# THE GERMAN-DUTCH WIND TUNNEL DNW
# DESIGN ASPECTS AND STATUS OF CONSTRUCTION

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## Abstract

As a co-operative project of DFVLR and NLR the German-Dutch Wind Tunnel DNW is under construction in the Noordoostpolder, The Netherlands. The DNW will belong to the largest and most efficient low-speed wind tunnels in Europe and contribute to aircraft development work after being commissioned in 1979. Typical design features are: closed and cooled circuit, three interchangeable atmospheric test sections with cross sections of 9,5m x 9,5m, 8m x 6m and 6m x 6m with maximum air speeds of 62, 110 and 145 m/s, air exchange system. The equipment includes among others: model sting support, external balance, computers for data handling and controls, compressed air plant, moving belt ground plane, q-stopper, scoop for hot gas removal. The DNW will cover a wide range of testing capabilities including aero-acoustics (open test section) and the testing with real engines. This paper especially refers to overall and aerodynamic design aspects and the development of selected components. Furthermore, the present status of construction is described.

## Notation

| | |
|---|---|
| A | cross-sectional area |
| B | cross-section width |
| $C_p$ | static pressure coefficient, p/q |
| D | fan diameter |
| f | fan pressure rise coefficient, $\Delta p/\rho n^2 D^2$ |
| H | cross-section height |
| J | advance ratio, v/nD |
| K | circuit loss factor, $\Delta p/q$ |
| n | fan speed |
| p | static pressure |
| $\Delta p$ | fan pressure rise |
| q | dynamic pressure, $\frac{1}{2} \rho v^2$ |
| SPL | sound pressure level |
| v | velocity |
| $\eta$ | breather flap angle |
| $\rho$ | density |

Index:

| | |
|---|---|
| o | test section |

## 1. Introduction

National studies of the sixties and investigations co-ordinated under NATO auspicies in the early seventies identified a strong need for new and larger wind tunnels in Europe, especially in the low-speed area, in order to provide the European aircraft industries with adequate aerodynamic testing capabilities for an effective development work. Therefore four national projects of large low-speed wind tunnels were originated to meet the requirements of future aircraft development programmes. Among these projects were the Grosse Unterschall-Kanal (GUK, Federal Republic of Germany) and the Lage Snelheids Tunnel (LST 8x6, The Netherlands). For economical reasons the fusion of both these projects had been considered by the Deutsche Forschungs- und Versuchsanstalt für Luft- und Raumfahrt (DFVLR) and the Nationaal Lucht- en Ruimtevaartlaboratorium (NLR) as well as on government levels. The bilateral co-operation seemed to be an obvious solution also from the technical point of view as both concepts showed similar design features regarding tunnel type (closed and atmospheric air circuit), size, and performance and were mutually complementary regarding the tasks and the equipment.

In May 1975 a German-Dutch group of experts had been charged with a feasibility study for a common technical concept which should

- meet the users' requirements of both countries
- incorporate the previous basic performance data
- make the most possible use of the pre-design studies
- define the required flow qualities and equipment
- enter into the construction phase in 1976
- enable commissioning of the facility in 1979.

For the joint project venture which was named DNW, the DFVLR and the NLR established a new organisation, the DNW Foundation. The objective of the foundation is to construct, operate, maintain and further develop the wind tunnel facility DNW on the basis of parity. The foundation will carry out wind tunnel investigations under contract on a non-profit basis. The construction costs are shared equally by both countries. The principle of parity also holds for the composition of the (supervisory) Board and the project team which is equally staffed by DFVLR and NLR. The project team is charged with planning, specification and design work as well as with the co-ordination and supervision of all construction activities. For reasons of flexibility and in order to match the design targets within budget and schedule limitations preference is given to a direct interface and control management against the numerous main contractors. The daily management is assisted by several engineering consultants and by technical experts from both parent organisations.
The design work especially aims at

- high aerodynamic and aero-acoustic qualities
- comprehensive and advanced equipment for a wide range of types of test
- high testing productivity
- flexible and economic operation
- maximum system reliability

and is based among others on

- proven techniques and materials
- advanced engineering and calculation methods
- experimental design support by tests in model tunnels.

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†) DNW = Duits-Nederlandse Windtunnel/Deutsch-Niederländischer Windkanal

## 2. Tasks and Specifications

### Tasks

The DNW facility is designed to the effect that problems associated with the development of airborne vehicles in the low-speed regime can be treated successfully. The main testing activities will in the first instance aim at the improvement of the low-speed characteristics, with special reference to take-off and landing behaviour, and under safety and economy aspects. Such "standard" force and pressure measurements will be carried out on aircraft models which are fully equipped with flap systems, control surfaces, landing gears, and engine simulators. The development of effective high-lift devices will require true model scaling and sufficiently high Reynolds numbers at moderate speeds and hence test sections of considerable size.

Large test sections will also be needed for the planned studies on V/STOL and rotor aerodynamics because of the strong engine/airframe interference effects, and for optimization tests of full-scale aircraft components and post-stall investigations. Relatively high maximum wind speeds will be required for tests on high-speed helicopters and for flutter and jettison tests.

A special world-wide interest has been identified in aero-acoustic tests (far field noise of airframes and engines at forward speeds) for which an adequate wind tunnel facility, i.e. of sufficient size and of good aerodynamic and aero-acoustic properties in like manner, is not yet available.

### Specifications

According to the described tasks the following basic specifications (1) for the joint German-Dutch Wind Tunnel had been established:

- closed, atmospheric circuit based on the LST 8x6 concept
- three closed, interchangeable test sections with cross-sectional sizes of 9,5m x 9,5m, 8m x 6m and 6m x 6m with maximum continuous wind speeds of at least 55, 100 and 130 m/s respectively (in the presence of a typical model)
- one open test section for aero-acoustic measurements (8m x 6m, 80 m/s)
- air exchange system and scoop for the rapid removal of hot or contaminated gases (tests with engine simulators or full scale engines)
- continuous drive power of 11,5 MW (plus 10% design margin to cover prediction risks)
- standard and special equipment.

The flow quality in the empty test sections should meet the following requirements:

- relative deviation of static and dynamic pressure across the centre section: ± 0.3%
- local deviation of flow direction: ± 0.1°
- local temperature deviation: ± 0.5 C
- turbulence: 0.1 to 0.2%

Slightly higher values will be allowed for:

- wind speeds below 40% of the maximum speeds
- V/STOL and high-lift models
- test with full air exchange
- the vicinity of the test section walls.

## 3. General Arrangement of the Facility

Figure 1 shows the arrangement of the total wind tunnel plant. Central item is the closed tunnel circuit shaped as a slender rectangle in the plan view. The centre line has a total length of 318 m and is 10 m above the ground level. The testing hall covers the area of the test sections. The most significant architectural amplification against the previous projects is the large parking hall with a span of about 84 m, which accommodates all the interchangeable test sections not being in operation. Both halls are separated from each other by a sliding wall in order to protect the parking hall against pressure fluctuations during transient operation modes and to apply acoustic treatment to the testing hall only. Several smaller halls are annexed to the parking hall, such as the experimental hall (next to the circuit, with all necessary auxiliary supplies for static pre-tunnel tests on models), two model assembly halls and a calibration hall for the external six-component balance. The office building also accommodates functional rooms (small workshops, off-line data reduction) and provides direct access to the control room. The control room is close to the test sections for easy observation and houses also the on-line data handling and remote control system.

