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OPEN QUESTIONS - TRANSITION TO TURBULENCE AT HIGH SPEEDS, 1971

by

M. V. Morkovin

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13 ABSTRACT

For supersonic and hypersonic vehicles the absence or occurrence of transition to turbulence often becomes a primary design consideration. Yet testing facilities cannot duplicate the corresponding environmental design conditions and the designer must rely on extrapolations, generally with several parameters varying simultaneously. This paper attempts to clarify what type of information appears currently most desirable. First a succinct review of the known factors affecting high-speed transition is presented. In particular, the areas of uncertainty are outlined and their implications discussed. Extra background (including on work in progress) is furnished on more crucial and somewhat controversial issues. This factual information is then used as a basis for an assessment of possible transition research projects and their relative priorities.

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OPEN QUESTIONS - TRANSITION TO TURBULENCE AT HIGH SPEEDS, 1971*
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ABSTRACT
(Unclassified)

The shock of the 1967 Boundary-Layer Transition Study Group Conference (AF Rpt. No. BSD-TR-67-213, Vols. I-IV, W. D. McCauley, Editor) started many repercussions in our national attempt to cope with the dilemmas it bared. From the vantage of the author's 1971 reevaluation of the scientific and practical problems (Ref. 5) a succinct recapitulation of the salient aspects of transition is first presented. The up-to-date unclassified information is then compressed into twenty-two observations which are quite inconsistent. Four groups of targets for longer-range transition research are then identified and speculated about. The main objective of the paper is to provide concise background information and some stimulus for the discussions of the various Committees at the Workshop.

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(U) OPEN QUESTIONS - TRANSITION TO TURBULENCE AT HIGH SPEEDS, 1971

FIGURES

INTRODUCTION

For supersonic and hypersonic vehicles the absence or occurrence of transition to turbulence often becomes a primary design consideration. Yet testing facilities cannot duplicate the corresponding environmental design conditions and the designer must rely on extrapolations, generally with several parameters varying simultaneously. This "working paper" attempts to clarify what type of information appears currently most desirable for longer-range objectives of rational design for transition.

Most of the information, on which the paper rests, has been described and documented in the USAF sponsored "CET" (Ref. 1,which has an Index), in "MM" (Ref. 2)*, and in Mack (Ref. 3), where the reader will find specific details and references. Newer information has been compiled for a briefing to the NASA Advisory Research Subcommittee on Fluid Mechanics (unpublished) and for the forthcoming volume of Advances in Aerospace Sciences, edited for Pergamon Press by D. Küchemann (Ref. 5).

CET (Ref. 1) represented an approximate 1968 consensus of some sixty researchers in high-speed stability and transition, experimental and theoretical. The groundwork for that consensus was laid here at the Aerospace Corporation in 1967: Ref. 6. This paper succinctly recapitulates key concepts and findings of the earlier consensus, weaves in the newer data, and speculates about the consequences and prospects. Perhaps it will be of use for the deliberations of the Committees at this Workshop. For that purpose each subtopic is numbered separately for easy specific reference.

1. FACTORS IN HIGH-SPEED TRANSITION

(1.01) Boundary-Layer (BL) instabilities comprise a group of runaway phenomena in which disturbances are selectively amplified by factors of 100 - 10,000 before self-regenerative wall turbulence sets in.

(1.02) Criteria for self-regeneration of wall turbulence (intensity, scale, phase relations; existence of minimum Reynolds numbers, R_{min}, for guaranteed growth or decay; relaminarization of turbulent shear layers) are barely discernible at low speeds and completely unknown at high speeds.

*The Mack-Morkovin lectures are now available on tape, with all the supporting material: Ref. 4.

(1.03) Theory and experiment indicate a multiplicity of competing runaway modes (generalized Tollmien-Schlichting waves ~ 2Dim. TS mode; Mack's higher "acoustic" modes; oblique waves in 2D boundary layers, more unstable at supersonic speeds; modes associated with streamwise vorticity of mean shear layer - cross-flow modes; nonlinear vorticity stretching and deformation of 3D patterns behind roughness; vorticity stretching in accelerated layers; etc.) each of which can dominantly or cooperatively with others grow to the self-regeneration threshold and generate a local turbulent spot at a position x,z,t, (y being normal to BL and z spanwise). See the instability-transition flow chart in Fig. 1.

(1.04) The relative distribution of unsteady free-stream disturbances (vorticity ≡ turbulence; temperature-density-entropy spottiness; sound) and their relative 3D spectra (characteristics which are extremely difficult to measure) apparently determine which of the modes dominate the growth to transition in a particular boundary layer at a given Mach number, M, Reynolds number, R, cooling ratio, H_w/H_r (enthalpy or temperature at wall to that at recovery conditions), for a given streamwise and lateral pressure gradient, three-dimensionality of the mean layer, wall ablation or transpiration rate, $\dot{m}$; etc.

(1.05) The process of assimilation of the free-stream vorticity, entropy fluctuation, or sound, into the various unstable modes (1.03) (BL receptivity or transfer function) remain essentially unexplored, theoretically or experimentally.

(1.06) The parameters or Operation Modifiers, (Fig. 1), cited in (1.04): M, R, H_w/H_r, p(x), p(z), 3D'ity, $\dot{m}$, etc., determine the mean BL profiles, and through them, (often rather sensitively) the amplification rates of the different competing runaway modes of (1.03). For small (linearizable) disturbances, amazingly rich functional dependence on M, R, and H_w/H_r, of the selective amplification rates has been partially charted by Mack (Ref. 3) for $M \leq 10$ (quasi-parallel assumption) and quantitatively verified on an adiabatic flat plate at M of 4.5 by Kendall in the acoustically aseptic Jet Propulsion Laboratory supersonic wind tunnel. (No other tunnel currently has acoustically nonradiating laminar sidewalls at R's of interest.)

(1.07) No comparable high-speed theoretical information exists on the effects of the other operation modifiers, p(x), p(z), 3Dity, $\dot{m}$, etc., either singly or in various combinations.

(1.08) Roughness elements, 2D, 3D, single or distributed, are not "true disturbances" but rather passive operation modifiers, which alter the profiles (even causing local separation) and hence the amplification rates of the assimilated free-stream disturbances. At low speeds, single 3D roughness elements may bring about locally unstable motion, which even though vigorous, remains below the threshold of self-regeneration, see (1.02). When the disturbed motion decays, vigorous or not, the roughness effect is called subcritical (with respect to the whole BL, rather than local profiles). A slight increase in unit Reynolds number, R/L, may then cause the local unstable motion to change to a sequence of self-regenerative turbulent spots, growing into a turbulent wedge - the supercritical behavior.

(1.09) At high and low speeds, an increase in wall cooling (decrease in H_w/H_r) which is stabilizing on smooth walls (first mode of the linear theory see (1.10) - and substantial verification of transition trends at lower M's) may cause a shift from subcritical to supercritical role of roughness elements. Since the transition distance with increasing cooling then stops growing and starts moving toward the leading edge one speaks of transition reversal in presence of roughness.

