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Report of the High Reynolds Number Wind Tunnel Study Group of the Fluid Dynamics Panel

NORTH ATLANTIC TREATY ORGANIZATION

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NORTH ATLANTIC TREATY ORGANIZATION

ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

REPORT OF THE
HIGH REYNOLDS NUMBER WIND TUNNEL STUDY GROUP
OF THE FLUID DYNAMICS PANEL

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This Report was prepared at the request of the Fluid Dynamics Panel of AGARD–NATO

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REPORT OF THE HIGH REYNOLDS NUMBER WIND TUNNEL STUDY GROUP OF THE FLUID DYNAMICS PANEL

1. INTRODUCTION

Modern aeronautical and aerospace systems are so expensive that every reasonable effort to minimize the risk in their development is warranted. If a weapon system like the F-111 or an airplane like the Concorde suffers delays or outright failure as a result of unforeseen technological problems, the penalties to the companies and nations involved are staggering. The tried and proven way to minimize such risks on aerodynamic systems is to conduct extensive tests in adequate wind tunnel facilities. Higher costs of the future, large sophisticated aeronautical and aerospace systems make such testing even more imperative than is indicated by history.

Wind tunnels of the NATO countries have been shown, during recent years, to be quite *inadequate* for tests for the large aeronautical systems under development. This fact was brought out by Dr Küchemann at the 1968 AGARD Conference on Transonic Aerodynamics in Paris[1]. The intricacies and inaccuracies associated with extrapolation of wind tunnel data taken at a Reynolds number of 3 to 7 million for design of airfoils that operate at Reynolds numbers of over 150 million were thoroughly discussed at the von Kármán Institute's lecture series on "Large Airplane Aerodynamics" (Ref. 2).

Mr J.L.Jones of NASA showed at the September 1969 meeting of the AGARD Fluid Dynamics Panel how close the C-141 airplane had come to failure because of inadequate Reynolds number capability of existing transonic wind tunnels[3]. Recognizing the inadequacy of existing transonic wind tunnel capability, as reflected in the above mentioned references, and in view of the concern of several members of the Fluid Dynamics Panel, Dr W.R.Sears, Chairman of the Panel wrote to the director of AGARD, Mr F.J.Ross, October 13, 1969, recommending the study which is discussed in this report. Mr Ross' affirmative response was immediate and work was begun by the AGARD FDP <u>Hi</u>gh <u>R</u>eynolds Wind <u>T</u>unnel working group in October 1969.

Membership of the HIRT group is given in Appendix I. Consideration was given by the HIRT group to:

(a) Aeronautical and aerospace systems that will operate at high Reynolds numbers at Mach numbers from 0.2 to 3, with the emphasis on transonic aircraft;

(b) Reynolds number sensitive, aerodynamic phenomena anticipated for those systems;

(c) Simulation required to study these phenomena;

(d) Available evidence on model testing in transonic and trisonic wind tunnels;

(e) New test facility capability required (performance and operating characteristics);

(f) Economical means to provide the new facility capability.

The study reported herein is adequate for the purposes of defining the performance and operating characteristics required in new, high Reynolds number wind tunnels, and conceptual tunnel designs which meet these requirements are proposed.

Although the attention of the HIRT group was devoted almost exclusively to the transonic flight regime, the proposed tunnels could be designed to meet the high Reynolds number testing requirements throughout the trisonic speed range.

The wind tunnels recommended in this report can be built using existing technology. However, utility of the tunnels and the quality of the data that they will yield will be enhanced by vigorous support of a relevant research program. Parts of that research program are disoussed in this report.

2. STUDY METHOD AND ACTIVITIES OF THE HIRT WORKING GROUP

An independent study, in depth, of high Reynolds number testing experience and future requirements was not attempted because the six working group members were located in six different countries and each of them could only devote a limited amount of time to this AGARD assignment. Each member of the HIRT group gathered information available in his country that related to the six problem areas listed in the introduction. Most of the group members solicited, as well, individual contributions from representatives of industry, government, and academic organizations. This material was forwarded to the chairman who in turn distributed copies so that each HIRT group member had all reports and information from all countries by the end of February 1970. Except for the Canadian contribution, these data were reviewed and analyzed by the group members prior to their first meeting. A list of the information distributed to the members is given in Appendix II.

In addition to the foregoing efforts to gather information on related studies under way in the different NATO nations, the chairman of the HIRT group visited the laboratories in France where important studies on transonic testing techniques are under way. Mr Poisson-Quinton and his associates of ONERA provided extensive unpublished information on wall interference studies, transonic testing techniques, and methods of inducing boundary layer transition. An offer was made to provide a set of standard airplane models which are being used in the French studies of transonic wind tunnel wall effects for use by other nations in similar tests.

All members of the HIRT group attended the first meeting at the von Kármán Institute during the week of April 20. Other participants present at the meeting are listed in Appendix III. Each of the invited participants made a presentation to the HIRT group and answered questions raised by the group members. Discussion concentrated on high Reynolds number testing requirements, capabilities and possibilities of Europe. As a result of the discussions specific studies and/or inputs were requested from individual HIRT group members.

After the first meeting Mr J.Y.G.Evans supplied information on the quality of flow needed in transonic tunnels as well as data on model deflections in a transonic air stream at a stagnation pressure of 5 atmospheres. Mr R.Hills was asked to supply cost data for blowdown tunnels designed to operate at stagnation pressures of 5 atmospheres and at 15 atmospheres, and a Ludwieg tube tunnel designed to operate at 26 atmospheres.

All members of the HIRT group attended the second meeting held at the U.S. Air Force Arnold Engineering Development Center, May 21 and at the National Aeronautics and Space Administration, Marshall Center, May 22, 1970. Other participants at the second meeting are listed in Appendix IV. Technical presentations given to the group by engineers from AEDC/ARO, Inc. are listed in Appendix V. Mr Lowe and Mr Cahill made inputs on industry requirements for high Reynolds number transonic tests and possible means of acquiring the needed data. Mr Ohman described the 5 foot Canadian high pressure trisonic blowdown tunnel and discussed some of its aerodynamic problems.

The HIRT group members inspected the 4′ x 4′ and the 16′ x 16′ continuous flow transonic wind tunnels at AEDC. A careful inspection was made of the AEDC 7.3 inch x 9.2 inch pilot high pressure Ludwieg tube transonic tunnel. Experimental data obtained with this small scale tunnel on flow starting processes, noise problems, instrumentation and test techniques, flow quality, and model data taken in the tunnel were discussed. The NASA-Marshall personnel described the design, performance, operation, instrumentation and test techniques used in their 32 inch diameter Ludwieg tube tunnel which is the highest unit Reynolds number transonic wind tunnel in the western world. The HIRT group members witnessed a firing and partial recycle of this facility, which operates with a maximum supply tube pressure of 700 psi. Models and instrumentation used in the tunnel were viewed and discussed.

Most of the other attendees at the second meeting of the HIRT group made significant inputs to, and answered questions of the group members.

Following the discussions at the second HIRT group meeting, Professor Lukasiewicz further analyzed the severe pressure disturbances (noise) present in the Canadian high Reynolds number transonic wind tunnel, and submitted the results to the HIRT group[6].

Conclusions of the HIRT group were set down and unanimously agreed upon during the last half day of the second meeting of the HIRT group. A general report outline was agreed upon during the meeting. A draft report was written by the chairman and mailed to the group members for review. The final report incorporates the important suggestions of the group members and is a consensus report of the members.

3. DISCUSSION

3.1 Regime of Concern

Figure 1 shows the Reynolds numbers as a function of Mach number that will be encountered by some aeronautical and aerospace systems scheduled for development during the coming decade, and the available wind tunnel Reynolds numbers. Based on vehicle length, Reynolds numbers of more than 10^9 will be encountered in the transonic speed range by large aircraft, space boosters, and recoverable orbital vehicles. These are an order of magnitude higher than the capability of the highest Reynolds number wind tunnels of the western world. Flight Reynolds numbers of fighter aircraft are several times the capability of present day wind tunnels.

