Recent Developments in Boundary-Layer Transition Research

The following seven articles are from the "Recent Developments in Boundary-Layer Transition Research" session of the AIAA 12th Aerospace Sciences Meeting that was held in Washington, D.C., January 30–February 1, 1974. These papers present the combined research results of the NASA Transition Study Group which was founded in 1970. The Editor and staff of the *AIAA Journal* wish to thank Eli Reshotko, Case Western Reserve University, and *AIAA Journal* Associate Editor Fernando L. Fernandez, R & D Associates, for organizing the session at the Meeting and expediting the preparation of the papers for publication.

A Program for Transition Research

ELI RESHOTKO*
Case Western Reserve University, Cleveland, Ohio

The NASA Transition Study Group was founded in late 1970 to develop and implement a program that would do something constructive toward resolving the many observed anomalies in boundary layer transition data and that might provide some basis for future estimation of transition Reynolds numbers. The group formulated specific experimental programs emphasizing careful and redundant measurements, documentation of the disturbance environment and eliminating, wherever possible, facility induced transition. It recommended continued study of stability characteristics as well as theoretical studies of the coupling of various types of disturbances to boundary layers. This paper describes the nature of the program and its details. The remainder of the papers of this session give some of the results obtained under the program to date.

I. Introduction

THE current programs involving design of high-speed aerodynamic configurations require reasonably dependable transition information because of the following factors that are affected by transition: 1) aerodynamic heating and its influence on thermal protection systems; 2) observables; and 3) vehicle dynamics.

The interest in transition as affecting thermal protection system design is obvious for entry vehicles and shuttle systems. But even for hypersonic cruise vehicle designs where length Reynolds numbers will be as large as 200×10^6 and the flow will be predominantly turbulent, the designer will ask: What parts of the configuration are laminar? Can we count on their being so? What is an effective means of boundary-layer tripping so that such configurations can be tested at smaller length Reynolds numbers?[1–3]

Regarding observables: simply put, a vehicle can be observed not only by "seeing" its physical size but also by its flowfield and particularly its wake. Transition is known to affect wake behavior. Vehicle stability, both static and dynamic, is affected when transition is observed on the back of an entry cone, particularly at angle of attack. The effect is greatly enhanced when ablation is involved.[4–5]

An early hypothesis on the mechanism of transition from laminar to turbulent flow is that due to Reynolds and developed further by Rayleigh. This hypothesis, that transition is a consequence of instability of the laminar boundary layer, remains most highly regarded by workers in the field. It has certainly stimulated much theoretical and experimental work in boundary-layer stability. The excellent agreement between the boundary-layer stability experiments of Schubauer and Skramstad,[6] Liepmann,[7] Laufer and Vrebalovich,[8] and Kendall,[9] with appropriate theories has provided a basis for proceeding in developing the consequences of the Reynolds-Rayleigh hypothesis.

Nevertheless, over the years transition data have been accumulated and correlated by the traditional aerodynamic testing procedures and quite independently of stability considerations. These tests have yielded lots of information on the effects of Mach number, surface temperature level, the mysterious "unit Reynolds number," surface roughness, bluntness, pressure gradient, suction and blowing, angle of attack, sweep, etc. These efforts, however, have yielded neither a transition theory nor any even moderately reliable means of predicting transition Reynolds numbers.

In the last six years or so,[10–13] attention has again focused on the importance in the transition process of the response of the boundary layer to the available disturbance environment. For example, it has been shown that the transition behavior in supersonic wind tunnels above Mach number 2.5 can be clearly ascribed to the noise radiated from the turbulent boundary layers on tunnel walls.[14–17] In the JPL 20″ Supersonic Tunnel at $M = 4.5$, Kendall observed no transition on a flat plate of length Reynolds number 3.3×10^6 when the tunnel wall boundary layer was laminar ("quiet" operation) whereas in the same tunnel at the same Mach number but with turbulent side wall boundary layers, Coles[18] observed transition on a plate at Reynolds numbers of the order of 1×10^6. Thus the vast body of transition data obtained in supersonic wind tunnels is suspect.

Nor are ballistic ranges free of difficulties. In a series of experiments in an enclosed range where the model preceded any disturbances resulting from sabot impact, Potter[19] nevertheless obtained a variation of transition Reynolds number with unit Reynolds number for reasons that have yet to be explained.

