

Deep Dive of Reentry F Nose Tip Step and Gap

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Preface or Abstract:

This white paper provides an in-depth review of all available documents providing details of the Reentry F (flown in 1968) nose tip step and gap. The goal of this effort is to suggest possible follow up analysis that might further improve the credibility of this existing high Mach number boundary layer transition dataset. English units are used throughout for consistency with the historical literature.

Introduction:

The Reentry F Turbulent Heating Experiment was a successful basic science flight research program flown out of NASA Wallops on April 27, 1968. The purpose of the flight was to obtain measurements of fully turbulent convective heating and to determine the transition Reynolds number at conditions representative of reentry systems. The vehicle geometry, shown in Fig. 1, was a slender 5° half-angle cone that was 13 feet long with a relatively sharp ablatively cooled nose-tip. The primary measurement surface was beryllium calorimeter with surface mounted thermocouples. The payload weight was 600 lbs. The nose tip was an ATJ graphite shell that had an initial nose tip radius of 0.1 inch that would ablatively recess during entry. The graphite nose tip covered the first 8.5 in of the spacecraft. This flight project was part of the Scout program, utilizing a three-stage launch vehicle to provide reentry conditions near Mach 20. The general mission profile is shown in Fig. 2, indicating that the third stage provides additional entry velocity during the descent phase of a ballistic trajectory. The test window during reentry was from an altitude of approximately 100,000 ft to 60,000 ft, providing freestream unit Reynolds numbers from 2 million/ft to 16 million/ft with total enthalpy conditions of around 7500 BTU/lbm. The wall to total temperature ratio was approximately 0.1. The vehicle angle of attack was small, generally less than 1°. This flight experiment was commissioned by NASA Langley Research Center, under the NASA Contract No. NAS 1-6039 (June 1966 start date) to the General Electric Company, Missile and Space Division, Reentry Systems Department. NASA Wallops was involved as the launch facility and Ling-Temco-Vought (LTV) Corporation as the launch vehicle contractor. Within NASA Langley, the program was being managed by the Applied Materials and Physics Division. Note that initially this program was considered a classified program but was declassified in 1976 and is now considered as strictly CUI information, although some details have been published in the open. This dataset has been widely used by the aerothermodynamic community as a classic high Mach boundary layer transition case study.



Fig. 1. Photo of assembled vehicle.

[<https://ntrs.nasa.gov/citations/20250007312>]

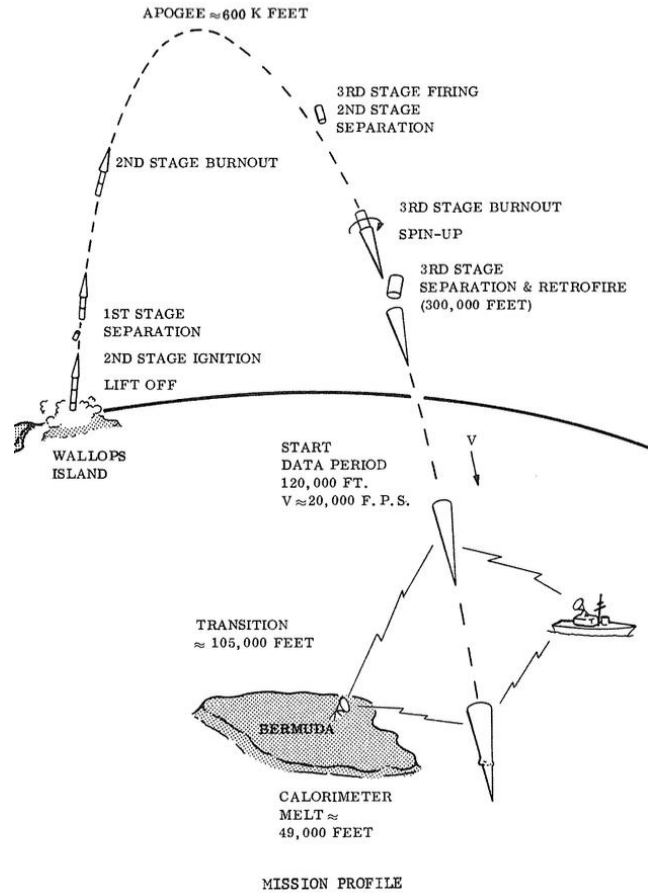


Fig. 2. Reentry F mission profile.

[NASA CR-66501]

Preflight Design Details

Most design details were captured in a series of preflight contractor reports generated by GE Reentry Systems, see Table 1. Two relevant documents capture in red font were heavily referenced in many documents, but thus far have not been found and reviewed. These two reports could provide important details regarding the nose tip step and gap.

Table 1. Preflight reports providing design details.

Report #	Title	Date
NASA CR-66501	Reentry F Turbulent Heat Experiment Familiarization Manual	30 Oct 1967
NASA CR-153731	Reentry F Turbulent Heat Experiment Quarterly Technical Progress Report #2	15 Jan 1967
NASA CR-154044	Reentry F Spacecraft Structural Mechanics Stage 4 Release	8 Sept 1967
NASA CR-154364	Reentry F Stage 3 Materials Release	7 Apr 1967
NASA CR-154469	Stage 3 Aerodynamics – Reentry F	23 Jan 1967
	Thermodynamics Stage II Release - Reentry F	22 Nov 1966
	Reentry F Nose Tip Malta Tests, Results and Evaluation	Aug 1967
NASA LWP-460	The Results of Several Ablation Tests of Full-Scale Models of the Reentry F Nose Tip	20 Jul 1967

Some key details of the Reentry F nose tip can be provided as a general introduction. The nose tip was an ablatively cooled ATJ Graphite cone that was 8.5 inches long with an initial nose radius of 0.1 in. At the joint location between the nose and body, a step and gap were prescribed to allow for thermal growth and surface recession. An 0.040-inch rearward facing step with a gap of 0.1 in. was selected based on preflight analysis. The following in-depth review of the preflight documents will shed some light on why these values were chosen for the step and gap.

NASA CR-153731 was the quarterly technical progress report, which indicated that BL trips were considered for a while as part of this flight experiment. The trips, which were to be imbedded in the graphite nose tip and would be exposed as the graphite recessed, were based on the work of P. Calvin Stainback of NASA Langley. In the end, the project decided against trying to include the BL trips. “Interference effects between the trip and nose surface and uncertainties in the ablation performance of a protruding trip are the primary contributors.” Regarding the thermal analysis of the graphite nose: “The nose tip design has been summarized in a preliminary document, PIR HTT-8151-666 [*Vehicle Nose Tip Thermodynamic Report*]. The nose tip thermal analysis reported in the Thermodynamics Stage II Release, TTFM- 8151-052 has been updated and the temperature profiles presented. The analysis methods used in the nose tip design are outlined. The results of the analysis show that the 2.5- inch overhang, 0.1-inch nose radius baseline design is thermally adequate.” [*Copies of the two reports above have not been located.*]

NASA CR 154044 was the structural mechanics report that provided the structural analysis of the Reentry F spacecraft, including structural design loads, environments, and stress analysis. “The nose tip analysis includes new data obtained from a static load test of the ATJ plug load capability for axial compression. In addition, the reader is referred to Reference 38, which describes the evaluation of the Malta test of the Re-entry F nose tip.” Later, in discussing the nose design temperatures: “The nose temperature distributions were taken from Reference 19 (Figures 4.1.1 thru 4.1.5) and unpublished data provided by Thermodynamics. These temperature distributions are shown in Figure 50.” Fig. 50 provides temperature distributions for three entry altitudes (or three levels of nose tip recession from 0.5” to ~1.0”). The initial discussion of the nose tip describes the primary areas of concerns and steps required for final assembly. The five issues that this report addressed are (1) concerns related to assembly, specifically thermal stresses that might exist during bonding cure cycles, (2) flight loads, (3) differential thermal expansion during reentry, (4) shell thermal stresses, and (5) the nose tip gap and concentricity. Each of these issues were discussed. The analysis of the nose tip gap indicated a primary concern of the linear expansion of the ATJ graphite would account for more than half the 0.1” preflight gap. No contact was allowed between the nose tip and main frustrum.

References

19. Hecht and Hann, "Thermodynamics Stage II Release - Re-entry F", PIR TTFM 8151-052 of November 22, 1966.
38. "Re-entry F Nose Tip Malta Tests, Results and Evaluation", Document No. 67SD989 of August 1967.

