50 YEARS HIGH SPEED WIND TUNNEL TESTING IN THE NETHERLANDS

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Foundation Historical Museum NLR

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Bram Elsenaar

Foundation Historical Museum NLR

Contents

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Preface

It is a privilege to introduce this book on half a century of high speed wind tunnel testing in The Netherlands. The task of the Foundation Historical Museum NLR is to preserve and to document the history of the National Aerospace Laboratory NLR. Wind tunnel testing has been on the agenda of NLR and its predecessors for almost a century now. The author, Bram Elsenaar, was responsible as a volunteer for the section on Aerodynamics in the museum. He documented the still existing hardware and equipment and researched numerous documents. In 2010 the 50th anniversary of the High Speed Wind tunnel was celebrated. In a series of presentations many aspects of this famous wind tunnel were highlighted. As a former aerodynamicist in high speed wind tunnel testing Bram Elsenaar had his share in this celebration.


Kees Bakker

The Board of the Foundation was really pleased when he suggested writing a book on 50 years high speed wind tunnel testing in The Netherlands. It was clear that such a book would become a historical document fitting the task of the Foundation. It was originally intended to make it a museum publication with a limited distribution. However when the document came closer to completion it became clear that it was potentially interesting for a larger circle of readers interested in the history of aeronautics. In a very accurate way a lot of background information on the (international) development of the high speed wind tunnels of NLR has been collected. And the book describes how these tunnels contributed to many projects in civil and military aviation. It was finally concluded that the book deserved a professional and representative publication.

It then became a challenge for the Board of the Foundation to find the required additional budget. We were very happy that NLR as well as the Netherlands Association of Aeronautical Engineers (NVvL) expressed their willingness to support the publication of this book. I hope you will appreciate the book. ■

Kees Bakker
Chairman of the Foundation Historical Museum NLR

Acknowledgement

In 2010 it was 50 years ago that the transonic High Speed Tunnel (HST) of the National Aerospace Laboratory NLR was officially opened in the presence of representatives of the Dutch Government and of the 'International Association of Aircraft Manufacturers' (AICMA). Since that time this tunnel and the related supersonic facility SST that became operational a few years later, have been used extensively by the aircraft industry from The Netherlands and abroad. Till today these facilities are among the best wind tunnels in the world, used by customers from all over the world. Why were these technically advanced wind tunnels built? And why have they been so successful from the beginning of their operation? These questions triggered a study into the origins of the HST and SST just after World War II. At that moment the first ideas for these tunnels took shape following a well structured policy by the Dutch Government to support and facilitate a national aeronautical industry. The decision to build these wind tunnels reflects the new élan in 1945 to rebuild the industry after the devastating years of war. This message, as a result of a clear vision by the Government, was picked up by the Directors and the Staff of NLR (NLL at that time). The book tells the story how, through intensive international contacts, these facilities could be built, facilities that were up to date or even ahead of their time when they were opened.

The step from subsonic to transonic and even supersonic flight was made during and just after World War II. This by itself already represents a tremendous technological achievement. Wind tunnels were essential to develop these new airplanes. But around 1950 the techniques to measure pressures and forces on wind tunnel models were still very conventional and based on the height of a column filled with water or the dead weight on a bascule to balance the aerodynamic forces. All data recording and the subsequent calculations were done by hand. The development of new measuring techniques for these facilities, leading to fully automated systems with a very high productivity, is equally interesting. And finally, the succession of many models tested in these facilities gives an interesting view of the development of the aircraft industry after World War II although many configurations didn't reach the market.

These three topics, the design and construction of the hardware of the transonic and supersonic tunnels, the development of the measuring techniques and the aerodynamic testing in these facilities are documented in this book. The rapid rise of numerical aerodynamics or Computational Fluid Dynamics (CFD) is touched upon in so far as the wind tunnels have been instrumental in its development, first to understand aerodynamics and later to validate the new numerical calculation methods. This development was in time also directed towards the use of CFD to enrich wind tunnel testing itself.

Basically this study covers the period between 1945, the end of World War II and 1996, the year of the bankruptcy of Fokker, followed by a transfer of all wind tunnels to the DNW organisation, the German-Dutch co-operation that operated already the large Low Speed Windtunnel in the Noordoostpolder. In some cases, such as measurement techniques and CFD, information after 1996 has been added to complement developments started earlier. Model manufacturing has been discussed, though not very extensively. This is a very important area and the advances in aerodynamic testing would not have been possible without the equally impressive development in model design and manufacturing. NLR has been and still is leading in this area as well. The impressive work of the RSL, NLL and NLR design office and workshop deserves a separate study, a study for which I don't feel competent.