Performance of wind tunnels capable of testing aircraft models have not been extended significantly since 1956 when the 16 ft x 16 ft continuous transonic and supersonic tunnels were completed at AEDC. Performance of these and the Ames 12 ft tunnel which constitute the highest Reynolds number test capability for airplane models are given on Figure 1. Several blowdown tunnels which produce component and two dimensional data at the same or slightly higher Reynolds numbers are in operation. Among these is the 5ft, 10 atmosphere stagnation pressure tunnel at the National Aeronautical Establishment in Canada. Performance of the 32 inch diameter Ludwieg type tunnel of NASA Marshall Center shown on Figure 1 is limited to use primarily on aircraft components and missile and booster models because of its test section size and shape.

Data reviewed by the HIRT group show that aircraft sizes have increased an average of 8% per year since 1935. Engineers from industry told the HIRT group that all of their studies show that aircraft much larger than those presently under development are feasible and will become economically advantageous. It is therefore clear that design information applicable to aeronautical and aerospace systems and components for operation at Reynolds numbers an order of magnitude higher than are presently available will remain a critical need for the foreseeable future.

3.2 Aerodynamic Problems

The C-141 airplane developed for the U.S. Air Force provided one of the first indications of large discrepancies between wind tunnel and flight data in the high Reynolds number, transonic regime. Figure 2 taken from the paper delivered by Mr J.L.Jones at the September 1969 meeting of the AGARD Fluid Dynamics Panel illustrates a typical problem. Turbulent boundary layer separation occurred further aft on the wing than was predicted from tunnel tests. This meant that in flight there was increased circulation around the wing and the shock wave on the suction surface moved aft. This changed the pressure distribution on the suction surface of the wing and hence the location of the lift-center. Consequently, trim of the airplane required greater forces from the tail surfaces and imposed greater loads on the fuselage structure than had been anticipated. No doubt both good engineering and serendipity were involved in the final, successful solution of this unanticipated problem. Representatives of industry from several nations emphasized to the HIRT group that data on models of new aircraft must be obtained at sufficiently high Reynolds number to avoid future difficulties of the type mentioned above.

Figure 3 gives a list of the major aerodynamic phenomena which require investigation at high Reynolds numbers. Many of these problems are associated with interference effects and arise because of the difficulty of calculating boundary layers in body-wing junctions, over jet exits, etc.; others are due to the effects of separated flow on aerofoils and on bodies when at appreciable angles of incidence. It is not possible with present theoretical methods to calculate these effects and so allow for differences between full scale and model Reynolds numbers. Penalties for errors in performance prediction are now greater than they were in the past, and designers can no longer afford a safe margin for allowances for scale effect. For these reasons, the crude methods of extrapolating model results which have been used are no longer adequate and in the future, wind tunnel data of greater precision are desired necessitating testing at realistic Reynolds numbers. More sophisticated methods are now being applied to aerofoil design which aim to utilize the maximum possible adverse gradient over the rear of the aerofoil without separation. Particularly at transonic speeds, these separation boundaries are altered by change of Reynolds number in a way that cannot be predicted and full advantage cannot be taken of these new aerofoil designs unless tests can be made at full scale Reynolds numbers.

3.3 The Need for Reynolds Number Duplication

In the light of the data mentioned above it is apparent that, particularly in the transonic regime, some means of checking flows at flight values of Reynolds number is essential. This view was corroborated by all (except one) aeronautical system designers, who made contributions to the HIRT group and who favored the construction of new transonic and trisonic high Reynolds number wind tunnels. Many of the engineers from industry stated a high priority for even a limited amount of data at conditions that duplicate flight Reynolds numbers. They felt that such data coupled with present day computer use would give them confidence in their designs. Representatives of industry were also interested in extensive testing at high Reynolds numbers for the purpose of refining aeronautical system design but in this connection they always mentioned cost effectiveness. They stressed that, for the latter type of testing, the cost per test point would have to be low so that the increased economy or performance gained from such tests would justify the testing. Workload surveys that were discussed with the HIRT group showed that industrial use alone would justify construction of more than one very high Reynolds number wind tunnel.

As regards artificial simulation of high Reynolds number, many devices for tripping boundary layer transition and thus simulating high Reynolds number flow are in use in the various laboratories of the NATO countries. These include roughness in the form of particles glued to the surface of the aerodynamic model, wires on the surface that are in some cases normal to the flow – in other cases parallel to the flow, etc. By testing aerofoils at low Reynolds number with the transition trip some way back on the aerofoil chord, Blackwell has shown that the boundary layer thickness at the trailing edge can be made the same as for an aerofoil at higher Reynolds number with the transition located near the leading edge. Under these conditions the turbulent separation at the trailing edge is the same and at transonic speeds the shock pattern and pressure distributions are similar. This technique has been used in model testing at Reynolds numbers of 3 to 5 million based on aerofoil chord to try and reproduce full scale flow conditions. There are considerable difficulties in this technique and the location of the transition position can only be determined empirically; moreover the technique cannot be used on aerofoils which have adverse gradients over the front part of the chord and which thus produce natural transition near the leading edge even at wind tunnel Reynolds numbers. Some full-scale or high Reynolds number tests are required for each type of airfoil or aerodynamic shape to be tested to check this technique – consequently its utility is limited. The same limitation applies to a technique described by Mr Poisson-Quinton in which a full-scale leading edge portion of an airfoil is tested in a relatively small wind tunnel by substituting, for the aft portion of the airfoil, jets that force the correct amount of circulation on the flow field.

3.4 Wind Tunnel Types Suitable for Transonic Testing at High Reynolds Number

Having assessed to its satisfaction the need for a much higher Reynolds number wind tunnel capability in the transonic range than is now available, the HIRT group has considered the wind tunnel types with which the desired requirements could be satisfied. First, consideration has been given to the model aspects. Since, at a given Mach number, model stresses are directly proportional to the tunnel stagnation pressure, the maximum unit Reynolds number is determined by the maximum allowed model stress and, in turn, the minimum wind tunnel size for a given model Reynolds number is a function of the maximum allowed model stress. It was agreed that for developmental type testing of large aspect ratio models with thin wings (subsonic jet transport type) up to maximum lift at transonic speeds, tunnel stagnation pressures in excess of about 5 atmospheres (or 75 psi) were not practical if excessive wing deformation and auxiliary support interference is to be avoided and if productivity is to be kept high. This was the point of view of NASA, RAE and ARA. For component testing, design verification testing, two dimensional testing, for other (e.g., booster) configurations and for various research type investigations with special models, higher stagnation pressures could be contemplated. For example, AEDC investigations have shown that using a C-5A type model with a wing root stress of 100,000 psi, the flight Reynolds number at $C_L = 0.8$ could be satisfied in a 9 x 12 ft wind tunnel operating at a stagnation pressure of 20 atm or 300 psi.

It was agreed that the minimum useful running time of 10 to 15 seconds was required for developmental testing and to provide for studies of buffet and flutter and low frequency unsteady aerodynamic phenomena.

In view of the above considerations, it was apparent that two different facilities might be needed to provide the required high Reynolds number capability: (1) a developmental, industrial testing tunnel of blowdown or continuous type with which Reynolds number, short of full scale flight values but nevertheless much higher than presently available, could be obtained, and (2) research and component testing tunnel providing much higher unit Reynolds number which could also be used for verification testing of designs.

