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THE FUTURE OF WIND TUNNEL TECHNOLOGY IN GERMANY

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16. Abstract

Practical value of a wind tunnel is not dependent solely on size or achievable Reynolds number. Measurement, interpretative and evaluative procedures can be developed almost equally as well in smaller facilities.

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1. Introduction /1*

The extensive development of aerodynamic calculation procedures in the last few years has occasionally given rise to the idea that in the foreseeable future the wind tunnel will have had its day as an instrument of aerodynamic research and flight development.

This hope or fear (of the wind tunnel engineers!), however, has not been confirmed up to now; the demand for new high-performance test facilities is more energetic than ever.

The high level of flight technology leaves room for only slight advances, which must be realized in costly developments, but which nevertheless are of decisive importance for the market chances of new aircraft. Equally high are the demands for further increases in the performance and reliability of the most modern computer procedures. Furthermore, one cannot fail to see that even the most modern design and computation procedures contain essential empirical elements that must be tested in the wind tunnel.

Economically, too, the wind tunnel will maintain its raison d'etre in the foreseeable future. The computer equipment required for modern calculations is so extensive that particularly for larger variations of parameters, the wind tunnel yields results far more cheaply than the computer.

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*Numbers in the margin indicate pagination in the foreign text.

2. Capacity of Present Wind Tunnels /2

At present, subsonic tunnels for speeds up to ca. M 0.3 and transsonic tunnels for the compressible flow range M 0.5 to M 1.3 are of significance. Their capacity is measured almost exclusively by the achievable Reynolds number, which depends on the tunnel size and the maximum static pressure for which the tunnel is designed. An upper limit for the static pressure is given by stresses on the stability of the model; this limit might be ca. 6 bar.

Fig. 1 gives a general view of the sizes of the wind tunnels available in West Germany, compared to the situation at the end of the war. For various reasons wind tunnel capacity in postwar German flight research fell far behind the 1945 status.

Fig. 2 shows as an enclosure the Reynolds numbers achievable in German wind tunnels as a function of Mach number. For comparison the capacity of tunnels in other European countries and the USA is shown. The inadequate equipment of German flight research is particularly well illustrated by the flight area of the VFW 614.

However, the inadequate capacity of the wind tunnels does not affect Germany alone. Fig. 3 shows on a larger scale the capacity of existing wind tunnels in comparison to the cruising design of a series of well-known airplanes. Project CXX represents goals for a new cargo plane to be developed in the '90s.

The enormous gap between wind tunnel capacity and aircraft design is particularly problematic for the transsonic cruising range. Significant progress in aircraft development is possible here only because of supercritical wing design. This flow type, however, reacts sensitively to the Reynolds number; it seems impossible to exhaust developmental potential with present wind tunnels.

One explanation of the low capacity of the tunnels is given in Fig. 4, which graphs drive power of large wind tunnels against year of construction. The graph shows a rise in drive power by about a power of ten per decade. This development reached the limits of the technically and economically possible almost 30 years ago. Since then wind tunnel technology has stagnated.

3. Wind Tunnel Planning /3

In the low speed range, national planning has been particularly realized. Fig. 5 gives an overall view. Variable density tunnels were built in England and France with the F1 in Toulouse and the RAE-5m tunnel; both are shortly to have test runs.

In West Germany a large subsonic tunnel (GUK) was planned by the flight industry and the DFVLR together; its measurement cross sections were to be 6 x 6 m^2 and 9.5 x 9.5 m^2. This project and the Dutch plan for a subsonic tunnel of similar size were combined in the joint project DNW (German-Dutch Wind Tunnel) in the Nordost Polder (cf. Fig. 6).

Although it was not easy for the German technical world to give up a high-performance facility like this one for Germany, the achievement of the DNW is to be hailed. German and European flight research will thus have a modern, unusually capable and versatile subsonic tunnel.

3.2. Transsonic Range

It is significantly harder to close the Reynolds number gap in the transsonic range. Because of the installation and operating costs, which are rising by powers of two to three, this is not possible with conventional, continuous-operation tunnels. Various intermittently operating large tunnels have been studied.

The AGARD-HIRT Group (High Reynolds Number Tunnel) published its report in 1971; it called for the construction of a large tube wind tunnel (Ludwieg Tube) and a large blowdown tunnel. The tube tunnel was to reach Re numbers of ca. $130 \cdot 10^6$, and the blowdown tunnel ca. 36, at air flow times of ca. 1 or 10 seconds, respectively. The idea of a tube wind tunnel has been brought to the construction stage in the USA.

At the end of 1972 the LaWs Group (Large Windtunnels) of AGARD published its wind tunnel plan for Europe. The core of this plan was a large transsonic tunnel (LEHRT, Large European High Reynolds Number Tunnel), for which Germany, Great Britain and France developed different technical designs. The design provided a measurement cross section of 5 x 4.2 m^2, a maximum static pressure of 6 bar and a maximum Mach number of 1.35 bar. /4
At M 0.9 a Reynolds number of $40 \cdot 10^6$ was to be achieved. The planned operating range is shown in Fig. 7 compared to previous wind tunnels and some aircraft designs.

Detailed feasibility studies yielded very high costs on the order of 200 to 300 million DM for all suggested technical solutions.

Both the HIRT plan and the LaWs plan were outmoded by the "Cryogenic Tunnel" developed by NASA. Its principle exploits the dependency of kinematic viscosity on temperature. Fig. 8 shows the effect of various measures to raise the Reynolds number of a wind tunnel design on the necessary drive power and thus on the cost of the facility.

The simplest measure, an enlargement of the tunnel, increases power and costs quadratically. An increased statuc pressure raises power almost linearly. But raising the Re number by cooling the air *lowers* the necessary drive power. This fact is also made clear by Fig. 9, which shows the effect of a temperature decrease on gas properties, test conditions and drive power. Static pressure, Mach number and tunnel size are assumed as constant.