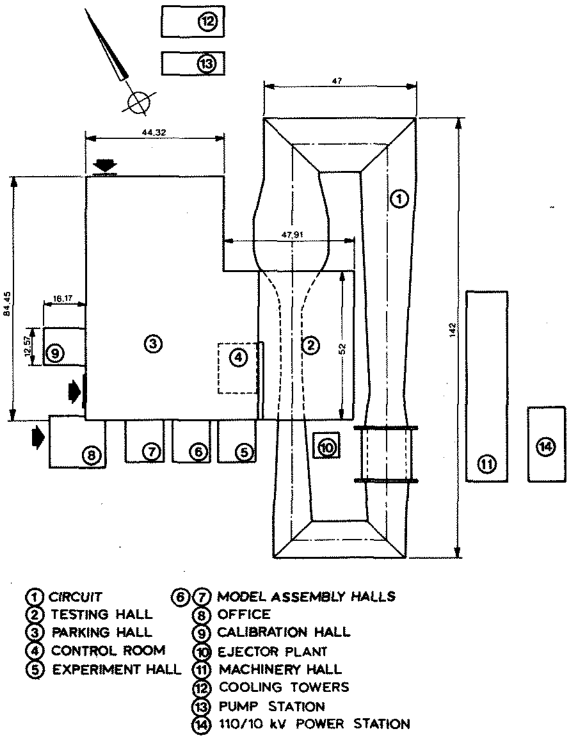

Figure 1 Arrangement of the Wind Tunnel Plant

These buildings are supplemented by a machine hall for the compressed air plant and the low-voltage distribution system and by a 110/10 kV power station. Figure 2 is an artist's impression of the main building complex. Due to the nature of the ground the whole facility rests upon a fundament of about 1500 piles. The halls are of a steel lattice construction and have a maximum height of 23 m. The circuit and the halls are covered with aluminium sheet. The circuit and the belonging-to installations were the main subjects to a careful aerodynamic design and will be discussed in chapter 6. General surveys over the DNW project and its technical features are given in summarizing papers (2)(3).

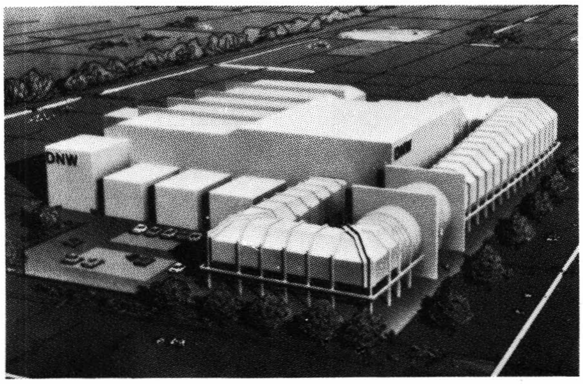

Figure 2 Building Lay-out (Without Machine hall and Power Station)

## 4. Testing Equipment

### Test Sections

In order to reduce the size of the parking hall and to speed up the change of the flow cross-section in the model area, the 8m x 6m and the 6m x 6m test sections have been combined to one convertible set-up. This convertible test section is provided with movable side walls and the belonging-to contraction with inserts. The 9.5m x 9.5m test section is a separate arrangement. Each test section arrangement consists of three movable parts: the contraction, the test section and the transition part, with a total length of 44 meter. In the open (8x6) test section mode the transition part of 9.5 x 9.5 test section will serve as the collector. All section elements can be moved between the testing and the parking hall by an air cushion transport system and are equipped with a hydraulic/pneumatic connecting and locking system. As a special feature all test sections will be provided with slotted walls of variable width. Further equipment includes breathers, hatches, and synchronized turntables and will allow testing complete and half models as well as 2D wing sections. If a model has to be exchanged the movable part of the contraction will be removed to provide access to the test section. The model will be transported by an air cushion supported vehicle (movable elevator).

### Model Support

Mounting models in the test sections is facilitated by a sting support mechanism. It consists mainly of a streamlined vertical structure (which in the parking position descends into a pit of 16 m depth) and a horizontal sting movable into all directions. The standard sting allows for models to be placed in extreme positions (angle of attack ± 45°, angle of yaw ± 30°); it can also be used in connection with a moving belt ground plane or may serve as a probe support on the occasion of flow field measurements. Vertical positioning can be performed with a maximum speed of 5 m/s and a deceleration of 5 $m/s^2$. This enables the simulation of landing and moderate flare phenomena. The vertical loads are limited to + 60 kN and - 15 kN. As an alternative model support an external six-component balance ('platform' type) of high accuracy and with maximum vertical loads of ± 65 kN will be available. For calibration purposes the balance can be moved on air cushions into the calibration hall (figure 1, building 9) where a rigid frame construction for applying test loads is installed.

### Special Equipment

In order to make full use of the basic capabilities the DNW will be equipped with several auxiliaries, e.g.:

- compressed air plant with a capacity of 6 kg/s for continuous operation and 35 kg/s for intermittent operation, at 280 bars storage pressure. Compressed air will be used for engine flow simulation, high-lift systems, drive of suction systems (ejectors), and for the test section logistics.
- air exchange system (throttle and hatches)
- tunnel cooling (heat exchanger, re-cooling system)
- hydrogen peroxide plant for hot gas simulation
- moving belt for ground simulation (width: 6m, length: 7m, maximum belt speed: 60 m/s)
- q-stopper as a rapid flow deceleration device for flutter tests
- scoop for sucking off hot and/or contaminated gas from the test sections
- hydraulic drives
- equipment for aero-acoustic measurements.

### Computer and Control System

For remote control and data handling a distributed computer system will be provided, complemented by programmable control units attributed to the various components. The data acquisition and processing system is divided into two compound computer systems. One is mainly used for actual tunnel testing and controlling while the other is mainly charged with supporting tasks such as model check-outs, calibration, and post-processing of test data.

## 5. Main Design and Performance Data

In the course of the iterative design process it turned out that the ambitious basic specifications were compatible and could be fulfilled. As a result of experimental design support and refined engineering the function of various components have been optimized and their performance improved.

It is expected that the specified maximum wind speeds will be exceeded by more than 10%. Table 1 summarizes the main design and performance data.

| TYPE OF TUNNEL | CLOSED RETURN CIRCUIT (OVERALL LENGTH OF CENTERLINE: 320m) | | |
|---|---|---|---|
| SIZE OF WORKING SECTION | 9.5 m x 9.5 m | 8m x 6m | 6m x 6m |
| TYPE OF SECTION | CLOSED | CLOSED AND OPEN | CLOSED |
| CONTRACTION RATIO | 4.8 | 9.0 | 12.0 |
| MAX. SPEED (m/s) | 62 | 110<br>(90) | 145 |
| STATIC PRESSURE IN TEST SECTION | ATMOSPHERIC (1 BAR) | | |
| REYNOLDS NUMBER $\times 10^{-6}$ *) | 3.9 | 5.2 | 5.8 |
| MAIN DRIVE | THYR. SYNCHR. MOTOR; NORMAL RATING: 12.7 MW | | |
| AUXILIARY DRIVES | MAINLY FOR COMPR. AIR; ≈ 7 MW | | |
| FAN | SINGLE STAGE; 8 BLADES; DIRECT DRIVE 225 RPM; CONST. PITCH, WIND SPEED CONTROL BY MOTOR | | |

*) BASED ON $V_{max}$ AND $0.1\sqrt{A}$ (A: TEST SECTION AREA)

Table 1 Main Design and Performance Data

The maximum Reynolds numbers given are based on an average chord length (0.6 to 1.0 m) of a complete model of a transport aircraft. The fan drive motor can be operated four times within one hour at an overload power of 14.5 MW. The capacity of the 110/10 kV transformer is 40 MVA.