This history of the high speed wind tunnels has been written primarily with the intention to preserve the past of NLR, the prime mission of the Foundation Historical Museum NLR. It is specifically of interest for those who have been or are still working with these tunnels, either as a customer or as an employee of NLR or DNW. But this history might also be of use for those interested in

the history of technology of aeronautics. Since some readers will not be familiar with wind tunnels and wind tunnel testing, a '*Short course on wind tunnel design and testing*' and a '*Glossary of technical terms*' have been added as Appendices E and F respectively. In April 1961 NLL changed its name to NLR, to indicate that space activities ('*Ruimtevaart*') were part of its mission. In the text NLL is used before that date (or even RSL before June 1937) and NLR after that date.

The study is largely based on reports and publications that are now preserved by the Foundation Historical Museum NLR. I would like to thank the Board of this Foundation, Kees Bakker, DirkJan Rozema, Jan te Boekhorst and Floor Pieters explicitly for their commitment to preserve the historical heritage of NLR and for their always stimulating interest and contributions. The museum has a large collection of wind tunnel models and instruments that are on display for the public. In this book a reference is made to these items whenever possible (the particular item in the text is marked with a *). It provides an interesting three-dimensional illustration of the text. The objects of interest are listed in Appendix G.

Most of the official reports have been preserved. But many internal notes that could have provided interesting information on the choices that were made or technical details of the selected solutions are only known by their title. This is rather unfortunate, also because there is a real danger that information from some of the internal reports that have been preserved, might have guided the reconstruction of what has happened in a biased way. Fortunately, the Annual Reports of RSL, NLL and NLR have provided a wealth of information and have been used extensively. They have not been referenced in the text.

Initials and titles of the persons appearing in the text have been omitted. The titles have also been omitted in the List of References. However, they have been included in the 'Index of names' at the end of the book.

I would like to thank many former colleagues who contributed to this book. In alphabetical order: Jan Besseling, Simon Boersen, Klaas Breman, Bob van Dillen, Ernst Folkers, John Hartzuiker, Frerik Jaarsma, Piet van Leest, Bert de Moes, Karl Möller, Ed Obert, Jos Slottje, Peter Stenvers and Hans van der Zwaan. Fortunately, they were able to fill many white spots and some of them provided very interesting details as eyewitnesses. Many of them have read draft versions of the book and made corrections wherever necessary. Quite a few foreign companies contributed to the high speed tunnels and their equipment. It was possible to retrace some of these companies and it is very remarkable that in three cases the sons of those who contributed in the past and who continued in the tradition of their fathers, were so kind as to provide me with additional information. I would like to mention them explicitly and to thank them in particular: Howard Ward, the son of Elmer Ward who started the TASK balance development in 1951 (through contacts with Tony Snyder, Owner and President of Aerophysics Research Instruments), Addison Pemberton, President of the Scanivalve Corp and son of J.C Pemberton, the founder of the Company, and Urs Isler, son of the business partner of Hausammann in the Company Hausemann & Co (who built the HST test section and the SST), the company later to become Hausammann & Isler and now Ingenieurbüro Isler AG (through contacts with Jürg Wildi, Chief Technology Officer of RUAG Aviation and Raffaelo Pozzorini, also of RUAG).

This book has been written in the universal language 'broken English' described by H.B.G. Casimir (the former head of Philips NatLab) as '*a more or less successful attempt to write correct English*'. It is the language I used for my technical reports or in discussions with my colleagues abroad. My style is certainly no as fluent and as rich as a native speaker's. I have asked a professional, Gerard Oonk, to read the entire manuscript and to correct my English. He volunteered to do so and his contribution is highly appreciated. Moreover, he cannot be blamed for remaining errors in the text since I had the bad habit to keep changing its contents. ■