(1.10) The cited functional richness of Mack's solutions (1.06) includes a distinctly different response of his higher acoustic modes and the first mode (1.03) to changes in the cooling ratio H_w/H_r. While the first mode is stabilized by cooling, the higher modes actually become more amplified and shift to higher frequencies. Therefore, the input spectra not only influence which competing mode may dominate transition, as in (1.04) but also which mode governs the transition sensitivity to cooling. Reshotko (Ref. 7,8) pointed out on dimensional grounds that it may be difficult to escape the higher modes in steady-flow hypersonic wind tunnels, while they may have little relevance to the boundary layers on bodies in ballistic ranges. If so, one would expect differences of transition behavior with H_w/H_r in these facilities.

(1.11) An additional significant characteristic length enters most of the practical configurations at high speeds: the nose or leading edge "thickness", which generates a shockwave and, through the subsequent entropy blanket, modifies the mean BL properties until the layer grows sufficiently with x to "swallow" the entropy layer (x_{sw}, the swallowing distance). For such bodies, transition is again sensitive to a combination of functionally distinct Reynolds numbers, and hence to the dimensional unit Reynolds number R/L. (Empirically, small and moderate nose blunting tends to move transition downstream.)

(1.12) Configurations for which BL development is nonsimilar because of geometry, pressure gradient, boundary conditions (e.g. decreasing Hw(x) in the heated-nose effect), etc., essentially harbor additional characteristic lengths which also tend to make Reynolds-number scaling R/L dependent.

(1.13) Once a turbulent spot is formed in laminar surroudnings, it moves downstream while growing in all directions. The lateral or transverse growth (contamination) of a turbulent spot or wedge decreases from about 11° semiangle at low speeds to about half the angle at hypersonic speeds. As a nonlinear turbulent process it is essentially R independent, in contrast to the linear amplification region. Two turbulent spots or wedges, growing side by side, apparently grow into each other without an increase in lateral growth rate.

If R_{xB} denotes the Beginning x (nondimensionalized) at which the first turbulent spots are generated, the region over which additional spots are seeded and over which they grow until the laminar patches disappear at R_{xE} (end), may be extensive. The length of the transition region may be significant for design: $R_{xE} - R_{xB} = C\,R_{xB}$, where C may range from 0.5 to 2.0, with C~1 commonly observed in wind tunnels. All the preceding observations are empirical - there is no theory of transverse contamination.

2. INDETERMINACY OF HIGH-SPEED TRANSITION, PARADOXES, AND DISCREPANCIES

(2.01) As a runaway phenomenon of multiple competing modes, (1.03), feeding in an unknown manner, (1.05), on unknown input mixtures of disturbances with nonwhite 3D space-time spectra, (1.04), transition is intrinsically nondeterministic. (By contrast high-Reynolds-number turbulent layers are quasi-deterministic on larger, average scales, except near separation - Ref. 9.) Any design predictions should take into account in some way the disturbance environments of the operational vehicle and of the facilities from which the transition information was obtained.

(2.02) The mean properties of the BL in question are seldom measured or well enough computed. Hence, additional uncertainties-and causes for discrepancies between experiments - often creep in. (Mack's linear theory (1.06) indicates that amplification rates are occasionally very sensitive to temperature profiles.) In many experiments, especially flight tests, one does not even have information on BL thicknesses δ^* or θ.

(2.03) In a given family of facilities, such as continuous wind tunnels, ballistic ranges, or shock tubes (Ref. 10) the unknown unsteady and steady disturbances tend to evolve in more or less repeatable group patterns - unless willfully modified when testing for sensitivity to disturbances, e.g. Fig. 2, borrowed from Spangler and Wells (Ref. 11). For a given model shape, the large number of potentially independent parameters characterizing the unsteady and steady disturbances (1.04), (2.02), are then hidden. Their combined effects blend with those of the amplification controlling parameters and appear as variations in R_{xB} with M- and with the trouble-indicating dimensional parameter R/L, (stagnation pressure). Observed repetition of "similar" R/L variations creates a temptation to lump the factors (1.02) - (1.07), (1.11), (1.12) into a mythical single "Unit R Effect" and approximate it by the simplest power formula: $R_{xB} \sim (R/L)^n$, n an empirical constant. The pressing needs of the designer may justify such procedures for a current design, but hardly endow it with general research validity.

(2.04) In the same facility the exponent n generally takes on different values even for simple shapes like 2D wedges or hollow cylinders, sharp cones, and wedges with sweepback (the corresponding n variation being roughly from 0.6 to 0.1 in "noisy" hypersonic wind tunnels). This testifies to the fact that R/L variation represents a combined response to many factors.

(2.05) For a given model, transition moves upstream as R/L increases even for n ~ 0.6. Physical considerations make one doubt that the power formula could continue to hold generally: the experiments in a given facility seldom span factors of R/L more than 12-15. In fact, there are hypersonic wind tunnels (Softley, Ref. 12a,b; Mateer and Larson, Ref. 13; Neal, Ref. 14) where at some operating conditions the R/L dependence disappears while it is present at others. For applications, credible extrapolations (!) rather than interpolations are needed.

(2.06) Since much of high-speed transition research consists primarily of "macroscopic" detection of R of transition (some value between R_{xB} and R_{xE}, depending on technique and facility) as function of M and R/L, for nominally fixed H_w/H_r, and for normal facility constraints, a number of investigators in NASA, ARO, etc., feel that the information is inadequate to separate the "true" M and R variations, i.e. those corresponding to a free-stream without group variation of disturbance parameters. Some feel that the so-called M bucket (minimum of transition R near $M \sim 4$) reflects primarily the ignorance variation with R/L (see MM Sections H and I). Lester Lees does not expect the issues to be clarified until enough of "microscopic" transition research is carried out which would trace the distinct effects of disturbances and amplification rates (CET, Section I).

(2.07) Kendall's evidence from JPL "quiet" tunnel (which can be made willfully noisy by tripping of sidewall boundary layers), the Pate-Schueler 2D correlations (Ref. 15), and Pate's cone correlations, (Ref. 16), make it clear that for $3<M<8$-10, transition in wind tunnels tends to be dominated by powerful acoustic disturbances radiated from the turbulent sidewall boundary layers. The intensity, scale, and spectra of this radiation, its interaction with the bow shock wave, and its assimilation within the laminar layer in question (with its own scales and receptivity) certainly depend on M and a number of distinct characteristic lengths. The processes are exceedingly complex as this afternoon's presentations by Kendall and Mack will undoubtedly demonstrate. Earlier evidence indicated that generalized TS waves, etc., (1.03), may be growing in presence of sidewall sound irradiation, but that they are probably not the primary mechanism responsible for "irradiated" transition. The new hot-wire evidence of Kendall, (Ref. 17), seems to point to three-dimensional non-linear processes. Closer quantitative comparisons with Mack's new computations of directly driven, non-TS, disturbance growth, (Ref. 18), will be needed to ascertain which part of the development this new linear theory can match. In "noisy" wind-tunnels for $M > 3$ perhaps one should look to this new theory rather than to the free TS modes for a rational guide to parameters which govern amplification (or to both?).