Even a cursory calculation indicates that provision of transonic capability at a stagnation pressure of 5 atm in a continuous mode would require very large amounts of power, and therefore would not be economical. A practical alternative is provided by a blowdown intermittent tunnel and it was agreed that a practical size would correspond to the sizes of larger transonic tunnels already available, i.e., about a 5 meter or 16 foot square test section. In view of the relatively long run time required, see above, a Ludwieg tube design was not considered for this application. Tentative and preliminary cost estimates for a 16 foot transonic tunnel operating over a range of conditions of interest were prepared by Mr Hills and presented to the HIRT group. They are here reproduced in Figure 4. Two 16 foot blowdown tunnels were estimated, one of them operating at a maximum of 5 atm stagnation pressure with a run time of 10 seconds. This tunnel could run at 10 atms stagnation pressure for 1.8 seconds if the structure of the tunnel was strengthened for the extra loads (at some increase in cost over the figures given). If, however, a higher stagnation capability is required, it is better to increase the storage pressure and the second, but more expensive, tunnel has a capability of 1.5 seconds run at 15 atms with the structure boosted to take the additional stagnation pressure. This change in performance is reflected in the costs, which are respectively $33 million and $51 million. In the light of these estimates it appears that a developmental, high Reynolds number transonic tunnel of 16 foot test section could be procured at a cost in the region of $30 to $50 million, at UK prices. Description of a 16 foot blowdown tunnel configuration is given in Appendix VI.

As regards provision of a data verification, full-scale flight Reynolds number tunnel with a run time on the order of 1 second, a short duration blowdown tunnel and a Ludwieg tube configuration presented themselves as possible options. Because of the need for relatively long starting time and large losses related to the presence of a large settling chamber (needed to damp out flow disturbances resulting from processing of air through a throttling valve), the blowdown type tunnel appeared to be less economical for this application than a Ludwieg tube configuration. Moreover, the Ludwieg tube type design appeared to offer the unique possibility of reducing the tunnel aerodynamic noise in the test section to an absolute minimum, by elimination of the throttling process and provision of the cleanest possible aerodynamic configuration. The cost estimate for a Ludwieg tube tunnel with a 10 foot square test section, is $21 million. The useful run time was estimated at one second for a stagnation pressure of 26 atm (i.e., 390 psi) or a corresponding Reynolds number of 130 million (based on a mean chord equal to 1/10 of the tunnel width). Description of a 10 foot Ludwieg tube type tunnel configuration is given in Appendix VII.

An aspect which is significant in arriving at the above distinction between a developmental and a maximum Reynolds number tunnel is the productivity of these facilities. It was felt that with state-of-the-art instrumentation the productivity of a developmental, blowdown wind tunnel operating, as indicated in the cost estimates, 10 seconds every 20 minutes, could be made comparable to the present continuous wind tunnel productivity. On the other hand it was felt that operation at very high stagnation pressures, which require the maximum in model strength would preclude quick configuration changes and extensive model instrumentation, for example for pressure testing. It was felt, therefore, that the productivity of a Ludwieg tube tunnel operating at very high stagnation pressure would be inadequate for developmental testing, and that this type facility should be used for study of high Reynolds number effects and for critical verification of designs evolved in development.

Although, as indicated above, the productivity of a high Reynolds number Ludwieg tube type tunnel would be less than that of a lower Reynolds number blowdown facility, nevertheless, AEDC studies indicated that relatively high levels of productivity could be obtained with a Ludwieg type tunnel operating for periods of one second. The problem of making sufficiently accurate measurements of model loads and pressures, in the short time available, are large, but AEDC engineers considered that models could be pitched at the rate of 7 degrees per second while satisfactory accuracy of measurements was obtained.

3.5 Tunnel Flow Quality; Aerodynamic Noise

The HIRT group was concerned about the flow quality attainable in blowdown and Ludwieg tube tunnels, the resulting precision of aerodynamic test data, and ability to perform buffet and flutter tests. The need for effective control of flow unsteadiness which is the result of high throttling ratio applied in blowdown tunnels was stressed. Most blowdown tunnels have a high noise level but at least two small ones (the 14 inch transonic tunnel at NASA Marshall Center and the 27 inch x 27 inch H.S. tunnel at Brough U.K.) have low aerodynamic noise levels. Special measures were taken in these cases to reduce the noise level and it would appear that these measures were successful. It was also pointed out that starting temperature gradients, due to compression in the settling chamber, as observed in the NAE Canada wind tunnel, could be detrimental to data quality. On request of the HIRT group, Mr Evans of RAE[5] has provided quantitative specification for maximum permissible levels of unsteadiness and aerodynamic noise based on continuous wind tunnel experience. An example of one type of pressure disturbance which has been occurring in transonic wind tunnels and the mechanism which is responsible for it is discussed in Reference 6.

It has been known for some years now that wind tunnel results were not only subject to freestream model Reynolds number effects, but also depended on the particular wind tunnel in which the data were taken. A correlation of these tunnel effects, which have been sometimes referred to as unit Reynolds number effects, has been achieved in terms of empirical variables related to tunnel wall boundary layer flow.

Mr J.L.Jones of NASA has presented data showing that the separation length ahead of a step changes with increasing Reynolds number at supersonic velocity. However, the separation length increases if the increased Reynolds number is achieved by increasing model scale. On the other hand the separation length decreases if the increased Reynolds number is achieved by increasing wind tunnel stagnation pressure[3]. One possible cause of this is the change in noise or high frequency pressure fluctuations in a wind tunnel with changing operating conditions. Mr Jones presented data showing that such pressure fluctuations differ when measured on a model in a wind tunnel as opposed to measuring the fluctuations on the same model in flight. There has also been evidence from free flight, aeroballistic range tests that ambient pressure or unit Reynolds number effect may exist independently of the effects observed in wind tunnels.

The HIRT group has been convinced that noise levels in a Ludwieg tube transonic tunnel are probably the smallest that can be achieved and that effort should be made to devise means of minimizing aerodynamic noise due to transonic, ventilated wall flow.

3.6 Design of Models for Wind Tunnel Testing

Model design is one of the key criteria that determine performance and design of high Reynolds number, transonic tunnels. Therefore, the question of model design was discussed at length by the HIRT group. AEDC studies have indicated the possibility of obtaining full-scale Reynolds number with model design for maximum stresses of 100,000 psi. The practical difficulties in providing high strength in complicated models fitted with pressure orifices, high lift devices, etc. has been pointed out. Distortion of a model of a swept wing aircraft as discussed in reference 7 necessitates care in interpretation of wind tunnel data. Figure 5a gives spanwise change of incidence due to aeroelastic distortion of the model wing when tested transonically in an air stream at a stagnation pressure of 5 atm. The model was assumed to be of solid steel and no allowance was made for loss of stiffness due to the inclusion of pressure-plotting tubes or air supply pipes of the type needed for boundary layer control or for engine simulation. It is necessary to go to the expense and delay of making a whole series of distortion-corrected models, or it is necessary to test a given model over a range of conditions where the lift coefficient varies by at least a factor of two from design conditions and where the stagnation pressure also changes by a factor of two or more and to correct the results so that they can be used to predict full-scale airplane performance. Figure 5b shows the change in spanwise distribution of lift due to model distortion when testing at 5 atm at a lift coefficient which is twice that of the design value. The comparison shown is for the distorted model compared to a rigid model. Differences between the distorted model and the distorted full-scale airplane would be significantly lower. As pointed out in Reference 7, it is possible that discrepancies in spanwise loading due to distortion could cause very large changes in the performance characteristics, particularly when the wing flow is supercritical.

The present technique, in transonic wind tunnels operating at low stagnation pressures, has been to build a model with standard materials, to determine its shape under aerodynamic loading during tests and to subsequently correct the data to account for the distortion of the model. Mr J.F.Cahill of Lockheed-Georgia considered that satisfactory corrections can be made if the aeroelastic effects on the model were no more than twice the bending of the full-scale airplane, and the model wing twist was one-half the wing twist of the full-scale airplane. AEDC design studies show that model deflections can be held within those limits for stagnation pressures of over 20 atmospheres at transonic velocities.

It has been recognized that in order to take advantage of large Reynolds number tunnels, improved model design and fabrication methods should be developed. In this connection, Mr P.Antonatos of the U.S. Air Force Flight Dynamics Laboratory, suggested that research be undertaken on the use of fibers and composites to evolve models that are structurally similar to full-scale airplanes under steady loads.