NASA realized this idea very quickly; since 1974 a pilot tunnel has been in operation. According to publications to date, it fully confirms the utility and advantages of the principle. The technical data and operating range at M 0.85 are shown in Fig. 10.

Fig. 10 also shows that the "cryotunnel" technology allows a whole new degree of freedom in wind tunnel measurements. In addition to the independent variation of Mach number and Re number that every variable density wind tunnel offers, by varying temperature and static pressure it is also possible to vary dynamic pressure at a constant Reynolds number or vary the Re number at a constant dynamic pressure.

This makes it possible to separate Reynolds number effects completely from effects of model deformation. The additional aeroelastic research possibilities offered by this degree of freedom cannot yet be fully predicted.

On the basis of pilot wind tunnel results NASA decided to build a large "cryotunnel" designated the "National Transsonic Facility." It will be ready for operation in 1982. The technical data are:

Measurement cross section	2.5 x 2.5 m^2
Mach number range	0.2 - 1.2
Static pressure range	1 - 8.8 bar

Temperature range	100 - 340 °K
Drive power	ca. 88 MW

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Fig. 11 shows the simulation range of this tunnel in comparison to existing tunnels, the LEHRT plan and the cruise configuration of various aircraft. This tunnel, which will cost ca. 65 million dollars, closes the Reynolds number gap in transsonic wind tunnel measurements. The importance of this facility for American flight development can only be compared to the construction of the large AEDC facilities in Tullahoma in the '50s.

The availability of a similar facility is essential for the survival of a competitive European flight industry. The LrWs group is thus looking at the execution of the LEHRT project as a "cryotunnel;" draft studies to this end are in progress.

The future role of German flight research and development will probably depend, at least in the area of flow mechanics, on decisive participation in the completion and operation of this project. Corresponding preparatory work and work to achieve knowhow should thus be begun without delay.

Besides basic studies on flow mechanics, model technology and measurement technology in such a tunnel, the most important preparatory work is doubtless the fast construction of a pilot tunnel. In addition to the pilot function of such a tunnel, the tunnel's applicability for such things as two-dimensional profile measurements with high Reynolds numbers should be kept in mind.

A German location for the LEHRT project is desirable and would be a suitable compensation for the voluntary renunciation of the national GUK project.

4. Wind Tunnel Measurement Procedures

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The wind tunnel planning described previously shows that at least in the low-velocity range, wind tunnels are no longer built in West Germany, and such a facility for the transsonic range is in the early planning stage.

But it would be an error to assume that fruitful wind tunnel work is possible only in large facilities and that wind tunnel technology in West Germany is thus doomed. Fruitful wind tunnel work does not just depend on the size of a tunnel, but also on advanced and scientifically accurate measurement methods. In this respect, unfortunately, little progress can be seen in wind tunnel technology; ideas that open new dimensions, such as the introduction of perforated or slotted tunnel throats for the transsonic range over 25 years ago, have become very rare.

Certainly the operation of a modern wind tunnel differs greatly from that 30 years ago. But this fact does not reflect new wind tunnel measurement procedures and experimental theories, but rather technological advances in electronics, measurement technology and fine mechanics, which have been brought into wind tunnel technology from outside.

As an incitement for aerodynamicists and wind tunnel engineers who want to further develop their tool, i.e. their measurement procedures, a series of areas and problems will be touched on in which progress in wind tunnel technology seems possible or especially desirable.

4.1. Transferability

In addition to the Reynolds number, the laminar-turbulent boundary layer turnover, and the effects of flow characteristics of the wind tunnel on this turnover, are of significance in applying wind tunnel results to large-scale structures.

The influence of the tunnel's natural turbulence, or noise in perforated transsonic tunnel throats, on measurement results is not yet well clarified. A schlieren photograph of an empty transsonic tunnel throat with its decorative pattern of Mach lines demonstrates this problem.

Also, the long-used tricks for simulating a higher Reynolds number, such as raising the turbulence in a subsonic tunnel, or transition strips in a transsonic tunnel, are basically closer to black magic than to strict science.

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A few years ago, in the context of the ZTL program, a promising study was begun on the influence of natural and artificially increased turbulence in subsonic tunnels. Turbulence ball tests, hot wire measurements and measurements with various models were performed in 5 different tunnels with an absolutely identical arrangement. Unfortunately this procedure died out after only a year; not even one complete evaluation was finished.

By now practically every wind tunnel institution has its own hypotheses on the use of transition strips, and these views are hotly discussed. The state of knowledge in this area has not developed beyond hypothesis.

It seems unsatisfactory just to wait for the construction of facilities that can reach higher Reynolds numbers. By targeted research in this area, even relatively small facilities can be highly useful in the future next to the large facilities.

4.2. Tunnel Corrections

In the area of tunnel correction, i.e. compensating for the error caused by the finite measurements of the wind tunnel throat, the "self-correcting tunnel" with active wall adjustments represents one of the few fundamentally new ideas developed in wind tunnel technology. This principle, which simulates an unlimited flow field for the body under flow with theoretically any desired accuracy, has already been successfully realized for two dimensional tests.

For three dimensional tests in the subsonic or transsonic range, however, feasibility is still an open question. This offers the wind tunnel engineer one of the most intriguing and rewarding areas of work at present. Even when one thinks pessimistically in estimating the gain in model size, and thus in Reynolds number, obtainable with this principle, if one converts this Reynolds number gain into construction savings one gets such high sums for a large facility like LEHRT that energetic research in this direction could be very profitable.

However, this brilliant principle should not make us forget computer tunnel correction, which in the last 25 years has not been further developed to any degree worth mentioning. The enormous progress in aerodynamic computer processes and large computers has fertilized this area very little, so that great advantages are conceivable. The same applies to the possibility of eliminating tunnel correction in subsonic tunnels with semi-permeable walls.

