise direction.

AERODYNAMICS

Aerodynamic coefficients have been determined for the ASTRID-1 vehicle geometry for the range of Mach numbers $M = 0$ to 3.0. The estimates are for the sea level condition as the effects of altitude (i.e., Reynolds Number) are not significant for the altitude range of interest, $Z = 0$ to 6.10 km (20,000 ft). Shown in Table 3 are the resulting axial, normal, and side force coefficients or derivatives, the pitching, yawing, and rolling moment coefficients or derivatives, and the pitch and roll damping derivatives. ASTRID-1 will operate at low angles of attack, α , and sideslip angle, β , and incorporates a small tail fin incidence angle, $\delta = 1^\circ$. Therefore, it is valid to use a linear approximation for the dependence of the coefficients on angle of attack, sideslip angle, and tail incidence angle. The axial force coefficients, C_A , are applicable to both the

power-off and power-on flight phases. Testing, documented in Reference 11, indicates that, for the geometry and exhaust nozzle flow rates of the ASTRID-1 vehicle, there is essentially no change in base drag for the power-on phase of flight. Two commonly accepted computer codes were used to estimate the aerodynamic coefficients; MISSILE DATCOM, Reference 12 and NSWC DD Aerodynamic Prediction Code, APC, Reference 13. The force and moment coefficients were determined with DATCOM and the APC was employed to determine the damping derivatives. The two codes were used to provide a measure of comparison between the predictions and to take advantage of the strengths of each code. The code documentation, References 12 and 13, confirms that the ASTRID-1 geometry and flight parameters are within the applicability of both codes.

ASTRID-1 flight will occur at speeds below $M = 1.0$; our present interest in trajectory accuracy is in this speed regime though future flights will operate at higher speeds. Ideally, the accuracy of aerodynamic coefficients would be derived by comparison of code predictions with experimental results for a vehicle similar to the ASTRID-1 at the Mach numbers of interest. The DATCOM and APC codes have broad applicability and this type of specific information is available in the literature only for the APC code. The general accuracy of DATCOM in the range $0 < M < 6$ and $-20^\circ < \alpha < 30^\circ$ is addressed in Reference 14. The general overall accuracy numbers in Table 3 for all items except for C_{lp} and C_{mq} , were taken from Reference 14 and are applicable to the entire M and α range for the code. The general accuracy of the APC in the range $0 < M < 8$ and $0^\circ < \alpha < 180^\circ$ is addressed in Reference 15. Specific comparison of prediction to experiment is provided for the Basic Finner rocket which bears substantial geometric similarity to ASTRID-1. The accuracy numbers in Table 3 for the C_{lp} and C_{mq} derivatives are extracted from Reference 15 for $1 < M < 3.0$. The reference area is based on the 0.165 m (6.5") diameter, $A_{ref} = 0.0214 \text{ m}^2$ (0.2304 ft^2). Shown in Figure 4 are the axial force contributions due to skin friction, launch lugs, base, fins and body wave (pressure) as a function of M . Note the large contribution of the base drag in the $M < 1$ range.

The fins are in a cruciform configuration, Figure 3, and at launch the north east fin is designated No.1 with the sequencing increasing in a clockwise direction.

The reference center for the moment data is 1.14 m (45.0 in.) from the nose.

MASS PROPERTIES

Center of gravity coordinates (x , y , and z), moments of inertia (I_{xx} , I_{yy} , and I_{zz}), and products of inertia (I_{xy} , I_{yz} , and I_{zy}) were supplied by LLNL, Reference 16, and are listed in Table 4. Based on the inertia values in Table 4 the principal axis is aligned with the x axis to within 0.05° .

BUOYANCY ANALYSIS

The hydrazine fuel tank is 0.152 m (6.0 in.) in diameter with 2:1 ellipsoidal end caps. The cylindrical section length is 0.787 m (31 in.). The total volume in the tank is 0.0162 m³ (0.5727 ft³) and the resulting empty ASTRID-1 density is 0.525 g/cc (32.77 lb/ft³). If the ASTRID-1 survives the water impact intact it will float. For the baseline trajectory the impact velocity is 145 m/s (476 ft/s). Two beacons are located on the vehicle, one in the forward avionics section and the second in the #1 tail fin. The beacons have a range of 1 to 2 mi with a 10 day lifetime. Recovery is to be attempted with a small craft after the mission.

BASELINE TRAJECTORY

Two computer codes are employed for the trajectory analysis: a three-degree-of-freedom (3DOF) simulation, Reference 17, and a 6DOF simulation, Reference 18. The 6DOF code, Program to Optimize Simulated Trajectories (POST), was developed by Martin Marietta Corporation for NASA and has been validated in numerous test flights. The 3DOF code is a JHU/APL developed code that has been employed in numerous Ballistic Missile Defense Organization (BMDO) funded experiments. The 3DOF code was also validated by comparison to the 6DOF results for the ASTRID-1 baseline trajectory.

The results reported below have been generated for a rotating spherical earth model. The base-line trajectory is calculated for zero winds.

The 6DOF code is not capable of simulating a rail launch so that the initial conditions for the 6DOF analysis are the conditions at the end of the rail. The end of rail conditions were determined with the 3DOF code. For the $\gamma_0 = 80^\circ$ trajectory, the conditions at the end of the 18.29 m (60 foot) long rail are:

time,sec	1.67
velocity,m/s (ft/s)	22.0(72.1)
altitude, m (ft)	20.0(65.7)
weight, kg (lbs)	16.83(37.10)

The effects of rail friction were investigated employing a simple kinetic friction assumption where the frictional force is given as the product of the kinematic friction coefficient and the normal force between the rail and the launch shoes. Note that, to a first approximation, the frictional force is independent of contact area and velocity. The normal force is given by the weight times the cosine of the rail elevation angle. The kinematic friction coefficient is assumed as $\mu = 0.1$ applicable for steel on steel. The frictional force is then given as,

$$F_f = \mu * W * \cos(\gamma_0) = 1.397 \text{ N (0.31 lbs)}.$$

Subtracting F_f from the sea level delivered thrust for the rail phase of the flight resulted in a 0.5% loss in end of rail velocity and a 0.5% increase in time on rail. The effects of rail friction have been neglected in the results reported here-in.

For the nominal (90 lb sea level thrust) trajectory, altitude, velocity, flight path angle, and range as a function of time, are tabulated in the Appendix. Shown in Figure 5 are the latitude, longitude, and altitude plot for the baseline trajectory. The altitude/range profile is shown in Figure 6. Burnout occurs at 36.06 sec at an altitude of 3.52 km (11,542 feet) with apogee at 38.83 sec at a 3.56 km (11,670 foot) altitude. Total range is 9.664 km (5.22 nm). The ground track of the baseline trajectory is shown in Figure 7. The next 8 Figures show time histories of Mach number in Figure 8, dynamic pressure in Figure 9, spin rate and aerodynamic frequency in Figure 10¹, angle of attack and yaw angle in Figure 11, flight path angle in Figure 12, range in Figure 13, altitude in Figure 14 and axial acceleration in Figure 15. Total time of flight is 75.53 sec.