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* Professor of Engineering; Chairman of the NASA Transition Study Group, Associate Fellow AIAA.

These severe effects of facility on transition Reynolds number are some of the salient difficulties among the many catalogued and discussed in the comprehensive report by Morkovin.[13] It is clear that the interpretation and utilization of wind tunnel and ballistic range transition data will require resolution of these various difficulties.

II. Formation of NASA Transition Study Group

The state of the transition problem was taken up by the NASA Research and Technology Advisory Subcommittee for Fluid Dynamics about five years ago.† Recognizing the importance of the problem, the Subcommittee endorsed the need for doing something constructive toward resolving the observed anomalies and providing some basis for future estimation of transition Reynolds numbers.

Following a recommendation by the Subcommittee, NASA Headquarters requested the participation of a number of recognized transition investigators encompassing the directly interested federal agencies and government laboratories plus one member from the Subcommittee. The original membership of the NASA Transition Study Group was: E. Reshotko, Chairman, Case Western Reserve University; R. D. Wagner, Secretary, NASA-Langley Research Center; M. H. Bertram, NASA-Langley Research Center; P. F. Brinich, NASA-Lewis Research Center; A. Gessow, NASA Headquarters; J. M. Kendall, Jr., Jet Propulsion Laboratory; P. S. Klebanoff, National Bureau of Standards; W. C. Lyons, Jr., Naval Ordance Laboratory; E. D. McElderry, Jr., AFFDL-Wright-Patterson AFB; J. D. Whitfield, von Kármán Gas Dynamics Facility-ARO; J. G. Marvin, NASA-Ames Research Center. The only changes have been the succession to the group in late 1972 of I. E. Beckwith, NASA-Langley Research Center, following M. Bertram's untimely death and the much regretted resignation of R. Wagner because of a new work assignment.

The NASA Transition Study Group had its first meeting in November 1970. After presentations by the membership and subsequent deliberation, the Group arrived at the position that there was clearly a need for further research of a fundamental nature toward resolving inconsistencies and anomalies in the transition picture. It was also made clear that the transition information available to that time was dominated by factors such as wind tunnel boundary-layer noise and other facility and model disturbances whose specific influence on transition had not been delineated quantitatively. The group agreed that an effective, practicable research program should be undertaken that is limited in scope with attention directed to identification and evaluation of the effects of the disturbance environment in quiet wind tunnels and in ballistic ranges. The program would be primarily experimental but with close theoretical support and should be directed toward understanding of fundamental processes. Program coordination should be accomplished by a committee of people who are active in transition research; it was concluded that the Transition Study Group could satisfactorily perform this function. The facilities of the represented laboratories were deemed adequate to initiate such a program, and the group members expressed a willingness to participate in a cooperative effort. It is to be stressed that the program is not to be considered an exclusive effort of the represented laboratories and it is hoped that the work of other groups will complement the program.

III. Proposed Programs

The Group met again in January 1971 at which time preliminary plans for its program were formulated. At a subsequent meeting in July 1971, the program was subjected to further scrutiny and refinement.

The deliberations of the Group yielded a number of guidelines to be used in the formulation of specific programs:

1) Any effects specifically and only associated with test facility characteristics must be identified and, if possible, avoided. This points to emphasizing studies in ballistic ranges and "quiet" tunnels.

2) Attention must be given to disturbances introduced by model surface, model material and internal structure. This includes effects of tip material and integrity, model ringing and the effect of nonuniform temperature distribution due to tip heating. Experimental studies should include documentation of these various factors.

3) Details of coupling of disturbances of various kinds of the boundary layer must be understood theoretically and experimentally, so that the sensitivity of the transition process to the flight environment might be determined.

4) The models should be of simple geometry. A slender cone (5°–10° half angle) is favored with tip bluntness (needed to avoid melting in range tests) held to less than 3%.

5) Tests should have ranges of overlapping parameters, and where possible experiments should have redundancy in transition measurements.

6) When coupled with information on atmospheric disturbances, it should be shown how the work can be related to transition in flight.

The specific programs proposed are: a) program for resolution of wind tunnel data; b) program at $M = 4.5$; c) program at $M = 2$; d) low speed experimental program; e) development of quiet wind tunnels; and f) theoretical program. The level of effort available for the program was estimated as about 8 man-years per year which was about 30% of the total existing effort in the transition area for the combined represented laboratories. The Group agreed that the program should be incorporated into the current research at a high level of priority. A description of the supersonic facilities available to the program is given in the Appendix. The Transition Study Group or subgroups thereof have continued meeting on the average of twice a year for program planning, direction, and review.