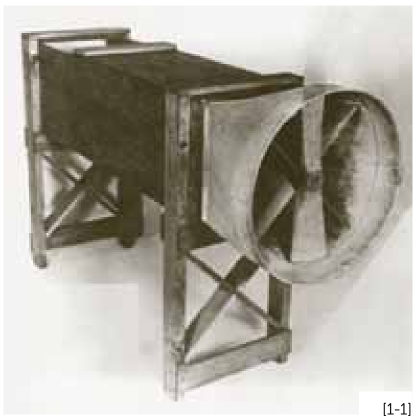
Bram Elsenaar
Amsterdam
December 2011

Towards high speed wind tunnels

WIND TUNNEL TESTING BEFORE 1945

THE FIRST WIND TUNNEL

During World War I the Dutch Government decided to form an institute for aeronautical studies. On April 5, 1919 the new laboratory with the name 'Government Service for Aeronautical Studies' ('*Rijksstudiedienst voor de Luchtvaart*' or *RSL*), was officially opened[1,2]. The establishment of an aeronautical research institute at that time, only 16 years after the first powered flight by the Wright Brothers and only 10 years after the first 3½ minutes flight in The Netherlands by the French count Charles de Lambert, reflects the great interest in aeronautics in The Netherlands[3]. Wolff, the first director of RSL, was convinced that flight testing by scientifically educated test pilots and wind tunnel testing were indispensable to bring aeronautics forward. In this respect he followed Wilbur and Orville Wright[4] who built a wind tunnel [figure 1-1] to optimize their wing design before their first powered flight in December 1903. In a wind tunnel a controlled air stream is generated. Sub-scale models of wing sections, wings or complete aircraft can be tested in this air stream to observe the flow and to measure the aerodynamic forces. These tests can be used to advance the understanding of aerodynamics but also to develop and optimize specific aircraft designs. Around 1911 the first wind tunnel in The Netherlands, a bit similar to the Wright wind tunnel, had been built in Delft by a group of enthusiasts' students, members of the 'Dutch Society for Aeronautics' ('*Nederlandse Vereniging voor Luchtvaart*'). Already in January 1918, prior to the official opening, the construction of a wind tunnel for the RSL started under the leadership of Pigeaud, early enough to have a working facility at the official opening of RSL in 1919[5]. After consulting Eiffel in France, it was decided to build a tunnel of the 'Eiffel' type, a tunnel without a return circuit where the air at the end of the test section returned through the building to the inlet section (see Appendix E). The tunnel had an open test section (which was closed later) with a diameter of 1.6 m and was about 3 m long, sized to result in a maximum speed of 35 m/s [figure 1-2]. From the beginning the quality of the measurements and the productivity of the tunnel were important issues. In the first years of operation the inlet section and the test section were modified to improve the flow quality. The external balance for a strut mounted model [figure 1-3], also based on a design by Eiffel that required four separate measurements to obtain one point on a drag polar, was quickly abandoned. Instead, the model was suspended by wires, attached to external balances that measured three aerodynamic coefficients simultaneously. This tunnel was intensively used till the beginning of World War II by a number of Dutch aeronautical companies such as Fokker, Koolhoven, Van Berkel, De Schelde, Aviolanda and Pander.



[1-1]

[Figure 1-1]

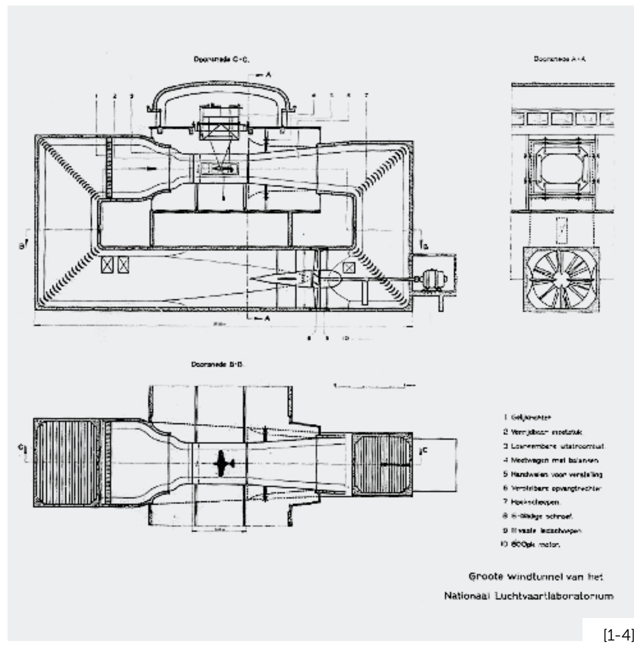
A replica of the self-made wind tunnel of Wilbur and Orville Wright for aerodynamic tests prior to their first flight.

[Figure 1-2]

Inlet section of the Eiffel tunnel, the first wind tunnel of the 'Governmental Services for Aeronautical Research' (RSL) in 1919. Shown here is the original inlet shape that was replaced with a 'bell mouth' to improve the flow quality in the test section. See also Appendix E [figure E-2].

