ICAS VON KARMAN LECTURE 1994

THE EUROPEAN TRANSONIC WINDTUNNEL ETW
- A BREAK-THROUGH IN INTERNATIONAL TEST FACILITIES -

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Preface

All those who were involved in the realization of the European Transonic Windtunnel - ETW - are extremely happy with the selection of the Von Karman Award for International Cooperation by the International Council of the Aeronautical Sciences for the year 1994.

It is the year in which the tunnel reaches the initial operation. It is now more than 20 years since the need for this facility was identified by an international AGARD Working Group under the Chairmanship of the late Dr. D. Küchemann.

The ICAS decided in 1980 to institute this Award, to be accompanied by a special lecture during its biannual meetings. The first Award was given in 1982. Indeed, the distinction of ICAS is that it promotes international cooperation in aeronautics.

ETW is very honored to have been selected for this year's Award, particularly since the name of von Karman, the founder of both ICAS and AGARD,is associated with it. Despite many national and political hurdles this facility was realized in his spirit. It will remind us of his inspiring guidance during the many decades of operation to come.

Abstract

After five years for the final design and two and a half years for the construction the European Transonic Windtunnel (ETW) was commissioned in 1993 and entered the initial operation phase mid-1994 as the first large multinational test facility in the field of aeronautical research and technology, open to clients in all continents.

The ETW has a closed aerodynamic circuit and a compressor drive power of about fifty megawatt. Liquid nitrogen is injected into the circuit during operation to reach temperatures down to about ninety degrees Kelvin. The tunnel will be able to reach Reynolds numbers up to about fifty million, thus guaranteeing high flight simulation quality. The ETW is a powerful tool to develop the aerodynamic design of future aircraft challenged by high flight performance, economy and environmental constraints.

Starting from the needs for a high Reynolds number transonic windtunnel in Europe seen in the 1970's years the different phases, the technology steps and the decisions of this multinational European effort between France, Germany, Great Britain and The Netherlands are reviewed.

1. Introduction

In aerodynamics windtunnels are the major source of design data and for new aircraft projects in the hand of the design engineers, they are a cost-effective means of developing advanced aircraft technology guided by great flight safety and high fuel economy.

To meet market demands, to gain acceptance by the airlines and the customers by in particular economical and ecological aircraft, the engineers are challenged to optimize the aerodynamic design, the technology that integrates systems and propulsion as well as new and lighter materials and structures into a configuration of high flight performance.

In the 1970's years the need for large test facilities with high simulation quality, i.e. achieving on scale models Reynolds numbers close to those attained in flight, was seen on the background of an increasing market for large transport aircraft. Requirements for the low speed regime could be fulfilled in Europe by the German-Dutch Windtunnel DNW, the ONERA-F1 in Toulouse and the RAE 5-m-tunnel in Farnborough. For higher speeds even the world's largest transonic tunnel, the

ONERA-S1 in Modane was limited to about 1/3 to 1/5 of the actual flight Reynolds number.

The European Transonic Windtunnel (ETW) aimes at bridging this Reynolds number gap and as such represents a new generation of large windtunnels in Europe. The technology of a liquid nitrogen cooled circuit had to be worked out and applied, along with the appropriate development in components and measuring techniques.

The ETW is also a unique example of a very successful multinational cooperation in the field of aircraft technology on the political and cultural background of increasing European alliance in the last two decades, a perspective that was very early seen in this project.

During the work this became transparent by the way the technical questions were discussed and solved commonly, by the decisions and finally by the ETW institution.

Accordingly, Background/History, Design-Phases and Construction Phase are reported. Design features and performance will be presented shortly along with some initial calibration results.

2. Background/History

In the late 1960's it became more and more obvious that although rapid progress was observed in computerized fluid dynamics experimental aerodynamics should not stop developing. Lack of simulation technique was particularly significant in the case of large transport aircraft with improved propulsion. For the aerodynamicist one of most visible gaps in simulation technique was resulting from the corresponding increase in the flight Reynolds number, the aerodynamics simulation parameter combining the flight velocity, the reference length of the aircraft and the air viscosity.

In the United States this insufficient simulation technique in aerodynamics was responsible for some spectacular errors in the performance prediction for the Lockheed C-141A Starlifter and the Lockheed C-5 A Galaxy. For the Starlifter it was necessary to pre-trim every aircraft by a ballast mass of about 300 kg in the fuselage nose. The flight tests for the Galaxy in turn showed the optimum wing thickness larger than predicted, allowing 16% more volume, hereby enabling a 3 percent lighter structure. The US Airforce spent about 1 billion dollars to strengthen the wings of the Galaxy in order the get sufficient lifetime, a budget that clearly exceeds every cost estimate for a suitable ground test-facility.

Generally, there were two possible ways seen to improve the simulation situation.

The first one was to enlarge the dimensions of the windtunnel test section and to use larger wind tunnel models. This way relies upon available tunnel technique. It is, however, critical from an engineering point of view as well as from the costs which roughly increase with a power of 2.5 and also from the energy consumption that goes up with a power of more than 2.

The second one was to change the thermodynamic conditions. Pressurizing the tunnel enhances linearly the Reynolds number. But this approach is limited by considerations of model strength.

However, if the temperature is decreased (at constant pressure) the viscosity and the velocity of sound decrease and the density increases. The overall effect of cooling is that the Reynolds number increases rapidly whilst the model loads remain the same. Also the power required to drive the tunnel decreases. Thus a pressurized tunnel at very low ("cryogenic") temperatures can provide near-flight Reynolds numbers by virtue of both increased pressure and decreased temperature.

