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SUPERSONIC LAMINAR-FLOW CONTROL

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BENEFITS
LAMINAR-FLOW CONTROL FOR SUPERSONIC CRUISE

Detailed, up-to-date systems studies of the application of laminar-flow control (LFC) to various supersonic missions/vehicles, both civilian and military, are not yet available. However, various first order looks at the benefits are summarized on the figure and in references 1-4. The bottom line is that laminar-flow control may allow development of a viable second generation SST. This follows from a combination of reduced fuel, structure, and insulation weight permitting operation at higher altitudes, thereby lowering sonic boom along with improving performance. The long stage lengths associated with the emerging economic importance of the "Pacific Basin" are creating a serious and renewed requirement for such a vehicle.

● Civilian/SST

- Key to viable second generation SST ALA OSTP National Aeronautical R&D goals
- Increased range/payload
- Lower fuel weight/usage
- Lower skin temperature (reduced Stanton number, recover factor) 0 (100° F) reduction for $M \sim 3$, increases material options
- Reduced thermal/sound insulation for cabin (reduced skin temperature, P'_w), reduced air conditioning load
- Increased altitude/lower sonic boom
- Lower cost, reduced landing/take-off speeds

● Military

- All of above plus reduced I. R. signature

HIGH-SPEED TRANSITION PHYSICS

Before discussing supersonic laminar-flow control, it is reasonable to briefly examine the transition physics which must be altered to prolong the laminar boundary-layer state. This physics is summarized on the figure and in reference 5. Of particular importance is the existence, known for more than 20 years, of a second (inviscid) instability mode at higher Mach numbers. Conventional wisdom holds that, in the absence of cross flow, compressibility and wall cooling are stabilizing. This is not so in some speed ranges due to the second mode physics. The dominant fact of life in supersonic LFC is the presence and importance of the cross-flow instability mode, engendered by the large sweep angles necessitated by wave-drag reduction/control.

Three fundamentally different boundary-layer instability modes

<u>I</u> "T-S" modes	<u>II</u> Cross-flow mode	<u>III</u> Concave curvature (Taylor-Gortler) mode
<ul style="list-style-type: none"> ● First mode (viscous) ● Dominant up to $M_E \sim 4$ ● Damped by cooling ● Moderate to high Re_T 	<ul style="list-style-type: none"> ● Second mode (inviscid) ● Dominant beyond $M_E \sim 4$ ● Amplified by cooling ● Relatively high Re_T at high M 	<ul style="list-style-type: none"> ● Inflectional instability ● Characteristic of 3-dimensional B.L.s. ● Low Re_T ● Induced by wall or streamline longitudinal concave curvature ● Low Re_T

Note: Swept leading edges (attachment lines) constitute a separate case

TRANSITION BEHAVIOR
EXISTING SUPERSONIC CRUISE AIRCRAFT

Another preparatory phase to the consideration of supersonic LFC is an examination of transition occurrence/behavior on contemporary large supersonic vehicles. As summarized on the figure most of these vehicles were designed more than 20 years ago, and their surface condition is not consistent with extensive laminar flow. The prime difficulty is the occurrence and often dominance of thermal stresses and their impact upon obtainable surface smoothness/waviness. Newer technologies, such as super plastic formed diffusion bonded titanium (SPFDB) may allow design and fabrication of surfaces consistent with supersonic laminar-flow control (refs. 6 and 7).

- XB-70
 - X-15
 - SR-71
 - B-58
 - Concord and "Concordski"
 - MIG 25 Foxbat
- 50's and early 60's technology
- Surfaces have steps, gaps, joints, waviness (for thermal stress relief)
- Surface irregularities, combined with cross flow, induces early transition (within inches of leading edge)
- Outlook for smooth, low waviness skins for modern supersonic cruise machines good via molded sandwich skins made of thermoplastics or SPFDB titanium

ALTERNATIVE CONTROL TECHNIQUES
LFC FOR SUPERSONIC CRUISE

Much of the available research literature for supersonic LFC is summarized in references 8-11. The prime design driver in supersonic LFC is the prevalence of large cross flow. This tends to negate "natural" laminar flow except in very specialized circumstances/body areas. Therefore, the laminar-flow control approach of choice for supersonic/hypersonic speeds is suction. As will be shown herein, wall cooling has only a secondary influence upon cross flow, even at high speeds. Therefore, unless some other technique (other than large sweep) can be found to reduce wave drag at supersonic/hypersonic conditions, "natural" and hybrid LFC will be extremely difficult at high speeds.

- General consideration
 - Supersonic flow implies large sweep for wave-drag reduction, this results in boundary-layer cross flow and consequent destabilization upon imposition of $-DP/DX$, ∴ "natural" laminar flow restricted to body-nose regions only
- Suction
 - Usual approach of choice for $M > 1$ LFC, handles cross flow, (slot suction thus far)
- Wall temperature
 - Small cross-flow regions only (also $-DP/DX$)
 - $M < 4$, first mode, cooling ($R_{x_{Tr}} \rightarrow 34 \times 10^6$ at $M \sim 4$ on body of revolution, CCCP)
 - $M > 4$, second mode, heating

