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CRYOGENIC WIND-TUNNEL TECHNOLOGY MEASUREMENT POSSIBILITY AT HIGHER REYNOLDS NUMBERS

J. W. Beck

Translation of: "Kryo-Windkanal-Technologie: Ein Weg zur Messung bei hoeheren Reynolds-Zahlen", Reports, Publication on the Occasion of the 65th birthday of Prof. Dr. Eng. Erich Truckenbrodt; Scientific Colloquium, Technische Universitaet, Muenchen February 1, 1982, Munich, West Germany, 287/4-84, pp. 53-81, 83-87.

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16. Abstract

European cryogenic wind tunnel projects ETW (European transonic wind tunnel) and KKK (Cologne cryogenic tunnel) are described. Some special problems are discussed :condensation, model and measurement techniques, operations.

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CRYOGENIC WIND-TUNNEL TECHNOLOGY: MEASUREMENT POSSIBILITY AT HIGHER REYNOLDS NUMBERS /53*

By Dr. Eng. Juergen W. Beck, Director of the Area Scientific-Technical Operating Facilities, DFVLR [Deutsche Forschungs und Versuchsanstalt fuer Luft und Raumfahrt = German Research and Test Facility for Air and Space Flight], Oberpfaffenhofen, FRG

SUMMARY Unfortunately, to date all measurements in wind-tunnels usually had to be made at low Reynolds numbers. The problems arising herefrom are listed; they can be overcome by means of cryogenic wind-tunnel technology, which more specifically also allows a separation of various physical aerodynamics phenomena. The projects ETW (European trans-sonic wind-tunnel) and KKK [Kryo-Kanal Koeln = cryogenic tunnel Cologne] are briefly described. In addition, some special problems of cryogenic wind-tunnel technology (condensation, model and measurement technologies, operational aspects) are discussed. A critical cost study is followed by a clarification of the relationship with numerical aerodynamics. Result: progress in both areas will fruitfully supplement each other.

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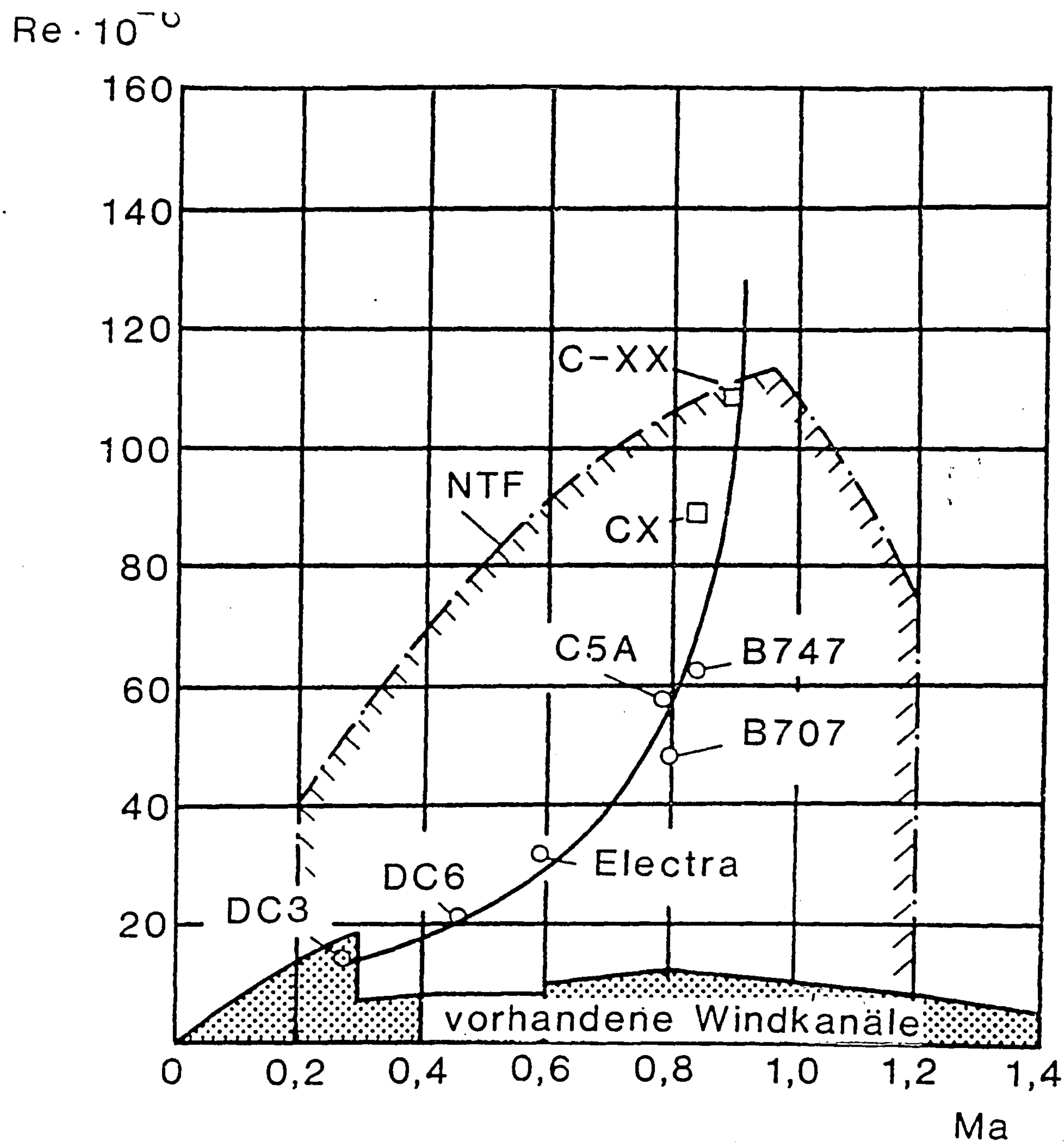
1 PROBLEM DEFINITION AND POSSIBLE SOLUTIONS

During the past four decades, the growing complexity and expanded flight ranges of aircraft have led to ever increasing requirements regarding the quality and quantity of wind-tunnel studies for the aerodynamical design process. Admittedly, the Reynolds numbers attained in the wind tunnel never did correspond - since the very beginning of wind-tunnel technology - to those occurring /54
in flight. The first Goettingen wind-tunnel (Ludwig Prandtl, 1908) with a closed throat achieved a maximum Reynolds number of $1.3 \cdot 10^5$ (formed with 10% of the root of the throat cross-section area), while the aircraft of the time were flying at Reynolds numbers of 10^6 and 10^7. Figure 1, below, shows how this problem has evolved since then, by presenting the Reynolds number discrepancy for transport aircraft. The problem is even more serious for modern fighter-planes: the expansion of the operational angle of incidence, combined with advanced technologies of many kinds as well as high power/weight ratios have led to the predominance of strongly Reynolds number-depending flow processes (such as cross-currents at the fuselage, free vortexes, strong interaction between compression shocks and boundary layers). At large Reynolds numbers the turbulent processes in the boundary layer have a fine structure and are subject to complex interactions, such that the flow behavior is strongly affected by viscous forces.

If in the wind-tunnel measurements are performed at Reynolds numbers small compared to those actually encountered, the following errors will occur, in the main:

- Boundary layer and displacement thickness will be larger for the model than in reality,
- the passage from laminar to turbulent will occur too far back,
- thereby the measured resistance coefficient becomes too large,
- detachment occurs already at lower lift coefficients than in the full-scale design,

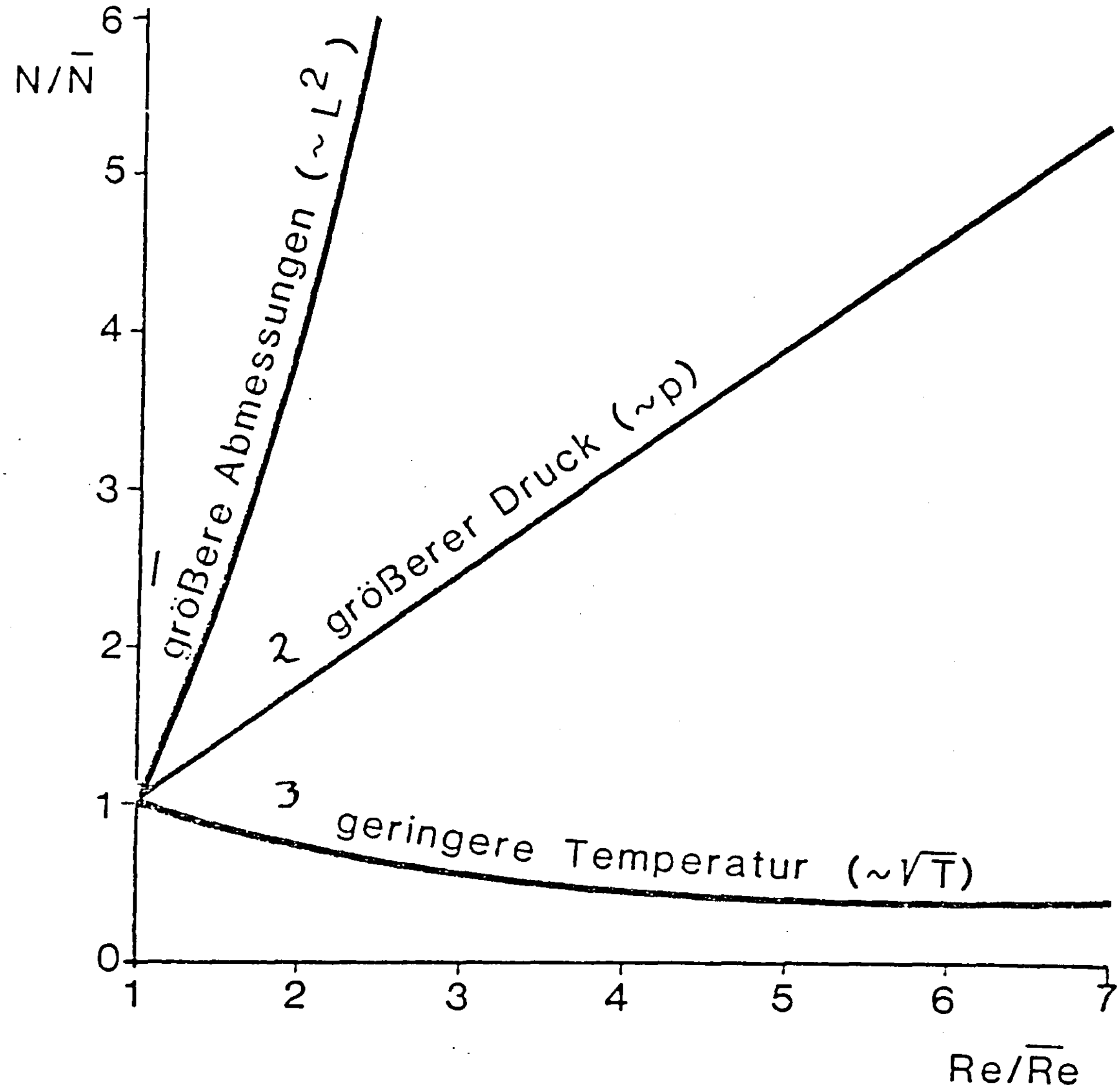


KEY 1 Existing wind tunnels

Figure 1 Reynolds number discrepancies

- the pressure distribution and moment coefficients are distorted,
- at transsonic flow, especially, at defective shock positions, with all ensuing consequences.

