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# TRANSONIC CRYOGENIC TEST SECTION FOR THE GÖTTINGEN TUBE FACILITY

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16. Abstract

The design of modern aircraft requires the solution of problems related to transonic flow at high Reynolds numbers. To investigate these problems experimentally, it is proposed to extend the Ludwieg tube facility in Göttingen by adding a transonic cryogenic test section. After stating the requirements for such a test section, the technical concept is briefly explained and a preliminary estimate of the costs is given.

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## LIST OF ABBREVIATIONS

| | |
|---|---|
| NTF | National Transonic Facility |
| DFVLR | Deutsche Forschung- und Versuchsanstalt für Luft- und Raumfahrt (German Aerospace Research Establishment) |
| ETW | European Transonic Wind Tunnel |

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# TRANSONIC CRYOGENIC TEST SECTION FOR THE GÖTTINGEN TUBE FACILITY

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## 1. Introduction /5*

Economy and productivity of modern aircraft are highly dependent upon the solution of aerodynamic problems that can be collectively arranged under the heading "Transonic Flow Phenomena at High Reynolds Numbers." The necessity of constructing wind tunnels necessary to solve these problems has been recognized for quite some time by all countries involved in the science of flight and aircraft construction and is manifested in the construction of the National Transonic Facility (NTF) in the USA and the planning of the European Transonic Wind Tunnel (ETW). As the design data of both large tunnels intended for aircraft development -- $Re_{max} = 120 \cdot 10^6$ for NTF and $Re_{max} = 50 \cdot 10^6$ for ETW -- show, there are different opinions concerning the Reynolds number range to be covered.

## 2. Requirements on a Research Tunnel

Within the DFVLR Institute for Experimental Fluid Mechanics is working on a solution of partial problems from the complex area of transonics. The facilities TKG, TWB and HKG, which belong to the wind tunnel division, are currently at our disposal to work on these problems experimentally. These facilities are unsuitable for longer term research programs with expanded experimental investigations because of cost considerations -- this also applies to the ETW. However, a more severe drawback is that they do not fulfill the necessary requirements for successful research in the areas cited, because the Reynolds numbers attainable are too low. For this reason, several suggestions for constructing a transonic cryogenic wind tunnel in the DFVLR have been made in recent years, e.g. [1].

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

In addition to research problems, the plans foresaw making series measurements on total models. This increases the dimensions and expenditure of the apparatus and raises costs.

-- The tunnel we propose is supposed to primarily serve the purpose of examining physical flow phenomena, allowing lower construction costs. /6

-- In this regard different wind tunnel principles were examined with special emphasis on their utility. The result was that a tube tunnel is best suited for fulfilling the requirements briefly mentioned below. It is therefore proposed to expand the Göttingen tube facilities accordingly.

Recent advances in the design of transport aircraft were obtained by the use of transonic airfoils. One can assume that the continued development of such airfoils, e.g. in conjunction with an active boundary layer control, will also in the future allow considerable improvements in flight performance. For that reason the tunnel should be designed in such a way that airfoils and the flow phenomena appearing upon them can be investigated under realistic conditions. This requirement dominates to a great degree the design of the tunnel.

## 2.1. Reynolds Number Range

The flow around transonic airfoils in all flow ranges can be highly dependent upon the Reynolds number [2]. This is represented in Figs. 1 and 2 by the example of lift and the aerodynamic performance parameter in Breguet's cruising distance equation, $(c_A/c_W) \cdot Ma$. In addition to the great Reynolds number dependency in the whole investigated range of $Re = 2 \cdot 10^6$ to $Re = 45 \cdot 10^6$, it is noteworthy that the curves give no clue whatsoever regarding the behavior of the aerodynamic parameters at the Reynolds numbers of $Re > 45 \cdot 10^6$.*

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*$Re = 45 \cdot 10^6$ is the maximum attainable Reynolds number in the [footnote cont'd next page]

The results leave the question unanswered whether the exploitation of transonic potential during aircraft development requires wind tunnel experiments at flight Reynolds numbers, or if it is /7 possible to achieve this by extrapolating the results, beginning with an unknown upper Reynolds number limit. The latter would require knowledge of the flow phenomena into the range of the flight Reynolds number. In conjunction with the results mentioned above, it can be deduced:

-- that Reynolds numbers of $Re > 45 \cdot 10^6$ must be achieved to investigate the flow phenomena that determine the Reynolds number sensitivity of a configuration. For a research tunnel with its low dimensions this would mean that it must be operated cryogenically. If one applies a minimum airfoild depth of $\ell_{min} = 150$ mm, we would like to mention that the maximum attainable Reynolds number in this tunnel will be $Re = 70 \cdot 10^6$. This covers a Reynolds number range that in many cases includes the flight Reynolds number (see Fig. 3).