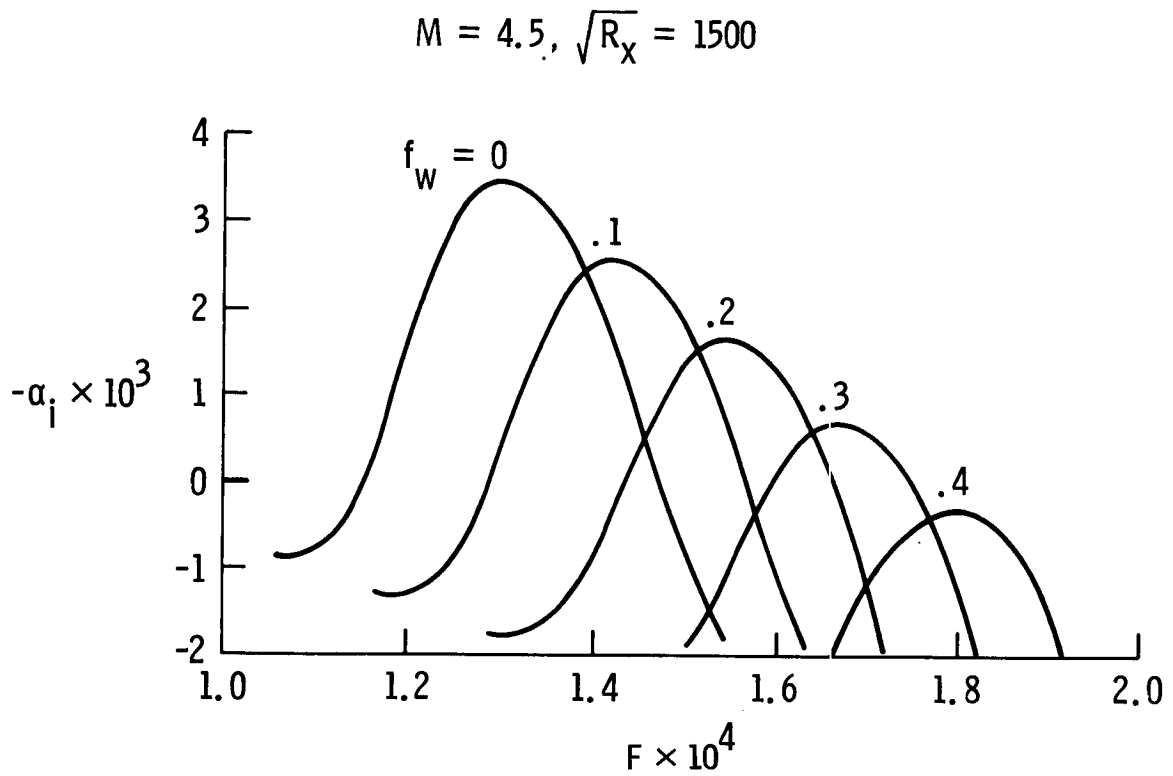
MACH NUMBER INFLUENCE UPON LFC/STABILITY PROBLEM

In general, LFC becomes both easier and harder as speed increases. LFC is easier due to somewhat reduced roughness sensitivity caused by outward movement of the critical layer and lower wall region Reynolds numbers and harder because increased suction levels are required due to the same outward movement of the critical layer and increased cross flow. The very limited high-speed cross-flow stability computations available thus far indicate that increasing Mach number may further stabilize the boundary layer for this mode, but this effect is generally overcome by the increasing cross flow/sweep at higher M. See reference 12 for the high Mach number Gortler case.

- First and second mode "T-S" disturbances (Tollmien-Schlichting)
 - Up to $M \sim 4$ (1st mode)
 - Amplification rate decreases
 - Wave angle increases
 - Absolute roughness sensitivity decreases
 - Beyond $M \sim 4$ (2nd mode)
 - High frequency transverse waves most unstable
 - Critical layer moves to outer part of boundary layer/further decrease in roughness sensitivity
 - Two-dimensional boundary layers extremely hard to trip
- Gortler mode
 - Increasing Mach number stabilizing
 - Suction/wall cooling less effective (for stabilization) as M increases
- X-flow mode
 - Weak dependence upon Mach number

