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Hypersonic Boundary-Layer Transition: Application to High-Speed Vehicle Design

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This paper reports the boundary-layer transition characteristics of airbreathing hypersonic configurations and their impact on design environments. It discusses the evolution of the National Aerospace Plane configuration from an axisymmetric baseline to a wedgelike configuration where the transition mechanism is dominated by "natural" transition. The natural transition is characteristic of the "quiet" environment in free flight of smooth slender vehicles. This type of transition mechanism gradually evolves spatially in different modes that can be computed analytically and verified experimentally. The paper discusses the effect of leading-edge bluntness, surface wall temperature, and adverse pressure gradient in compression ramp on transition. The effect of freestream Mach number, Reynolds number, and angle of attack are also studied over the range of peak aerodynamic heating conditions of the National Aerospace Plane environment. The transition behavior was investigated using e^N-type calculations based on a linear stability code known as the e^{Malik} code.

Nomenclature

$a = \sqrt{\gamma R_g T}$	=	speed of sound
C_h	=	Stanton number
C_p	=	static pressure coefficient for the local condition
c_p	=	specific heat of air at constant pressure, $\mathrm{Btu/lb}_m, {}^\circ\mathrm{R}$
c_v	=	specific heat of air at constant volume, $\mathrm{Btu/lb}_m, {}^\circ\mathrm{R}$
H_{aw}	=	adiabatic wall enthalpy, $\mathrm{Btu/lb}_m$
H_t	=	total enthalpy, $\mathrm{Btu/lb}_m$
H_w	=	wall enthalpy, $\mathrm{Btu/lb}_m$
h_i	=	heat transfer coefficient for the local condition, $\mathrm{Btu/ft^2 \cdot s}, {}^\circ\mathrm{R}$
L	=	length, inches or feet
M	=	Mach number
M_e	=	boundary-edge Mach number
Pr	=	Prandtl number
p_e	=	pressure at the boundary-layer edge, psia or psfa
p_i	=	pressure for the local condition, psia or psfa
p_t, p_{t1}	=	total or settling pressure, psia or psfa
p_{t2}	=	pitot pressure in test section, psia or psfa
p_∞, p	=	freestream static pressure, psia or psfa
$\dot{q}_w$	=	heat transfer rate based on wall temperature, $\mathrm{Btu/ft^2 \cdot s}$
q_∞	=	freestream dynamic pressure, psi or psf
R	=	radius, ft
R_g	=	gas constant per unit mass
Re	=	Reynolds number
Re_θ	=	momentum thickness Reynolds number
r	=	recovery factor
St	=	Stanton number
St_∞	=	freestream Stanton number
T_{aw}	=	adiabatic wall temperature, °R
T_o	=	total temperature, °R
T_t	=	total temperature, °R
T_w	=	model wall temperature, °R
T_∞	=	freestream static temperature, °R
v_∞, v	=	freestream velocity, ft/s
x/L	=	longitudinal position as a fraction of the reference length
α	=	angle of attack, degrees
β	=	angle of sideslip, degrees
γ	=	ratio of specific heats, c_p/c_v
θ	=	boundary-layer momentum thickness
μ_∞	=	freestream dynamic viscosity, $\mathrm{slugs/ft \cdot s}$
μ_e	=	dynamic viscosity at the boundary-layer edge, $\mathrm{slugs/ft \cdot s}$
μ_w	=	dynamic viscosity at the wall, $\mathrm{slugs/ft \cdot s}$
ν	=	kinematic viscosity, $\mathrm{slugs/ft \cdot s}$
ρ_∞	=	freestream density, $\mathrm{slugs/ft^3}$
ρ_e	=	density at the boundary-layer edge, $\mathrm{slugs/ft^3}$
ρ_w	=	density at the wall, $\mathrm{slugs/ft^3}$

Subscripts

aw	=	adiabatic wall condition
e	=	boundary-layer edge condition
effective	=	composite boundary-layer transition value used for vehicle design
rn	=	nosetip/leading-edge (bluntness)
t	=	total condition
threshold	=	baseline boundary-layer transition value from simple correlation
w	=	wall condition
∞, inf	=	freestream condition

I. Introduction

HYPERSONIC standoff missiles are candidate weapons for rapidly attacking time critical targets at long distances. Hypersonic missiles using airbreathing propulsion have been under study by industry and the U.S. Air Force for many years. The Boeing Company Phantom Works organization has developed several hypersonic missile designs since the early 1980s and is currently under contract to conduct three technology flight demonstration programs. These ongoing flight-test programs are HyFly and Scramjet Engine Demonstrator (SED) (Figs. 1 and 2). The combination of speed (Mach 6+), altitude (~90,000 ft), and a nearly vertical endgame maneuver makes the hypersonic standoff missile very survivable. NASA and its contractor team, ATK and

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Fig. 1 Defense Advanced Research Projects Agency (DARPA)/Office of Naval Research "HyFly" hypersonic missile flight demonstration program.

Fig. 2 U.S. Air Force Research Laboratory/DARPA X-51 scramjet engine demonstrator waverider flight demonstration program.

Fig. 3 NASA X-43 series of flight demos to provide technology for future hypersonic vehicles.