(2.08) The "sound-radiator" correlations of Pate and Schueler and of Pate show that, when cast as R_{xNE} (near end of transition) versus R/L, they account for most of the observed power variations, (2.03). Similarly, for a fixed R/L, the M variation appears consistent with expectations. Consequently, one might expect that if the irradiation were removed, the peculiar R/L dependence would disappear for cones and flat plates.

The quantitative verification of Mack's linear theory at M of 4.5 by Kendall, (1.06), was carried out under such circumstances where the r.m.s. pressure fluctuations were in fact decreased by factors from 50 to 100 from the "noisy" conditions for the relevant frequencies above 1000 Hz. While it appeared that these modes, which were stimulated by Kendall on purpose, grew according to the theory, one can only assume that transition would generally take place as a downstream development of such modes if left to itself: "natural" transition was never reached in the "quiet", laminar-sidewall condition.

(2.09) The only way that similar sound disturbances could be affecting a vehicle in atmospheric flight would be through the partially known mechanism of interaction of atmospheric free-stream turbulence and temperature-entropy spottiness with the bow shock (Chapter 3, Ref. 5). It is not presently certain that such atmospheric disturbances of sufficiently large amplitude exist down to the small scales relevant to vehicle boundary layers, CET, Appendix 2. One would be tempted to conjecture that transition Reynolds numbers based on hypersonic-tunnel information are low compared to those in atmospheric flight - unless a new set of effective disturbances took over the dominant seeding role.

(2.10) In 1957, flights in atmosphere revealed the "early blunt-body transition", i.e. transition in the nose region of cooled axisymmetric blunt bodies, which was previously considered stable on the basis of the usual linear theory. It is still the implication of CET Refs. 17, 140, 222-223, that unless surface roughness is reduced below 5 microinches r.m.s., a designer should expect transition at Reynolds numbers (based on momentum thickness θ) of 150-250 for free-stream R/L on the order of 10^8/inch in flights with substantial cooling. (This is often called the blunt-body limit.) Apparently, there is enough energy in atmospheric free-stream disturbances at small enough scales to excite the nose boundary layer, made three-dimensional by roughness, and possessing high density near the wall because of cooling. While one can conjecture that the dominant destabilizing effect is one of stretching of streamwise vorticity disturbances, the mechanism remains unknown and outside of the realm of the generalized Orr-Sommerfeld equations. Such transition mechanisms not corresponding to linear theory will be referred to as bypasses.

(2.11) Clearly, a designer must document experimentally all the bypasses which can possibly be present for his configuration before he can rely on linear theory, even for guidance. Systematic "spoiler" testing in ground facilities with on-purpose roughness, non-uniformities etc., somewhat larger than realistically anticipated to occur in the unclement flight environment, is in order. Only after such preparation are the usually much less informative flight tests indicated - for checking environmental conditions not otherwise obtainable.

(2.12) Flight tests in ballistic ranges (cleared of dust; with long settling time) by and large remove the combination of free-stream disturbances plaguing the hypersonic wind tunnels. In accordance with (2.08), one would expect a substantially increased R_{xB}, unless another bypass rose out of the "noise level", as the front-runner disturbances are discarded. Potter' results (Ref. 19) on 20^o total-angle cones with 0.005 inch nose radius, however, exhibit lower transition Reynolds numbers, CET, Section IV, 3. Furthermore, Potter observed an R/L variation similar to those in wind tunnels, even though the dominant turbulent radiation of Pate and Schueler, with its R/L dependence, was not present. The dilemma of the lower transition R and the $(R/L)^n$, $0.6 < n < .7$, variation of Potter remain unreconciled. (Two factors may be relevant: the cones were rather cold, T_w/T_r of 0.18, and the unit Reynolds number moderately high, R/inch of $1.22 \cdot 10^6$.) One could speculate with respect to the possibility of transition reversal,(1.09), nose disturbances, (see Jedlicka, CET, Ref. 114), and other so-called auto-disturbances in highly stressed models.

Sheetz' independent verification of the R/L effect of Potter in the NOL Ballistic Range was cut off after six shots, Ref. 20. The contrast between

Potter's results and Sheetz' small sample is tabulated below in terms of local properties at edge of BL.

	M_e	R/in x 10^{-6}	T_w/T_r	Nose rad.	Cone angle	R/L power, n
Potter	4.4	0.7 - 4.3	0.18	0.005 in.	20^o total	.6 - .7
Sheetz	6.9	1.1 - 11.6	0.11	0.001 in.	10^o total	.2+

Since the techniques of determining R_{tr} appear similar, the substantial difference in the R/L sensitivity poses further questions as to its causes. Potter will undoubtedly have wiser comments on this in his presentation (Ref. 21) than any speculations the author might adduce.

(2.13) Strong arguments have taken place between experimenters as to whether transition is sensitive to the cooling ratio H_w/H_r at M's > 6.5 (CET pp 50-52 and Chapter 9, Ref. 5). Little sensitivity is found in near-continuous hypersonic tunnels, where, however, transition is likely to be dominated by sidewall sound, e.g. Sanator et al, Ref. 24. A partial collection of published temperature-sensitive transition data is shown in Fig. 3. It includes the "insensitive" sample of Sanator et al, the recent information of Mateer (Ref. 22) and Maddalon (Ref. 23), as well as a typical "re-reversal" behavior of Richards and Stollery (ref. 25) and Wisniewski and Jack (Ref. 26). In the NOL ballistic ranges transition reversals - for highly polished bodies, but cold and at relatively high R/L values - are inferred for the full explored range $0.02 \leq H_w/H_r \leq 0.26$. Sheetz' newly discovered R/L sensitivity (2.12) is mild so that the transition reversal of his earlier experiments (Ref. 27) apparently remains.

The cluster of points near T_w/T_r of 1.1 on the extended Maddalon curve in Fig. 3 indicates a new type of reversal - with heating, which is also implicit in the work of Wagner et al (Ref. 28) in the same M ~ 20 helium wind tunnel.

(2.14) Rhudy and Whitfield (Ref. 29) raised the possibility that some of the reversals in Fig. 3, e.g. those in gun tunnels and ballistic range, might be associated with the time-dependent gradient of wall temperature $T_w(x)$, as per factor (1.12), an effect not specifically investigated at supersonic speeds. Controlled hot-lip experiments at low speeds (McCroskey and Lam, Ref. 30; Cebeci and Smith, Ref. 31) demonstrate that the effects can be large - but stabilizing! In effect, the wall farther downstream was absorbing the heat liberated at the nose. Cebeci and Smith used a non-similar boundary-layer program to generate the evolving profiles (just like Rhudy) and tackled the stability problem on a quasi-parallel, x-independent basis. The linear theory confirmed well the experiments!

(2.15) It was thought of interest to relate the Wisniewski-Jack double reversal to published unclassified flight-test information on cones, which are presumably free of acoustic irradiation: Fig. 4. The same information in terms of local Re_{tr} and local M_{cone} is presented in Fig. 5, this time compared to tests on the same 5^o total-angle in six different wind tunnels. Discussion and more specifics of the reversals of the Merlet-Rumsey and Rumsey-Lee flights are found on pp 48-49 of CET. As related on p 47 of CET, a series of flight tests with different degrees of high surface polish convinced the NACA personnel that even 6-10 microinches, r.m.s., of surface roughness could have substantial effects on transition. The reversals were suspected to be such effects. It would be interesting to have the different roughness correlations applied to these cases.