In such a wind tunnel, investigations on components can be conducted where the basic flow phenomena of a total configuration occur. This is demonstrated by the example of an aircraft with wings of high aspect ratio, which also determines the geometry of the tunnel:

-- The flow around a wing of high aspect ratio depends largely upon the geometry of the basic airfoil. Therefore, the Reynolds number behavior of the configuration can first be studied on the basic airfoil.

-- Flow phenomena that depend primarily on the Reynolds number and that also determine the Reynolds number sensitivity of an airfoil are, for example, the shock boundary layer

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footnote from p. 2, cont'd:

0.3 m transonic cryogenic tunnel of the NASA facility in Langley. The measurements were conducted as a cooperative effort of the DFVLR/AVA. See bibliographic reference [3].

interaction and the behavior of the boundary layer when exposed to sustained rear adverse pressure gradients. These phenomena, including separation effects, can be investigated on basic models attached to the lower wall of the test section at Reynolds numbers exceeding the ones in regular airfoil tests.

-- In the future, investigations with respect to boundary layer control will be paid much more attention. These tests can be conducted on airfoil and basic models at realistic Reynolds numbers. /8

The tests planned in the research tunnel are briefly compiled in Table 1. This table also contains more, primarily secondary requirements.

### 2.2. Main Dimensions

We are assuming that the minimum dimensions of the test section are determined by the requirements for airfoil measurements. The geometry determined in this manner will also suffice for the other requirements in Table 1.

For reasons of technical measurement resolution, manufacturing accuracy and surface quality, and especially with regard to experiments concerning boundary layer control and the related machining of slots, we consider a minimum airfoil chord of $\ell$ = 150 mm necessary for testing airfoils.

-- Based on experimental values for the ratio of tunnel height to airfoil chord $H/\ell = 3$ and tunnel width to airfoil chord of $B/\ell = 2$, a minimum chord of $\ell_{min}$ = 150 mm leads to a test section cross section of B x H = 300 x 450 mm.

The naturally good flow quality in a Ludwieg tube is somewhat reduced by the boundary layer in the storage tube, the thickness of which increases with the tube Mach number. By using a nozzle with a contraction ratio of $K > 3$ the Mach number in the storage tube remains below $Ma_R = 0.2$; this guarantees a good flow quality. Thus, one obtains a tube diameter of approximately $D_R = 0.8$ m. The requirement for a measurement time of about one second demands a tube length of $L_R = 130$ m. Assuming the volume of the downstream tank to be $V_K \approx 2 \cdot V_R \approx 130\ m^3$, the main dimensions of the tunnel are established.

## 3. Technical Concept

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The technical concept is represented in Fig. 4. It differs from the supersonic tunnels in Göttingen primarily by the arrangement of the fast acting valve which is located behind the transonic test section and serves simultaneously as a diffuser for adjusting the Mach number. With the exception of the tank, which can be insulated on the inside, all parts are constructed of cryogenically suitable material. The liquid nitrogen is stored in a tank provided by the supplier. Part of the gas retrieved in the tank during a run can be pumped back into the tube by means of a compressor, and the cold losses can be replaced by using liquid nitrogen.

The most important performance data of the wind tunnel are compiled in Fig. 4. In addition to the model size, the Mach number and the stagnation temperature, the maximum Reynolds number is determined by the highest possible stagnation pressure. The stagnation pressure was limited to a value of $p_{omax} = 10$ bar according to an estimation of model deformations. If one assumes that the stagnation temperature is chosen in such a way that at a local Mach number of $Ma_M = 1.4$ saturation of the nitrogen is just reached, then the upper curve of the Reynolds number Mach number diagram depicted in Fig. 3 is obtained. When comparing this curve with those of the ETW and KKK it should be noted that for these tunnels, generally used for testing complete models, a Reynolds number reference length of $0.1 \cdot \sqrt{S_K}$ was utilized.