To date it has been attempted to at least partially compensate for these difficulties by semi-empirically extrapolating the /55



KEY 1 Larger dimesnions 2 Greater pressure 3 Lower temperature

Figure 2 Required propulsive power for three possibilities of increasing the Reynolds number (relative to a reference tunnel of the same Mach number)

measurement values obtained at low Reynolds numbers. To this end sometimes artificial roughness strips are attached near the leading edge, to appropriately affect the boundary layer (transition point). It is understandable that this procedure does not yield truly reliable results, despite the extensive accumulated experience, especially in the case of supercritical profiles or new kinds of wing shapes.

To this must be added that these are not the only problems in a wind-tunnel. Other disturbances are created by the model's suspension, the tunnel walls and the turbulence of the blower stream, whose correction can be quite problematic, especially in the transsonic range.

What means are available of increasing the Reynolds numbers attainable in transsonic tunnels? The following:

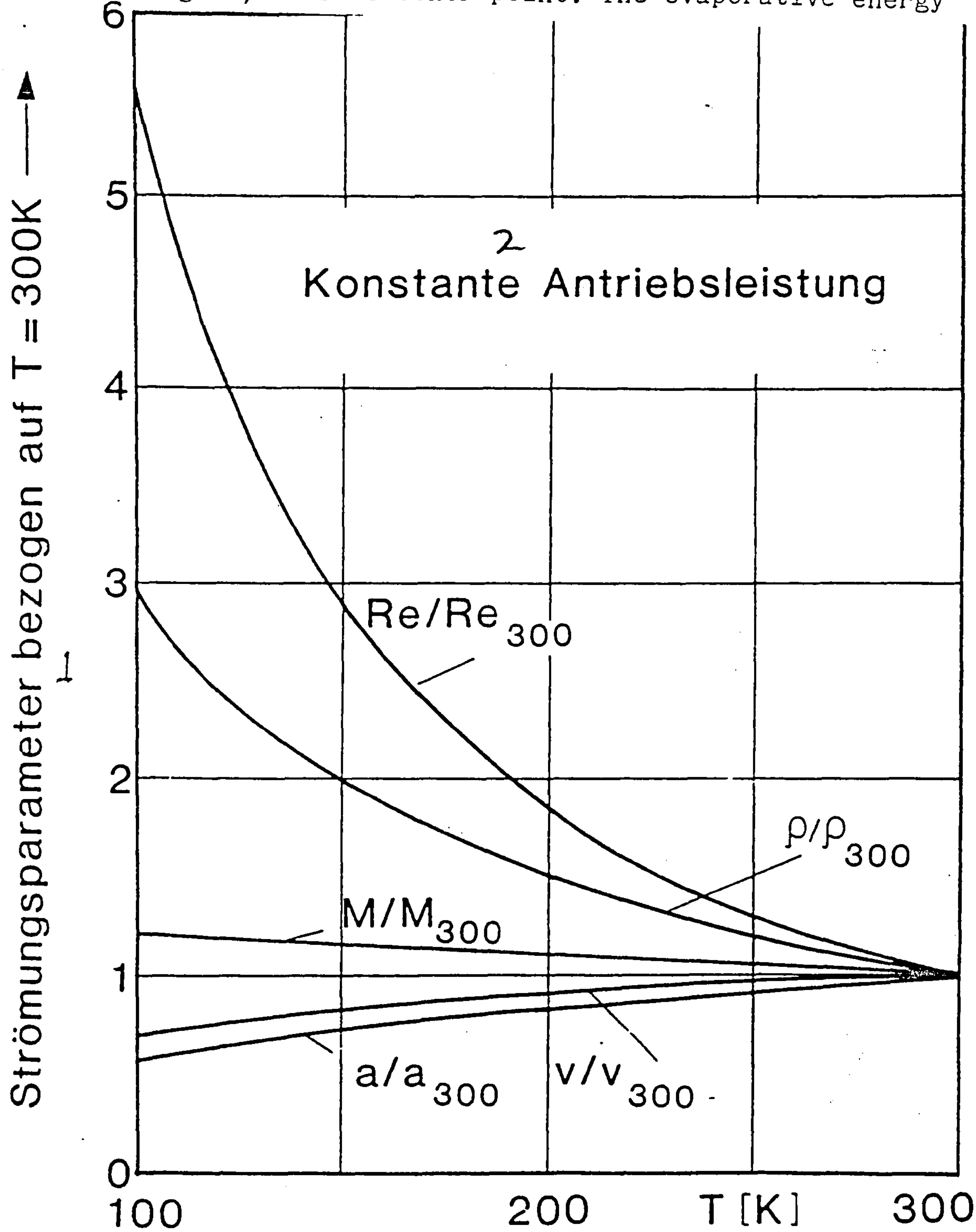
- One could simply build larger tunnels. But as Figure 2, above, shows, the required propulsion power would increase drastically and construction costs would become prohibitive.

- A significant pressure increase (beyond that available in current wind-tunnels) would be slightly less prohibitive in regard to power requirements; but this would lead to intolerably high stress to the model.

- The third possibility does offer an alternative: a decrease in temperature. This even results in slightly lowered power requirements and such a cryogenic tunnel is a favorable alternative for a continuous tunnel, in comparison to the blow-down concept, which shall be no further discussed here (for the rest, intermittently operating cryogenic wind tunnels also exist.)

The decrease in temperature causes a lowering in the dynamic viscosity and an increase in the density (cf. Figure 3, below), which makes possible a considerable increase in the Reynolds number. The fact that nitrogen is used here, instead of air, is due to both safety and cost reasons, which I can not further discuss here. /56

In practice, a "normal", closed tunnel with blower is used, of course appropriately insulated, and into which finely divided liquid nitrogen is sprayed, at one point. During stationary operation, the corresponding quantity of gaseous nitrogen is removed again, at some other point. The evaporative energy



KEY 1 Flow parameters relative to T = 300 K 2 Constant propulsive power

Figure 3

of the sprayed nitrogen compensates for the loss of heat through the insulation and the energy introduced into the circuit by the blower. Obviously sufficiently large quantities of nitrogen must be evaporated to cool the tunnel and the model.

The especially important feature, however, is that with the cryogenic wind tunnel the possibility is created, for the first time - by means of the appropriate control of temperature, pressure and blower performance - of achieving complete separation, during the model test, between

- viscosity effects (boundary layers, boundary layer detachment, vortex systems, etc),
- compressibility effects (especially, compression shocks, which interact with boundary layers and boundary layer detachment);
- aeroelasticity effects (deformation of components under aerodynamic stress or alternating stress, wing bending, vibration, etc.).

The possibility of separating these effects creates entirely new premises for the study of the individual phenomena, and hence for an optimal realization of the design goal, especially also in fighter aircraft.

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2 ETW (EUROPEAN TRANSSONIC WIND-TUNNEL) AND KKK (CRYOGENIC WIND-TUNNEL COLOGNE)

I just want to briefly introduce the two projects to which our efforts are related, within the European and national context: the ETW and the KKK.

The ETW's tunnel circuit is shown in Figure 4 (page 8). The points of injection of liquid nitrogen and of removal of gaseous nitrogen can be seen. The consumption of nitrogen is considerable