EFFECT OF SUCTION ON THE SECOND-MODE INSTABILITY

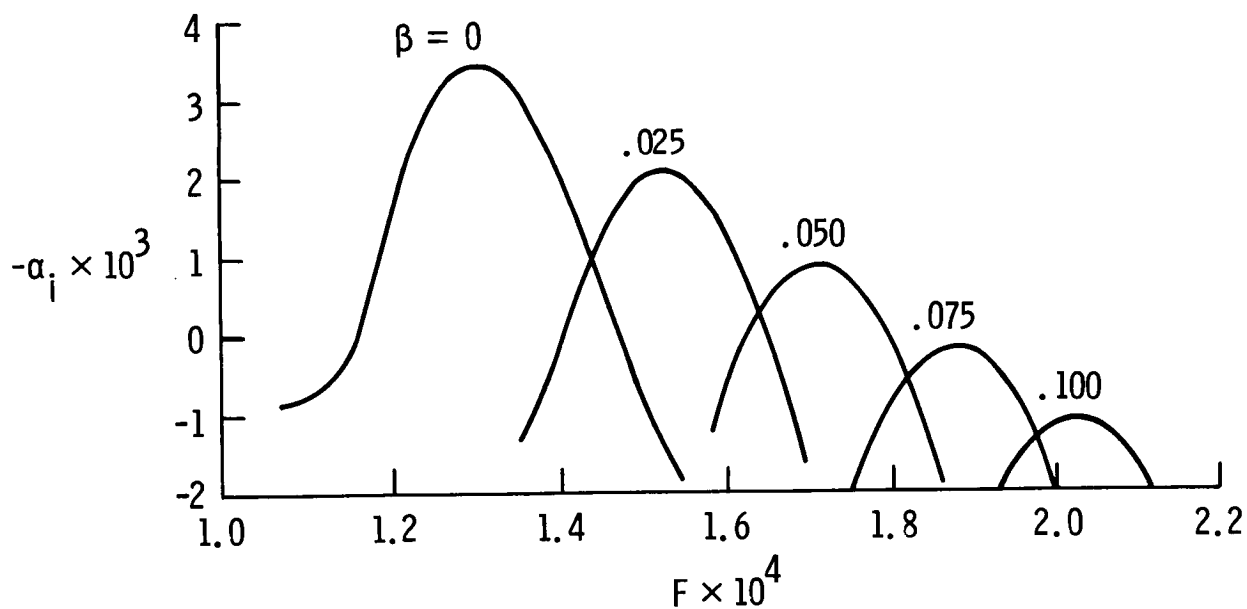
The second (inviscid) instability mode becomes important in the high supersonic/low hypersonic range, and these higher modes dominate the non-cross-flow/non-Gortler boundary-layer transition problem thereafter. The stability results shown on this figure (method of ref. 13) are among the first for the second mode control case and indicate that suction is still highly stabilizing for these disturbances.



EFFECT OF PRESSURE GRADIENT ON THE
SECOND-MODE INSTABILITY

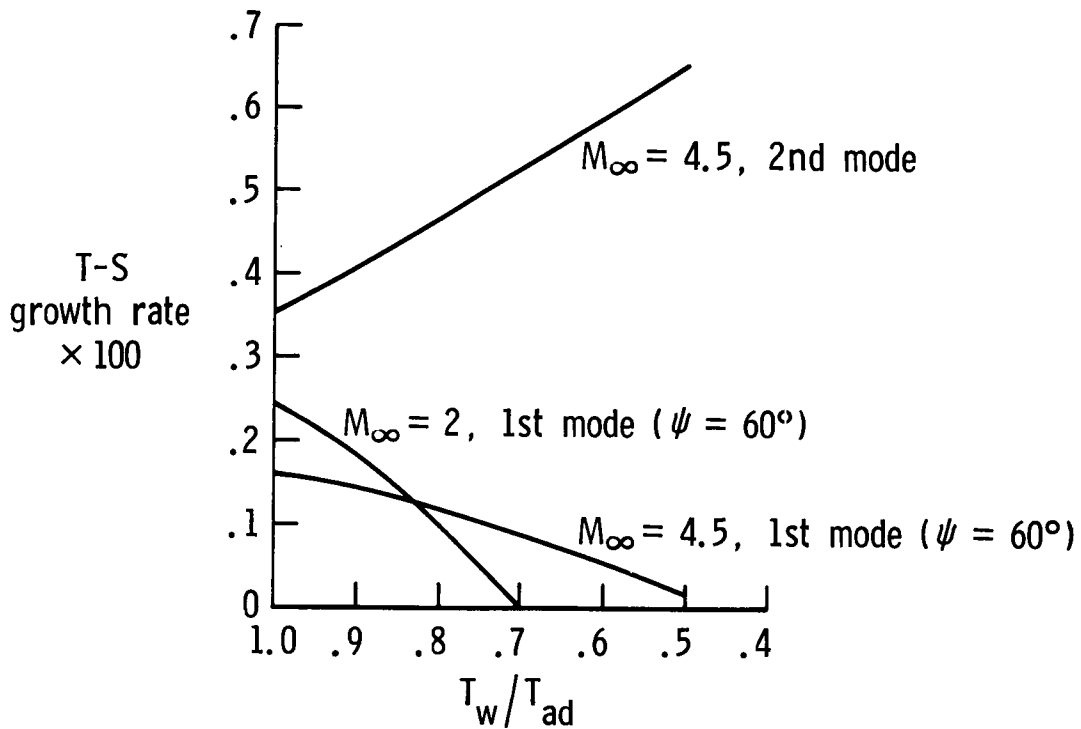
This figure is a companion to the previous figure and indicates that favorable pressure gradient is also stabilizing for second-mode instabilities. Therefore, in the absence of significant cross flow, natural laminar flow would still be an LFC option, even at high Mach number. However, pressure gradients in the presence of sweep exacerbate the cross-flow problem, which is one of the major reasons that natural laminar flow was dropped in the late 1940's with the advent of the jet engine and higher speeds/swept wings.