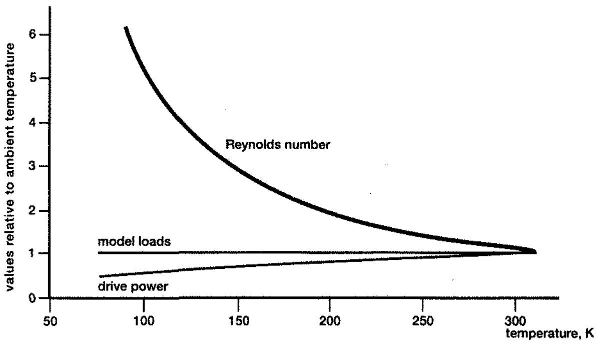

Fig. 1 Reynolds number gain over temperature variation.

A further advantage of the cryogenic concept applied to a pressurized tunnel is that Mach number, Reynolds number and dynamic pressure can each be varied, keeping the others constant so that their effects can be studied independently.

In the early seventies the cryogenic concept was extensively investigated and encouraged by the results of a pilot facilitiy at NASA Langley. The USA decided in 1975 to build the National Transonic Facility (NTF) as a cryogenic wind tunnel with closed circuit, using pure nitrogen atmosphere, cooled down to temperatures approaching condensation limit.

3. International Discussions in Europe

The windtunnel situation in Europe was always compared to the situation in the USA and discussed in due time.

At various meetings of the AGARD Fluid Dynamics Panel the technical requirements of wind tunnel testing were discussed: Paris 1968, Göttingen 1971, etc. The Defence Research Group - DRG - of NATO organized a Seminar at the Institut Franco-Allemand de Saint-Louis, France, near Basel, on "General Problems Relating to Aerodynamic Testing Facilities". At that meeting it was proposed to set up two Ad Hoc Groups, by DRG and AGARD, to deal respectively with the needs and the technical possibilities for future wind tunnel projects.

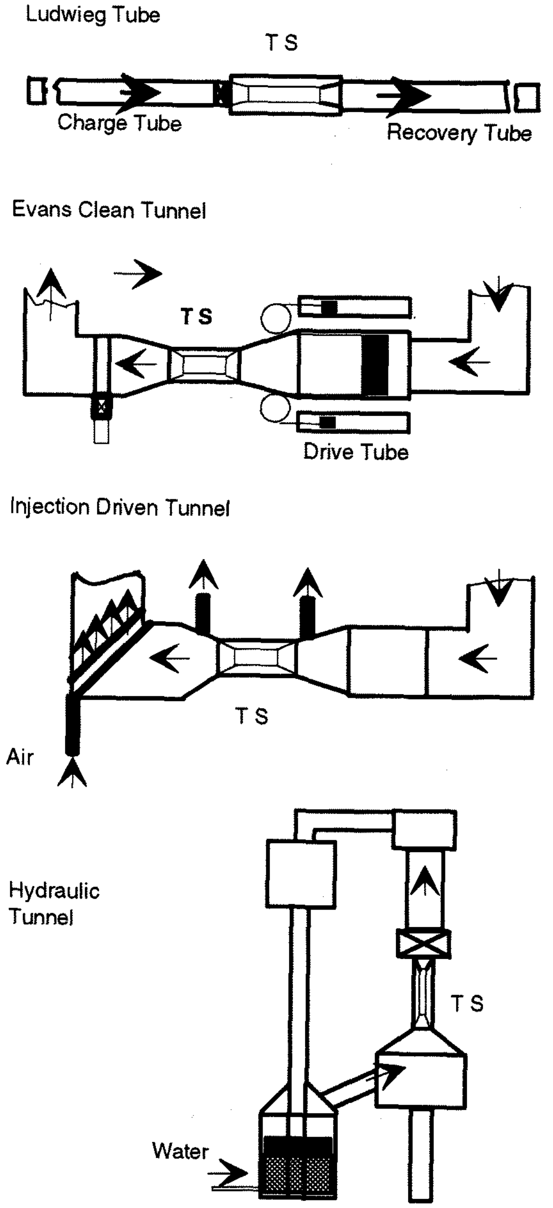

Fig. 2: Schematics of proposed drive systems for LEHRT

The result of the AGARD study, carried out by the Large Windtunnels Working Group (LaWs) under the Chairmanship of D. Küchemann was in 1972 a series of proposals for new wind tunnels. One of the proposals was for the "Large European High Reynolds Number Transonic Wind Tunnel" (LEHRT).

For the LEHRT four different drive systems were proposed which would circumvent the extraordinary power requirements for a classical closed circuit wind tunnel:

- Ludwieg Tube Tunnel	(Germany)
- Evans Clean Tunnel	(UK)
- Injection Driven Tunnel	(France)
- Hydraulic Tunnel	(France)

During the period of 1973-1977 these systems were tested in pilot facilities in Germany, France and the UK. A requirement for these intermittently operating facilities was a steady state run duration of 10 seconds or more.

The Canadian Consulting Engineering firm DSMA carried out preliminary engineering studies and made comparative cost estimates for transonic tunnels employing the different drive systems. On the basis of their report, issued April 1974, it appeared to be difficult to make a choice. There was also considerable uncertainty as to the problems which would be encountered when scaling up each of these facilities. For some time studies and experiments in the laboratories continued.

Under the auspices of DRG-NATO a Project Group (AC 243-PG. 7) of the then four participating countries was formed in 1975 under the Chairmanship of A. J. Marx, supported by a Technical Working Group headed by J. P. Hartzuiker.