[*Copies of these two references have not been found.*]

Nose Gap/Step Analysis within NASA CR-154044

The Reentry F nose tip was designed knowing that the ATJ graphite shell would experience extreme conditions, thus the shell had to minimize any stress concentration points. The shell did not have any attachment points or cut-outs to minimize “stress raisers.” The shell was bonded in place knowing that the bond could release during reentry and thus was likely to be “a free-standing shell without mechanical restraint.” The nose tip assembly (see Fig. 3) “consists of an ATJ graphite conical shell, a porous carbon insulator inner shell, and a tungsten alloy insert. The bond between the ATJ graphite skirt and the porous carbon is C-10 and the bond between the porous carbon and the tungsten alloy insert is PD162A.”

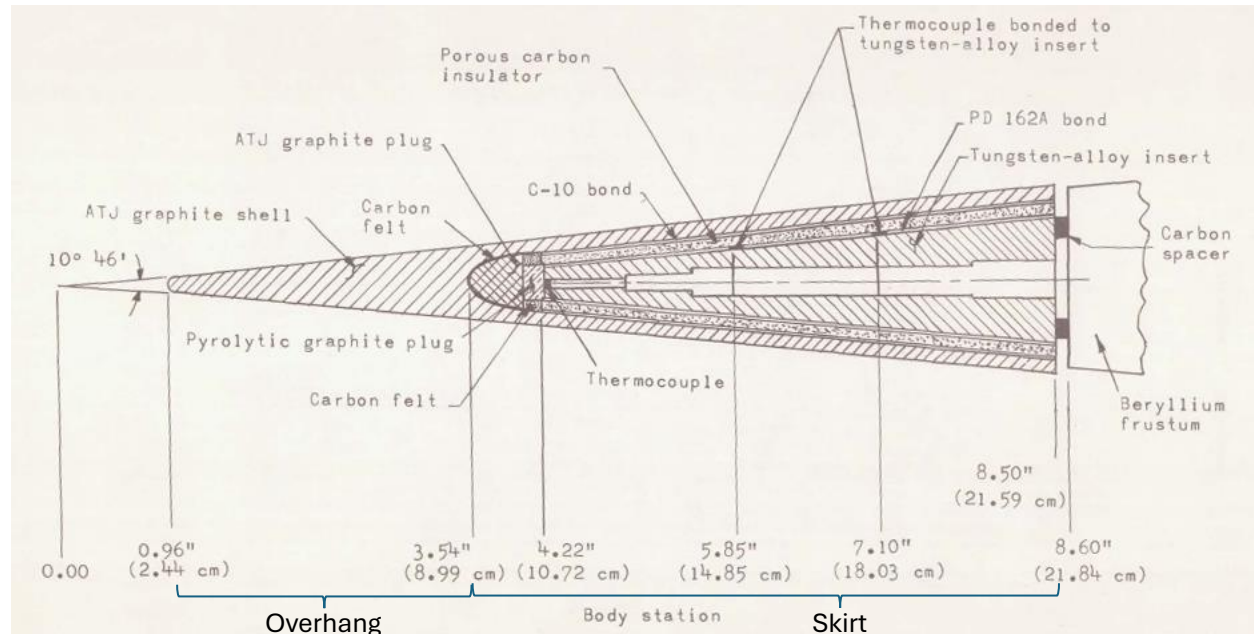


Figure 3. Nose-tip assembly. [NASA TM X-1856]

The following summation provides the recommended minimum preflight gap between the nose tip and the frustum $\Delta_F = \Delta_0 - \Delta_{ATJ} - \Delta_{GF} + \Delta_W$

The initial gap was preselected as $\Delta_0 = 0.1$ "

The thermal growth of the ATJ graphite nose tip shell was calculated using an unspecified CTE value at the assumed surface temperature near end of mission of 3260°F for the skirt length only. The skirt is the only portion that would grow backwards based on the internal graphite plug being the anchor point. $\Delta_{ATJ} = (4.96 \text{ in}) \times (3.4 \times 10^{-6} / ^\circ\text{F}) \times (3260^\circ\text{F}) = 0.054 \text{ in}$. The unverified value of CTE ($3.4 \times 10^{-6} / ^\circ\text{F}$) can only be assumed to be correct.

The graphite felt (GF) is designed to be compressed to a thickness of 0.020" (originally 0.040" \pm 0.020" thick, pg. 6-1). For the minimum gap analysis, it was assumed that this was fully compressed (see Fig. 4), or $\Delta_{GF} = 0.020 \pm 0.014 / 0.004 = 0.034 \text{ in}$

The tungsten washer (W) was assessed for thermal growth based on the following values (taken at face value): $\Delta_W = (8.5 - 4.05) \times (2.4 \times 10^{-6}) \times (590 - 70^\circ\text{F}) = 0.0055 \text{ in}$

The final summation of the minimum gap clearance at the end of the mission was thus

$$\Delta_F = 0.1 - 0.0545 - 0.034 + 0.0055 = 0.017$$

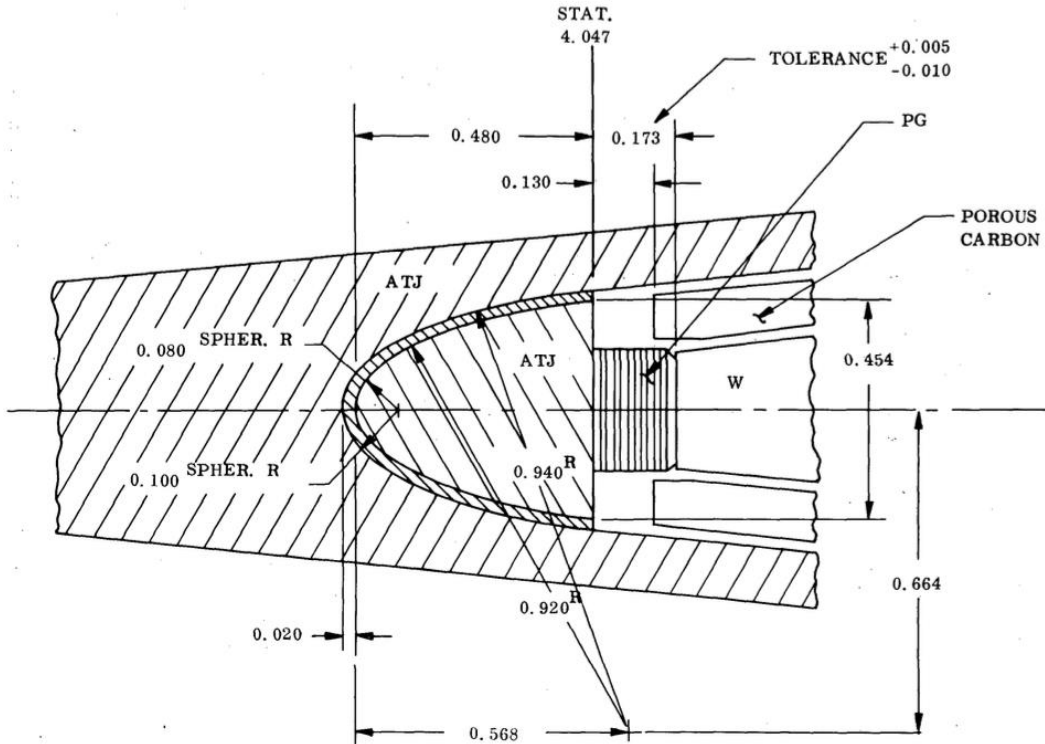


Figure 4. Details showing internal nose tip assembly. [NASA CR-154044]

For the preflight step analysis, the primary concern was the free-standing graphite shell being forced eccentric due to aerodynamic forces after bond failure. A similar summation of deltas to the initial step at station 8.5 to determine the minimum case to insure there would be no forward-facing step at any point. The radius of the ATJ graphite shell at station 8.5 was 0.8025 ± 0.004 in. The radius of the beryllium at station 8.6 was 0.7525 ± 0.003 in. Thus, the minimum aft-facing step after assembly (accounting for assembly tolerances) would have been: $h_0 = (0.8025 - 0.004) - (0.7525 + 0.003) = 0.043$ in.

To account for beryllium thermal expansion: $\Delta h_1 = -(0.7525 + 0.003) \times (0.008) = -0.006$ in.

To account for ATJ graphite recession: $\Delta h_2 = -0.016$ in (assumed by analysis).