Descriptions of Specific Programs

A. Program for Resolution of Wind Tunnel Transition Data

The Group recognized a responsibility to assist in the resolution of differences in transition data in noisy tunnels to gain better understanding of the limitations of wind tunnel transition data. These differences could be ascribed to different disturbance environments in the test section, different measurement techniques, different definitions of transition, or a combination of these and other factors. Accordingly, the Group recommended a joint undertaking by NASA personnel at the Ames and Langley Research Centers to resolve the differences in transition data obtained at $M = 8$ on a 5° cone in the Ames 3.5 ft Hypersonic Tunnel and the Langley 18-in. Variable Density Tunnel. The proposed resolution of these data was to be based on measurements of the characteristics of the freestream, cone shock layer, and cone boundary-layer disturbances made with "hot" wire anemometers and surface pressure transducers. In addition to the disturbance measurements, to avoid questions regarding anomalous model effects, transition data were to be obtained on the same model in both facilities. This program was initiated in September 1971 by having Ames personnel test the Ames models in the Langley tunnel using Ames equipment in the presence of the interested Langley researchers. The Langley model was later tested by Langley personnel in the Ames 3.5 ft Tunnel, and of course each group re-ran its own model in its own tunnel. This program has been completed and is described in the paper by Owen, Horstman, Stainback, and Wagner.[20]

B. Program at $M = 4.5$

The Group put together the following program of research to be performed in facilities at three of the represented laboratories: AEDC, NOL, and JPL. The reasons for choosing $M = 4.5$ are:

† More particularly, the matter was dealt with by an ad hoc committee consisting of C. D. Donaldson, A. Goldburg, and M. V. Morkovin.

a) the JPL "quiet" tunnel has a range of quiet operation at this Mach number; b) in the AEDC range, the model precedes disturbances resulting from sabot impact; c) NOL ranges are capable of overlapping test parameters of both of the above facilities; d) cone tip ablation can be avoided at $M \approx 4.5$; and e) higher modes of boundary-layer instability are active and therefore data at this Mach number are somewhat indicative of what may occur at higher Mach numbers.

AEDC Ballistic Ranges. The Group recommended that the following studies be initiated at AEDC:

1) Effects of Cone Vibrations Characteristics: Boundary-layer transition should be measured on models constructed of different materials. Bench tests can be used to determine the vibration characteristics of the models (ringing frequency for example).

2) Effects of Small Surface Roughness: For the small models and high unit Reynolds numbers of the range experiments, model boundary layers are quite thin and inadvertent model surface roughness may influence transition.

NOL 1000 ft Hyperballistics Range. A unique temperature control section in the NOL range offers considerable promise for increasing the understanding of the transition process at high Mach number where the stability theory predicts diverse T_w/T_r sensitivity for the instability modes. At Mach number 4.5, in the NOL range T_w/T_r can be varied from 0.08 to 0.58. The Group recommended that this T_w/T_r range be studied at two unit Reynolds numbers, about 1×10^7 and 4×10^6 per ft. Comparison of results at the two unit Reynolds numbers may: 1) uncover effects of variable surface temperature which should be more pronounced at the higher unit Reynolds number, and 2) help span the unit Reynolds number gap that will necessarily exist in the evaluations at JPL where the maximum unit Reynolds number for "quiet" is 0.7×10^6 per ft.

JPL 20 in. Supersonic Tunnel Including "Quiet" Operation. The Group recommended using the JPL Tunnel to investigate those factors that could not be adequately or systematically studied in the ballistic range, but which might influence boundary layer transition in the range experiments. These factors include:

1) Small Angle of Attack: This is perhaps one of the most undesirable elements in range boundary-layer transition studies. It is difficult to hold angle-of-attack variations in range tests to less than about 3 degrees, and an assessment of the effects of these small angles-of-attack on transition is critical to the interpretation of ballistic range data.

2) Model Surface Temperature Variations: This is another undesirable feature of ballistic range tests. Aerodynamic heating of the test model as it proceeds through the range can raise the model tip surface temperature above 2000°R while the remaining parts of the model have a surface temperature close to 500°R. The effects of the hop tip and the large surface temperature gradients near the tip must be documented.