The initial rail elevation (flight path angle, γ_0) has been selected as $\gamma_0 = 80^\circ$, and VAFB has requested that we investigate the possibility of lowering γ_0 from 80° to 70° , Reference 7. The higher γ_0 alleviates 'fuel starvation' problems whereas the lower γ_0 reduces impact dispersions due to winds. Shown in Figure 16 is the altitude-range profile of three trajectories with initial γ_0 of 70° , 75° , and 80° . Note that, for the $\gamma_0 = 80^\circ$ trajectory, burn out occurs slightly prior to apogee (approximately 2.77 sec), whereas for the lower γ_0 's burn out occurs after apogee. The ASTRID-1 will be rotating at approximately 3.74 rev/sec (23.5 rad/s) at burn-out, Figure 10. At apogee the total acceleration will be zero and the fuel remaining in the tank will be forced to the tank walls due to the centrifugal forces. Past apogee, the fuel will be forced to the forward region of the tank and the axial fuel port will be dry resulting in 'fuel starvation', with the possibility of vehicle impact with fuel remaining in the tank. The option of off-loading propellant, which would allow a lower initial γ_0 , would also result in a shorter propulsion system burn time and was not considered as it would compromise the flight test goal of evaluating the propulsion system performance.

DISPERSIONS

There are four general sources of error in predicting the impact location of the ASTRID-1 vehicle. These sources are - initialization, environmental, nominal mass/propulsion/aerodynamic properties, and missile asymmetries. The initialization errors include such items as errors in elevation, azimuth, launch velocity, and errors that result from tip-off that may occur when the forward launch lug leaves the launch rail. Impact errors resulting from environmental factors include errors in wind, air temperature, and air density. The mass properties when on the launch rail may be different than the values being currently estimated and some of the propulsion and aerodynamic properties

¹ Note that the two traces are sufficiently different that pitch-roll interactions will not be a problem.

cannot be predicted accurately. The missile asymmetries include such items as center of gravity offset from the longitudinal axis, inclination of the principal axis, misalignment of the fore and aft sections of the body relative to the center-body section, tail misalignment, misalignment of the thrust axes, and variation in thrust magnitude.

The vehicle/launcher tolerances to be presented are not based on statistical data as the launch of the ASTRID-1 is a first of its kind. The tolerances are the result of considerations by LLNL personnel based on recent experiences in assembling the vehicle and launcher. The first set of error sources is in the initialization. For these we have identified the launcher elevation $80 \pm 1.0^\circ$ and azimuth $245 \pm 5^\circ$ settings as "conservative" estimates. For the initial ASTRID-1 weights it is estimated that the inert weight is 8200 ± 100 g and the propellant load is 7600 ± 50 g. The nozzles, canted through the initial cg location, have been estimated to be set at $2.78 \pm 0.75^\circ$ and the fins set at $1.0 \pm 0.15^\circ$. The cg offset has been assumed as 0.0 ± 0.1 cm. The alignment of the three body sections, forward skirt, central fuel tank, and aft skirt is estimated as $0 \pm 0.15^\circ$. The dispersion resulting from a variation in flow rate is estimated to be 0.1163 ± 0.00233 lbs/sec (i.e., $\pm 2\%$) for each of the 4 nozzles. For the flow rate dispersions the vacuum propellant specific impulse was maintained at 225.5 sec with the vacuum thrust being therefore proportional to the flow rate.

In order to make 6DOF simulation predictions of the worst case aerodynamic loads and the maximum dispersions in the flight path, it was necessary to account for uncertainties in the aerodynamic estimates calculated by the prediction codes, References 12 and 13.

The uncertainties arise from two sources. First, there are uncertainties in the geometry of the vehicle due to manufacturing and assembly tolerances. We assumed a tail and body misalignment of 0.15° . Second, the accuracy of the aerodynamic prediction codes as listed in Table 3.

The effects of vehicle geometry uncertainties were accounted for using the assumption that the error in alignment of each of the four tail fins could occur simultaneously (i.e., all four off by 0.15°) but that these errors will occur independently of the error in alignment of the afterbody. Error in alignment of the nose fairing was determined to have negligible effect on the aerodynamic coefficients and was not considered further. The combined effect of the tail and afterbody alignment errors was approximated as the root sum of the squares (RSS) of the effects of the two individual misalignments. These effects were accounted for in the C_{m0} coefficient. Combining these factors, nominal 6DOF inputs were modified as follows:

C_A	multiply by 1.1 to account for code accuracy.
$C_{N\alpha}, C_{Y\beta}, C_{m\alpha}, C_{n\beta}$	multiply by 1.2 to account for code accuracy.
C_{lp}, C_{mq}	multiply by 1/1.2 to account for code accuracy
C_{lo}	multiply by 1.2 X 1.15 to account for code accuracy and tail misalignment in roll deflection
C_{mo}	includes pitching moment coefficient resulting from the launch lugs (a very small effect) plus the RSS of the moment coefficients resulting from 0.15° fin alignment and 0.15° aft body misalignment.

The multipliers for C_{lp} , C_{mq} and C_{nr} (i.e., 1.2 or 0.8) were selected to result in maximum trim angle of attack resulting from roll-pitch coupling effects. For the maximum load condition, a gust velocity of 8.99 m/s (29.5 ft/s) normal to the body centerline was superimposed on the trim angle of attack. Without the gust the trim angle of attack is 0.45°. With the gust, the angle of attack is 2.26°. For the maximum dispersion condition, no gust velocity was imposed.

In addition, the nozzles were all deflected $\pm 0.75^\circ$ in pitch and yaw.

The major source of dispersion is the winds. For the wind dispersions, the mean November wind at VAFB shown in Figure 17, taken from Reference 4, has been employed. The wind speed profile shown in Figure 17 was applied at wind azimuths of 0° , $\pm 30^\circ$, $\pm 60^\circ$, $\pm 90^\circ$, $\pm 105^\circ$, $\pm 120^\circ$, $\pm 135^\circ$, $\pm 150^\circ$, $\pm 165^\circ$, and $\pm 180^\circ$ with respect to the launch azimuth of 245° .

The impact points resulting from the above dispersion sources are shown in Figure 18. The aerodynamic uncertainties, fin misalignment, body misalignment, and nozzle misalignment have been combined, as described above, to represent a worst-case combination. The inert weight, propellant weight, flow rate, rail elevation and azimuth heading dispersions were individually evaluated with the 6DOF code. The dispersions can be grouped into three categories. The first category consists of the flight path angle, inert weight, propellant weight, and propellant flow rate. They are closely grouped about the nominal impact point. This group results mainly in down-range dispersions of the order of 0.135 km (446 ft). The second category consists of the launch azimuth and aerodynamic/nozzle dispersions with a RSS cross-range dispersion of ± 1.30 km (± 4256 ft). The third and most significant category is the dispersions due to the winds.

If we limit the wind azimuth to within $\pm 90^\circ$ of the headwind azimuth, the combined dispersion footprint is shown in Figure 19. Because of the non-linear response of the spinning vehicle to some of the error sources (e.g., winds and aerodynamic uncertainties), standard techniques for combining the individual error sources were not employed. The up-range, down-range, and cross-range impact dispersions about the nominal impact point were found by the RSS of the aerodynamic/ nozzle, propellant flow rate, inert weight, propellant weight, initial rail elevation angle and initial rail azimuth angle dispersions. The final values are 0.11 km (0.057 nm), 0.96 km (0.517 nm), and 1.30 km (0.70 nm) in up-range, down-range and cross-range dispersions, from the

nominal impact point, respectively. A circular dispersion of 1.13 km (0.7 nm) was applied to the mean November VAFB wind dispersions to arrive at the 'albatross' shape shown in Figure 19.