$$M = 4.5, \sqrt{R_x} = 1500$$



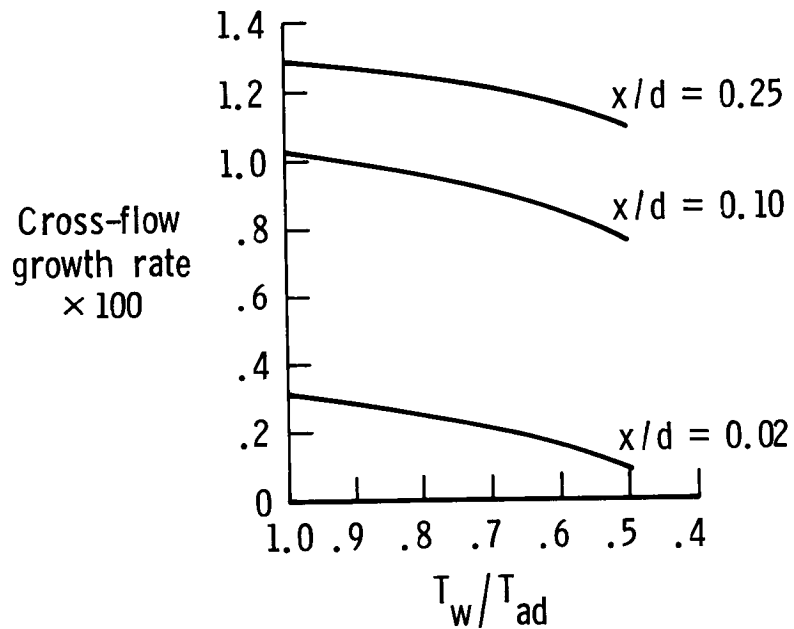
EFFECT OF COOLING ON T-S GROWTH RATES IN A
TWO-DIMENSIONAL BOUNDARY LAYER

These calculations, carried out using the method of reference 13, elucidate the dramatic difference in the effect of wall cooling upon instability growth rates for first- and second-mode disturbances. These results have been known to the stability theory community for many years but usually still come as a surprise to the design community. See reference 14 for corresponding experiments and the next chart for the influence of cooling upon the cross-flow mode.



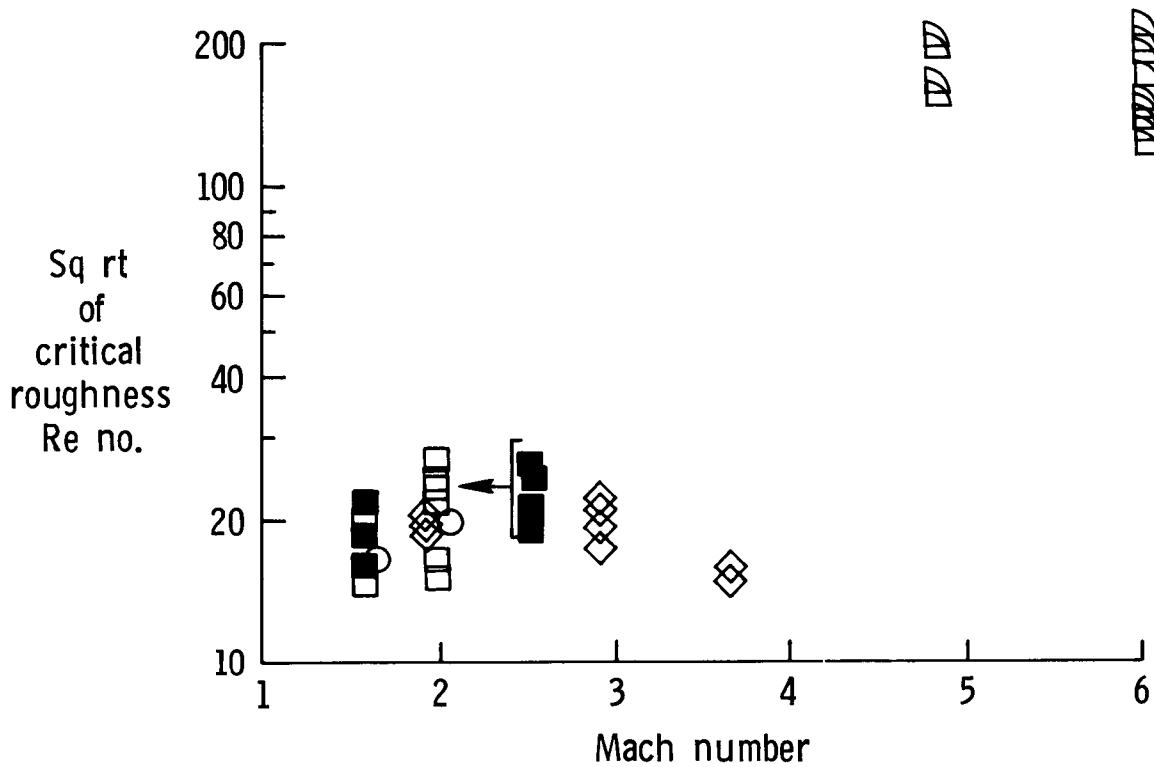
GROWTH RATES FOR STATIONARY CROSS-FLOW VORTICES ON A
60° SWEEP CYLINDER AT $M_\infty = 3.5$

The disturbance growth rates are seen to be only weakly dependent upon wall cooling for the high supersonic case. This result is in agreement with previous research at near transonic conditions (ref. 15) and indicates that, even if cryogenic fuel were utilized, suction would still be required for laminar-flow control on highly swept supersonic configurations.



MACH NUMBER EFFECT ON CRITICAL ROUGHNESS REYNOLDS NUMBER

As in conventional LFC applications, a smooth, relatively wave-free surface is a necessary (but obviously not sufficient) condition for LFC. For the non-cross-flow case the "second mode" disturbance growth occurs farther from the wall (compared to the low-speed case) and therefore the "smoothness" requirement is far less stringent as the figure indicates (from ref. 16). Note that the criteria shifts in the expected region, above Mach 4 where the second mode growth rates begin to exceed those from the first mode. Unfortunately, while definitive information is lacking, what information is available indicates that the roughness criteria for the cross-flow mode remains quite stringent, generally even more restrictive than for the two-dimensional low-speed case.