The work done in the United States in the meantime and the decision to build the NTF also had its impact to this group, that supplemented the drive systems by the concept of a continuously driven cryogenic tunnel. In a study, again carried out by DSMA, three versions of a Cryo-LEHRT were investigated, differing in test section size and in pressure and temperature range. The analysis clearly revealed potential for considerable lowering the capital cost for the cryogenic concept by nearly the same operating cost, that is, the cryogenic concept turned out to be clearly the cheapest way to reach the high Reynolds numbers in a transonic tunnel. The cryogenic concept also prevailed over the other four concepts because the technical risk of further developing and scaling up the other concepts was judged to take too long and might be too costly.

During 1977 the Project Group 7, following the recommendation of the Working Group decided to adapt the cryogenic wind tunnel concept as the preferred drive system for the European High Reynolds Number Transonic Windtunnel.

This decision concluded Phase 1 of the project.

4. Preliminary Design Phase (Phase 2.1)

After this decision in January 1978 a Memorandum of Understanding was signed by the four participating governments of France, Germany, The Netherlands and the United Kingdom covering the Preliminary Design Phase.

Two to three years were scheduled for the Preliminary Design Phase (Phase 2.1) and two years for the Final Design Phase (Phase 2.2).

Capital cost for construction was estimated at 330 Million FF, on the price basis of 1976.

Table I **Milestones of Initialization and Concept Finding**

1968	AGARD Fluid Dynamics Panel identified the need for advanced high Reynolds Number wind tunnels.
1974	Large Windtunnels Working Group (LaWs) of AGARD recommended to build a large transonic wind tunnel in Europe.
1975	USA decided to build the Cryogenic National Transonic Facility (NTF) at NASA Langley.
1977	Selection of the cryogenic, fan driven transonic wind tunnel concept for Europe by a Project Group of the NATO Defense Research Group.
January 1978	Memorandum of Understanding for the Preliminary Design Phase signed by the four participating governments. Small ETW Technical Group set up at NLR in Amsterdam.

On the basis of the MoU a two-tier organization was set up, comprising a Steering Committee of representatives of the participating governments and an international Technical Group. The Technical Group was located at NLR Amsterdam with J.P.Hartzuiker as the project leader. The group had the following tasks:

- Performing the pre-design for the ETW in close cooperation with the US firm Sverdrup Technology, Inc.
- To build and to test a pilot tunnel.

To support the Steering Committee and the Technical Group and to coordinate the work done in the partner nations three working groups were established.

WG 1: Cryogenic Technology, in particular model construction and measurement technique.

WG 2: Justification Report.

WG 3: Foundation Group, for organization proposals for the institution ETW.

Later, personnel matters were treated by WG 4.

In the "Justification Report" it was concluded:

"There is an urgent requirement for a high-Reynolds-number transonic wind tunnel to be built in Europe and operated for the use of the European aircraft industry and of European research and procurement agencies. A substantial tunnel work load is foreseen.

The provision of the tunnel will allow the simulation of high-Reynolds-number flows in model tests and hence reduce the risk of future aircraft design failures, enable European industry to maintain a competitive position in world markets and enhance European defence capabilities.

The most cost-effective means of achieving the requirement is a pressurized continuous flow tunnel using nitrogen as the test gas, and capable of being operated over a range of temperatures form ambient down to about 90 K. The case for such a tunnel, the ETW, is strongly supported by European aerospace industry and research organizations".

In all activities the consideration of industrial requirements was mandatory. Generally, the Steering Committee was advised by its individual members on the views of the national industries. Later an Industrial User Group, composed of representatives of the aircraft industry of the four countries was installed for discussing technical matters with the project management.

Within WG 1 technical questions, the operating range and the basic flow design were discussed. Starting with requirements set by the industry, including civil as well as military projects, the test section size and its geometry was evaluated and assessed against cost arguments. The pressure range was evaluated in view to Reynolds number regarding requirements set by the model-technique. The temperature range was considered by its trade-off against Reynolds number and limits dictated by condensation of the test gas at the lowest temperatures. On the base of the trade-off analysis of cost and technical requirements a first set of design data for the ETW was worked out. The test section size and the maximum pressure were initially recommended to be smaller than projected in the NTF leading to a difference in the maximum Reynolds number of about 2. To a large extent this difference could be compensated for by half-model concepts. The cross section size was later enlarged up to a value comparable to the NTF cross section area.

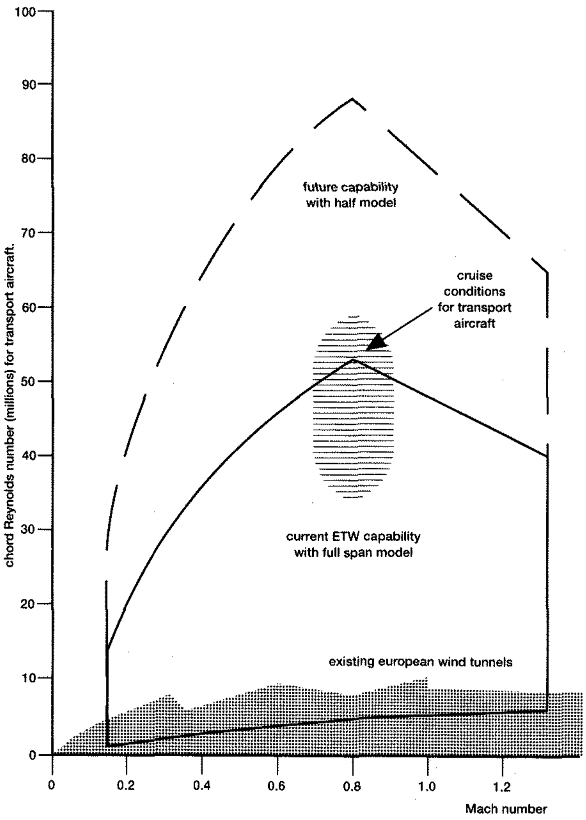

Fig. 3: ETW envelope compared to existing European wind tunnels

The overall flow quality was initially defined by its nominal degree of turbulence not exceeding 0.1 percent and a maximum deflection of center-flow-direction of 0.1 degree.

