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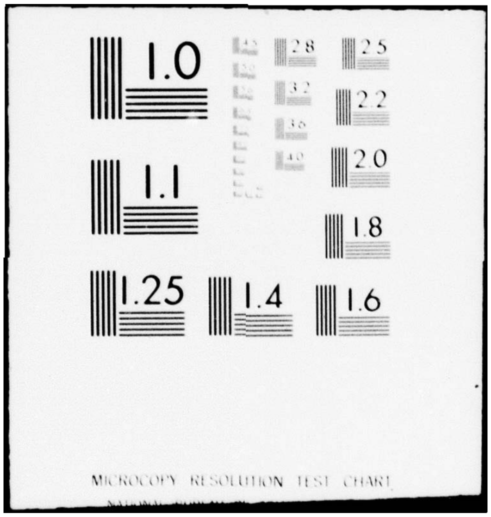
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Instability, Transition to Turbulence and Predictability

by

M.V. Morkovin

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(6) INSTABILITY, TRANSITION TO TURBULENCE AND PREDICTABILITY,

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PREFACE

This paper constitutes the "Opening Address" delivered by the author during the AGARD Fluid Dynamics Panel Symposium on "Laminar-Turbulent Transition" held at the Technical University of Denmark, Lyngby, Denmark, 2–4 May 1977 (AGARD-CP-224).

The manuscript was not ready in time for inclusion in the AGARD Conference Proceedings, CP-224, however, in view of its importance to the research community, the Fluid Dynamics Panel chose to publish it as a separate AGARD publication. Consequently, the author was able to include in the present report an up-to-date view of the phenomenon of transition. It is recommended that interested readers also obtain copies of AGARD-CP-224 and the Technical Evaluation Report on the Symposium on "Laminar-Turbulent Transition" by the present author, AGARD-AR-122.

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INSTABILITY, TRANSITION TO TURBULENCE AND PREDICTABILITY

by

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SUMMARY

Transition is described and analyzed as a system. The progress in our understanding of the various features of the system is examined and illustrated. This includes advances in the long confused problems of transition in channels and pipes. The role of linear and nonlinear theory and of microscopic experimentation is discussed.

The transition system is recognized as inherently nondeterministic and some consequences of this fact for research and design are drawn. The interrelationship between researchers, testers, correlators, computer predictors and designers is touched upon. Misunderstandings have been expensive. It is concluded that need exists for a more realistic philosophy of transition research and of transition-conditioned design.

1 INTRODUCTION

1a Framework of Reference for Our Task

When twenty years ago I was preparing my first survey paper on transition[1], it became clear that I could not convey adequately the complexity of the phenomena unless I borrowed the more familiar language of electrical systems: *hence Fig. 1 (rearranged into the present form in my later reviews*[2,7]). The details in the Figure deserve careful individual consideration, but Figure 1 will be used here primarily as an overall map to guide us with respect to our task to "review the progress achieved during the last ten years and to bring to light the still unsolved problems," as set for us by the Fluid Dynamics Panel under THEME AND OBJECTIVES. Much of the detailed progress (or lack of it) has been reviewed rather recently by Reshotko[3], Tani[4,5,10] (low speeds), Liepmann[6], Morkovin[11] (high speeds), Schlichting et al[8], Loehrke-Morkovin-Fejer[9] (for free streams $U = U_0(1 + A \sin \omega t)$), Mack and Morkovin[12], Hirschel[13] (swept wings), Stuart[18] and Stewartson[26] (nonlinear theories), Michalke[27] (free shear layers), and others. I will therefore assume that these reviews were or shortly will be studied* by this transition research community so that I can be free to focus here on a smaller set of observations and issues related to the state of our knowledge and its usage.

1b Development of Attitudes toward Transition Research

Ten years ago Lester Lees, keynoting a similar transition congregation[14] at San Bernardino, in the midst of gloomy confusion about transition in high-speed and three-dimensional flows, opened the discussion with "I think it might be appropriate to begin with a short prayer." He called for "microscopic** experiments," especially in the areas of confusion, to identify the disturbance environment and the multiple modes of instability and mechanisms of transition, preferably in conjunction with linear stability calculations. A crystallized list of critical high-speed transition issues and practicable high-priority research directions was presented *** to NASA's Subcommittee on Fluid Dynamics in October 1969 and led to the formation of the U.S. Transition Study Group (USTSG), still chaired by Eli Reshotko despite organizational metamorphoses. The Group's initial program of research and its philosophy was presented by Reshotko[15] in 1971 but continues to be relevant to our task here. A first crop of seven coordinated papers by the Group was published in the March 1975 issue of the AIAA Journal and was put into perspective by Reshotko[16] at the 1974 ICAS Congress. Similar recognition that transition had best be tackled cooperatively also grew in Europe in the early seventies and ultimately led to the formation of the Working Party on Transition in Boundary Layers within EuroVisc and to an outline of their credo by Hirschel[17], most pertinent to our task here. And, of course, the Fluid Dynamics Panel of AGARD has repeatedly focused on stability and transition questions and has convened us here for another sharing of views and appraisal.

1c Reliability of Evidence

In the latest review[3] Reshotko not only traced the interaction of microscopic experimentation and linear theory that did in fact remove some of the confusion which prompted Lees' 1967 sermon in Ref. 14, but also covered major developments through mid-1975 and ended with "Directions of current and future

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* Minimal starting background for appreciation of the complexities of transition: Tani[4,10], Reshotko[3], Morkovin[7], Hirschel[13].

** *Term incorrectly attributed to me.*

*** The report was published in 1971 with minor modifications as Ref. 11. The four groups of high-speed problems listed on pp. 16 and 17 therein remain essentially unsolved, although IIa, clarification of the role and limits of existing linear theory, has been much advanced by Mack and Kendall, and the Quiet Tunnel is making headway under Ivan Beckwith's leadership. The rest can therefore be part of the Copenhagen 1977 Open Questions List.

investigations," another assist for the task before us. Unlike any other contribution to the Annual Reviews series, Reshotko's incorporated a set of challenging USTSG guidelines for research in Transition Testing which in effect emphasizes the special multifaceted and hypersensitive nature of our subject. Because the fourth guideline relates to one of the themes of the present paper:

Q_1: What constitutes sufficient evidence for a result to be considered as established?*,

I will quote it in full: "4. Tests where possible should involve more than one facility. Tests should have ranges of overlapping parameters, and where possible, experiments should have redundancy in transition measurements." This guideline should perhaps be extended to theoretical research as well, and by a "facility" we could equally mean a "theoretical model with its computer program." One can have a good understanding of a theoretical treatment without being able to decide which paper (say on non-parallel stability theory) is most trustworthy, unless there is a harmonious overlap of computed results, or unless the sets of authors are willing to subscribe to a consensus position.

1d Funding and Philosophy for Transition Research

All in all, it would seem that Copenhagen 1977 is more blessed than San Bernardino 1967: we have a first approximation to a system's view of our subject in Fig. 1, we have a series of recent reliable critical reviews of various subfields of the subject, and part of our task has been accomplished through thoughtful lists of open questions established through discussion among researchers who recognize the necessity of coordinated and cooperative approach. However, what has been increasingly missing under the prevailing economic climate is sustained funding for such coordinated research and for facilities which are necessary to tackle whatever worthwhile lists of research targets any blue-ribbon groups may painstakingly work out. This is a serious and frustrating matter. Problems unresolved 40 years after the availability of hot wires are likely to yield only to sustained efforts of extra qualified minds and hands with special tools and facilities. We should of course convey our relatively harmonious and thus hopefully more convincing views with sufficient emphasis to the funding powers that be. But in face of genuinely limited resources we should perhaps also scrutinize our research shopping lists for priorities.

Perhaps we should also examine how our research product is used by the design community. Do we convey *to them adequately the unavoidably uncertain quality of our transition knowledge and estimates?* Does the designer understand well enough the probabilistic nature of the information given him, to include probabilities in the assessment of the risks of his design? Do the computer-armed transition predictors who furnish him with stacks of definitive transition variations with multiple parameters without estimates of possible errors really help the designer in his true task? A communal philosophy of transition research *has been emerging for some time, viz. the USTSG guidelines. Shouldn't we also pay attention to the philo*sophy of transmission of the transition information and of its utilization? This might help with the assessment of priorities for the unsolved problems and even with improving the climate for transition research funding.

2 SELECTED OBSERVATIONS ON TRANSITION SYSTEMS

The first group of observations simply translates into words selected features of the unstable system portrayed in Fig. 1. Here the box of linear amplification refers to Tollmien-Schlichting waves (generalized for compressibility and skewness), or Görtler waves (concave boundary layers), or unstable supersonic higher modes of Mack[8,12], or *instability waves in three-dimensional boundary layers (e.g. on* swept wings, see Stuart[20]), all growing in streamwise direction in response to oncoming non-uniform three-dimensional disturbance configurations of vorticity, sound, and entropy patterns(which include as a subset streamwise vorticity wave numbers capable of feeding the Görtler mode, see Fig. 3 of Bippes and Görtler[21]).

2a Forcing and Amplification of Eigenwave Packets

The disturbance environment forces transition to occur, often through a long process of concatenated development stages.

For moderate to small disturbances the responding motions at "incompressible speeds" behave as a superposition of free 2D and 3D eigenmodes, fully internalized past, say, Re_{cr}. Their total amplification in the linear regime is likely to exceed 500 - 2000 (pp. 12-13 of Ref. 19) and may reach 10000 to 12000.

2b Nature and Specification of Forcing Disturbances

The disturbance environments (the Input Box in Fig. 1) in which transition-dependent designs will operate are generally unknown.

Since the above amplification favors selectively small Re-dependent subregions to the wave-number space, proper characterization would call for full 3D spectra of all three types of disturbances near the excitable location of the shear layer. Vorticity and the density-temperature disturbances, being quasi-parabolic, are describable in terms of classical 3D Fourier decomposition. Acoustic disturbances in subsonic facilities need to be decomposed into progressive duct modes and streamwise and crossstream standing waves; see discussion on pp. 536, 545, and 547 of Loehrke et al[9].

Even for careful wind-tunnel experimentation requisite measurements tend to be prohibitive (especially when one recognizes that tunnel disturbances tend to change even during a single day).

2c Receptivity and Disturbance Propagation Speed

Even if the disturbance environment were known, the manner in which it induces the internalized eigenwaves which propagate at different speeds than the parent disturbances is generally not known. This receptivity process (arrows connecting the Input Box to the Linear Amplification Box in Fig. 1) probably

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* In transition work there is a tendency to overbelieve new insights which often turn out to be only partially valid--see Some Lessons from History, pp. 4-7 from Ref. 2.

results in transfer functions which attenuate the input at first; see pp. 6-8 of Ref. 19. The only conceptual models of the receptivity process with some accord with experiments thus far are for acoustic disturbances: for supersonic boundary layers (Mack, see Reshotko[3]) and for low-speed laminar jets (Morkovin and Paranjape[23]).

The receptivity transfer functions are in principle determinable by a combination of theory and experiment. Reshotko reviewed the state of the art in Ref. 3 and Rogler will describe the latest thinking tomorrow.

2d Nonuniversality of Ultimate Nonlinear Breakdown

In the nonlinear stages the ultimate development (left bottom of Fig. 1) is unlikely to be universal but is likely to depend on the specific disturbance-induced spectral mix of the internalized eigenmodes. (See for instance the rapid growth of oblique components in the wave packets of Gaster and Grant[22] and Miksad's description[29] of the "sensitivity of [nonlinear] wave number selection to initial and external conditions" in his and other people's experiments.) There may be topological similarity due to the constraints of mass conservation and wall boundary, but the secondary instabilities which frequently lead to breakdown of laminarity may be sensitive to finer details of the flow. It is known (e.g. Tani[4]) that when Komoda[39] increased the three-dimensional perturbation of his boundary layer the pattern of breakdown differed from that of Klebanoff, Tidstrom, and Sargent[28].

2e Secondary Instabilities

The transitions which arise from identifiable linear instabilities seem to need at least one secondary instability before turbulence sets in. Apparently the linearly triggered motions first build up larger-scale wave-eddy entities which lead to periodic thin local shear layers. The generally three-dimensional smaller-scale wave-eddy entities resulting from the secondary instability can then interact with the larger-scale structures (which may also be interacting among themselves as in the mixing-layer fusion processes) to provide a basic stage in the turbulence cascade. It is possible to generate turbulence at lower Reynolds numbers by activating the nonlinear three-dimensional source term of vorticity $\vec{\zeta}\cdot\vec{\nabla}\vec{V}$ ($\vec{\zeta}$ = vorticity, $\vec{V}$ = velocity vectors), but the production and dissipation appear then to go on at nearly the same scales, with no "room for honest turbulent cascades." (A quantitative version of this surmise would use arguments similar to those on pages 159-160 of Tennekes and Lumley[30].)

The secondary instabilities have been observed in boundary layers by Klebanoff et al[28] (multiple spikes), by Kovasznay et al[31], and by Hama and Nutant[32] (reproduced as Fig. 3 in Ref. 7); in Görtler instability by Bippes[33] and Wortmann[34]; in Ekman layers in spinups and spindowns by Faller and Kaylor[35] reproduced as Figs. 10 and 11 in Ref. 7); in the three-dimensional skew boundary layer on a spinning ogive-cylinder by students of F.N.M. Brown (reproduced as Fig. 17 of Ref. 2); and in mixing layers by Wille's associates, e.g. Freymuth[36], and others elsewhere.

In his presentation at the 1968 NATO Symposium on Transition[37], Michalke pointed out that, in the mixing-layer case, turbulence often sets in rather suddenly in the strongly sheared and deformed layers, as two vortices rotate around each other in the fusion mating dance (see Fig. 2), but the conference report labeled all free shear-layer transitions as inherently "slow" without reference to dimensionless scaling. Figure 2, courtesy of Michalke and Freymuth, shows that turbulence can appear within 1-2 fundamental wavelengths after the secondary instability sets in, just as it did for Klebanoff et al[28] in a boundary layer. At the same conference Thorpe[38] demonstrated the secondary fusion instability and consequent genesis of turbulence on the Kelvin-Helmholtz interface of water and brine (in an exceptional experiment which corresponds more closely to temporal instability theory than to spatial theory).

Nothing definite is known about secondary instabilities at supersonic speeds, mostly because microscopic measurements are so much more difficult to carry out and to interpret[52]. Special care in optical techniques often discloses the presence of grown wave-eddy entities just before the identifiable breakdown into turbulence.

2f Bypasses

Bypasses are those roads to transition which cannot be identified as starting from a known linear instability (direct connections from the Input Box to the Secondary Instability or the Turbulent Spot in Fig. 1). The very term bypass is a reaffirmation of the fact that judiciously utilized linear theories--generalized Tollmien-Schlichting (T-S) waves, Görtler theory, etc.--provide us with the basic framework within which some organization of our multifarious observations can be rationally effected (e.g., Reshotko's analysis[40] of contradictions among supersonic facilities). The classical baffling bypass has been that of transition in a pipe, first observed 96 years ago by Osborne Reynolds. We shall return to this geometry with a current interpretation of the phenomenon. Another bypass, as little understood in detail now as in 1943 when Charters[41] first described it, is the phenomenon of transverse or lateral contamination. We still cannot rationally predict the spreading angle of the turbulent front (wedge), nor why it drops to roughly a half at supersonic speeds[45]. Transition due to distributed roughness remains a bypass even though our observational and computational tools are probably ready for another deeper look. Referring to the ill-fated 1956-58 designs of heat-sink noses[43] of reentry vehicles and to experiments backing them (e.g., Peterson and Horton[44]), Donaldson wrote[42], " ...the nature of transition on blunt bodies at very high Reynolds numbers has been a source of embarrassment to aeronautical engineers." The lack of respect in the design for possible bypasses in uncharted regions of parameters cost tens of millions of dollars (or more), an embarrassing lesson that should make us rather sensitive to bypasses when transition risks imply risks to the basic mission of the design. (Capsule reentry on return from Mars is such a design.) The phenomena of "temperature reversal" and even "rereversal" at supersonic speeds (reviewed by Morkovin[2], pp. 16 and 50-52) represent further embarrassing bypasses which involve higher cooling rates and possibly relative protrusion of roughness into the boundary layer.