(2.16) It has been hoped that if regions of overlap of M, R, and T_w/T_r can be achieved between ground facilities, much could be learned and explained. Lemcke, Naysmith, Picken, and Thomann (Ref. 32) and Naysmith (Ref. 33) report agreement of laminar and turbulent heat transfer rates but not of R_{tr} between the flight of Jaribu MK.2, a parabolic-nose vehicle, and wind-tunnel tests at the Swedish FFA, despite "almost perfect aerodynamic simulation" at $M_\infty = 7.17$! For that condition, the flight T_w in the laminar region hovered around $0.37 \cdot T_t$ and R_∞ (based on 0.5 ft. diameter) was 5.32×10^6 while in the tunnel T_w/T_t were 0.43 and 0.32, and R_∞ was 5.10^6. R_{tr} (based on local conditions) in the presumably acoustically contaminated tunnel, even at $\alpha = 5^o$ remained above 10^6, while in flight R_{tr} was below $0.5 \cdot 10^6$, i.e. extremely low with respect to any values in Figs. 4 and 5. Since the actual flight model was tested in the tunnel (using the flight sensors) the surface roughness were "the same". The biggest difference was in the stagnation temperature T_t: flight 2115^oK vs. tunnel 700^oK. The authors make an indirect, fairly plausible case for the vibration of the rocket-motor as the culprit. See further discussion in Section 9.9 of Ref. 5.

(2.17) Yet another high-Mach number flight program ($M_\infty > 10$, unspecified; $M_e \sim 6.1$) did not produce very high transition Reynolds numbers: Sherman and Nakamura (Ref. 34). A series of four shots of identical, beryllium-skinned, graphite-tipped cones of total angle of 44^o, following "identical" unspecified trajectories, registered the following history. "Transitional flow began at the aft end of the vehicle" ($R_{tr} \sim 5.3 \pm 0.7$; $R/ft \sim 1.6 \times 10^6$; $R_\theta \sim 850 \pm 60$; $M_e = 6.2 +$; $T_w/T_r \sim 0.09$; all based on local values) "and moved forward along the conical surface at a decreasing (i.e. non-constant) value of the local Reynolds number", reaching the front measuring station for: $R_{tr} \sim 3.2 \pm 0.2$; $R/ft \sim 2.6 \times 10^6$; $R_\theta \sim 660 \pm 30$; $M_e = 6.1+$; $T_w/T_r \sim 0.12$; see Figs. 4 and 5. Could this represent the re-reversal leg of Wisniewski-Jack, Richards-Stollery mark of Z? Again, the freedom from acoustic irradiation, which poisons the tunnels, did not raise R_{tr} to the high levels one might expect...

(2.18) Obviously, there are problems with understanding and predicting transition on cones (at zero angle of attack) and on wedges. And yet these simple shapes are not amenable to many designs, e.g. those of lifting-entry vehicles. Figure 6 borrowed from the recent Young, Reda, and Roberge study (Ref. 35) the Multipurpose Reusable Spacecraft at Mach 10 demonstrates a special effect such as may unexpectedly develop for non-simple geometries. At $\alpha = 10\text{-}20^o$, the spherical nose flaring out into a flat bottom accentuates the formation of a local minimum of shock inclination, which occurs even on pure sphere cones as shown by L. N. Wilson (Ref. 36). The larger shock decelerations away from this minimum inclination produce a relative subsonic jet of faster fluid at the minimum; a jet, which can be seen traveling (as a density maximum) toward the body along the 3D streamlines in Fig. 28. The "Ames effect" (for Seiff, Sommer, Canning, Cleary and Larson from Ames Research Center who spoke to deaf ears for years) consists then of the transition of this highly unstable relative jet and of the contamination of the boundary layer (Coles' effect: Section 6.2 of Ref. 5) for angles for which the jet streamlines come close enough to the body. The observed Reynolds numbers of transition (causing severe heating) were extremely low despite the usually beneficial hypersonic effects at Mach 10. In fact any chief engineer who would have gambled a design on the best predictions and correlations would have probably lost his vehicle - see the educational Fig. 15 of Young et al.

(2.19) Even at zero angle of attack, the approach to the effects of pressure gradients is hardly rational. In fact, not even the linearized stability theory teaches one how to separate the effect due changes in M_e and due to the alterations in mean profiles. The concept of the entropy-swallowing distance has been very fruitful for small blunting radii (Section 5.2 of Ref. 5) but non-empirical estimates of the optimal effect and any characterization of the adverse blunt-body effect are lacking.

Michel and Schmitt (Ref. 37) present a systematic study of 3 cone-cylinders and 3 ogive-cylinders at $T_w/T_t = 0.36$, $M_\infty = 6.9$ (see their Figs. 6, 9, 13-15). There are differences due to mismatched gradients but the local R_{tr} values correlate quite well on the basis of local M_e for fixed R_∞/cm of $0.3 \cdot 10^6$. The adverse effect of the bluntness is clearly indicated in their Fig. 15.

Softley's empirical scheme (Ref. 38) for estimating optimal blunting and his comparisons with cones in pressure gradients are described on p. 62 of CET. An intriguing postponement of transition when the nose of a hollow cylinder was made to protrude into a region of considerable negative pressure gradient in the tunnel was reported by Bertram (Ref. 42) on his p. 23.

(2.20) The first case of relaminarization ever was observed and documented by Sternberg (Ref. 39), see also pp. G_8 - G_{11} of MM, Refs. 2 and 4, and Sections 3.8 and 3.9 fo Ref. 5. Apparently the Michel-Schmitt bodies did not reach the relaminarization conditions but other bodies are likely. Similar relaminarization (often only local) exists in the high accelerations in wind tunnel nozzles, e.g. Amick, Ref. 40, and Winkler and Persh, Ref. 41. A "quiet" supersonic tunnel must either sustain the relaminarization throughout (e.g. the JPL wind tunnel) or suck away the final turbulent boundary layer.

(2.21) Thus the pressure-gradient effects can be studied on the sidewalls of some supersonic and hypersonic tunnels at very low unit Reynolds number. Apparently the largest sidewall Reynolds numbers (based on distance from the throat) thus far achieved with laminar boundary layers are on the order of 5×10^6 at M of 4.5 at JPL ($R/L \sim 0.05 \times 10^6$/inch) and 13×10^6 at M = 18.7 in the Langley unheated 22 inch helium tunnel ($R/L \sim 0.17 \times 10^6$/inch)- Wagner et al, Ref. 28. Using hot wires, Wagner et al documented that as the sidewall boundary layer of the M 20 helium tunnel goes through transition at a given x, when R/L increases, the dimensionless pressure fluctuations at the downstream tunnel centerline position, to which the x station radiates, rise rapidly and then slowly subside as R/L continues to rise.