Boeing, have also recently completed the successful Hyper-X (X-43A) flight-test program. Figure 3 shows the NASA X-43 series of flight demos to provide technology for future hypersonic vehicles. These flight-test programs are not a technology development effort for a specific application, either a tactical missile family or a transatmospheric hypersonic transport. They aim to demonstrate that hypersonic airbreathing propulsion is practical for a variety of applications, ranging from rapid response standoff missiles to global reach to space access. The high-speed Reconnaissance and Strike weapon system can travel long distances in short times providing an element of surprise in the attack. Missions for these systems are far more demanding than those of currently deployed weapons because of faster flight at higher dynamic pressure. The aerodynamic environment can be characterized as extremely harsh and the vehicles often function near the edge of system capability. The design of these systems requires major advances in physical understanding and predictive capability in a number of areas, including airbreathing propulsion, thermal protection and management, control authority for maneuver and precision targeting,

First Off-Ramp	Second Off-Ramp	Third Off-Ramp
• Mach 7 reusable air-breathing 1st stage + expendable or reusable rocket 2nd stage RLV - TBCC (turbojet + scramjet) - ~ Mach 3 TBCC transition to scramjet	• Mach 10 reusable air-breathing 1st stage + reusable rocket 2nd stage RLV • Mach 7 cruise aircraft/UAV	• Mach 12-15 reusable air-breathing 1st stage + reusable rocket 2nd stage RLV • Mach 4-5 reusable air-breathing 1st stage + Mach 12-15 reusable air-breathing 2nd stage RLV • Mach 10 cruise aircraft/UAV
		

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Fig. 4 Potential operational vehicle off-ramps every 5–7 years in long-term plan.

boundary-layer transition prediction, and control. Figure 4 shows the industry view of a future hypersonic vehicle at Boeing.

Flight-test data are sparse and the flight environment is difficult to duplicate on the ground. In a 1992 National Aerospace Plane (NASP) review by the Defense Science Board, the board stated that "two most critical [technology areas] are scramjet engine performance and boundary-layer transition… Further design development and increased confidence in these two technical areas must be of paramount importance to the NASP program." In 2003, a Boeing Technical Fellowship Advisory Board on hypersonics identified boundary-layer transition prediction as one of the enabling technologies in hypersonic system development. Boeing has a long heritage in the study of hypersonic boundary-layer transition.

II. Boundary-Layer Properties: Axisymmetric vs Planar

Most current scramjet vehicles have a planar (nonaxisymmetric) flowpath. A brief discussion on the boundary-layer properties and their impact on turbulent transition are necessary before addressing the issues of design impacts. For flows over blunted noses or leading edges, the detached shock generates a rotational flow with very high entropy level. In a cone or other axisymmetric body, the boundary layer initially develops inside the entropy layer and will eventually "swallow" the entropy layer at a few hundred nose radii downstream of the nose. If transition occurs before the entropy layer is swallowed, the onset location is delayed as compared with a sharp cone. In a wedge or two-dimensional body, an inviscid entropy layer exists outside the viscous boundary layer over long distances. The next three figures are reproduced from a 1992 NASP symposium paper by the author [1]. The results were obtained from high grid density computational fluid dynamics (CFD) solutions of simple geometries using the CFL3DE code. The velocity and total enthalpy profiles from a slightly blunted cone and wedge clearly show the difference of this entropy effect in Fig. 5. In the flowfield of a blunted wedge, a persistent entropy layer causes a momentum deficit in the inviscid region near the surface.

The entropy effect is shown in Fig. 6 further downstream. From 400 to 4000 nose radii downstream, the velocity profiles of a blunted cone are geometrically similar when normalized by the boundary-layer thickness. Over the same distances, the velocity profiles of a blunted wedge continue to evolve. The displaced profile outside the viscous layer indicates the presence of high entropy flow. The difference between an axisymmetric and planar flowfield is demonstrated in the boundary-layer edge Mach number as showed in Fig. 7. The entropy layer has a strong influence on the value of the Mach number at the edge of the viscous layer which is often used as a correlation parameter for transition predictions. For a sharp or almost-sharp body, the edge Mach number reaches behind the shock inviscid value very quickly in either cone or wedge flow. For small nose bluntness, the downstream distance that the cone edge Mach reaches the sharp cone value is a function of bluntness. This distance is sometimes called the swallowing distance by researchers. In a

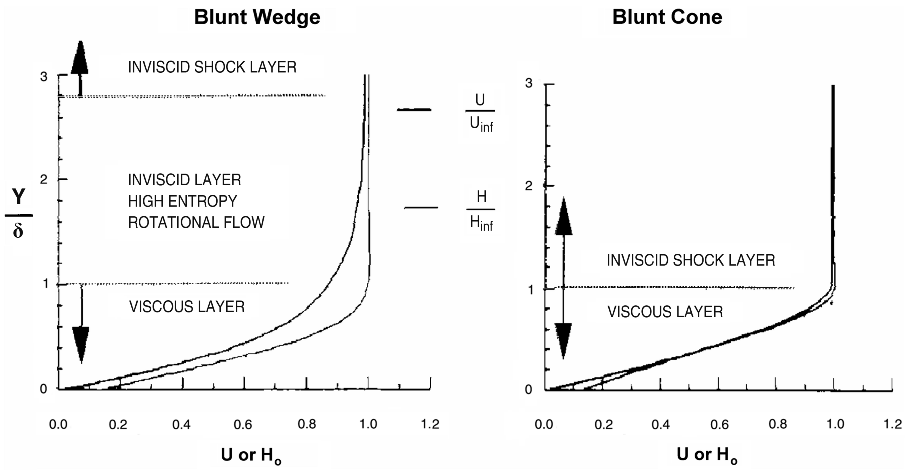


Fig. 5 Difference in velocity and total enthalpy profiles at 100 nose radii downstream.