3) Model Vibration: Launch accelerations in the ballistic range can be 100 to 200 thousand g's, and ringing of the model in flight introduces a source of disturbance not normally encountered in full scale vehicle flight or in wind tunnel tests.

4) Wall-to-Recovery Temperature Ratio: Ballistic ranges are limited in attainable wall-to-recovery temperature ratio; the JPL tunnel can extend the range data, from $T_w/T_r \approx 0.60$ up to near adiabatic wall.

Unfortunately, at the test conditions for "quiet" operation in the JPL 20 in. Supersonic Tunnel, boundary-layer transition cannot be obtained on a model. Conclusions, as to the behavior of transition will have to be inferred from measurements of the model boundary-layer stability. The results to date for this program are reported in the papers by Potter[21] and Kendall.[22] The NOL portion of the program has not yet been initiated.

C. *Program at $M = 2.0$*

The program at $M = 2.0$ parallels the $M = 4.5$ program; however, considerable abbreviation of the details should be possible. Following the Transition Study Group Guidelines, a series of tests were laid out for the AEDC Ranges, NOL Ranges, and JPL and NBS Tunnels. These tests deal with the factors of surface temperature level, unit Reynolds number, angle of attack, model vibration, surface temperature variations, tip bluntness, and surface roughness.

It is generally felt that at this Mach number, the noise radiated from the tunnel walls is not a significant factor. Hence, if the tunnel boundary layer were either all laminar or all turbulent, it would have negligible effect on transition on a model at Mach 2. If transition occurs somewhere on the tunnel wall, then waves result which can affect transition on a model. The results to date for this program are also in the papers by Potter[21] and Kendall[22] The NOL and NBS portions of this program have yet to be initiated.

D. *Low-Speed Experimental Program*

Measurements with hot wire anemometers at low speeds enable a microscopic examination of the transition process to a degree of detail that is not available in the compressible high speed studies. Evidence exists that some of the phenomena observed at low speeds still are present in the high Mach number boundary-layer transition. For example, NBS measurements of the amplification of freestream disturbances by low-speed boundary layers reveals amplification of low frequency disturbances that should be stable according to stability theory[23]; a similar phenomenon seems to be present in measurements at JPL at $M = 1.6$.

Because of the apparent promise for uncovering mechanisms that may be fundamental to the transition process at high Mach number, NASA Transition Study Group Recommended continued study by the NBS on amplification of freestream disturbances in low-speed laminar boundary layers. This work is in fact continuing although not reported at this meeting.

E. *Development of Quiet Wind Tunnels*

The "quiet" tunnel, having laminar rather than turbulent boundary layers on the nozzle walls, has shown itself to be attractive for transition related studies because it averts a prime cause of facility induced transition at supersonic Mach numbers above 2.5. This does not mean that the test section of a "quiet" tunnel is disturbance-free and one must proceed cautiously in assessing the usefulness of such facilities.

The JPL 20 in. Supersonic Tunnel achieves quiet operation when operated at low stagnation pressure. However, the unit Reynolds number is such that transition is not generally observed under the limited conditions of quiet operation.

It was felt desirable to develop a high unit Reynolds number quiet tunnel for transition research and also for the study of turbulent boundary-layer development in the absence of noise contamination due to turbulent nozzle wall boundary layers. As with other facilities, the proper utilization of a quiet tunnel depends on identification and documentation of its disturbance environment.

Klebanoff and Spangenberg have undertaken a study of nozzle laminarization by suction through a longitudinally slotted wall in the NBS Mach No. 2 tunnel. In a cooperative effort, NASA-Langley is providing to NBS a porous wall of weave construction to fit the NBS nozzle. These should enable a critical test of the validity of an area suction approach. NASA-Langley is seeking to build a quiet tunnel with test section unit Reynolds numbers up to 10×10^6 per ft at $M = 5$. The progress to date in the development of such a facility is described in the paper by Beckwith[24] and in the supporting paper by Stainback, Harvey, et al.[25]

F. *Theoretical Program*

The Group did not formulate a specific theoretical program. Nevertheless, it recommended that in addition to the continuation of the study of boundary-layer stability characteristics, that there be further theoretical studies of the coupling of various types of disturbances to the boundary layer to complement the experimental treatment of these effects. These should include: external moving pressure fields, freestream turbulence, model vibrations, surface roughness, etc.