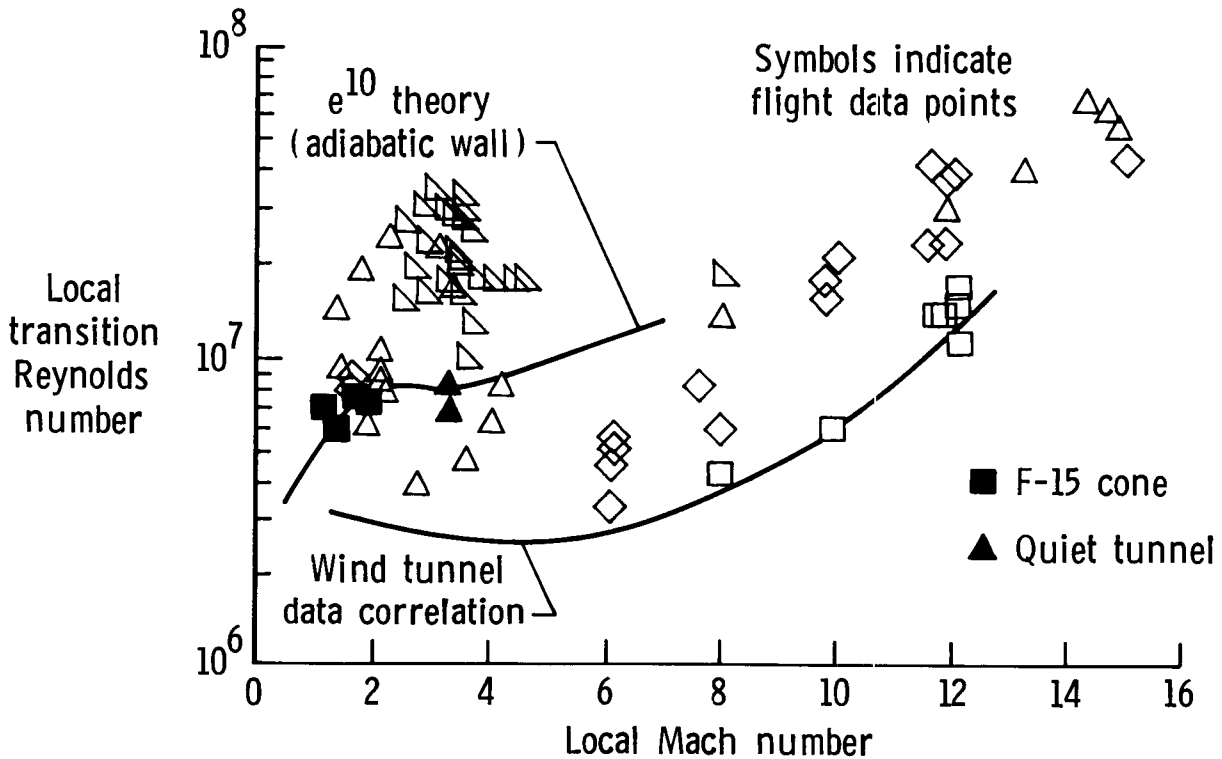
APPLICATION OF THE e^N METHOD TO SUPERSONIC LFC DESIGN

As discussed in reference 17 the e^N approach (see also ref. 13) constitutes the current best bet for LFC design and transition prediction. The basic idea is to integrate the growth rates of the most unstable wave between inception of instability and the location of transition and to represent the growth factor (final to initial amplitude) as e^N where N is determined from comparison with experimental transition loci. As noted on the figure the various comparisons with supersonic data indicate values for N in the same range as for the lower speed flows, 9 to 11. In LFC design the disturbance must remain small (linear) for ease of control, and therefore maximum N values the order of 5 to 7 are usually employed.

- N value calibrations, $M > 1$
 - Gortler mode ($M \rightarrow 3.5$, quiet wind tunnel wall)
 - Cross flow (F-106 wing, F-15 wing, swept cylinder in quiet wind tunnel)
 - T-S, first mode (cones, quiet wind tunnel and flight up to $M \sim 3.5$)
 - Second mode (inferred from matching flight transition data on cones)
- Conclusion from all of these cases is that an N of 9 to 11 usually corresponds to transition occurrence
- Utilization of e^N for LFC necessitates applying sufficient control to keep disturbances linear (N small)

TRANSITION ON SHARP CONES

This plot indicates that the e^N approach can be extended into the hypersonic regime. The bottom curve is a best fit through available wind tunnel data (not shown) and, due to large acoustic disturbances in ground facilities, the bottom curve indicates lower transition Reynolds numbers than the flight data (which are shown). The e^{10} theory line corresponds to the filled symbols (adiabatic wall case). Most of the flight data points above the curve below Mach 4 are for cold wall, and because this is first mode "territory", the transition levels are higher (as would be predicted by the e^{10} theory for the cold wall case). At higher Mach number the flight data are also cold wall, but now, in 2nd mode territory, this is destabilizing, and therefore the data are below the adiabatic line shown.