## 6. Aerodynamic Design Aspects

### General Design Considerations

The aerodynamic lay-out of the DNW circuit is based on the LST 8x6 concept which was originally tailored for only one test section 8x6 and a special air exchange system (4). By extensive tests in the model tunnel 1:10 it had been demonstrated that the basic design of the circuit yielded the required flow qualities also for the two additional test sections 9,5x9,5 and 6x6 of the GUK and that in the main only structural and power aspects had to be reconsidered to meet the new overall requirements. The interchangeability of the three test sections, however, required a redesign of the arrangements, especially of the contraction and transition sections.

The design philosophy aimed at an optimum shape of the circuit with respect to maximum flow quality and minimum power consumption. According to the specifications the emphasis was laid on flow quality.

The aerodynamic design started with the following assumptions: area of the fourth corner being 5 times the test section area (8x6), a wide-angle diffuser between the fourth corner and the settling chamber, an average turbulence level downstream of the fourth corner of about 5%.

### Circuit Geometry

In order to obtain the desired turbulence level of 0.1% in the test sections, an optimization of various parameters as the contraction ratio

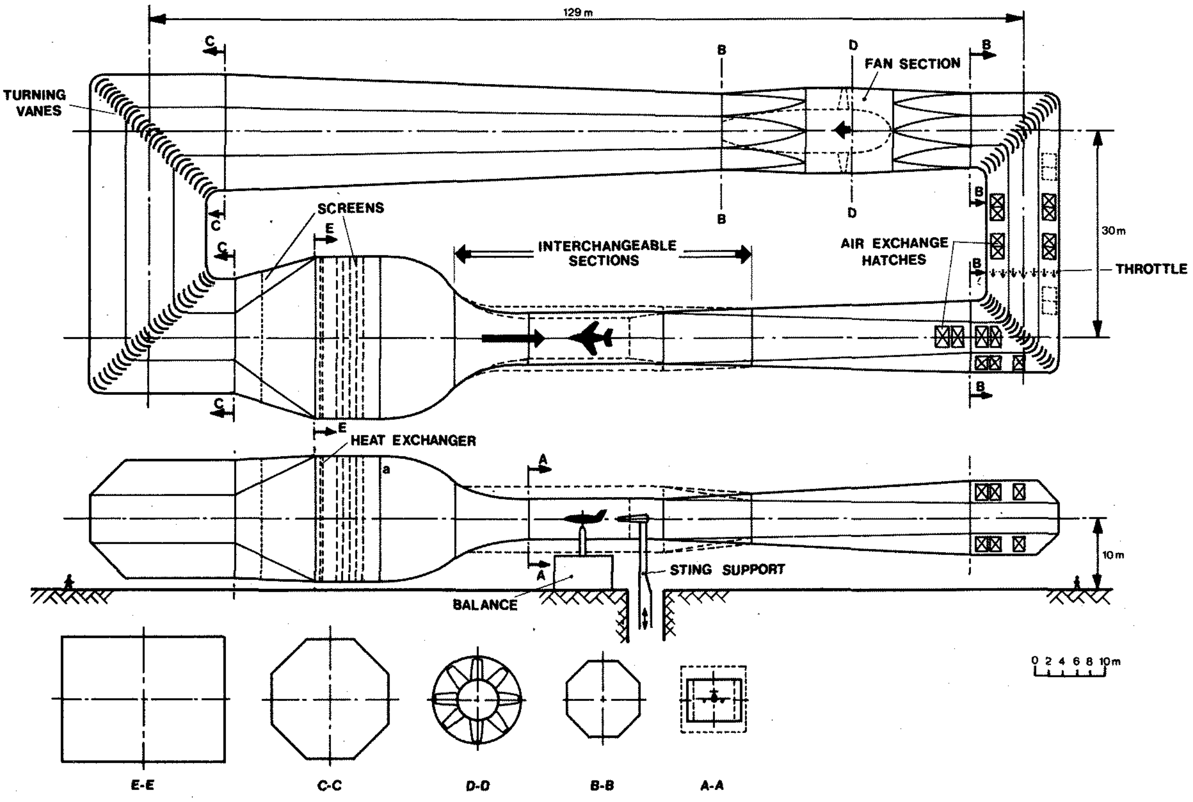

Figure 3 Plan and Side Airline Views of the Circuit

and the installations in the settling chamber was necessary. Aspects as low losses and hence low power consumption, reasonable length of the circuit, and the flow qualities of the diffusers lead to a contraction ratio of 9 for the 8x6 test section. The test section diffuser has been designed for avoiding flow separation rather than for maximum pressure recovery. Reynolds number considerations favoured the design principle of minimizing the total losses due to wall friction and turbulent mixing. This method yielded an opening angle of 4.1° at an area ratio of 2, with a sufficient safety margin for tuning both the movable and fixed diffuser behind the 6x6 test section. The post fan (main) diffuser has an opening angle of 5° at an area ratio of 2.5. Both cross-legs are of constant area and show a fully developed pipe flow. This design has a stabilizing effect on the boundary layer behind the diffusers and results in low local turbulence levels. Design of the wide-angle diffuser is based on zero pressure efficiency in avoidance of separation; the flow is stabilized by a single screen located at 1.3 times the entrance area (mesh gauge: 5 mm, thread diameter: 1.36 mm).

Figure 3 shows the lay-out of the circuit and its various cross-sections and installations.

The diffusers and the cross-legs show cross-sections shaped as isosceles octagons which are typical for the circuit of the DNW. This shape is a compromise of aerodynamic and civil engineering aspects and allows for smooth transitions to the circular cross-section of the fan and to the rectangular cross-sections of the settling chamber, contractions and test sections.

### Installations in Circuit

Installations in the settling chamber include - in downstream direction - a heat exchanger, a honeycomb flow straightener and screens. As they are dominating the flow qualities in the test sections extensive tests in the model tunnel at NLR had been carried out to achieve an optimum design of these installations. As a final result four screens (mesh gauge: 2.5 mm, thread diameter: 0.58 mm) were selected; the open area ratio is sufficiently small to permit a natural decay of the self-generated turbulence.

Tests with (models of) the 9,5x9,5 test section which has the smallest contraction ratio (4.8) revealed that the test section flow is extremely sensitive to off-size conditions of the installations (connection of the screen breadths, honeycomb burrs). Therefore it was deemed necessary to determine the total pressure distribution, flow angularity and turbulence in the test section also in presence of original heat exchanger elements in the settling chamber. The expectation that the heat exchanger owing to its construction (vertical elliptical tubes with narrow-spaced horizontal fins) could simultaneously serve as a flow rectifier unfortunately did not come true.