BALLISTIC WIND WEIGHTING FACTORS

The ballistic wind is the wind having constant speed and azimuth that has the same impact error as that of the real wind. The method is shown in Table 5. Nine altitude bands were selected to evaluate the ballistic wind weighting factors, and six wind speeds were selected to evaluate the range partials required for impact predictions. Note that 90% of the dispersion results from the winds at altitudes from 0 to 0.305 km (1000 feet).

The methodology was applied to the wind dispersion results discussed above and the comparison is shown in Figure 20. Note that the method yields reasonably accurate impact dispersions. The method will be employed at the launch site to evaluate potential dispersions due to measured winds.

The large crossrange dispersions due to wind conditions are due mainly to the high launcher elevation angle, γ_0 . The initial change in ground track azimuth at the end-of-rail is given approximately by,

$$\Delta AZ = \tan^{-1}[V_W/(V_0 \cos(\gamma_0))]$$

For a 5 knot cross wind with $V_0 = 22.0$ m/s (72.1 ft/s) and $\gamma_0 = 80^\circ$, $\Delta AZ = 34.0^\circ$. The large stability margin² of the vehicle (24 in. at launch) results in the vehicle weathercocking rapidly into the wind.

STRUCTURAL ANALYSIS

A static and normal modes analysis was performed on the ASTRID 1 vehicle, in order to verify the structural integrity of the vehicle and to characterize its dynamic behavior. A NASTRAN finite element model containing over 10000 degrees of freedom was developed in order to accurately represent the vehicle structure. A wire-frame representation of the model is shown in Figure 21. The ASTRID 1 vehicle's forward and aft skirt, pressure tank, thrust plate weldment, radome, and fins were modeled as plate elements. The thru tubes in the pressure vessel were not modeled, as they were not a part of the base-line design. The materials and dimensions for these parts were determined using the detailed drawings provided to JHU/APL by LLNL. Homogeneous material properties were assumed. The composite Kevlar/Epoxy fins were modeled using

² An analysis was conducted to investigate reducing the tail size to shift the center of pressure or employing ballast to shift the cg, both in a direction to reduce the stability margin. Neither option appeared promising with regard to reducing wind dispersions.

the data provided in Reference 19. There was not enough technical details on the composite layups or test data to provide an independent check as to the strength of the fins. Properties for the radome were used for the same reasons as for the fins.

The propulsion system avionics, thrusters, and nose plug were modeled with concentrated masses. The magnitudes were obtained from the data provided in Reference 16.

The two critical structural joints on the vehicle (i.e., between the pressure tank and the forward and aft skirt) were modeled using plate elements to represent the flanges and rigid elements to represent the bolts in order to recover forces and stresses in these elements.

The liquid hydrazine in the pressure tank was modeled using non-structural masses that were tied via rigid elements to the tank wall. The magnitude and inertia properties of these discrete masses varied linearly along the length of the tank. No free surface effects or fluid-structure interactions were modeled. The sum total of the fuel mass and the cg were made to agree with that of Reference 16, for the flight time in which the worst-case loading occurred.

The worst-case flight conditions were found to occur approximately 21 seconds into the flight. The weight of the vehicle at that time was estimated at 15.1 kg (33.2 lbs) with a center of gravity of 1.064 m (41.9 in.) from the nose. The finite element model was maintained to within 3 percent of these values. The aerodynamic loads corresponding to this flight condition are listed in Table 6, along with a second set of flight loads which includes the effect of a 8.99 m/s (29.5 ft/s) gust load. In addition to the aerodynamic and inertia loads, a thrust load of 131 pounds was applied to the aft end of the vehicle, the fuel tank was pressurized to 100.0 pounds per square inch, and the entire vehicle was subjected to a roll rate of 6.15 rev/sec.

The ASTRID 1 vehicle was designed to have a minimum factor of safety of 1.25 on ultimate, 1.10 on yield, and 1.25 on buckling. Stress contour plots of the vehicle are given in Figures 22 through 24. Figure 22 shows the von Mises stress on the surface of the vehicle for loading case without wind gusts. The high stresses occur in the wall of the pressurized fuel tank. The main contribution being the 100 psi internal tank pressure. Figure 23 shows the stresses on the vehicle surface for the load case with the specified wind gusts. The high stresses again occur in the wall of the fuel tank and also at the tank/aft skirt joint. A more detailed description of the stresses in the region are shown in Figure 24 with a maximum von Mises stress of 45 ksi. Table 7 summarizes the margins of safety for the major structural elements of the vehicle.

The static load test, described in Reference 21, was duplicated using the finite element model to validate the model and to provide a bench mark for the current vehicle design. For the 9.06 kg (20 lb) static load case, the measured deflection at the aft end of the vehicle, was 0.495 cm (0.195 in.) as compared to the finite element model with a deflection of 0.533 cm (0.210 in.).

The effects of the 100 psi internal tank pressure on the stiffness of the structure was found to be negligible. This was determined by comparing static load test data with the model. The deflection difference was negligible between a vehicle with a pressurized tank and one with no pressure in the tank.

Based on NASTRAN normal modes analysis, the primary resonant frequency (first mode bending) for the ASTRID 1 vehicle was determined to be 48.6 Hz - without the effect of the pressurized tank and is illustrated in Figure 25. This resonant frequency is comparable to the frequency calculated in Reference 20 when one considers the differences in the two models. The model in Reference 20 did not consider any structure forward of the tank and had assumed a vehicle weight of 11.16 kg (24.6 lbs). In addition the aft skirt was 0.33 m (13.0 in.) shorter than the current design.

Since the primary resonant frequency of the vehicle is far enough removed from the aerodynamic frequency of approximately 10 Hz, no significant interaction is expected. Figure 26 shows that the primary resonant frequency of the fins (first bending mode) is 82 Hz. This is comparable with the results presented in Reference 19, when one takes into account the increased mass of the fin and the boundary conditions imposed by the vehicle.

CONCLUSIONS

The structural, aerodynamic, and trajectory analysis of the ASTRID-1 vehicle has been completed. The dynamic behavior of the spinning propellant has not been considered. The two tubes that pierce the fuel tank head caps, to carry cables from the aft section to the forward section, has not been included in the structural analysis. The major conclusions are:

- 1) The vehicle is very stable throughout flight (stability margin = 17 to 24 inches).
- 2) The aerodynamic frequency and the roll rate are such that pitch-roll interactions will be small.
- 3) The high stability margin combined with the high launcher elevation angle makes the vehicle flight path highly sensitive to perturbations during the initial phase of flight, i.e., during the first second of flight after leaving the rail.
- 4) The major impact dispersions for the test flight are due to winds. The wind impact dispersions are 90% dictated by the low altitude, 0 to 1000 ft., wind conditions.
- 5) In order to minimize wind dispersions, head wind conditions are favored for the launch as November VAFB mean tail winds result in land impacts. The ballistic wind methodology can be employed to assess the impact points of winds at the launch site.

- 6) The stress analysis indicates that the vehicle is designed with sufficient strength to endure the proposed flight.
- 7) Structural and aerodynamic frequencies are separated sufficiently to preclude resonance phenomena.

A number of JHU/APL memorandum have been recently published (References 22 to 26) documenting the aerodynamic analysis conducted for the ASTRID-1 vehicle that were not referenced above.