2g Knowledge of Vorticity in "Undisturbed" Boundary Layers

The linear amplification rates depend rather sensitively upon the distribution of vorticity in the boundary layer, the filter-amplifier. Known or unsuspected, any one of the factors listed in the box of Operation Modifiers on the right of Fig. 1 changes the vorticity distribution and therefore will change the growth rates, directly or indirectly, over a portion of the disturbance wave packet trajectory or throughout.

The effects of changes in two modifiers are generally not linearly superposable.

Only in careful microscopic experiments can we assess the actual state of the BL amplifier, which depends on velocity derivatives--e.g. $\partial^2 U/\partial y^2$, as well as on $U(y)$ and $W(y)$.

Reliable computer programs yielding the mean BL properties for the various modifiers are a prerequisite to stability analyses and adequate conceptual understanding of even the linear stages of the instability of a specific BL of interest.

However, it is a sobering fact of life that only in the simplest cases has the BL vorticity distribution been predicted adequately when compared to experiments. Thus we seldom know well enough the characteristics of our amplifier.

Emotionally appealing but costly flight experiments invariably do not furnish adequate modifier and and BL information (not to speak of information on disturbance environment), and the inferred transition locations have to be rationalized through disappointing sets of suppositions, yielding little definite knowledge--e.g., the X-15 airplane[24] and the Jaribu[25]. The "sufficient-evidence" question Q_I fares poorly in flight tests and not much better in the majority of ground experiments in which detail probing of the boundary layer is not available.

Any practical body shape will have a number of important modifiers acting simultaneously, making computer calculations of the boundary layer or its experimental determination more difficult (e.g., Jaribu[25] at angle of attack or the simplest original shuttle shapes, seen in profile only, in Fig. 3).

2h Dominant and Multiple Responsibility

In any realization of a shear layer a significant number of determining factors is usually present simultaneously (Input and Modifier Boxes of Fig. 1). As these ingredients vary in relative strength, the frequently long developmental chain leading to transition will vary, and so will Re_{tr}. Changes in the strength of any two members of the Input and/or the Modifier Box reveal either dominant or cooperative responsibility for the transition onset (Fig. 1), the effect of the changes being generally nonlinear. Thus even for the relatively simple case of a mixing layer with just two changes in the Input Box alone, namely variations of acoustic excitation at frequencies f_1 and f_2, Miksad[29] observes both dominance with nonlinear suppression of the weaker disturbance as well as varied interactions between better matched disturbances. The suppression depends on both the amplitudes and amplification rates. In the cooperative case "the results suggest that mean-flow distortions may play a primary role in the equilibration process" and that there is a "finite amplitude triggered instability of the difference (eigen)mode (corresponding to) f_2-f_1."

The mechanisms of interaction between changes in free-stream turbulence and a temporary distortion of the boundary layer profile by a small two dimensional protuberance (amplification modifier through vorticity redistribution) were elucidated for us by Klebanoff and Tidstrom in an important microscopic experiment[46].

The aforementioned shuttle shape in Fig. 3 causes an overexpansion at some angles of attack and a resultant local minimum in the shockwave slope. This in turn generates a local velocity overshoot--a narrow jet which can be traced as the whitish line approaching the bottom of the shuttle in the shadowgraph of Fig. 3. Young, Reda, and Roberge[47] documented for us that this local jet is rather unstable (as a doubly inflected free shear layer should be) and that its turbulence contaminates the boundary layer near the arrow in Fig. 3, causing a premature transition. A long chain of modifier interactions and a multiple responsibility indeed. Awareness of the responsibility principle is an essential diagnostic tool and the key to postponing or hastening transition, whichever may be desirable.

2i On Unit Reynolds Number Effects

As I have discussed on pp. 23-25 of Ref. 2 and illustrated on pp. H1-H8 of Ref. 48, when in flight or experiment one changes the freestream velocity U_1 or the dynamic viscosity ν (through density and temperature) for a fixed body, one obtains a variable Reynolds number of transition, $Re_{tr}(U_1,\nu)$. This nonconstancy is a necessary consequence of the fact that not all the determining factors in Fig. 1 (including the freestream disturbances) scale uniformly with U_1 and $1/\nu$. This of course poses a problem for the designer to decide which Re_{tr} value would correspond to the "real life conditions." Usually Re_{tr} is plotted against the dimensional variable U_1/ν in loglog coordinates, a power law is fitted to the discrete points and used for extrapolation to the real-life unit Reynolds number. This corresponds to an act of faith that there is a unique dependence on the dimensional unit Reynolds number U_1/ν.

When for sharp bodies at higher Mach numbers it became clear that leading edge thicknesses as small as 0.001 inch (0.025 mm) played important roles as a second characteristic length and spoiled the U_1/ν dependence, it became necessary to test a number of leading-edge thicknesses and extrapolate to zero thickness to save the power function and faith. When we review the determining factors in the Input and Modifier Boxes in Fig. 1, we recognize that it does take faith to expect them to scale in the same fashion in ground facilities and in flight, since at least the freestream disturbances, roughness, and the wall temperature $T_w(x)$ are subject to different controlling factors of their own. Of course it is easy to criticize; it is another matter to offer a constructive suggestion to the designer.

When we restrict ourselves to comparisons of Re_{tr} information between, say, supersonic and hypersonic windtunnels for which the determining factors of Fig. 1 may bear closer family similarities, the faith might be more justified but less useful. If there were a single factor with dominant responsibility then we could expect orderly variations with the body Re and with the Re characterizing the dominant factor, and perhaps then also orderly variations with U_1/ν. We now know that at least for $3 < \text{Mach} < 8\text{-}9$, the freestream disturbances are dominated by the aeroacoustics of the turbulent sidewall boundary layers (without counterparts in flight or ballistic ranges). The correlations of Pate and Schueler[49], which helped to establish the current consensus, are in effect a reflection of this restricted orderliness. The corollary to this aeroacoustic dominance is unfortunately that even less faith can be placed in extrapolating from windtunnel data to design flight. *Hence the need for the Quiet Tunnel that* we shall hear about later from Beckwith, who with his colleagues at NASA Langley Research Center undertook this important but risky and courageous effort[50].

2j On Sufficient Evidence in Macroscopic Measurements

Most measurements of Re_{tr} are macroscopic, made by a variety of techniques with their distinct sensitivities which introduce further discrepancies--e.g., Potter and Whitfield[51]. This and the unit Re effects (plural!) hardly make macroscopic measurements of Re_{tr} sufficient evidence for design information, let alone for conclusions about instability mechanisms causing the transition, even when the instruments are in the most skillful hands. A case in point was the pre-1974 disagreement between two NASA Mach 7.5 tunnels, one yielding an exponent in the U_1/ν approximately four times that in the other. With the encouragement of USTSG under Guideline No. 4, cited in Section 1c, the Langley and Ames researchers got together, bringing their own techniques and tools with them, and after great effort reconciled the new Re_{tr} observations[53] which differ from the earlier ones. Free-stream disturbances measured with hot wires and pressure sensitive gauges turned out not to be as similar as was generally assumed. Careful attention to the sensitivity of the transition detection gauges and to consistent identification of "onset," "peak," and "end" of transition also contributed to the reconciliation. This special effort removed some conceptual difficulties and underscored the need for extra care in macroscopic measurements in the inclement supersonic environment. For deeper understanding one has to turn to the microscopic measurements of Kendall[54] and linear theories and computations of Mack[55], who cooperatively brought much light to the supersonic scene.

If the variation $Re_{tr}(U_1/\nu)$ for sharp cones were due solely to the Re-conditioned sound generation from the turbulent sidewall layers, one would expect no such variation in ballistic range experiments where the air disturbances are minimal. Alas, range experiments with slender cones disclose a strong Re_{tr} variation (with an exponent higher than in wind tunnels!), a fact which limits the utility of transition information from ranges. In a series of determinations culminating with Ref. 56, J.L. Potter has systematically eliminated or substantially modified the various suspected causes without significant changes in the variation with U_1/ν. Therefore at present there is no explanation, not even a plausible suggestion as to which of the interacting determinants of transition in Fig. 1 could be responsible for the observed effects. This conceptual impasse is sobering, especially since Potter had the benefit of constructive criticism and help of USTSG and of specially designed experiments by Kendall, who provided Potter with data on the sensitivity of slender-cone transition to small angles of attack and to tip vibration[51]. The impasse lays bare once again the limitations of our ability to understand deeply enough supersonic transition in environments where microscopic experimentation is not available.

3 AN UNCERTAINTY RESIDUE IN TRANSITION OBSERVATION AND KNOWLEDGE

3a Features Which Will Not Be Known

The preceding chapter analyzed and illustrated those features of the transition system which are most relevant to our task. Their character and some of their implications for transition prediction are summarized in Table I. Even if we could improve our tools and knowledge by orders of magnitude, feature A alone would still make the system nondeterministic on the basis of our information. However, in any practical situation feature E also entails operating with severe uncertainties. Among the parameters D are included the inadvertent modifiers generated by steady or quasisteady departures from ideal geometry of flow and body, which invariably arise in research or prototype environments (waviness, roughness, low frequency vibrations, leading-edge nonuniformity, unaccounted for wall-temperature nonuniformities, dead bugs impacted in take off and low-level flight[84,85], etc.). By their nature many of these modifiers of consequence will remain unknown even in rather controlled research environments with frequent inspection and recalibration. As an illustrative lesson, we need only to recall the vexing effects of category D type of spanwise nonuniformities in the historic Bureau of Standards wind tunnel; see Klebanoff et al[28,56]. We may improve our understanding of the interactions between parameters associated with D (essentially the Box of Modifiers in Fig 1), but the presence of the inadvertent imperfections and their amplitudes will generally remain unknown. We may also hope to improve our knowledge of C and F, more conceptually than quantitatively. But from our base of information the transition processes will remain nondeterministic.

3b The Residue

As engineers and students of continua we seldom think nondeterministically, even in turbulence problems. I have therefore chosen the provocative description of uncertainty principle for transition to emphasize the notion, but the allusion misrepresents the basis for the uncertainty.

The observation only recognizes the preceding evidence and states that in a given situation we shall never know enough about the conditions and factors determining transition and that a basic uncertainty margin will remain for transition predictability. We can strive and hopefully will be successful in understanding conceptually the workings of the transition system, but we shall remain unable to transform such understanding into accurate quantitative predictions.

3c Uncertainty Brackets and Absence of a Probability Framework

Whenever we can affirm that no bypasses will operate we should be able to place quantitative brackets on the expected range of Re_{tr}. Hopefully, these brackets will narrow with further progress in our conceptual understanding. However, observation X in Table I emphasizes that we do not have a probabilistic basis for the influence of the parameters in our transition system, nothing remotely comparable to the situation in problems of fatigue failure of materials. We simply have no ground on which to theorize about first-excursion probabilities past a parametric boundary for turbulence onset. Therefore the above estimation of brackets will retain a strong experiential and subjective element even if it is done on a computer and quoted to six significant figures (assumptions, choice of detail features of modeling, etc.).

3d Prediction Subjectivity

Because of this subjectivity the assessment of the brackets can best be done in conjunction with the user of the specific estimates, the designer. It is he who must judge the consequences of the estimates in performance and economic risks of the given design. Unless he is fully aware of the nature of the "predictions" prepared for him, serious misjudgments can take place. Of course, the predictor can and should examine the elements of subjectivity which crept into his own product. A sample test would be: "Would I recommend the same Re_{tr} brackets if I had the sole responsibility for the decision which could result in a loss of one million dollars? hundred million dollars? one life? hundred lives?" Unfortunately predictors seldom give Re_{tr} brackets or even perform ordinary sensitivity analyses of their predictive programs. And the philosophy of decision making for transition-sensitive designs has not been discussed. This is not the forum to examine organizational issues, but one can perhaps suggest that the groups interested in various phases of transition (listed on the right of Table I) try to allow for the system view of transition and appreciate each other's problems and roles. Communication would help.

3e The Bypass Problem

The preceding discussion stipulated the absence of bypasses in the given system, but how can we be sure that a fiasco like the heat-sink nose design will not be repeated in a design case involving previously uncharted regions of our parameter phase space? We can not be sure, but we can be forewarned. We should be on the lookout for bypasses and endeavor to clarify the mechanisms of those we know exist. In the next chapter the clarification and partial removal of the pipe-transition bypass can perhaps show that there is a way if the right research questions are asked. Furthermore, in tests of the "first-time" designs, known disturbances can be introduced deliberately to assay the sensitivity of the system to possible departures from ideal conditions--i.e., apply the "spoiler" technique (Ref. 2, see Index therein).

3f Some Consequences of the Uncertainty Residue for Research -- Personal Opinion

Observation Y in Table I stresses that in view of the uncertainties, experimental and theoretical research which is aimed at concepts and mechanisms has a special role to play with respect to design. It must provide the conceptual and experiential framework within which the more rational judgments are made. On the other hand, the existence of the uncertainties makes some research questions previously asked rather academic, if not wasteful. For instance, we do not have unlimited funds to pursue elaborate computations which do not hold real promise of answering basic conceptual questions; just to see what happens, to display elaborate vortex formations, especially in a movie form, is not enough. One can be seduced by such impressive displays to endow them with an unjustified sense of reality. It would probably be just as impressive if a term in an equation had a wrong sign. The point is that unless such computer solutions are integrated with analytical concepts and microscopic experimental information they remain merely pretty playthings. Numerical experiments need as much focus and foresight to extract the more universal and meaningful numbers and features from the avalanche of available "data" as do classical microscopic experiments[57,28,33,54]. Miksad[29] extracted four consistent Landau constants for a two-mode nonlinear equilibration process from his hot wire measurements in an unstable mixing layer, thus supporting at least a local validity of Stuart's weakly nonlinear theory[59] for that flow (where Reynolds number is growing!). Why should not numerical experiments be able to do at least as well?

In his recent review of nonlinear theories Stewartson[26] states that the Landau-Stuart theory (which led among other results to the concepts of threshold amplitude, subcritical instability, and supercritical equilibrium) "can justly be regarded as the most important theoretical advance in the subject since the discovery of the Tollmien-Schlichting waves." We shall indeed find these concepts useful when we discuss the telling experiments of Nishioka et al[58] in two dimensional channel flow, but we shall also find that three dimensionality is nigh unavoidable in real life flows. Some analysts also seem to expect that the weakly nonlinear primary instability theory (which allows only small amplifications because of power expansions in the vicinity of the neutral curve) can describe phenomena well beyond its likely reach, such as the beginning of the breakdown to turbulence. Convergence problems (which trouble most nonlinear theories) and evidence of secondary instabilities in the shear flows which have been probed in sufficient detail (section 2e) makes this approach rather unrealistic. (See also section 4g.)

Research is a matter of personal values and taste. But when one asks that one's research be funded it becomes a matter of public values as well. We can perhaps ask that in stability and transition research the expected product aim at the numerous gaps in our concepts and understanding in Fig. 1. The worthwhile problems are hard, and this brings us back to coordinated research efforts discussed in section 1d and to the questions asked therein. In establishing one's research priorities and influencing those of others, one must of course exercise care that potentially promising, but not necessarily popular, ideas should not be squelched.