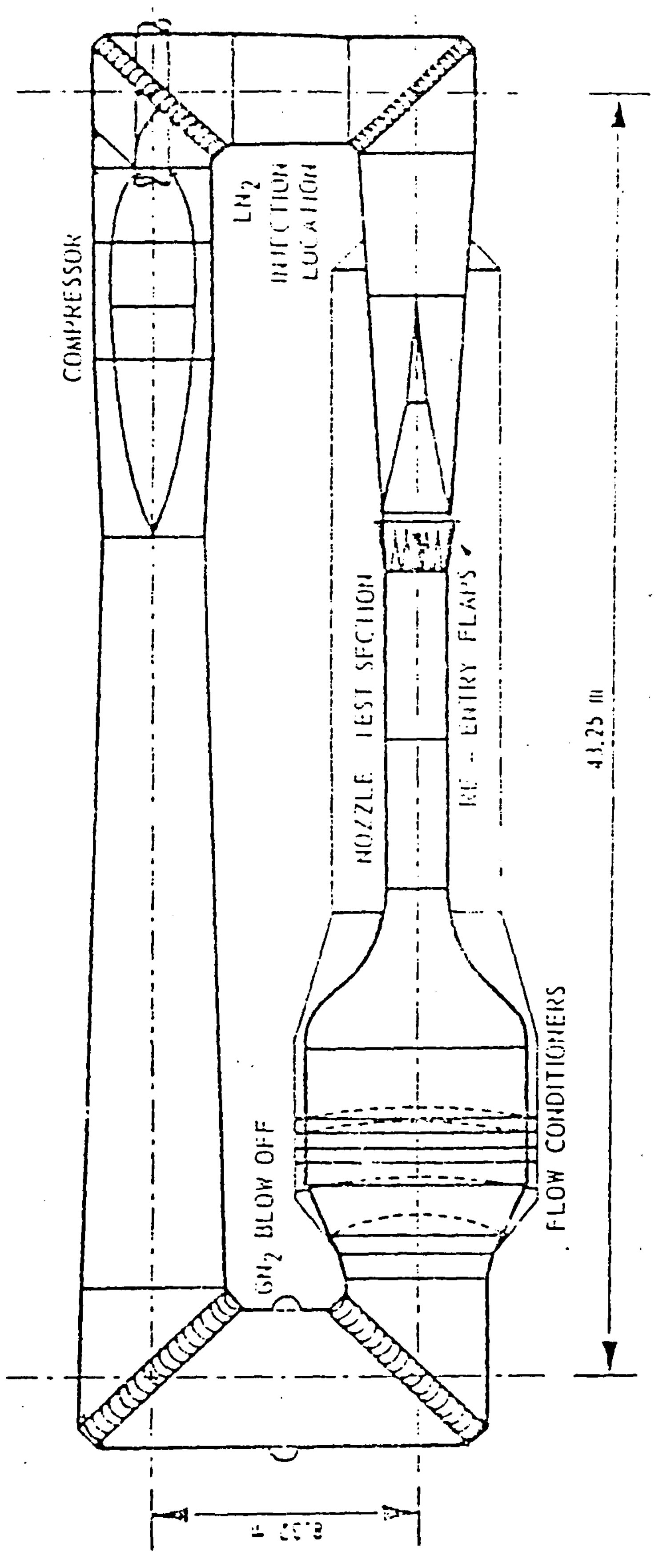


Figure 4 ETW wind-tunnel circuit

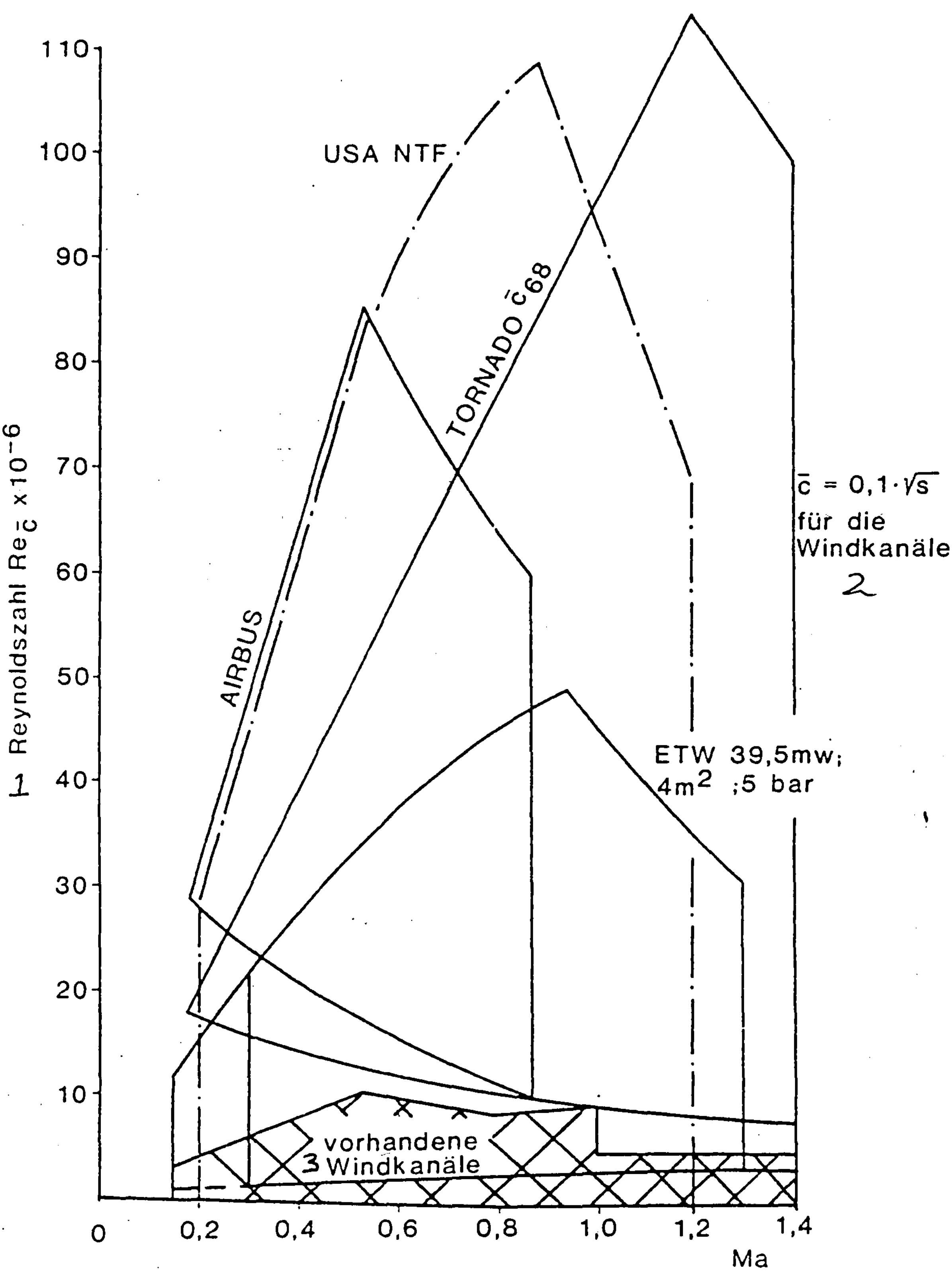
and reaches 40,000 tons per year. Depending on the permanent location of the ETW, it may be more advantageous to bring the nitrogen in with tank trucks, or to operate a dedicated liquid nitrogen production facility on site. The equilibrium temperature in the wind-tunnel is intended to be at approximately 110-120 K. The ETW will require an investment of approximately 350-400 million DM and the operating costs are estimated at approximately 20 million DM per year.

The ETW's operating range is shown in Figure 5, page 10 (for a 4 m^2 throat cross-sectional area and a maximum operating pressure of 5 bar) and compared to the operating ranges for the Airbus and the Tornado. Thus, the ETW will be able, for the first time, to simulate important operating ranges with free flight conditions. However, for cost reasons the ETW has from the beginning been limited to maximum Reynolds numbers of approximately $40 \cdot 10^6$, which implies considerable losses in comparison to the NTF [National Transonic Facility] at NASA-Langley. Thus, once again we shall be required to extrapolate from intermediate to large Reynolds numbers. The suitable strategies for this still need to be developed, ultimately on the basis of measurement experiences obtained at NTF.

Figure 6, page 11, shows the ETW's operational range on a p-Re diagram, for design Mach values. It is limited by:

- the maximum blower power of 39.5 MW;
- the maximum pressure (resistance of the construction)
- the minimum temperature, to avoid local condensation phenomena (here very conservatively assumed at local Mach numbers of 1.7 at 122 K static temperature in an undisturbed flow field);
- the minimum pressure of 1.25 bar in the measurement chamber, that must be kept to expel the gaseous nitrogen;
- the operation at environmental temperatures.

It may be possible - and I shall return later to this point -



KEY 1 Reynolds number 2 for the wind-tunnels 3 existing wind-tunnels

Figure 5 Operating ranges

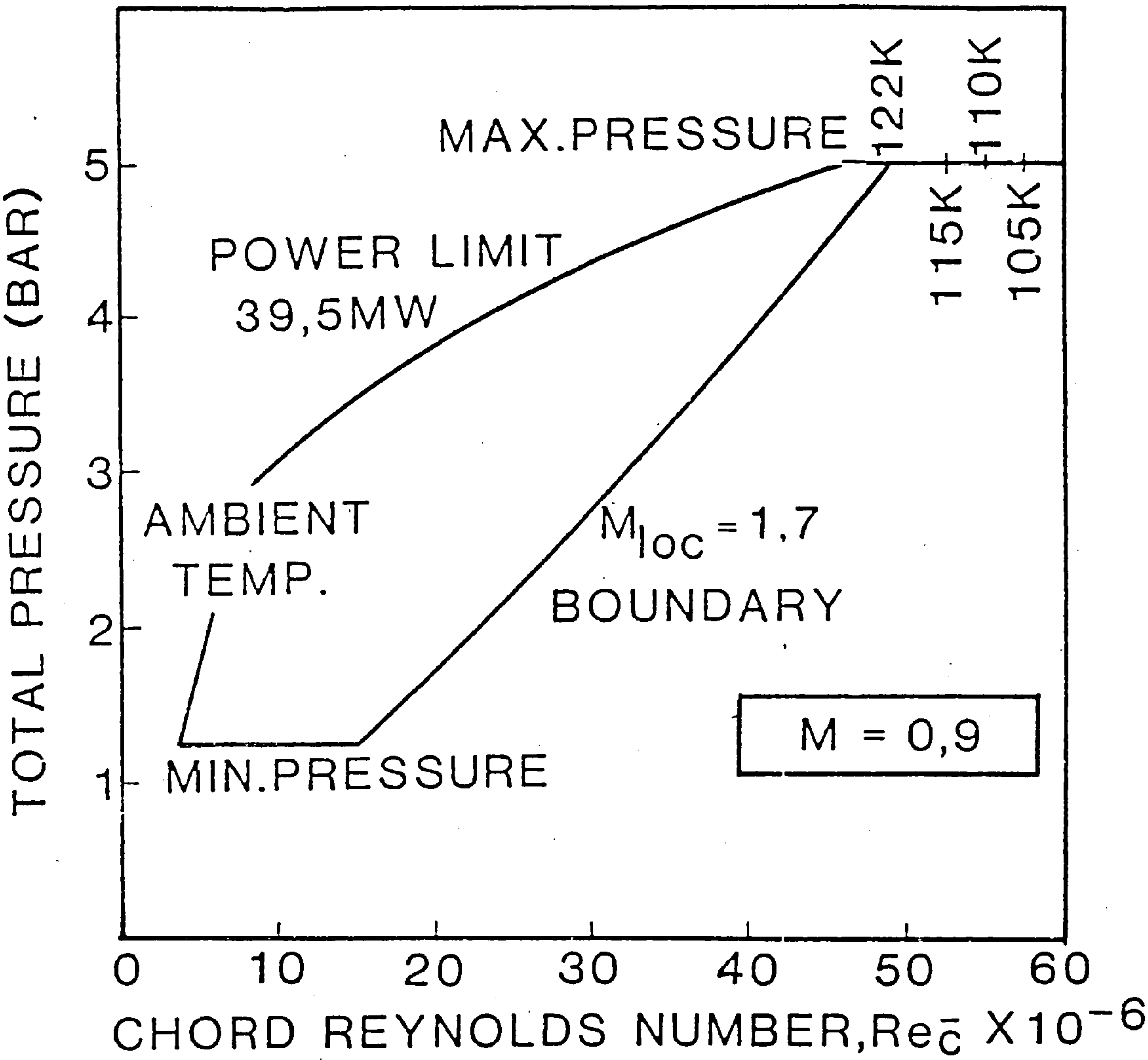


Figure 6 Operating range of the ETW at design values of the Mach number

to further reduce the static temperature in the undisturbed flow field, by suitable utilization of condensation delay, leading to the possibility of attaining Reynolds number greater than $50 \cdot 10^6$.