L. S. Glover

L. S. Glover

A. P. Iwaskiw

A. P. Iwaskiw

M. A. Oursler

M. A. Oursler

L. L. Perini

L. L. Perini

E. D. Schaefer

E. D. Schaefer

REFERENCES

- 1) "Range Safety Requirements," Western Space and Missile Center, WSMCR 127-1, December 15, 1989.
- 2) Whitehead, John C., "Demand Thrust Pumped Propulsion With Automatic Warm Gas Valving," AIAA paper 92-3539, Presented at AIAA/SAE/ASEE 28th Joint Propulsion Conference and Exhibit, July 6-8, 1992.
- 3) Downey, R. M., "Explosives Safety Standards," Department of the Air Force, Headquarters US Air Force, Wash. DC, AF Regulation 127-100, August 3, 1990.
- 4) "Vandenberg Air Force Base, California, Range Reference Atmosphere, 0-70 km Altitude," Document 362-83, Range Reference Atmosphere committee, Meteorology Group, Range Commanders Council, April 1983.
- 5) Bertolini, Lou, Fax to Luigi Perini, JHU/APL, "ASTRID Launch Tower," October 6, 1993.
- 6) Fax from Michael Richardson, 30 SPW/SEY, to Luigi Perini, JHU/APL, "Information for ASTRID Trajectory Analysis," July 22, 1993.
- 7) Fax from Ron Cortopassy, 30 SPW/SEY, to 30 RANS/DOR, "Launcher Position Requirement for ASTRID," August 3, 1993.
- 8) Bertolini, Lou, Fax to Luigi Perini, JHU/APL regarding change of launch azimuth, October 6, 1993.
- 9) Telecon from John Whitehead, LLNL, to Luigi Perini, JHU/APL, July 22, 1993.
- 10) Telecon from Lee Pittenger, LLNL, to Luigi Perini, JHU/APL, September 1993.
- 11) Sykes, D. M., "Cylindrical and Boat-Tailed Afterbodies in Transonic Flow with Gas Ejection," AIAA Journal, Vol. 8, No. 3.
- 12) Burns, K. A., Deters, K. J., Stoy, S. L., Vukelich, S. R., and Blake, W. B., "MISSILE DATCOM," Wright Patterson Air Force Base, OH, Report WL-TR-93-3043, June 1993.
- 13) Devan, L. and Mason, L., "Aerodynamics of Tactical Weapons to Mach Number 8 and Angle of Attack 180°: Part II, Computer Program and Users Guide," NSWC TR 81-358, Sep 81, NSWC, Dahlgren, VA.

- 14) Vukelich, S. R., Stoy, S. L., Burns, K. A., Castillo, J. A., and Moore, M. E., "Missile DATCOM Volume I-Final Report," AF WALTR-86-3091, December 1988, Air Force Wright Aeronautical Laboratory, Wright Patterson AFB, OH.
- 15) Mason, L., Devan, L., Moore, F. G., and McMillan, D., "Aerodynamic Design Manual For Tactical Weapons," Naval Surface Weapons Center, Dahlgren, Virginia, Report NSWC TR 81-156, July 1981.
- 16) L. Pittenger, "Mass Properties," Lawrence Livermore National Laboratory memorandum, August 25, 1993.
- 17) Perini, L. L., "Users Manual for the 3DOF Trajectory Computer Program," ANSP-M-6, JHU/APL, September, 1973.
- 18) Brauer, G. L., Cornick, D. E., Olson, D. W., Petersen, F. M., and Stevenson, R., "Six-Degree-of-Freedom Program to Optimize Simulated Trajectories (6D POST)," Martin Marietta Corporation Report numbers Vol. 1-MCR-87-583, Vol. 2-MCR-87-584, and Vol. 3-MCR-87-585, September 1990. NASA contract NAS1-18147 under the direction of Mr. Richard W. Powell, NASA Langley Research Center.
- 19) "Kevlar Fins Calculated Natural Frequencies," Telecopy Transmittal Report, from Al Harral to Lee Pittenger of LLNL; May 4, 1993
- 20) "Primary Probe Model and Structural Analysis," Telecopy Transmittal Report, from Al Harral to Lee Pittenger of LLNL, Feb 3, 1993
- 21) "Flexure Test Prototype Rocket Frame," Fax from Lee Pittenger, LLNL, to Ed Schaefer, JHU/APL, October 2, 1993.
- 22) Glover, L. S., "A Ballistic Wind Procedure for Estimating the Effects of Wind on Impact Dispersion and on Time of Apogee for ASTRID Flight Tests", JHU/APL memorandum, November 27, 1993.
- 23) Glover, L. S., "Summary of Aerodynamic Effort on ASTRID", JHU/APL memorandum, January 5, 1994.
- 24) Oursler, M. A., "ASTRID Aerodynamic Model Development", JHU/APL memorandum SSD/PM-94-0005, January 18, 1994.
- 25) Oursler, M. A., "Anomalies Noted in MISSILE DATCOM, Rev 4/91, During ASTRID 1 Modeling", JHU/APL memorandum SSD/PM-94-0006, January 18, 1994.
- 26) Oursler, M. A., "Determination of Aerodynamic Loads for ASTRID 1", JHU/APL memorandum SSD/PM-94-0007, January 18, 1994.

Table 1. Vandenberg AFB November Reference Atmosphere

Altitude ft	Temperature Rankine	Pressure lb/ft	Density slugs/ft ³	Sound Speed ft/s
0.00	519.29	2089.00	0.00237000	1116.835
2500.00	510.38	1907.31	0.00220790	1107.212
5000.00	501.47	1738.43	0.00204820	1097.505
7500.00	492.56	1581.87	0.00189750	1087.711
10000.00	483.65	1395.28	0.00175560	1077.828
12500.00	474.74	1302.72	0.00162190	1067.854
15000.00	465.83	1179.55	0.00149620	1057.785
17500.00	456.94	1065.68	0.00137810	1047.641
20000.00	448.03	960.74	0.00126730	1037.376
22500.00	439.13	864.57	0.00116340	1027.030
25000.00	430.24	776.33	0.00106630	1016.579
27500.00	421.35	695.48	0.00097544	1006.019
30000.00	412.46	621.63	0.00089068	995.347
32500.00	403.57	554.27	0.00081169	984.560
35000.00	394.67	492.96	0.00073820	973.652
37500.00	390.59	437.47	0.00066196	968.599
40000.00	390.59	388.11	0.00058737	968.599
42500.00	390.59	344.33	0.00052103	968.599
45000.00	390.59	305.50	0.00046227	968.599
47500.00	390.59	271.05	0.00041015	968.599
50000.00	390.59	240.50	0.00036391	968.599
52500.00	390.59	213.39	0.00032290	968.599
55000.00	390.59	189.35	0.00028652	968.599
57500.00	390.59	167.94	0.00025412	968.599
60000.00	390.59	149.10	0.00022561	968.599
70000.00	390.59	92.48	0.00013993	968.599
80000.00	390.59	57.38	0.00008683	968.599
90000.00	403.08	35.83	0.00005253	983.967
100000.00	419.39	22.79	0.00003211	1003.674

Table 2. ASTRID-1 Propulsion Parameters.