4 PLANE POISEUILLE FLOW NO LONGER A BYPASS

4a Theoretical Disagreement

For about fifty years, the inability of experimenters to keep two dimensional channel flows free from turbulence at relatively low Reynolds numbers Re, (U_{max} · half width/ν), when the parabolic flows are supposed to be stable according to linear theory (Re_{cr}, the critical Re, is 5772 for an infinite aspect ratio) has stimulated many sophisticated attempts at explanation of this bypass. Thus McLaughlin and Martin[60] write: "Channel flow, coaxial pipe flow...are examples of inverted bifurcation" and, according to them, as the neutral point is approached "the system immediately spirals out and enters a strongly nonperiodic orbit", which "maps out an invariant surface in the phase space of the system...an example of a strange attractor". According to Chen and Joseph[61]: "Disturbances which escape the domain of attraction of the steady solution snap through the unstable bifurcating solution and are attracted to (possibly 'turbulent') solutions with larger amplitudes", and: "The discontinuous transitions which are implied by the snap-through instability are in excellent agreement with experimental observations". Directly or indirectly these authors are taking issue with the Landau view of transition to turbulence as a succession of instabilities at increasing frequencies as the parameter of the system increases; see Joseph[72] for details. Landau postulated that the essential features of the evolution of the amplitude A of each instability would be given by $\partial A^2/\partial t = k_1A^2 + k_2A^4$. Stuart developed a formal expansion scheme (valid sufficiently close to the conditions of zero amplification rate of linearized theory) which specialized to the Landau equation when truncated at A^4 and which was lauded by Stewartson[26] (section 3f). This approach was first applied to channel flow by Stuart[64] and Watson[65]. In 1967, Reynolds and Potter[66] and Pekeris and Shkoller[67] independently computed the equivalent of k_2. The results indicate subcritical threshold instability and supercritical stabilization. The question remains into what state will the flow develop once the subcritical threshold is transgressed, and could that state evolve into the supercritical equilibria. Recent numerical experimentation with "drastically truncated" set of equations by Zahn et al[86] suggest that the threshold instabilities lead to "upper branch" equilibrium states which are contiguous with the above supercritical Landau-like equilibria. For others, inverted bifurcation implies that the states must be turbulent. All authors assume perfectly two-dimensional base flow.

4b Experimental Difficulties

The 1974 experiments of Karnitz et al[68] (with freestream disturbance $u'/U_1 \sim 0.3\%$ at the entrance to the channel pushed the laminar regime up to 0.87 Re_{cr}, higher than in any of the previous tests, but still with no trace of Stuart-type features. This, of course, is a bypass par excellence. At comparable freestream disturbances, the transition Reynolds number on a flat plate exceeds its Re_{cr} by at least 60% and hot wire traces and spectra show T-S presence[75] and presumably "cooperation in the instability". However, freestream disturbances in wind tunnels had been reduced to 0.02% by Schubauer and Skramstad[57] by 1942 and have been bettered since.

Freestream disturbances in tightly confined flows may be harder to tame: feedback through pressure fluctuations (pseudosound as well as sound) is enhanced, and instantaneous changes in velocity profiles cause changes in mass flux (unless that is closely controlled, say by a sonic throat, as is desirable) which are coupled with the overall pressure drop. Accessibility of probes and their interference with the flow (also enhanced) present special problems. However, IIT experience, visualization[77], and 3D probing evidence by others lead me to believe that another major suspect is found in base-flow three dimensionality, the inadvertent modifier of type D (section 3a). Because of the tight confinement the walls have to be exceptionally flat, and careful attention must be paid in design to the lurking secondary flows.

4c The New Experiment

The confused state of knowledge on such a fundamental flow called for an all-out effort, and recently Nishioka, Iida and Ichikawa[58] succeeded in bringing down the background turbulence to 0.01% (with some 0.049% u'/U_1 due to fan noise at 715 Hz, a frequency too high to influence stability) in a 6 meter long, 40 cm x 1.46 cm channel. Furthermore, as in the thought experiment mentioned in section 3a, they provided for controlled monochromatic excitation by placing a vibrating ribbon at x=400 cm, definitely downstream of the formation of the fully developed flow (at x∼200 cm for Re of 7500). Unlike their predecessors they also provided for spanwise traversing, which did disclose some three dimensional development at the higher Re values (gradual, from about 3500) as in the plate experiments of Klebanoff and Tidstrom[56]. They acknowledge that this is likely to have some influence on the stability characteristics, an effect which they are currently studying.

4d Three Dimensionality and Comparison with Theory

It should be remarked that a similar departure from two dimensionality was present in all the experiments on flat plates where it was checked and that these experiments were used without any misgivings for comparison with theoretical 2D results. Schubauer and Skramstad explicitly caution in 1943: "The presence of the w-component (spanwise) thus indicates that the oscillations were three-dimensional" and "...how this should affect the agreement with theory is not known". Liepmann observed in 1943 that $w' \sim 2v'$ toward the end of his linear regime (Fig. 8 of Ref. 69), and the researchers at the Bureau of Standards finally concluded that three dimensionality was unavoidable, nay natural. They decided to introduce their own controlled three dimensionality[56] and thus did set the stage for the capture of the 3D breakdown module with its "spikes" and "hairpin eddies" just before the formation of the Emmons[76] turbulent spot, and verified that the pattern under "natural" conditions matched well the controlled module[28].

These insufficiently appreciated historical facts are most relevant to any comparison of theory and the Nishioka et al experiment. On the basis of the Bureau of Standards experience one should anticipate that the three dimensionality would spoil the balance for the supercritical equilibrium but that finite disturbances could damp out below some threshold level if the Stuart theoretical model is appropriate for the idealized two dimensional flow. Whether the three dimensionality would make the proofs of the existence of an inverted bifurcation inoperable is not clear.

Three dimensionality is of course unavoidable in the corners of the finite-width channel. Chen and Sparrow[78] showed that the ideal 2D developing flow is more stable than the fully developed flow (opposite to the situation in axisymmetric Poiseuille flow). Although no theoretical information is available for the flow in a channel corner, this is likely to be the least stable location, especially because of the difficulties in suppressing the category D secondary flows associated with the facility inlet or bends and the contraction from the settling chamber[77]. Those flows in which the disturbances would amplify and become turbulent first in the corner (see discussion and references of Mojola[79]) would almost surely contaminate laterally the rest of the channel by Charters bypass[41] and could therefore not be compared to any of the theoretical results.

The curious reader is invited to diagnose which of the determining parameters caused the very low critical and transitional Reynolds numbers in the 1 by 8, 2.54 cm x 20.32 cm, channel of Kao and Park[80]. Kao and Park, working with water, were the only other researchers to introduce controlled disturbances through an externally supported (and therefore interfering) "wave maker". They judged their experimental neutral Re to be 2600 (based on average velocity and the hydraulic diameter) which corresponds to 2925 based on maximum velocity and half depth. Kao and Park observed T-S waves, often highly distorted, and three dimensional effects.

4e Temporal versus Spatial Instability in Poiseuille Flow

For two dimensional fluctuations in Poiseuille flow, the insistence on thinking purely in terms of temporal instability concepts is questionable. In the real world the disturbances do not suddenly appear all along the x axis at time t=0. The vortical disturbance mode is fed through the oncoming stream to the developing boundary layer and ultimately to the fully developed flow. The pressure mode (also dangerous if its spectrum covers the T-S frequencies) enters both ends of the channel (see the difference in the Spangler-Wells[70] transition due to downstream sonic choking).

When the ribbon is oscillating, the dominant disturbance some distance downstream of the ribbon would appear as $A(y)\cdot\delta(x - 400)\sin\omega t$, (where δ represents the Dirac function). Mathematically, then, the disturbance is introduced all along the t axis at a fixed x corresponding to the classical conditions for spatial stability analysis. Watson[71] recognized that Gaster's spatial stability approach provided "a better model" for Poiseuille flow and reformulated the weakly nonlinear theory from this point of view. Itoh[73,74], in apparent cooperation with Nishioka, also developed a spatial theory and extended it to the computation of the threshold amplitude $(u')_t$ as function of driving frequency for several subcritical and supercritical Re values. Again, it is unclear whether the proofs of the existence of inverted bifurcation are essentially dependent upon the assumptions of the temporal approach.

4f The New Results

The reader needs to study the twenty-two selected figures of Nishioka et al[58] to appreciate the full impact of these new findings on the issues before us. Clearly the bypass is removed. It should probably be ascribed to a combination of destabilizing mean-flow three dimensionality and to finite disturbances acting over long distances in a tightly confined space (sections 4b and 4d). At a Reynolds number of 8000, equal to 1.39 Re_{cr}, the flow remained laminar at the exit from the channel after it had traveled a length of 410 channel heights (at least 240 of them in fully developed flow) from the location of the input of vorticity disturbances. If we should speculate on continued laminarity, should the duct length be extended, we should keep in mind that unlike in a boundary layer, the ideal 2D flow here retains constant stability characteristics. If the given spectrum of disturbances does not excite unstable modes in a distance of 240 channel heights, it should not do so as the length is increased, unless the three dimensionality became stronger with distance.

The measured excited eigenamplitudes and phases are in as good an agreement with Itoh spatial linear theory (Fig. 5 of Ref. 58) as in any of the other classical microscopic experiments. The 180° phase change takes place at the center of the duct and not at the critical layer near the wall as is sometimes inferred from one constituent in the asymptotic theories. It is near this layer that maximal u' fluctuations and Reynolds stresses generally develop. When the x development of the fundamental fluctuation is plotted on a semilog graph, 2D theory indicates straight-line growth or decay, with the slope corresponding to the dimensionless spatial amplification rate $-\alpha_i$. Figure 7 of Ref. 58 shows that in many cases the straight lines tend to bend downward, presumably due to 3D effects when amplitudes are small, especially subcritically. The extracted linear growth rates again compare as reasonably with Itoh's theory (as in comparable boundary layer situations) in Fig. 10 and 11 of Ref. 58. These are well behaved T-S waves, apparently with a touch of three dimensionality but without singular behavior.

The u' vs $x - x_0$ semilog plots with increasing disturbance amplitude as parameter (Fig. 15 of Ref.58) at the subcritical Re of 5000 = 0.87 Re_{cr} exhibit at first a slow growth at station x_0 (which is 32 cm downstream of the complicated field near the ribbon), then zero slope and finally continued gradual decay for maximum $u'(x_0)$ amplitude up to about 1% of the center-line Poiseuille velocity U_c. As our sketch in Fig. 4 indicates, a u' disturbance of 1.2% of U_c also levels off, but then it takes off with increased vigor. Disturbances of 1.5% of U_c and higher grow nonuniformly but do ultimately develop instantaneous inflectional velocity profiles (documented by Nishioka et al) with intense shear near y/h = 0.7 and spikes reminiscent of Klebanoff et al[28,46] and become turbulent shortly thereafter. It is difficult to interpret these results in other than Stuart's terms: a threshold behavior below amplitudes of about 1% (again rather close to those where Klebanoff and coworkers found departures from linear behavior and the start of the nonlinear module cum secondary instability in a Blasius layer but lower than for onset of nonlinearity in free shear layers). Perhaps the theory leading to inverted bifurcations[60,61] needs reconsideration or perhaps it is valid but its assumptions as discussed in sections 4d and 4e make it correspond to a different world.

The intriguing Fig. 16 of Ref. 58 is presented in a simplified manner in our Fig. 5. It compares the threshold amplitude variations with frequency as predicted by Itoh's weakly nonlinear theory[74] with the experimental data extracted from sets of graphs as in our Fig. 4 for Re of 4000, 5000, and 6000. The experimental shape ∽ for 5000 fits between those of 4000 and 6000 and has therefore been omitted for clarity. The minima on the left correspond nearly to the conditions of maximum amplification and are consistent with the trends of the theory. The occurrence of the maxima on the right "was unexpected" and is interpreted as possibly "due to the highly three dimensional nature of a disturbance with a large $\omega h/U_c$", a possibility being explored in follow-up experiments. The consideration of high-frequency 3D phenomena will be taken up again in section 4h.

Nishioka and colleagues carefully map out in x, y and t the development of both the subcritical and supercritical growth and find major similarities with the patterns of Klebanoff et al[28] but with an apparently stronger role for the harmonics (their Figs. 17 and 19). The "harmonic components travel downstream at the same phase velocity." "The fundamental markedly changes its amplitude and phase distributions downstream", but "the mean velocity distribution undergoes no large distortions" until turbulence sets in, etc. These succinct statements should tantalize the reader to go to the original paper which sheds much light on this fundamental flow after fifty years of darkness.

4g *Later-Stage Uncertainty and More Opinion*

A passage (p. 744 of Ref. 58) has a bearing on the Personal Opinions of section 3f: "But especially at the later stage of the breakdown, various different features are observed at the same station, without apparent changes in the experimental conditions". This is for smallest freestream disturbances which appear successfully overriden by the controlled ribbon imprinting throughout most of the development! Yet somehow slow random modulation manifests itself all over again in the later nonlinear but still nonturbulent stages. Research on the breakdown and its transformation to turbulence has been thwarted at the Illinois Institute of Technology by just such later-stage modulation and nonrepeatability.

Such observations, also evident in Fig. 2, add to the uncertainty residue of section 3b. It is my opinion that the nonlinear unaveraged field $\vec{V}(x,y,z,t)$ associated with the later stages of the secondary instabilities is unlikely to be extractable from measurements in sufficient detail even when driven monochromatically. A very repeatable and violent event would have to occur in this randomly modulated three dimensional motion with large amplitudes to be extractable by conditional sampling techniques and ensemble averaging. It will probably be very difficult to distinguish between nonlinear theories of breakdown by comparison with experiments (unless a theory turns out to be obviously deficient). The later-stage uncertainty again has clear implications for research, both theoretical and experimental.

4h Other Possible High-Frequency Skew Wave Bypasses

In section 4f the Nishioka et al surmise concerning the downward trends of the experimental curves in Fig. 5 focused on the "highly three dimensional nature of the disturbance" at high frequency. If their tentative interpretations are correct, there could be connections with other not fully documented bypasses which are worthy of a digression, since bypasses are the bêtes noir of transition (section 2f and 3e). According to Craik's nonlinear resonant theory[81], skew 3D waves play a crucial role and even though they are usually excited at a higher Re, once the nonlinear coupling is established they may dominate the energy extraction from the mean flow in the resonant-triad mechanism. Hopefully some experimentalist will adapt Kendall's technique of stimulation of skew waves[83] to incompressible speeds and test Craik's theory directly.

Direct nonlinear excitation of the skew waves due to large disturbances would constitute a bypass. Donaldson and his coworkers[42] in a search for a bypass which could explain the blunt-body paradox (section 2f) discovered that in the highly accelerated and stable Falkner-Skan ($\beta = 1$) boundary layer they could generate disturbances with a vibrating ribbon that would grow into turbulence provided they had three dimensionality at higher frequencies. The admixture of *3D and high radian frequency* ω could be obtained by adjusting the ribbon tension so that the electrical driving frequency was near the natural frequency of the ribbon system. The turbulence would result when the initial u' fluctuations exceeded approximately 4% of the initial $U_0(x)$. When the same level of initial u' (which was also monitored spanwise) was generated by driving the ribbon at 2/3 of the natural ribbon frequency, the disturbances invariably damped out. The Reynolds number of the experiment based on displacement thickness δ^* was 920 whereas $Re_{\delta^*_{cr}}$ is 12600. Diagnosing and documenting unknown nonlinear characteristics is a time consuming task, and the exhaustion of funds for the Donaldson-Snedekker experiment left us only with an incomplete tantalizing glimpse of a potentially important bypass. In a practical situation on blunt bodies such a disturbance might conceivably arise from a 3D configuration of isolated roughness elements in presence of freestream fluctuations, especially at Reynolds numbers higher than in Ref. 42.

The third possible connection is with the work of Raetz[82], who apparently was the first to propose, in 1958, the resonant theory for boundary layers and who correctly kept pointing out that passive roughness does not generate unsteady waves per se, but that a coupling, probably nonlinear, with an exciting freestream input is necessary. Unfortunately most of his theoretical structure was not carried out computationally. However, he believes (section 5 of Ref. 82) that he found new linear highly unstable spatial skew modes. These have higher frequencies and propagate "with about two-thirds of the freestream velocity", as presumably would the freestream turbulence which gets ingested into the growing boundary layer.

Some of these findings may be erroneous, but they deal with potentially important concepts and should fall under the USTSG generalized Guideline No. 4 (section 1c). Hopefully, funds can be found *to inspire someone to check these views of* bypasses and improve on the preceding quasi-information (at higher Re in the Snedekker-Donaldson case[42]).