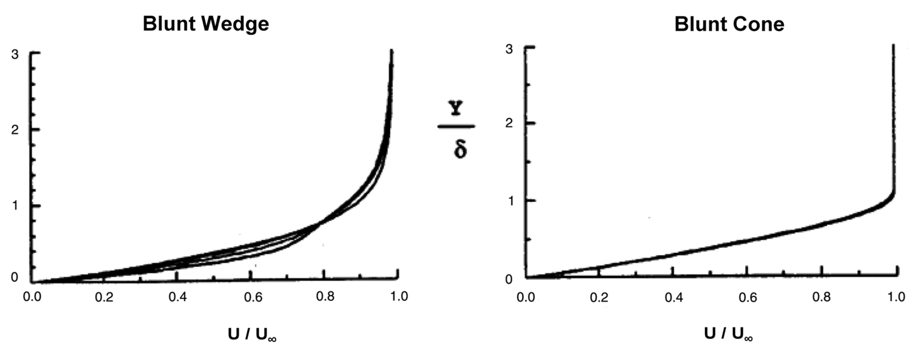


Fig. 6 Velocity profiles continue to evolve at long distance downstream from 400 to 4000 nose radii in blunted wedge.

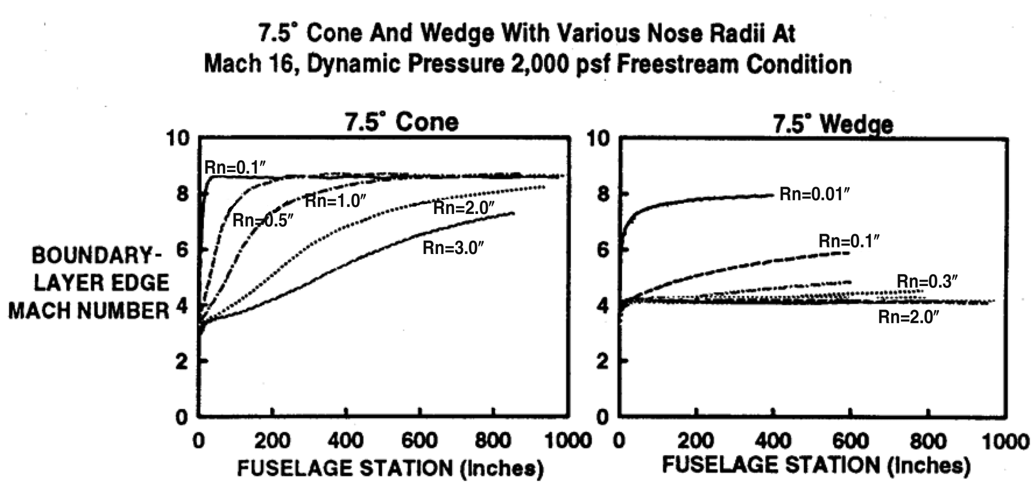


Fig. 7 Difference in boundary-edge Mach number shows the effect of nose bluntness and unswallowed entropy layer in wedge flow.

blunted wedge, the edge Mach number decreases rapidly with increasing leading-edge bluntness. It is very interesting to notice that the edge Mach numbers are almost a constant over a range of small radii and are also relatively uniform downstream of a blunted wedge.

The effect of the planar flow entropy layer on transition was not studied extensively until the NASP program in the late 1980s.

III. Transition Impacts on Configuration Design and Thermal Protection

Since the NASP program, most airbreathing hypersonic vehicle configurations have been designed to generate a sufficient area of planar (two-dimensional) flow for propulsion performance. The flowpath side of the forebody is part of the propulsion system used to generate compression for the scramjet engine. The lower surface of the vehicle is an incremental compression surface with discrete compression ramps. The adverse pressure gradient created by the compression corners has a destabilizing effect on the boundary layer and creates a severe aerothermal environment which is a challenge to the thermal protection system design.

For the NASP vehicle, which is primarily an airbreathing accelerator, propulsion system operation requires a high dynamic pressure trajectory. The condition of the boundary layer which determines heat transfer and skin friction affects surface and structural temperature over large areas of the vehicle. A small amount of prediction uncertainty can translate into substantial increases in structural weight and reduction in inlet performance.

For traditional aircraft, the prediction and control of boundary-layer transition is primarily a matter of operational efficiency. For a scramjet vehicle like NASP, inaccurate prediction of drag, heat transfer, or propulsion efficiency may endanger the whole project and waste investments of major economical impact. Even though transition prediction methods are still deficient and become more unreliable at hypersonic speeds, there are several transition technology developments which will make transition prediction of NASP different from previous hypersonic programs.

During NASP, the national team made a coordinated effort to address the aforementioned deficiency in boundary-layer transition technology. The effect of leading -edge bluntness, surface wall temperature, adverse pressure gradient in compression ramp, freestream Mach number, Reynolds number, and angle of attack have been studied comprehensively using the then most advanced analytical tools. The three-dimensional configuration effect on transition was studied experimentally at a quiet ground test facility.

The development of the NASP planar (two-dimensional) flowpath was influenced by many considerations from many aspects. Boundary-layer transition is an important, but not the deciding, factor in the selection of the planar flowpath. During the early phase of the NASP program, all three contractors, General Dynamics (now a division of Lockheed Martin), McDonnell Douglas, and Rockwell Aerospace (now both Boeing), had a primary design that featured axisymmetric shape flowpath. In 1986, McDonnell Douglas won a contract under the NASP Technology Maturation program to develop an experimental database for CFD validation, which was called the Generic Option 2 program. The database was to be used by the government team and the contractors for CFD development works. The shape for the Generic Option 2 was chosen to be a blended-wing body (BWB) configuration derived from a McDonnell Douglas (MDC) design. The Generic Option 2 program had several tests, including aerodynamics, aerothermodynamics, inlet, and nozzle. The Generic Option 2 data were well documented in an eight volume final report, and a few CFD comparisons were published publicly [2,3].

The BWB configuration has a bielliptic cross section as shown in Fig. 8. Figure 9 shows the installation of the 36 in. aerothermal model in the Calspan 96 in. shock tube facility.