4.3. Flow Diagnosis /8

The task of experimental aerodynamics can be viewed as fully achieved when the experiment delivers the complete spatial and temporal data on the flow field: a desire that naturally lies in the distant future. But is shows the importance of flow diagnosis with its multiple visualization methods, and especially the importance of velocity vector measurements at any arbitrary point in the flow field.

With the laser anemometer we have for the first time in the history of flow research an imstrument that allows measurement of the velocity vector in a flow field even close to the wall, without any feedback and with high temporal and spatial resolution. The development of the laser anemometer into a non-critical measurement instrument for normal wind tunnel operation will bring enormous progress in experimental flow diagnostics. In addition to the instrument itself, however, it is also necessary to develop working methods that exploit the full possibilities of the instrument. Only this will turn the production of measurements into true flow diagnostics.

Another important advance in flow diagnostics would be the development of a method for direct circulation measurement in a flow field. The lack of such a method is especially noticeable in wind tunnel work with configurations with low span-chord ratios.

4.4. Force Measurements

The possibility of getting more and better information out of normal 3- or 6-component measurements has been little exploited to date.

The use of "DMS" scales and models, which in addition to total forces also pick up practically any partial force desired, makes it possible to get valuable additional information. Examples of this are the VFW-Fokker partial load method as well as the integrated horizontal tail surface scale, also developed by VFW-Fokker, which can be built into all force models as a standard component instead of the usual horizontal tail surface attachment, and which allows simultaneous remote operation of the horizontal tail surfaces and separate measurement of horizontal tail surface forces.

4.5. Half Model Technology

For many purposes, half model technology offers better utilization of wind tunnel measurements while simultaneously lowering model costs. However, tunnel corrections, especially the effects of the boundary layer at the wall of symmetry on results, are inadequately clarified. Resistance measurements with half models are viewed with mistrust.

Improving half model technology to a reliable standard procedure would doubtless lead to better utilization of even smaller wind tunnels.

4.6. Pressure Distribution Measurements /9

Pressure distribution measurement permits particularly detailed evaluation of aerodynamic configuration and provides the basis for structural dimensioning of an aircraft. The enormous resources in model construction, instrumentation, measurement time and evaluation called for by pressure distribution measurements should instigate a search for basic improvements. The replacement of "scanivalves" by a fast monolithic multiple pressure converter, or the replacement of the borehole-hose-multiple pressure converter by a fundamentally new technique seems overdue.

4.7. Non-Stationary Measurement Technology

The development of a modern aircraft is inconceivable without wind tunnel measurements of non-stationary pressure distribution, non-stationary or quasistationary coefficients, or flutter measurements. But all these measurement methods are still far from being as routine and standardized as stationary measurement methods are.

Favorable prospects for the near future are visible in the area of non-stationary and quasistationary coefficients. In the context of the "Dynamic Wind Tunnel Scales" program being sponsored by the Minister of Research and Technology, an exemplary collaboration between the flight industry, institutions of learning and the DFVLR has yielded several test arrangements for non-stationary coefficients in the subsonic and transsonic range, and for roll and tailspin coefficients.

4.8. Acoustical Measurements

The drastic decrease of flight noise is probably the most humane goal in the development of new aircraft. Advances in this area in propulsion mechanism development have been considerable and will soon make the flow noise in the aircraft frame partially responsible for the total noise made by an aircraft. Thus acoustic measurements in wind tunnels are gradually entering wind tunnel engineers' field of interest. Such measurements are made very difficult by the wind tunnel's own noise. Significant new developments in measurement technology and drastic reductions of intrinsic wind tunnel noise are necessary to permit useful wind tunnel work in the area of acoustics.

4.9. Propulsion Mechanism Simulation

Practically no other field in wind tunnel technology has been so intensively developed in the last 10 to 20 years as propulsion mechanism simulation in wind tunnel tests. In West Germany too, many different techniques have been developed, yet one cannot call the problem completely solved.

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New problems are raised by the construction of the DNW. If only because of the large model scale, propulsion mechanism simulation in the tunnel provides whole new opportunities, but also raises new development problems.

A problem that reaches into the distant future will be propulsion mechanism simulation in the "cryotunnel;" up to now this has not even started to be discussed.

4.10. Model Construction

Today designing and constructing an overall model with a certain minimum supply of flap and rudder surfaces means a cost of at least DM 200,000 to 300,000. Complicated configurations with exchangeable parts or pressure distribution measurement equipment can easily exceed this amount by 2 or 3 times.

This enormous cost is anything but satisfactory. It is often in a disproportionate relationship to the subsequent actual measurement costs and painfully limits the extent of performable wind tunnel programs.

Model designers and builders should exert their entire imagination to achieve cheaper and simpler procedures. The development of numerically controlled machine tools has not yet led to any significant savings. The continuous high program costs of any model, despite the availability of numerical smooth outlines, raise the suspicion that suitable translation programs might provide a significant opportunity for rationalization.

One reason for the high cost of models is surely the distribution of model construction, which in Germany, despite the relatively low amount of model construction, is spread out to at least 10 different places. In spite of the building autonomy carefully preserved in all these places, one may permit the critical question whether a concentration of model construction activity and the knowhow in this field would not yield a significant rationalization.

5. Summary

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The construction of jointly run large wind tunnels on a European scale, planned or -- in the form of the DNW -- already begun, and indispensable for the progress of flight development, has often led to the conclusion that wind tunnel work in smaller facilities would lose its practical significance.

The present paper has tried to show that the practical value of wind tunnel work is not dependent solely on the size of the facility or the achievable Reynolds number. The desperately needed development of measurement, interpretative and evaluative procedures can be carried out nearly as well in smaller facilities. A broad work program to this end is likewise capable of improving the utility of smaller facilities for industrial wind tunnel measurements and aerodynamic research, and also assuring the collaboration of West Germany in large European facilities.