A set of propulsion parameters was received from John Whitehead, LLNL, Reference 9 and Reference 10. The final propulsion parameters, per nozzle, employed in the analysis are based on a January 7, 1994 telephone conversation with Lee Pittinger, LLNL, that recommended a sea level thrust of 88.76 N (20.0 lbs):

w, Propellant flow rate	0.1164 lbs/s
P_C , Chamber pressure	458 psia
P_e , Nozzle exit pressure	7.33 psia
C_T , Thrust coefficient, sea level	1.398
T_{SL} , Sea level delivered thrust	20.00 lbs
T_v , Vacuum delivered thrust	26.24 lbs
$I_{sp,SL}$, Sea level propellant specific impulse	171.9 sec
$I_{sp,v}$, Vacuum propellant specific impulse	225.50 sec
$\epsilon = A_e/A^*$, Nozzle expansion ratio	8
D^* , Nozzle throat diameter	0.260

From the above parameters the characteristic velocity, C^* , can be computed,

$$C^* = g \cdot P_C \cdot A^* / w = 4770 \text{ ft/sec},$$

and the throat area for each nozzles is

$$A^* = \pi \cdot D^{*2} / 4 = 0.05309 \text{ in}^2,$$

with an exit area,

$$A_e = 8 \cdot A^* = 0.4247 \text{ in}^2.$$

The effective nozzle diameter, for 4 nozzles, is given by,

$$D_e = \text{Sqrt}(4 \cdot 4 \cdot A_e / \pi) = 1.47''.$$

Based on Mach function tables (ratio of specific heats, $\gamma = 1.3$) the exit Mach number is

$M_e = 3.68$ for a nozzle area ratio, $\epsilon = 8$.

Table 3. ASTRID-1 Aerodynamic Coefficients and Derivatives.

Mach	C_A	$C_{N\alpha}$	$C_{Y\beta}$	$C_{m\alpha}$	$C_{n\beta}$	$C_{l\delta}$	C_{lp}	C_{mo}
0.00	0.331	0.384	-0.384	-0.938	0.938	0.249	-39.3	0.00507
0.50	0.331	0.384	-0.384	-0.938	0.938	0.249	-39.3	0.00507
0.80	0.346	0.428	-0.428	-1.085	1.085	0.285	-41.6	0.00942
0.90	0.534	0.454	-0.454	-1.164	1.164	0.303	-45.1	0.01198
1.00	1.140	0.503	-0.503	-1.264	1.264	0.334	-48.1	0.01318
1.05	1.240	0.587	-0.587	-1.644	1.644	0.395	-49.8	0.01312
1.20	0.947	0.535	-0.535	-1.473	1.473	0.353	-57.1	0.01282
1.50	0.791	0.330	-0.330	-0.619	0.619	0.231	-48.8	0.01163
1.75	0.717	0.275	-0.275	-0.424	0.424	0.190	-41.3	0.01097
2.00	0.655	0.240	-0.240	-0.291	0.291	0.161	-35.8	0.01061
3.00	0.520	0.172	-0.172	-0.093	0.093	0.102	-23.5	0.01013

Mach	C_{mq}		C_{nr}	
	cg=35"	cg=47"	cg=35"	cg=47"
0.00	-1110.	-456.	-1110.	-456.
0.50	-1110.	-456.	-1110.	-456.
0.80	-1246.	-513.	-1246.	-513.
0.90	-1404.	-590.	-1404.	-590.
1.00	-1228.	-480.	-1228.	-480.
1.05	-1123.	-417.	-1123.	-417.
1.20	-1213.	-441.	-1213.	-441.
1.50	-1038.	-456.	-1038.	-456.
1.75	-911.	-420.	-911.	-420.
2.00	-826.	-395.	-826.	-395.
3.00	-632.	-326.	-632.	-326.

C_A , c_a axial force coefficient, power on and off.

$C_{N\alpha}$, c_{na} normal force derivative, deg^{-1}

$C_{Y\beta}$, c_{yb} side force derivative, deg^{-1} ,

$C_{m\alpha}$, c_{ma} pitching moment derivative, deg^{-1}

$C_{n\beta}$, c_{wb} yawing moment derivative, deg^{-1}

$C_{l\delta}$, rolling moment derivative, deg^{-1}

C_{lp} , c_{llp} rolling moment derivative due to roll rate, per rad

C_{mo} , c_{mo} pitching moment coefficient due to asymmetric launch lugs

C_{mq} , c_{mq} pitching moment derivative due to pitch rate, per rad

C_{nr} , c_{wr} yawing moment derivative due to yaw rate, per rad

Item	Accuracy
C_A	$\pm 10\%$
$C_{N\alpha}$	$\pm 20\%$
$C_{Y\beta}$	$\pm 20\%$
$C_{m\alpha}$	$\pm 20\%$
$C_{n\beta}$	$\pm 20\%$
$C_{l\delta}$	$\pm 20\%$
C_{lp}	$\pm 20\%$
C_{mo}	$\pm 20\%$
C_{mq}	$\pm 20\%$
C_{nr}	$\pm 20\%$

Table 4. ASTRID-1 center of gravity, moments of inertia, and products of inertia as a function of weight.

Metric Units:									
cg location-----				Moments of Inertia,kg/m ² -----					
m, kg	x,m ⁽¹⁾	y,m	z,m	Ixx	Iyy	Izz	Ixy	Iyz	Izy
7.9984	-1.0497	0.00036	0.00071	0.05412	3.104	3.110	-0.00113	-0.00039	-0.00212
22.9984	-0.9310	0.00012	0.00025	0.09767	4.125	4.131	-0.00079	-0.00039	-0.00145
21.9984	-0.9511	0.00013	0.00026	0.09477	3.918	3.925	-0.00085	-0.00039	-0.00156
20.9984	-0.9706	0.00014	0.00027	0.09187	3.742	3.748	-0.00091	-0.00039	-0.00167
19.9984	-0.9893	0.00014	0.00028	0.08896	3.593	3.600	-0.00096	-0.00039	-0.00178
18.9984	-1.0071	0.00015	0.00030	0.08606	3.471	3.478	-0.00101	-0.00039	-0.00188
17.9984	-1.0238	0.00016	0.00032	0.08316	3.373	3.380	-0.00106	-0.00039	-0.00197
16.9984	-1.0394	0.00017	0.00033	0.08025	3.297	3.304	-0.00110	-0.00039	-0.00206
15.9984	-1.0535	0.00018	0.00035	0.07735	3.242	3.248	-0.00115	-0.00039	-0.00214
14.9984	-1.0659	0.00019	0.00038	0.07445	3.203	3.210	-0.00118	-0.00039	-0.00221
13.9984	-1.0762	0.00021	0.00041	0.07145	3.179	3.186	-0.00121	-0.00039	-0.00227
12.9984	-1.0839	0.00022	0.00044	0.06864	3.167	3.173	-0.00123	-0.00039	-0.00232
11.9984	-1.0884	0.00024	0.00047	0.06573	3.162	3.168	-0.00125	-0.00039	-0.00234
10.9984	-1.0887	0.00016	0.00052	0.06283	3.160	3.167	-0.00125	-0.00039	-0.00234
9.9984	-1.0837	0.00029	0.00057	0.05993	3.156	3.162	-0.00123	-0.00039	-0.00231
8.9984	-1.0716	0.00032	0.00063	0.05702	3.141	3.147	-0.00120	-0.00039	-0.00225
English Units:									
cg location-----				Moments of Inertia,slugs-ft ² -----					
m, lb	x,ft ⁽²⁾	y,ft	z,ft	Ixx	Iyy	Izz	Ixy	Iyz	Izy
50.71147	-0.6956	0.000394	0.00082	0.072048	3.042895	3.047321	-0.00058	-0.00029	-0.00107
48.50647	-0.6296	0.000427	0.000853	0.069909	2.890197	2.895361	-0.00063	-0.00029	-0.00115
46.30147	-0.5657	0.000459	0.000886	0.067770	2.760367	2.764793	-0.00067	-0.00029	-0.00123
44.09647	-0.5043	0.000459	0.000919	0.065623	2.650454	2.655618	-0.00071	-0.00029	-0.00131
41.89147	-0.4451	0.000492	0.000984	0.063484	2.560458	2.565622	-0.00075	-0.00029	-0.00139
39.68647	-0.3911	0.000525	0.001050	0.061345	2.488166	2.493330	-0.00078	-0.00029	-0.00146
37.48147	-0.3399	0.000558	0.001083	0.059198	2.432103	2.437267	-0.00081	-0.00029	-0.00152
35.27647	-0.2937	0.000591	0.001148	0.057059	2.391531	2.395957	-0.00084	-0.00029	-0.00158
33.07147	-0.2530	0.000623	0.001247	0.054920	2.362762	2.367926	-0.00087	-0.00029	-0.00163
30.86647	-0.2192	0.000689	0.001345	0.052707	2.345058	2.350222	-0.00089	-0.00029	-0.00168
28.66147	-0.1939	0.000722	0.001444	0.050634	2.336206	2.341632	-0.00091	-0.00029	-0.00171
26.45647	-0.1792	0.000787	0.001542	0.048487	2.332518	2.336944	-0.00092	-0.00029	-0.00173
24.25147	-0.1782	0.000525	0.001706	0.046348	2.331042	2.336206	-0.00092	-0.00029	-0.00173
22.04647	-0.1946	0.000951	0.001870	0.044209	2.328091	2.332518	-0.00091	-0.00029	-0.00171
19.84147	-0.2343	0.001050	0.002067	0.042062	2.317026	2.321452	-0.00088	-0.00029	-0.00166
17.63647	-0.3061	0.001181	0.002329	0.039923	2.289733	2.294159	-0.00084	-0.00029	-0.00156