LFC SUPERSONIC SUCTION EXPERIMENTAL DATA BASE

An active supersonic suction LFC research program existed coincident with and following the Air Force-Northrop X-21 program for transonic LFC. This work is documented in references 8 and 18-21. A summary of the key experimental results are shown on the figure. Note that the experiments covered a wide range of flow disturbance conditions (two-dimensional, axisymmetric, swept) and even considered the problem of laminarization through incident shock waves. The cogent results from these works are summarized on the following charts.

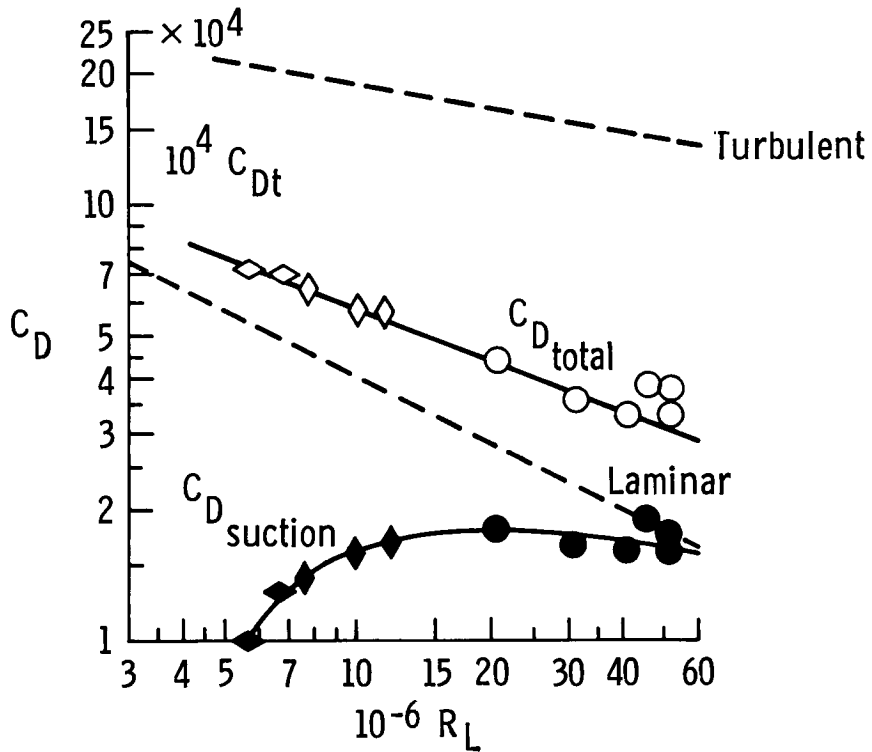
Mostly Northrup/Pfenninger*/AEDC Tunnel A

Model	Mach number	Reynolds number with laminar flow (using suction)
● Flat plate (with and without reflective shock wave, $P_2/P_1 \sim 1.1$)	2.5 - 3.5	25.7×10^6
● 6° half-angle cone	5 - 8	30×10^6
● Axisymmetric model, cylindrical after-body (with and without reflective shock, $P_2/P_1 = 1.16$)	2.5 - 3.5	51×10^6
● 36° swept wing, 3.0% T/C, biconvex	2.5 - 3.5	25×10^6
● 50° swept wing, 2.5% T/C, biconvex	2.5 - 3.5	17×10^6
● 72.5° swept wing	1.99 - 2.25	9×10^6

* W. Pfenninger (Analytical Services and Materials, Inc., Hampton, Virginia) was instrumental in this work.

TOTAL DRAG FOR SUPERSONIC LFC - AXISYMMETRIC FLOW, $M_\infty = 3$

This sample result from the Northrop work indicates the increasing and increased importance of the suction drag component. Turning the flow into and along the body in supersonic flow produces a train of shock waves, thereby producing additional wave drag. Also, required suction rates are generally higher in the supersonic case due to critical layer movements and increased cross flow.