The question as to whether it would be better or not to build the ETW for lower pressures and a larger throat cross-section was extensively and heatedly debated. A balancing of very different but very important effects became necessary, in the process:

- the strength and rigidity of the model's wings and model suspension
- the absolute size of the model (space for an internal balance, compatibility with other wind-tunnels for connecting measurements),
- blocking the tunnel: upper limit to the Mach number
- model design and manufacture (for instance, also surface quality)
- wind-tunnel operation and model manipulation
- costs (investment, operation, model manufacture).

Currently there is agreement for a maximum operating pressure of 4.5 bar, for the ETW.

Onbviously, the maximum operating pressure of 9 bar at the NTF /59 can also not be used for all simulations. The high Reynolds number is attainable only when due to low model stress there is no limit to the equilibrium pressure. However, simulation at high Reynolds numbers is usually of interest precisely where large lift is desired (for instance, buffet limit, maneuvrability limit).

The DFVLR decided, approximately two years ago, to finance the change-over of the 3 m subsonic wind tunnel at Cologne-Porz, to build a large cryogenic wind-tunnel and to operate it with the following goals:

- development of model and test technologies at cryogenic temperatures
- development of the theoretical standard model for the ETW
- development of the DFVLR's own know-how, for a better evaluation of the ETW's detailed planning
- preparation of DFVLR colleagues and others in industry for the utilization of the ETW,
- to perform measurements on aircraft models of the next generation.

- Antriebsleistung: [1] $N = 1\ MW$
- Messquerschnitt: [2] $F_{TS} = 2{,}4 \cdot 2{,}4 = 5{,}76\ m^2$
- Verlustfaktor: [3] $K_0 = 0{,}2159$

- Geschwindigkeit: [4]
  - $T_0 = 300\ K \quad v = 102\ m/s$
  - $T_0 = 200\ K \quad v = 91\ m/s$
  - $T_0 = 100\ K \quad v = 72\ m/s$

-Reynolds-Zahl: [5]
  - $T_0 = 300\ K \quad Re = 1{,}5 \cdot 10^6$
  - $T_0 = 200\ K \quad Re = 2{,}9 \cdot 10^6$
  - $T_0 = 100\ K \quad Re = 8{,}9 \cdot 10^6$

-Maximale Einspritzmenge [6] LN_2: $\dot{m}_{LN_2} = 10\ kg/s$
-Maximale Absaugmenge [7] GN_2: $\dot{m}_{GN_2} = 10\ kg/s$

KEY 1 Propulsion power 2 Throat cross-section 3 Loss factor 4 Velocity 5 Reynolds number 6 Maximum injected quantity 7 Maximum removed

Figure 7 Technical data for the KKK [Cryogenic wind-tunnel Cologne]

The design values for the KKK and its simulation range can be seen from Figure 7, above and Figure 8, page 14. It must be pointed out that the KKK is in no way intended - or suitable - for measurements in the transonic range of velocities. Since the dimension of its throat cross-section matches that of the ETW fairly closely, it is well suited for connection measurements in the lower velocity range, and especially, also to test models

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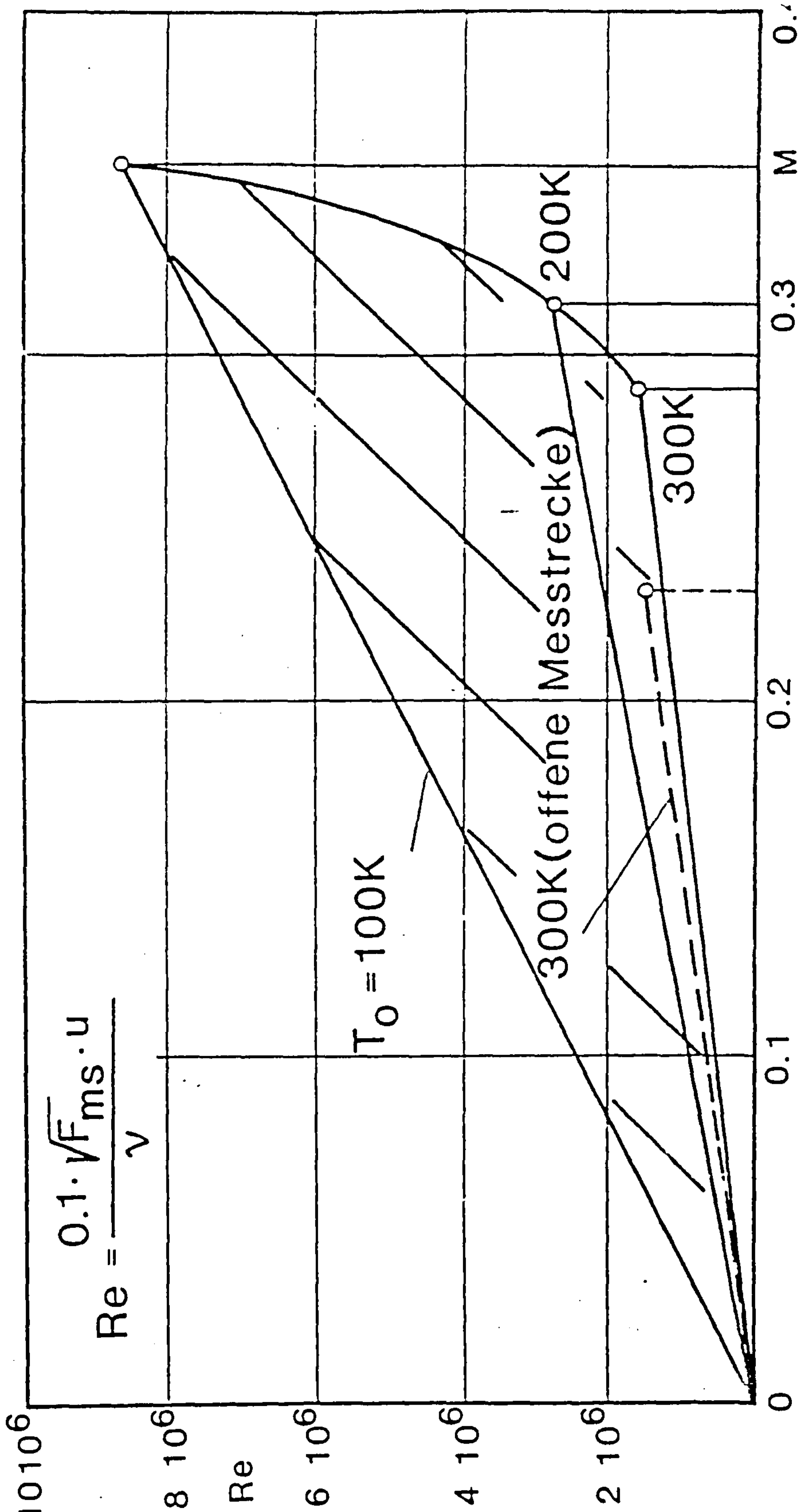

KEY 1 Open throat

Figure 8 KKK simulation range

intended for measurements in the ETW, as a preliminary wind

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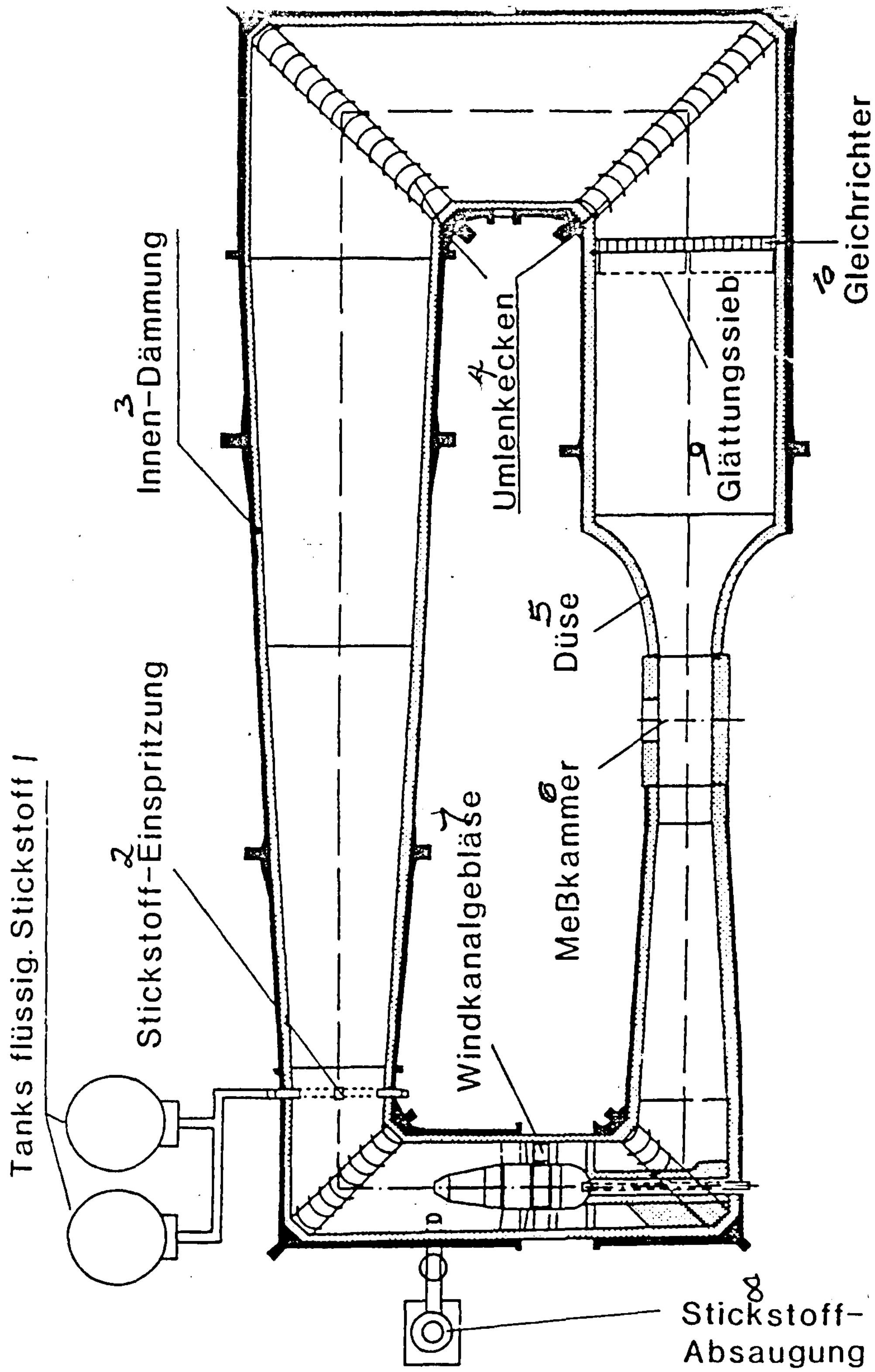