[1-2]

[1-3]



[1-4]

NEW LOW SPEED WIND TUNNELS

Till 1937 the RSL was engaged in two types of activities: 'Regulatory oriented' (notably inspection of new designs) and 'Aeronautical studies on behalf of the industry'. The Dutch Government feared that there might be a conflict of interests and decided to split RSL into two parts, a regulatory part, the 'Government Department of Civil Aviation' ('*Rijksluchtvaartdienst*' or *RLD*) and a research part. The aeronautical research continued in the 'National Aeronautical Laboratory' *('Nationaal Luchtvaartlaboratorium'* or *NLL*). At the same time it was realised that, in view of the heavy workload, larger and better wind tunnels were required. Wolff and Koning (who succeeded Wolff as Director when he fell ill and died during the war) went on a fact finding tour in Europe and the United States and in 1938 it was decided to build two new tunnels of the 'Göttinger' type (a tunnel with a closed return circuit). The design [figure 1-4] was very similar to a tunnel in Zürich built by Ackeret. Two tunnels, the big and small Low Speed Tunnel or LST no. 3 and no. 4, were subsequently designed and built with test section dimensions of 3 x 2.1 m^2 and 1.5 x 1.5 m^2 and maximum speeds of 80 m/s and 40 m/s respectively. Similar to the Eiffel tunnel, the fan was driven by an electric motor connected to the public (electricity) grid. A pilot facility of 1/10 scale, tunnel no. 2, was used to check the design*. De Lathouder was involved in the design and commissioning of these tunnels. It was also decided to move NLL from the original site at the Navy wharf ('*Marine Werf*') in the harbour of Amsterdam to a new area on the outskirts of Amsterdam where it is still located. When World War II broke out, the tunnels were almost ready. Since it was feared that the installations at the Navy wharf might be attacked, nearly all equipment and archives were quickly moved to the new site during the first days of the War in May 1940.

STARTING HIGH SPEED RESEARCH

The two new tunnels were quickly finalized and started operation in June (no. 3) and November (no. 4) of the same year. During the occupation by Nazi-Germany, NLL was placed under the supervision of the 'Beauftragte' Käufl, who reported to Betz, the director of the 'Aerodynamische Versuchsanstalt' (AVA) in Göttingen, Germany. Betz was well-known in the aerodynamics community. He made very important contributions to the 'lifting line theory' for the calculation of the lift distribution on a wing. His name is also connected with the 'Betz manometer'*, a precision manometer. In a discussion with Betz in July 1940 it was agreed that NLL would not contribute directly to the war effort but could continue basic research activities in consultation with or even under contract from AVA. The relatively minor involvement in German war activities is probably due to the very good personal relations between Betz and the staff of NLL which dated from before the War. Nevertheless some war related activities took place, notably in the new wind tunnels. Under contract of a Dutch company special landing skis to be used on snow

[Figure 1-3]

A Fokker F.II model in the first wind tunnel of the RSL. The strut was connected to the Eiffel balance mounted above the test section. The first test aircraft of RSL was also a Fokker F.II (around 1920).

[Figure 1-4]

Lay-out of the big Low Speed Tunnel (LST, tunnel no. 3). This tunnel of the 'Göttinger type' was similar to a wind tunnel built by Ackeret in Zürich. The tunnel became operational in June 1940 and was used till 1984.
See also Appendix E [figure E-3].

were tested, a contract that probably could not be refused without repercussions. In fact, the tunnels were quite busy. However, judging from the publications during the war period, the larger part of the time of the staff was devoted to rather fundamental theoretical studies and to wind tunnel tests to establish and improve flow quality and testing techniques.

In 1939 a new high speed wind tunnel with an open ('free jet') test section of 11 x 11 cm² became operational at AVA in Göttingen. This tunnel could be run in a high subsonic (0.5 < Mach < 1) and supersonic (1.2 < Mach < 3.2) mode. One of the first tests was an experimental investigation by Ludwieg of a swept wing[6]. The concept of the swept wing was presented in 1935 by Busemann[A] on the 5th Volta conference[B] on 'High Velocities in Aviation' in Rome, Italy. With a swept wing the negative effects of compressibility on the aerodynamic characteristics of a wing could be postponed to higher velocities. The first signs of the importance of adverse compressibility effects were observed in the twenties on propellers when the tip speeds of the blades approached the speed of sound. From airfoil tests it was found that the airfoil characteristics deteriorated rapidly above a certain speed, denoted the 'critical Mach number'. These effects could be related to the appearance of shock waves on the airfoil, as visualized in 1934 by John Stack at NACA Langley with a schlieren system[7] (see page 57). These results were presented as well at the Volta conference together with similar pictures taken by Prandtl in Göttingen. Research on high speed flow phenomena and compressibility effects was rapidly gaining momentum. Flying speeds became so high that compressibility effects could no longer be disregarded.