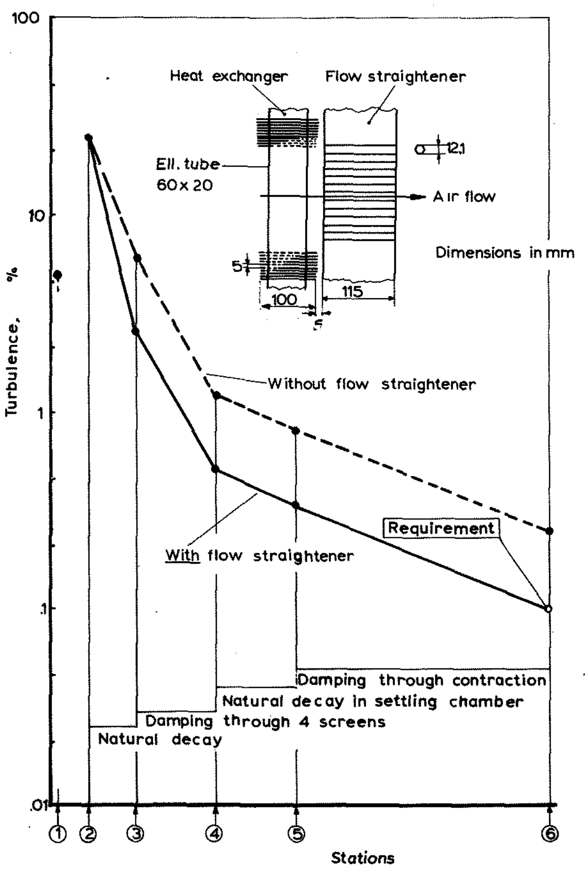

Figure 4 Reduction of Turbulence Level

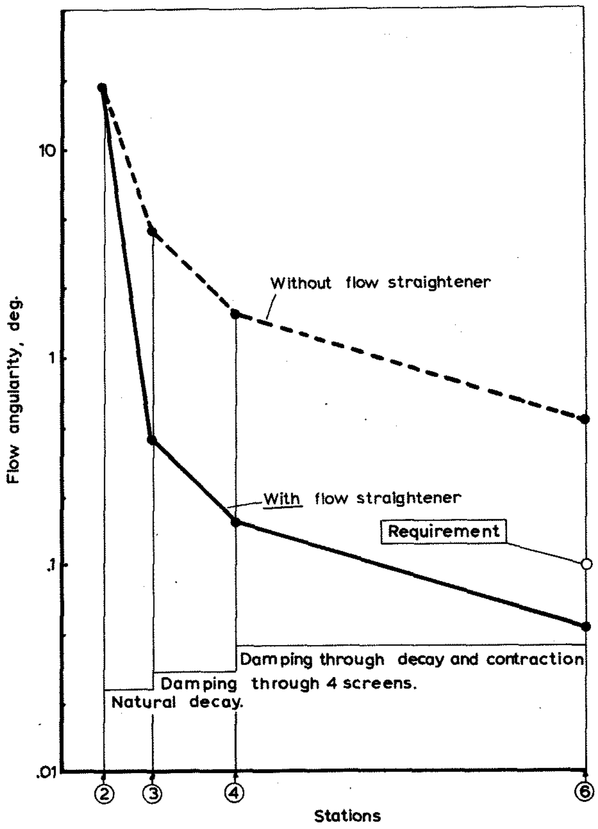

Figure 5 Reduction of Flow Angularity

Figures 4 and 5 show that even with tight fin tolerances the specified values for the turbulence level and the flow angularity could not be achieved. Therefore it was decided to install a honeycomb flow straightener with a cell diameter of ½" and a length of 115 mm closely behind the heat exchanger at station 3. (The stations referred to in the figures 4 and 5 are indicated on figure 8.)

The corner vane geometry has been selected in view of good turning effectiveness rather than minimum loss coefficients. The vanes are made of bended steel plates stiffened by horizontal splitter plates. For noise attenuation acoustic lining pads are fixed to the inner curvatures of corner 1 and 4 which results in a thickness/chord ratio of 0.074. The pitch/chord ratio is 0.29 for all vanes. The aerodynamic loads acting on corners 1 and 2 are 800 kN (radial) and 9 kN (tangential), and on corners 3 and 4 about 1800 kN (radial) and 3.3 kN (tangential).

A special feature of the DNW circuit is an air exchange system in the vicinity of the first corner, consisting of a throttle (vertical structures with split flaps) and of air inlet and outlet hatches. Throttling the circuit is envisaged especially at low velocities to compensate extra thrust of model engines and hence to assist in fan speed control. Air exchange is required to remove hot and/or contaminated exhaust gases from the circuit. To perform this ventilation the throttle will block the passage between the first and second corner completely while simultaneously the hatches are opened.

## Fan Characteristics

The fan design is based on the so-called arbitrary vortex method using an optional radial distribution of the tangential velocity component, and yielded a fan with a specified exit velocity profile for given entry conditions (which were actually measured in the model tunnel). With the known pressure losses of the different tunnel components (Table 2) the circuit loss factor $K_o$ and thereupon the fan pressure rise coefficient f and the advance ratio J could be determined. The maximum fan speed was selected at 225 rpm. This lead to the following fan geometry: rotor with eight tapered and tilted blades, the chord varying from 2.0 m at the root (Gö 797) to 1.2 m at the tip (Gö 796), aspect ratio: 1.9, blade length: 3.09 m, tip diameter: 12.35 m, twist: 15.9°, blade setting: 42° ; seven stator vanes. The selected profile lift coefficients for empty tunnel conditions are about 0.5, i.e. sufficiently low to avoid premature stalling of the fan even