As a testing site the available tube facility of the Research Center in Göttingen offers special advantages, as many aggregates and measurement devices can be shared. Figure 5 shows a floor plan. It depicts the most advantageous solution from an operating standpoint, but it requires constructing an annex between houses 30 and 19, which is much preferred to maintaining the tunnel in house 30.

## 4. Costs /10

The following cost estimate for commercially available parts such as pipe, tank, etc., is based upon suggested retail price offers of relevant firms. Part costs that could only be calculated with the help of detailed plans are estimated by using older plans as a scale. The final investment sum will amount to 2.6 million German Marks. (Approximately $1,083,333.00. One US dollar equals 2.40 West German Marks, March, 1983).

### Cost Itemizing

| | TDM (thousands of marks) |
|---|---|
| Pipe (including insulation) | 320 |
| Gate valve | 350 |
| Nozzle | 100 |
| Test section | 350 |
| Fast-closing valve | 450 |
| Tank | 100 |
| Control, safety devices | 280 |
| Construction | 450 |
| Engineering expenses | 200 |
| Total investment costs | 2,600 TDM |

Table 2 is a labor and cost development plan.

The operating expenses of the wind tunnel depend greatly upon the portion of cryogenic operating time, as primarily the expenses for liquid nitrogen become noticeable. These expenses are estimated at DM 150,000 (approximately $62,500) per annum. The expenditures can be reduced considerably by installing a refrigerator for recooling the used nitrogen.

## 5. Summary

The economy and productivity of modern aircraft are highly dependent upon the solution of aerodynamic problems in transonic flow at high Reynolds numbers. Since basic problems are /11 currently largely unsolved, intensive research of these flow phenomena is necessary. As a test conducted in the summer of 1981 by the DFVLR in cooperation with NASA in the 0.3-m cryogenic wind tunnel at Langley demonstrated, transcribing experimental results from wind tunnels with too low Reynolds numbers to flight conditions is still not assured. For that reason, an experimental facility allowing basic examinations at flight Reynolds numbers at reasonable cost is necessary. At current levels of knowledge, this can only be economically feasible with cryogenic technology. The principle of the tube tunnel guarantees that the investigation can be conducted at the best possible flow quality.

With the planned facility the DFVLR is creating a unique research tool for testing the most important current aerodynamic problems of flight technology, the solution of which is required for sensible industrial utilization of the ETW.

# REFERENCES

1. Ludwieg, H. and P. Krogmann, "The transonic cryogenic wind tunnel project of the German Aerospace Research Establishment," DFVLR Report IB 251-78 A 39, Göttingen, West Germany, 1978.

2. Stanewsky, E., Wechselwirkung zwischen der reibungsfreien Aussenströmung und der Grenzschicht an transsonischen Profilen [Interaction between the outer inviscid flow and the boundary layer on transonic airfoils], Thesis, Technical University of Berlin, D83, 1981.

3. Ray, E., C. Johnson and E. Stanewsky, NASA/DFVLR Advanced Technology Airfoil Program, Tests in the 0.3 meter cryogenic tunnel with the airfoil CAST 10-2/DOA 2, August, 1981. To be published as a NASA report.

TABLE 1. PROBLEM AREA AND REQUIREMENTS ON THE RESEARCH TUNNEL. /13

| Problem Area | Requirements |
|---|---|
| 1. Wings with high aspect ratio<br>- Airfoil tests<br>- Thrust boundary layer trailing edge interference<br>- Boundary layer interaction (removal by suction, heat transfer) | Test section cross section: 0.3 x 0.45 $m^2$<br>Schlieren window, floor mountable model<br>Probe drive<br>Auxiliary mechanisms |
| 2. Wings with small aspect ratio | Half model technology |
| 3. Missiles<br>- Influence of Mach and Reynolds number upon asymmetric vortex shedding | Rectangular cross section<br>Drive mechanisms for flow field measurements |
| 4. Flow quality | The investigation of its influence requires high flow quality. Therefore: contraction ratio tube/ test section cross section 3:1 |
| 5. Wall interference | Exchangeable wind tunnel walls. Boundary layer suction on the side walls |
| 6. Measuring technique<br>- Boundary layer and flow field measurements (average)<br>- Measurement of unsteady phenomena<br>- Development of short duration measurement methods | Measurement time 1 s<br>Storage tube length 130 m |