A most successful blending of theory with experiment has been in the work of Mack[26] and Kendall[22] and is reported in their respective papers. Another study aimed at the effects of freestream turbulence on a laminar boundary layer is by Rogler and Reshotko.[27]

IV. Conclusion

The program of the NASA Transition Study Group is a fundamental one with the objective of developing procedures yielding information relevant to transition in flight. This is not a modest objective; nor is the adopted cooperative approach entirely conventional. Success is felt to depend on just this kind of concerted national effort, experimental and theoretical, encompassing the talents and facilities of the many participating laboratories.

Appendix: Suitable Test Facilities and Their Capabilities

Ballistic Ranges

1) *VKF Hypervelocity Range G—AEDC*

Length, ft.	1000
Diameter, ft	10
Launcher bore diam, in.	0.5 to 2.5
Pressure, mm Hg	20×10^{-3} to 760
Maximum freestream unit Reynolds No. at $M_\infty = 5$, ft^{-1}	33×10^6

2) *VKF Hypervelocity Range K—AEDC*

Length, ft	100
Diameter, ft	6
Launcher bore diam, in.	0.5 to 2.5
Pressure, mm Hg	1×10^{-3} to 1500
Maximum freestream unit Reynolds No. at $M_\infty = 5$, ft^{-1}	65×10^6

3) *NOL Pressurized Ballistic Range*

Length, ft	300
Diameter, ft	3
Launcher bore diam, in.	0.8 and 1.25
Pressure, mm Hg	3 to 4500
Maximum freestream Reynolds No. at $M_\infty = 5$, ft^{-1} (room temperature)	200×10^6
Temperature capacity, °R	180 to 1310

4) *NOL 1000 ft Hyperballistic Range*

Length, ft	1000
Diameter, ft	10
Launcher bore diam, in.	2.0 and 4.0
Pressure, mm Hg	0.2 to 760
Maximum unit Reynolds No. on model at ambient temperature at $M = 5$, ft^{-1}	33×10^6

Both NOL ranges have sections capable of cryogenic cooling or heating the range air. The model, wall temperature to recovery temperature ratio can thereby be varied from about 0.58 to 0.09 at $M_\infty \approx 4.5$.

Wind Tunnels

5) *JPL 20 in. Wind Tunnel*

Test section, in.	18×20
Stagnation pressure, psia	60
Stagnation temperature, °R	600
Mach No.	1.2 to 5.6
Maximum unit Reynolds No. at $M = 4.5$, ft^{-1}	3.6×10^6
Running time	continuous
Quiet operating range, *Re*/ft:	
$M = 4.5$	4.8×10^5 to 7.2×10^5
$M = 2$	2.4×10^5

With turbulent sidewall boundary layers, the disturbance level in this facility at $M_\infty = 4.5$ is on the order of 1%. With laminar sidewall boundary layers the turbulence level is only about 0.03%.

6) *NBS $M_\infty = 2$ Tunnel*

Test section, in.	3×4
Stagnation pressure, atm	0.1 to 3.0
Stagnation temperature, °R	540 to 600
Maximum unit Reynolds No., ft^{-1}	12×10^5
Mach No.	1.96
Running time	Continuous

This facility is currently undergoing a modification which offers potential for operation with laminar sidewall boundary layers; suction is being used in an attempt to stabilize the nozzle wall boundary layer and maintain sidewall flow.

7) *Ames 3.5 ft Hypersonic Tunnel*

Stagnation pressure, atm	13.6 to 190
Stagnation temperature, °R	1200 to 2800
Maximum unit Reynolds No. at $M-7.4$, ft^{-1}	10^7
Nominal Mach No.	5, 7, and 10
Running time, sec	120

This facility employs a nozzle cooling system whereby either air or helium can be injected through an annular slot in the subsonic section of the nozzle to provide a cool layer of gas along the nozzle and test section walls.

8) *Langley 18-in. Variable Density Tunnel*

Test section diam, in.	18
Stagnation pressure, atm	1 to 200
Stagnation temperature, °R	1160 to 1510
Maximum Reynolds No., ft^{-1}	10^7
Nominal Mach No.	8
Running time, sec: exhausting to vacuum tank	90
Exhausting to atmosphere	600

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