Nitrogen supply was discussed in detail. The annual consumption of liquid nitrogen was estimated. For the site Köln it was stated that the presence of the large storing capacity in the neighbouring Ruhr district would guarantee economical supply by existing companies. The analysis also showed that a dedicated nitrogen liquefaction plant could only be operated profitably if a large amount of produced nitrogen can again be commercialized. The effect of the cold nitrogen emission into the atmosphere during operation of the tunnel was analyzed by an official German agency. The effect was assessed as non-critical.

The Working Group (WG 1) in Amsterdam also discussed and supervised the pilot-ETW (PETW) a small sized tunnel, following the cold box concept. The pilot tunnel - located at NLR - was designed by DSMA, and constructed by various European firms. It scales 1:8.8 to the ETW. The experiments were primarily oriented towards the investigation of flow quality.

First low temperature nitrogen operation of the PETW started 1984 in Amsterdam. The experiments also provided information on various aspects of the cryo technology, the second throat performance and the noise spectrum in the test section.The PETW was moved to the ETW site at the end of the experiments.

Experiments were also carried out in the framework of national programmes. The most remarkable investments in these programmes are the KKK at the DLR Köln, a conventional subsonic tunnel converted to cryogenic operation, and the small transonic pressurized cryogenic T2 at ONERA Toulouse. Both provided later considerable know-how to the ETW design teams.

The study on the Preliminary Design Phase, carried out by Sverdrup Technology, including all information from the industry and research institutes was continuously coordinated by the Steering Committee.

The Steering Committee also, with the assistance of the Technical Group and the Working Groups, prepared a complete plan for the Construction and Operation Phase.

The originally planned time frame of two to three years for preliminary design had to be extended to seven years due to both, technical and political reasons. It turned out that the time needed for the preliminary design of the large facility and for constructing PETW had been underestimated. On the other hand a difficult discussion process started already in 1978 on the proposed sites for construction. The sites proposed were Le Fauga, near Toulouse (ONERA), Farnborough (RAE), Köln (DLR), and the Noordoostpolder (NLR). At a later stage the proposal of Farnborough was withdrawn. For the remaining proposals the nations made attractive offers based on a long list of requirements including not only technical and cost aspects like energy cost, but also infrastructural requirements and conditions of living. Finally, after Köln and Toulouse emerged as the most attractive sites, a decision on very high political level was taken in 1985 in favour of Köln, taking into account also the siting of other large research facilities in Western Europe.

5. Final Design Phase (Phase 2.2)

After the decision on the site was taken a Memorandum of Understanding was signed covering the Final Design Phase.

This MoU also expressed the firm intention of the four governments to construct the tunnel.

For the first time in this MoU the distribution of the overall construction cost was fixed:

France	28 %
Germany	38 %
The Netherlands	6 %
United Kingdom	28 %

The German share of 38 % included an additonal charge of 10 % because the site is located in Germany. An additional charge for the host country of multinational research facilities in basic research is an established practice in Western Europe based on the assumption that economic benefits would accrue from having the facility on the own soil.

The two-tier management organization was retained.

In the Appendix the following technical data and cost figures were fixed:

Mach Number Range	0.15 - 1.3
Operating Pressure Range	1.25 - 4.5 bar
Operating Temperature Range	90 - 313 K
Test Section Dimensions	2.4 m x 2.0 m

Overall construction cost including calibration: 460 Million DM (price level 1984).

An important management decision of the Steering Committee was to engage an Industrial Architect (INA), a consortium of firms, supporting the Project Group in all acitivities concerning cost management, project management including specifications and the interfacing of work packages.

During the Final Design Phase several major decisions were taken and rather radical changes were introduced:

- Originally, the complete tunnel was encased in a "cold box" to avoid the risk of cracks developing in the insulation which was directly applied to the wind tunnel shell. The tunnel would remain near the nitrogen liquefaction temperature for extended periods of time and it was to be operated at cryogenic temperatures only. Only once or twice per year the tunnel would be warmed up to room temperature for maintenance purposes. In fact the pilot facility, PETW, was constructed along these lines.
  After long discussions and intensive investigations carried out in close cooperation with Sverdrup Technology the Steering Committee decided to apply internal insulation.
- During this phase studies were also carried out by several firms for the final drive system. Finally, a two-stage compressor was chosen, powered by a 50 MW drive system consisting of a synchronous motor supplied with power at a variable frequency via a static converter. The blades of 4.5 m diameter rotors are made of composite materials.
- A removable model cart system was developed. Initially the model carts were to be entered into the tunnel from below. During this phase it became apparent that insertion from the top would be far more practical and offer more flexibility. The novel cold model handling technique is a key to the expected high productivity of the ETW.

Further technology steps were prepared and later developed during Construction Phase. These include:

- Mechanical design: Computerized finite element design led to novel solutions for the decoupling of structures in order to maintain aerodynamic configuration whilst providing stability and rigidity throughout the temperature range.
- Nitrogen Systems: Substantial quantities are injected with high accuracy and uniformity over a large area through more than 200 individually controlled cryogenic valves.
- Others include:
  - insulation systems
  - dry air systems
  - control systems

- seals
- balances
- fillers for models
- personal safety

Generally, no essential component of the plant is based on materials or techniques which were not totally mastered at that time - as one key factor to prevent delays and cost overruns.