5 TRANSITION IN CIRCULAR PIPES; SLUGS AND PUFFS

5a Recent Results in Linear Stability Theory for Pipe Flow

With one exception (which most theoreticians ascribe[87] to an error or doubtful asymptotic approximations) all theoretical results have concluded that fully developed pipe flow is stable to infinitesimal disturbances. The recent and extensive computer studies of Salwen and Grosch[87] cover azimuthal wave numbers n=0-5, axial wave numbers $0.1 < \alpha < 10$ and $0 < \alpha Re < 50000$, and provide phase speed and decay development with Re for the temporal stability formulation: $\exp i[\alpha x + n\theta - \alpha(c_r + i c_i)t]$. Garg and Rouleau[88] set $\alpha c_r = \omega$ and $c_i = 0$ and allow for complex α in order to come closer to the experimental studies such as that of Leite[93]. They computed eigenvalues over a sufficient range (up to Re of 10000) to state: "It may be inferred from the asymptotic behaviour of the eigenvalue trajectory for the least stable mode (n=1) that instability does not occur even at higher Reynolds numbers." Their eigenfunctions agree well with the two sets of center- and wall-disturbance families computed asymptotically and described earlier by Gill in the first of his basic papers[97,98]. In 1973 Gill[99] confirmed the quoted asymptotic surmise of Garg and Rouleau for the least damped disturbances. The least damped disturbance mode has very small amplitudes for dimensionless radii > 0.3 and its phase velocity approaches the center-line velocity. The stretching of ζ_θ vorticity, occasioned by radial motion, changes the nature of the problem from that for channel flow (Gill, 97, 98).

5b An Experiment and Interpretations

Leite[93] demonstrated that up to the limit of his experiments, Re=13000, small disturbances, which were generated electromagnetically in the fully developed flow, invariably decayed with distance "whether they were axially symmetric or not". However, "instability and transition to turbulent flow were excited when the disturbance exceeded a given amplitude", and this threshold "decreased with increasing Reynolds number". This larger disturbance was generated by a "ring airfoil" which also modified the mean flow field and suffered some support interference.

For Leite's small-disturbance measurements "good agreement" with spatial theory was reported by Gill[97]. To explain Leite's large-disturbance results Gill[98] had to estimate the effect of the Modifier in the system--i.e., the decay of the instability-inducing mean-flow wound which was caused by the ring airfoil. The decay was judged slow enough to allow fluctuations to amplify past some nonlinear threshold and to proceed to turbulence before the destabilization subsided. "The theory as developed...seems to fit the conditions of Leite's experiment very satisfactorily, but what about the situation of Reynolds' original experiment?" asked Gill[98]. There the disturbances were brought in at the inlet and must have decayed in the central accelerating region throughout the development length of the pipe flow. Tatsumi[89] had concluded back in 1952 that it is the boundary layer in this entry region which is unstable ($Re_{cr} \sim 19400$), but Gill wrote in 1965, "...it is not clear whether this instability plays an important role in producing the observed effects such as the sudden rapid oscillations of the dye column in Reynolds' experiment at a certain distance from the nozzle." He performed an inconclusive thought-experiment in terms of a "wound" or "bump" on the uniform entry flow and called for a real experiment to settle the effect of two counter trends.

Davey and Nguyen[100] set aside the entry flow issue and worked on refinements of finite-disturbance theory for the fully developed flow--i.e., on a finite-input bypass. In contrast, Gill's model is a Modifier bypass through finite-distortion of the mean flow vorticity. Mackrodt's 1976 paper on linear stability theory of pipe flow with superposed rigid-body rotation[94] offered the possibility of yet another inadvertent bypass: "The results suggest that, at high axial Reynolds numbers, the amount of rotation required for destabilization could be small enough to have escaped notice in experiments on the transition to turbulence in nominally non-rotating pipe flow". Mackrodt's model leaves out the important issue of the entrance-flow development as was pointed out by Sarpkaya[92], but that too could be swirl sensitive. Wygnanski and Champagne[95] in their exhaustive microscopic studies of pipe flows never once observed transition to turbulence "while the velocity profile was close to parabolic". They state : "Thus stability calculations in the developing region of the pipe (Tatsumi 1952) are more relevant to the natural process of transition in a pipe than the numerous analyses which are solely concerned with the stability of Poiseuille flow."

5c Stability of the Entrance Flow

With the availability of presumably better theories of entrance flow and with the advent of computers since Tatsumi's 1952 asymptotic efforts, Huang and Chen recently reexamined the stability issue for axisymmetric[90] and non-axisymmetric[91] disturbances, (n=1). Using temporal stability formulation, as Tatsumi did, they found the flow considerably more stable, their neutral $Re = \bar{U}D/\nu$ being 39800 and 39560, respectively. Compared to the infinite Re_{cr} for the parabolic distribution, the entrance flow is indeed more unstable. However, if Tatsumi's Re_{cr} of 19400 was thought high and unconvincing as to its significance for "boundary-layer instability" in pipe transition, what about the still higher Reynolds numbers of Huang and Chen?

Then why not disturb the entrance flow experimentally with a suitable fluctuation generator and settle the issue? That is exactly what Sarpkaya set out to do[92], using an electromagnetically streamwise driven "sleeve" at the wall, similar to Leite's[93], and other disturbances. Actually this fluctuation generator is more suitable for the entry flow; in a Poiseuille flow the sleeve-driven wall shear waves might not have been efficient in exciting the least stable central modes. Sarpkaya also improved on Leite by rotating the sleeve electromagnetically inside the pipe, thus generating non-axisymmetric disturbances.

The essence of Sarpkaya's Fig. 2 is sketched in our Fig. 6. The nominally same disturbances which were damped (in basic agreement with infinitesimal theory) in Leite's fully developed flow now amplify past $Re \sim 7500$ where they should be stable according to Tatsumi (19400) and even more so according to Huang and Chen (39800)! Sarpkaya also repeated some of Leite's efforts: "Experiments in the fully developed region of the flow did not show a single case of growth for the disturbances," which is also in agreement with the Wygnanski-Champagne quotation in section 5b. The combination of the experiments of

Leite, Sarpkaya, and Wygnanski & Champagne argues heavily that in the real world we no longer should think in terms of a bypass for the Poiseuille Flow but in terms of a simpler discordance in small-disturbance stability information for the entrance flow: Sarpkaya's disturbances, both axisymmetric and non-axisymmetric, grow at uncomfortably low theoretically subcritical Reynolds numbers.

5d The New Discordance and the Old Bypass

Sarpkaya assures us that "The disturbances generated did not become nonlinear within the range of Reynolds numbers and disturbance amplitudes and frequencies encountered." Also, "The rates of growth or decay were nearly linear, particularly for the most slowly decaying or growing disturbances". (These were obtained from unpublished $\log u'/u'_0$ versus $(x-x_0)/D$ plots similar to those discussed in section 4f in connection with Nishioka et al[88].) So the finite-input bypass seems inappropriate. Sarpkaya did not specifically mention measuring the mean profiles close enough to the generator when the generator was oscillating. We do know that the brass sleeve was against the inner wall and 2/3000 radii thin, but we do not know the local (variable) thickness of the wall shear layer nor whether any local separation regions of consequence were present. Thus the profile Modifier bypass functionally similar to Gill's,[98] as discussed in section 5b, cannot be explicitly ruled out at this time. But since a steady wound would be local and should heal farther downstream, the u' amplitudes might be increased and x_{tr} lowered, but their rate of amplification in the linear regime and Re_{cr} itself should remain unaffected.

According to Sarpkaya, "The differences...may be due to the combined effect of free-stream turbulence level (0.07%, misprinted in Ref. 92), the rate of growth of the disturbances, the small differences between the gradients of the measured velocity field and the one used in analysis, the superposition of some non-axisymmetric disturbances on axisymmetric disturbances and the manner of introduction of the disturbances". If the unsteady disturbances are certified as linear as quoted, it is hard to see how a superposition of decaying processes would yield a growing disturbance. So in Sarpkaya's list, the major suspect would seem to be the "differences in gradients". Sarpkaya's "main-flow field agreed with" that used by Huang and Chen "to within approximately 5%" and "the error in repeatability was of the order of 3%".

Wygnanski and Champagne's partial compilation of experimental variation of $U_{max}/\bar{U}$ with x/DRe (Fig. 10 of Ref. 95) demonstrates that contrary to theory "x/DRe does not uniquely determine the shape of the velocity profile" and that for purely laminar flow "the length of the inlet region depends...also on the nature of the input disturbances"! (This is the reason why the qualifier "presumably" was inserted in the first sentence of section 5c.) Since no comparable statement has apparently been advanced with respect to the Blasius profiles for small freestream disturbances, it would seem that the enhanced coupling in confined flows as discussed in section 4b is a factor influencing the mean flow distributions in pipes. And, as Sarpkaya implies, the neutral point could be quite sensitive to the mean vorticity gradients, although the gap we have to explain, 39800 to 7500, is sobering.

Some part of the effect can probably be ascribed to the usage of parallel-flow stability theory. Later today Saric and Nayfeh[101] will clarify for us the nature of expected theoretical shifts as well as the necessity for taking into account the distortions of the fluctuation profile with x when computing amplification rates from experimental data. Both effects might be contributing to the Re_{cr} gap.

The qualitative arguments in this section illustrate the type of detective thinking which goes on when we are faced with a new unexpected disagreement or bypass. We do have a problem in determining *rationally the causes of the differences in Fig. 6.* However, despite this quantitative disagreement, the multiple evidence points to the removal of the far more uncomfortable ninety-six-year old bypass of Osborne Reynolds. No one probing microscopically has yet seen transition to occur after the profile had become parabolic. Exceptions can of course occur when flow-distorting and large fluctuating disturbances. such as those of Leite's ring airfoil[93] or of Fox, Lessen and Bhat's low-aspect ratio leaf spring[102], are introduced locally in the fully developed flow as does not happen in normal pipe flow. We should perhaps invoke Guideline No. 4 (section 1c) with respect to the specific separate evidence which gives rise to the new difficulties. Nevertheless, we are at the point where the full evidence could be considered sufficient to believe that for small and moderate inlet disturbances, transition takes place in the wall layer of the entrance flow. Such conditions lead to turbulent formations called slugs by Wygnanski and Champagne.

5e Slugs and Puffs

Slugs designate extended turbulent formations, $L \gg D$, filling the entire cross-section of the pipe, with largest fluctuations occurring near the wall. Sharp changes in the character of the flow occur at the leading and the trailing edges of a slug--i.e., at both interfaces with the adjacent laminar flow. These conceptually very important transition regions have been mapped out and analyzed in great detail by Wygnanski and Champagne[95]. The structure of the flow away from these interfaces was shown to be the same as in a fully developed (non-intermittent) turbulent pipe flow.

In the range $2000 < Re < 2700$ Wygnanski and Champagne identified for the first time very different and peculiar turbulent entities, dubbed puffs, with largest fluctuations in the central region of the of the pipe. At a fixed Reynolds number, some distance from the pipe entrance, the puffs assume lengths and structure documented to be independent of the nature of the large disturbances which created them. At the leading edge of a puff the character and velocity of the flow change very gradually (in clear contrast to the behavior at the front of a slug). The trailing front is sharp near the center of the pipe but becomes undefined at larger radii where the wall vorticity layer refuses to participate in the turbulent activity.

In contrast, the slug is evidently born in the wall shear layer (pp. 299-300 of Ref. 95), first as a local spot (akin to Emmons' turbulent spot[76]). It "begins on one side of the pipe wall and grows into a slug as its dimensions become comparable with the pipe diameter". When a transition burst occurred where the laminar wall layer had grown to a significant fraction of the radius--i.e., for larger x/DRe--

the turbulence spread "almost instantaneously across the entire cross-section".

Wall turbulence was not observed much below a Reynolds number of 3200. However, large enough initial disturbances could make the flow near the entrance turbulent at Re values as low as 2000, as has been known for decades. High turbulence is not readily sustained in the pipe at these dissipative Reynolds numbers; it tends to decay in an intermittent fashion as Lindgren[103] had shown visually back in 1957. Wygnanski and Champagne traced this development with increasing x: "Further downstream the flow becomes intermittent as smaller chunks of turbulence break away and move downstream. The process of subdivision may repeat itself until an equilibrium is reached and 'fully developed' puffs move down the pipe". These quantized turbulent entities represent self-sustaining open turbulent systems which in our terminology constitute a nonlinear bypass. They present a special challenge to the various computerized models of turbulence.

5f The Challenge

More recently Wygnanski, Sokolov and Friedman[96] combined an especially refined version of conditional sampling with controlled pulse disturbances. The finer observations disclosed that a true equilibrium puff, which does not change its length, occurs only near Re=2220. For Re $<$ 2200 the puffs decrease slowly in length, while for Re $>$ 2300 puffs would lengthen and split. At Re of 2600 one disturbance pulse at the entrance would result in an average of 4 puffs at x/D=500. Can this splitting phenomenon be predicted by theory and computers?

To present a clear quantitative target Wygnanski et al[96] provide us with a very detailed anatomy of the equilibrium puffs at Re=2220: streamline patterns in a frame of reference moving with the sharp trailing interface, distributions of mean velocity, of u'^2, v'^2 and w'^2 fluctuations, of Reynolds stress, and of some dissipation rates. The equilibrium puff as a whole dissipates as much turbulent energy as it generates, but the spatial distribution is important. The authors speculate how an observed localized negative production could be enhanced at somewhat higher Reynolds numbers and lead to the splitting phenomenon.

5g The Emerging View of Pipe Transition

The preceding picture of the genesis of slugs and puffs and of their characteristics differs from the idealized views of instability and transition in pipes. The Wygnanski-Champagne schematic "guide" to the dependence of the various regimes, in a long pipe, on the strength of the inlet disturbances and Reynolds number is reproduced in Fig. 7. It is satisfying that after nearly one hundred years a conceptually consistent view of Reynolds' phenomenon is emerging. Figure 7 is in agreement with the theoretical and experimental work on the stability of the entrance flow, discussed in section 5c.

The main discordant element is not the onset of turbulence before the parabolic flow is established but the disagreement between Sarpkaya's small-disturbance experiments[92] and linear stability theory; see section 5d. Should Sarpkaya's results be sustained by desired additional evidence, the picture would be very consistent. In view of the Wygnanski-Champagne quotations in section 5d concerning mean-profile development, it would also seem very desirable to check the theory for sensitivity to changes from the assumed velocity distributions. The nature of this difficulty is very different from that cleared up in Chapter 4, where the problem was the earlier experimental inability to generate channel flows free of inadvertent Modifiers, at sufficiently low inlet disturbances. Here the inlet disturbances, quoted as $u' \sim 0.0007\, U_{max}$ by Sarpkaya, were apparently low enough to exclude unsteady nonlinear effects as suspects in lowering experimental Re_{cr}. Then according to Fig. 1, the presently most rational explanation is in terms of differences in mean-flow vorticity distributions (including inadvertent Modifier effects) as used in the theories and as encountered in the experiment, plus corrections associated with non-parallel flow aspects.

However, this discrepancy seems minor in comparison with the previous conceptual difficulties. It was brought out in part to underscore the realism of our considerations in sections 2g and 3a even for the simplest geometry, under controlled laboratory conditions (as against practical configurations under field conditions). The lessons of history are numerous; if only we were willing to incorporate them into our philosophy in approaching transition problems!

6 SOME RECEPTIVITY ISSUES

6a The Unanswered Questions

The last ten years unquestionably brought progress in resolving major difficulties in the channel and pipe flow dilemmas (Chapters 5 and 6) and in clarifying the nature of instability at supersonic speeds (see Reshotko[3,16]). We have also had a first wave of efforts to understand the key issues of shear-layer receptivity:

(1) what are the mechanisms by which the environmental disturbances, the vorticity fluctuations, sound, and entropy disturbances (ρ', T' at constant p) cause the instabilities to develop within the shear layers? and

(2) can the causal relationships be described quantitatively?

In 1943, when Schubauer and Skramstad[57] demonstrated that the Tollmien-Schlichting mechanism indeed governs flat-plate transition in a benign environment, they also showed that both freestream turbulence and sound do generate the T-S waves (at Mach numbers on the order of 0.02). More than forty years later we do not even know whether the induction processes for an attached boundary layer are generally linear! According to Norman[107], the presence of a small 3D protuberance in an otherwise Blasius boundary layer can make the reattached boundary layer sensitive to difference tones of two higher-frequency acoustic disturbances on the order of 80 db which the layer damps individually. This nonlinear induction process was traced to the short separated shear layer behind the obstacle which amplified the tones to nonlinear levels and led to interfering laminar vortex loops. These rose to the top of the boundary layer but induced T-S waves below, at the difference frequency. Spangler and Wells[70] *had some difficulties in* reconciling their measured freestream excitation spectra with the trends of the observed transition Re *and suspected nonlinearities* in some cases. The relatively simple experiment of measuring the spectral amplitudes of T-S fluctuations in a boundary layer as function of measured controlled acoustic excitation spectra and performing various cross-correlations has not yet been rigorously performed (but see Freymuth[36] and Morkovin and Paranjape[23] for some results in free shear layers). Since freestream turbulence is much harder to control and characterize, the corresponding desirable two-sensor experiments are much more difficult and will be harder to interpret.