The Generic Option 2 aerothermal test was very successful and generated a set configuration heating data from Mach 11 to 18 at flight Reynolds numbers. The NASP Generic Option 2 program was the first time that "boundary-layer rakes" were used systematically for off-body flow profiles at the Calspan facility. An extensive design effort went into the probe size, spacing, and sensor selection to overcome the constraints of short-duration test time. The pitot profiles were successfully obtained in the boundary-layer region and considered a significant contribution to the validation database. The test set included configurations with sharp and blunt nose tips. It showed some puzzling boundary-layer transition behaviors that were not expected. At 0 deg angle of attack, the sharp nose boundary-layer transition onset occurred at the expected location. But the blunted nosetip did not move the onset location aft. When the angle of attack

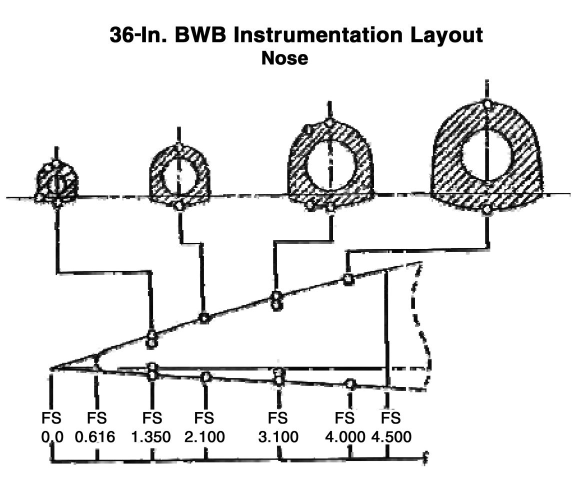


Fig. 8 NASP generic option 2 BWB model cross sections.

Fig. 9 NASP generic option 2 aerothermal model.

was increased, the sharp nose onset location moved forward and the blunt nose onset location moved aft. Additional test runs were conducted using distributed roughness strips at the nose location. The strip usually worked very effectively on cones at the Calspan tunnels. It tripped the sharp nose boundary layer, but had no effect on the blunted configuration. The early transition onset with the blunt nose is obviously not an artifact of tunnel noise. An explanation was needed to understand the transition behavior of this class of configuration.

The blunt nose puzzle was resolved after an extensive study of the CFD and boundary-layer rake data. The study provided insight into the impact of the blunt nosetip on the characteristics of the boundary layer. The bielliptic forebody was optimized using a method of characteristic and streamline tracing during the configuration development. There was no crosstalk between upper and lower surfaces in sharp configuration analysis. The blunted nosetip was an addition for thermal protection purposes afterward. The introduction of the blunt nose caused strong crossflow on the windward surface which resulted in flow bifurcation along the windward centerline and a thick boundary-layer buildup. The crossflow bifurcation destabilized the boundary layer and caused very early transition along the windward centerline. The crossflow diminished with increasing angle of attack and allowed the onset to move aft. At the nominal design angle of attack of 4 deg, the blunt nose had a small effect in delaying transition onset compared with the sharp nose data, but the resulting nonuniformity of boundary layer circumferentially caused drag increase and inlet performance impact.

In late 1986, the MDC NASP program established a tiger team to investigate the scramjet engine to airframe integration. In addition to mechanical issues, the figures of merit included propulsion performance, vehicle controllability, boundary-layer control, thrust vs drag tradeoff, inlet performance, and flight angularity sensitivity. The lessons learned from the Generic Option 2 test program on the difficulty in boundary-layer control of a bielliptic shape were one of the considerations when MDC made a major configuration switch to a noncircular-body (NCB) design.

In 1987, Beckwith et al. reported differences in boundary-layer transition onset between wedge and cone to the NASP symposium at NASA Ames Research Center based on an earlier AIAA paper they published on quiet flow tunnel design [4]. Figure 10 shows the details of this finding from a later publication by Chen et al. [5]. The discovery helped affirm the decision to further develop the NCB configuration by the McDonnell Douglas NASP team. This configuration eventually evolved into the NASP forebody shape as we know it today.

It has been known that a planar (wedge) flow boundary layer is more stable than that for an axisymmetric body. It is also known that small bluntness and increasing surface temperature both have stabilizing effects on second-mode boundary-layer transition. The

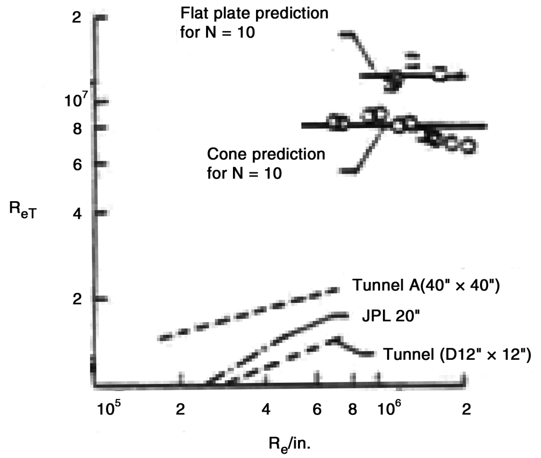


Fig. 10 Boundary-layer transition on a cone and flat plate at Mach 3.5.

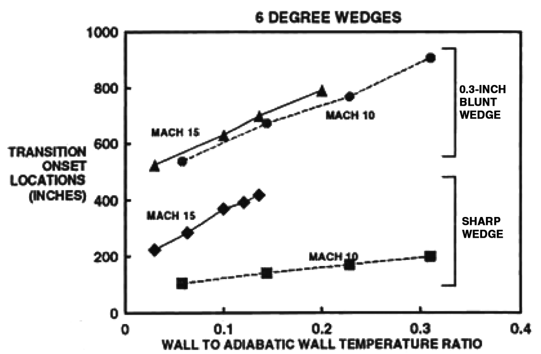


Fig. 11 Bluntness and wall temperature effect interact in hypersonic flow.

combined effects of these parameters show some very interesting implications that affect hypersonic vehicle design.