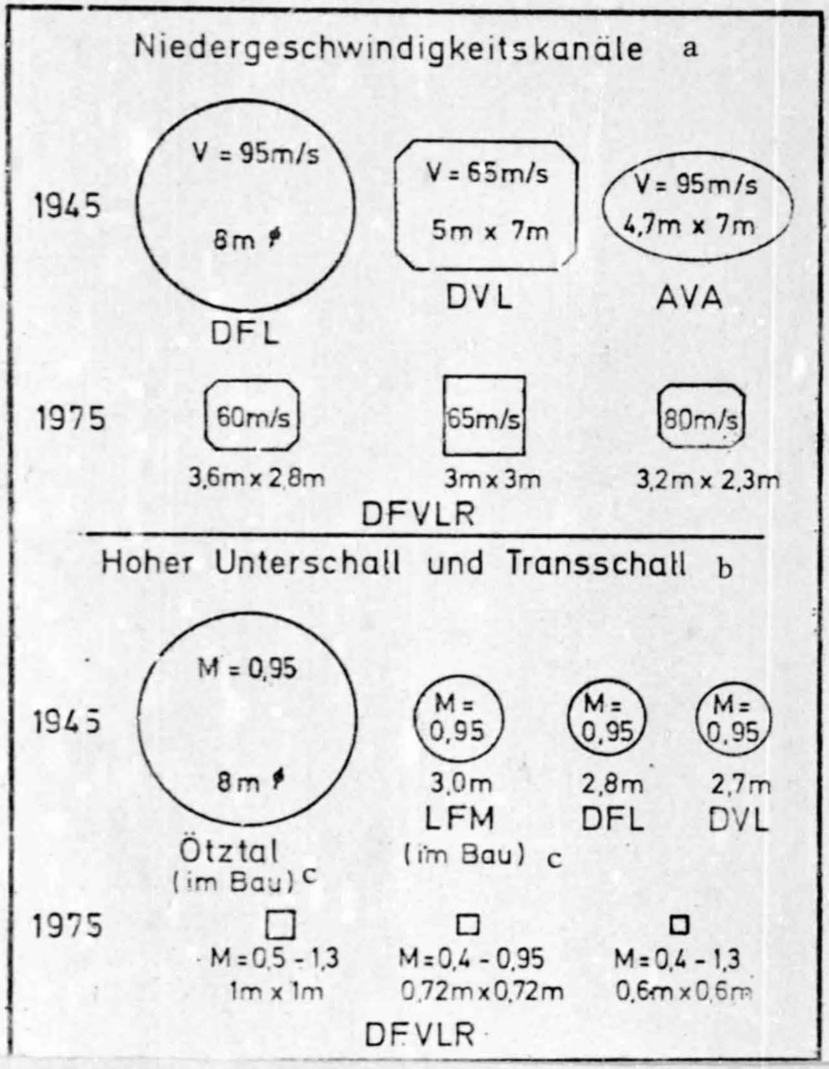


Fig. 1. Measurement cross sections of German wind tunnels, 1945 and 1975.

Key: a. Low velocity tunnels
b. High subsonic and transsonic
c. Under construction