(2.22) It is this subsidence which is apparently responsible for the n-power rise, (2.03), of R_{xB} at beginning of transition on models inserted into supersonic and hypersonic tunnels. This trend is present on a wedge model (local M_e) in the above M~20 helium tunnel. However the shift to the extra high R_{xB} corresponding to a truly laminar sidewall layer at low R/L values were not reached (as they were at JPL at M of 4.5), even though the pressure fluctuations in the empty tunnel were substantially lower. (Perhaps the subsonic turbulent boundary layers are not perfectly relaminarized in the nozzle region leading to the possibility of very long transitional stretches with nondense turbulent spots as in the case of Jedlicka et al, Ref. 114 of CET, also with high accelerations.)

3. SPECULATIONS ON POSSIBLE TRANSITION RESEARCH AND DEVELOPMENT

The first two pages of Appendix: "Major Open Questions Relevant to Applications" were discussed, with sketches, on pp. J_1-J_4 of MM Ref. 2 and on the cassettes, Ref. 4. The possibly presumptuous adjective "relevant to applications" refers to the fact that most of these questions arise when one wishes to extrapolate effects of two or more parameters and discovers that they indicate countertrends in R_{tr}. Generally, these countertrends occur when the responsibility for transition shifts from e of the multiple factors to another. These are also the conditions where a designer needs more guidance - hence the adjective.

The two pages and Sections 1 and 2 represent one man's shopping list for stability and transition research but without indication of priorities. (Further comments can be found on pages 64-66 of CET.) The manner of presentation already imposes some bias and it would be altogether presumptuous to indicate one's subjective priorities.

The third page of the Appendix represents a personal view of the Nature of the Problem as the author understood it when he was associated with the design of the SV-5 Entry Vehicle. The philosophy of design for transition is further discussed in Chapters 10 and 11 of Ref. 5.

Among the problems listed in the Appendix and the issues described in Sections 1 and 2 four related groups of problems, with high priority both for urgent engineering applications and for clarification of the basic structure within which other questions can be more meaningfully researched, can perhaps be identified without much controversy.

(I) Resolution of the 1967 San Bernardino dilemma of the M, R, and T_w/T_r variations with new but not especially encouraging information. More specifically:

(Ia) Reconciliation of information from wind tunnels (quasi-continuous and "pulsed"), (2.01)-(2.08), (2.16), (2.18)-(2.22), ballistic ranges (2.02), (2.12), and free atmospheric flight: (2.01), (2.02), (2.10), (2.15)-(2.17).

(Ib) Full clarification of the increasingly more irritating phenomena of reversal of transition with cooling, see (1.09), (2.13), (2.14), (2.15), and Figures 4 and 5.

(II) More consistent conceptual framework, especially

(IIa) Clarification of the role and limits of existing linear theory, e.g. with respect to temperature effects, including entropy-layer and hot-lip effects (2.14).

(IIb) Identification and classification of transition "bypasses" of linear theory, e.g. (2.10), (2.11), acoustic irradiation in tunnels (?).

Note: basic research on (IIa) and (IIb) at low speeds is far from complete, and even there the role of nonlinearity remains confused, CET pp 8-10, and Chapters 3, 4, and 10 of Ref. 5.

(III) Sound approach to streamwise pressure gradients which should probably lean on both the concepts of physical mechanisms and of linear theory - see (2.18), (2.19), and relaminarization (2.20). Variable heat transfer and ablation often complicate these effects and need to be tackled in due course.

(IV) Same objectives for cross-flow gradients, which are likely to have additional instability mechanisms (judging by low-speed linearized theory for flows with streamwise vorticity, see Chapter 7 of Ref. 5). Sporadic evidence of formation of streamwise vortices, especially in presence of sweepback, edge-unevenness, local separation and/or ablation, calls attention to the implications of this phenomenon.

These broad categories encompass many, many problems and forbiddingly many variables and parameters. The task of characterizing adequately the mean profiles for I-IV alone is a formidable problem. Current design clearly cannot wait for the broad, longer-range approach. One needs to take the correlation road, but with circumspection. For a given design with strong "family constraints" on the parameters (e.g. due to special trajectories such as those of Ref. 34), the procedure may well be safe, but one would be wise to evaluate the risks carefully and keep in mind the possibilities of unexpected effects such as those encountered on Jaribu, (2.16), and on the Multipurpose Reusable Vehicle, (2.18). And the basic question remains: which ground facilities can be relied upon for the design estimates?

That question alone suggests that the longer-range program has to be pursued as well. But where is the best pay-off? If a "quiet tunnel" with high enough R/L could be successfully designed and built at a Mach number 10-15, its laminar operation might well (or might not) validate the results from other hypersonic tunnels which are currently suspect. The implications of the published experiences in the Langley M20 helium tunnel, (2.20)-(2.22), make the author currently less optimistic as to the prognosis. Hopefully the report of E. Reshotko and his Committee at this Workshop can shed some better light on the prospects of the quiet tunnel.

In his recent academic ignorance of flight results the author would like to ask a question which has been bothering him with respect to the incomplete information of Figs. 3-5. Can hypersonic vehicles with high cooling, say $H_w/H_r < 0.3$ consistently reach the high values of R_{tr} which linear theory would indicate? Without and with ablation? If not, would not this fact point to the temperature sensitivity as the key problem? For what conditions is the achievement of high R_{tr} "spoiled"? Judging by the available information: this occurs for high cooling, relatively high R/L, and small roughness combinations of conditions, (2.10), (2.12), (2.15)-(2.17). Such conditions have been little explored experimentally* and the cognoscenti of the various facilities can perhaps feel challenged and encouraged to devise telling experiments for such combinations

*The kinematic viscosity based on wall values may be more significant for correlations in such cases.

of conditions. If the above premise is correct, any information gleaned from such efforts may well have an important bearing on target category I. But these speculations belong more appropriately to the Committee sessions on Friday, which hopefully can lean on the projections of facts in Sections 1 and 2 herein.

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APPENDIX

MAJOR OPEN QUESTIONS relevant to applications	MM page (Ref. 2) CET page (Ref. 1)
*Early blunt-body transition	p 24, 46-47 MM: H-9 to H-11
Non-quasi-parallel stability theory including vorticity stretching	MM: H-9
*Effect of nonsimilarity, e.g. Whitfield's hot-lip effect	pp 23-28 p 25, Fig. 11 MM: H-8, H-9
**R_{tr} sensitivity to H_w/H_r; M > 6 < Ball range; gun tunnel / more conventional tunnels	
**Reversal with cooling for "smooth" bodies < blunt flat	p 46 p 49-52
**R_{tr} rereversal with high cooling	p 51
**Unit R effects < Wind tunnel Pate & Schueler Ballistic range Potter, Sheetz	MM: Section H, I
*Existence of "bypasses" flight	p 59 MM: G-2, G-21
*What part of R_{tr} variation is M-effect?	MM: H-17 to H-20
and what part is R/L-effect?	MM: Section I
*Role of favorable $\partial p/\partial x$ at M > 1	MM: F-35
**Role of streamwise vorticity at supersonic and hypersonic M's - 3D BL's	pp 40-45
sweep; α	
protuberances	MM: F-28, H-2, H-14-17
spanwise nonuniformities	MM: F-19, F-20
*$\dot{m}$ (transpiration, ablation)	p 66 Figs. 32, 33
*Interactions of $\dot{m}$ and H_w/H_r effects (cf. countertrend (6) p J-2 of MM)	
*Interactions of $\dot{m}$ and cross-flow effects	
*Interaction of cross-flow and H_w/H_r effects	
Free-stream disturbance fields + their variations	MM: H-4, H-5 pp 26-28
and	
Receptivity of B.L to all disturbance modes	MM: Section G pp 23, 27, F-37

Interaction of bow-shock with modal disturbances	p 96 MM: G-11 to G-14
*Variation of transverse contamination with M	MM: F-19, F-20
**Nature of turbulent BL's at high M's	p 66 MM: F-1, H-12

See also Index of Ref. 1 and Table of Contents of Ref. 5.