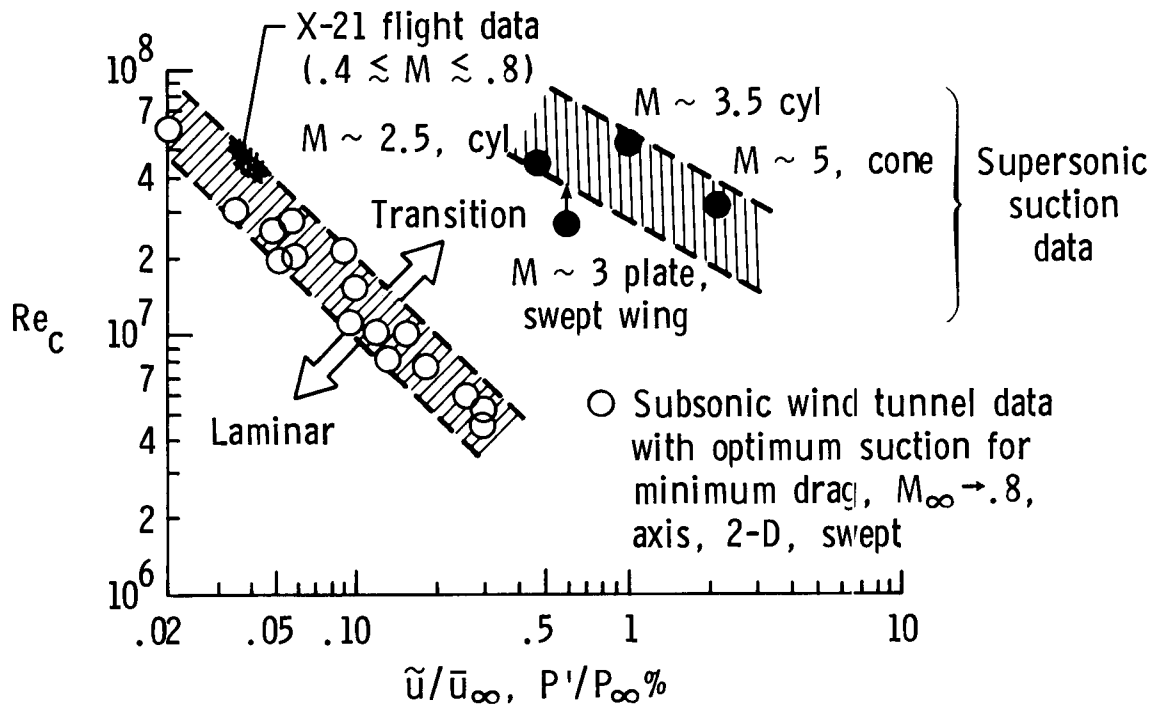
RESULTS, SUMMARY OF "LESSONS LEARNED"
SUPERSONIC SUCTION LFC EXPERIMENTS

This figure and the following summarize many of the major results from the extensive Northrop (Pfenninger) research in supersonic suction LFC. This work was conducted in conventional (noisy) ground facilities. In spite of this, in most cases laminar flow was obtained using suction up to the maximum performance limits of the facility (total pressure, model size) i.e., these studies obtained/proved LFC at huge unit Reynolds and in the presence of large stream disturbance levels. In the analogous low-speed case LFC was extremely difficult, if not impossible, in high disturbance tunnels even at reasonable unit Reynolds numbers. It should be noted that increasing difficulty in attaining LFC was encountered with increasing sweep/cross flow.

- Overall drag ($C_F + \text{suction}$) 0 (25% to 60%) of turbulent level
- Required suction rates increase with sweep and Mach number, i.e., suction drag greater for supersonic LFC (for 2-D case, $(V_W)/(U_E) \sim .001$ vs. $.0003$ for low speed)
 - Caused by (a) increased cross flow (increased sweep), and (b) outward movement of critical layer
- Slot sizes (for R/ft up to order of magnitude greater than flight applic.) of $.004''$ to $.008''$, approximately $1/2''$ spacing, $.003''$, $.080''$ spacing on highly swept wing
- Slot width $< 20\%$ of "sucked height"
- Sucked height per slot $<$ momentum thickness
- For most tests, R_X with laminar flow was limited by tunnel size/pressure, i.e., absolute limits for supersonic LFC are considerably in excess of demonstrated capability
- These excellent results obtained in noisy, high-stream disturbance conventional $M > 1$ tunnels (subsonic LFC not even attainable in high disturbance subsonic tunnels)
- For axisymmetric bodies even small incidence (1°) can be highly destabilizing due to large induced cross flow
- Spanwise contamination locus on lower surface of swept wing may necessitate laminarization of wing fuselage junction