Figure 11 (from [1]) shows the transition onset locations of a sharp and a blunt wedge predicted by linear stability analysis. The effect of wall temperature is significant and is well correlated by wall to adiabatic wall temperature or enthalpy ratio. The effect of bluntness is much stronger than expected and, surprisingly, it seems to get more prominent at lower Mach numbers. For the sharp wedge, the Mach 15 flow is much more stable than the Mach 10 flow and the difference increases with increasing wall temperature ratio. The leading-edge bluntness reduced Mach number sensitivity of boundary-layer transition. The difference for the blunt wedge is much smaller with the Mach 15 flow being slightly more stable.

In a typical NASP trajectory, the dynamic pressure is relatively constant. The wall to adiabatic wall enthalpy ratio decreases rapidly when the vehicle accelerates to higher Mach number. The combined bluntness and wall temperature effect will cause the NASP vehicle to have more turbulent flow at higher Mach numbers compared with the low hypersonic range. Details of the study was reported at a NASP symposium and briefed to a Defense Science Board reviewing the NASP program in 1992 [1].

Many more lessons on boundary-layer transition and its impact to scramjet airframe design were documented in the NASP final report. Additional test data of boundary-layer transition on NASP configurations from Arnold Engineering Development Center (AEDC) tunnel B were obtained. During the later part of the NASP program, a subscale flight test was planned. Two flights were included for propulsion performance and boundary-layer transition under the "HyFlite" program. The test vehicle was limited to 45 ft or smaller due to the booster capability. In support of the flight tests, a ground test program of roughness effect on transition was performed by the NASA Aerothermodynamic Branch at Langley Research Center. The objectives of the test were to 1) assess effect of thermal protection system roughness on the transition test vehicle, and 2) determine the roughness trip sizes required to assure turbulent boundary layer at the inlet for the propulsion test vehicle.

These roughness test data were invaluable to the Hyper-X airframe design. Many of these data remain restricted by the U.S. Government's International Traffic in Arms Regulations. Only public domain information is included in this paper.

IV. NASP Tools for Transition Prediction: Quiet Tunnel, CFD, and Linear Stability Analysis

Axisymmetric and planar air vehicle bodies have significantly different flowfield characteristics. On the NASP vehicle, the configuration is designed to generate a large area of planar (two-dimensional) flow for propulsion performance. Experimental database and transition prediction methods are deficient for hypersonic planar flows. During NASP, progressive enhancements of boundary-layer transition prediction methodology were built upon by the cooperative activities of both the government and the contractor teams. Some of the early work on NASP boundary-layer transition was reported by Malik et al. in 1990 [6]. The government team was responsible for developing new analytical capability, such as the linear stability code (Government Work Package 4), and providing an experimental database (Government Work Package 2). The contractor teams applied the analytical codes to conduct sensitivity studies which resulted in better understanding of the physics of transition. The result of the sensitivity studies and government provided database were used to develop overall boundary-layer transition criteria, and the criteria were integrated into the NASP vehicle design process. The government organized an annual NASP Boundary-Layer Transition (BLT) Workshop where nationally and internationally known experts were invited to provide advice and consultation to the NASP community. A total of seven workshops were conduct from 1987 to 1993:

1) October 1987: The title of the workshop was "Status of BLT and recommended prediction criterion."

2) December 1988: The title of the workshop was "NASP high-speed roughness/waviness-transition interaction."

3) November 1989: The title of the workshop was "Transition prediction in external flow via linear stability theory."

4) December 1990: The title of the workshop "3-D effects."

5) February 1992: The title of the workshop was "BLT and SCRAM inlet."

6) November 1992: The title of the workshop was "A N-factor feast."

7) November 1993: The title of the workshop was "HyFlite."

In the late 1980's, two sets of configuration boundary-layer transition database were created by the contractors using the Mach 3.5 quiet tunnel at NASA Langley Research Center [4]. McDonnell Douglas tested with an early NCB (noncircular body) design configuration to gain more insight into boundary-layer transition behavior of planar flow. The model was built of machined solid stainless steel block and micropolish to better than a 1 μm finish. A surface-mounted pitot tube was used for transition onset detection. The test successfully demonstrated that the NCB configuration behaved like a wedge in transition onset. Figure 12 shows the MDC test model.

The General Dynamic–Fort Worth (GD-FW) team took a different approach and tested four generic configurations. The models were void-free vacuum remelt stainless steel thin-skin model micro-polished to a 1 μm finish except weld lines. Each model had 93 or 94 chromel-alumel surface-mounted thermocouples for an efficient test schedule. Figure 13 shows the GD-FW test models.

During the early days of NASP, there were very few boundary-layer transition test data that were directly applicable to the NASP-like configuration and almost none at high Mach numbers. The NASP team recognized that they had to rely on higher-order analytical methods to establish the trend of planar flow boundary-layer transition behavior to support configuration design for the short term, and develop a boundary-layer transition flight experiment to reduce prediction uncertainty for the long term. One of the most

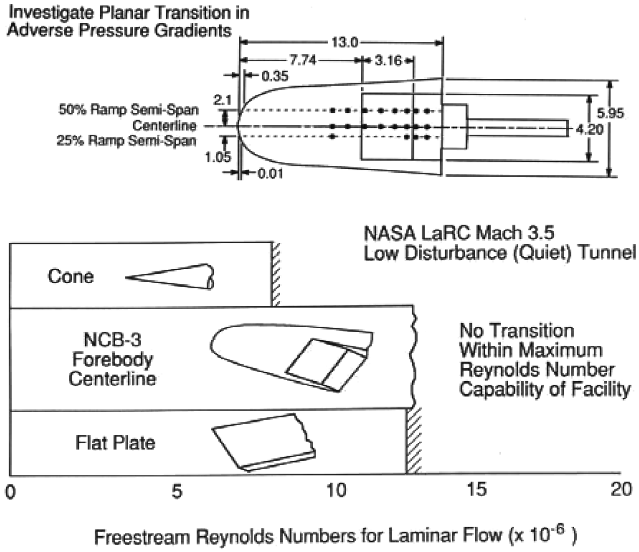


Fig. 12 NASP MDC contractor BLT test at Mach 3.5 quiet tunnel.