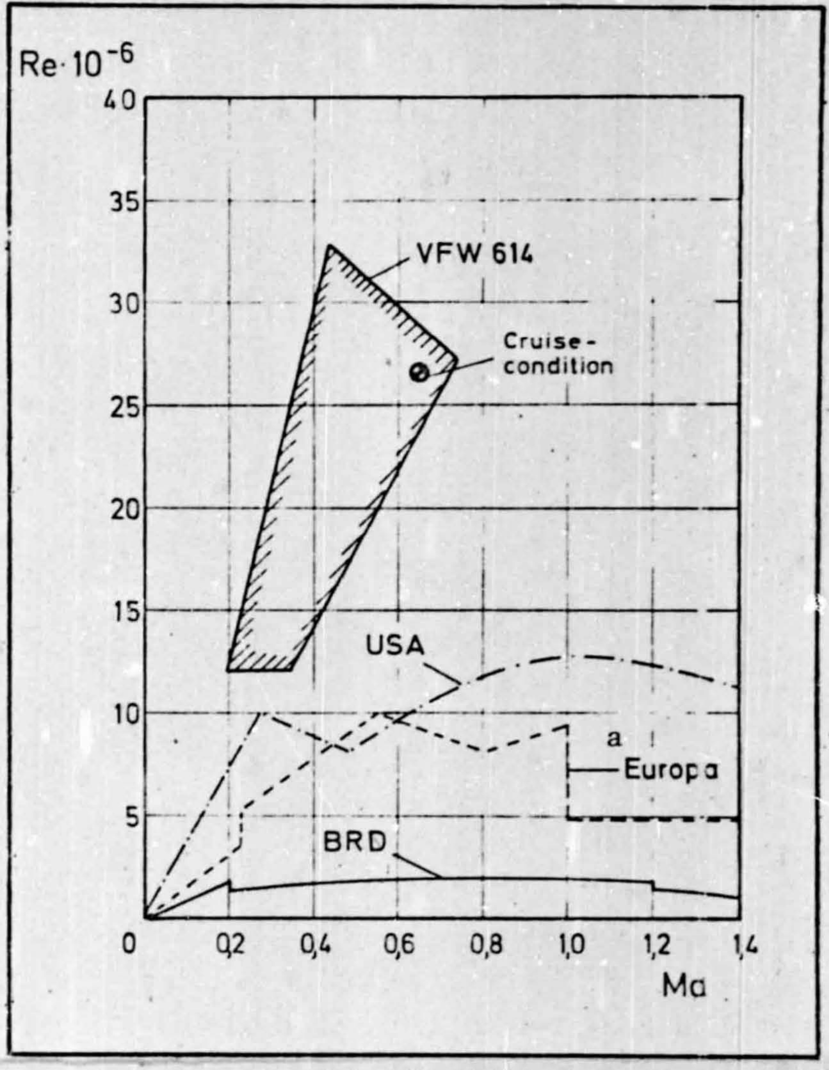
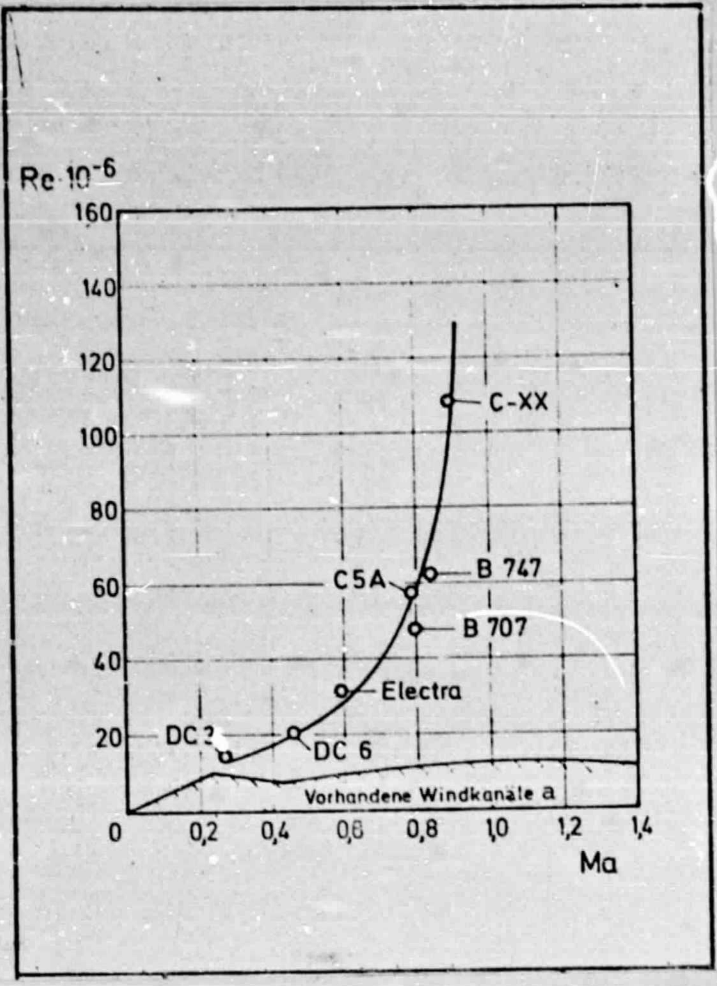


Fig. 2. Simulation range of available wind tunnels.

Key: a. Europe



(left:)

Fig. 3. The "Reynolds number gap."

Key: a. Available wind tunnels

(below:)

Fig. 4. Drive power of large wind tunnels.

Key: a. Drive power
b. Year of construction
c. Germany
d. France
e. USSR

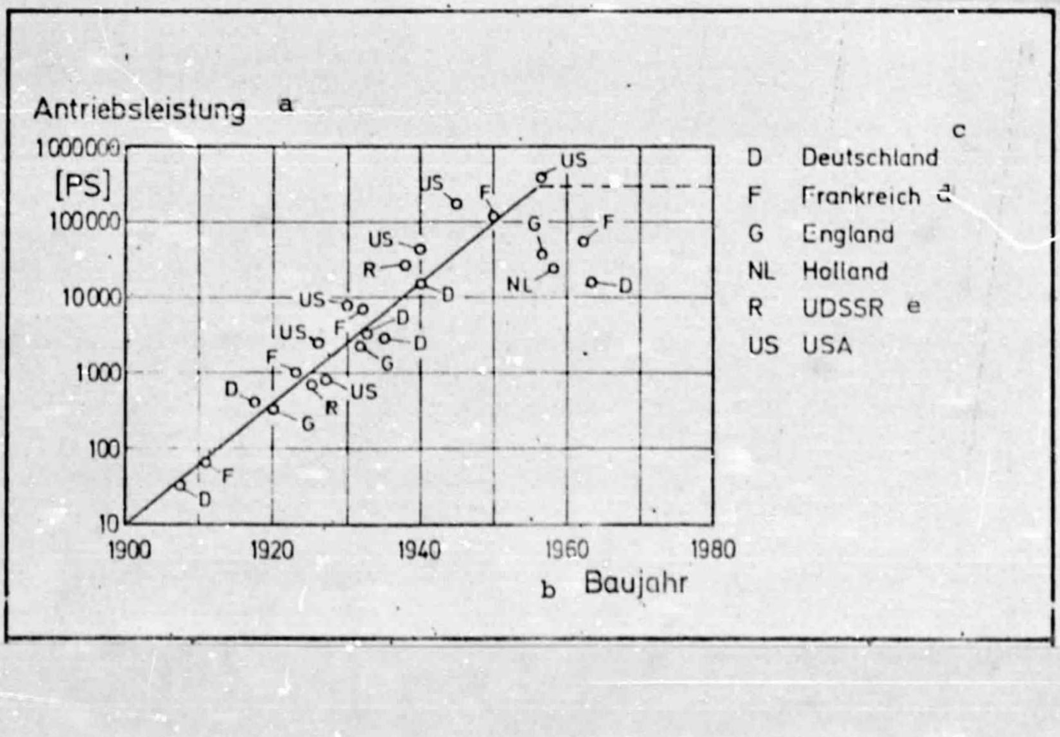


Fig. 5. New large subsonic wind tunnels in Europe

	France Toulouse F1	Great Britain RAE 5m	(GUK) (LST) German-Dutch Wind Tunnel DNW
Type of operation	Variable pressure	Variable press.	Atmospheric
Measurement cross section	$4{,}5 \times 3{,}5\ m^2$	$5 \times 4{,}2\ m^2$	$9{,}5 \times 9{,}5\ m^2$ $6 \times 8\ m^2$ $6 \times 6\ m^2$
Max. Velocity	120 m/s	109 m/s	60 m/s 110 m/s 145 m/s
Max. Reynolds number	$6{,}5 \cdot 10^6$	$6{,}5 \cdot 10^6$	$4{,}4 \cdot 10^6$
Drive power	8 MW	11 MW	12,7 MW