NATURE OF PROBLEM:

MULTIPLE RUNAWAY PHENOMENA, COMPETING

UNKNOWN INPUTS

TOO MANY PARAMETERS

BASE FLOWS (= MEAN PROFILES) POORLY PREDICTABLE, YET AMPLIFICATION-CONTROLLING

INSUFFICIENTLY KNOWN CRITERIA FOR TURBULENCE SELF-REGENERATION, ESPECIALLY FOR LARGE M'S

NECESSITY OF EXTRAPOLATION OF INFORMATION FROM LIMITED GROUND FACILITIES

NUMBER OF SUFFICIENTLY CONTROLLED EXPERIMENTS FORMS TOO SMALL A SET OF SAMPLES FOR ANY SCIENTIFIC PROBABILITY STATEMENTS

NEED FOR THEORETICAL (LINEAR) AND CONCEPTUAL (INCLUDING NONLINEAR EFFECTS) FRAMEWORK TO GUIDE JUDGMENTS OF NON-STATISTICAL PROBABILITIES

DESIGN ASSESSMENTS OF RISKS OF SUCH PROBABILITIES

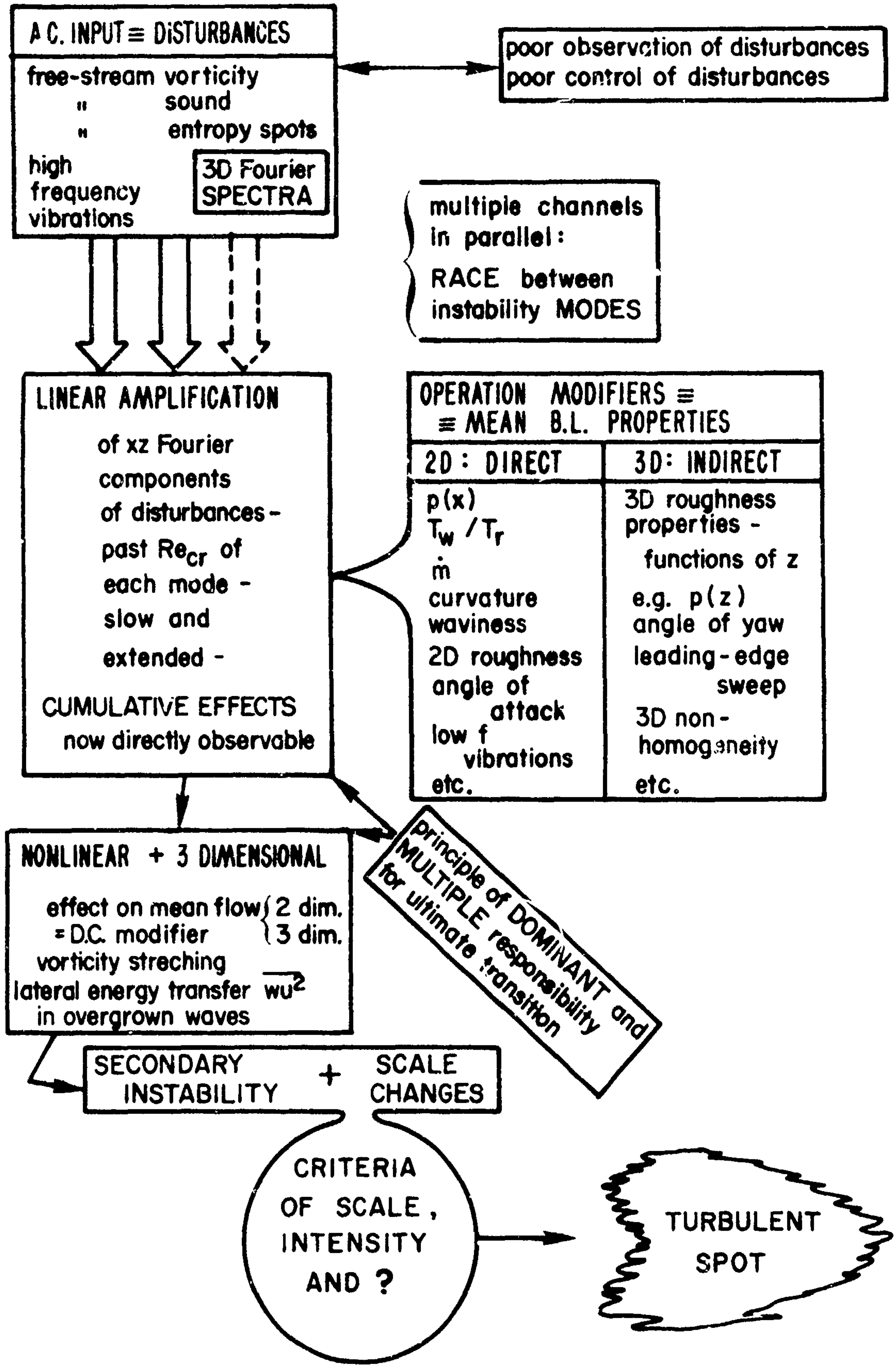


Fig. 1 - Laminar Boundary Layer As A Linear And Nonlinear Operator

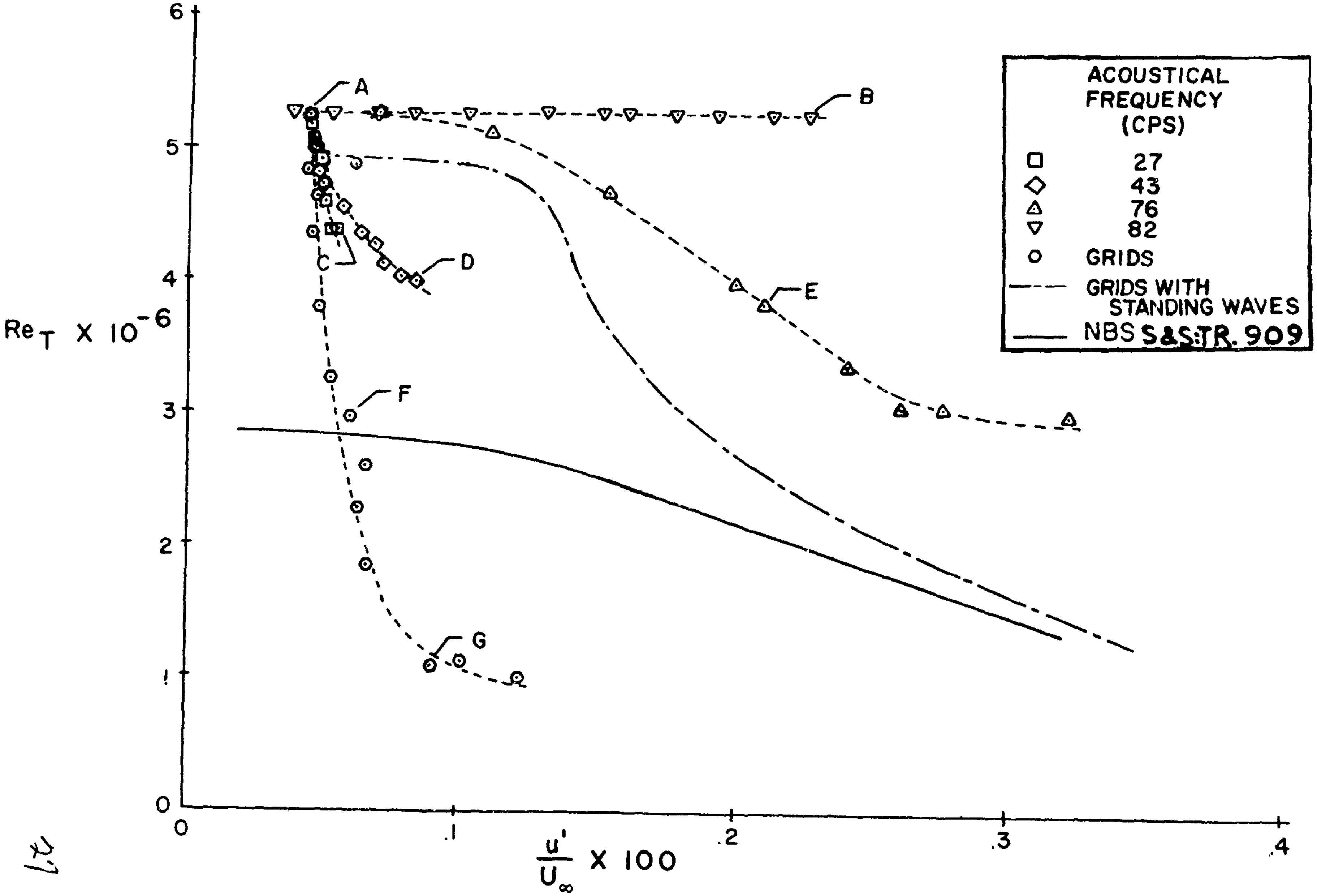
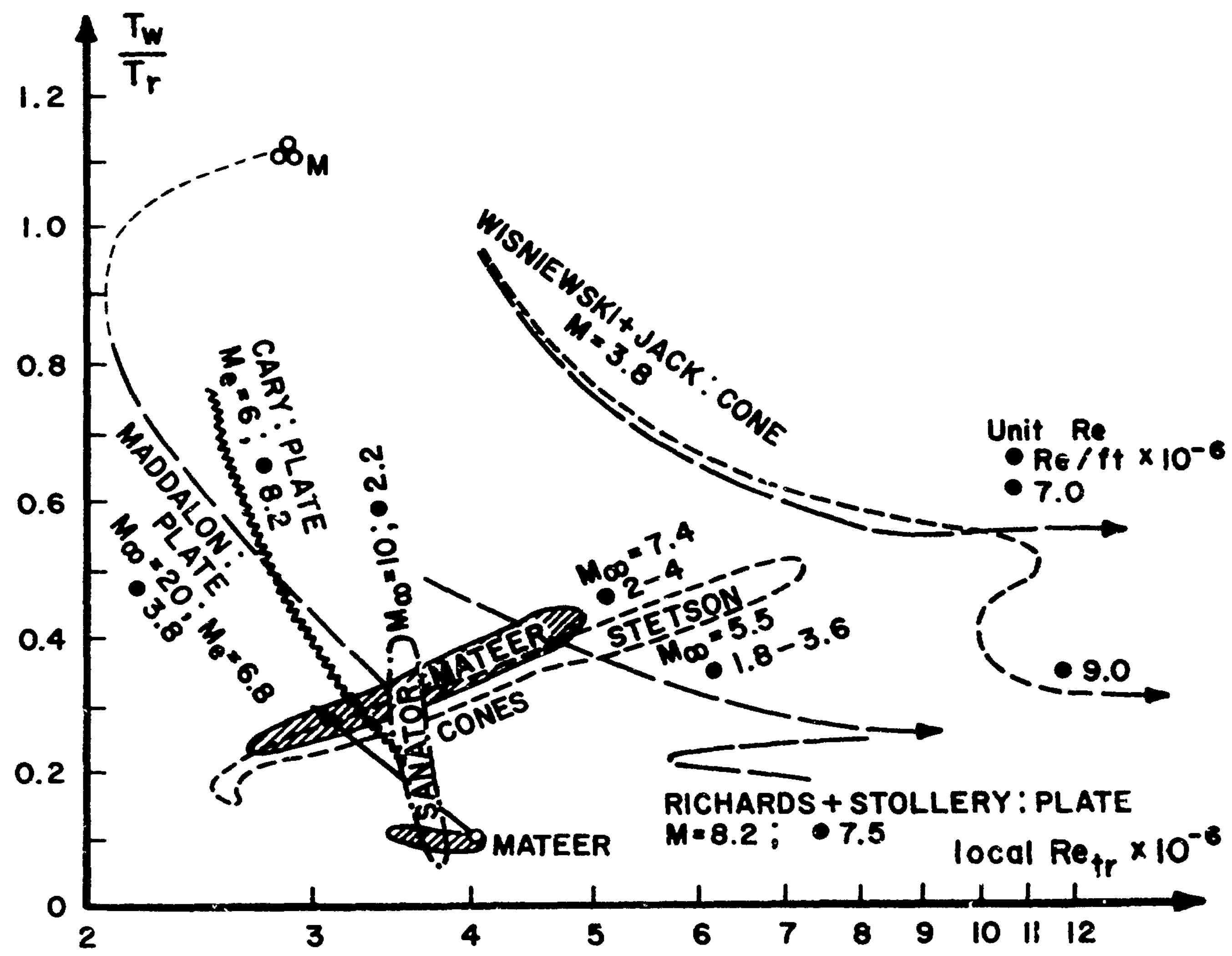


Fig. 2. Transition Reynolds number as function of free-stream disturbance intensity. ($U_o/\nu = 2.4 \times 10^5$/ft; $U_o = 38.5$ fps). From Spangler and Wells. Ref 11.