## TABLE 2. WORK AND COST DEVELOPMENT PLAN

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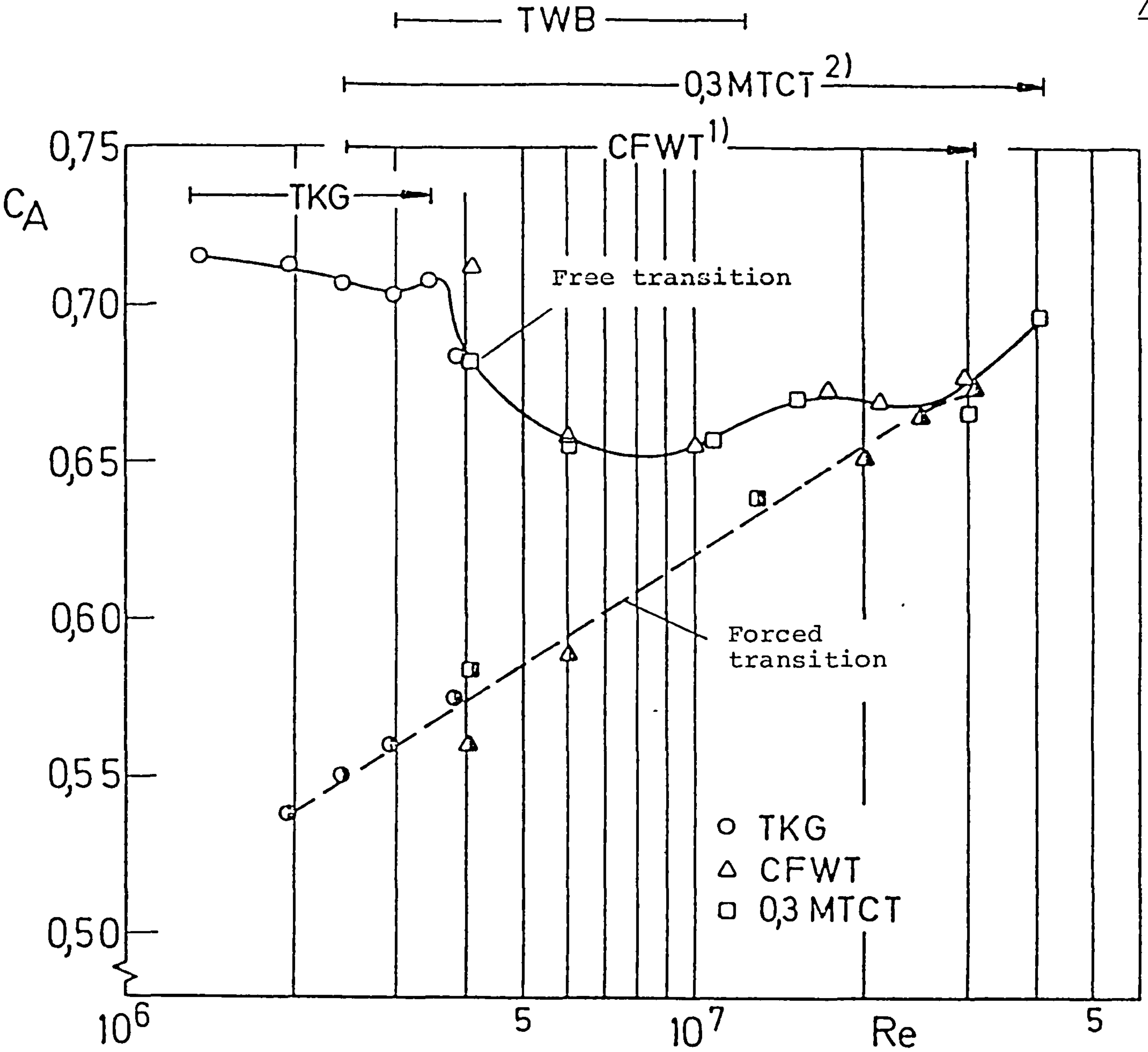
| Work Phase | 1st Year | | | | | | 2nd Year | | | | | | 3rd Year | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1. Total concept and final specification | — | — | — | — | | | | | | | | | | | | | | |
| 2. Detailed design proposals, issuance of work orders | | | — | — | — | — | — | — | — | — | | | | | | | | |
| 3. Component manufacture | | | | | | | | | | | | | | | | | | |
| 3.1 Storage tube and tank | | | | — | — | — | — | — | | | | | | | | | | |
| 3.2 Test section with nozzle, diffuser and starting valve | | | | | | | — | — | — | — | — | — | — | — | | | | |
| 3.3 $LN_2$ supply and exhaust system | | | | | | | | | — | — | — | — | | | | | | |
| 3.4 Control system | | | | | | | | | — | — | — | — | — | — | | | | |
| 4. Construction | | | | | | | | | | | | | | | | | | |
| 4.1 Foundation and alteration work | | | | | — | — | — | — | | | | | | | | | | |
| 4.2 Storage tube and tank | | | | | | | | — | — | — | — | | | | | | | |
| 4.3 $LN_2$-System | | | | | | | | | | | — | — | — | — | | | | |
| 4.4 Test section | | | | | | | | | | | | — | — | — | — | — | | |
| 4.5 Insulation | | | | | | | | | | | | — | — | — | — | — | — | |
| 4.6 Extension of data acquisition system | | | | | | | | | | — | — | — | — | — | — | — | — | |
| 5. Functional testing, alterations, improvements | | | | | | | | | | | | | | | | | | — |