The PD162A bond is considered soft and pliable such that it can be forced eccentric under load. Thus: $\Delta h_3 = -0.020$ in (bond thickness). The summation of those deltas provides the minimum aft facing step under the worst of conditions.

$$h_{\min} = h_0 + \Delta h_1 + \Delta h_2 + \Delta h_3 = 0.043 - 0.006 - 0.016 - 0.020 = 0.001 \text{ in.}$$

The above summations provide the context by which the Reentry F nose tip gap and step were sized based on preflight assumptions. But what were the final dimensions after assembly, and what if the assumptions did not go according to plans? If the graphite felt did not further compress or the plug had some thermal growth, the gap could have been larger during flight than assumed. Based on information contained in the report, the plug could have thermally grown by as much as 0.011 in. That, factored with the graphite felt not further compressing, could have meant an additional 0.0456 in of axial extension of the gap, for a total gap size of 0.063 in. If the bond failure and aero forces did not contribute to eccentric behavior, and the recession rate on the skirt was less, the step similarly could

have been larger than assumed. Also, accounting for the maximum allowable step based on the hardware tolerances, it could have been as much as 0.053 inch initially. If one assumes no eccentricity, based on the aero loads acting equally on both sides of the shell, then the step could have been as large as 0.032 in during the measurement period. That is without assuming less recession on the skirt, which would make the step even larger. Figure 5 provides the preflight assessment of the nose tip thermal gradients and recession during reentry.

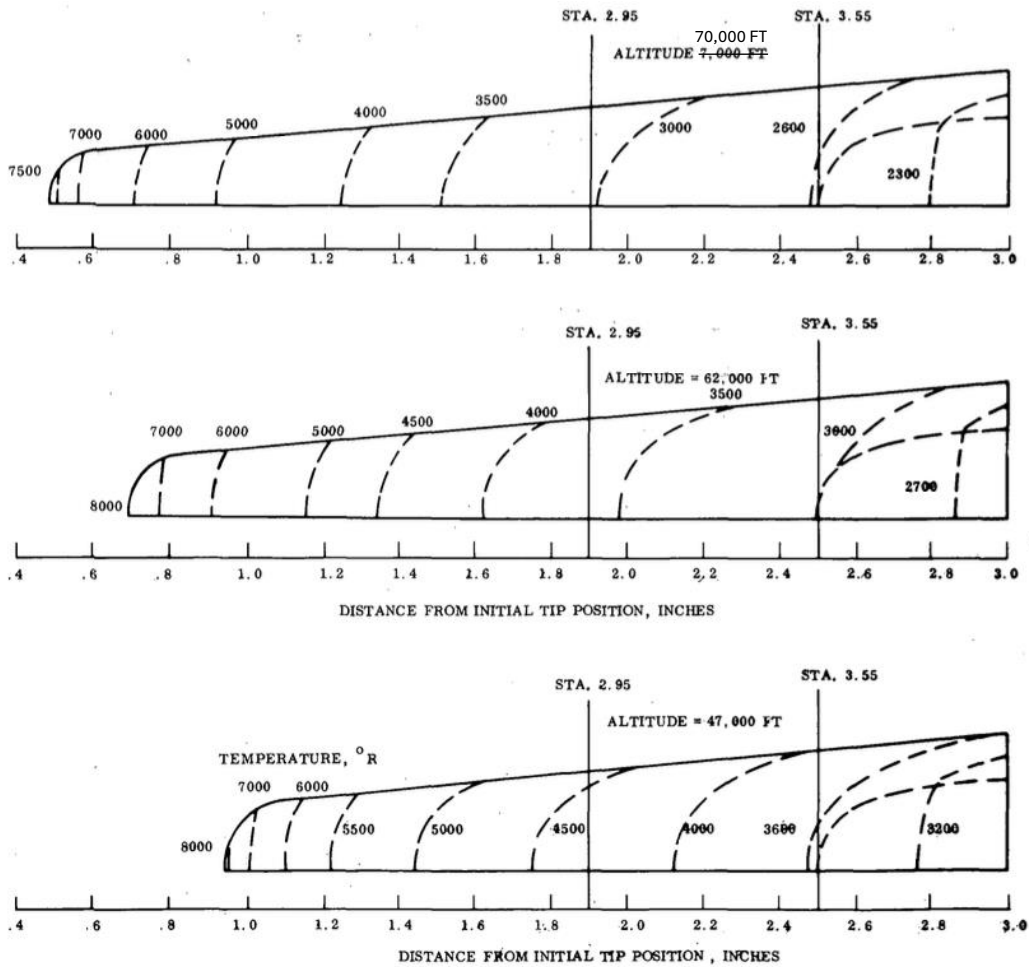


Figure 5. Predicted nose tip recession and thermal gradients. [NASA CR-154044]

This report included other comments regarding a preflight assessment of the step/gap. Page 6-2 discussed the aerodynamic loads to ensure the nose tip stays in place after failure of the bonds “due to thermal strains.” The “net axial compression load” on the nose tip was calculated to be 132 pounds during flight. The document also describes that a “belleville spring arrangement is used” to preload the nose tip assembly during the bonding process. “Twenty springs are compressed an amount 0.100 ± 0.030 to create a 0.890 inch total spring height and a resultant preload of 470 ± 175 pounds.” The preloading was used during bonding to compress the graphite felt that wrapped around the plug to a thickness of 0.020 inch (nominal thickness of 0.040 ± 0.020 inch). On page 6-15, it was mentioned that

“preliminary test data at room temperature indicates that 90% compression requires a compressive stress of about 250 psi.” Assuming that the surface area of the ogive plug was about 0.7 in² (based on the dimensions shown in Fig. 4), would suggest an axial load of around 174 lbf would be required for that amount of compression. Since actual loading during flight is only on the order of 132 pounds, then perhaps the graphite felt was able to maintain some thickness to resist closing the gap and preventing any tendency towards eccentric behavior. One other factor that seemed ignored in the preflight design documents is the fact the thermal growth on the skirt (near the joint) could have also contributed to an increase in the size of the rear facing step height. Using the same CTE value, thermal growth of shell in the cross-plane direction would be $\Delta_{ATJ} = (0.803 \text{ in}) \times (3.4 \times 10^{-6} / ^\circ\text{F}) \times (3260^\circ\text{F}) = 0.009 \text{ in}$, meaning the radius of the ATJ graphite shell at station 8.5 could have grown by as much as 0.009 in. Factoring the maximum assembly tolerance with cross plain thermal growth and less recession could imply a rear facing step as large as 0.051 in.

NASA CR 66501 is the “Reentry F Turbulent Heat Experiment Familiarization Manual” that was the contractor’s final compendium of all the design details. Figure 1-1 [Fig. 2 above] provides a nice overview of the mission profile and staging. The launch was on a three stage Scout, with the 3rd stage being used after apogee. All 3 stages were separated from the spacecraft. There were 4 versions of the spacecraft built as part of this effort, the first one being a developmental mockup, the second a prototype, the third the primary version for the initial flight, and a backup (for possible second flight). Some nose tip specs are listed, but “details of this design are discussed in Document SM-TM 8156-202 Reentry F Spacecraft Structural Mechanics Stage 3 Release dated March 17, 1967.” [This report is NASA CR-154044.] Some interesting quotes include “total recession of 0.77 inches at 49,000 Ft” with a “nose radius of 0.171” and “0.008 inches sidewall ablation average, and 0.005 inches recession at end of skirt.” Also, “the nose tip has a manufactured gap of 0.100 inches and a rearward facing step of 0.042 inches when attached to the P1 frustrum.”

Note that the graphite recession at the end of the skirt noted here is less than what was assumed in the structural mechanics report [NASA CR-154044], which could suggest the possibility of a larger rear facing step at the joint location.

NASA LWP-460 was also a preflight document that provided additional investigation of the graphite nose tip performance from three Langley facilities: the 11-Inch Ceramic-Heated Tunnel, the 20-Inch Hypersonic Arc-Heated Tunnel, and the High Enthalpy Arc Tunnel. The report summary provided the following insight:

Full-scale models of the ATJ nose tip of the Reentry "F" flight spacecraft were tested at four conditions in the ground test facilities of the Applied Materials and Physics Division. The objective of the tests was to measure and observe the ablative behavior of the stagnation point at graphite sublimation conditions and at the highest pressure available in AMPD facilities. Sublimation of the ATJ graphite was obtained at low pressures (0.27 and 0.59 atm.) and the measured recession rates agreed within ±15% of theory. The stagnation point retained a smooth but slightly blunted shape. At the higher pressure tests (6 to 15 atm.) there was the formation of

an irregular shape at the stagnation point which started to form between 6 to 10 atmospheres.