6. Construction Phase (Phase 3.1)

In April 1988 the Memorandum of Understanding for the joint construction and joint operation was signed. It included:

- the location Köln,
- the cost estimate of 562 million DM for erection, commissioning and calibration (price level 1. January 1988),
- the cost estimate of the Initial Operation Phase,
- the time schedule 1988 to mid-1994 for construction and mid-1994 to mid-1997 for initial operation,
- the cost sharing for construction (as envisaged in phase 2.2), and for the initial operation (France, Germany, and the UK each sharing 31 percent and The Netherlands 7 percent),
- the obligation of the host country to provide and finance the local infrastructure.

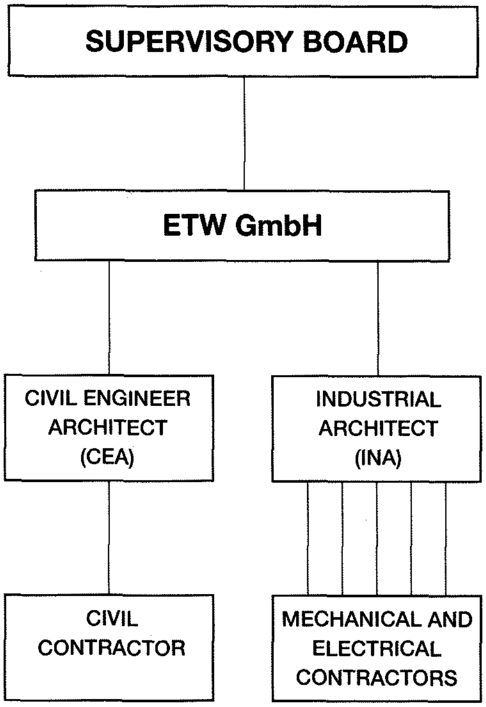

Fig. 4: Organization chart during Construction Phase

On the basis of this MoU a cooperation agreement between the national research establishments, DLR, ONERA, RAE and NLR was signed which led to the establishment of the jointly owned ETW GmbH, the responsible organization for constructing and operating the tunnel.

The ETW GmbH and the INA Team moved into temporary offices next to the site and already in 1989 three major work package contracts were awarded to companies in Great Britain, France and Germany with an overall volume of 200 MioDM. Due to the nature of the project - initially very much a development project - the design and construction of the ETW was carried out as an "owner-managed project" as contrasted with a "turn-key project".

During the Construction Phase the Management of the ETW GmbH, was directed by:

K. J. Fergusson (UK) (Head of ETW Working Group since 1986)	1988
G. L. Harris, (UK)	1988 - 1992
X. Bouis, (FR) (Technical Director since 1988)	1992 -1993
T. B. Saunders (UK), since October 1993	

Table II Milestones of Design Phases and Construction Phase

January 1978	Memorandum of Understanding for the Preliminary Design Phase signed by the four participating governments. Small ETW Technical Group set up at NLR in Amsterdam.
March 1984	First low temperature nitrogen operation of the scaled-down Pilot ETW in Amsterdam.
1985	Decision at high government level to construct ETW in Köln. Memorandum of Understanding for the Final Design Phase signed by the four ETW governments.
1986	International ETW Project Group set up at DLR in Köln.
April 1988	Memorandum of Understanding for the Construction and Operation signed by the four participating governments. Cooperation Agreement between the four associates of ETW (DLR, ONERA, RAE, NLR). Establishment of ETW GmbH.
October	ETW GmbH and INA Team move

1988	into temporary offices next to the site.
April 1989	Three major Work Package Contracts awarded to companies in Great Britain, France and Germany (overall value 200 Mio DM).
March 1990	Start of construction work on the ETW site.
15 May 1990	ETW Corner-Stone Ceremony.
29 April 1991	ETW Topping-Out Ceremony.
December 1991	Pressure test of the stainless steel wind tunnel shell. Move of the ETW Team into the new Office Building of the ETW Plant.
December 1992	First run of the ETW compressor and mechanical completion of the ETW Plant.
May 1993	First cryogenic operation, Mach number around 1.
June 1993	Inauguration Ceremony.
Sept.1993	First reference model test.
December 1993	Maximum pressure, Mach number and lowest temperature achieved.

Some 300 contracts for design, fabrication, construction, erection and installation were placed with companies from mainly the four participating countries.

While at some time during final design and fabrication some 3000 people were working on components for the ETW plant, the peak work force on the ETW site was 450 during construction and erection.

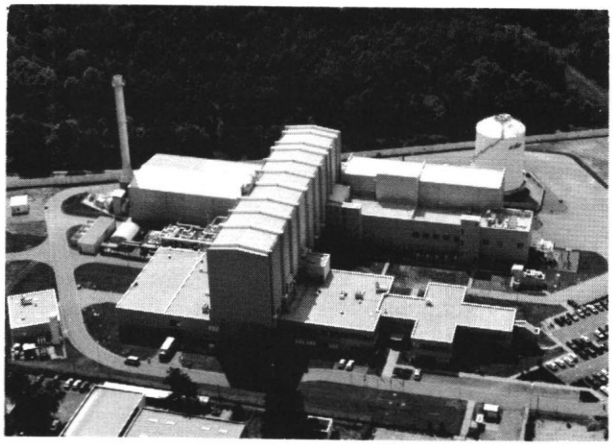

Fig. 5: Overview of ETW plant. The large building in the middle is the Transfer Hall

7. Operating Range

The Mach number range from 0.15 up to 1.3 allows comparative tests with modern low speed tunnels as well as trans- or supersonic aircraft or space vehicle testing in high subsonic and low supersonic conditions.