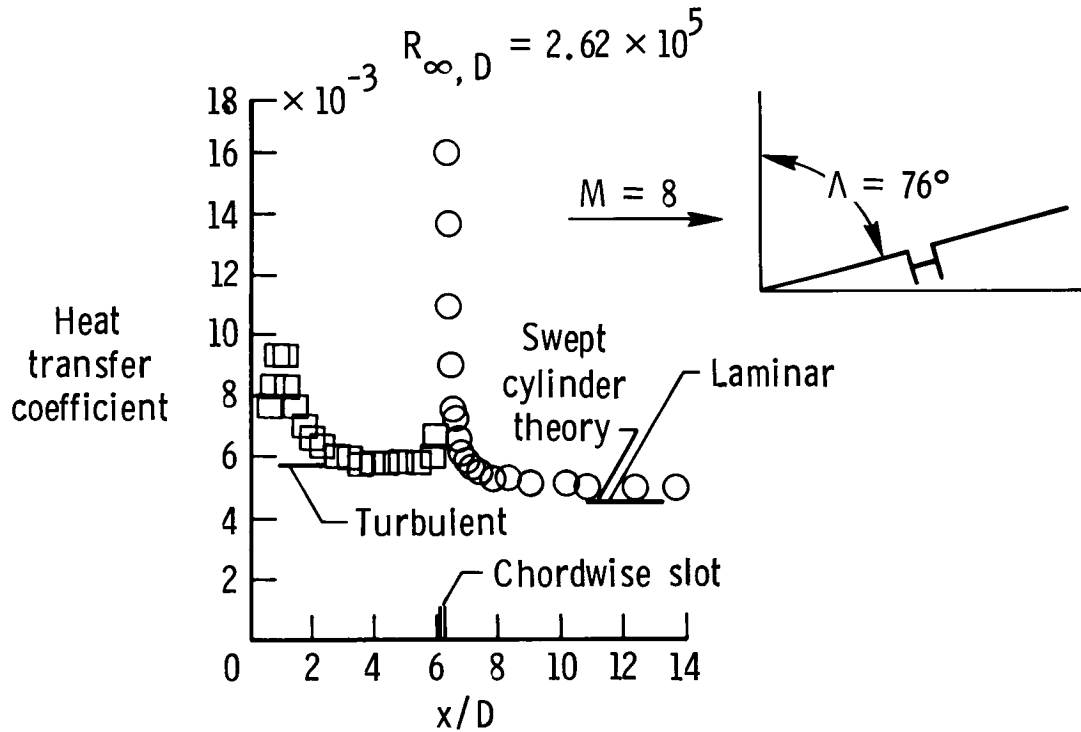
EFFECT OF TURBULENCE LEVEL ON
TRANSITION REYNOLDS NUMBER

This figure indicates the improved performance obtained in the supersonic case compared to conventional (lower speed) studies. Possible reasons for this improved performance include (a) decreased boundary-layer receptivity/internalization for acoustic as opposed to vortical disturbances of the same relative intensity, and (b) decreased stream disturbance/roughness coupling due to the reduced roughness sensitivity/lower wall Reynolds number.



DISTRIBUTION OF HEAT TRANSFER COEFFICIENT ALONG
STAGNATION LINE OF A SINGLE SLOTTED FIN

This figure, taken from reference 22, corresponds to stagnation line heating data for a highly swept fin upstream and downstream of a single chordwise slot. The slot allows natural stagnation line boundary-layer bleed, which in this case, is sufficient to "relaminarize" an initially turbulent swept attachment line. Such fixes for the attachment line contamination problem are well known for low speeds, but this experiment at Mach 8 indicates that the process also works at high speeds.



APPLICATION ISSUES FOR SUPERSONIC (SUCTION) LFC

The major issues are as indicated. Supersonic specific problems include maintenance of smoothness and waviness conditions in the presence of large thermal stresses, suction penalty minimization, and duct volume/sealing management. Passive efflux (in lieu of suction pumps) may be of particular importance for the supersonic case where the bodies approach wave-rider designs. Allowing bleed through the wing (bottom to top) would simultaneously (a) provide LFC on the bottom surface, (b) provide turbulent C_f reduction on the top surface, and (c) reduce wave drag by reducing the strength of the upper surface closure shock, all at nearly minimal system weight and duct volume (depending upon detailed structural design). A possible added benefit would be a reduction of thermal stresses through a tendency to make the entire wing structure more nearly isothermal.

- Minimization of suction drag penalty required for reasonable "return on investment"
- Aerodynamic heat transfer induces high temperatures/thermal stresses which can severely compromise
 - Surface smoothness/waviness
 - Suction duct sealing
- SPFDB honeycomb titanium with electron beam perforations appears to constitute a "best bet" surface
- Suction duct volume requirements are in opposition to the thin wing requirement for wave drag reduction

Suction options include (a) active and (b) passive (bleed)

- Passive efflux can
 - Reduce turbulent drag
 - Reduce wave drag (increase δ^*)

ALTERNATIVE CONFIGURATION APPROACHES
- SUPERSONIC CRUISE LFC -

A basic design decision for supersonic LFC is whether to reduce wave drag but increase LFC difficulty/cross flow by increasing sweep or to reduce sweep, increase wave drag, but simultaneously improve the LFC design problem. In fact, for the nearly zero pressure gradient attached shock flat wing case, the cross flow may be reduced sufficiently to allow wall cooling to become a major LFC factor.

Blunt subsonic leading edges

- Λ large
- Low wave drag
- Large cross flow, makes suction LFC difficult
 - High suction rates required
 - Increased sensitivity to roughness including suction surface geometry (partially plugged slots, perforations)

Sharp supersonic leading edges

- Λ moderate
- High wave drag
- Smaller cross flow, makes suction LFC "easier"
 - Lower suction rates
 - Reduced roughness sensitivity
 - Wall cooling (for SST speed range) an adjunct/alternative control technique (cryo fuel)

SUPERSONIC LFC - BOTTOM LINES

Essentially, supersonic LFC is attainable. Considerable detailed research remains, but there are presently no known "stoppers", and many benefits. The porous surface suction technology must obviously be worked. All of the previous research employed slotted surfaces, and such research should be carried out in low-disturbance facilities for maximum "intellectual" return on investment, i.e., improved understanding of disturbance growth physics and control thereof.

- Aerodynamically, supersonic LFC is attainable, perforated surface physics/efficiency still to be determined
- Critical issues for application include
 - Minimization of suction drag penalty to maximize net drag reduction
 - Approaches include improved slot pressure recovery, passive bleed rather than active suction, cross-flow minimization
 - Necessitated by increased suction requirements due to high sweep/cross flow and High M
 - Duct volume, heated air handling/sealing

SUGGESTED RESEARCH TOPICS FOR SUPERSONIC LFC

This chart provides some suggestions for fluid physics research applicable to supersonic LFC. The possibility that some of the "unit Reynolds effect" observed in flight may be due to disturbances engendered by atmospheric particle-shock interaction is particularly intriguing (see refs. 23 and 24). Also, as noted previously, the suction process creates myriad flow field shocks which should tend to amplify the existing disturbance field in the boundary layer. Information on this process is required for suction surface optimization.

- Perforated surface suction with and without cross flow, experiments and theory especially at large sweep angle/cross flow
- Disturbance amplification through shocks
 - Impinging
 - Suction generated
- Disturbances induced by atmospheric particle/bow-shock interactions
- Further theory/analysis for steps, gaps, waviness, roughness (and combinations) with and without cross flow at high speed

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