| Investment (thousands of German Marks) | 300 | 1.300 | 1.000 |
|---|---|---|---|



1) Lockheed Compressible Flow Wind Tunnel

2) 0.3 Meter Transonic Cryogenic Tunnel NASA-Langley

Fig. 1. Reynolds number dependency of the lift and regions of different wind tunnels. Airfoil CAST 10-2/DOA 2. Ma = 0.765; α = 2°.

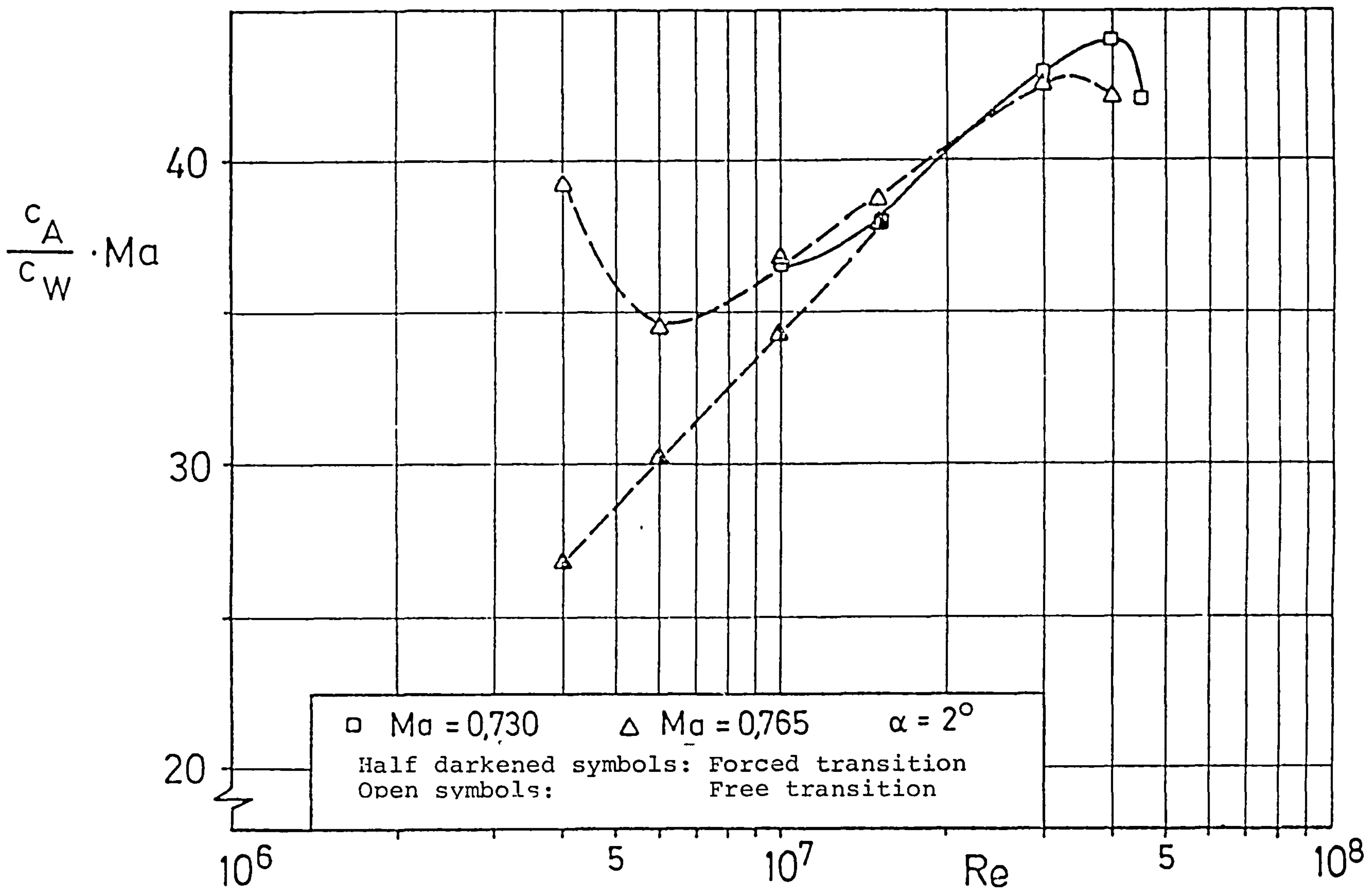


Fig. 2. Aerodynamic performance parameter $(c_A/c_W) \cdot Ma$. Measurements in the 0.3 meter TCT of NASA, Langley.

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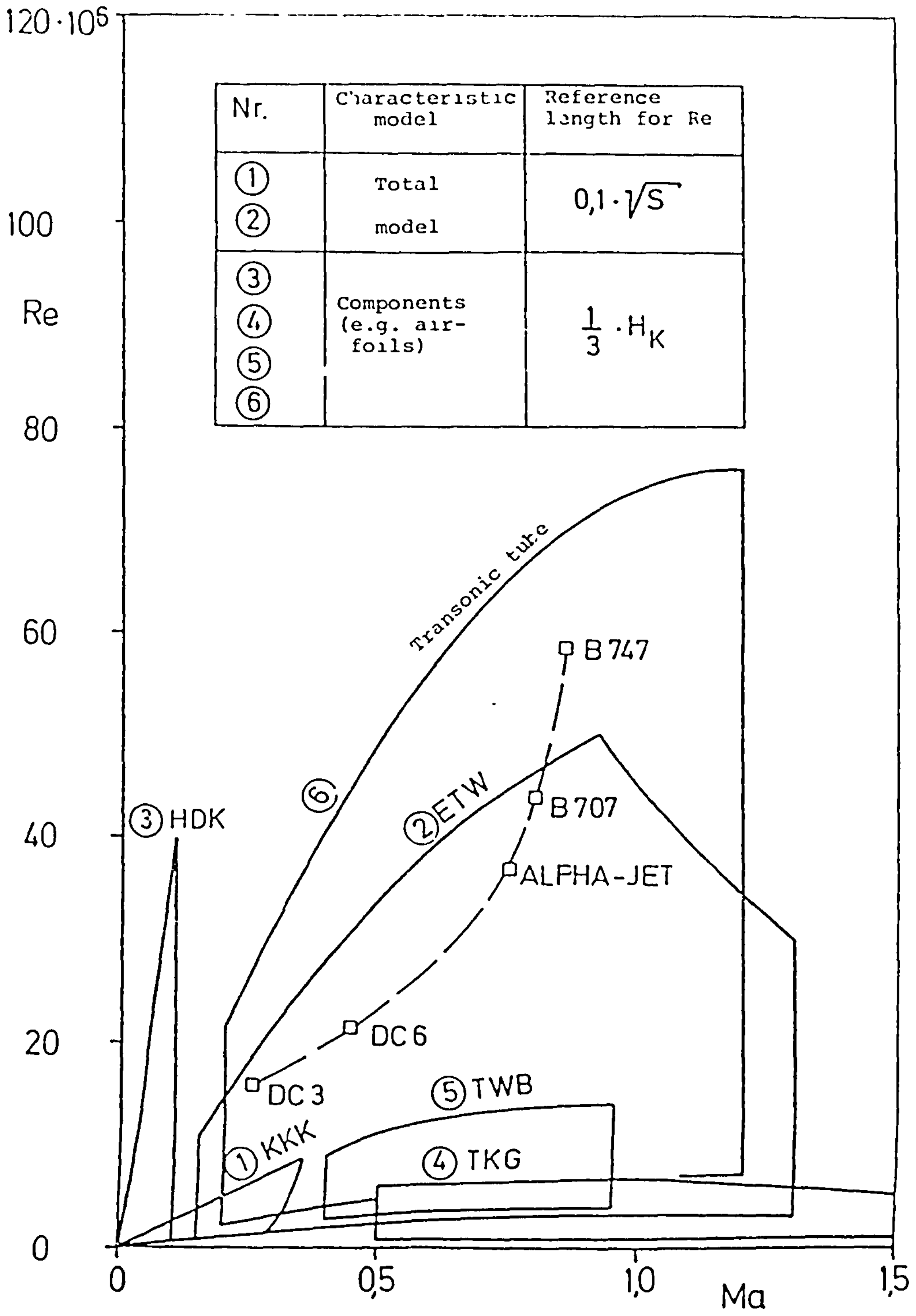