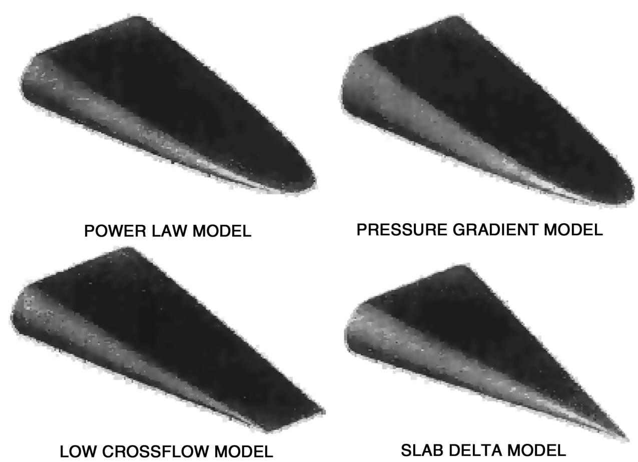


Fig. 13 NASP GD-FW contractor BLT test at Mach 3.5 quiet tunnel.

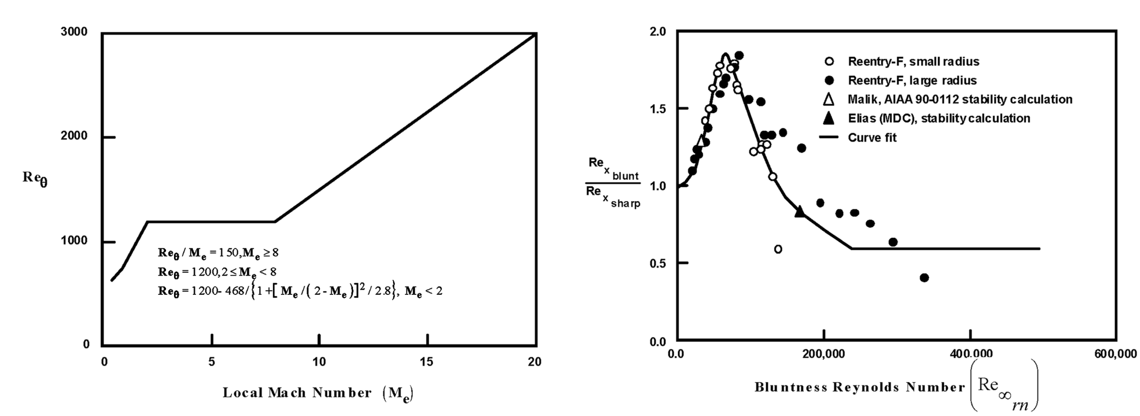
successful of the transition prediction schemes, the e^N method, is based on a correlation of experimental results for the transition onset with the linear growth properties of small disturbances in the laminar boundary layer. A fairly comprehensive summary of the boundary-layer stability theory is given by Mack in [7]. M. R. Malik at NASA Langley Research Center extended the applicability of the e^N method into the cold wall hypersonic domain. A two-dimensional stability code (e^{Malik}, Government Work Package 4) was delivered to the NASP contractors in 1990. It can handle higher mode (≥ 4th order) instability (high Mach, cold wall) in addition to first mode, Gortler, and crossflow modes, and account for the entropy swallowing and equilibrium gas chemistry effects. The e^{Malik} stability code became the NASP standard tool in analytical prediction for the remaining duration of the program and played an important role in the development of the engineering prediction criterion discussed next.

V. NASP Transition Prediction Criterion

The traditional method of using a form of correlation of momentum thickness Reynolds number and boundary-edge Mach number has been applied successfully for many hypersonic programs using engineering codes. During NASP, the airframer teams used AEROHEAT, CASH, XF-0002, and MINIVER for aeroheating predictions. For vehicle performance predictions, AEROHEAT was the designated tool for fuselage aerothermal environment analyses, including boundary-layer state predictions. After the NASP national team was formed in 1989, the airframer teams developed a consensus boundary-layer transition prediction approach which was documented in NASP Coordination Memorandum No. 90-111. This approach was designated BLT-1A.

The BLT-1A transition criterion was based on many detailed studies of available flight data during preteaming and a limited number of linear stability analyses. Only ground test data from quiet tunnel facilities were included in the correlation. The BLT-1A criterion starts with a sharp cone data correlation similar to those used by the contractors preteaming, but adds explicit correction factors for nose bluntness and planar flow. The BLT-1A criterion has shown good agreement with many flight tests, quiet tunnel tests, and linear stability analysis results when applied to a slender axisymmetric body. The BLT-1A does not explicitly distinguish the entropy swallowing effect of an axisymmetric and a planar configuration. Figure 14 shows the essence of this criterion.