3.7 Transonic Test Techniques

The HIRT group views the extensive investigations of transonic test techniques in France and the work of the same nature in the United States as critically important to the improvement of understanding of transonic test data. The French have calibration or standardized transonic models, Figure 6, with four different spans. The model is a representation of a modern transonic transport. Each model is being tested in the French transonic wind tunnels, the main aim of the program being to obtain information on wind tunnel wall effects. Mr Poisson-Quinton stated that the models could be loaned to groups in other countries so that international comparisons of wind tunnel capability and test techniques could be made. Such models might be added to the group of AGARD calibration models discussed in Reference 8. The similarity between these models and a modern transport aircraft is advisable. (Pages 159-160, Reference 9.)

A similar program using a 0.0226 scale model of the C-5A aircraft has been started in the United States. This effort was reported in reference 4. The report suggests wind tunnel wall effects that have not been taken into account. It also shows a need for critical review of test techniques, data acquisition and processing methods.

4. CONCLUSIONS AND RECOMMENDATIONS

1. The AGARD Fluid Dynamics Panel HIRT group has studied transonic wind tunnel requirements, capabilities, and future possibilities as well as transonic model testing experience. Based on these studies it is concluded that there is a critical need for provision of high Reynolds number, transonic wind tunnels and it is recommended that NATO nations should acquire two new types of transonic wind tunnels as soon as possible in order to insure the success of aeronautical and aerospace systems for military and civilian programs that will be developed during the coming decade. One type of tunnel is a blowdown tunnel with a test section about 16 foot square and a run time of about 10 seconds at a stagnation pressure of 5 atm. This tunnel will provide Reynolds numbers about 4 times those now existing. Although this facility would not provide the full scale flight Reynolds number, it will make available, within practical economical constraints, developmental capability at the highest, practical Reynolds number.

The other type of tunnel would be a Ludwieg tube tunnel with a test section about 10 foot square, and a run time on the order of one second at a stagnation pressure of 26 atm. This tunnel is not intended primarily for developmental testing in view of its higher model strength requirements. This tunnel would serve as a research tool for investigations of high Reynolds numbers phenomena and as a design verification facility for configurations evolved in the blowdown type developmental tunnel.

The costs of these facilities have been tentatively estimated at $33 million for the developmental 16 foot tunnel and $21 million for the 10 foot Ludwieg tube tunnel (U.K. prices).

Square test sections have been used in the descriptions of the two wind tunnels. These are used to indicate size of the required major dimensions. Additional study may show that a rectangular or other test section cross section is more advantageous.

It should be possible to operate such tunnels through the transonic regime up to Mach numbers of about 1.3. This would be accomplished by use of scheduled bleed through the porous walls and positioning the plug at the test section outlet.

2. It is recommended that the FDP should use its influence to encourage research to determine the performance and operating potential of Ludwieg tube type transonic tunnels. A request to the NATO Science Committee to provide funds for the expansion of the program might be in order.

3. It is recognized that extensive new studies in the area of transonic test techniques are needed before transonic tunnels can be utilized to the maximum benefit. It is suggested that an AGARD wind tunnel standardization and

calibration program should be developed in the transonic regime and that this might be done by the extension of the transonic tunnel comparison studies now under way in France and in the U.S.A., to encompass international comparisons of test techniques and wind tunnel wall corrections.

4. It is recommended that the FDP should encourage the investigation of noise and noise alleviation in transonic wind tunnels not only to gain a better understanding about present day results, but also to provide the support needed for design and operation of future large facilities here described.

5. In view of the interest shown by European and American engineers from industrial, educational, and governmental organizations in this HIRT group study, it is suggested that the FDP should recommend to AGARD that the conclusions of this report be sent to the Military Committee of NATO and then to the Secretary General of NATO with a letter requesting discussions aimed at provision of international funding for construction of the recommended high Reynolds number wind tunnels.

REFERENCES

1. Summary Report on 1968 AGARD Conference on Transonic Aerodynamics by Dr Kücheman.

2. VKI Course Note No. 16 on Large Airplane Aerodynamics 1969.

3. Minutes of AGARD – FDP Round Table Discussion in Munich Germany, September 1969.

4. AIAA Paper No. 69–794 *Data Correlation from Investigation of a High-Subsonic Speed Transport Aircraft Model in Three Major Transonic Wind Tunnels.*

5. Unpublished letter on this subject from J.Y.G.Evans to J.Lukasiewicz, April 29, 1970.

6. Unpublished note on *Disturbances Observed in Transonic Flow in a Perforated Wall Wind Tunnel* by J.Lukasiewicz, May 27, 1970.

7. Letter concerning this subject from J.Y.G.Evans to R.O.Dietz, April 24, 1970.

8. *AGARD Wind Tunnel Calibration Models.* Specification 2, September 1958.

9. *A Review of Measurements on AGARD Calibration Models.* AGARDograph 64, November 1961.

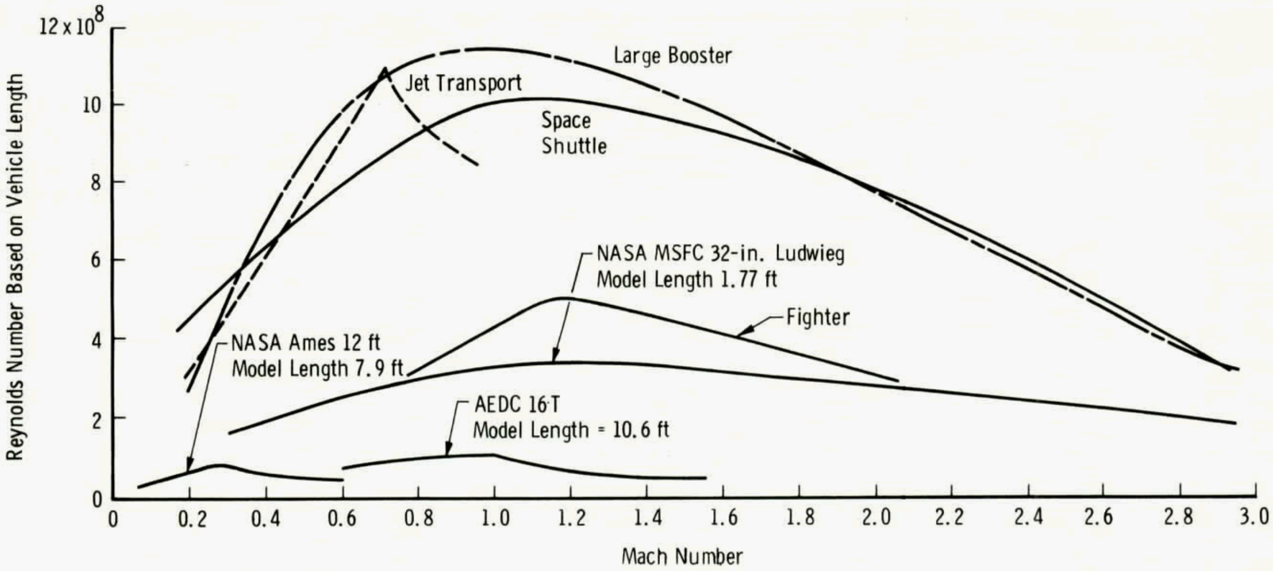


Fig.1 Reynolds number as a function of Mach number for scheduled aeronautical systems and existing high performance wind tunnels