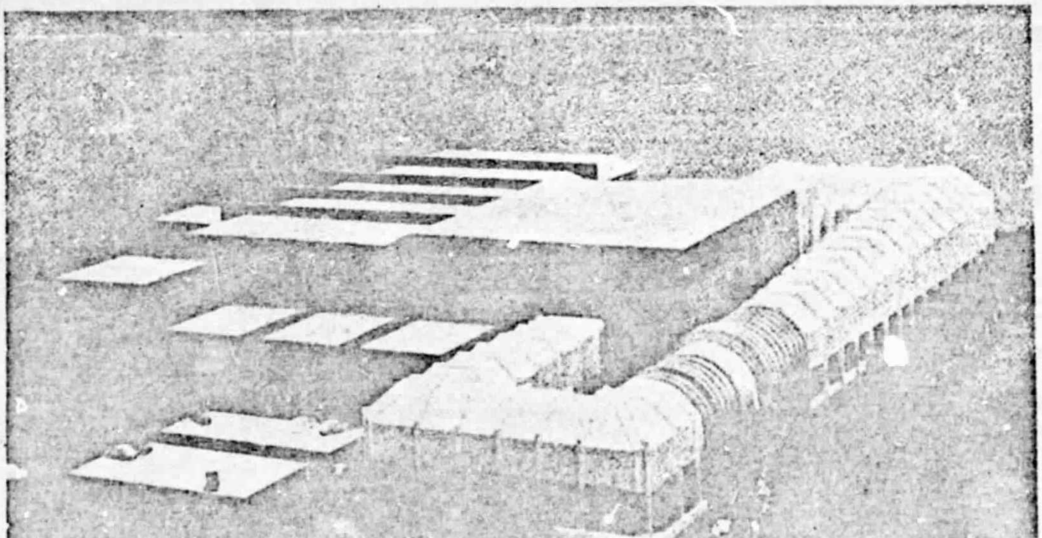


Fig. 6. German-Dutch Wind Tunnel (model photo)

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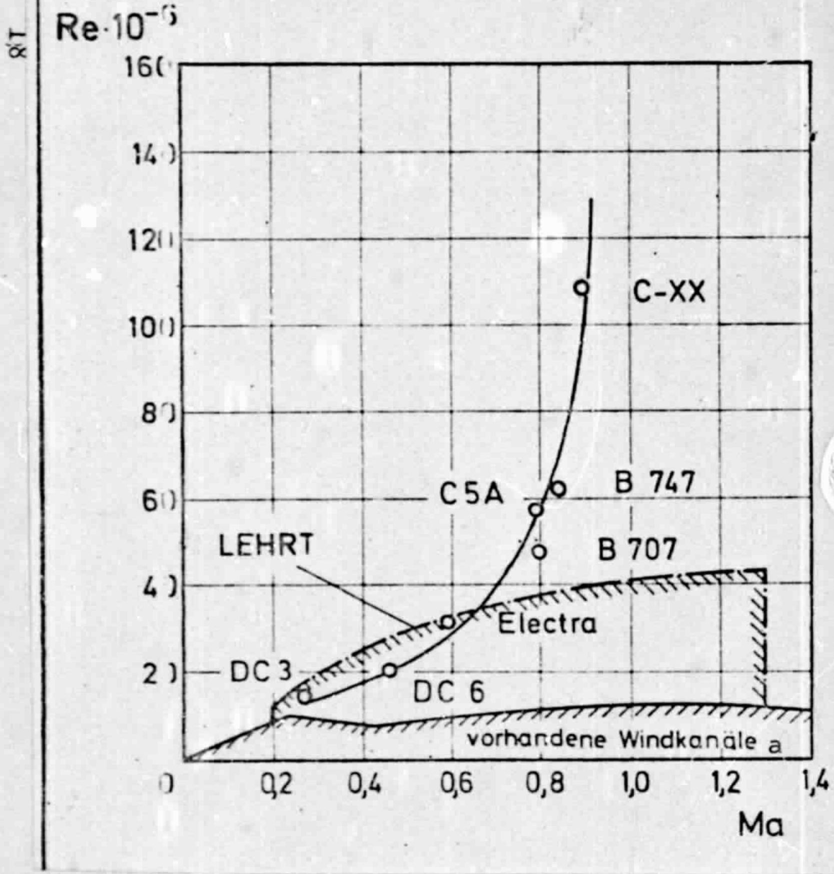


Fig. 7. Operating range of the LEHRT project.