The entropy layer has a strong influence on the value of the Mach number at the edge of the viscous layer which is often used as a correlation parameter for transition predictions. For sharp or nearly sharp bodies, the edge Mach number reaches behind the shock inviscid value very quickly in either conic or wedge flow. For small nose bluntness, the downstream distance in which the cone edge Mach reaches the sharp cone value is a function of bluntness. This distance is sometimes called the swallowing distance by researchers. In a blunted wedge, the edge Mach number decreases rapidly with increasing leading-edge bluntness. It is very interesting to note that the edge Mach numbers are almost a constant over a range of small radii and are also relatively uniform downstream of a blunted wedge.



$$\left(\frac{\mathrm{Re}_\theta}{\mathrm{M}_e}\right)_{\mathrm{effective}} = \frac{\mathrm{Re}_{\theta_{\mathrm{threshold}}}\sqrt{\dfrac{\mathrm{Re}_{x_{\mathrm{blunt}}}}{\mathrm{Re}_{x_{\mathrm{sharp}}}}}}{\mathrm{M}_e}$$

Fig. 14 NASP BLT-1A boundary-layer transition criterion.

After a series of trade studies on vehicle configuration, the NASP national team selected a planar flow configuration shape which was called configuration 200. Subsequent enhancements of this baseline configuration were called 201, 202, etc. The result of BLT-1A prediction of NASP configuration 201 transition onset locations raised some concern among the design team members because the transition was much delayed at high Mach numbers compared with preteaming results. The impact of the transition uncertainty on aerodynamic heating was the main concern. The nose bluntness correction factor derived from cone flight data was the major source of the uncertainty.

The NASP team recognized that they had to rely on higher-order analytical methods to establish the trend of planar flow boundary-layer transition behavior to support configuration design for the short term and develop a boundary-layer transition flight experiment to reduce prediction uncertainty for the long term. The stability analyses in the first half of 1992 focused on transition behavior around the design Mach number of 15. An interim criterion, BLT-1B, was derived to supplement BLT-1A in application of planar flow predictions based entirely on two-dimensional linear stability analyses. Both BLT-1A and BLT-1B were applied to predict the ascent and reentry heating for configuration 202.

In September 1992, the NASP team initiated a "boundary-layer transition enhancement" task under WBS 4110E. The objective of this task was to extend the work done earlier and develop transition methodologies that will focus on analyzing both airframe, inlet, and nozzle components of the NASP vehicle. It also addressed the tasks of linear stability code calibration and parametric transition database development. In September 1993, the transition criterion was updated to BLT-1C. Table 1 and preceding equations show the essence of the BLT-1C criterion in addition to the original BLT-1A,

$$(Re_\theta/M_e)_{\text{sharp}} = 318$$

$$(Re_\theta/M_\varepsilon)_{\text{effective}} = (Re_\theta/M_\varepsilon)_{\text{sharp wedge}}(\text{wedge angle factor})$$
$$(\text{bluntness factor}) \quad (\text{pressure gradient factor})$$
$$(\text{Twall factor}) \quad (\text{3D correction factor})$$

$$\text{bluntness factor:} \quad \frac{(Re_\theta/M_e)_{\text{blunt}}}{(Re_\theta/M_e)_{\text{sharp}}} = K_1 + K_2[(Re_{\text{rn}})_\infty]^{K_3}$$

The BLT-1C criterion addressed the sensitivity of Mach number, wall temperature, pressure gradient, leading-edge bluntness, dynamic pressure (Reynolds number), and flow deflection angle. Only the bluntness factor was shown in Table 1 for simplicity. The basic two-dimensional planar flow criterion was correlated from two-dimensional stability analysis calculations. A three-dimensional crossflow correction was developed from configuration 201 quiet tunnel test data (Government Work Package 2). The study of three-dimensional geometry and crossflow effect was reported in the 1993 NASP Midterm Technology Review at Monterey, California [8]. A detailed description of this criterion with all correction factors and its impact on vehicle performance was documented in "Award Fee Milestone #1: Boundary-Layer Transition Criterion Enhancements and Impacts" final report for performance period no. 4. It was also summarized in the NASP final report [9].

Table 1 NASP BLT-1C boundary-layer transition criterion

		K_1	K_2	K_3
$M_\infty \leq 6$	——	1.0	0.0854	0.32
$6 < M_\infty < 15$	——	1.0	0.1082	0.25
$M_\infty \geq 15$	$Re_{\text{rn}} \leq 5000$	1.0	−1.9794E-5	1.0
	$Re_{\text{rn}} > 5000$	0.8511	9.986E-6	1.0

The NASP had two subscale flight tests planned to address the boundary-layer transition issues, but they were canceled together with the termination of the NASP program in 1995. It was not until 2004, after the two successful Hyper-X X-43A flight tests that we got a assessment of the usefulness of these criteria [10].

VI. CFD Lessons Learned in NASP Hypersonic Boundary-Layer Transition Study

The two-dimensional stability code (e^{Malik}) was developed by M. R. Malik under a NASP government work package. M. R. Malik extended the applicability of the e^N method into the cold wall hypersonic domain. It can handle higher mode instability (high Mach, cold wall) in addition to first mode, Gortler, and crossflow modes, and account for the entropy swallowing and equilibrium gas chemistry effects. The code came with a built-in boundary-layer solver and the input format for using other flow solvers was well documented. More detailed description of the NASP version of this code can be found in two High Technology Corp. (HTC) reports, no. 88-6 and no. HTC-8902.

The two-dimensional version of the e^{Malik} code was released to the NASP contractors in late 1991. It was immediately realized that it is essential to develop an efficient procedure to apply the Malik linear stability code for hypersonic vehicle design support. An interface code was developed at McDonnell Douglas to convert CFL3DE output into a stability code input file and it can be easily expanded to include solutions from other CFD codes. In late 1992, the contractors received a prerelease version of the three-dimensional Malik stability code from M. R. Malik

The two-dimensional code was soon routinely applied to support NASP design activities and became the cornerstone of the short-term solution of NASP boundary-layer transition technology. (The long-term solution is a subscale flight test.) Preliminary results from the Malik stability code were very encouraging and was briefed to a Defense Science Board reviewing the NASP program in 1992. But the challenge lay ahead.