The test section size of 2.4 m x 2.0 m and the pressure and temperature ranges, 1.25 to 4.5 bars and 90 to 313 K, represent the best combination of parameters to meet the requirement from the aerospace industry to achieve a Reynolds number of 50 million on a typical large transport aircraft.

In fig. 6 the operating range of the facility at a given Mach number is shown for M=0.6, 0.9 and 1.2 in terms of Reynolds number against stagnation pressure.

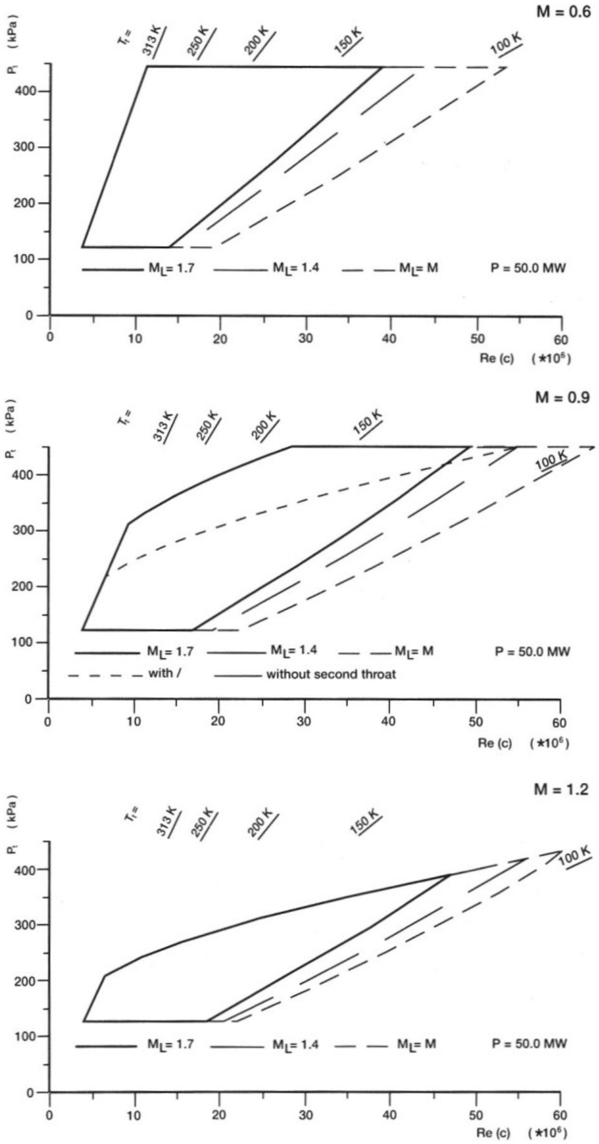

Fig. 6: ETW operating range at subsonic up to supersonic conditions. The parameter ML denotes local Mach numbers

Bounds are set by the maximum and minimum pressure and temperature lines. A further restriction is due to the maximum power available to drive the compressor.

8. General Design

ETW has a closed aerodynamic circuit. A compressor drive power of up to 50 MW moves the nitrogen test gas around the circuit. To achieve the desired low temperature of the test gas, liquid nitrogen is injected into the tunnel upstream of the compressor. The corresponding gaseous nitrogen exhaust is upstream of the stilling chamber and is controlled by valves. Noise abatement is provided by a silencer prior to the gas entering the exhaust stack where it is mixed with the surrounding air.

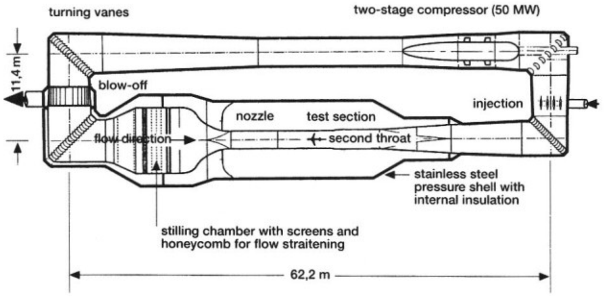

Fig. 7: The ETW aerodynamic circuit

Between test runs, the complete model cart is moved together with the upper test section wall, model support, tunnel pressure door and instrumentation cabin, by means of a special crane, to one of the adjacent "Variable Temperature Check-out Rooms" (VTCR's). Here configuration and temperature changes to the model can be easily made, and the instrumentation checked at the actual test temperature.

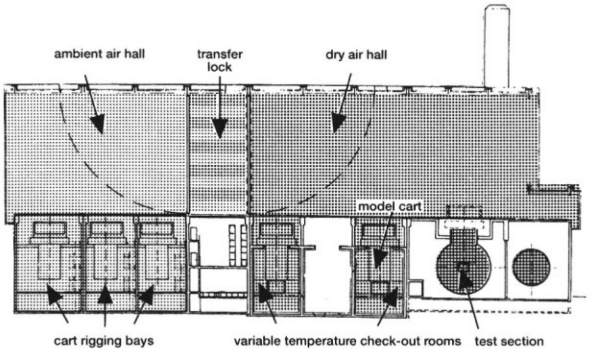

Fig. 8: Section through Transfer Hall

The nitrogen injection system consists of 4 vertically mounted rakes. In each rake are between 50 and 70 individually controlled banks of nozzles, providing in total 1400 possible spray points.

Considerable care has been taken to secure high productivity. With its model handling technique, its design for quick model configuration changes, client test preparation requirements, tunnel control methods and its quick change from one tunnel condition to the other, the ETW is optimized to maximum testing time and minimum preparation time. Security of the tests is guaranteed throughout, by the design of the building, the tunnel, the control systems and the software development.