6b Enhanced Sound Effects at Sharp Corners

Reshotko[3] reviewed the state of the receptivity concepts only last year. Rogler's presentation[109] should give us an even more up-to-date view of the theoretical approaches and results. Here I would like to add some more intuitive and physical speculations which can perhaps provide glimpses of issues beyond the constraints of the strictly parallel flow theory.

An instructive model of induction of vorticity waves at a 2D stagnation point by a plane irrotational sound wave (with wave number $\alpha = 2\pi/\lambda$ and circular frequency ω) was put forth by Saxena[104] in 1971. In the proximity of the stagnation point, $x=y=0$, (with the freestream coming from the negative y direction), the classical local solutions of Hiemenz[8] approach the expressions $u=ax$ and $v=-ay$ at the edge of the viscous layer $\delta \sim 3\sqrt{\nu/a}$, where ν is the kinematic viscosity and a the gradient-scaling constant $\sim U_\infty / R_{LE}$ (R_{LE} = leading edge radius). Asymptotic theories tell us (e.g., Amiet and Sears[108]) that well behaved, matchable approximations to sound waves travelling in the x direction are locally incompressible, and therefore, in the proximity of the origin, a forcing plane wave, with $\lambda \gg R_{LE}$, can be rigorously represented by $u_s = b\exp(i\omega t)$. Bernoulli equation applied at the edge of the layer then introduces the process nonlinearity and yields $-ab\exp(i\omega t)$ for the unsteady component of $\partial P/\partial x$. The no-slip boundary condition, $u = 0$ at $y = 0$, links this gradient to the source strength of vorticity induced at the wall: $-(\partial P/\partial x)_0 = \nu(\partial\zeta/\partial y)_0 = ab\exp(i\omega t)$. The unsteady equation for the vorticity $\zeta(y;a,b)$ involves nonlinear products of the known Hiemenz solution and its derivatives with the desired response function and its derivatives. With the specified boundary condition on $(\partial\zeta/\partial y)_0$, it can be readily solved on a computer for any given frequency ω.

The resulting vorticity wave is bilinear in a and b, the magnitudes characterizing the abruptness of the stagnation point ($\sim U_\infty / R_{LE}$) and the local amplitude of the inducing plane wave. This local amplitude is enhanced by the acceleration of the unsteady velocity field around the leading edge, an enhancement which varies with inverse 1/2 power of R_{LE} for thin flat plates according to Saxena[104]. Thus as long as $\delta/R_{LE} \sim \sqrt{\nu/U_\infty R_{LE}}$ is sufficiently small for the stagnation region approximation to remain valid, leading edges with small radii would appear to be particularly sensitive to acoustic induction of vorticity.

6c *In Search of a Rational Linear Link to the Tollmien-Schlichting Waves*

This induced vorticity field, however, is not the Tollmien-Schlichting field. One can speculate that, as the boundary layer turns around the leading edge, the convected remnants of the above induced field at a given x_0 could serve as the upstream boundary conditions for the downstream spatial development of T-S waves. In principle, one could hope to decompose the variations normal to the surface at x_0 in terms of the sequence of eigenfunctions of the Orr-Sommerfeld equation. However, at these precritical Reynolds numbers even the lowest mode, the Tollmien-Schlichting mode, decays with x so that only "infinitesimal" fluctuations would reach x_{cr} corresponding to the given frequency ω. Thereafter they would amplify. But the presence of the precritical bottleneck makes it likely that other disturbances operating through more efficient receptivity paths would have reached higher amplitudes and become the primary agents leading to instability and transition.

The situation is different at trailing edges and at nozzle lips or edges from which free shear layers separate. Although we do not have the equivalent of a Hiemenz solution, the acoustic induction process of vorticity through the curvature-enhanced acoustic particle velocity, u_s, operates as before. Again, the bifurcation point or separation point is the most easily influenced location by the relatively small u_s. Just like the attachment point of Saxena[104], the separation moves back and forth. The vorticity variations at a station x_0 just downstream of the oscillating separation point can indeed serve as upstream boundary conditions for the spatial instability without any intervals of decay. However, the mean vorticity profiles change relatively rapidly in these important early stages of free shear layers, and this fact has to be taken into account, as pointed out by Michalke[27]. He does it by solving a series of eigenvalue problems, each for a parallel flow with the mean profile corresponding to the successive x positions (Figs. 9 and 10 of Ref. 27). The limited correspondence between theory based on early changing profiles and experiments of Miksad[111] is also relevant. For more accurate results the non-parallel aspects would probably have to be considered.

To think in terms of an upstream boundary condition at x_0 for the spatial instability development seems natural when one has a rapid x variation in geometry, in boundary layer properties, or in the strength of the disturbances (e.g., loss of acoustic enhancement or sharp drop in vorticity generation, as above). It also provides a reasonable linear link with the Tollmien-Schlichting process. The expansion of the vorticity $\zeta_0(y)$ in terms of the Orr-Summerfeld eigenfunctions would be a practically forbidding process. However, ten years ago Nagel's early computations of instability waves in the Navier-Stokes framework[110] showed that different "initial conditions" evolved quite readily into the T-S eigendistributions. So perhaps current, more efficient Navier-Stokes programs could calibrate for us, if desirable, the transfer factors (loss of amplitude) in the takeover by the Tollmien-Schlichting waves.

6d Experiments on Receptivity of Free Shear Layers

The preceding picture of receptivity of free separating shear layers or jets is fully consistent with the various available tidbits of experimental information. Using a movable acoustic "point source", Paranjape[23] demonstrated rather conclusively that the region of sensitivity is near the lip and the separation point. By measuring a purposely nonuniform acoustic field in and near the nozzle with a "point microphone" in absence of the jet and by analyzing the differences in the response of the two separating shear layers when the jet was on, he provided evidence that the amplitude of instability waves is proportional not to the acoustic pressure, but rather to its gradient near the separation point--i.e., to the local time derivative of our u_s.

A dramatic visual evidence of the localization of acoustic receptivity and its consequences to various aeroacoustic feedback phenomena came from Poldervaart and his coworkers[105]. The reader is urged to look up the easily accessible Plate 2 of Ref. 106 to convince himself of the localization of the response in the two shear layers of a 2D subsonic jet to a compressive sound pulse, made visible by shadow photography. The pulse (and its weak compressive reflection from the exterior of the nozzle) creates vorticity at the right lip, which amplifies and rolls up into two vortices as it propagates downstream. There is no evidence of vorticity formation other than at the lip. The pulse runs ahead along the right shear layer (being reflected as an expansion fan in consonance with gasdynamic theory), and the two orphaned vortices follow at their slower propagation speeds. The weak transmitted portion of the pulse also generates a weaker vortex at the left lip of the nozzle. For good measure, Poldervaart et al send in another compressive pulse in short succession: more vorticity is generated and amplified into another pair of vortices, the second pulse runs far ahead, while the two sets of vortex pairs execute a complicated nonsymmetric fusion dance and end up in a single big vortex. Such fusion fields correspond to aeroacoustic generation of sound which, in turn, can cause vorticity changes at the lip, some of which are identifiable in the various visualizations. Because of the strength of the pulses, the described processes have undoubtedly transgressed any linear behavior, but the essential physics of the vorticity induction should be the same.

6e Receptivity over a Flat Wall

It is useful to consider what differences in the above behavior would take place (1) if the shear layer were attached to a solid wall, and (2) if additionally the speed of propagation of any resulting amplified vorticity subfield would equal that of the foot of the sound pulse (as could happen in a supersonic boundary layer or a supersonic wall jet). From Saxena's example in section 6b we saw that the no-slip condition at the wall was the dominant instrument for induction of new vorticity by the unsteady velocity at the edge of the boundary layer. To generate rotational vorticity waves of first order from irrotational sound waves in two dimensions, a differential intervention of viscosity is needed--at a solid boundary. In the free mixing layer or jet the unsteady vorticity input into the layers sharply drops past the separation point as the Eindhoven film[105] illustrates. (See also section 6j.)

Periodic traveling sound waves will thus induce vorticity all along a flat wall. For frequency parameters $f\,\delta^{*2}/\nu$ on the order of unity or higher, the forced unsteady vorticity sublayer will be essentially uniform: a Stokes wall layer traveling with the sound wave. If one attempted to choose an x_0 for the T-S upstream boundary conditions in order to link this forced vorticity field to the Tollmien-Schlichting waves as before, what about the continued forcing and vorticity induction downstream of x_0? Since the sound waves and the T-S waves propagate at different speeds, there would be much plus-minus cancellation of effects in any superposition scheme one may consider. The cumulative effects are likely to stem from relative streamwise changes in the instability characteristics of the growing boundary layer and in the forced vorticity field.

In the corresponding problem of excitation of T-S waves by freestream turbulence at small Mach numbers Mack's application-oriented method for predicting transition[112] chooses the beginning of T-S amplification, x_{cr}, for the single x_0 T-S takeover point. The choice of this special point may be effective, especially in absence of any guiding experimental information. But the fundamental question remains as to the possibility of distributed seeding of decaying T-S waves upstream of x_{cr} and especially of growing T-S waves downstream of x_{cr}. Mack was probably influenced by his rather successful experience[55] in describing the growth behavior of precritical and postcritical boundary-layer disturbances, mapped out experimentally by Kendall[54] at supersonic speeds. (See pp. 329-333 of Reshotko's review[3] for detailed discussion of this instructive forward step in receptivity.)

6f The Supersonic Evidence of Kendall and Mack

At supersonic speeds the precritical forced response is a neutral solution of Mack's instability equations evoked by traveling oblique Mach waves which impinge on and reflect from the boundary layer and thus simulate acoustic radiation from supersonic turbulence on the tunnel sidewalls. Kendall's hot wires had revealed the existence of the strong precritical boundary layer disturbances (see left side of Fig. 8), documented their source by cross-correlating their signals with those of the oncoming freestream disturbances, and indicated that their propagation speeds shifted to nearly that of the T-S waves after they acclimated themselves fully to the boundary layer. This last feature suggests that at least random disturbances which possess substantial temporal and spatial variations can be partly transformed into T-S waves. It is this acclimatization or linkage process which is crucial in understanding receptivity, and it is ironic that the most important evidence should have blossomed forth in the experimentally inclement supersonic environment!

Mack's precritical vorticity-density response field travels at the same speed as the external acoustic field. While it has zero rate of amplification as such, the response first grows in x as the boundary layer thickens and then diminishes. Thus for a given frequency ω the capacity of the external sound to disturb the profiles of the thickening boundary layer (with a maximum of mass fluctuation in the outer half of the layer) apparently increases at first and then drops off. The maximum in x of the effectiveness of the external disturbance is rather flat and occurs near the critical position for the given frequency. Any forced disturbances which had acclimated themselves earlier and became decaying T-S modes would have small amplitudes in comparison with the local forced disturbance. The forced disturbances that would transform into T-S waves downstream of the critical position would have smaller amplitudes than those acclimatized just at $x_{cr}(\omega)$, but there is no clearcut reason why they should not be added and cumulated. However, these different T-S contributions are not likely to be in phase because of the randomness of the oncoming sound and because of differences in lags associated with differences in distance from the effective x of acclimatization. The reader can judge for himself from the right side of

Fig. 8 how Mack's decision to use the single imprinting position, $x_0 = x_{cr}(\omega)$, and to disregard any postcritical cumulation, compares with Kendall's experiments.

6g Low-Speed Experiments on Acoustic Receptivity?

Returning to our discussion of discrete nonrandom acoustic disturbances at small Mach numbers, we have fewer reasons to adopt a single takeover point $x_0 = x_{cr}(\omega)$. Nevertheless, the preceding discussion of supersonic experience suggests a conceptual framework for the long overdue subsonic microscopic experiments on acoustic receptivity. At low speeds we have better accessibility, and quantitative correlations between two or three sensors centered around x_{cr} should help to clarify the picture. Furthermore, a quasi-two-dimensional controlled movable source (Paranjape[23]) should again minimize reverberations and make the acoustic environment much easier to work with than at supersonic speeds. Subsonic facilities do possess unwanted resident acoustic disturbances in the form of fan noise and various standing and duct waves, but one should be able to avoid their interference if one knows about them. In this connection an intriguing clue to acoustic receptivity, which calls for explanation, was furnished by Spangler and Wells[70]. They have evidence that their laminar boundary layer on the inside of a circular duct was far less receptive to standing waves than to traveling waves of the same frequency. However, according to Guideline No. 4 of USTSG, section 1c, the effect perhaps ought to be first rechecked experimentally.

6h Low-Speed Receptivity to Turbulence

For sound waves at low speeds the unsteady pressure gradients normal to the wall are negligible and the response functions are relatively simple. In trying to describe the response to vortical patterns and turbulence, we had better allow for pressure variations in y--i.e., use the Navier Stokes equations, linearized. This leads to the Rogler-Reshotko[113] neutral, forced solutions of a nonhomogeneous Orr-Sommerfeld equation, a counterpart of Mack's supersonic neutral solutions discussed in section 6f. At present there is no evidence that these forced disturbances, satisfying a linearized equation, could cause transition by themselves. On the contrary, the available evidence suggests that an instability process must contribute to the growth of the fluctuations to some 10 - 18% of U_0 before the turbulence can sustain itself in the form of a turbulent spot, or a puff, or a slug (section 5e). It follows that the issue of sections 6c and 6e faces us once again: how can at least part of the energy of the forced fluctuations of Rogler and Reshotko be transferred to the free Tollmien-Schlichting eigenmodes or otherwise couple with the T-S process? Similar questions arise with respect to Criminale's work.

Some fourteen years ago Klebanoff[114] was doing interesting two-sensor experiments which ran out of sustained funding and remain sadly incomplete and unpublished. One of his findings concerns fluctuations upstream of the critical point as sensed by a fixed hot wire. The signal indicated a maximum u'/U_0 (at about $y/\delta = 0.5$), as much as ten times the freestream value at the edge of the boundary layer! He documented that these fluctuations were primarily due to random-modulated low-frequency thickening and thinning of the boundary layer. Considerations of quasi-steady changes in thickness of a Blasius layer confirmed to him that the wire would indeed sense large u' values at mid-thickness. He also discovered that the random undulations of the boundary-layer edge increased with distance from the leading edge of his plate and had some Gaussian properties.

These are, of course, real-life responses to free stream disturbances. As large as the magnitude of the fluctuations appears, they are unlikely to feed into an instability process, except perhaps as modulators. A ten percent change in δ corresponds to a 20% change in effective U_0. If such changes in U_0 did actually occur locally, they would cause a great deal of tuning and detuning of the T-S processes. In particular they could account for the wave-packet appearance[57,75] of T-S waves whenever these are not artificially stimulated. T-S waves tend to form wave packets of 4 - 9 waves, which correspond to patches of 40 - 90 boundary layer thicknesses. The cause of such low-frequency, large-area breathing of the boundary layer remains unclear, and it should be instructive to find how this phenomenon would vary with purposeful changes in freestream turbulence. Such a study could give us a clue as to the conditions which control the conversion of the forced oscillations to T-S waves.

6i Can We Have Resonance at Low Speeds?

Finally, let us consider question (2) of section 6e: "What if additionally the speed of propagation of any resulting vorticity subfield would equal that of the foot of the sound pulse?" This may well be happening sporadically in some supersonic tunnels, but here we should extend the question to forced responses to freestream turbulence which travels essentially at U_0. Intuitively one feels that the plus-minus cancellations due to mismatch in propagation (section 6e) would be replaced by a directly cumulative effect, the attacker keeping in step with the victim, so to speak. Some call this condition resonant, but ours would be a special case of resonance because past x_{cr} our system is weekly but increasingly unstable.