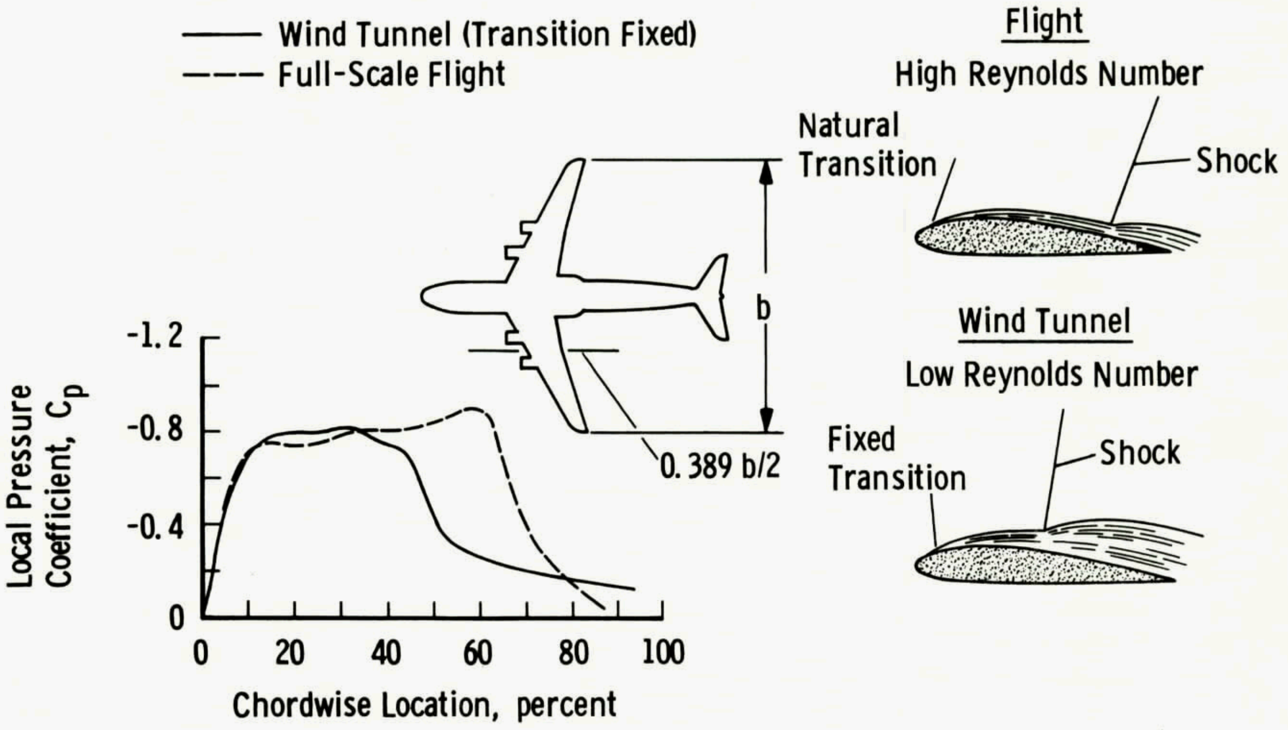


Fig.2 Shock induced flow separation
$M_\infty = 0.85$

AIRCRAFT

Drag Including Wing-Body Interference

Transonic Drag Rise

Buffeting

High Lift Transonic Load Distribution

Inlet and Exhaust Jet Interference Problems

MISSILES AND SPACE VEHICLES

Base Flows and Effect of Base Flows on External Aerodynamics

Base Recirculation and Heating

Load Distribution on Launch Vehicles (Viscous Cross Flows)

Fig.3 Aerodynamic Phenomena which require investigation at high Reynolds number

HIGH REYNOLDS NO.TRANSONIC TUNNEL

	BLOW DOWN				LUDWIEG TUBE	
Test Section	16' x 16'	16' x 16'			10' x 10'	
Stagnation Pressure	5	5	10	15	26	ATMS.
Storage Pressure	40	120	120	120	40	ATMS.
Pressure after Blow	7	7	14	21	-	ATMS.
Reynolds No.* (chord)	36	36	72	110	130	$\times 10^6$
Flow per sec.	64	64	128	192	135	10^3 lb.
Starting flow	173	173	376	580	70	10^3 lb.
Air remaining	327	177	267	354	300	10^3 lb.
Total storage	1,140	1,220	1,220	1,220	500	10^3 lb.
Useful run time	10	13.5	4.5	1.5	0.5 to 1.0	sec.
Compressor						
Pumping rate$^{\phi}$	680	730	730	730	170	lb/sec.
Motor Power	210	280	280	280	52	10^3 H.P.
COST (U.K.PRICES) 10^6 Dollars						
Tunnel Structure	12.5	25			10	
Storage	3	4			1.25†	
Working Section	2.5	3			1.5	
Compressor	10	13			2.5	
Valves	1.25	2			2.5	
Buildings etc.	2.5	2.5			2	
Instrumentation	1.25	1.5			1.5	
TOTAL	33.0	51.0			21.25	

* Reynolds No. based on mean chord = 1/10 tunnel width at M = 0.8

† Cost of 1000 ft.of tube

ϕ Based on one run every 20 mins.

Fig.4 Tentative cost estimates for high Reynolds number, transonic tunnels

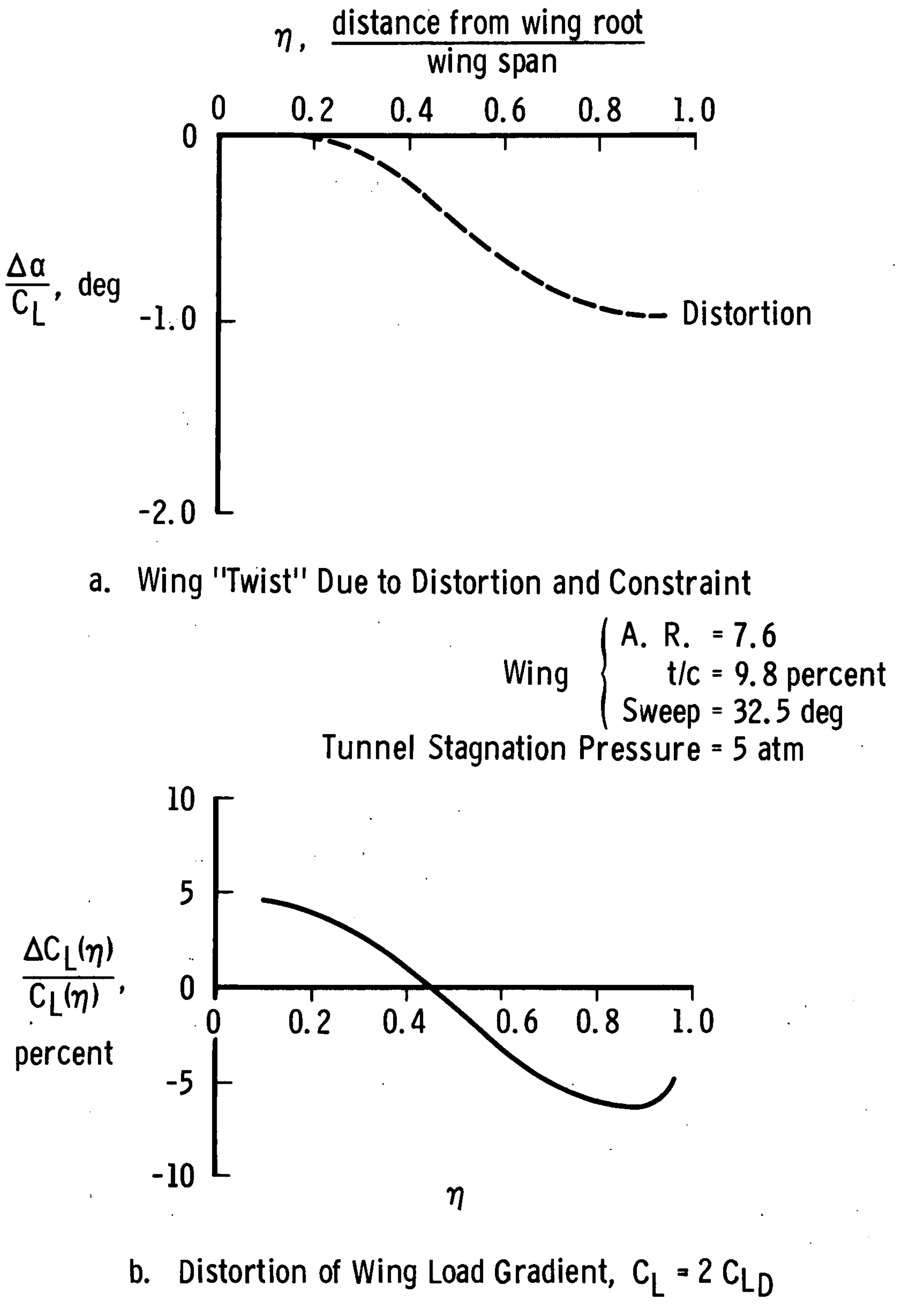
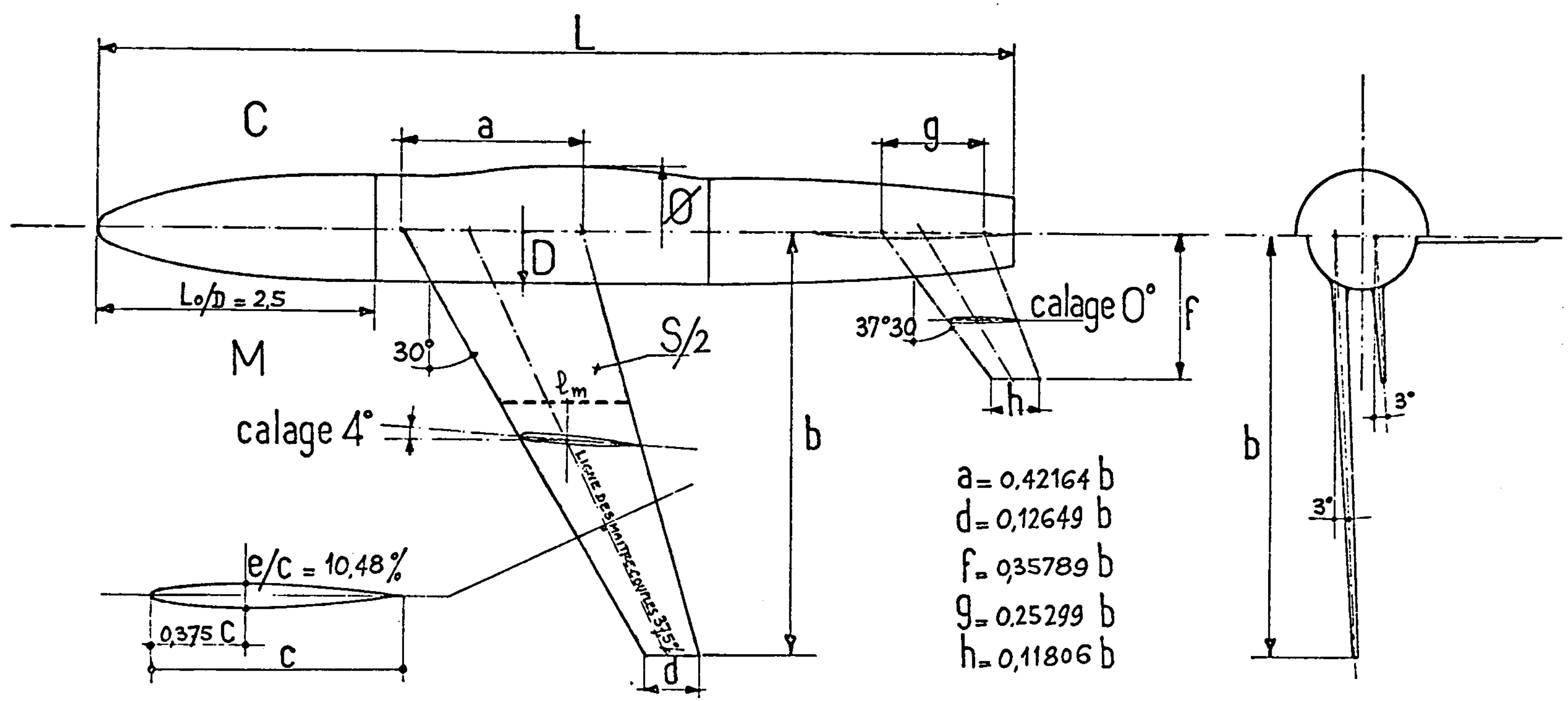