[1-5]

[Figure 1-5]

Poster made by the Dutch Government just after the war with the text: 'A necessity for prosperity: industrialization'.

One Dutch scientist, Burgers, was invited for the Volta conference in Italy. Burgers was professor in aero- and hydrodynamics at the Delft Technical University and he advised NLL on aerodynamics. He got the new developments out of the first hand. In view of the close contacts between Göttingen and NLL it is likely that the NLL staff was already aware of most of these new developments. Similar contacts existed with NACA in the US. During a visit to the US in 1939, Marx, who became director of NLR later, learned about laminar airfoil sections studied at NACA Langley at high subsonic speeds in a pressurised wind tunnel. Enough reasons to put high speed research on the agenda of NLL. According to the 1939 NLL Annual Report *'it is important to have a small wind tunnel to study flow phenomena at high speed'*. To reduce the costs, a blow-down or vacuum driven intermittent facility was considered. In 1940 a study was initiated to see if high subsonic speeds could be obtained in the just finished low speed tunnels by mounting an insert with a smaller cross sectional area inside the existing test section. This problem must have been studied extensively during the War and it is likely that this was even investigated in the pilot tunnel no. 2. In July 1945, only two months after the end of the War, a report was published by Wiselius[8], showing that the energy loss in the diffusor would be excessive and that the use of an insert was not feasible. This report was part of a series of six reports[9] which discussed various aspects of the construction of high speed wind tunnels. It is probable that most of the work reported here reflects work done during the War, partly after September 1944, when the 'Beauftragte' Käufl had returned to Germany because of the changing war situation. It appears that at the end of the War the aerodynamicists at NLL were well prepared to make plans for new wind tunnels. ■

[A] BUSEMANN POINTED OUT THAT THE AERODYNAMIC CHARACTERISTICS OF A WING DEPEND ON THE MACH NUMBER COMPONENT IN A DIRECTION PERPENDICULAR TO THE WING LEADING EDGE. BY SWEEPING THE WING THE ADVERSE COMPRESSIBILITY EFFECTS COULD BE POSTPONED TO HIGHER FLIGHT MACH NUMBERS. AS WILL BE DISCUSSED AT PAGE 19, BUSEMANN HAS PLAYED A CRUCIAL ROLE IN THE SELECTION OF THE TRANSONIC TEST SECTION FOR THE HST.

[B] THIS CONFERENCE WAS ORGANISED BY THE 'ALESSANDRO VOLTA FOUNDATION'. IN ALTERNATE YEARS THE CONFERENCE TOPICS WERE SELECTED IN THE FIELD OF SCIENCES OR HUMANITIES. THE ITALIAN DICTATOR MUSSOLINI CHOSE THIS CONFERENCE TO ANNOUNCE THAT ITALY HAD INVADED ETHIOPIA.

1945: THE BIG PICTURE

GETTING STARTED AGAIN

The last half year of the War was very difficult. There was some fear that valuable goods might be confiscated and transferred to Germany. Therefore it was decided to hide important equipment at various farms in the neighbourhood. Electricity was cut in September 1944 and due to the shortage of energy the area around NLL (below sea level!) flooded occasionally [figure 1-6]. Since the tunnels could not be run anyhow, all scientific reports and the archives were stored in the circuit of tunnel no. 3 to keep them dry. The workshop was busy, though, with the production of small 'table' stoves to provide for some form of heating for the employees at their homes during the very cold winter of 1944/45 (also named 'the hunger winter'). Since there was hardly anything to eat, a 'food committee' was set up within NLL to organise food expeditions to farming areas, sometimes as far away as 100 km.


[1-6]

[Figure 1-6]

A neighbour of NLL (Sloterweg 75) during the war in 1944 when the area was flooded. The house is still there but has been renovated recently.

After the German capitulation on May 5, 1945 it took about one week to collect the equipment and other inventory from the neighbourhood. Electricity was reinstalled on June 13. There was much work to be done to get the equipment going again. Before the end of 1945 a number of business trips were made to renew contacts with the US and elsewhere to find out how aeronautics had developed in the mean time.