KEY 1 Liquid nitrogen tanks 2 Nitrogen injection 3 Inner insulation 4 Reversal corners 5 Nozzle 6 Throat 7 Wind-tunnel blower 8 N_2 removal 9 Smoothing sieve 10 Straightener

Figure 9 KKK wind-tunnel circuit. Throat cross-section: 2.4x2.4 m^2; Temperature range: 100-300K; velocity: 5-100 m/sec

tunnel at cryogenic temperatures. Even though the Reynolds numbers

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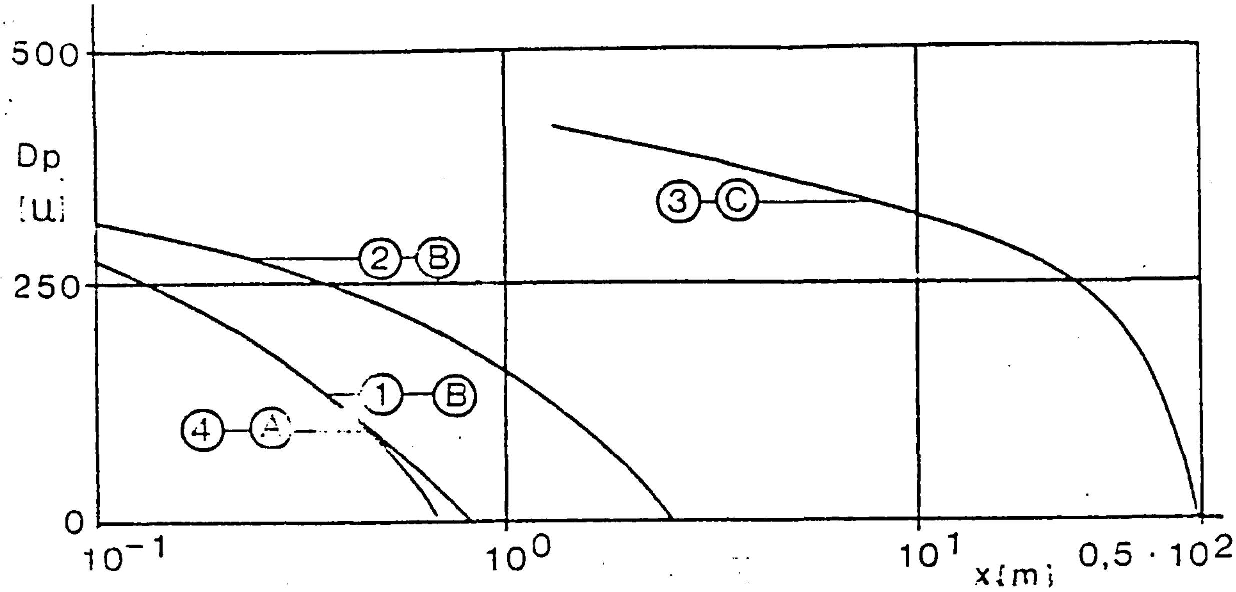
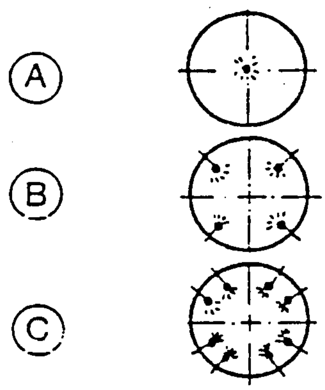


Test conditions

	T	U_{ms}	$\dot{m}_{LN_2}$
	K	m/s	kg/s
(1)	300	103.6	2.1
(2)	200	92.7	2.9
(3)	100	71.3	4.6
(4)	300	82.0	1.2

Tuyere arrangement



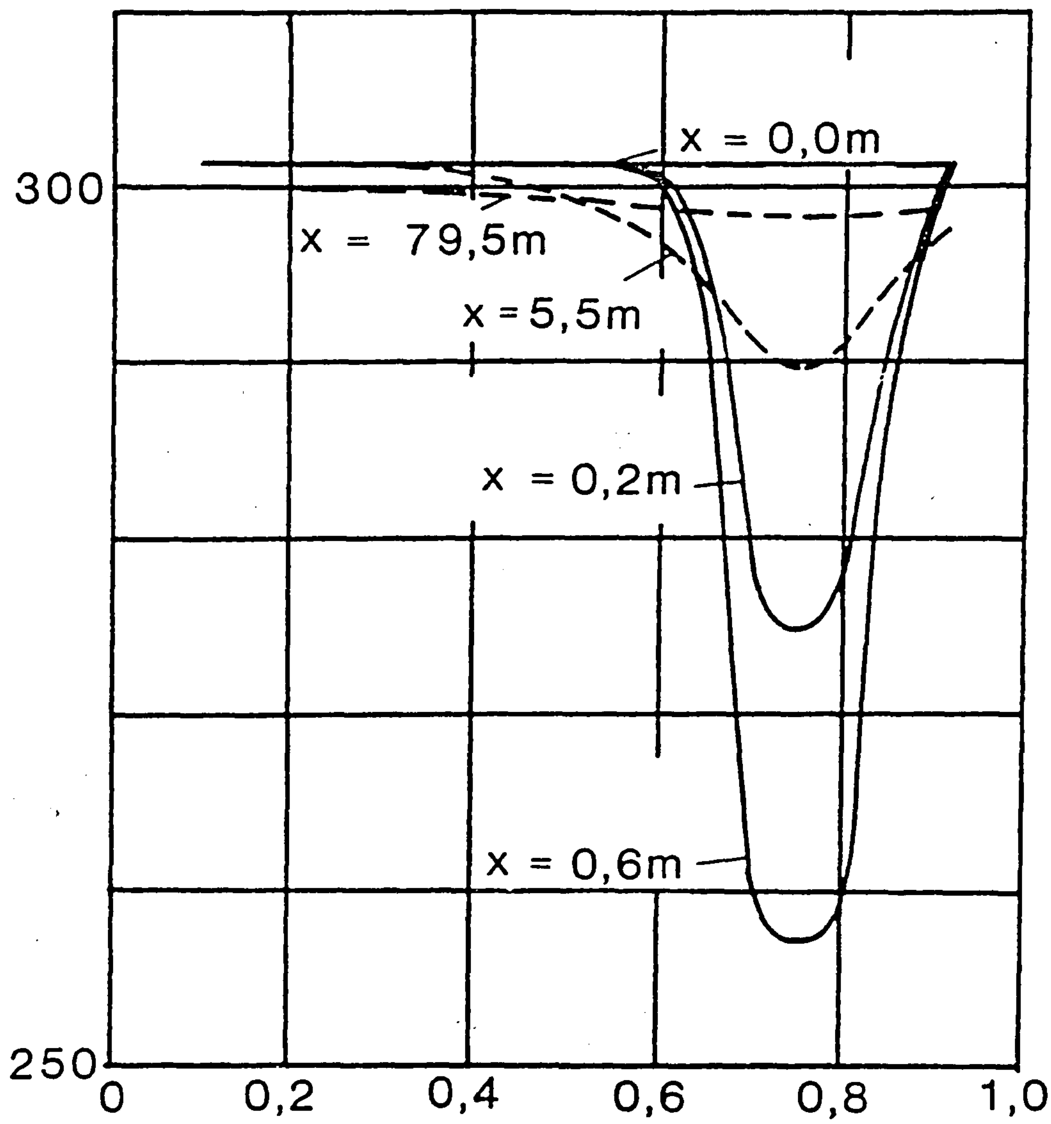
Development of the drop diameter for various test conditions and Tuyere arrangements

Figure 10

attainable at the KKK are quite within the range of the large subsonic wind-tunnels during its operating phase - such as DNW* RAE* 5 m and F1 - it is unlikely to act in competition with these tunnels, since model manufacturing and operation at cryogenic temperatures will pose problems of an entirely new type.

Figure 9 (page 15) shows the KKK wind-tunnel circuit. The main modifications are the installation of an internal insulation,

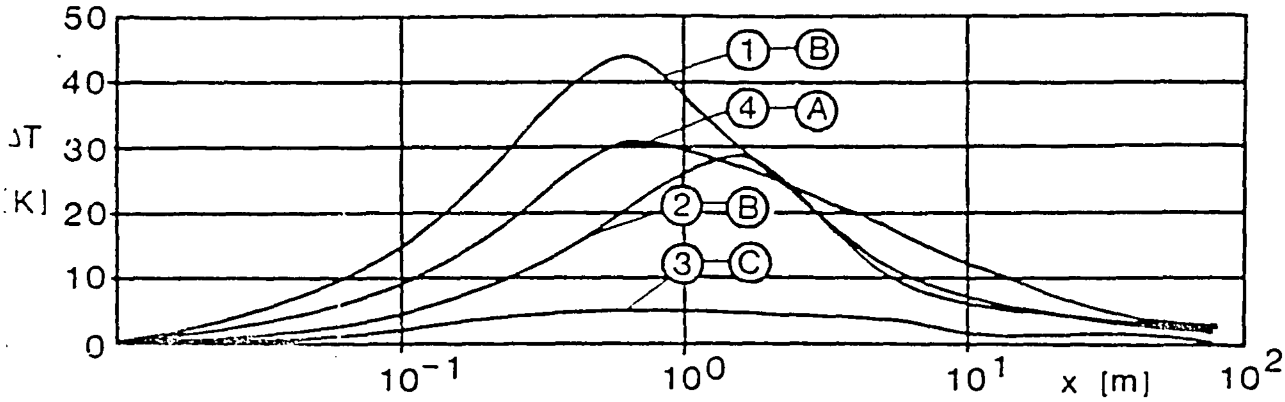
* No expansion provided in the foreign original



Development of the temperature profile between the injection site and the pre-chamber (X=79.5 m)

Figure 11

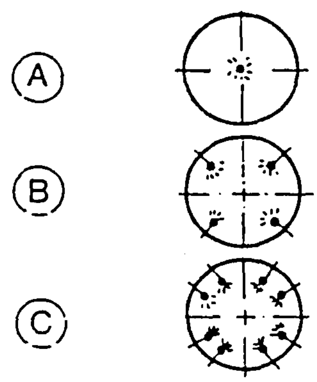
which with a total surface area of 2,000 m^2 poses some very considerable technical problems (shrinkage, brittleness, vapor lock, etc.). In addition, there is the installation of a new blower with new reversible blades that resist cryogenic temperatures, the installation of a measurement chamber, including a



1 Versuchsbedingungen

	T	U_{ms}	$\dot{m}_{LN_2}$
	K	m/s	kg/s
1	300	103,6	2,1
2	200	92,7	2,9
3	100	71,3	4,6
4	300	82,0	1,2

2 Düsenanordnung



KEY 1 Test conditions 2 Tuyere arrangement

Temperature uniformity along the wind-tunnel axis for various test conditions and tuyere arrangements

Figure 12

preparation chamber for model exchange, as well as - naturally - the systems necessary to nitrogen supply and removal. The overall investment for the refurbishing of this wind-tunnel is approximately 7 million DM (in addition to DFVLR's own performance). Completion and begin of operations is expected for approximately mid-1983.