Additional insight was provided of the nominal preflight trajectory in the following figure.

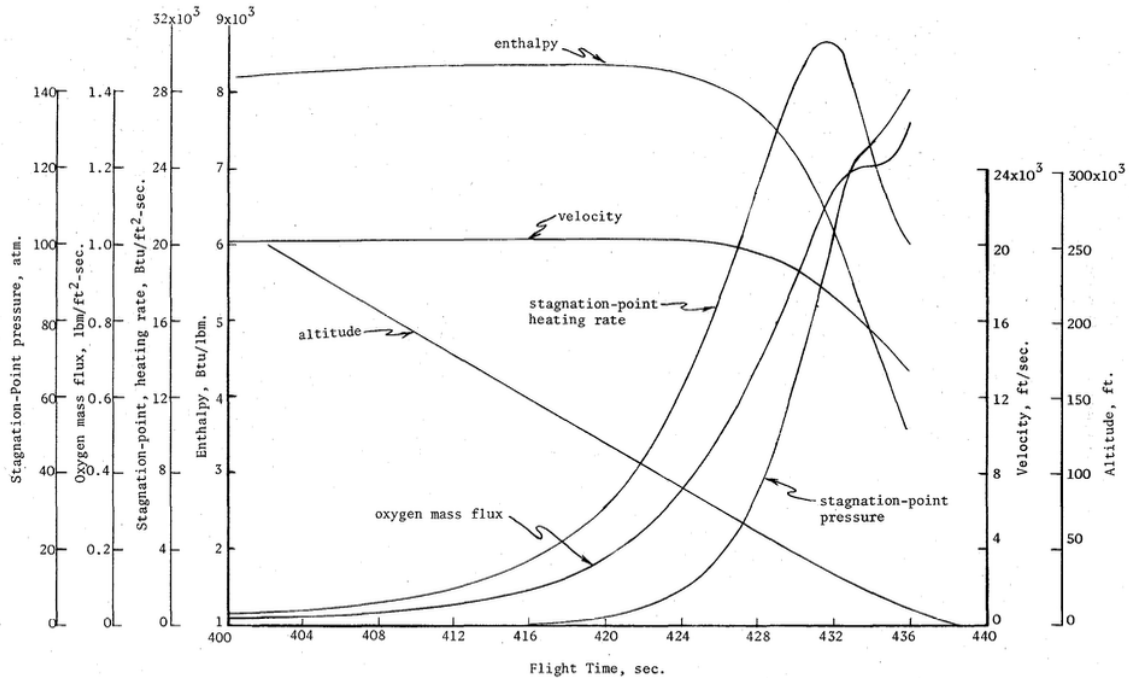


Figure 1.- Nominal Reentry "F" trajectory.
Reentry angle = 21.2°; Reentry velocity = 20,300 ft./sec.

Figure 6. Nominal preflight Reentry F trajectory. [NASA LWP-460]

This figure provides some of the environmental conditions that the graphite had to endure during the notional test window of altitudes from 100,00 to 50,000 ft while the vehicle was reentering with a velocity near to 20,00 ft/s and enthalpy of around 8000 BTU/lbm: stagnation point pressures from 5 to 60 atmospheres, stagnation point heating of 9000 to 28000 BTU/ft²s, and oxygen mass flux of 0.25 to 0.9 lbm/ft²s.

Postflight Analysis and Reporting

After the successful flight on April 27, 1968, several NASA postflight reports were published that went into various aspects of the flight data analysis. Initially, these reports were deemed confidential, but in 1975 all were retroactively declassified leading to some of the results also being shared openly in conference papers (although some details may still be considered as CUI/ITAR). The first AIAA paper was published in 1977 by Wright and Zoby (AIAA Paper 77-719), which has led to the wider aerothermodynamic community to consider this flight dataset for further analysis (which will be discussed in the next section). The following review of the material covered within these postflight reports is primarily focused on capturing any discussion relative to the performance of the nose tip and more specifically any information regarding the nose tip step and gap. For the most part, these reports considered the nose tip to have performed nominally (as designed) with the step and gap being functionally a non-factor. But based on the prior review of the preflight

documents, further consideration of the size of the nose joint step and gap may still be warranted.

Table 2. Postflight reports providing flight data and analysis.

Report #	Authors	Title	Date
NASA TM X-1856	Rumsey, Carter, Hastings, Raper, and Zoby	Initial Results from Flight Measurements of Turbulent Heat Transfer and Boundary Layer Transition at Local Mach Numbers near 15 (Reentry F)	Sept 1969
NASA TM X-2210	Dillon	Analysis of Surface Pressure on a 5° Cone in Free Flight near Mach 20 (Reentry F)	Feb 1971
NASA TM X-2250	Alley and Guillotte	Postflight Analysis of the thermal distortions of the Reentry F Spacecraft	May 1971
NASA TM X-2253	Wright and Zoby	Flight Measurements of Boundary Layer Transition on a 5° Half-Angle Cone at a Freestream Mach Number of 20 (Reentry F)	May 1971
NASA TM X-2282	Howard	Thermal Analysis Methods and Basic Heat Transfer Data for a Turbulent Heating Flight Experiment at Mach 20 (Reentry F)	May 1971
NASA TM X-2308	Carter, Raper, Hinson, and Morris	Basic Measurements From a Turbulent-Heating Flight Experiment on a 5° Half-Angle Cone at Mach 20 (Reentry F)	Sept 1971
NASA TM X-2335	Zoby and Rumsey	Analysis of Free-Flight Laminar, Transitional, and Turbulent Heat-Transfer Results at Free-Stream Mach Number Near 20 (Reentry F)	Sept 1971
NASA TM X-2468	Dillon and Carter	Analysis of Base Pressure and Base Heating on a 5° Half-Angle Conne in Free Flight near Mach 20 (Reentry F)	Jan 1972
NASA TM X-2560	Stainback, Johnson, Boney, and Wicker	A Comparison of Theoretical Predictions and Heat-Transfer Measurements of a Flight Experiment at Mach 20 (Reentry F)	Jul 1972
NASA TM X-2584	Johnson, Stainback, Wicker, and Boney	Boundary-Layer Edge Conditions and Transition Reynolds Number Data for a Flight Test at Mach 20 (Reentry F)	Jul 1972
NASA TN D-5948	Woodbury and Morris	Angle of Attack Analysis of a Spinning Slender Cone with Slight Aerodynamic and Mass Asymmetries (Reentry F)	Sept 1970

NASA TM X-1856 was the initial postflight report presenting heat transfer measurements made at 20 locations along the body. The following quote described considerations of the nose tip joint based on the preflight analysis:

“In designing the individual segments of the spacecraft structure (nose tip and seven frustums) it was necessary to take into account thermal stresses during reentry heating as well as the geometric tolerances associated with machining and assembling the various segments. These considerations led to the design of prescribed gaps and rearward facing steps at the surface between each segment. Between the nose tip and the first frustum (fig. 3) the measured gap was 0.100 inch (0.254 cm) and the rearward facing step was 0.050 inch (0.127 cm). Between each of the frustums, the measured gap was 0.003 inch (0.008 cm) and the rearward facing step was 0.010 inch (0.025 cm). Analyses based on experimental data showed that these designs had negligible effects on the heat transfer at the measurement stations. These analyses were actually conservative since the gaps

closed because of thermal expansion during heating and were expected to be completely closed in flight at an altitude of about 40 000 feet (12.19 km)."

Later this report had the following discussion about "nose-tip performance:"

The graphite nose tip, described previously and shown in figure 3 [same as Fig. 3 above], had predicted and estimated tip-radius-growth histories during entry as presented in figure 11. Curve 1, figure 11, is based on the results of a computer program in which recession of the stagnation point during entry was computed by analyses using the one-dimensional ablation program described in reference 3. For curve 1 surface recession was determined from consideration of only the thermochemical oxidation process with equilibrium assumed at the graphite surface. The tip radius, assuming hemispherical shape, was then determined for successive times by geometric relationships. However, recent ground tests have shown that mechanical erosion of the nose tip would be expected in the reentry environment for this spacecraft. Reference 4 has correlated the effects of pressure and enthalpy on graphite erosion and has been utilized to adjust curve 1 to curve 2 so that a more realistic prediction is obtained.