Fig.5 Aeroelastic distortion of a model of a swept wing aircraft in a wind tunnel at transonic speeds (5-atm stagnation pressure)



MAQUETTES "ETALONS" D'UN AVION DE TRANSPORT POUR LA COMPARAISON DES SOUFFLERIES TRANSSONIQUES

Allongement $\lambda = 4b^2/S = 7,25$

Effilement $\varepsilon = d/a = 0,30$

corps de révolution	C1	C2	C3	C4	C5	Corps "loi des aires"
maquette d'avion	M1	M2	M3	×	M5	Profils d'aile et d'empennages identiques, du type à "pic de survitesse". Corde aérodynamique moyenne $\ell_m = 0,71\ a$ à $y = 0,41\ b$.
échelle	0,604555	0,777605	1	1,28617	2,07	
longueur (m) L	0,30895	0,39736	0,511	0,65722	1,05777	
envergure (m) 2b	0,28718	0,36384	0,474324	×	0,981871	
diamètre fuselage (m) D	0,03628	0,04666	0,060	×	0,1242	
diamètre maître couple (loi des aires) (m) Ø	0,0443	0,05736	0,07375	0,09486	0,15268	
surface de référence S m²	0,01129	0,01867	0,03088	×	0,13230	
corde aéro.que ℓ_m	0,04315	0,05542	0,07128	×	0,14754	

Fig.6 ONERA standard transonic aircraft models

APPENDIX I

Membership of the AGARD Fluid Dynamics Panel High Reynolds Number Wind Tunnel Study Group.

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Monsieur l'Ingénieur Principal de l'Air G. Ville
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75 Paris 15e
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APPENDIX II

Material Distributed to HIRT Group for Review and Analysis

Dutch Material

– On the Need of High Reynolds Number Transonic Wind Tunnel Facilities in the Netherlands. NLR – AC-70-02.

French Material

– Principal French Subsonic and Transonic Wind Tunnels:
Fig.1
Fig.2

– Wind Tunnel Data Sheets Fb 1-1
Fb 6-1
Fb 7-1
Fb 8-1
Fb 8-2
Fb 8-3

German Material

- Letter from Professor Ludwieg to Mr Dietz
  6 March 1970 – Ref. II 79/70-Lu/Wi
- Letter from Dornier to DFVLR
  18 February 1970 – Ref. 2782
- Letter from Messerschmitt-Böklow-Blohm to DFVLR
  2 March 1970 – Ref. 2208
- Letter from Professor Heyser to Professor Ludwieg
  19 February 1970 – Ref. Dr. Mr/Be
- Letter from Professor Thomas to Professor Ludwieg
  3 February 1970 – Ref. Th/Me
- Letter from Professor Göthert to Professor Ludwieg
  9 February 1970 – Ref. Gö/E/70-109

U.K. Material

- Possible Designs for a High Reynolds Number Transonic Tunnel Memo No. 94 (Revised)
- Possible Use of the 8 ft x 8 ft Tunnel at RAE Bedford as a Very-High-Reynolds Number High-Subsonic Speed Tunnel. RAE Tech Memo Aero 1161a

U.S. Material

- Contribution No. 1

  Marshall Space Flight Center, NASA, Alabama

  1. Status Report of High Reynolds Number Test Equipment
  2. AIAA Paper No. 68-18, A Shock Tube Technique for Producing Subsonic, Transonic, and Supersonic Flows with Extremely High Reynolds Numbers
  3. Aero Internal Note No. 21-65, Discussion of a Proposed High Reynolds Number Test Facility
  4. NASA Technical Note D-5469, A Theoretical and Experimental Study of Unsteady Flow Processes in a Ludwieg Tube Wind Tunnel
  5. Ten photographs of the 32-inch MSFC/NASA Ludwieg tube facility

- Contribution No. 2

  Lockhead-Georgia Company, Marietta, Georgia

  Letter from J.F.Cahill to J.Lukasiewicz – 12 February 1970

- Contribution No. 3

  Lockheed-California Company, Burbank, California

  Letter from E.J.Stollenwerk to J.Lukasiewicz – 18 February 1970

- Contribution No. 4

  AFFDL, AFSC, USAF, WPAFB, Ohio

  Set of 13 figures with comments

- Contribution No. 5

  NASA (Ames, Langley and Lewis Research Centers)

  1. Information on Development of High Reynolds Number Wind Tunnels (HIRT) in the U.S.
  2. Reproduction of 18 slides presented by J.L.Jones at the AGARD-FDP Round Table Discussion in Munich on High Reynolds Number Problems, September 1969.