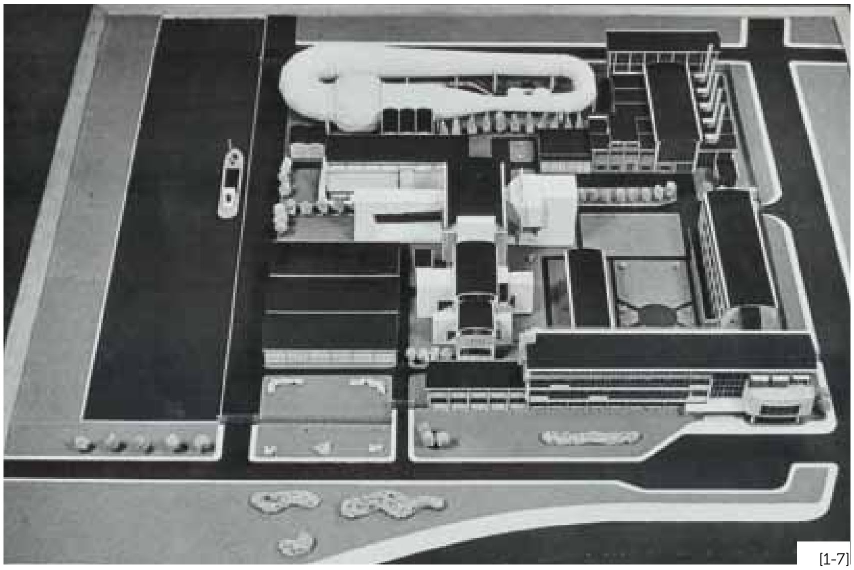
The Netherlands as a whole were in the mood of rebuilding the country that had been devastated during the War [see figure 1-5]. In September 1945 the Government formed a committee, officially named 'Interdepartmental Committee of Advice on the Construction of Aircraft' ('*Interdepartementale Commissie van Advies inzake de Bouw van Vliegtuigmaterieel hier te lande*'), here referred to as the 'Tromp Committee'[10] after its chairman Tromp. This committee had to find out if there were sufficiently promising opportunities for an aircraft industry with a '*full design and development capability'*. What was the situation of the industry at that time? During the War the aeronautical industry was forced to work for Nazi Germany. In fact 8,000 to 10,000 workers (!) had a job at different companies. The most important factories were those of Fokker, Aviolanda and De Schelde. The 'Tromp Committee' realized that a merger between these companies was essential to create a successful industry, although the Government could not enforce this[C]. It was recommended, next to aircraft maintenance and production under license, to concentrate on the building of small military trainers and to co-operate with foreign companies in the field of fighter aircraft. Civil transport type aircraft, such as a replacement for the Douglas DC-3, were also suggested. Since the Royal Dutch Airlines KLM could not be forced to buy Fokker products and in order to reduce the risk for Fokker, in June 1946 a new body, the 'Netherlands Institute for Aircraft Development' ('*Nederlands Instituut voor Vliegtuigontwikkeling*' or *NIV*), was established. Van der Maas became the first chairman. This institution got the task to advise the Government and to manage a 'revolving'[D] fund to support new projects of the aircraft industry. It was recognized that aeronautical research was essential and NLL was specifically tasked to engage in long term general research programs financed by NIV through rolling budgets. Three million guilders, about half of which was to be spent on a so-called high speed wind tunnel, were provided for investments to bring the facilities of NLL up to date. The work of the 'Tromp Committee' is still an outstanding example of industrial policy, pressing the industry to do its job and at the same time providing the proper financial and scientific infrastructure. For NLL the task was clear: design and build new wind tunnels.

NEW WIND TUNNEL PLANS

Based on previous studies, the information from fact finding trips to the US and elsewhere and in close consultation with the Dutch aircraft industry, a very ambitious wind tunnel plan was put together and made public in 1948[11]. The main elements of this plan were, in order of the estimated date of realisation:

- PT: the Pilot Tunnel, a 1:5 scale model of the high speed tunnel HST (to be discussed below) for atmospheric test conditions only. This tunnel was to be modified at a later date into a transonic facility for research purposes.
  To be ready mid 1949

[C] SINCE MARCH 1946 THE THREE PARTIES WERE WORKING TOWARDS A MERGER BUT THIS IDEA SHATTERED IN 1949; AFTER THAT FOKKER REMAINED BY FAR THE LARGEST COMPANY.
[D] THE IDEA WAS TO FEED THIS FUND WITH MONEY FROM AN ADDITIONAL CHARGE ON THE SALES OF AIRCRAFT THAT WERE FINANCED PREVIOUSLY BY NIV.