At an altitude of approximately 60 000 feet (18.29 km) an anomalous rise in the forward nose-tip thermocouple occurred and the nose-tip-radius history therefore became uncertain. Consequently a worst case radius history (curve 3, fig. 11) was somewhat arbitrarily constructed by assuming a monotonic radius increase beginning at the time in the trajectory where mechanical erosion is thought to begin and extending to a radius which exposes the graphite plug in the nose tip at the time of the rapid temperature increase. The effect of this radius history on the flow-field parameters and analysis of the thermal data are discussed subsequently. Further correlation of flight data provides convincing proof that curve 3 does not represent the actual case because exposure of the graphite plug at the indicated time (458.7 seconds) would have resulted in rapid nose-tip destruction which would have been apparent in the other nose-tip thermocouple data, the body motions, and the surface pressures.

Concurrent with the analysis of the thermal data, downstream surface pressure measurements have been utilized in an attempt to derive the effective hemispherical radius of the nose tip. In this analysis a pressure distribution for an assumed hemispherical nose radius was computed and matched as nearly as possible to the actual pressure measurements. It was necessary to take into account the angle-of-attack component presented in figure 9, an estimate of the additional local angle of attack due to thermal distortion, and an estimate of pressure variation due to local boundary-layer growth. Iterations were continued until a best match between measured and computed pressure distributions was obtained. It is significant to note that all measured pressures cannot presently be matched with a given radius and that an uncertainty in the final radius exists. The results of this analysis are presented in figure 11. The uncertainty in radius is indicated by the bar length. These computations are preliminary in that the final

analysis of the thermal distortion is not complete and the term α_0 has not been considered in the present work.

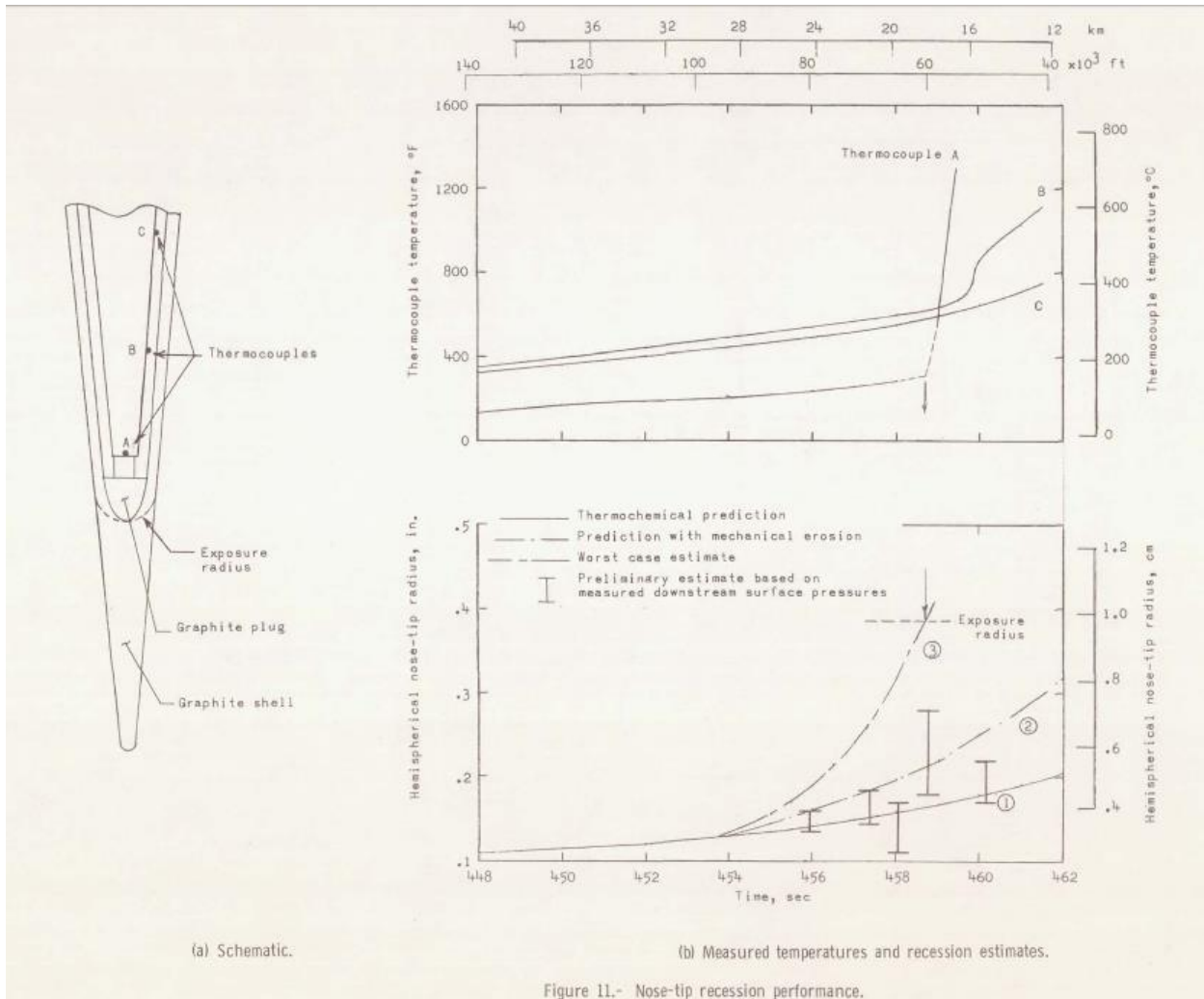


Figure 7. Postflight assessment of nose-tip performance. [NASA TM X-1856]

While the above discussion considers the state of the graphite shell, it does not provide any insight into any postflight assessment of the step and gap, other than the earlier suggestion that “all” the gaps had closed per design and expectations.

In the “results” section, there is a discussion of “angle-of-attack effects” where it is mentioned that “peak heating is estimated to be 2 ft (61.0 cm) farther forward on the secondary ray than on the primary ray at altitudes of 80,000 feet (24.38 km), 70,000 feet (21.34 km), and 65,000 feet (19.81 km) (figs. 13(b), 13(d), and 13(e), respectively), and 1.5 feet (45.7 cm) farther forward at 75,000 feet (22.86 km) (fig. 13(c)).” The primary ray was on the leeside and the secondary was windward. Thus, the flight data indicated that wind side transition was significantly ahead of transition on the leeside. Considering that the actual angle of attack during reentry is quite small (less than 1 deg), it could also be explained by

locked-in differences to the nose tip joint step and gap for the two sides. Or the influence of the step and gap on measurements at very small AoA (like BOLT 1b).

NASA TM X-2210 was focused on the surface pressure data but did note a different interpretation of the nose radius history as predicted by an ablation analysis. “As can be readily seen from figure 17, the nose radius history indicated from the analysis of measured pressure data was different from that predicted by the ablation analysis. This difference is not understood and the performance of the nose tip cannot presently be precisely defined from the limited onboard measurements pertinent to an analysis of the nose tip history. However, this analysis of the pressure data indicates that the postulated largest nose radii possible (upper curve of fig. 17) did not occur.” Could this difference (shown in Fig. 8 below) be explained by inclusion of steps and/or gaps in the flow field predictions?