During the design phase for the re-equipment of this wind-tunnel considerable preliminary scientific work of various kinds had to be performed. As an example of many other investigations, the graphics in Figures 10, 11 and 12, above, show the behavior of the drop diameter, the temperature profile and the temperature uniformity along the wind-tunnel axis, during the injection of liquid nitrogen.

3 SPECIAL PROBLEMS POSED

The results just shown are only an example for many other studies necessary during the design phase for a wind-tunnel of this kind, posed by flow physics (such as condensation), thermodynamics (such as insulation) and control technology problems. If the tasks of the operating phase were included, then it would be clear that a substantial R & D program is necessary for an effective utilization of test facilities of the type of KKK or ETW. Figure 13 (page 20) shows the focal points of these efforts in the context of the work related to cryotechnology, at the ETW.

Extensive investigations have already been performed at NASA-Langley, during the last year, which in regard to flow mechanics concentrated especially on the following areas: /61
laminar/turbulent transition, surface roughness, measurements in the 0.3 m pilot wind-tunnel, real-gas effects, condensation, buffeting, flow quality, rendering flows visible, laser and heating-wire measurement technology. As an example, Figure 14* shows the appearance of buffeting as a function of the Reynolds number (measurements in the 0.3 m pilot cryogenic wind tunnel).

Regarding the problems posed by flow mechanics, recommendations were made for high-priority experiments in cryogenic wind-tunnels,

* Translator's Note: Figure 14 was not included in the foreign text

Figure 13 Studies performed by the ETW work-group "cryotechnology" (/81)

TASK	Status	Organization	Remarks
1 Condensation and real gas effects	Work start: mid-1979	DFVLR/Dornier	Dornier part financed by TG-ETW & BMFT*
2 Cryo-mixing chamber (generation of a cold N_2/air mixture)	Work start: 1979, cryo-mixing chbr in operation	DFVLR	Basic financing DFVLR
3 Multicomponent wire strain gauge balance	Work start: 1979, first component balance tested	DFVLR/VFW*	VFW part financed by BMFT
4 Demands on wind-tunnel model construction under cryogenic conditions	Work start: mid-1979; material selection completed	Dornier/MBB*	Work financed by TG-ETW and BMFT
5 Development of selfcorrecting tunnel walls for 3-dim. throats	Work start: 1979, 2-dim. prelim. work concluded	TU* Berlin ILR*/DFVLR	ILR portion financed by BMFT
6 Instrumentation of ETW wind-tunnel models	Work start: 1979	MBB	Work financed by BMFT
7 Study on mechanism for fast maneuvrability of wind-tunnel models	Work start: end of 1979	MBB	Work financed by BMFT
8 Fundamental study for construction and testing of elastic and dynamically similar models	Work start: end of 1979	MBB	Work financed by BMFT

* BMFT = Bundesministerium fuer Forschung und Technologie = Federal Ministry for Research and Technology

VFW = Vereinigte Flugtechnische Werke = United aeronautical works

MBB = expansion unknown

grouped as follows:

- confirmation of the results of numerical calculations,
- basic experiments (cone, level plate, wing profile, wall temperature effects),

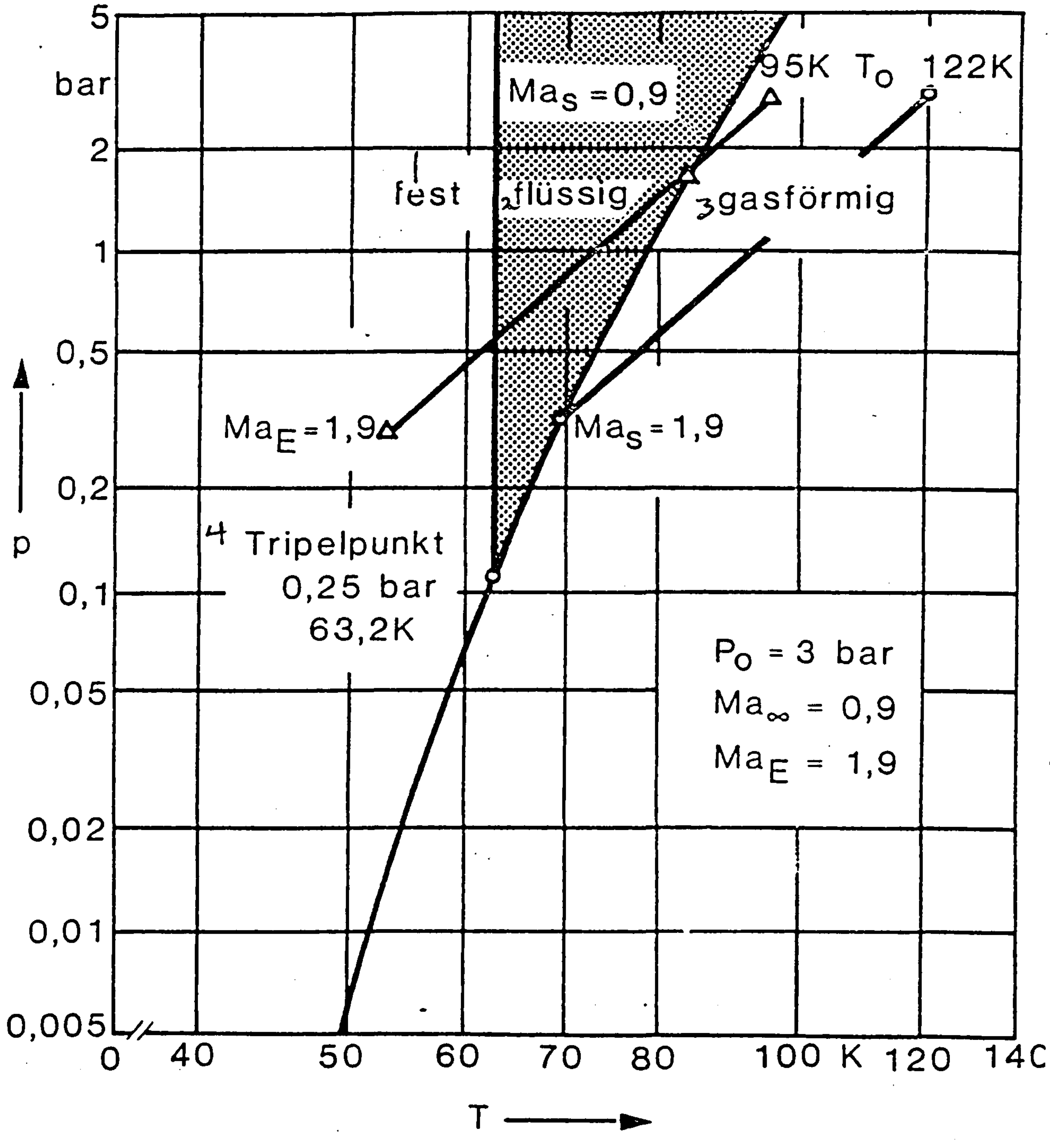
- configuration studies
- "pure" Reynolds number effects (without Mach number and pressure level effects),
- rendering flow visible and measurement methods,
- wind-tunnel calibration.

We already briefly touched on condensation phenomena. The lower temperature limit at which a cryogenic wind-tunnel can be operated results from

- attainment of the saturation limit at the model site or even in free flow,
- the possible occurrence of real-gas effects, i.e., departures of the pressure ratio during the compression shock or during isentropic expansion, from the ideal-gas conditions. These effects are fairly small up to close to the saturation limit, but increase very steeply in the supersaturation domain.

Figure 15 (page 22) shows the phase diagram for nitrogen. If it is absolutely necessary to avoid a phase transition, then according to the conditions indicated, the ETW must be operated at a cavity temperature of 122K. With isentropic expansion, a Mach number of 1.9 can then be attained at the model, just at the phase limit between gaseous and liquid N_2. If the cavity temperature is lowered to 95K, for instance, the isentropic line crosses the liquid phase and ends in the solid domain, where condensation effects will distort the course of the expansion. However, under certain conditions a condensation delay will occur, whose intentional utilization can readily lead to an expansion of the operating range of the Reynolds number. Relevant research efforts are underway.

As already mentioned, the high pressure stress places stringent demands on model construction. Costs and time requirements for model construction are considerably higher than for conventional wind-tunnels. The measurement technology also poses new problems.