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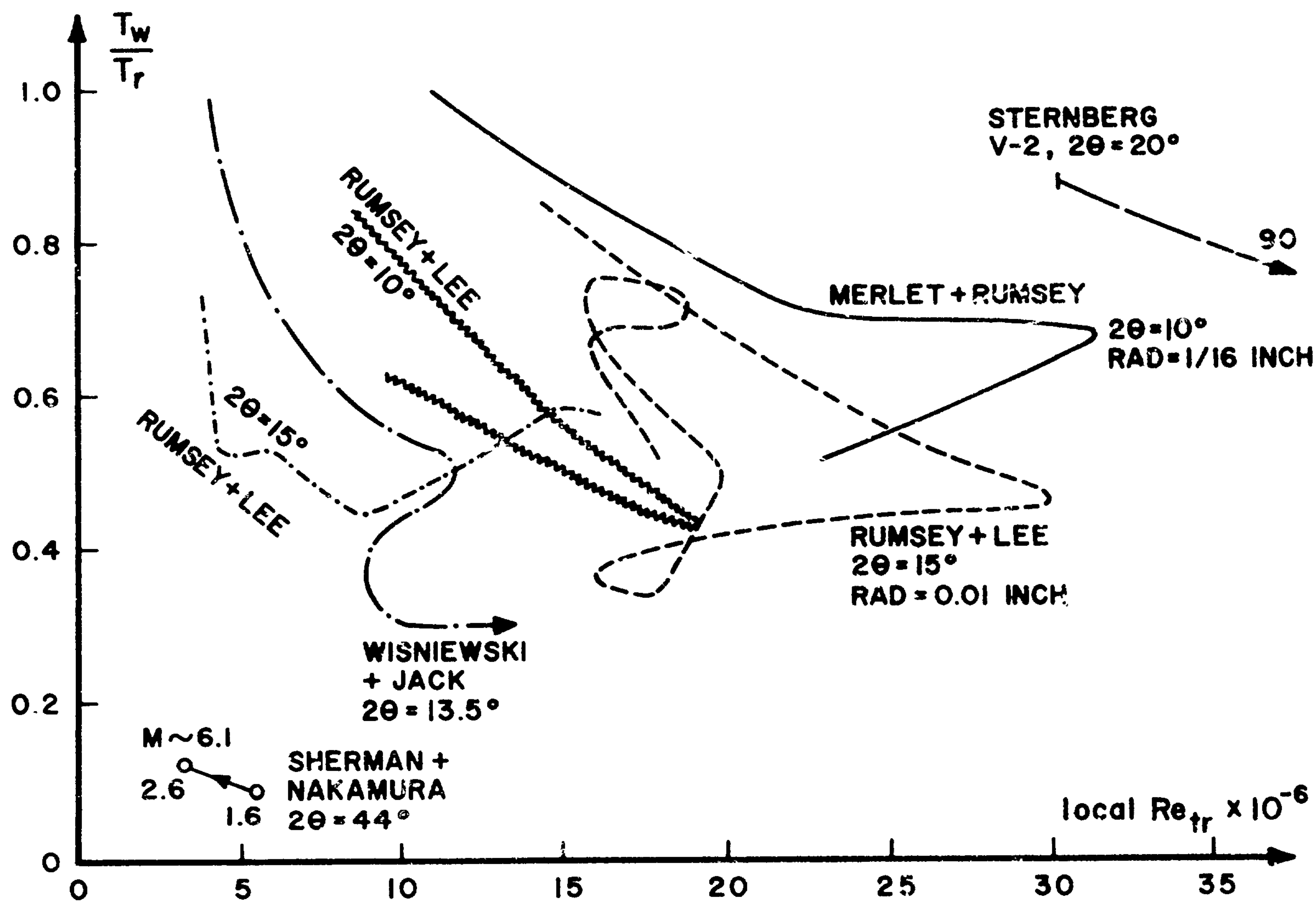
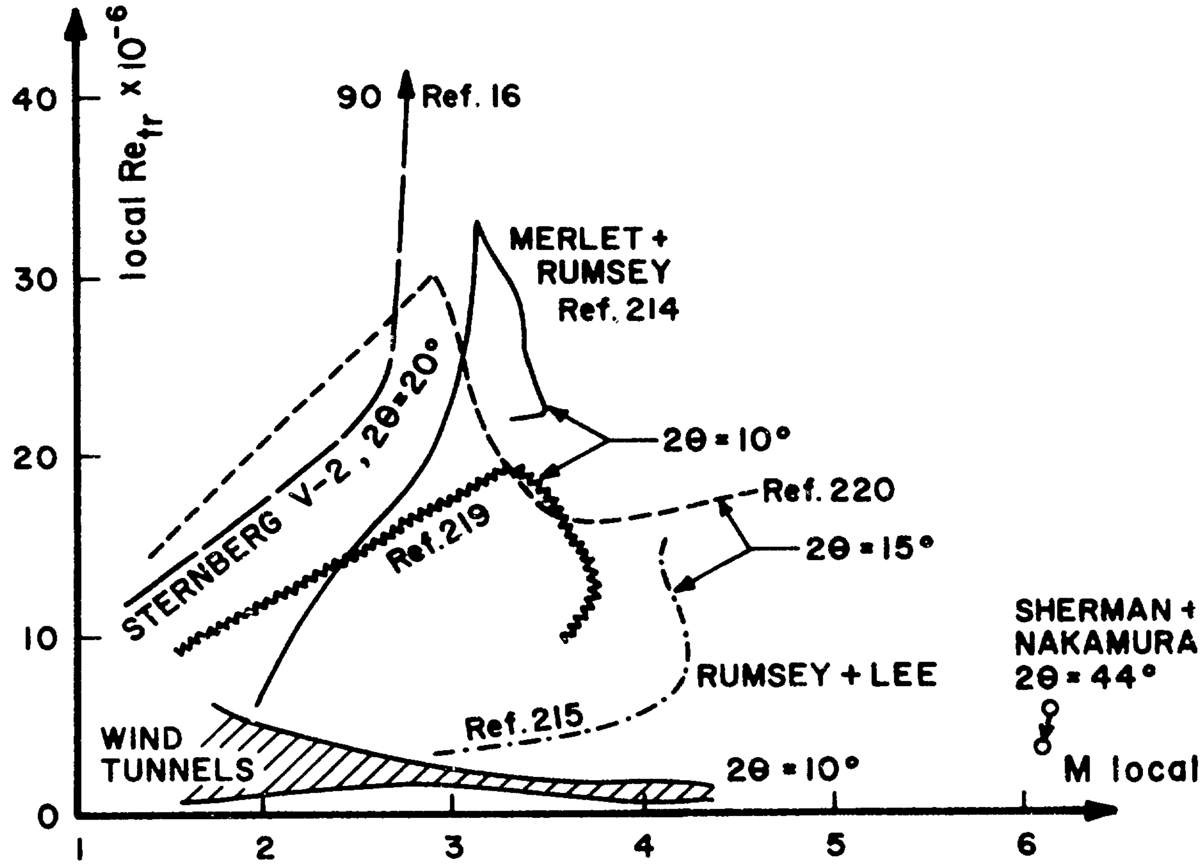
3. Transition Sensitivity to Cooling in Various Wind Tunnels



4. Transition on Cones in Flight in Terms of Local Reynolds Number and Local Cooling Ratio.



5. Transition on Cones in Flight in Terms of Local Mach Number and Local Reynolds Number.