| Nr. | Characteristic model | Reference length for Re |
|---|---|---|
| ①<br>② | Total model | $0,1\cdot\sqrt{S}$ |
| ③<br>④<br>⑤<br>⑥ | Components (e.g. airfoils) | $\frac{1}{3}\cdot H_K$ |

Fig. 3. Mach number, Reynolds number range of some DFVLR wind tunnels.

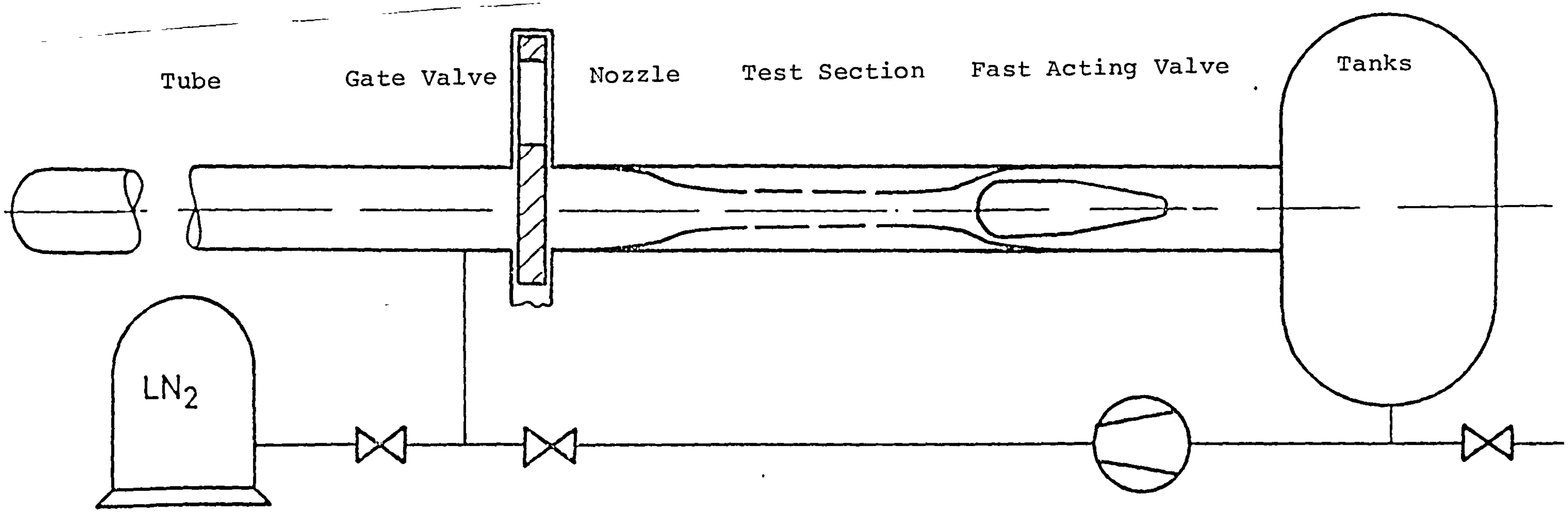

Fig. 4. Technical concept.

| | | |
|---|---|---|
| Tube | Diameter | 800 mm |
| | Length | 130 m |
| | Nominal pressure | 16 bar |
| Gate Valve | Cross section | 0.3 x 0.45 $m^2$ |
| | Model depth | 0.15 m |
| Tank | Volume | 130 $m^3$ |
| | Nominal pressure | 6 bar |