KEY 1 Solid 2 liquid 3 gaseous 4 Triple point

Figure 13 Isentropic expansion in the phase diagram for nitrogen

Thus the measurement error at pressure holes increases

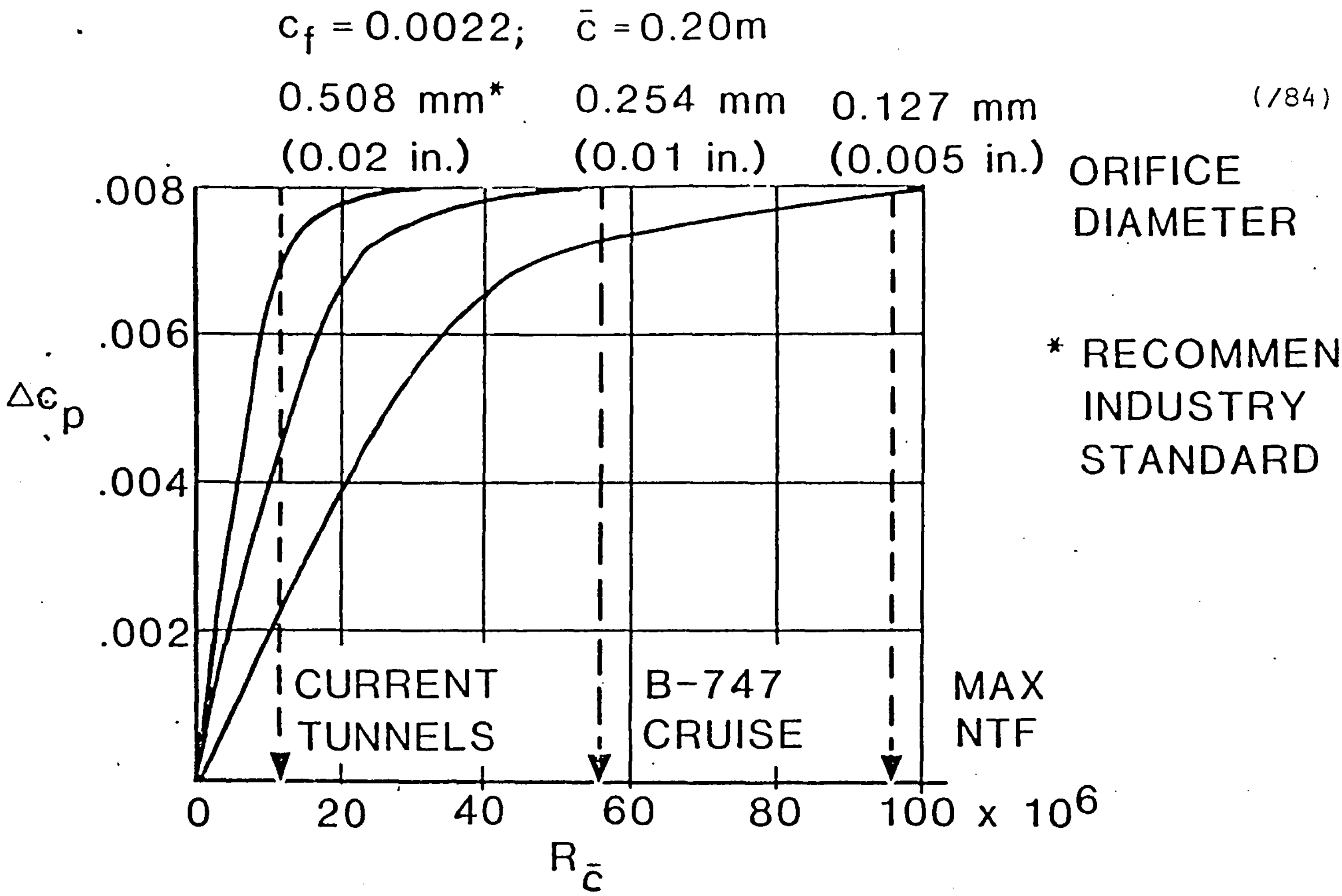


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Figure 16 Measurement error at pressure holes as a function of the Reynolds number and hole diameter

considerably as a function of the Reynolds number, as shown in Figure 16, above. The values shown apply to "perfect" holes. If even minute burrs exist, the error increases by factors and even this all the steeper, the larger the Reynolds number is. In addition, the values shown in Figure 16 are valid only to a ratio of hole diameter to displacement thickness of approximately 4. However, at the leading edge this value may be of the order of magnitude of 100, which makes severe distortions of the measurement results possible. Investigations are underway at NASA-Langley to clarify these phenomena.

Unstationary thermodynamic processes during cooldown of the wind-tunnel and the model also deserve special consideration.

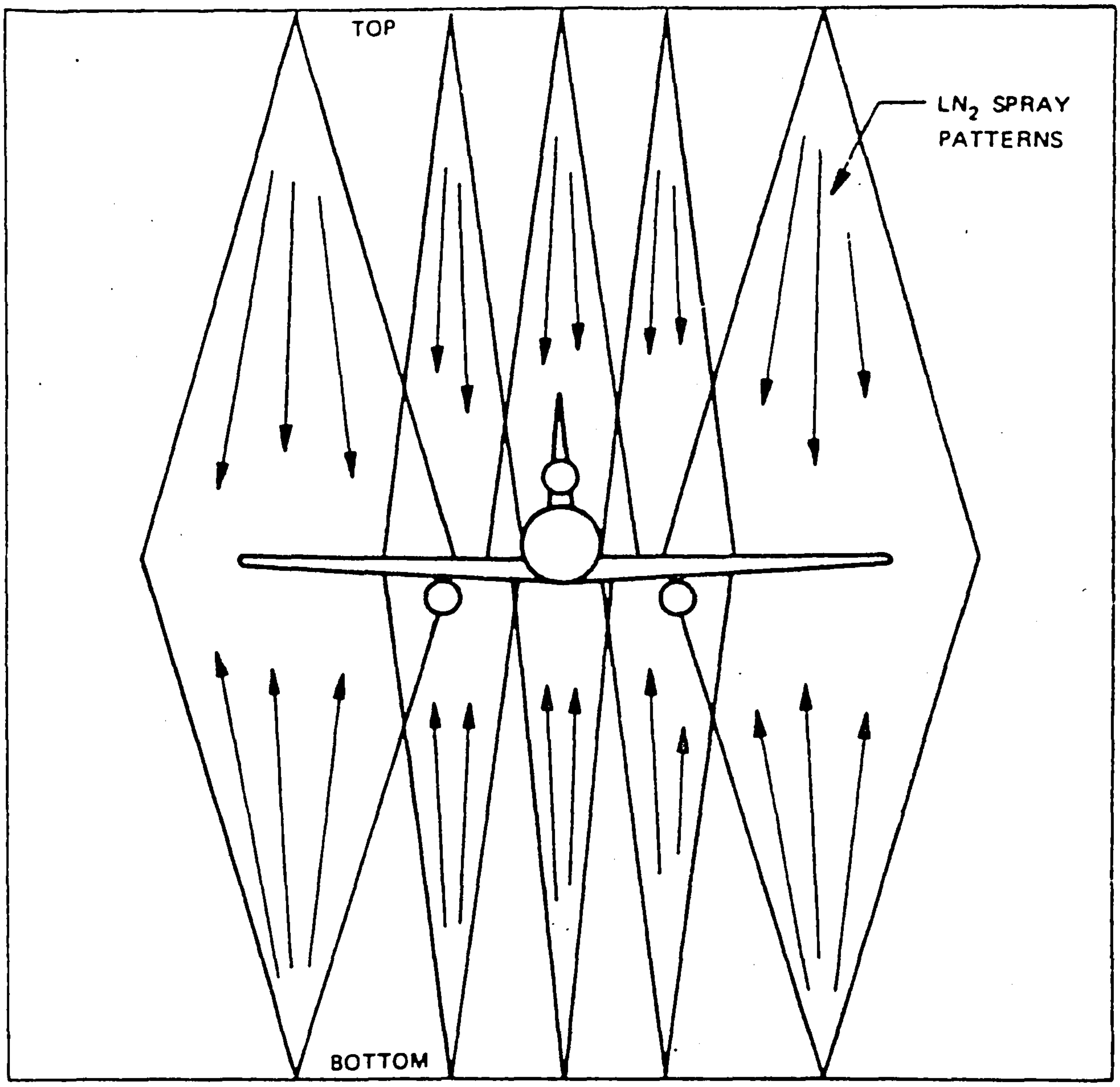

Figure 17 Pre-cooling of the model by nitrogen spraying

Here, direct cooling of the model by spraying can be worthwhile (Figure 17, above).

It must also be considered that the design of the rear strut, in conventional wind-tunnels (at low Reynolds numbers) is only slightly less important (since the boundary layer is too thick anyway) than during the simulation with true Reynolds numbers, where especially high requirements are placed on the rear strut /63 design and the required corrections.

Research and development for the design and construction of internal balances - which must be able to reproducibly and precisely measure large forces over a wide temperature range - is equally important. The problems with wire strain gauge balances at a temperature of approximately 100K are these:

- embrittlement of steel and changes in the E-module and the tensile strength,
- significant changes in the proportionality factor of the wire strain gauge and the apparent strain
- normal solder turns to powder
- synthetic adhesives and wiring embrittle.

It is important to obtain a suitable temperature correction for the coefficients of the calibration matrix and to insure adequate long-term stability. The possibilities exist for building the balances with or without temperature regulation (in the latter case the effects are compensated for by using a microprocessor).

The high costs associated with the operation of such a wind-tunnel make a detailed analysis and planning of the cycling time within the measurements program necessary. A special lock is necessary for model exchange and model adjustments, as well as a model climate chamber, which is shown in Figure 18 (pagr 26).

Finally I want to mention that due to the toxicity of nitrogen (indirect: by decreasing the air's oxygen content), special studies become necessary, to see how the cloud of eliminated nitrogen becomes distributed over the surrounding area, especially of course at low wind velocities or under inversion conditions.