If such a condition could arise it would not be easy to analyze. One can obtain guidance from the papers of Phillips[115] and Stewart and Manton[116] on the generation of waves by turbulent winds. When the wind is high enough there are two skew wave directions in which the convective speed of turbulence just matches the speed of gravity waves with surface tension. According to Stewart and Manton: "The resonant mechanism as described by Phillips is usually credited with supplying to the water surface an initial disturbance" which can be enhanced subsequently by other (nonlinear) mechanisms. Stewart and Manton argue that Phillips' ideas should be phrased in terms of group velocities rather than phase velocities. The point here, however, is that the energy transfer is indeed maximized. Yet gravity waves correspond to a stable situation; the already heavy mathematics would get heavier for our weakly unstable system for which we do not have the relatively simple transfer function of Phillips before the stochastic aspects are tackled.

Can such "resonant" conditions take place in subsonic boundary layers? The propagation speeds of amplified T-S waves rise above 40% of U_0 only for adverse pressure gradients with inflected profiles and higher y_{cr}. Freestream turbulence propagates with U_0 in the mean. It would seem, therefore, that some turbulence would have to be ingested, slowed down within the boundary layer, and still have enough energy left at x_{cr} to seed the T-S waves. At this time we do not have enough information to judge whether this is impossible or unlikely.

6j Prediction and Receptivity

Since receptivity is a relatively new concern and it has been tackled mostly analytically, the preceding sections have brought out some of the underlying physical considerations as I see them. In sections 6b - 6e I may have overemphasized the role of the no-slip boundary condition. Formal perturbations of the nonlinear convective terms in the momentum equations will yield "generation terms" of vorticity in and along any shear layer--e.g., $v\,\partial^2\bar{U}/\partial y^2$, where v is any normal perturbation velocity, whether irrotational or vortical, and $\partial\bar{U}/\partial y$, the local time-mean shear. However, as noted in sections 6d and 6e, the vorticity response in free-shear layers is dominated by the seeding at or near the mean separation point and the x and y integrated effects of the above distributed sources are not in evidence. Furthermore, the propagation speed of the forcing perturbation v does not match that of the free O-S solutions and the transfer is again to the forced solutions of the nonhomogeneous O-S equations. So the formal identification of these distributed source terms helps little with the main difficulties in finding the link to free T-S waves discussed in preceding sections. The picture is rather confused. One thing seems clear, however: we need clever and careful experiments and sustained funding to ensure their success.

The dearth of experimental information concerning the receptivity to free-stream turbulence makes it possible for computer programs which do not incorporate any T-S mechanism to reproduce the known data even when turbulence is known to feed the T-S waves. The power of current computer programs to carry out sophisticated functional interpolation between limited number of data points (whether the programs take into account the multiple relevant mechanisms or not) may seduce the users to overtrust the information even when extrapolation beyond the original data base is involved. An increasing problem for the user is that he is less and less capable of verifying the programs as they get increasingly complicated. The scarcity of reliable and detailed experimental information makes the task of discriminating between various predictive computer techniques even more difficult.

6k Effects of Free-Stream Turbulence at Low Speeds

A still valid evaluation of the status of the low-speed experimental knowledge of transition behavior with free-stream turbulence and pressure gradients was presented in 1972 by Hall and Gibbings[118]. The authors also evaluated critically the then existing prediction methods of van Driest and Blumer[119], Crabtree[120], Granville[121], Smith and Gamberoni[122], van Ingen[123], Jaffe, Okamura and Smith[124], and Michel[125]. With the feel for the experimental evidence (partly their own) and the various predictive features, they summarized the key data and proposed a semi-empirical best-bet chart of their own; see their Fig. 7. To be able to use the charts wisely and appreciate possible pitfalls, the reader is advised to follow the preparatory discussion with care. For balanced perspective, a study of Mack's thoughtful 1977 approach (Section IV of Ref. 112) based on T-S computations is recommended.

6l The Issue of "Sufficient Evidence"

The flavor of Hall and Gibbing's evaluation perhaps had best be gaged by some direct quotations: "Unfortunately, transition experiments are difficult to set up, principally because transition is sensitive to changes in a large number of variables besides the dominating factors of pressure gradient and stream turbulence. These experimental difficulties result in an undesirably large degree of scatter in the results, even when collected on a single apparatus. This makes prediction an uncertain matter under accurately specified flow conditions, and the use of results from one system for prediction on another reduces accuracy even further." When one follows their careful weighing of partially contradictory evidence in a two-parameter prediction space and thinks of the additional parameters of Mach number, wall temperature and roughness, sweepback, and aeroacoustic free-stream disturbances, one begins to appreciate what, for instance, the transonic designers are up against in knowing and improving the properties of their boundary layers. And perhaps the reasons for many of the statements in Chapter 3 and the meaning of Table I become clearer. Judgments of sufficient evidence for a given design decision or for the validity of a theory will remain very tentative for decades, judging by the slow rate of our enlargement of the desirable data base. And here again USTSG Guideline No. 4 for double checks needs to be recalled--see section 1c.

6m Another Historical Lesson

Perhaps an instructive old example is in order, involving two historical figures whom the writer deeply admired both as scientists and men. In 1948, H. L. Dryden, trying for perspective on the broad 1938 rejection of the T-S mechanism as relevant, wrote[126], "Transition occurred intermittently and suddenly, with no development of amplified disturbances...Not only did the experimental group obtain this negative result; their experiments confirmed a theory developed by G. I. Taylor[127], which attributed transition to the presence of free-stream turbulence...For ordinary wind tunnels the stream turbulence usually lies in the range 0.2 to 1 percent. In these wind tunnels the turbulence is the controlling factor and the mechanism is that of the Taylor theory." Turbulence indeed is a strong determinant in such flows, but the mechanism would have been identified as T-S coupled had adequate spectral analyzers been available.[75] Hall and Gibbings' charts[118] for the influence of turbulence are in fact T-S conditioned, with distinctly different behavior in favorable and adverse pressure gradients. For the latter they suggest that the e^9 criterion for transition for small turbulence is overconservative, a trend which they see persisting to relatively high free-stream turbulence.

In retrospect there was not sufficient evidence to conclude that Taylor's theory and mechanism were confirmed, only that they were not inconsistent with the then very limited data base. The mechanism postulated a local separation due to an instantaneous pressure pulse associated with turbulence. Although no one has documented such instantaneous separation, it is intriguing that several of the secondary instabilities observed just before turbulence onset (Refs. 28, 31-34) seem to be associated with instantaneous, nearly stagnant regions near the wall built up in the nonlinear regimes of the T-S waves or of the Görtler upwelling. Finally we should note that a modified rationale leading to a Taylor-like parameter was used with apparent success by Sternberg[128] in analyzing the occurrences of new transition after relaminarization (Sternberg's discovery in 1952).

7 THE ROUGHNESS ISSUE

7a A Basic Experiment on Two-Dimensional Roughness

The 1967-1977 progress in clarifying the mechanisms by which roughness promotes transition grew directly out of the productive Fifties. Most of the earlier results were ably analyzed and summarized by Tani[129] and von Doenhoff and Braslow[130] in the Lachmann collection, which remains the point of departure for anyone interested in the subject. The most significant recent basic contribution to our understanding is that of Klebanoff and Tidstrom[46], who improved on the earlier microscopic hot-wire findings of Tani and Sato[131]. It was shown unequivocally that placing a two-dimensional roughness element of height k into a slightly unstable flat-plate boundary layer constitutes a powerful modifier in the sense of Fig. 1, equivalent to a series-inserted broad-band preamplifier. The roughness does not generate unsteady disturbances (as is often incorrectly stated) but provides a local redistribution of mean vorticity such as documented by Klebanoff and Tidstrom in their Figs. 11 and 13 over a series of unit Reynolds numbers. This new entity amplifies more effectively a broader band of disturbances already present in the layer (see Fig. 8 of Morkovin[7]) and provides for "ingestion" of additional disturbances from the free stream. (It has been verified at IIT that, in accordance with section 6d, the local separation regions near the roughness make the modified layer much more receptive to acoustic disturbances and one would surmise also to freestream turbulence.)

7b Verification of Dominant Mechanism -- 2D

Klebanoff and Tidstrom measured the spectral development of the disturbances over the 30k - 40k long, locally separated region and beyond, to the onset of turbulence wherever it occurred. Fully cognizant that parallel-flow stability theory has to be inaccurate for the rapidly changing profiles near the roughness, K-T nevertheless compared amplification rates measured over the rear separated region for three frequencies with estimates based on the (frictionless) charts of Pretsch (NACA T.M. No. 1343, 1952). The agreement was so much "better than might have been expected" that K-T caution the reader not to make inferences with respect to the validity of Pretsch's calculations. H. Obremski[132] computed properties for several of the K-T measured profiles with the aid of the Kaplan-Landahl MIT program and found differences on the order of 25%. Such scatter in no way influences the important conclusion that the phenomenon is stability controlled.

K-T further demonstrated that as long as the unsteady disturbances remained below about 1% of the freestream speed, the mechanism was indeed that of Tollmien-Schlichting. They devised a clever experimental nondimensional self-consistency check, which also brought out the dominance of k/δ^* (δ^* = displacement thickness) as a parameter. Selecting further a series of experimental conditions to yield the same k/δ^*, they also showed that the shape factor H (the single factor most indicative of the degree of instability) is then a very slow function of Uk/ν, the viscous parameter. This and the fact that amplification rates of inflectional profiles (which dominate the effect) are also weakly dependent on Reynolds number provide the reasons behind the substantial success of correlations based on k/δ^*; see Tani[129]. The amplification rates of inflected and separated profiles decrease substantially with respect to those of attached profiles as Mach number increases (p. 15 and Fig. 6 of Morkovin[2]). This fact and the low-speed evidence of Klebanoff and Tidstrom are thus consistent with the known loss of effectiveness of two-dimensional trippers at supersonic speeds, a bonus of understanding through mechanisms.

7c Some Implications

Two-dimensional protuberances, planned or accidental[24], *thus have to be extremely small not to have* any influence on transition. Even when all the frequencies, which had amplified locally in the separated regions, decay in the reattached boundary layer, the protuberances thicken the boundary layer through its incremental momentum loss (its drag), thus making it more unstable. The Reynolds number based on the momentum thickness θ, Re_θ, obviously is increased. By the nature of the equations, both the steady and unsteady modifications cause downstream effects to reckon with, even if one disregards the change of receptivity near the roughness. The concept of a single critical Reynolds number, $Re_k = u_k k/\nu$ (where u_k is the velocity of the undisturbed layer at height k, there being no velocity overshoots in presence of the roughness[46]) below which there is no effect on transition and above which transition jumps to the near wake of the element, is incompatible with the evidence concerning the dominant mechanism. Nevertheless practical criteria, such as that for suitably defined "tolerable roughness" may profit from the usage of a modified limiting Re_k; see Gibbings and Hall[133].

7d Wall Waviness and Freestream Unsteadiness

One can speculate that wall waviness, another modifier in the sense of Fig. 1, should work similarly: through the integrated effects of changes in the amplification properties and in the thickness of the boundary layer. The modifications in these properties may be nonlinear and nonsuperposable, as for the K-T profiles, but the important mechanism is likely to be that of linear instability, at least qualitatively, for a wide range of parameters. A definite illuminating experiment, such as that of Klebanoff and Tidstrom, which would also clarify the range of validity of the hypothesis is yet to be performed.

The tracing of amplifications along paths of T-S wave packets in the case of harmonic oscillations of up to about 20% of the freestream speed confirmed a similar "local validity" of the T-S mechanism and disclosed some surprising, otherwise unexplainable consequences for unsteady flows; see Loehrke et al[9]. One can speculate also that when the time scales of changes in the free stream are long enough with respect to the time scales of T-S waves, the mean flow changes need not be periodic to be at least qualitatively understandable in terms of the patterns described in Loehrke et al. In particular, one aspect of receptivity to low freestream turbulence in good wind tunnels (where turbulence in the test section has little energy left in spectral regions commensurate to the boundary layer scales) may be conditioned by irregular low-frequency large-scale decelerations of the boundary layer, with consequent irregular boundary-layer thickening and appearance of T-S oscillations in form of wave packets. A wave packet of 7 to 9 T-S waves corresponds approximately to a length of 56 to 72 boundary layer δ's. P. Klebanoff and A. Favre have observed such irregular low-frequency thickening of boundary layers. (These can give a falsely high signal on a hot wire which is held fixed relative to the shifting near-Blasius velocity profiles. This occurs even where the boundary layer is stable--i.e., upstream of the genesis of the T-S wave packets.)

7e Isolated Three-Dimensional Roughness

In connection with his 1961 analysis of extensive 3D data Tani[129] described the "quick movement" of transition toward the roughness element as the free stream speed increased in a narrow range. He added that this "seems to distinguish the effect of three dimensional roughness from that of two-dimensional roughness". The reasons for this difference have now been fairly well understood as a result of subsequent hot-wire and visualization efforts of Tani et al[134], Mochizuki[135,136], G.R. Hall[137], Norman[107], and of extensive unpublished explorations at IIT.

The key is the nature of the modifier at the Reynolds numbers of interest: due to the side flow the mean separation length is short, 3k to 8k, depending primarily on the height to width ratio for the squat protuberances used. This modified vorticity nevertheless represents a powerful amplifier, a fact which was not given its proper weight until fully revealed by smoke visualization. The frequencies which are amplified here are thus similar to the high frequencies amplified very near the obstacle in the K-T 2D experiments. The K-T high frequencies were damped farther downstream, especially in the reattached layers and did not contribute to the movement of transition except when transition occurred near the element.

The second crucial distinguishing feature of the 3D separated thin shear layer is its narrowness. Once the periodic instability of this shear layer commences it leads rapidly to nonlinear rolled up vortex loops which are lifted up toward the edge of the boundary layer as they march downstream. u_{rms} fluctuation levels of 4 to 5% of freestream U were measured in many configurations at IIT without causing the quick movement of transition toward the protuberance described by Tani! In a sense the reattached boundary layer was not receptive to these extraneous vortical entities even though they gave rise to much more intense fluctuations than the critical 0.01U fluctuations of Klebanoff and Tidstrom.

7f The Mechanisms of Breakdown -- 3D

Once the u fluctuation exceeded an apparent threshold of 0.04U to 0.05U because of increased U, increased k, or increased freestream disturbances (particularly acoustic ones), a slow growth of low frequency fluctuations in the inner third of the boundary layer ensued. It would lead ultimately to formation of intermittent turbulent spots at distances comparable to those in Tani's data collection. Where did those low frequencies come from? Did they bear any conceptual relationship to the three-dimensional T-S wave packets described by Gaster and Grant[22] for their localized three-dimensional excitations?

In 1969 this writer conjectured[7] that because of their formation these rather intense disturbances had more favorable phase relationships than Elder's spark-generated intensities[138] and could therefore activate the $\vec{\zeta}\cdot\vec{\nabla}\vec{v}$ vorticity production in the equation for the vorticity $\vec{\zeta}$ (section 2e) at lower u_{rms} levels. Turbulent spots could then be generated directly without any additional secondary linear instability at u_{rms} levels below those of (0.18 ± 0.25)U cited by Elder. Norman's thesis[107] (see section 6a) suggests strongly that the low frequencies mentioned above may well be T-S connected. Norman used simultaneous sound excitation at two distinct frequencies designed so that the difference signal f_2-f_1 (which is invariably generated in the nonlinear instability region of the locally separated shear layer; see also Miksad[29]) would fall in the excitable T-S range. Norman found that the subsequent growth of the f_2-f_1 fluctuations was also T-S like. The phenomenon existed as well when there was a single pure excitation frequency and a nearly random acoustic field caused by the bearings in an ancient fan motor. Whether this peculiar secondary nonlinear excitation can be and is generally responsible for the generation of the amplified low frequencies near the wall when only the natural frequency of the separated shear layer downstream of the protuberance and nonacoustic freestream turbulence are present, is a matter of conjecture at this stage. One sees no a priori reasons why the effect could not be rather general.