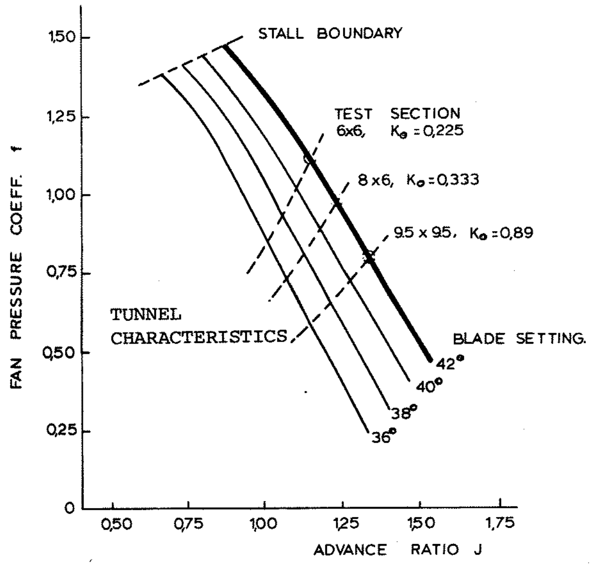

Figure 6 Fan Characteristics

| TEST SECTION | | 9.5m x 9.5m | | 8m x 6m | | 6m x 6m | |
|---|---|---|---|---|---|---|---|
| PRESSURE LOSS COEFFICIENT OF TUNNEL COMPONENT | i | $K_{oi}$ | % | $K_{oi}$ | % | $K_{oi}$ | % |
| TEST SECTION AND CONTRACTION | 1 | 0.031 | 3.6 | 0.028 | 9.9 | 0.024 | 11.9 |
| FIRST DIFFUSER | 2 | 0.088 | 10.2 | 0.053 | 18.7 | 0.068 | 33.8 |
| 1ST AND 2ND CORNER | 3 | 0.137 | 15.9 | 0.038 | 13.4 | 0.021 | 10.4 |
| THROTTLE (OPEN) | 4 | 0.040 | 4.6 | 0.011 | 3.9 | 0.006 | 3.0 |
| 1ST SHORT LEG AND FAN HOUSING | 5 | 0.035 | 4.1 | 0.010 | 3.5 | 0.005 | 2.5 |
| 2ND (MAIN) DIFFUSER | 6 | 0.073 | 8.5 | 0.020 | 7.1 | 0.011 | 5.5 |
| 3RD AND 4TH CORNER | 7 | 0.022 | 2.6 | 0.006 | 2.1 | 0.003 | 1.5 |
| 2ND SHORT LEG | 8 | < 0.001 | < 0.1 | < 0.001 | < 0.1 | < 0.001 | < 0.1 |
| WIDE ANGLE DIFFUSER | 9 | 0.096 | 11.2 | 0.026 | 9.2 | 0.014 | 7.0 |
| HEAT EXCHANGER | 10 | 0.113 | 13.1 | 0.029 | 10.5 | 0.015 | 7.5 |
| FLOW STRAIGHTENER | 11 | 0.017 | 2.0 | 0.005 | 1.6 | 0.003 | 1.5 |
| SETTLING CHAMBER SCREENS | 12 | 0.154 | 17.9 | 0.042 | 14.8 | 0.023 | 11.4 |
| SAFETY SCREEN | 13 | 0.054 | 6.3 | 0.015 | 5.3 | 0.008 | 4.0 |
| $K_o = \Sigma K_{oi} = \Sigma \Delta p/q_o$ | | 0.860 | 100 | 0.283 | 100 | 0.201 | 100 |

Table 2 Breakdown of Pressure Losses for Tunnel Components

during operation with air exchange up to 25% of the maximum wind speed in the test sections. Figure 6 shows the fan characteristics. Considering effects of Reynolds number, compressibility and tip clearance, and based on model tunnel experiments the fan efficiencies vary between 0.90 for the 9,5x9,5 test section configuration and 0.95 for the 6x6 configuration. Due to table 2 the design conditions for the 6x6 configuration are determining for the required drive shaft power. A more detailed description (4) also refers to design alternatives and relevant tests in the model tunnel. The fan blades are being manufactured of carbon fibre reinforced plastics; they will have a mass of about 120 kg and natural frequencies sufficiently above the blade passing frequency.

## Contractions and Test Sections

The test sections and adjacent parts have a total length of 48 m (equalling the length of the testing hall) and form an essential structural and functional part of the complete closed circuit (total length of the centre line: 318 m). The aerodynamic design of these sections had to take into account several limiting conditions:

- specified flow qualities
- required effective lengths of the three test sections
- basic design of the fixed part of the circuit
- interchangeability
- slotted walls and breathers
- fixation of one model centre
- mutual tuning of movable parts and installations in the settling chamber
- convenient logistics

According to the specifications(1) the design included the requirement that the static pressure deviations should not exceed 0.3% of the average dynamic pressure along an effective, i.e. fully usable test section length, and within a "usable" area of 64% of the cross-section. The required effective test section lengths amount to 9 m (6x6x20, width x height x length), 12 m (8x6x20) and 14 m (9,5x9,5x20). Furthermore, the geometry should have no unfavourable influences on the stationary (angularity, total head) and instationary flow qualities (turbulence).

## Contractions

For the design of the contraction parts of DNW a special numerical method based on three-dimensional potential flow theory had been developed at the NLR (5). This method enables the calculation of internal flows through channels of varying rectangular cross sections and the pressure distribution along the walls. Reliability was proven by means of several correlations between theoretical and experimental results for model tunnel configurations. Ample consideration was given to the avoidance of flow separation and the minimization of secondary flow effects; these phenomena were expected to appear in the wide part and in the narrow part of the contraction respectively. The Stratford criterion was used to predict boundary layer separation. For the fixed part of the contraction, which is identical for all test section configurations, contours were selected according to Börger (6). These contours show moderate curvatures with smooth gradients and are not critical with respect to flow separation. Downstream of the intersection area which is located 11 m aft of the contraction entrance the contours are faired to the various test section dimensions by means of polynomials of different order. The final contours resulted from a lenghthy iterative calculation process; they are shown on figure 7 for the 9,5x9,5 contraction. This configuration was the most critical with respect to secondary flow effects. It was possible, however, to reduce all contractions to a total length of 22 m and hence allow for sufficient lengths of the test sections. The 6x6 contraction has been realized by prismatic inserts of 5 m length to be installed in the downstream part of the 8x6 contraction. The side wall contours of all three contractions were corrected for the displacement effect of the boundary layer. The wall divergence is 0.2 °, according to a displacement thickness of 20 mm, and matches the divergence of the test sections' entrance.

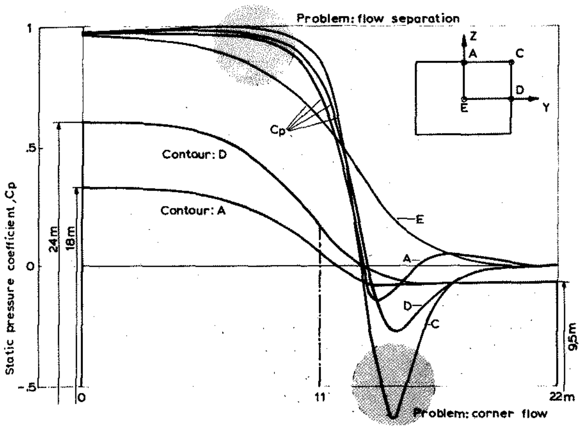

Figure 7 Contours and Static Pressure of the 9,5x9,5 Contraction.

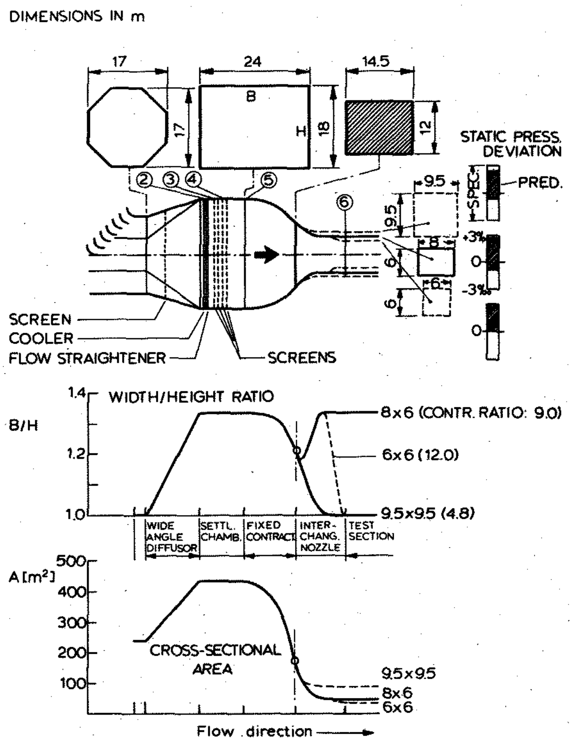

Figure 8 Design of the Contractions

Figure 8 illustrates the difficulty of the design task arising from the strong variation of the cross-sectional shapes between the fourth corner and the contraction exit as a result of the interchangeability of the various test sections. The hatched area is the intersection between the fixed and movable part of the contractions. The predicted static pressure deviations in the test sections are still within the specifications.