Notes: (1) Xcg measured from nose, LLNL coordinate system, x positive from nose forward
(2) Xcg measured from Xref = 45" from the nose, 6DOF coordinate system, x positive rearward.

Table 5. Ballistic Wind Weighting Factors and Ballistic Wind Range Partial

Altitude Range, ft	Mid-Altitude, ft	Weighting Factor(W)
0 to 300	150	0.6605
300 to 600	450	0.1706
600 to 1,000	800	0.0747
1,000 to 2,000	1,500	0.0596
2,000 to 5,000	3,500	0.0365
5,000 to 10,000	7,500	0.0060
10,000 to 15,000	12,500	-0.0080
15,000 to 20,000	17,500	0.0000
20,000 to 30,000	25,000	0.0000

D, Down Range Matrix, nm							
ψ/VW	0	3	6	9	12	15	20
0.00	0.000	-0.0960	-0.2870	-0.5600	-0.9280	-1.3840	-2.1040
30.00	0.000	-0.1000	-0.3010	-0.5780	-0.9330	-1.3700	-2.1090
60.00	0.000	-0.1080	-0.3490	-0.6630	-1.0240	-1.4270	-2.1740
80.00	0.000	-0.1130	-0.3970	-0.7800	-1.2040	-1.6390	-2.3680
90.00	0.000	-0.1140	-0.4230	-0.8560	-1.3400	-1.8250	-2.5870
110.00	0.000	-0.1080	-0.4660	-1.0300	-1.7010	-2.3770	-3.3600
120.00	0.000	-0.1010	-0.4750	-1.1160	-1.9210	-2.7490	-3.9310
135.00	0.000	-0.0860	-0.4680	-1.2190	-2.2790	-3.4360	-5.0480
150.00	0.000	-0.0700	-0.4340	-1.2670	-2.6350	-4.2770	-7.2150
165.00	0.000	-0.0560	-0.3920	-1.2480	-2.9010	-5.1860	-7.7150
180.00	0.000	-0.0510	-0.3730	-1.2220	-2.9850	-5.6820	-8.9670

C, Cross Range Matrix, nm							
ψ/VW	0	3	6	9	12	15	20
0.00	0.000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
30.00	0.000	0.4450	0.7420	0.9290	1.0250	1.0420	0.9680
60.00	0.000	0.8210	1.4310	1.8500	2.1060	2.2190	2.1310
80.00	0.000	0.9930	1.8120	2.4210	2.8290	3.0580	3.0900
90.00	0.000	1.0440	1.9610	2.6750	3.1700	3.4670	3.5860
110.00	0.000	1.0570	2.1250	3.0580	3.7570	4.2010	4.4690
120.00	0.000	1.0100	2.1150	3.1510	3.9630	4.4870	4.8020
135.00	0.000	0.8690	1.9390	3.0810	4.0660	4.7130	5.0460
150.00	0.000	0.6410	1.5220	2.6130	3.6990	4.4450	4.6960
165.00	0.000	0.3410	0.8490	1.5710	2.4370	3.0880	3.1450
180.00	0.000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Table 5 (Cont'd) Ballistic Wind Weighting Factors and Ballistic Wind Range Partial

VW = Measured wind speed at the mid-altitude values listed above, ft/sec
AZW = Measured wind azimuth at the mid-altitude values listed above, deg
W = Weighting factor listed above
CRD = Cross range dispersion, positive right of nominal track.
DRD = Down-range dispersion, positive greater than no-wind range.

$$BCW = \sum VW * W * \sin(AZW-245), \text{ ft/s} \qquad BHW = \sum VW * W * \cos(AZW-245), \text{ ft/s}$$

$$BW = \text{Sqrt}(BCW^2 + BHW^2) \qquad \psi = \sin^{-1}(BCW/BW).$$

$$CRD = C(BW, \psi), \text{ nm} \qquad DRD = D(BW, \psi), \text{ nm}$$

Table 6. Aerodynamic Loads at Time of Flight = 21.0 Sec.

Aerodynamic Parameter	Without Gusts (Lbs)	With Gusts (Lbs)
Fwd Body, Normal Force	4.3	24.9
Fwd Body, Axial Force	53.3	53.3
Aft Body, Normal Force	8.7	45.1
Fin, Normal Force (2 Fins)	27.8	144.8
Fin, Axial Force (4 Fins)	30.4	35.2
Angle Of Attack (deg)	.45	2.26

See Reference 26 for additional details.

TABLE 7 - ASTRID I Vehicle Structural Margins of Safety

Item	Without Wind Gust Loading	With Wind Gust Loading
Forward Skirt	26.2	26.2
Forward Bolted Flange	1.9	1.1
Forward Flange Bolts	149	138
Fuel Tank	2.8	2.4
Aft Flange Bolts	40.5	6.9
Aft Bolted Flange	4.0	0.1
Aft Skirt	3.6	1.1
Thrust Plate	1.9	1.1

FIG. 1. ASTRID-1 LAUNCH VEHICLE

1 of 3 20' TV tower sections
concrete blocks.