7g Contrast between 2D and 3D Mechanisms

To recapitulate the contrast: when a 2D modifier amplifies the "received" disturbances beyond 0.01U, transition is unavoidable within a short distance. For a 3D modifier the amplified disturbances reach truly nonlinear levels of 0.04U or higher without influencing the transition location practically, because (1) the vortex loop lift-up limits the region of interaction with the inner sensitive layer of the reattached boundary layer physically to short distances, and (2) the short separated region selectively amplifies only a band of higher frequencies which are unpalatable to the reattached layer directly. This previously undocumented nonlinearity does not cause a runaway toward transition as in the 2D cases of Klebanoff and Tidstrom. However it brings about a probably rather inefficient transfer of energy to lower frequencies, in particular by "nonlinear differencing"[29] between whatever frequencies are present in the amplified band. In the Norman experiment[107] of two clean dominant frequencies the difference frequency could be clearly identified as growing slowly but exponentially in the reattached non-2D boundary layer in a T-S like manner. Transition behavior induced through the indirect mechanism depends sensitively on the enhancement of receptivities by the roughness and by the particular mix of frequencies and amplitudes that are available and "received".

For higher Reynolds numbers and larger disturbances the process may or may not bypass the difference-excited T-S path. For lower Reynolds numbers, Tani, Komoda, Komatsu and Iuchi[134] demonstrated convincingly how in absence of the Norman path the direct T-S path is enhanced by the steady effects of the 3D roughness. Even far downstream, three-dimensionality of the protuberance brings about strongly localized effects in the spanwise redistribution of the thickness of the essentially Blasius boundary layer. In the example studied in detail by Tani et al, the displacement-thickness Reynolds number Re_{δ^*} varied from 700 to 920 in a spanwise distance of about two boundary-layer thicknesses. Using a vibrating ribbon for a controlled excitor, they showed that this three-dimensionality is important to spanwise transfer and local accumulation of disturbance energy in the nonlinear stage of the T-S growth. Consequently local breakdown intensities are reached earlier at the edge of steady wakes of even very small protuberances than in pristine undisturbed layers. Knicks and nonuniformities in leading edges cause similar local spanwise corrugations of mean boundary layers and facilitate earlier than normal breakdown.

It is noteworthy that for the 2D roughness of Klebanoff and Tidstrom[46] the boundary layer was two dimensional upstream of the element within the accuracy of careful measurements and yet significant spanwise variations of the fluctuation velocity u_{rms} were observed over the rear-facing separated region. Thus it appears that even carefully installed 2D objects which generate $\partial p/\partial x$ (especially adverse) enhance three-dimensionality of amplified disturbances. This three-dimensionality again hastens transition.

7h Additional Effects and Practical Recourse

In his 1973 assessment of the roughness effects, Tani[10] comments that the additional influences of pressure gradients and freestream turbulence on transition (and we might add sound) are inadequately understood. It seems plausible that the microscopic picture presented in this Chapter concerning the receptivity and amplification characteristics of the local modifiers-amplifiers can serve as a springboard for design of systematic experiments which should advance this understanding substantially. In the light of the new findings, unguided collection of data and correlations without regard for the spectral nature of the phenomena are unlikely to be of much use. Similarly computer prediction techniques purporting to include roughness effects would have to do more than assume injection of "equivalent" disturbance intensities to be credible.

For design purposes at incompressible speeds the three-dimensional roughness may perhaps be characterized well enough by the single critical Reynolds number Re_{kt}, at which transition moves to the near wake of the element, see Fig. 12 of Tani[139]. For roughness of known height k one can then expect the narrow-range behavior described here to be centered on the critical condition. At high, especially supersonic speeds, the difficulties in obtaining microscopic information are likely to keep any modeling speculative and macroscopically empirical.

7i The Problems of Distributed Roughness

The term "distributed roughness" refers generally to a collection of 3D protuberances with some statistical distribution of heights k and protuberance density ρ_k in the x,z surface. Many researchers believe that the largest elements will govern the onset of transition in a pattern similar to that described here for single 3D roughness. This seems plausible in view of Norman's picture: the high frequency amplification over the short separated regions attached to the largest protuberances could well be modified but not qualitatively changed by the presence of neighboring smaller elements except in extreme cases. One can visualize densities and geometries with both enhancing and damping interference factors. And since, as with bad apples, it takes only a few seeds of turbulent spots to spoil the batch permanently, the use of a critical Re_{kt} seems to offer a sensible practical course[130,139,140].

Nevertheless we should not delude ourselves that the basic understanding is at hand and that no further surprises are in store. The problem remains essentially of the bypass type where analysis and computers have been of little help. Singh and Lumley's 1971 spectral analysis[141] of the flow over a rough surface is restricted to precritical conditions and yields a mean velocity profile with an inflection point which, however, "is buried deep in the inner viscous region and will not contribute to instability". Merkle, Kubota and Ko[142] also tried to two-dimensionalize the model by replacing the disturbed flow near and around the distributed roughness shapes with an eddy-viscosity sublayer patched on to the ordinary-viscosity layer for both mean velocity profile and O-S computations. They claim reasonable agreement with past experiments but call for microscopic experimental verification of the mechanisms in the proximity of the distributed roughness (not downstream as in the past).

It would seem desirable to settle early the practical limitations, if any, on the concept of dominance of transition onset by the largest roughness elements in the distribution, and on the usage of the associated Re_{kt} criteria. This concept and the model of Merkle et al do not appear to be compatible. The implications of limited hot-wire information[139] for the case of relatively sparse distributed roughness are that the spanwise density of turbulent spot seeding is increased. According to recent thinking--e.g., Coles and Barker[146]--the interaction between growing turbulent spots should influence not only the latter part of the transition region, but also the developed turbulent boundary layer itself. Experimental study of the development of turbulent spots over a surface with distributed roughness would then hold both basic and applied interest.

In a design situation the roughness information is very crude or not available. Roughness also increases with the age of the prototype. A designer is thus faced, vis-à-vis roughness, with the issues discussed in sections 2g, 2i, 3a and 3d. Aerodynamicists testing models in cryogenic wind tunnels may face similar difficulties.

7j O-S Subcritical Transition

In his 1973 review Tani also included a revised correlation of Re_{kt} for 3D protuberances placed in various pressure gradients. This correlation is reproduced here as Fig. 9 with arrows indicating the displacement Reynolds numbers at which infinitesimal disturbances begin to amplify according to parallel flow theory[19] for zero and 2D stagnation-region pressure gradients, 500 and 12600, respectively. This figure, and its unavailable companion with $Re_{\theta t}$ as absissa, are of interest with respect to the issues of O-S subcritical transition and of minimum Re_{θ} at which turbulence can sustain itself in boundary layers. Schubauer and Klebanoff[143] and Klebanoff et al[144] concluded that the spreading of spark-generated turbulent spots and of wakes of 3D single roughness elements in zero pressure gradients $\lambda^* = (\delta^{*}/\nu)(dU/dx) = 0$, was not truly turbulent below Re_{δ^*} of 480. It could be argued that non-parallel O-S theory indicates amplification from $Re_{\delta^*} \sim 400$ for $\lambda^*=0$, and that the Mochizuki data points[136] below Re_{δ^*} of 500 in Fig. 9 also do not exhibit clear-cut turbulent spreading. If so, turbulence onset and spreading on flat plates would be all O-S supercritical. Schubauer and Klebanoff commented that the agreement with stability theory "may be partly fortuitous". However, the belief grew that the rapid damping shown by *linear* theory below O-S critical conditions was associated in some way with the quenching of *nonlinear* turbulent phenomena as well.

Linear theory predicts rapid increase in neutral Re_{δ^*} values in accelerated flows, $\lambda^* > 0$. On the other hand, Tani's collection of experiments corresponding to the solid symbols in Fig. 9 documents turbulence formation at substantially subcritical conditions[44,145], in sharp contrast to the above belief. This brings us back to the practically dangerous problems of bypasses discussed in section 2f. The interesting feature of the solid-symbol data in Fig. 9 is that they are completely consistent with the correlation of $(Ux/\nu)_t$ vs. Re_{kt} by Tani[139] for isolated 3D roughness previously mentioned. Rather, the discrepancy is with respect to tacit generalizations of the conditions observed for zero pressure gradients by Schubauer and Klebanoff.

If the analysis of reentry flight data on blunt heat-sink noses of Murphy and Rubesin[43] were expressed in terms of the coordinates of Fig. 9, it would indicate subcriticality for many conditions. It is with respect to these flight tests that the designation of the "blunt-body paradox" was coined and Donaldson's provocative quotation in section 2f written. Murphy and Rubesin[43] inferred Re_θ of transition in the range of 100-200 from computations of *laminar* boundary layers. Re_θ of the self-sustaining *turbulent* layer (in the form of early spots or wedges) would be larger by ΔRe_θ associated with drag increments over the short intervening distances, including the drag of any tripping device or inadvertent roughness.

7k Minimum Re_θ for Self-Sustaining Turbulence

Preston[147] proposed a minimum Re_θ of 320 for a self-sustaining turbulent layer on a *flat plate* on the basis of extrapolations of pipe information to low Reynolds number. Coles[148] considered 320 too low and remained unconvinced that "turbulent flow may have been observed at Re_θ as small as 290..." because of the "indirect evidence". His important observation, "The main difficulty in the case of boundary-layer flow is that the inherent increase in Reynolds numbers with distance may act to convert a temporary, abnormal response to a strong disturbance into a permanent one," has to be heeded by all who analyze macroscopic transition information and may well explain the differences between estimates of the Re_θ minimum. For flat plates O-S critical laminar Re_θ values are 193 (parallel theory) and 154 (nonparallel theory) so that a substantial incremental drag would be required to reach Preston's criterion or higher values. This provides a different, essentially nonlinear rationale for the aforementioned flat-plate observations of Schubauer and Klebanoff. Having no Preston-like estimates for the minimum turbulent Re_θ of accelerated (and cooled) boundary layers, we lack any framework in terms of which we could interpret the low Re_θ values in the early transition on blunt bodies. From the viewpoint of linear stability theory this early transition remains a bypass.

8 CONCLUDING REMARKS

In this compact report the writer attempted to facilitate the task outlined for the present Conference by the AGARD Fluid Dynamics Panel, namely to "review the progress achieved during the last ten years and to bring to light the still unsolved problems". It would be gratifying if the report could serve as a backdrop and connective link for new research ideas and efforts to tackle the numerous "unsolved problems" touched upon. Needless to say, the writer gained much additional perspective on transition research and information utilization through months of preparatory study and hopes that the report conveys some of this perspective.

It is rather clear that the existing experimental data base is inadequate for providing a consistent framework of *understanding* which is needed in technological applications. The sensitivity of transition to a large number of parameters, which are hard to characterize and control, endows the field with a peculiar nature. Much of the past information is "macroscopic"--i.e., without detailed flow information which would clarify the many competing mechanisms. This macroscopic evidence as well as the necessarily simplified theoretical modeling often point to contradictory conclusions.

It has recently become recognized that cooperative efforts are needed to add to our fragmentary understanding and to resolve the many existing contradictions (section 1c). The U.S. Transition Study Group and the Eurovisc Working Party on Transition made possible substantial discussion of selected priority issues and provided channels for deeper communication among researchers interested in related problems. However, as voluntary groupings of interested individuals, they exert influence only through persuasion of the public at large and of the internal funding officers within their own organizations. The desirable coordinated experimental and theoretical programs will be sophisticated and relatively expensive. It is unclear where *sustained* funding required for any successful *coordinated basic effort* could come from. Whatever funding becomes available, careful scrutiny of research priorities seems to be called for in view of the magnitude and the nature of the problem described in Chapters II and III.

Chapters IV through VII report on the more recent progress in transition understanding in four problem areas of long standing: the two-dimensional channel flow, the flow in circular pipes, the impact of turbulent and acoustic freestream disturbances, and the impact of wall roughness. The original issues, their partial resolution, the remaining major questions and possible follow-up efforts are discussed in the light of the functional description of the transition process in Fig. 1.

It is interesting to note that in these four areas invariably the important steps forward in the last decade were associated with careful experiments, largely microscopic, and with their subsequent interpretation and modeling. With a few exceptions these experiments were not planned by a committee, but many benefited from critical discussions by cooperating or interested specialists.

Lists of transition problems appear larger than the lists of qualified researchers and can be found in the report and in the cited references. It would seem wise to heed the above lesson of the last decade or two and perhaps improve on it by *encouraging basic microscopic experimentation* so as to both *enlarge* *our data base and provide understanding of the mechanisms* linking the various aspects of Fig. 1. Once the mechanisms are clarified (e.g., the role of roughness in section 7b, 7e-7i) the understanding can guide systematic data acquisition (even macroscopic) to enlarge the data base further as special *ad hoc* needs become apparent for applications.

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TABLE I

QUANTITATIVE TRANSITION PREDICTION -- NATURE OF THE PROBLEM

A SENSITIVE MULTIPLE RUNAWAY PHENOMENA WITH COMPETING MODES

B MULTIPLY-VARIABLE INPUTS WHICH OF NECESSITY WILL REMAIN UNKNOWN, YET THEIR EFFECT, VASTLY AMPLIFIED, DRIVES THE SYSTEM

C NON-UNDERSTOOD RECEPTIVITIES

D TOO MANY PARAMETERS WHICH INTERACT IN MOSTLY UNKNOWN WAYS, INTERACTING MOSTLY NONLINEARLY

E MEAN VORTICITY PROFILES, INADEQUATELY CALCULABLE, ESPECIALLY IN PRACTICAL 3D CASES, YET AMPLIFICATION-CONTROLLING

F UNKNOWN CRITERIA FOR TURBULENCE ONSET AND SELF-REGENERATION

↓ ↓

RESIDUE OF UNCERTAINTY IN TRANSITION

Background for theoretical and experimental research, for computer prediction, for testing, for design, for research funding

W NECESSITY OF EXTRAPOLATION OF INFORMATION FROM LIMITED EXPERIMENTS IN LIMITED GROUND FACILITIES

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

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

Z DESIGN ASSESSMENTS OF RISKS OF SUCH PROBABILITIES

FUNDING OFFICERS

RESEARCHERS
  Analysts
  Experimenters

TESTERS

CORRELATORS

PREDICTORS

DESIGNERS

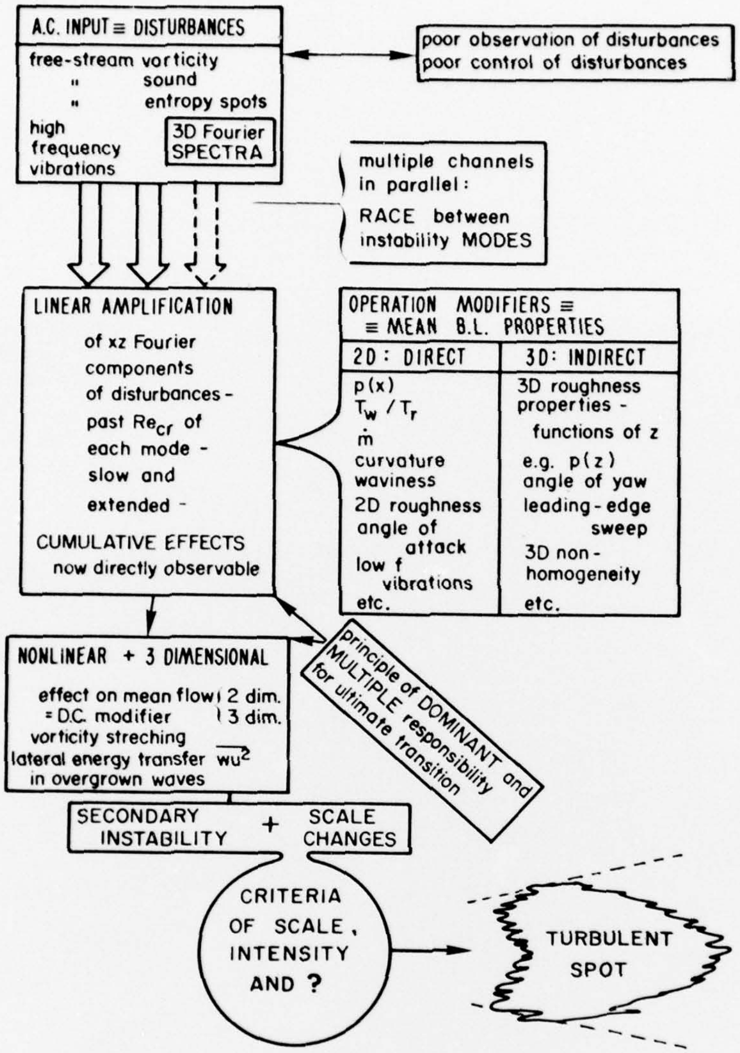

Fig. 1 System view of TRANSITION PROCESS

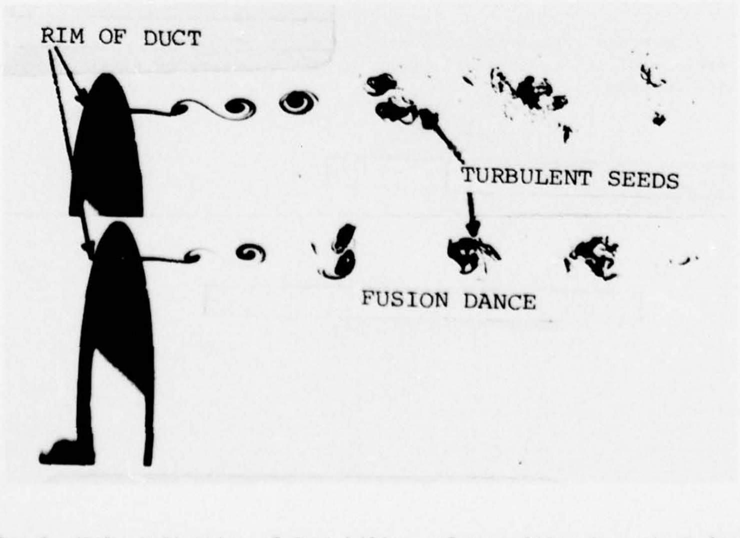

Fig. 2 Smoke indication of instability and transition in a shear layer leaving the rim of a duct: two successive views, shifted for easier comparison. Courtesy of A. Michalke and P. Freymuth.