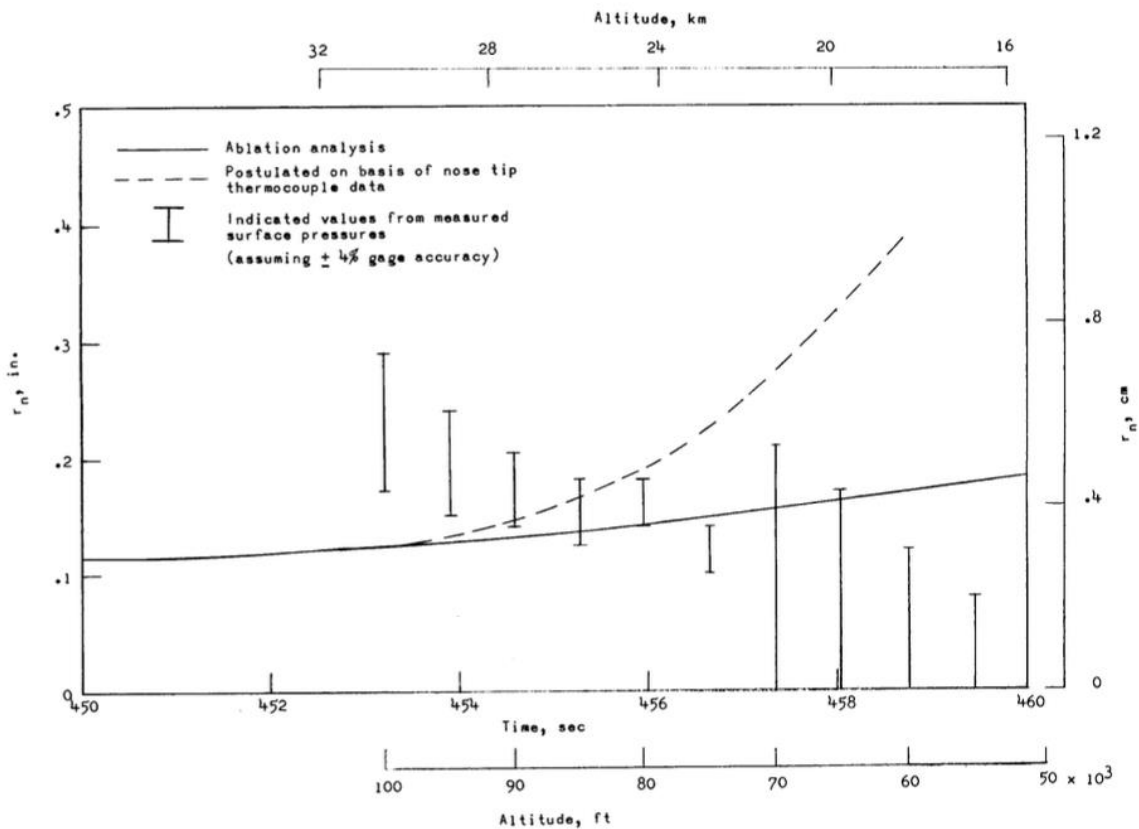


Figure 17.- Nose radius time history during reentry.

Figure 8. Nose radius history derived from pressure data [NASA TM X-2210].

NASA TM X-2250 provided an analysis of the thermal distortions “due to asymmetric heating of the Reentry F payload” resulting presumably from the slight vehicle angle of attack. It was concluded that “thermal deformation is considered to be a significant contributor to total angle of attack at lower altitudes and forward body stations and, doubtless, had an influence on the aerodynamic distributions of the body and reentry flight behavior.” Figure 7 of that report provides the effect of the calculated thermal distortions on the induced angle of attack. It was calculated that late in the flight, at a flight time of

461.4 seconds (just before vehicle failure), that the nose would have seen “an increase in the pitch angle of attack of 3.64° and a decrease of 0.808° in yaw” due to thermal heating. This effect was most pronounced at later times of flight, beyond $t=458s$ (or altitudes lower than 65,000 feet). For the times most important to the transition measurements, the thermal distortions were less significant (less than 1° influence on the nose tip AoA). Still, considering both rigid body alpha plus induced alpha due to thermal effects, perhaps the total AoA at times of importance are more than generally considered, which could be made worse with the steps and gaps that should also be factored in?

NASA TM X-2253 provided further review of the flight data specifically focused on the transition behavior. In speaking about “effect of angle of attack on transition” the following discussion is informative:

“For the Reentry F spacecraft, transition on the windward side (secondary ray) is observed to be continually farther forward than on the leeward side (primary ray). This result is contrary to most of the wind-tunnel transition data at angle of attack which shows that transition moves farther forward on the leeward side. Most of these tests did not provide data on combined angle of attack and blunting effects and some models were instrumented along only a single ray. However, the phenomena (transition farther forward on the windward ray at angle of attack) was found on a slightly blunted 7.2° half-angle cone at angles of attack of 1° and 2° (ref. 13), a slender 2.87° half-angle cone at an angle of attack of 2° (ref. 14), and a blunt 25° half-angle cone at an angle of attack of 5° (ref. 15).”

There was no additional discussion of the nose tip step and gap and there was only minor discussion of nose tip recession effects.

NASA TM X-2282 was more focused on the thermal analysis of the spacecraft and measurements of the main frustrum (beryllium) section. No other discussion of the nose tip and joint step or gap, other than to reference NASA CR-66501 for further details.

NASA TM X-2308 provided additional review of the flight to “compile in one volume the reentry data (with emphasis on the heating measurements) and complementary information required to analyze that data.” Although there was very little discussion of the nose tip step and gap, the following quotes do speak to “nose tip performance” largely consistent with previous reporting.

Starting on page 4: “The nose-tip assembly is shown in figure 4. To limit the bluntness effects of the nose tip on the reentry conical flow conditions, the initial nose-tip radius was 0.254 cm (0.10 in.). The nose was made oversize (1.07 mm (0.042 in.) in radius) at the rear end (station 21.8 cm (8.6 in.)) to allow for sidewall ablation. The gap at the graphite-beryllium joint (station 21.8 cm (8.6 in.)) was made fairly large (0.254 cm (0.10 in.)) to allow for rearward thermal expansion of the graphite outer shell during reentry and still maintain the longitudinal loads through the tungsten core. Design calculations indicated that this gap would close to about 0.254 mm (0.01 in.) during reentry at 12.19 km (40 000 ft) altitude.

The internal dimensions and shape of the ATJ graphite outer shell were determined primarily by the sensitivity of the graphite to temperature gradients. The porous carbon (spongelike at high temperatures) inner shell was bonded between the outer shell and the tungsten core and provided an insulation for the tungsten and a stress-relief mechanism for the outer shell during reentry. This porous carbon shell was designed to yield under radial and shear loads at about 39.62 km (130 000 ft) altitude during reentry and thereby permit the outer shell to become free standing, while seated on the ATJ graphite plug by aerodynamic drag. Full-scale tests of this stress-relief system at the General Electric Malta Test Station indicated that it would be adequate.

The ATJ graphite and pyrolytic graphite plugs shown in figure 4(b) provided the longitudinal load path for the outer shell, and at the same time the pyrolytic graphite plug provided thermal insulation for the tungsten load-carrying core structure. Carbon felt was placed between the ATJ nose and plug to provide a uniform load over the surface of the two mating pieces and thereby avoid high local stress conditions.

The nose tip was instrumented with three thermocouples located as shown in figure 4(a). These thermocouples were to serve primarily as diagnostic indicators of nose-tip performance during reentry.

Because of the sensitivity of the nose-tip performance to specific heat and thermal conductivity, considerable effort was made to obtain accurate values of these parameters for the particular graphite used. These properties are presented in figure 5. For the Reentry F nose tip, the "with grain" of the graphite was streamwise. The density of the graphite was 1730 kg/m³ (108 lb/ft³).

Starting on page 17: "The graphite nose tip, described previously and shown in figure 4, had tip radius growth during reentry, as presented in figure 64. Curve 1 of figure 64(b) is based on the results of a computer program in which recession of the stagnation point during reentry was computed by analyses using the one-dimensional ablation program described in reference 17. In this one-dimensional program, surface recessions at the stagnation point and on the conical surface were determined from consideration of only the thermo-chemical oxidation process with equilibrium assumed at the graphite surface. The tip radius, assuming hemispherical shape, was then determined for successive times by geometric relationships. However, recent ground tests have shown that mechanical erosion of the nose tip would be expected in the reentry environment for this spacecraft. Reference 18 has correlated the effects of pressure and enthalpy on graphite erosion and has been utilized to adjust curve 1 to curve 2 so that a more realistic prediction is obtained.

At approximately 18.29 km (60 000 ft) altitude, an anomalous rise in the forward nose-tip temperature occurred, and the nose-tip radius history therefore became uncertain within limits. Consequently, a worst-case radius history (curve 3 in fig. 64) was somewhat arbitrarily constructed by assuming a monotonic radius increase beginning at the time in the trajectory when mechanical erosion is thought to begin

and extending to a radius which exposes the graphite plug in the nose tip at the time of rapid temperature increase. It should be noted that further correlation of flight data provides convincing evidence that curve 3 does not represent the actual case because exposure of the graphite plug at the indicated time (458.7 sec) would have resulted in rapid nose-tip destruction, which would have been apparent in the other nose-tip thermocouple data, the body motions, and the surface pressures.”

NASA TM X-2335 provided complementary (to the previous report) analysis of the flight results. The only relevant discussion regarding the nose tip behavior is captured in the following quote: “Surface pressures were measured at 13 locations on the spacecraft. Measurements from the most-forward locations were used in reference 4 [TM X-2210] in calculations of the tip radius of the graphite nose during entry. The results, though not definitive, agree best with the lowest (smallest radii) of the three histories of nose tip radius shown in reference 1 [TM X-1856]. This nose tip history was used for the calculation made by the methods of references 6 [TN D-4961] and 7 [TN D-6217] in the present paper.”