Launch rate
W = 600 lbs-1

FIG. 3. REAR VIEW OF ASTRID VEHICLE

FIG. 4. ASTRID-1 VEHICLE AXIAL FORCE CONTRIBUTIONS

FIG. 5. ASTRID-1 FLIGHT-BASELINE TRAJECTORY

FIG. 6. ALTITUDE vs RANGE
ASTRID BASELINE TRAJECTORY

FIG. 7. ASTRID BASELINE TRAJECTORY GROUND TRACK

FIG. 8. MACH NUMBER vs TIME
ASTRID BASELINE TRAJECTORY

1/29/94,MVT7.DRW

**FIG. 9. DYNAMIC PRESSURE vs TIME
ASTRID BASELINE TRAJECTORY**

**FIG. 10. AERODYNAMIC FREQUENCY AND SPIN RATE vs TIME
ASTRID BASELINE TRAJECTORY**

**FIG. 11. ANGLE OF ATTACK & YAW ANGLE vs TIME
ASTRID BASELINE TRAJECTORY**

**FIG. 12. FLIGHT PATH ANGLE vs TIME
ASTRID BASELINE TRAJECTORY**

1/29/94,FPAVT7.DRW

FIG. 13. RANGE vs TIME
ASTRID BASELINE TRAJECTORY

**FIG. 14. ALTITUDE vs TIME
ASTRID BASELINE TRAJECTORY**

1/29/94,ZVT7.DRW

**FIG. 15. AXIAL ACCELERATION vs TIME
ASTRID BASELINE TRAJECTORY**

1/29/94, GEEV17.DRW

**FIG. 16. EFFECT OF RAIL ELEVATION ANGLE
ON ASTRID-1 TRAJECTORY.**

FIG. 17. VANDENBERG AFB MEAN NOVEMBER WIND SPEED

FIG. 18. IMPACT POINTS OF ASTRID-1 DISPERSIONS

FIG. 19. ASTRID-1 DISPERSION FOOTPRINT.

± 90 deg Nov VAFB Winds-0.70 nm Dispersions.

FIG. 20. BALLISTIC WIND PREDICTIONS vs 6DOF RESULTS

Mean November VAFB Winds

V3
L40
C1

Figure 21 - Finite Element Wire Frame Representation of ASTRID I Vehicle

V3
L40
C1

Output Set: Mode 2 46.54978 Hz
Deformed(0.1): Total Translation

Figure 25 - First Computed Body Bending Mode Shape for ASTRID I Vehicle

V3
L40
C1

Output Set: Mode 4 80.31504 Hz
Deformed(0.178): Total Translation

Figure 26 - First Computed Fin Bending Mode Shape for ASTRID I Vehicle

The Johns Hopkins University

Applied Physics Laboratory
Laurel, Maryland 20723-6099

**Appendix. Nominal Trajectory Data, Position and Velocity Components,
Altitude, Velocity, Ground Range, and Flight Path Angle vs Time.
Nominal Sea Level Thrust = 90 lbs.**

Range reference coordinate system, Ref. 1, WSMCR 127-1, para. 2.3.5, p2-6

Time(s)	X(ft)	Y(ft)	Z(ft)	X-dot(f/s)	Y-dot(f/s)	Z-dot(f/s)
Alt(ft)	Vel(ft/s)	FPA,deg	RN,nm			
1.627						
1.51	-0.01	65.66	12.8878	-0.0013	73.0765	
65.66	74.20	80.00	0.00			
2.000						
5.43	0.09	95.90	17.8925	0.0026	89.7688	
96.04	91.53	78.73	0.00			
3.000						
31.75	-0.17	206.71	35.3603	-0.1193	133.9513	
207.97	138.54	75.21	0.01			
4.000						
77.74	0.27	363.55	57.5148	-0.0547	177.1084	
363.60	186.21	72.01	0.01			
5.000						
148.32	-0.19	560.99	83.4513	-0.0932	218.8743	
561.73	234.24	69.13	0.02			
6.000						
246.10	0.15	800.14	112.7210	-0.0763	258.8679	
800.77	282.34	66.47	0.04			
7.000						
374.45	0.59	1078.71	144.8740	-0.0398	296.7345	
1078.77	330.21	63.98	0.06			
8.000						
536.43	0.25	1392.70	179.3908	0.0123	332.2061	
1393.46	377.55	61.63	0.09			
9.000						
734.34	0.66	1741.53	215.9087	-0.0217	365.0353	
1742.33	424.11	59.40	0.12			
10.000						
968.58	0.15	2122.36	253.9914	0.0547	395.0378	
2122.60	469.64	57.26	0.16			
11.000						
1242.03	0.65	2530.91	293.3158	0.0949	422.0370	
2531.41	513.96	55.20	0.20			

The Johns Hopkins University
Applied Physics Laboratory
Laurel, Maryland 20723-6099

12.000					
1555.72	-0.06	2965.48	333.4954	0.1129	446.0089
2965.72	556.91	53.22	0.26		
13.000					
1909.22	-0.29	3421.82	374.1897	0.1457	466.8825
3422.46	598.33	51.29	0.31		
14.000					
2304.62	-0.09	3897.78	415.1368	0.0907	484.5754
3898.47	638.08	49.42	0.38		
15.000					
2740.17	-0.58	4390.25	456.1371	0.1817	499.0955
4390.62	676.13	47.58	0.45		
16.000					
3216.66	-0.70	4894.85	496.8866	0.1115	510.5936
4895.80	712.46	45.79	0.53		
17.000					
3733.80	-0.63	5409.88	537.2258	0.1174	519.1595
5411.00	747.09	44.03	0.61		
18.000					
4290.98	-0.74	5931.92	577.1196	0.1255	524.8502
5933.32	780.09	42.30	0.71		
19.000					
4888.15	-0.53	6458.59	616.4401	0.1181	527.7930
6459.99	811.52	40.58	0.80		
20.000					
5523.54	-1.14	6986.76	655.0634	0.2173	528.1415
6988.35	841.46	38.89	0.91		
21.000					
6197.66	-1.23	7515.02	692.8291	0.1648	526.1794
7515.90	869.99	37.23	1.02		
22.000					
6907.79	-1.57	8037.44	726.3763	0.1981	519.0738
8039.34	892.78	35.57	1.14		
23.000					
7647.50	-1.44	8550.98	753.5211	0.0879	506.3907
8552.73	907.87	33.92	1.26		
24.000					
8413.18	-1.70	9049.28	776.6540	0.2240	489.8083
9051.34	918.21	32.26	1.38		

The Johns Hopkins University

Applied Physics Laboratory
Laurel, Maryland 20723-6099

25.000					
9200.55	-2.20	9529.55	797.2074	0.1319	470.5933
9532.08	925.74	30.58	1.51		
26.000					
10006.80	-1.84	9990.41	815.8790	0.0420	449.7841
9992.78	931.64	28.89	1.65		
27.000					
10831.42	-2.38	10428.60	833.2755	0.1624	427.4597
10431.87	936.52	27.19	1.78		
28.000					
11673.06	-1.78	10844.14	849.6684	0.1503	403.8114
10848.05	940.74	25.45	1.92		
29.000					
12531.25	-2.30	11236.17	865.0671	-0.0009	379.2734
11240.23	944.56	23.71	2.06		
30.000					
13403.44	-2.16	11602.59	879.5831	0.0125	353.9416
11607.44	948.12	21.96	2.20		
31.000					
14289.71	-2.78	11943.54	893.2953	0.1323	327.6304
11948.81	951.49	20.18	2.35		
32.000					
15189.31	-2.18	12257.76	906.1756	0.1091	300.4356
12263.54	954.68	18.38	2.50		
33.000					
16101.78	-2.63	12544.40	918.1069	-0.0314	272.6174
12550.88	957.73	16.58	2.65		
34.000					
17025.21	-2.92	12802.48	929.0280	-0.0864	244.2621
12810.14	960.60	14.78	2.80		
35.000					
17959.25	-2.30	13032.57	937.7145	-0.0023	214.9417
13040.51	962.03	12.96	2.95		
36.000					
18900.62	-1.94	13232.45	944.9150	0.0926	184.8735
13241.22	962.83	11.12	3.11		
37.000					
19848.42	-1.93	13401.68	951.0666	0.0553	154.3466
13411.76	963.51	9.27	3.26		