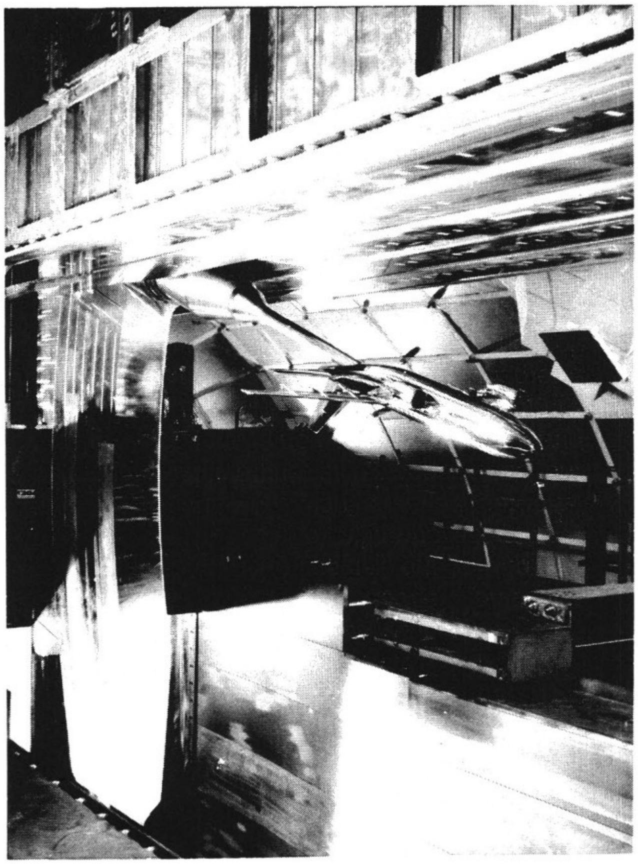

Fig. 9: Model cart with model being lowered into the test section

9. Test Section

The concept of a slotted test section was selected for the first build. Provision has been made for retrofitting adaptive walls at a later stage.

The test section is followed by a second throat, designed to minimize flow disturbance propagating upstream and to provide Mach number control during tunnel operations.

10. Flow Quality Requirements

The ETW specification finally calls for a turbulence intensity not exceeding 0.05%. This ambitious goal is to be achieved through the use of 4 screens and a honeycomb of large depth/cell diameter ratio and a contraction with a ratio of 12.

Acoustic effects and the effect of mixing the nitrogen on the flow quality are minimized through the complete design, e.g. also by employing the low noise two-stage compressor.

Fig. 10: Model in test section

Further requirements are the following:

- The Mach number spatial uniformity of a maximum deviation of ±0.001 in subsonic conditions and ±0.008 in supersonic conditions within the test volume and for an empty test section.
- The temperature set point during a polar is to be kept within ±0.25 K. This corresponds also to the expected temperature uniformity within the test volume.
- The ETW target is to obtain a flow angularity of less than 0.1 degree, repeatable and measurable within ±0.01 degree.

11. Calibration Results

After completion of the mechanical erection an extensive programme has been carried out to demonstrate the tunnel's performance and to calibrate the test section flow properties. An important aspect is the validation of the operating system to control dominant flow parameters like Mach number, temperature and pressure during test runs with high accuracy and a minimum of operating time.

The control of a pressurized, cryogenic, transonic wind tunnel is complex. Coupling between the individual flow parameters, non-linearities over the operating range, propagation times along the circuit, and internal heat fluxes have to be studied carefully. The major control parameters are the compressor drive speed (maximum 846 rpm), the injection rate of liquid nitrogen (maximum 240 kg/s) and in turn the blow off the gaseous nitrogen, the setting of the second throat downstream of the test section and the adjustable nozzle upstream of the test section. With novel control techniques, developed by the specialists at ETW-GmbH and derived from those in use at T2, fully automatic operation of the facility has been possible from the first run.

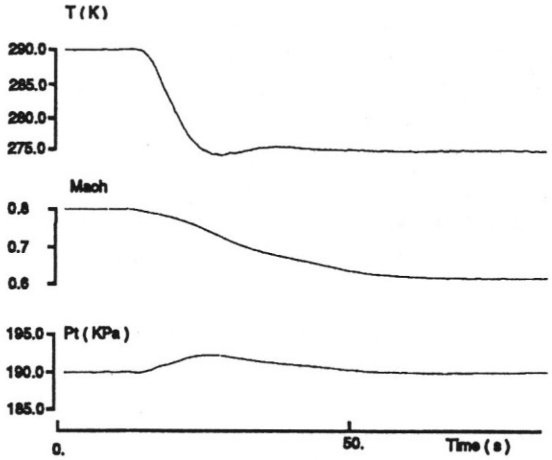

Fig. 11:Combined Mach/temperature change

Results in terms of flow stability obtained during the execution of a measuring polar in spring 1994 were the following:

- Mach number stability < ± 0.001
- Temperature stability < ± 0.1 K
- Pressure stability < ± 0.001 bar

The liquid nitrogen injection system was studied in detail. The 230 spray nozzles mounted on the four vertical rakes located upstream the compressor allow to optimize the flow to high spatial temperature uniformity, measured by a thermocouple grid installed in the settling chamber. Using the automatic control system optimum configurations of the nozzles were determined and proved well controlable.