[1-7]

[Figure 1-7]

Mock-up of NLL as envisaged in 1948 by the architects Van Tijen & Maaskant. Behind the two existing smaller wind tunnels (middle/below; see [figure 1-8]) the Low Turbulence Tunnel LTT. At the top the High Speed Tunnel HST and the Power Plant (with the five smoke stacks). The (small) Supersonic Tunnel SST was originally foreseen in this building.

- LTT: a low speed, low turbulence wind tunnel for aircraft development. At that time laminar flow airfoils got much attention. The low drag characteristics of these airfoils enabled a significant increase in range. In combination with the available engines (piston driven propellers) direct flights across the Atlantic appeared to be within reach. However, testing laminar flow airfoils required very low turbulence levels, similar to those in flight. The LTT was also regarded as a back-up for the existing LST (which was heavily used) and for that reason the same test section dimensions (2.1 x 3 m^2) were selected. A maximum speed of 120 m/s was envisaged. To test aircraft models with propellers installed, a minimum span of 3 m was deemed essential. For these tests the test section could be enlarged to 2.1 x 4 m^2 at the expense of the maximum speed.
  To be ready mid 1950
- HST: a high speed wind tunnel with a test section of 2.1 x 3 m^2 to be pressurised till 4 bar absolute and a maximum speed of Mach = .95.
  To be ready at the beginning of 1951
- SST: a small, compressor driven supersonic facility with test section dimensions of 0.4 x 0.4 m^2 for Mach numbers up till 5 to be used for fundamental research
  To be ready at the beginning of 1952

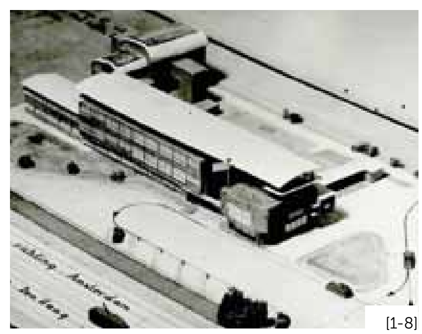
This plan was amazingly challenging. Immediately after the War detailed studies had started already on diffusor design, corner vanes and cooling aspects. The Dutch companies Stork and Heemaf were directly involved, as well as the architects Van Tijen & Maaskant (responsible for the NLL complex built in 1940 [see figure 1-8]). They prepared a mock-up to show what the NLR site would look like after all projected tunnels were finished [see figure 1-7].

The speed at which these plans were partly realised was even more amazing. At the end of 1948 the foundation for the PT was ready, the lower leg of the circuit for the LTT was poured in concrete and at the beginning of 1949 the ground preparation for the HST was also ready. Moreover, in 1947 three escort ships of the 'Buckley Class' were purchased* for a very good price in order to re-use the steam and turbo-electrical installations as a power plant to drive the new facilities. These ships, the HMS Halstead (US name Reynolds), HMS Duff and HMS Ekins [see figure 1-10 and 1-11] had been built in the US and were used by the Royal Navy in a 'lend-lease' agreement[E]. Each ship had two 'Foster-Wheeler' water-tube boilers that supplied steam to General Electric steam turbines and generators. This all electric drive-train was considered particularly innovative at the time. This action solved the problem of powering the HST, since the Energy Company of Amsterdam ('*Gemeentelijk Energie Bedrijf*' or *GEB*) could only deliver the required power at night. Moreover, a very expensive cable had to be laid. The building to house the power plant (*'Centrale'*) was also commissioned in 1947 and was ready in 1948 (see also figure 1-18). These early plans for the HST and SST will be discussed more extensively in the next sections.

EARLY DESIGN OF THE HST

Was the technical know-how available to design and build these new facilities? The LTT was rather similar to the LST (tunnel no. 3) that had been built and finished less than a decade before. Some of those who were involved at that time, such as De Lathouder, were still around. But the design of high speed and supersonic tunnels was very much different (see Appendix E).