Characteristic data:

| | |
|---|---|
| Maximum stagnation pressure | 10 bar |
| Temperature range | 90-300 K |
| Mach number range | 0.2-1.2 |
| Maximum Reynolds number | $70 \cdot 10^6$ |
| Measurement time | 0.7-1.1 s |

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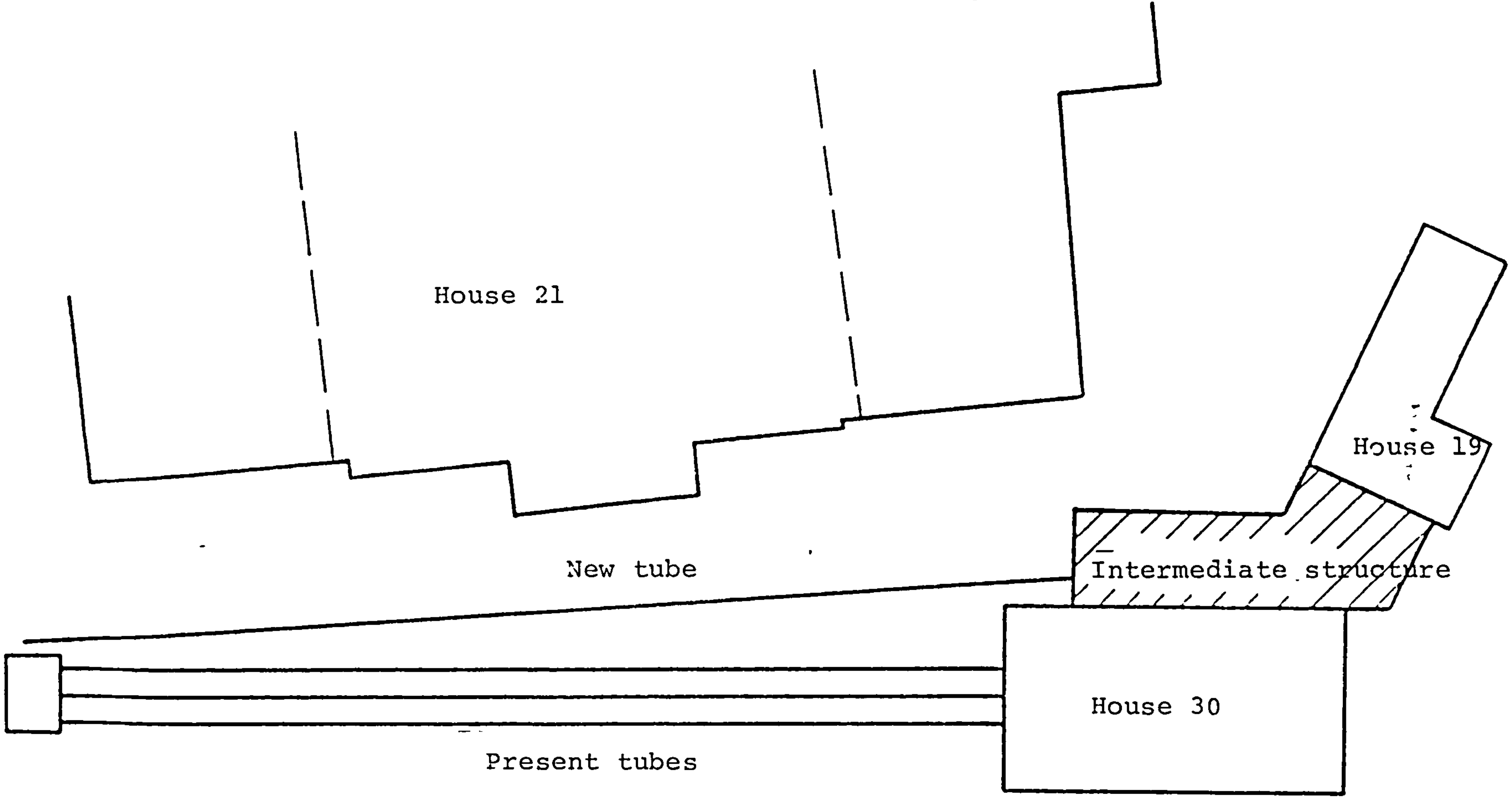

Fig. 5. Location diagram, scale 1:500.

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