## Test Sections

The design of the contraction has yielded acceptable flow qualities for "effective" test section lengths of 9 m (6x6), 16,5 m (8x6) and 15.5 m (9,5x9,5), beginning 3 m, 0 m and 0 m respectively downstream of the test section entrance.

In order to provide atmospheric conditions in the test sections these have to be vented by breathers located near the downstream end. The size of the breathers is governed mainly by the maximum allowable transient pressures acting on the structure of the test section components during the acceleration and deceleration of the fan. This dynamic behaviour of the flow in the circuit has been determined by applying the mass conservation principle as proposed by Templin, relating the change of air mass in the circuit variable with time to the mass flow through the breathers. By aid of experiments in the model tunnel with various types of breather arrangements the maximum transient pressure was found for the case of a sudden deceleration from maximum velocity. For an optimum breather performance for all three configurations and - also under stationary tunnel conditions - perforated plates will be inserted flush in the walls about 2 m upstream of the test sections' end. The 6x6 test section requires the most intensive air exchange; in this case the total opening area is 3.2 m$^2$ and the open area ratio about 57%.

In order to minimize the effect of wall constraint and to increase the tolerable size of models the idea of slotted walls has been strongly supported by many aerodynamicists during the last decade. Though the practical application still has to do without reliable prediction methods, especially because of the scarcely known viscosity effects in the case of ventilated walls, modern low speed tunnels (e.g. Boeing 20 ft x 20 ft, NASA 6,5 m x 4,5 m) are equipped with slotted test sections. As also DNW deemed such fitting advantageous all three test sections will be provided with slotted walls. The design aims at a minimization of wall constraint under application of known correction methods. If pressurized plenum chambers are provided (at a later stage) the slots will also permit to ventilate the test sections. The geometry of the slots had been determined with the aid of a special method for the calculation of lift interference with slotted test sections:

- slot width: variable from 0 to 0.12 m
- pitch: 1 m
- length: about two times the test seciton width
- position: in all four walls, upstream of the breathers

Experience showed that the slots should be tapered at both ends to reduce distortions of the boundary layer. A smaller pitch (and consequently a smaller width) would have resulted in a more homogeneous condition near the walls; the slots, however, would be more sensible to viscosity effects. Furthermore, sufficient space between the slots is needed for lighting units, windows etc. With respect to the interchangeability of hatches, turntables, moving belt etc. the same slot arrangement is applied to all test sections.

Tests in model tunnel showed that open slots cause a considerable drop of the static pressure along the centre line in downstream direction (figure 9). Therefore the breathers have been designed as a flap which can be deflected inwards and enable an easy control of the static pressure.

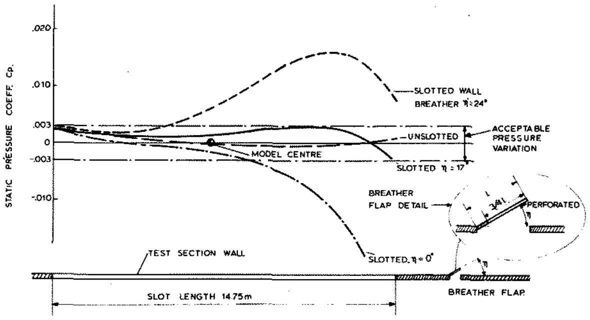

Figure 9 Static Pressure Control by Breathers (8x6 Test Section)

As an example, the static pressure deviation in the 8x6 test section can be kept within the specified tolerances by setting the breathers at $\eta = 17^{\circ}$, slots being completely opened.

Finally, all design considerations had to be checked repeatedly in order to determine the optimum position of the model reference centre. For practical reasons the model centre should have the same position for all test sections and harmonize with the arrangement of the balance, sting support, moving belt, effective test section length, breathers and slots. As a compromise the model centre is projected at 7 m downstream of the contraction exit and coincides with the axis of the external balances and the turntables.

## 7. Aero-Acoustic Features

As future aircraft design will take into account noise consideration still more seriously, aero-acoustic measurements on models in wind tunnels may probably become an essential part of the development work, especially concerning airframe noise. The measurement of this type of noise necessitates exacting test provisions:

- low back-ground noise level, below model noise (DNW: < 85 Hz in the 1000 Hz octave)
- possibility to determine the far-field noise

## Testing Hall

According to the present state-of-the-art, DNW found an open jet (8x6 contraction) within an anechoic testing hall the most promising solution for far-field measurements. A proper location of the microphones requires distances from the model of at least once the jet width for "fly-over" and twice the jet width for the sideline position. In order to meet these requirements one wall of the testing hall has a distance of about 20 metres from the centre line of the jet. To obtain an anechoic environment the walls (including the sliding doors to the parking hall), the ceiling, and the floor will be covered by noise absorbing wedges (base area: 0.2 m x 0.2 m, length: 0.8 m, absorption: about 99% of the normal incident sound energy above 100 Hz). The acoustic properties of the wedges will have to be proven by interference tests with pure tones at frequencies of 100 to 8000 Hz in 1/3 octave intervals. Furthermore, sound absorbing ventilation openings had been designed.

Fan Design

As the fan is the main noise source in low-speed wind tunnels, the fan design has been tuned also to a low noise level:

- no stall of the 8 fan blades and the 7 stator vanes (located downstream) under all stationary test conditions
- stator vanes with 15° sweep
- direct fan drive by a low-speed electric motor results in
  . low fan tip speeds (maximum about 150 m/s)
  . low blade passing frequency (maximum about 220 Hz)
  . no gear noise

The use of 11 stator vanes (instead of 7) which would have suppressed the blade-passing frequency noise completely was not compatible with the structural design aspects of the fan house.

Fan Noise Attenuation

In order to reduce the fan noise propagated to the testing hall acoustic treatment has been applied to the turning vanes of the first and fourth corner, i.e. downstream and upstream of the test section. Tests in the 1:10 model tunnel showed that a treatment of the inner curvature of the vanes is most effective, although it is more susceptible to contamination than the outer curvature. The treatment consists of prefab elements filled with glass wool and covered with a filter mat and an aluminium sheet of 30% perforation; it yields a noise reduction of about 17 dB at the fourth corner and about 6 dB at the first corner, both at 2,5 kHz and 85 m/s. The treatment of the first corner resulted in a power increase of 1 to 1.5%. As symmetrically thickened vanes are more sensible to changes of the angle of attack than plate vanes with respect to turning effectiveness, the lined vanes will have a flat plate extension of the trailing edge.