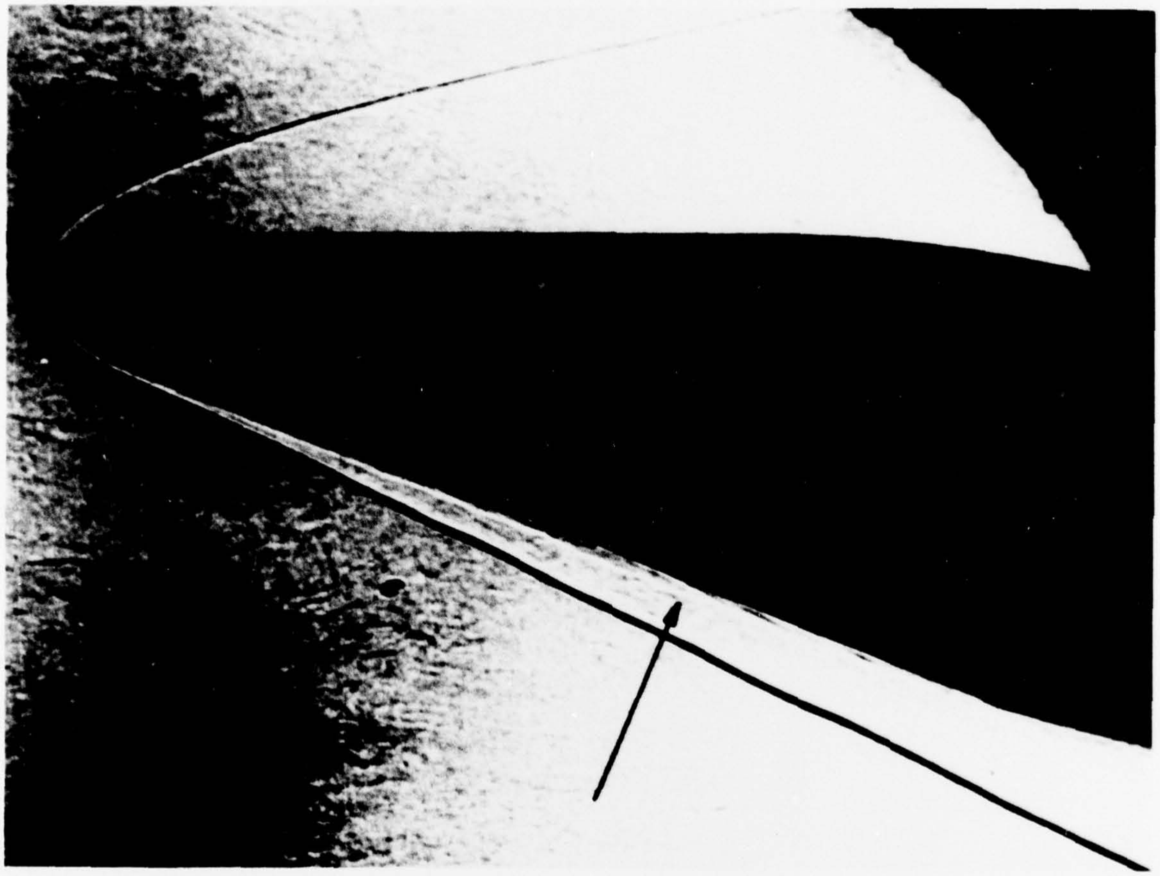

Fig. 3 Hypersonic transition on a shuttle shape caused by overexpansion and formation of a local unstable weak "jet". Courtesy of AIAA and Young, Reda, and Roberge.

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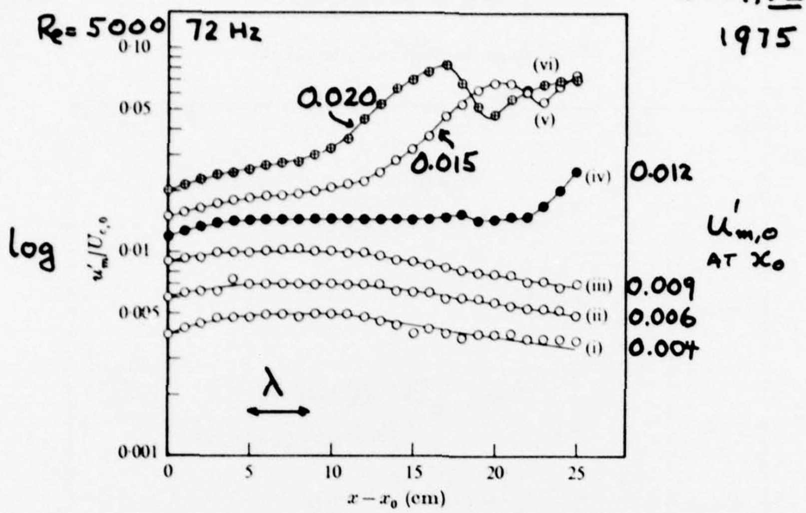

Streamwise variations of maximum intensity u'_m/U shown at the following different values:

$u'_{m,0}/U_{c,0}$	0·004	0·006	0·009	0·012	0·015	0·020
	(i)	(ii)	(iii)	(iv)	(v)	(vi)

Fig. 4 Growth or decay of a subcritical disturbance with f = 72 Hz at Re = 5000, depending on its initial intensity $u'_{m,0}/U_{c,0}$. Courtesy JFM and Nishioka, Iida and Ichikawa.

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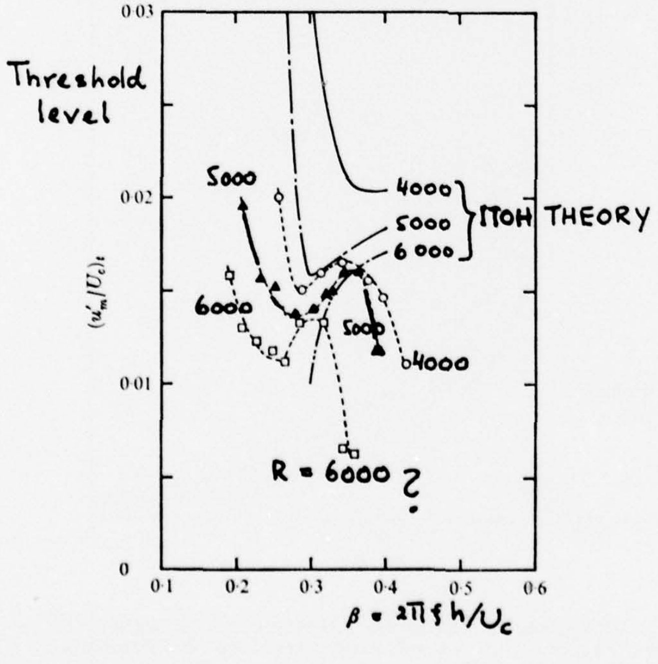
Stability of plane Poiseuille flow



R (× 10^{-2})	40	50	60
Theory (Ito)	——	—·—	—··—
Present	○	△	□

Fig. 5 Threshold value for the subcritical instability $(u'_m/U_c)_t$ against angular frequency β. Courtesy of JFM and Nishioka, Iida, and Ichikawa.

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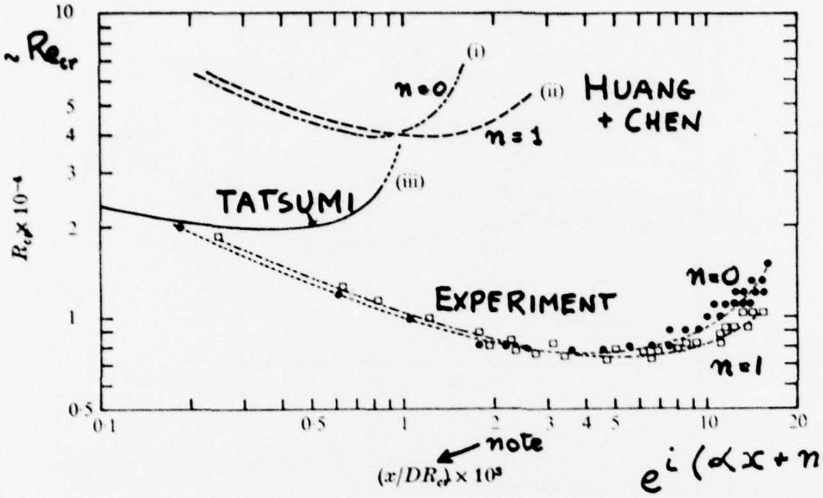

$e^{i(\alpha x + n\theta - \omega t)}$

Curves (i) and (ii) show the results of Huang & Chen's (1974*a*, *b*) analysis for axisymmetric and non-axisymmetric disturbances respectively. Curve (iii) shows the result of Tatsumi's (1952*a*, *b*) analysis for axisymmetric disturbances. Experimental data obtained in the present study: ●, axisymmetric disturbances; □, non-axisymmetric disturbances.

Fig. 6 Axial variation of the critical Reynolds number. Courtesy of JFM and T. Sarpkaya.

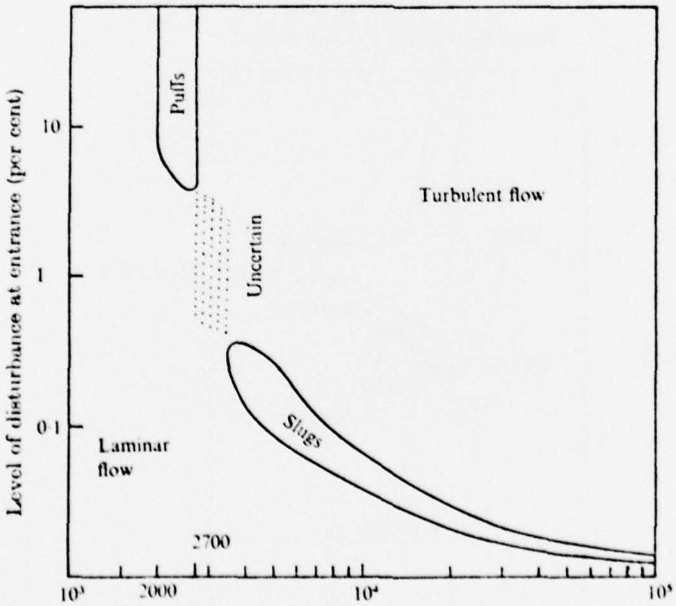

Fig. 7 Sketch of regimes of disturbance levels and flow structures in circular pipes. Courtesy of JFM and I. Wygnanski and F. Champagne.

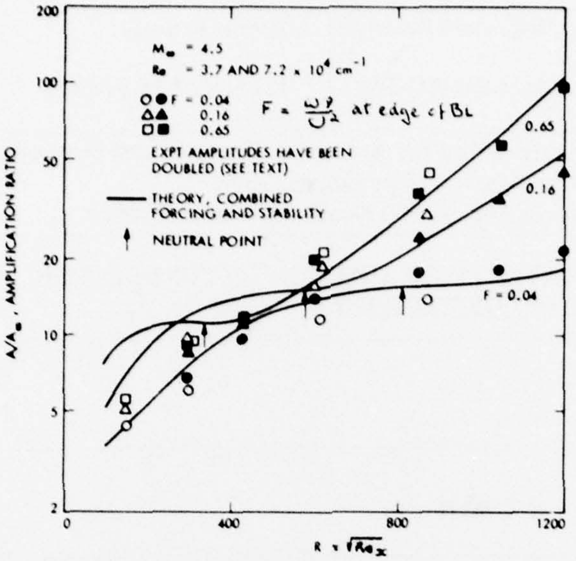

Fig. 8 Mack's precritical forced disturbance growth linked to free growth at neutral points, as compared to Kendall's measurements; $M_\infty = 4.5$. Courtesy of AIAA and J. Kendall and L. Mack.

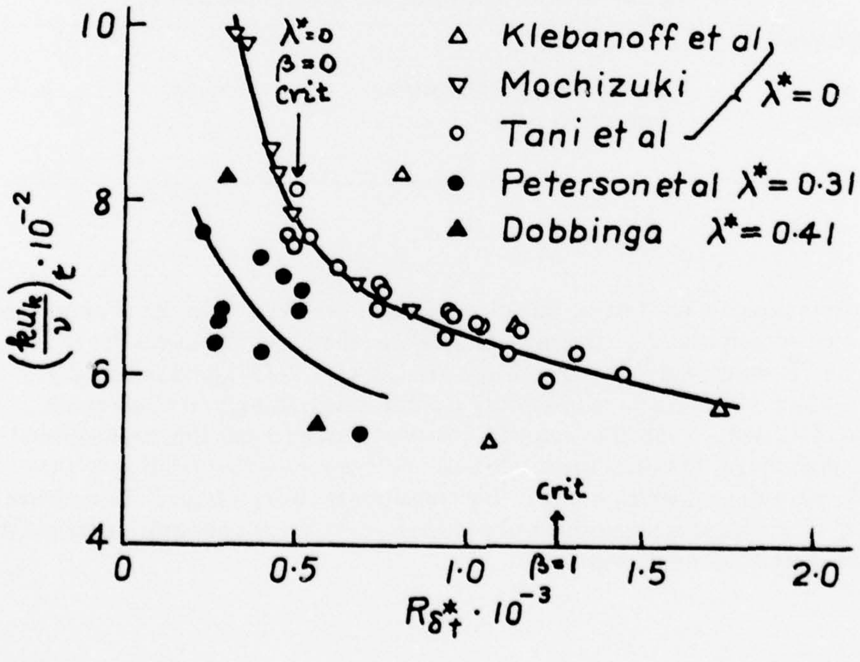

Fig. 9 Tani's correlation of Re_{kt} (the 3D-roughness Reynolds number for transition reaching near wake) with displacement Reynolds number for various pressure gradients. Arrows indicate linear neutral Re_{δ^*} values. Courtesy I. Tani.

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14. Abstract

Contained herein is a concise state-of-the-art review and perspective on the phenomenon of transition which constituted the "Opening Address" at the Fluid Dynamics Panel Symposium on "Laminar-Turbulent Transition" (AGARD-CP-224) held in Lyngby, Denmark, 2–4 May 1977. Various instability mechanisms leading to transition are proposed and discussed. A valuable insight is provided based on existing experimental evidence and postulated flow structures. Critical questions are asked relating to the conceptual foundations on which much of the transitional effort is based. To enhance our understanding of the basic mechanisms and processes, detailed microscopic experiments are encouraged to increase the data base.

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INSTABILITY, TRANSITION TO TURBULENCE AND PREDICTABILITY
by M.V.Morkovin
Published July 1978
38 pages

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