Key: a. Available wind tunnels

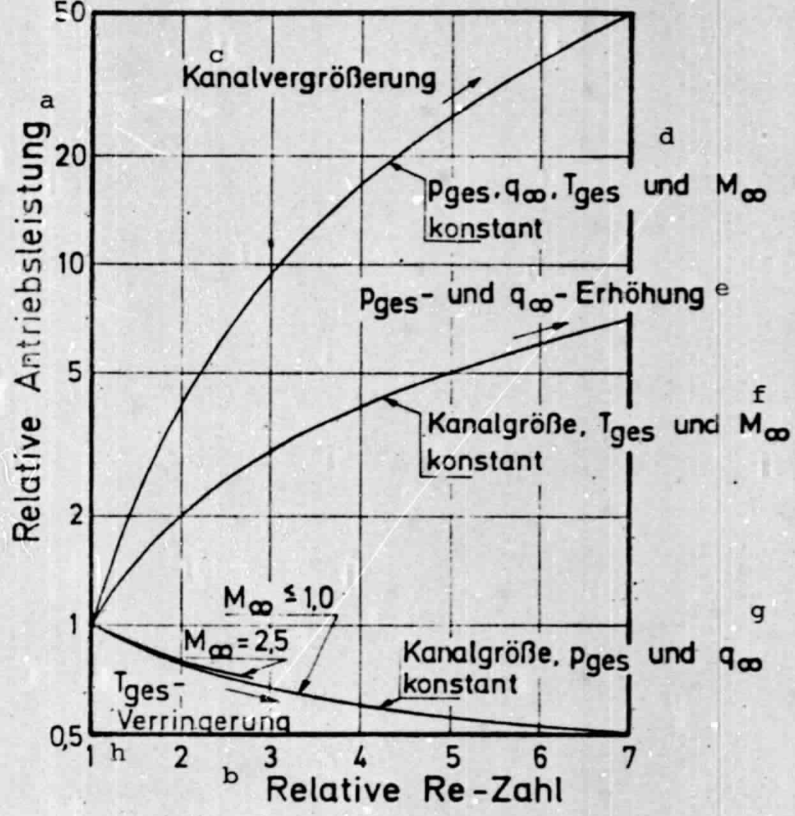


Fig. 8. Possibilities for raising the Reynolds number.

Key: a. Relative drive power b. Relative Re number c. Tunnel enlargement d. P_{tot}, q_∞, T_{tot} and M_∞ constant e. P_{tot} and q_∞ increase f. Tunnel size, T_{tot} and M_∞ constant g. Tunnel size, P_{tot} and q_∞ constant h. T_{tot} decrease

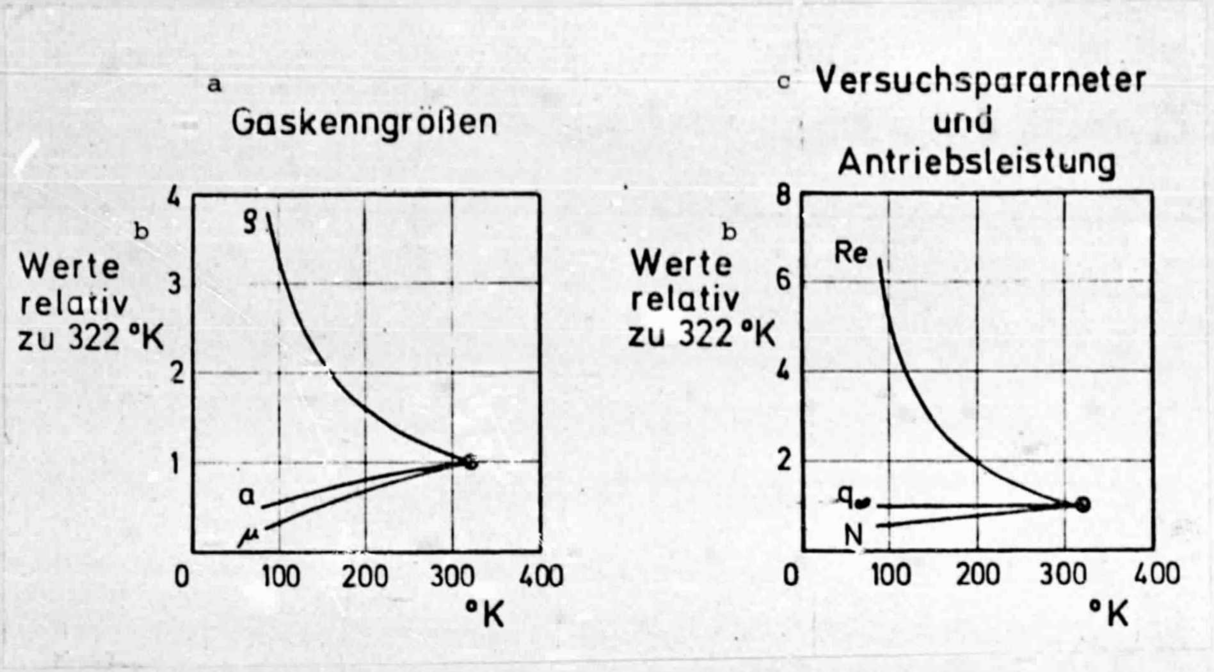
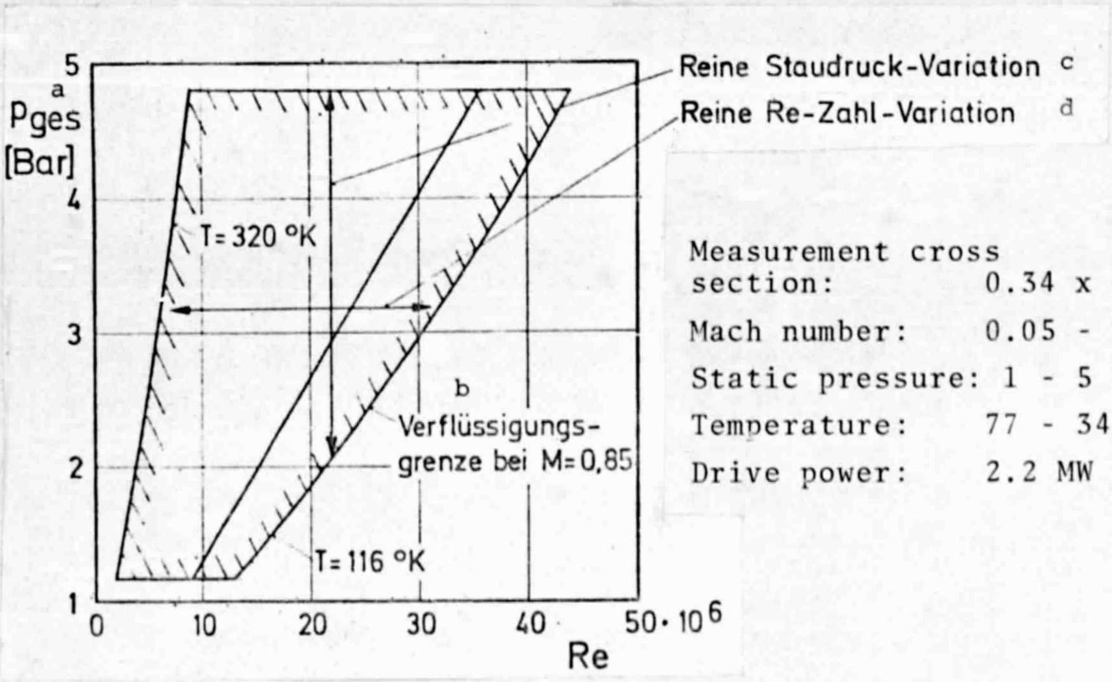