NASA TM X-2468 was mainly focused on base pressure and heating measurements. No specific comments about the nose tip performance or the joint step and gap were provided. There was one interesting fact to quote: “The launch vehicle provided the spacecraft with a roll rate of 62 revolutions per minute prior to separation.” ~1 Hz roll.

NASA TM X-2560 compared the flight measurements to theoretical predictions and limited wind tunnel results. Relevant to the nose tip step and gap, the following details were discussed: “The nose of the vehicle, from $x = 2.44$ cm (0.96 in.) to 21.59 cm (8.5 in.), was constructed from graphite to withstand the severe heating near the apex. This nose section had an initial cone half-angle of 5.38° . This change in cone angle resulted in a 1.016-mm (0.040 in.) rearward-facing step at the graphite-beryllium junction which prevented a forward-facing step during the data acquisition period. A gap was also provided at the graphite-beryllium junction to allow for thermal expansion of the outer graphite shell of the nose. This gap tended to close during the data period. (See ref. 10 [TM X-2308] for construction details of the nose.)”

As mentioned, this report also included results of a wind tunnel investigation of truncated Reentry F nose model (the first 28.5 in at full scale). This model, which was tested in the Langley Mach 8 variable-density hypersonic tunnel, allowed for variations in nose bluntness, gaps, and steps. The wind tunnel data presented within this report is a little hard to decipher. A better source for looking at the wind tunnel trends might be found by reviewing NASA TN D-4961.

NASA TM X-2584 further refined the analysis of the flight data to include boundary layer edge condition calculations. Discussion of the nose tip gap and step were identical to the previous report. There was however this on page 13 discussing comparison to wind-tunnel transition results: “It has been previously noted that the graphite nose of the Reentry F vehicle was designed with an initial rearward-facing step at the graphite-beryllium junction that prevented a forward-facing step during the data acquisition period. In addition, a gap provided at this junction allowed for thermal expansion of the outer shell of the graphite

nose piece. (See fig. 1 and refs. 4 [TM X-1856] and 6 [TM X-2308].) A wind-tunnel investigation was conducted at a Mach number of 8 to determine the possible effect of this gap and step on transition.” Later it was stated on page 14: “The present wind-tunnel data do not agree with the trend shown by the Reentry F data (refs. 4 [TM X-1856] and 5 [TM X-2253]) and found by others (ref. 31 [AIAA J6.1, 1968]) - namely, a more forward movement of transition on the windward ray than on the leeward ray.”

NASA TN D-5948 was focused primarily on analysis of the aerodynamic data to determine the actual angle of attack due to asymmetries of the (bent) body.

Other Postflight Reports

As mentioned previously, this flight experiment and the resulting analysis of the data was initially publicized to the wider aerothermodynamic community with the release of AIAA Paper 77-719 by Wright and Zoby. Since then, other published reports have utilized (to some degree) the results from the Reentry F flight. Captured below, see Table 3, are some of the more relevant documents that discuss the Reentry F data, primarily focused on the captured discussion of the graphite nose tip and/or the joint step and gap.

Table 3. Additional reports with reference to Reentry F data.

Report #	Authors	Title	Date
AIAA 77-719	Wright and Zoby	Flight Boundary Layer Transition Measurements on a Slender Cone at Mach 20	June 1977
AIAA-87-1475	Thompson, Zoby, Wurster, and Gnoffo	An Aerothermodynamic Study of Slender Conical Vehicles	June 1987
AIAA 89-1769	Wurster, Zoby, and Thompson	Influence of Flowfield and Vehicle Parameters on Engineering Aerothermal Methods	June 1989
AIAA 1990-5232	Malik, Zang, and Bushnell	Boundary Layer Transition in Hypersonic Flows	Oct 1990
NASA TM 112856	Wood, Riley, and Cheatwood	Reentry-F Flowfield Solutions at 80,000 ft.	May 1997
JSR 36.1	Schneider	Flight Data for Boundary-Layer Transition at Hypersonic and Supersonic Speeds	Jan-Feb 1999
JSR 40.3	Malik	Hypersonic Flight Transition Data Analysis Using Parabolized Stability Equations with Chemistry Effects	May-Jun 2003
UMN Master's Thesis	Rogers	Investigation of Boundary Layer Stability Using the Parabolic Stability Equations on a Coupled Simulation of the Reentry F Flight Experiment	July 2022

AIAA 77-719 was the initial public release of the Reentry F flight results to the public. For the most part, this report stayed consistent with the presentation of the results and analysis captured in NASA TM X-2253.

AIAA-87-1475 (Thompson et al.) included comparisons of new computational approaches to wind tunnel and flight data, including Reentry F. There is no mention of the nose tip step and gap.

AIAA 89-1769 (Wurster et al.) also compared engineering methods to the Reentry F data. There is no mention of the nose tip step and gap.

AIAA 1990-5232 (Malik et al.) discussed the Reentry F case and provided initial boundary layer stability calculations where the temperature discontinuity of the graphite to beryllium sections was accounted for “but ignored the physical discontinuity.” The resulting stability calculations revealed “second mode N factors (presented in Figure 11) form an envelope as a fixed frequency disturbance begins to decay after some initial region of growth. The envelope curve has a change in slope around $x = 0.6 \text{ m} - 0.8 \text{ m}$. This region coincides with the location where the effect of nose bluntness on flow field diminishes. At $x = 2.9 \text{ m}$, the N factor is around 7.5. Presumably due to the joint induced roughness effects, this value is somewhat lower than usual lower speed smooth-wall values (order of 9-11) but not disastrously so. These data therefore extend the e^N method into the hypervelocity, reacting gas, cold wall regime of interest for NASP.” The thermal discontinuity was investigated assuming a smooth surface.

NASA TM 112856 (Wood et al., 1997) revisited the Reentry F with new computational approaches, including LAURA. There is no mention of the nose tip step and gap.

JSR 36.1 (Schneider, 1999) reviewed various flights with emphasis on boundary layer transition data. For the Reentry F case, he reported that “The nosetip radius at 80 kft is between 0.14 and 0.19 in. An 0.040-in. backward-facing step between the nosetip and the beryllium heat shield “...prevented a forward-facing step during the data acquisition period””. Later he reports “Tables I and II in both Refs. 45 [NASA TM X-2253] and 64 [AIAA 77-719] list the boundary-layer thickness, but the units are wrong, and the values are in error. The thicknesses are probably in feet instead of inches and are, therefore, off by a factor of 12 (private communication, Zoby, August 1996). Transition was observed to be farther forward on the windward ray, compared to the leeward ray, contrary to most wind-tunnel investigations (Ref. 45, p. 4).” In reference to AIAA 1990-5232, the following discussion was provided:

“Malik et al. have performed e^N computations for this vehicle, for one point in the flight test. The second mode is dominant, and the frequencies range from 160 to 270 kHz. Nose bluntness effects begin to decay at around 0.7 m from the nose; transition occurred at 2.9 m. The reference shows that the N factor at transition was about 7.5. Malik et al. speculate that the somewhat low N factor may be caused by disturbances generated at the joint between the graphite nosetip and the beryllium heat shield. Equilibrium chemistry was included in the computations.⁶⁸ Limited details are available for these computations, and Zoby has commented (private communication, August 1996) that the mean heating in the Malik et al. computations appeared high. These results are valuable, but it seems that definitive computations for re-entry F remain to be carried out.”

JSR 40.3 (Malik, 2003) revisited the Reentry F case to also include “nonparallel, as well as body curvature effects...” providing for slightly higher N factor values at the point of transition. “Calculations showed that the estimated transition location (using $N = 10$ as the

criterion) in the Reentry-F case would shift from about 3.1 to 4.4 m, if chemistry effects are ignored.” Consistent with the previous work, the physical discontinuity was ignored, only the temperature distribution was included. “The wall temperature distribution used in Ref. 20 is given in Fig. 7. Wall temperatures in the region $x \geq 0.4$ m were taken from the experimental measurements⁴⁷ and the temperature in the region $x < 0.4$ m were computed estimates provided by E. V. Zoby of NASA Langley Research Center (private communication, 1988). The physical discontinuity (step/gap) referred to was ignored in the analysis of Ref. 20, as well as here.”

Rogers Master’s Thesis (2022) also looked at providing more recent boundary layer stability analysis coupled with realistic modeling of graphite ablation chemistry. “The objective of this thesis is to couple many of the flight physics and generate laminar base flows to then examine how boundary layer stability is affected on a blunt cone during atmospheric reentry. The coupled physics include ablation chemistry, a realistic wall temperature, altitude variation, and non-spherical nose tip blunting.” While the ablation and chemistry of the graphite were now considered as part of this analysis, the physical surface discontinuities were still not included, unfortunately. The resulting analysis and conclusions of the boundary layer stability assuming a smooth body were on par with the results presented by Malik in 2003.