In early 1990, the hypersonic community had barely begun to understand the requirements for obtaining a high-quality heat transfer solution for complex vehicle shapes from full Navier–Stokes solvers. The NASP team at McDonnell Douglas added grid adaptation to the NASA Langley supported CFL3DE and showed excellent comparison with historical flight data and NASP ground test data. Using the laminar heating flight data at Mach 20 from Reentry-F [11], a general guideline was established that a Y-plus (cell Reynolds number) value of 0.5 and under is good for heat transfer. The shock boundary grid adaptation needed no more than a 120 radial grid for good resolution. But the preceding guidelines were soon found to be inadequate for flow solution input to linear stability analysis.

The first lesson learned was that it is as important to resolve the shock layer boundary as the viscous boundary layer. Any numerical noise generated at a ragged shock layer boundary will propagate to the boundary layer causing erroneous results. The linear stability analysis-based grid study resulted in a new radial grid stretch function and doubled the number of grid requirement. Figure 15 shows the Reentry-F transition onset prediction, which compared reasonably with recent values published by Malik [12], and unpublished results by Graham Candler at the University of Minnesota. The grid was adapted the bring the computation domain close to the shock boundary and maintain a Y-plus of less than 0.5. It is also very important to resolve the boundary-layer edge adequately. It was not practical to have a third grid adaptation location at that time. The new stretch function for radial grid distribution seemed to do a good job meeting the requirement without adaptation at the boundary-layer edge.

The CFD solutions for stability analysis input were usually adequate if converged to the same criterion as getting heat transfer results. To obtain more consistent results, a new convergence parameter output was implemented in the CLF3DE using second-order derivatives of the X direction velocity at selected locations. This was easy in the two-dimensional code.

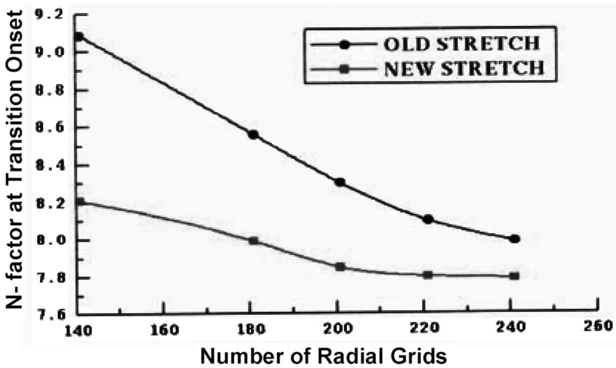


Fig. 15 N-factor values at reentry-F transition onset location at 100,000 ft.

The NASP version of the three-dimensional e^{Malik} code was exercised by the NASP team. But there was no conclusive results from the three-dimensional analysis. Some interesting results were reported in follow-up works on an elliptic cone by Kimmel et al. [13].

VII. Boundary-Layer Transition Flight Results from X-43A

In 1995, NASA's Hypersonic Office initiated a program to develop a conceptual design of a Mach 10, global reach reconnaissance aircraft after the cancellation of the NASP program. The result was a dual propulsion system that was called NASA Dual Fuel Airbreathing Hypersonic Vehicle [14]. This technology study program included a subscale flight test in phase 3 which eventually became the X-43A Hyper-X program.

The boundary-layer transition prediction method adapted for the X-43A airframe design was based on methodology and analytical studies developed during the NASP program. As discussed in an earlier section, it was determined that distinctive threshold values of Re_θ/M_e must be used for axisymmetric and planar flow conditions. Correction factors were applied to account for specific effects, such as nose or leading-edge bluntness. For configurations with a flat forebody cross section, such as the X-43A vehicles, the planar flow criterion was applied to the upper and lower centerline locations, and the axisymmetric criterion was applied to the chine locations.

The subscale X-43A was shown to have no natural boundary-layer transition in its inlet flowpath. A tripping device was needed to assure inlet operability. The design of the boundary-layer trip was reported by Berry et al. [15]. The size of the trip is a good indication of the difficulty in tripping a boundary layer in hypersonic flow of a planar configuration.

When the X-43A was reported in 2004 and 2005, the upper surface natural transition onset data were shown to agree very well with the NASP developed criterion [10,16]. A summary of the boundary-layer transition results and its excellent agreement with the criterion can also be found in Sec. E, Fig. 12 of [17].

VIII. Conclusions

1) Two "new" tools, compressible linear stability code and quiet tunnel, in boundary-layer transition control technology emerged during NASP. They were the enabling technology that allowed the NASP engineers to gain insight into the mechanism of boundary-layer transition of a new class of hypersonic shape.

2) The NASP Boundary-Layer Transition Workshop allowed broad reach to many support groups. It demonstrated that intensive technical exchanges among government, industry, and academia cooperation were very beneficial. It allowed efficient allocation of limited resources to address a difficult technical issue.

3) NASP lessons confirmed the importance of nose bluntness effect and identified the need to separate boundary-layer flow characteristics based on vehicle shape, axisymmetric vs planar. It is particularly important in the development of engineering correlation to support vehicle design efforts.

4) A phenomenological study helped identify an important transition mechanism. The NASP study demonstrated the interactive nature of the transition mechanism and how it should be handled in vehicle design.

5) It is very difficult to trip hypersonic boundary layer in planar flow. It is demonstrated by the relatively large trip size for the X-43A flight test. A ground-test-based trip optimization program is highly desirable to fully understand the margin of tripping effectiveness and to avoid adverse impact on flight performance.

6) NASP Re_θ/M_e-based onset criterion became the industrial standard. The excellent correlation with X-43A flight data is the first verification of its validity.

7) Engineering prediction correction such as the BLT-1A/1C criterion is analysis code specific and needs recalibration before using with different codes.

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