The Johns Hopkins University
Applied Physics Laboratory
Laurel, Maryland 20723-6099

38.000					
20802.39	-2.93	13540.98	956.2020	-0.0651	123.5672
13551.76	964.15	7.42	3.42		
38.935					
21697.94	-2.50	13642.96	960.0569	-0.0283	94.7528
13654.75	964.72	5.70	3.57		
38.935					
21697.94	-2.50	13642.96	960.0569	-0.0283	94.7528
13654.75	964.72	5.70	3.57		
39.000					
21760.53	-2.34	13649.25	949.4655	-0.1322	91.5843
13660.87	953.87	5.57	3.58		
40.000					
22648.87	-2.35	13719.42	841.8599	0.0421	51.3349
13732.41	843.43	3.55	3.73		
41.000					
23455.28	-2.17	13753.62	771.5521	-0.0294	16.8477
13767.07	771.73	1.32	3.86		
42.000					
24196.45	-2.57	13754.23	712.5311	0.0165	-14.8014
13768.66	712.68	-1.12	3.98		
43.000					
24882.91	-2.52	13724.55	662.1086	0.0644	-44.2917
13739.73	663.58	-3.76	4.09		
44.000					
25522.85	-2.04	13666.08	618.3728	0.0206	-71.8204
13682.31	622.53	-6.56	4.20		
45.000					
26120.86	-2.03	13581.02	579.9183	0.0557	-98.0186
13598.02	588.15	-9.52	4.30		
46.000					
26684.21	-2.61	13470.44	545.7183	0.1313	-122.8769
13488.22	559.38	-12.62	4.39		
47.000					
27214.36	-2.83	13335.75	514.9652	0.1753	-146.6294
13354.09	535.43	-15.82	4.48		
48.000					
27714.37	-3.14	13177.63	487.0060	0.2004	-169.3931
13196.69	515.62	-19.10	4.56		

The Johns Hopkins University

Applied Physics Laboratory
Laurel, Maryland 20723-6099

49.000					
28188.75	-3.03	12998.16	461.3392	0.2088	-191.2074
13016.98	499.39	-22.44	4.64		
50.000					
28638.45	-3.34	12795.50	437.5971	0.2219	-212.1099
12815.88	486.30	-25.78	4.71		
51.000					
29064.97	-3.58	12573.44	415.4977	0.2684	-232.1294
12594.27	475.95	-29.11	4.78		
52.000					
29469.56	-4.42	12331.84	394.7599	0.3520	-251.3267
12353.01	467.98	-32.40	4.85		
53.000					
29853.93	-4.24	12071.40	375.1808	0.3811	-269.7168
12092.96	462.07	-35.63	4.91		
54.000					
30220.33	-4.99	11792.52	356.6658	0.3651	-287.1872
11814.99	457.91	-38.76	4.97		
55.000					
30567.73	-4.44	11496.90	339.0694	0.4290	-303.7511
11519.94	455.23	-41.77	5.03		
56.000					
30898.45	-5.94	11185.09	322.2167	0.5013	-319.5027
11208.71	453.77	-44.67	5.08		
57.000					
31212.62	-6.51	10858.51	306.1055	0.4865	-334.3401
10882.20	453.30	-47.44	5.13		
58.000					
31511.48	-6.77	10517.00	290.6971	0.5180	-348.2182
10541.29	453.60	-50.06	5.18		
59.000					
31794.43	-6.67	10161.85	275.8341	0.6010	-361.2258
10186.91	454.50	-52.55	5.23		
60.000					
32063.13	-8.04	9794.74	261.5287	0.5956	-373.3276
9819.98	455.81	-54.90	5.27		
61.000					
32317.39	-8.10	9415.38	247.8392	0.5911	-384.4594
9441.41	457.42	-57.10	5.32		

The Johns Hopkins University

Applied Physics Laboratory
Laurel, Maryland 20723-6099

62.000					
32558.60	-9.36	9026.18	234.6415	0.6830	-394.7122
9052.11	459.19	-59.18	5.36		
63.000					
32786.91	-9.76	8626.28	221.8819	0.7061	-404.1062
8652.98	461.02	-61.14	5.39		
64.000					
33002.39	-9.78	8218.09	209.6860	0.6756	-412.5979
8244.91	462.82	-62.97	5.43		
65.000					
33206.38	-11.46	7801.59	197.9930	0.7194	-420.2151
7828.76	464.53	-64.68	5.46		
66.000					
33398.99	-11.81	7378.20	186.7166	0.7809	-427.0489
7405.35	466.08	-66.29	5.49		
67.000					
33580.32	-12.23	6948.07	175.8908	0.7792	-433.0966
6975.51	467.45	-67.81	5.52		
68.000					
33751.02	-13.29	6512.31	165.5907	0.7524	-438.3679
6540.00	468.60	-69.21	5.55		
69.000					
33911.66	-14.14	6071.91	155.7540	0.8097	-442.9160
6099.56	469.50	-70.53	5.58		
70.000					
34062.22	-14.78	5626.89	146.3009	0.8561	-446.8079
5654.88	470.15	-71.78	5.60		
71.000					
34204.27	-15.66	5178.76	137.2792	0.8404	-450.0639
5206.63	470.54	-72.94	5.63		
72.000					
34337.15	-16.24	4726.42	128.7621	0.8167	-452.7091
4755.42	470.66	-74.03	5.65		
73.000					
34461.58	-17.54	4273.38	120.6701	0.8662	-454.7908
4301.83	470.53	-75.05	5.67		
74.000					
34578.65	-18.32	3816.96	112.9214	0.9101	-456.3917
3846.38	470.15	-76.01	5.69		

The Johns Hopkins University

Applied Physics Laboratory
Laurel, Maryland 20723-6099

75.000					
34687.82	-18.98	3360.84	105.5723	0.8866	-457.5050
3389.59	469.53	-76.91	5.71		
76.000					
34790.29	-19.68	2902.46	98.6748	0.8540	-458.1813
2931.88	468.68	-77.75	5.72		
77.000					
34885.21	-21.01	2443.80	92.1650	0.8981	-458.4525
2473.70	467.62	-78.54	5.74		
78.000					
34974.29	-21.34	1985.56	85.9400	0.9393	-458.3795
2015.40	466.37	-79.28	5.76		
79.000					
35057.07	-22.94	1526.90	80.0816	0.8987	-458.0156
1557.32	464.96	-79.99	5.77		
80.000					
35134.67	-24.11	1069.77	74.6423	0.8785	-457.3532
1099.75	463.40	-80.63	5.78		
81.000					
35206.44	-24.30	613.08	69.5039	0.9269	-456.4363
642.96	461.70	-81.25	5.79		
82.000					
35273.71	-25.54	156.78	64.5989	0.9463	-455.3107
187.17	459.88	-81.83	5.81		
82.415					
35299.79	-25.91	-31.66	62.6715	0.8887	-454.7879
-1.63	459.08	-82.06	5.81

Figure 22 - Stress Contour Plot of ASTRID I Vehicle for Worst Case Flight Conditions
(without wind gust loading)

Figure 23 - Stress Contour Plot of ASTRID I Vehicle for Worst Case Flight Conditions
(with wind gust loading)

**DATE
FILMED**

8/18/94

END