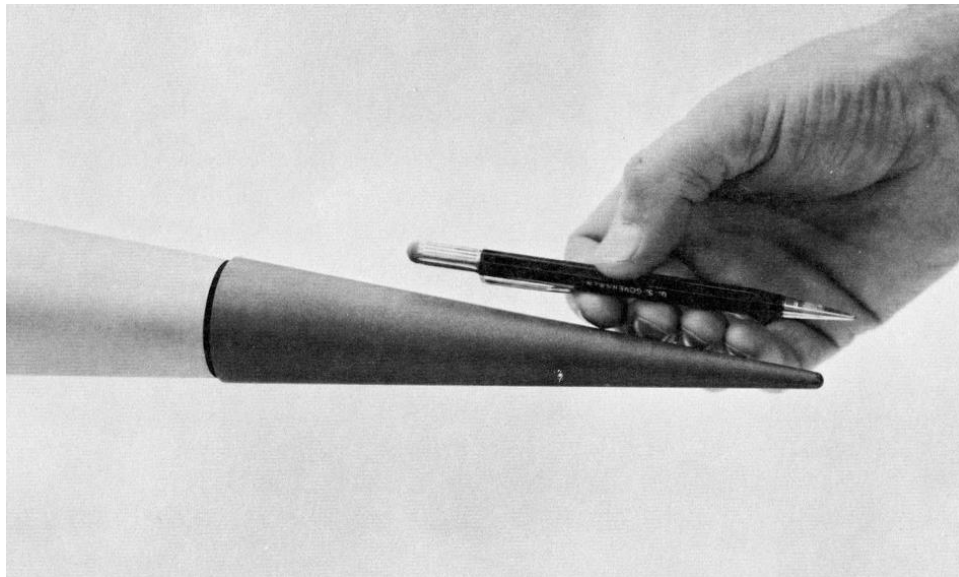


Figure 9. Photo showing the assembled nose tip prior to flight.

[\[https://ntrs.nasa.gov/citations/20250007312\]](https://ntrs.nasa.gov/citations/20250007312)

Recommendations for Future Study

To finally close out the Reentry F flight data analysis, the physical step and gap should also be considered. Figure 9 presents a preflight photo of the assembled Reentry F nose tip, providing a sense of scale for the step and gap. The preflight reports provided the minimum step height and gap requirements considering thermal effects and ablation to insure no physical contact between the brittle graphite nose tip and the beryllium body. The postflight analysis showed that the graphite nose behaved as expected, so the assumption

was the joint step and gap sizes were minimal per design. None of the postflight reports provided any “as-built” measurements of the joint step and gap, which would greatly improve our current assessment of the deltas during flight. Nor did they consider that the step and gap could have been larger in flight than what was predicted based on preflight assumptions. In fact, the NASA reports were inconsistent in their description of the step, with the initial report (TM X-1856) discussing a “rearward facing step of 0.050 in” but then later reports (such as TM X-2560) saying it was a “0.040 in rearward-facing step.” There is no explanation for this discrepancy, but the difference is on the order of the preflight tolerances allowed during final assembly. This difference could also be explained by accounting for the surface slope when making measurements, see sketch shown in Fig. 10, which compares the initial condition to some of the influences on the step and gap during flight. See also Table 4, which provides various known increments to the step and gap, allowing for a summation based on the initial state.

The gap was likely small during flight based primarily on the thermal growth along the body axis of the graphite, but it was not zero. All documents state the gap as 0.100 in wide prior to launch, thus during flight it could have been as small as 0.017 in or as wide as 0.052 in (depending on which deltas are included). The step, on the other hand, is a little harder to pin down. How much recession was there at the end of the skirt at various altitudes? Did the internal bonding material completely fail to allow for the eccentric nose tip condition to occur? To this second point, two different bonding agents (C-10 and PD-162A) were used during assembly. Final assembly included heat treatment to 500°F, which can be assumed to be a temperature that both bonds should be able to handle. During flight, the thermocouples within the nose assembly recorded temperatures on the order of 400°F or so (see Fig. 7). Thus, these bonds should not have been severely overloaded. Which leaves the skirt recession as the main consideration. There were the two different predicted recession amounts reported (0.005 in from CR 66501 or 0.016 in from CR 154044). There are no known documents providing the as built step dimension, thus this variation in recession thickness is applied against the initial min or max step values (accounting for assembly tolerances) to suggest a rearward facing step range of 0.030 to 0.055 in during flight, if the graphite shell remains centric to the body, and 0.010 to 0.035 in if the nose shifts to an eccentric condition. Listed with the table are possible combinations of the range of steps and gaps based on the current review of the available documentation of the Reentry F flight dataset. The worst case being if the gap is the biggest of possible outcomes combined with the smallest step, which might induce flow to get diverted into the gap even for small angles of attack. This could be an explanation for why the flight data trends are not consistent with the ground test data.

A first order assessment could include computations for combinations of the steps and gaps captured in Table 4, to see if it helps explain the wind side forward results with small angles of attack during flight. Further analysis could try to model the graphite nose as a free-standing shell balanced on the front end of nose cone assembly with aerodynamic forces exerted on the graphite felt and bonding agents.

Initial condition (no as built measurements found so must include tolerances)

Radius of ATJ graphite @ Sta 8.5 0.8025" ± 0.004"

Radius of beryllium @ Sta 8.6 0.7525" ± 0.003"

Table 4. Various increments to the initial Reentry F step and gap.

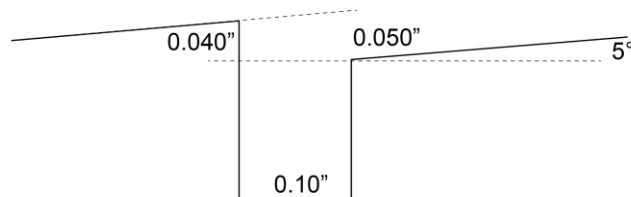
Input/Source	Probability	Gap (in)	Min Step (in)	Max Step (in)
Initial gap, defined by design		0.1		
Initial step, consider tolerance range			0.043	0.057
ATJ thermal growth, streamwise direction (CR-154044)	High	-0.054		
ATJ thermal growth, spanwise (Est)	Med		0.009	0.009
Beryllium thermal growth, spanwise direction (CR-154044)	High		-0.006	-0.006
Graphite felt, minimum thickness with assembly tolerances (CR-154044)	Low	-0.034		
Tungsten washer, thermal growth streamwise direction (CR-154044)	High	0.0055		
ATJ skirt recession (CR-154044)	Med		-0.016	
ATJ skirt recession (CR-66501)	Med			-0.005
Bond material, minimum thickness for eccentric tip condition (CR-154044)	Low		-0.020	-0.020
Final summation, considering all		0.0175	0.010	0.035
Final summation, only med & high		0.0515	0.030	0.055

Smallest step & gap combo G = 0.017 in & St = 0.010 in

Largest step & gap combo G = 0.052 in & St = 0.055 in

Worst step & gap combo G = 0.052 in & St = 0.010 in

Initial Condition



Inflight Condition

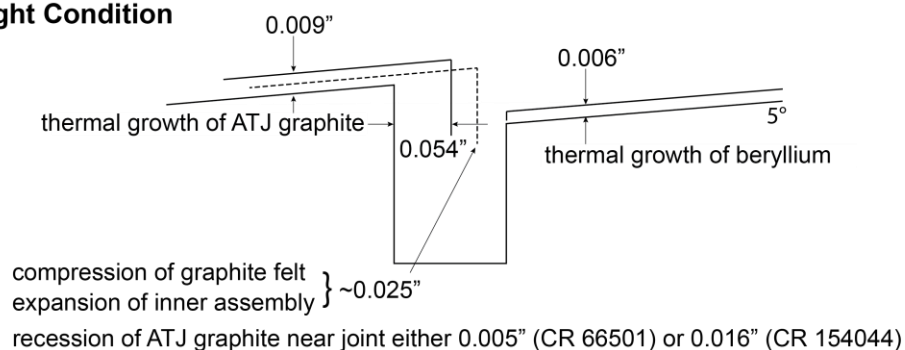


Figure 10. Sketch showing preflight measurements and inflight step/gap assessment