- Contribution No. 6

  U.S. Army Aeronautical Research Laboratory, Ames Research Center, Moffett Field, California

  Information on Development of High Reynolds Number Wind Tunnels (HIRT) in the United States

– Contribution No. 7
The Boeing Company, Seattle, Washington
Letter from J.H.Dwindell to J.Lukasiewicz – 13 February 1970 – with Attachments A, B, and C

Canadian Material

– Letter from W.J.Rainbird, Head, High Speed Aerodynamics, National Aeronautical Establishment, Ottawa, Canada to J.Lukasiewicz, 14 April 1970, with seven attachments. This material was presented to the HIRT group by Dr J.Lukasiewicz at April 21-22 1970 meeting.

APPENDIX III

Participants at the April 21-22 1970 Meeting of the HIRT Group.

1. The six HIRT group members
2. Rolland Willaume – AGARD
3. P.Poisson-Quinton – (ONERA) France
4. R.Maurer – (DFVLF) Germany
5. J.Y.G.Evans – (RAE) U.K.
6. Dr Knoche – (Messerschmitt-Bölkow-Blohm GmbH) Germany
7. Ewald – VFW Company

APPENDIX IV

Participants at the May 21-22 1970 Meeting of the HIRT Group.

1. The 6 HIRT group members
2. P.Poisson-Quinton (ONERA) France
3. L.H.Ohman (Natl. Aero Est.) Canada
4. P.Antonatos (AF-FDL) USA
5. J.F.Cahill (Lockheed Ga.) USA
6. J.L.Jones (NASA-Ames) USA
7. J.Whitfield (AEDC) USA
8. L.Ring (AEDC) USA
9. C.J.Schueler (AEDC) USA
10. R.Starr (AEDC) USA
11. H.Doetsch (AEDC) USA
12. C.Bennett (AEDC) USA
13. D.R.Eastman (AEDC) USA
14. W.Lowe (Convair) USA
15. Sam Hastings (Naval Ordnance Lab) USA
16. W.Bradley (Hq USAF) USA
17. K.Daum (NASA/Marshall) USA
18. A.R.Felix (NASA/Marshall) USA
19. Heaman (NASA/Marshall) USA
20. H.S.Gwin (NASA/Marshall) USA

APPENDIX V

May 21, 1970, Technical Presentations by AEDC on High Reynolds Transonic Requirements

Preliminary Criteria – Jack D.Whitfield

- Verification Role
- Reynolds Number Requirements
- Facility Size and Performance
- Effect of Operating Temperature

Comparative Study – C.J.Schueler

- Description of Blowdown and Ludwieg Tube Tunnels and Operating Modes
- Commonality
- Flow Quality
- Productivity
- Data Acquisition
- Costs and Basis of Estimate

Conclusions – C.J.Schueler

- Ludwieg Tube Approach

Current Study Areas – C.J.Schueler

- Noise
- Extension to Supersonic Speeds

Current Status of Ludwieg Tube Facilities – C.J.Schueler

Current Transonic Test Problems – Dr L.E.Ring

- Acoustic Measurements
- Transition Measurements
- Wall Interferences

APPENDIX VI

Description of Blowdown Tunnel

A sketch of a blowdown type tunnel configuration is shown in Figure A.VI-1. Overall length of the facility is 600 ft. The air storage consists of 24 – 10 ft dia 200 ft long reservoirs. A settling chamber 130 ft long and 50 ft in diameter houses grids and screens required to minimize test section turbulence. A 40 ft contraction section changes the cross section from 24 ft diameter to 16 ft x 16 ft square. A ventilated wall test section is 40 ft long. The quadrant for sting mounting models is located in a transition section which changes the cross section from 16 ft x 16 ft square to 23 ft diameter circular. A movable conical plug with a base diameter of 23 ft provides for variation of throat area in the flow channel. A 32 ft diameter exhaust manifold 160 ft in length distributes the air flow from the tunnel into the exhaust silencer building. Flow rate through the ventilated walls is set by the outlet valves of the 30 ft diameter plenum which surrounds the test section.

The tunnel is operated by first filling the air storage tank with air at a pressure of 600 psi. The tank contains about 1,100,000 lbm of air at this pressure. The position of the plug in the choke device is set for the desired test section Mach number before a test is started. A test is started by opening the throttle valves sufficiently for the plenum and test section to fill rapidly and the flow to be established. The throttle valves are then modulated throughout the run time of the tunnel to maintain a test section stagnation pressure of 5 atmospheres. Useful run time of the tunnel is more than ten seconds. At the end of a run the throttle valves are closed and the air storage tank is recharged for the next run. At the end of a run 327,000 lbm of air remain in the air storage tank. If a test run is made in the tunnel every 20 minutes a 210,000 horsepower compressor system would be required. Reynolds number of a 12 ft model at the test section pressure of 5 atmospheres would be about 270 million based on model length. Operating time of this tunnel could be extended for certain types of tests by operating the tunnel at lower stagnation pressures.

A number of blowdown type transonic wind tunnels are in operation in the NATO countries. While the throttle valves make the flow inherently noisy, experience indicates that the problem can be essentially solved by the investment of sufficient pressure drop in the settling chamber. Careful engineering is required to achieve steady test conditions in the blowdown tunnel as indicated by the experience with the 5 ft NAE (Ottawa) trisonic tunnel. Engineering studies should be made of problems related specifically to the performance and flow quality in blowdown tunnels. Consideration should be given, among other problems, to the reduction of air consumption during starting, and the effect of adiabatic compression in the plenum during tunnel start on stagnation temperature during useful test time. Test section size of this tunnel is compatible with existing large continuous transonic tunnels. The run time which it provides is required for some important transonic development testing.