Test Section Configuration

Due to the testing requirements only an open jet configuration came into question. Extensive optimization studies on 26 different configurations had been carried out in the model tunnel to find a technical solution with the 8x6 contraction acceptable from both the aero-acoustical and aerodynamical point of view. In order to provide a lateral microphone "view" on the aircraft model as wide as possible, tests started with a long jet configuration (full scale jet length 32 m). The jet was blown through an acoustical separation wall (diaphragm) which was located at half the jet length perpendicularly to the jet axis. The wall should stop the noise travelling upstream from the first diffuser. This configuration had the lowest background noise level above 200 Hz but suffered from a severe low frequency instability of the flow - known as wind tunnel "pumping" - which could not be cured by usual measures as partial ventilation by the air exchange system or a slotted or teeth type collector intake. Therefore a configuration with a shorter jet had been finally selected having the following features:

- length of the jet: 20 m (no diaphragm), no flow pulsation
- movable transition of the 9,5x9,5 test section as flow collector, supplemented by an intake cowl
- acoustic lining of the inside of the collector to attenuate diffuser noise

Scaling of Noise Tests

The prediction of the background noise level of the DNW facility on the basis of tests in the model tunnel caused some scaling problems. A simple frequency scaling (1:10) would have yielded a noise spectrum 18 dB below that of the model tunnel. Experimental results from various open jet wind tunnels, however, show that the noise levels differ only about 10 dB in the 1000 Hz octave. For want of proven scaling laws it is assumed that tunnel background noise and airframe noise can be scaled in the same way.

The model tunnel showed a background noise of 87 dB in the 1000 Hz octave. Frequency scaling would result in 69 dB for DNW. Taking into account that the acoustic treatment is more effective in the DNW than in the model tunnel for the 1000 Hz range, the background noise of the DNW is estimated to be about 73 dB which would be well below the specified maximum of 85 dB.

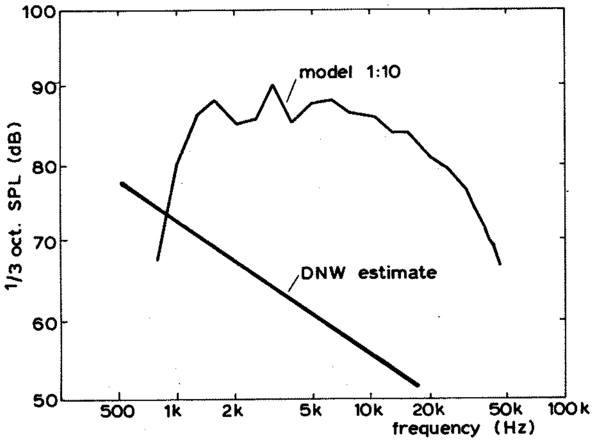

Figure 10 Noise Spectra of DNW and of an Airliner (Take-Off: 95 PNdB at 150 m)

Figure 10 shows that the noise of an aircraft model can be clearly identified at frequencies above 1 kHz. By tests with a model of the streamlined sting support it had been proven that this equipment produces a rather low noise and hence will be a suitable model support for aero-acoustic measurements.

## 8. Aspects of Civil Engineering

In order to realize the careful aerodynamic lay-out of the circuit adequate design studies were carried out on the civil engineering side, mainly by the Adviesbureau voor Bouwtechniek, Arnhem (NL). Because of restrictive regulations for noise propagation into the environment it was decided to construct a concrete tunnel shell. From several alternatives a construction of prefab reinforced concrete plates and steel frames, resting on poured concrete walls and pillars, had been selected as the optimum solution (7). This alternative shows favourable features as:

- smooth and wear-resistant inside surface
- tight tolerances (specified: maximum linear deviations ± 0.3% with a maximum of ± 30 mm; actually achieved: 5 to 15 mm for all cross-sections)
- efficient acoustic damping (sound level at 1000 m distance and at maximum fan speed: about 30 dB)
- few concrete casings at site (only for the supporting construction)
- short construction time to minimize interference with other contractors

To cope with the temperature differences of 18 C between the upper and the lower side of the circuit and 35 C between inside and outside, the shell has been covered with glass wool and aluminium sheet. Without this outside insulation a much heavier construction and larger expansion joints would have been necessary to compensate thermal deformation effects. As a starting point for the calculation of the shell structure the horizontal forces had to be determined, considering

- internal static pressures in the range of + 13.5 kN/m$^2$ to + 2 kN/m$^2$
- inside air temperature rise up to about 40° C
- flow momentum
- external wind loads up to 1 kN/m$^2$

As a result longitudinal tension forces of about 2500 kN and maximum tangential forces of 1400 kN will act on the "fixed sections" of the circuit, i.e. on the wall constructions upstream and downstream of the fan house and the test sections. Sliding supports will permit a horizontal expansion of the two halves of the circuit. The final iterative calculation of deformations, tensions and forces was based on the finite element method. By the initial calculation step ('forward pass') the stiffness of the shell elements were determined. Afterwards the overall forces were obtained from a 'global run', which was followed by a 'retracking cycle' to calculate the deformation of the elements. Several novel design details (e.g. connection of plates in longitudinal and cross direction) supplemented the unusual engineering task.

## 9. Development of Equipment

For the numerous installations and equipment special design and engineering studies have been carried out which are based on the initial specifications and shall mutually harmonize within the overall wind tunnel system DNW. As an example for an unorthodox equipment the development of the "q-stopper" is illustrated. This device shall be used as a quick-acting flow deceleration system during flutter tests to avoid severe damages or even the total loss of the model. For this purpose the dynamic pressure in the test section must be reduced by 10% within 0.2 seconds. A review of possible technical solutions revealed that the installation of purely mechanical devices (e.g. braking parachutes, spoiler flaps) would cause serious structural problems both for the fan and the test sections. Therefore an aerodynamically acting device had been suggested according to the principle of a retro-jet.

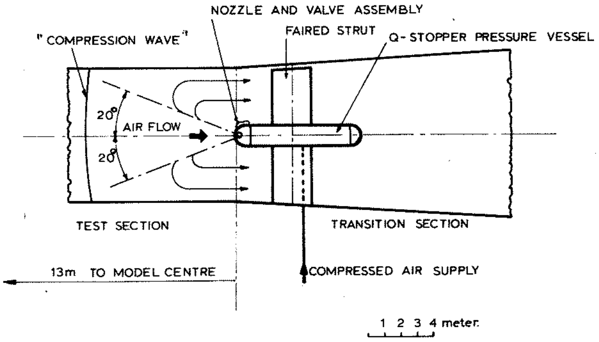

Figure 11 Principle of the Q-Stopper

Figure 11 shows the general arrangement and the mode of operation. The main structure consists of a pressure vessel provided with several nozzles at the upstream end and supported by faired vertical struts. In case of need the vessel is located on the tunnel centre line at the entrance of the test section transition. By means of a quick-opening valve inside of the nozzle head compressed air is ejected through 8 outward inclined supersonic nozzles against the test section flow. After interaction with the tunnel walls the bursted jets form a curved compression wave which runs over the model and effects the required flow deceleration. By tests in the model tunnel of the DFVLR the effectiveness of the retro-jet principle could be successfully demonstrated and the performance of a q-stopper model determined. The results can be summarized as follows:

- the q-reduction was obtained within that time which the pressure wave needs to move from the q-stopper to the model centre
- the magnitude of q-reduction depends on the pressure in the vessel
- the duration of the q-reduction is determined by the volume of the vessel
- the strength of the initial pressure wave is reduced to one third after having rounded once the circuit

A theoretical treatment of the q-stopper (8) showed excellent agreement with the model tests. Therefore the performance of the full-scale q-stopper of DNW could be predicted. According to figure 12 the q-stopper becomes fully effective already 0.1 s after tripping of the valve (distance of the model centre: 13 m, pressure in the vessel: 110 bar) whereas the fan contributes to the q-reduction but 0.5 s after the synchronous tripping of the emergency switch. The final design of this equipment has been made by the consultant Dilworth, Secord, Meagher Ass., Toronto, who was also charged with engineering work for installations in the concrete circuit, the fan and the test sections. Further examples of equipment specially developed for the DNW are the scoop and the moving belt ground plane.