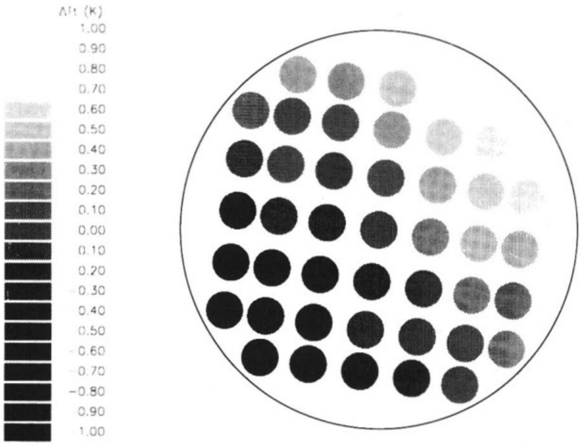

Fig. 12: Temperature distribution in the settling chamber at 0.7 Mach and about 150 K temperature

To determine the test section Mach number distribution in flow direction a long axial probe was installed on the test section center line, provided with 0.3 mm orifices. Additional information was obtained by the analysis of the wall pressure distributions measured by about 400 wall orifices. A typical result at 0.9 Mach showed a scatter of ± 0.002 in the pressure coefficient corresponding to ± 0.001 in Mach number. During the calibration campaign it was verified, that zero Mach number gradients can be easily realized over the entire model volume by remote adjustment of the test section top and bottom walls and re-entry finger flaps.

The combination of high control accuracy and high flow quality enables a very fast high quality response of operating parameters to set point changes. A temperature change of 15 K or a Mach number change of 0.2 requires typically only about 1 minute.

The automatic Mach number control during a polar and automatic sequencing of data acquisition/polars/Mach number changes allow running times to be substantially reduced compared to all large conventional wind tunnels.

A proof of concept was demonstrated less than six months after the completion of the erection phase. By making use of an existing European reference model (Garteur F4) it was possible to complete a 120 polar programme in two days, including three model configuration changes in the variable temperature checkout room. The results of these initial tests showed excellent repeatability (± 0.5 drag counts) and compared very well to result data obtained in other European wind tunnels under comparable test conditions. In addition, an ETW reference model has to date been tested under cryogenic conditions up to a Reynolds number of 30 million, based upon mean aerodynamic chord. All results described in this section were obtained before April 1994 [9].

12. General Achievement

The approved budget of the MoU for Phase 3.1 of 562 million DM after escalation amounts to 663 million DM. The real construction cost remain under this amount. The time schedule of this phase was met.

With the ETW the flight Reynolds number of large aircraft is obtained in a ground facility at subsonic and transonic speeds. The facility sets new standards in the performance of nitrogen cooled technology and makes it accessible to the aircraft industry. The simulation quality obtained in the transonic regime is unique in Europe.

Substantial progress was made in cryogenic wind tunnel technology including wind tunnel model design and construction, balance technology, pressure measurement and optical position measurement. Methods to visualize the flow are presently under development and will complement the conventional methods.

Technically, the higher accuracy of data gives an optimization potential in aircraft building that combines all technology fields: advanced propulsion technique, advanced materials and structures, and advanced aerodynamics, in particular integration problems, e.g.:

- wing - fuselage integration,
- propulsion integration,
- systems integration,
- control surface integration, and
- trim concept integration.

Access to new and more complete experimental information challenges the theory. Even the best theoretical methods available are not advanced enough to treat the Reynolds number depending flow phenomena appropriately. In many crucial aspects theoretical modelling, presently, must still accept artificial assumptions that more or less are uncertain and bear a source for failing.The ETW - technique makes the Re-number depending phenomena as the transition from laminar to turbulent flow, i.e. the real flight location of the transition regime and in general the generation of vortex flow experimentally accessible to engineers that can now better identify flow-critical configuration elements and components. By using these advantages the configuration can then be optimized with a higher degree of accuracy - before first flight, hence reducing technical and financial risks. A new era in aircraft design is established.

The ETW is directed towards industry requirements. With the cold model handling concept the ETW offers quick and well prepared usage of the tunnel. The productivity of 5000 polars yearly, that is an average of three runs daily, guarantees low testing costs and a high data acquisition within short time - an advantage that converts to shorter development time in the aircraft industry.

Currently, a team of about 60 is finalizing the commissioning and calibration activities. The overall staff during initial operation will be of similar order of magnitude.

Early in 1993 commissioning and calibration of the tunnel and its systems has started. Presently, the test series on reference models has started and will be followed in these days by tests for industrial clients.

The aerospace community now has at its disposal a unique transonic wind tunnel offering the combination of outstanding Reynolds number capability with high productivity.

13. Marketing Policy

Although initiated as a European organization by four European nations, ETW's services as a high Reynolds Number Facility are not restricted to the European Aerospace Industry. On the contrary. Vested as a commercial company in Köln, Germany, not being restricted by national constraints, ETW's marketing will have a strictly commercial character and address aerospace industries all over the world. Truly, an international venture of global proportions.

14. Lessons Learned

- Personnel continuity of the upper management level is vital during the emerging phases of a multinational project until the point of no return is reached; in this case over a period of 11 years (1974-85).
- Consultation and involvement of future industrial users proved to be very useful in the early design stages.
- The building-up of a highly experienced multinational integrated team supported by an Industrial Architect proved to be a flexible and efficient means in developing an owner-managed project.
- The principle of functional specifications, validated by feasibility studies and fenced by a simple set of detailed interfaces worked very well. The set of key specifications could be kept to a minimum.
- Executing within the original cost and time estimate was possible only, because:
  - the basic specifications were kept unchanged during construction phase,
  - the management of the ETW-GmbH had been given adequate authority to negotiate technical, financial and planning adjustments within the clear and simple limits set by the MoU,
  - and no rigid "fair return" restictions existed.

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