Fig. 9. Effect of temperature at constant Mach number, static pressure and tunnel size.

Key: a. Gas characteristic values b. Values relative to 322 °K c. Test parameters and drive power



Measurement cross section: 0.34×0.34 m^2

Mach number: 0.05 - 1.3

Static pressure: 1 - 5 bar

Temperature: 77 - 340 °K

Drive power: 2.2 MW

Fig. 10. NASA Cryogenic Pilot Tunnel. Technical data and operating range.

Key: a. P_{tot} (bar) b. Limit of liquefaction at M = 0.85 c. Pure static pressure variation d. Pure Re number variation

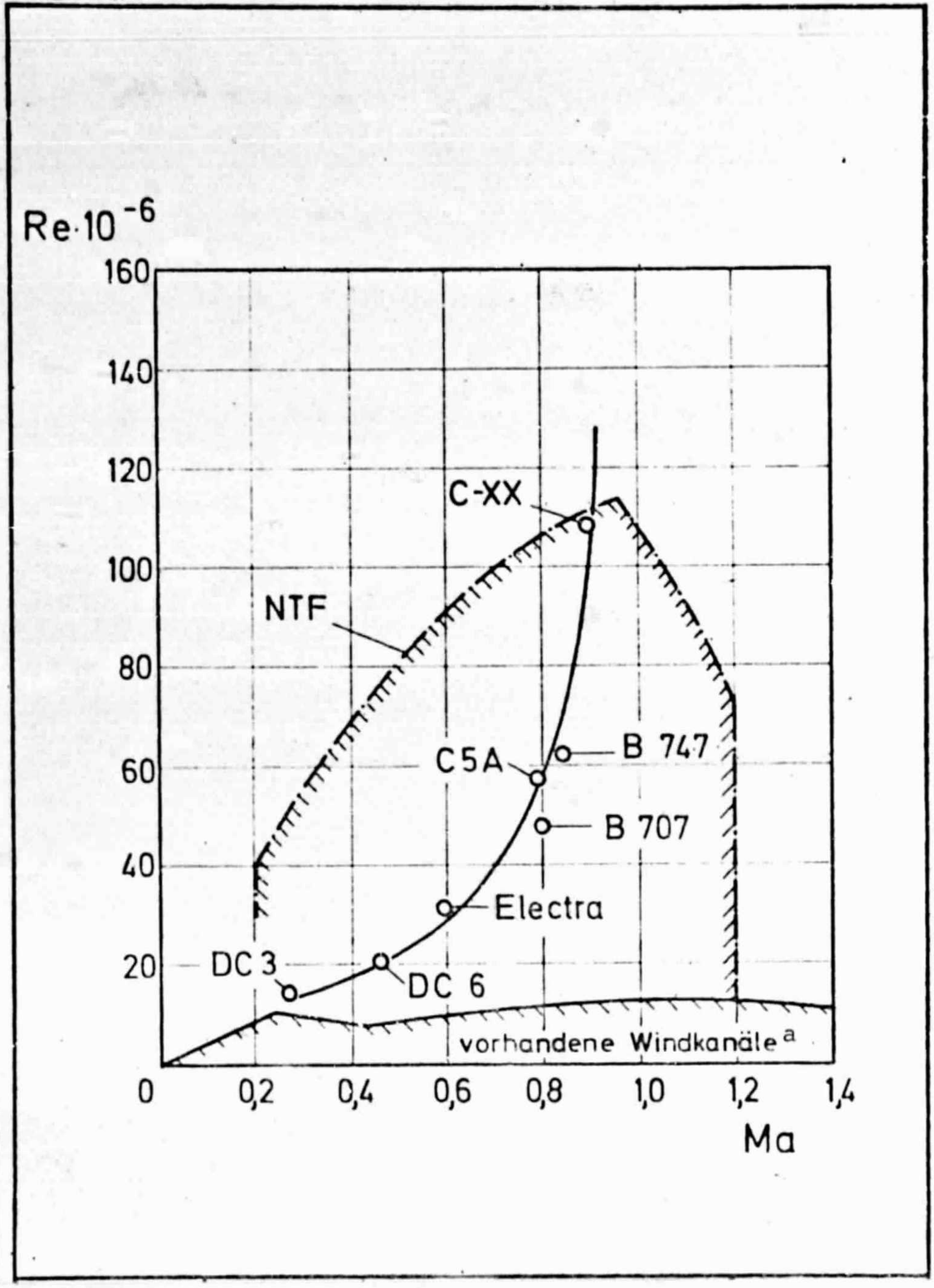


Fig. 11. Operating range of the National Transonic Facility project.

Key: a. Available wind tunnels