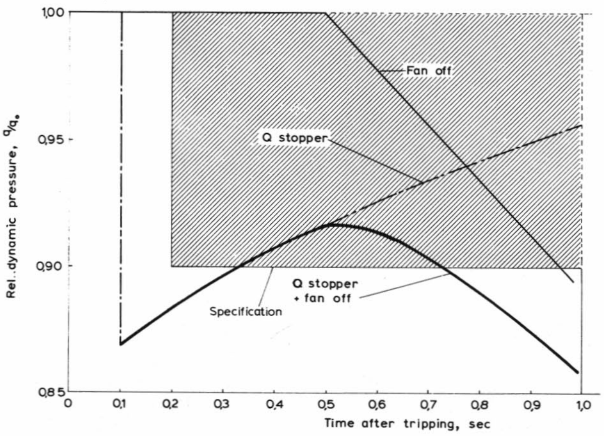

Figure 12 Performance of the Q-Stopper

In some important cases even the manufacturers are strongly involved in detailed design and development as for the external balance and the sting support mechanism.

## 10. Status of the Construction

The co-operative project work officially started in the begin of 1976 when the common project group had been established. On July 1, 1976, the execution of the construction work was commenced ceremonially at site by driving the first pile. The aerial photograph (figure 13) shows the extent and progress of the civil work in August 1977 and displays some typical design features. By the end of 1977 the circuit and two of the four corner vane assemblies had been finished in the rough. The year 1978 is earmarked by the completion of the civil work and by the installation of first rate equipment as the fan section and the 8x6/6x6 test section components. In April 1978 the fan housing had been completed so far that the drive motor could be installed in the centre body (figure 14).

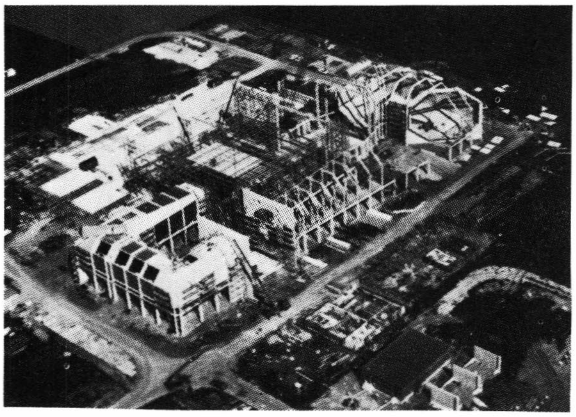

Figure 13 Aerial Photo of the Site (Photo: KLM Aerocarto of 28.8.1977)

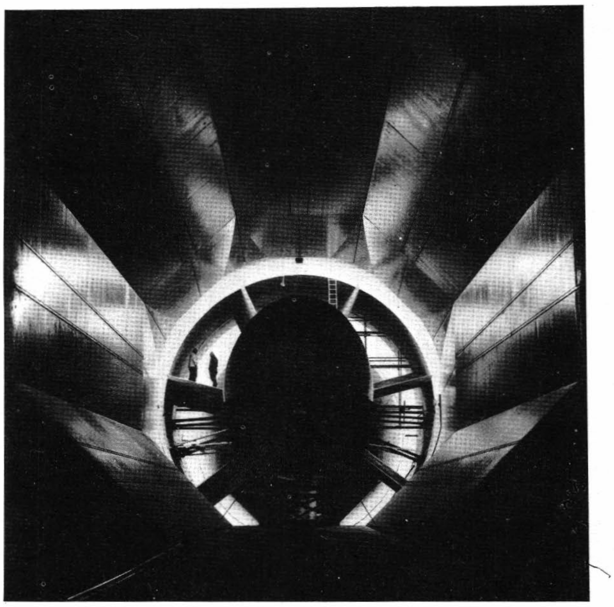

Figure 14 Upstream View on the Fan Section

The power station was commissioned duely so that the no-load functional tests of the motor are set going. These are being continued now by balancing the motor/rotor boss assembly so that the rotor blades can be mounted in October. At the time being the erection of the re-cooling system (cooling towers, pump station, water treatment facility), the compressed air plant and the convertible test section is in full swing. In parallel peak activities can be recognized for the installations in the control room. A first trial run ("wind-on") is planned by the turn of this year and will be followed by a series of check-out runs, commissioning tests and calibration measurements. In this period the data handling and control system, the sting support mechanism and the moving belt ground plane will be completed so that the DNW can enter upon the operation phase in the second half of 1979. The external balance and the 9,5x9,5 test section will be available before the end of 1979.

The progress hitherto achieved gives some confidence in the applied methods and procedures and in the kind of co-operation of all parties involved. These have well realized that the design and construction of a very large and complex wind tunnel facility as DNW should aim at a "non-failure" project, as any major correction of design defects or unforeseen amendments will cause considerable technical, financial and scheduling problems and may call the purpose of the project in question. Therefore the necessity of careful and comprehensive design work has been stressed from the beginning. In order to meet the ambitious technical requirements and to minimize any risk it also became evident that experimental design support by specially built model tunnels is undispensible.

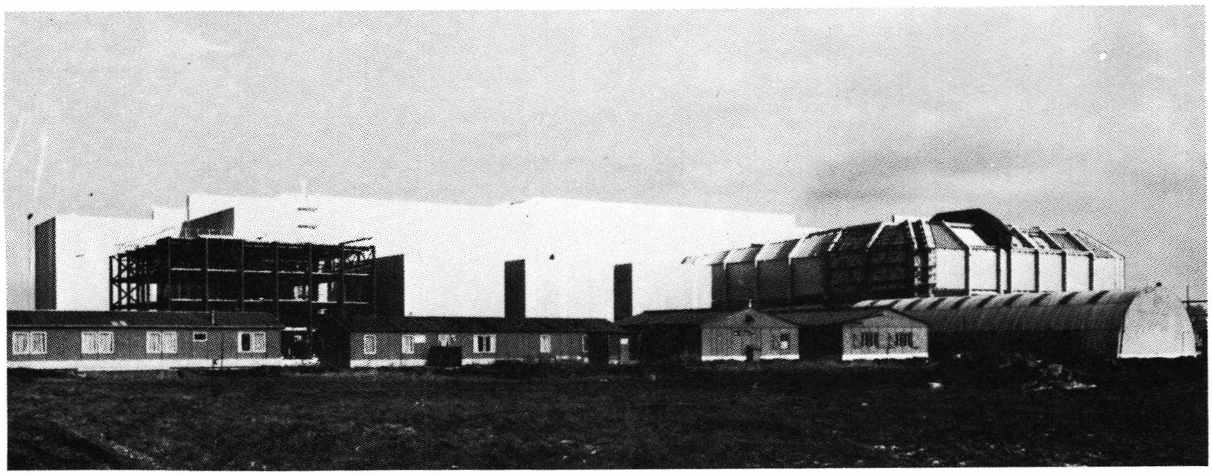

Figure 15 DNW Facility; Status: Mid 1978 (View From West)

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