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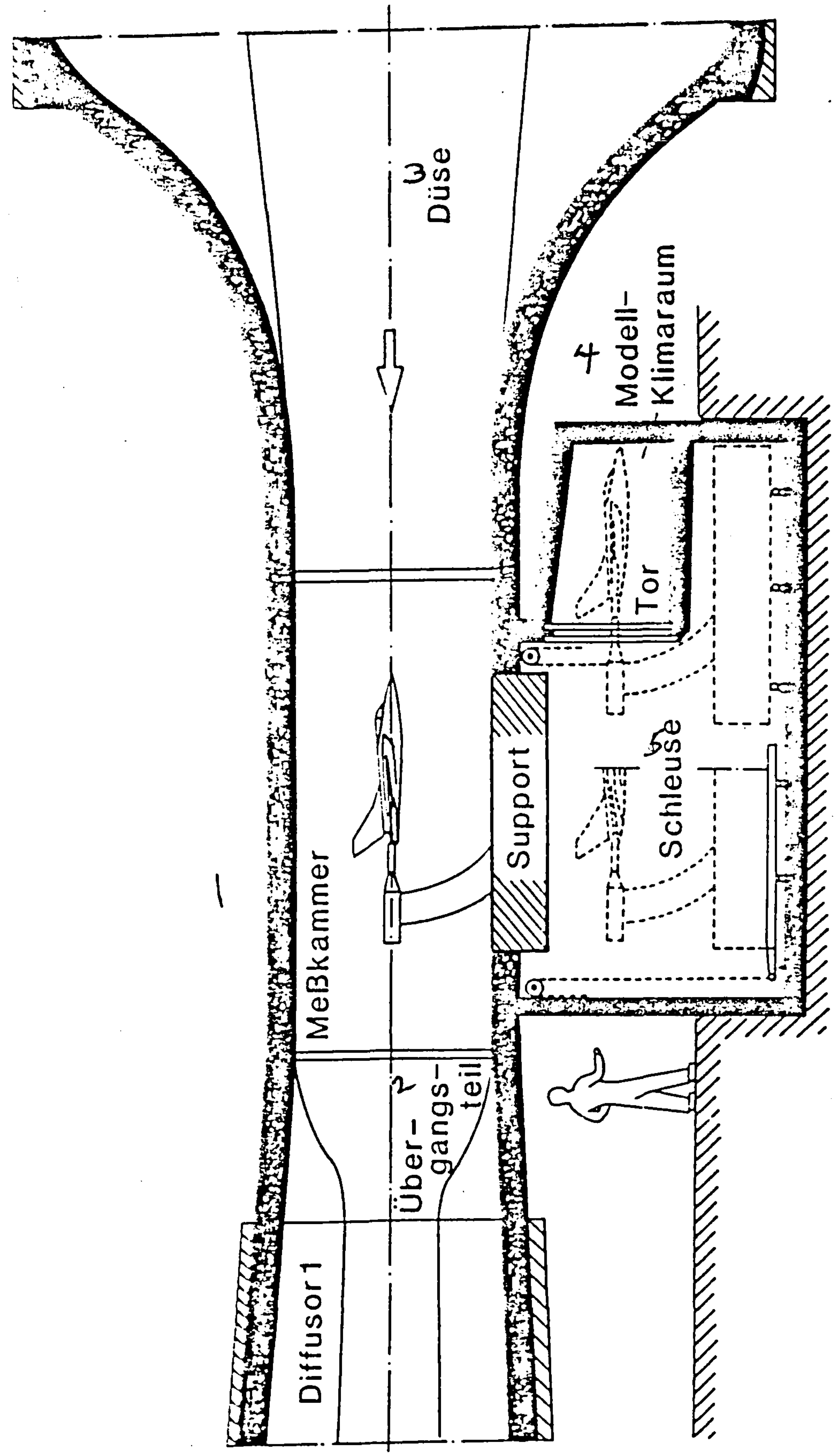
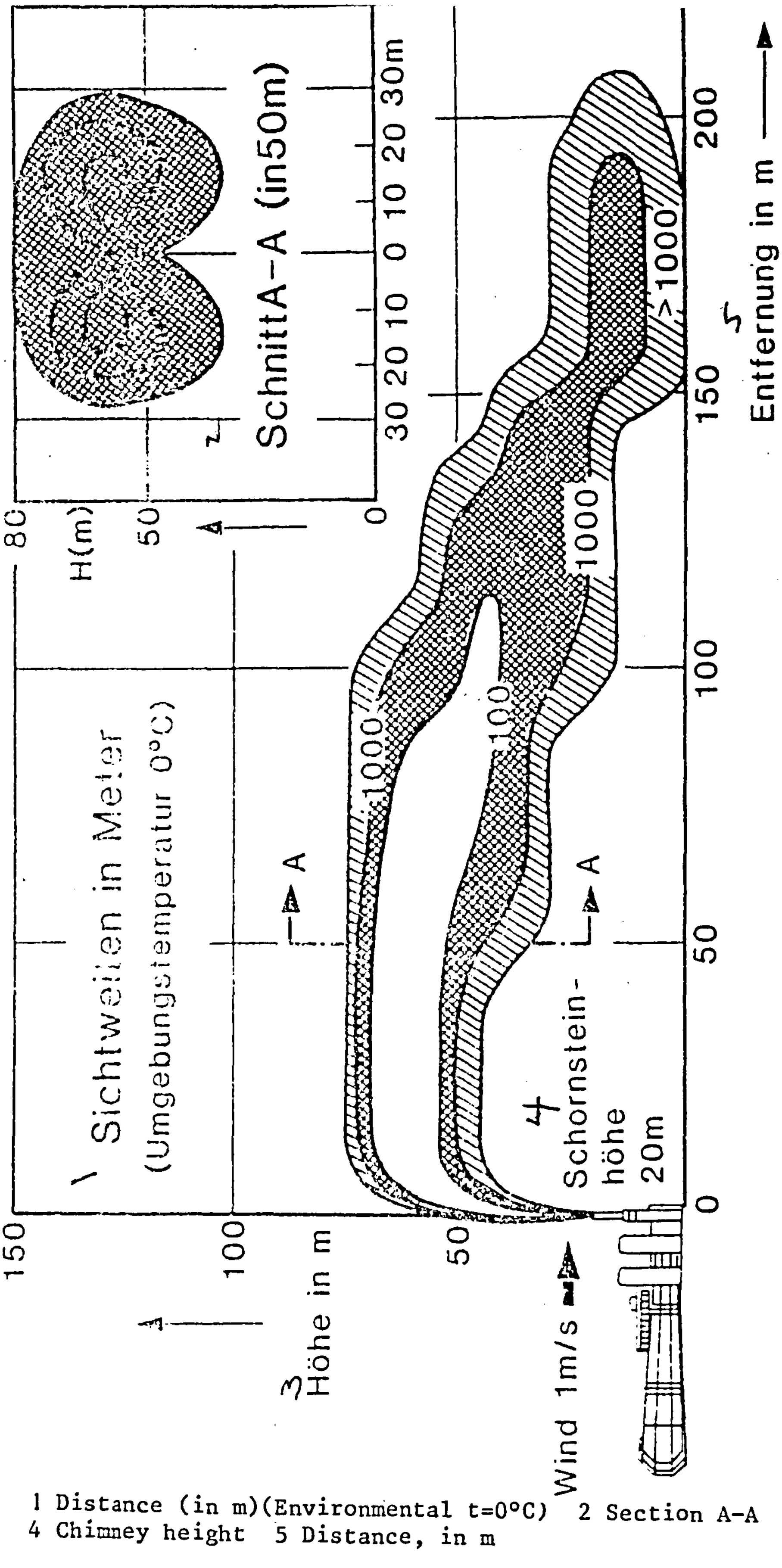


KEY 1 Measurements chamber 2 Transition portion 3 Nozzle 4 Model climate chamber 5 Lock

Figure 18 KKK throat area



KEY 1 Distance (in m)(Environmental t=0°C) 2 Section A-A 3 Height, m
4 Chimney height 5 Distance, in m

Figure 19

Figure 19 (page 27) shows the results of such a study.

4 SUMMARIZING EVALUATION AND RELATION TO NUMERICAL AERODYNAMICS

The question of whether the expected improvements in measurement results at very high Reynolds numbers justify the enormous expense and effort related to the construction and operation of a cryogenic wind-tunnel of the order of magnitude of the ETW must be allowed.

Personally, I doubt - and I can supply the reasons for it - that this tool will significantly increase our knowledge of the fundamental phenomena of the physics of fluids.

Obviously, matters are completely different from the point of view of project aerodynamics. Here the cost/effectiveness ratio of aerodynamic technology work must be calculated. Determinations for civilian transport aircraft (whose premises and peculiarities I can not discusee here) show that an improvement in the lift/drag ratio - and hence, of fuel consumption - by 1% justifies an increase in the overall research and development effort by up to 50%.

Other determinations for civilian aircraft lead to the following results: success in increasing the design c_A by 10 to 15% lowers fuel consumption by 6-7% and direct operating costs by 2%, which for a fleet of 600 aircraft would lead to a decrease in the life-cycle costs of approximately 2.5 billion DM over 15 years. For combat aircraft, a decrease in the combat weight of 5% would lower fuel consumption by 7%, which for a fleet of 600 combat aircraft would lower life-cycle costs by approximately 1.2 billion DM.

Even though such figures should be digested with great caution, they do indicate the order of magnitude of the possible improvements and allow an estimation of the level to which investments to attain aerodynamic improvements are reasonable.

It has often been stated that long-term, the availability of large and extremely fast parallel computers - such as that planned for the NAS [National Aerodynamic Simulator] for NASA-Ames - will make simulations in wind-tunnels superfluous. I am firmly convinced that this is not going to be the case, but rather, that the measurements now possible at true Reynolds numbers and especially, the separation possibility of effects due to viscosity, compressibility and aeroelasticity due to cryogenic wind-tunnels, will be a possible and indispensable aid in the development of numerical calculation procedures and their evaluation. /65

If wind-tunnel results suffer from limitations in Mach and Reynolds numbers, wall effects, strut interferences, aeroelastic deformation and real-gas effects, numerical procedures are limited by simplifying assumptions regarding the physics of flow (for instance, turbulence models). Especially in the treatment of flow processes at large Reynolds numbers, the difficulties and the effort for an acceptable model description of the turbulence processes increase drastically, due to the increasing fine structure of the vortexes, especially in the boundary layer.

An analysis of the investment necessary for numerical procedures shows that the computational effort increases at least with the second or third power of the Reynolds number. The rigorous treatment of project-aerodynamics problems by numerical simulation would require an increase in memory size and calculation speed by factors of order of magnitude 10^5, compared to today's efficient mainframe computers. It is not likely that such computers will be available in the foreseeable future; even the NAS would be too small, by two or three orders of magnitude, in that case. It must also be considered that in regard to their development time, the preparation and execution time of simulation projects, such computation centers are quite similar to wind-tunnel facilities. None of which changes the fact that great efforts are necessary in the area of numerical aerodynamics. Mr. Wengle just reported on the thereby expanded possibilities, and Mr. Sacher will return later to this subject, in greater detail.

In the context of design aerodynamics, numerical flow calculations will in future be used mainly for /66

- optimization and definition of the configuration variations to be tested in the wind-tunnel,
- complex optimization and design programs for the total aircraft, and
- substantially refined corrections of wind-tunnel results.

The results obtained by means of cryogenic wind-tunnels at high Reynolds numbers are important to theoretical aerodynamics in order to

- confirm algorithms and results of numerical flow mechanics
- noticeably improve scaling procedures for the extrapolation of results from small wind-tunnels to large Reynolds numbers, in order to
- expand data banks on turbulence models to high Reynolds numbers.

Conversely, theoretical aerodynamics can make an essential and even indispensable contribution to cryogenic wind-tunnel technology, by a precise determination of wind-tunnel interference effects. Without them, in turn, it will not be possible to confirm numerically obtained results, which are calculated for undisturbed flows. This is particularly important in the domain of transonic flow, which is exceedingly sensitive to even small disturbances in the geometry and/or the flow parameters.

Allow me to conclude with the statement that I am firmly convinced that the new cryogenic wind-tunnel for large Reynolds number, in conjunction with the next generation of parallel computers and the associated development of numerical aerodynamics, will be able provide us with decisive progress in aircraft design at the threshold of the Twentyfirst century.

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