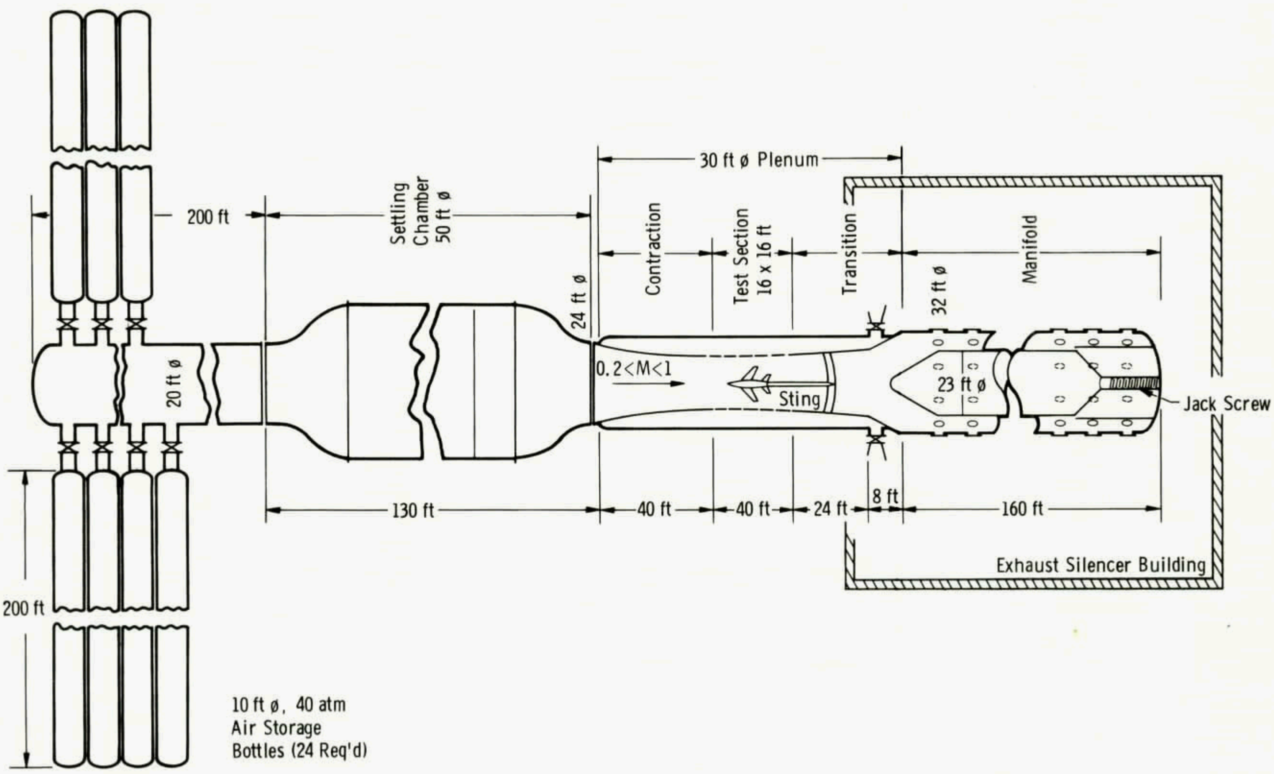

Fig.A.VI-1 Sketch of a blowdown tunnel configuration

APPENDIX VII

Description of a Ludwieg Tube Type Tunnel

A sketch of a Ludwieg tube type tunnel configuration is shown in Figure A.VII-1. Overall length of the facility is 1114 ft. The Ludwieg tube is 14 ft in diameter and 1000 ft long. A 20-ft long contraction section changes the cross section from 14 ft diameter circular to 10 ft x 10 ft square and has an area ratio of 1.53. A ventilated wall 10 ft x 10 ft test section is 14 ft long. The quadrant for sting mounting the models is located in a transition section which changes the cross section from 10 ft x 10 ft square to 12 ft diameter circular. A movable conical plug with a base diameter of 12 ft provides for variation of the throat area in the flow channel. The outlet valve manifold of the wind tunnel is 60 ft long and 17-1/2 ft in diameter. One hundred quick-acting 2-ft diameter valves are installed on the manifold. The pressure inside the 12-ft center body does not change during operation of the tunnel. Flow rate through the ventilated walls is set by use of outlet valves from the 16-ft diameter plenum.

The tunnel is operated by first filling the entire system with air at a pressure of 600 psi. The system contains about 500,000 lbm of air at this pressure at a temperature of 294°K. The position of the plug in the choke device is set for the desired test section Mach number before a test is started. A test is started by quickly opening the 2-ft diameter valves. An expansion fan then moves up through the system and flow through the test section is established. The expansion fan moves along the 1000-ft Ludwieg tube, reflects from the end of the tube and then travels along the tube in the opposite direction. When the leading edge of the expansion fan reaches the test section, the stagnation conditions change and the test is terminated by closing the fast-acting 2-ft diameter valves. Time required for the expansion fan to traverse the two thousand feet from the test section to the end of the tube and back to the test section varies from (a) 1.4 seconds at a test section Mach number of 1 to (b) 1.5 seconds at a test section Mach number of 0.3. Estimating a starting time of 0.5 seconds provides a test duration of about one second. At valve closing at the end of a test, approximately 300,000 lbm of air remain in the system. 200,000 lbm of air are used during a test and for a recovery time of 20 minutes, a 52,000 horsepower compressor system would be required. Test section stagnation pressure is 26 atm and test section temperature is 260°K with a test section Mach number of 0.8. Reynolds number of an 8-ft model at these conditions would be about 10^9 based on model length.

A test-section isolation valve is located upstream of the test section. The valve allows access to the test section with high pressure in the 1000 ft tube and makes it possible to conserve air which is not used during a run.

The Ludwieg tube transonic tunnel is a relatively new concept. However, performance and operating data are being rapidly accumulated through work in the MSFC 32 inch diameter 45 atmosphere tunnel and the AEDC 7.3 x 9.2 inch test section HIRT model. Starting times are lower than expected. Starting loads on models are lower than operating loads. Model force and pressure data from the Ludwieg tunnel at MSFC agrees with data from a good continuous flow tunnel. It has been possible to find successful methods for overcoming problems with the Ludwieg tunnels, including the tube temperature gradient problem of the MSFC tunnel. Test section noise data from the Ludwieg transonic tunnels were not available when the study was made, but all HIRT group members are of the opinion that the Ludwieg type tunnel should excel in this respect.

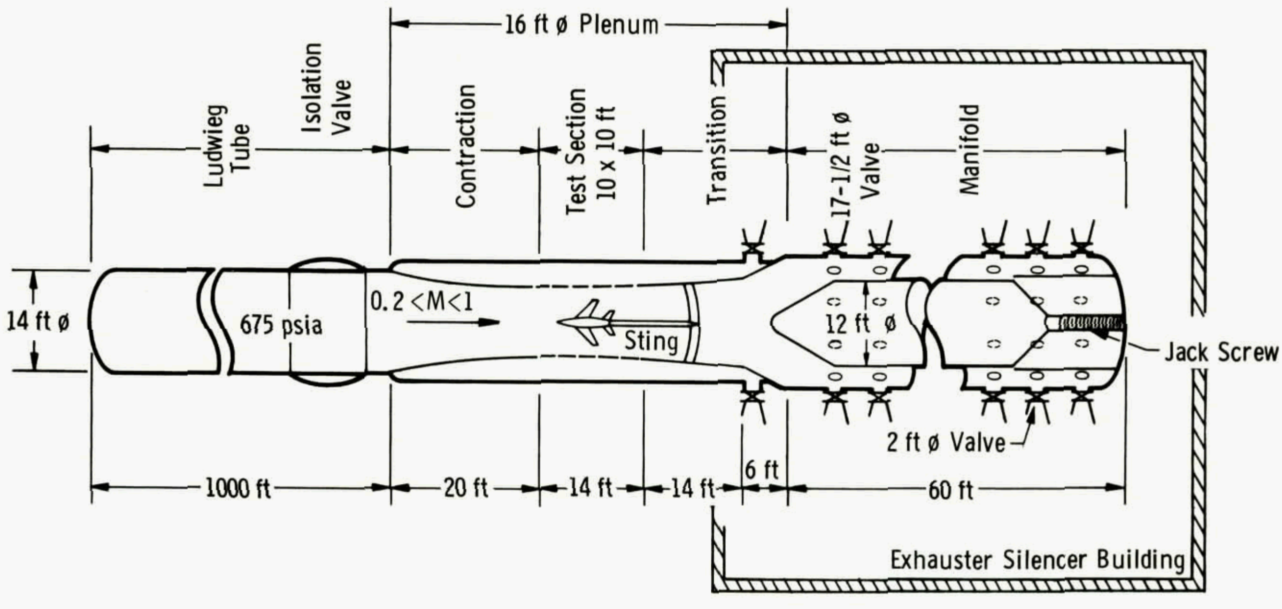

Fig.A.VII-1 Sketch of a Ludwieg tube type tunnel

conclusion that the NATO nations should acquire, as soon as possible, two types of new wind tunnels. One tunnel should *duplicate* transonic flight Reynolds numbers and have a run time on the order of one second. The second should have a 16 ft test section and should provide Reynolds numbers that are 3 or 4 times the maximum presently available, with a run time on the order of 10 seconds. It was also concluded that AGARD should support current research and development in design, operation and test techniques in transonic tunnels of the continuous, conventional blowdown and Ludwieg tube type, and that AGARD should encourage expansion of these activities in the future. AGARD should recognize that significant benefits would accrue to the future aeronautical and aerospace systems from the new transonic test capabilities recommended by the HIRT working group.

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North Atlantic Treaty Organization, Advisory Group for Aerospace Research and Development
REPORT OF THE HIGH REYNOLDS NUMBER WIND TUNNEL STUDY GROUP OF THE FLUID DYNAMICS PANEL
Published April 1971
18 pages, including figures and Appendices.

The working group considered transonic wind tunnel performance and operating characteristics required to support evolution of military and civil, aeronautical and aerospace systems during the coming decade. These considerations, along with a review of experience on model testing at transonic speeds, led to the

P.T.O.

532.5.011.12:533.6.071

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