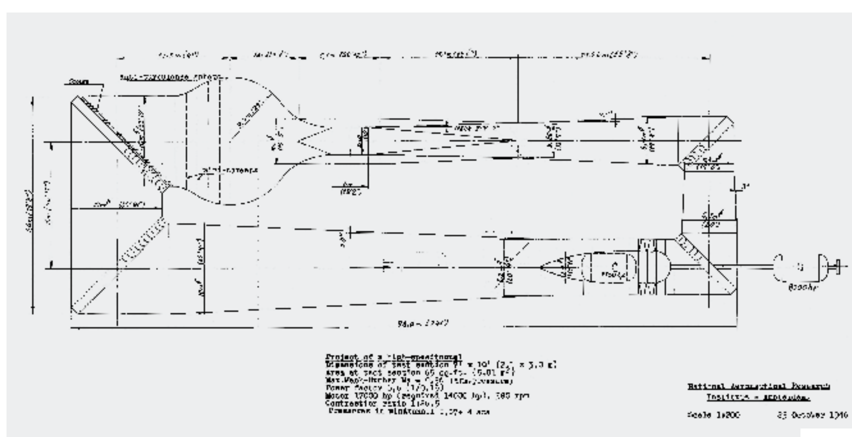
During the War a theoretical analysis of various aspects of the design of a high speed tunnel was already made by Wiselius as mentioned before. Six reports on high speed tunnels were ready just after the



[1-8]

[Figure 1-8]

Mock-up of the first buildings of NLL in 1940. Note the main building, the wood workshop (the low building to the left) and the two low speed wind tunnels (at the top/left).



[1-09]

[Figure 1-09]

One of the HST designs from 1946 shown for comments at the trip made by de Lathouder and Wiselius in the US in 1946/1947. This design resembles the final design of 1953.

[E] IN 1956 A SIMILAR SHIP OF THE SAME CLASS, THE HMS HOTHAM, WAS BOUGHT, MAINLY FOR SPARE PARTS.

[1-10]

[1-11]

[Figure 1-10]

The escort ships HMS Duff (left) and Ekins at the quay in England. The steam and turbo-electrical installations of these ships formed the core of the power plant to drive the HST and SST.

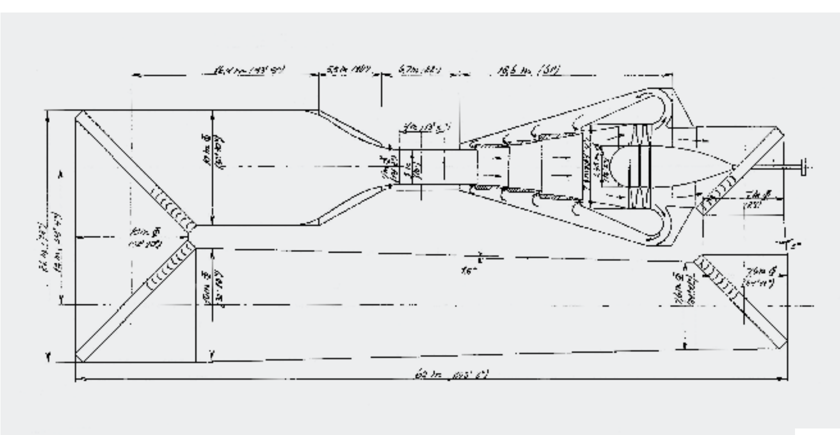
[Figure 1-11]

The name plate of HMS Duff. These plates were attached to the steam boilers in the Power Plant.

War[8,9]: a general introduction, theoretical principles, a description of other existing high speed facilities, diffusor performance, a design of a pilot diffusor and finally a pre-design for the high speed tunnel[F]. At that time there were various options to realise a tunnel with the before mentioned requirements:

- a rather conventional design similar to the LST (tunnel no. 3) with straight long and short legs separated by (in total) 4 rows of corner vanes. The contraction ratio was 1:13.5. An estimated 8,500 hp was needed to drive a two-stage fan.
- A similar design but with a much larger settling chamber (named an 'anti - turbulence sphere') giving a contraction ratio of 1:26.5 [see figure 1-9 of October 1946].
- A design without a large settling chamber and a much shorter circuit, using a jet diffusor [see figure 1-12].

To learn about the state of the art a fact-finding tour to the US was made from December 1946 till January 1947 by De Lathouder and Wiselius from NLL, together with Busquet from Stork (the intended contractor for the HST). With some of the above mentioned pre-design drawings in their suitcase, various research establishments and equipment companies (in total 17!) were visited[12]. Later visits were made to Canada, England, Sweden, Switzerland and (occupied) Germany.



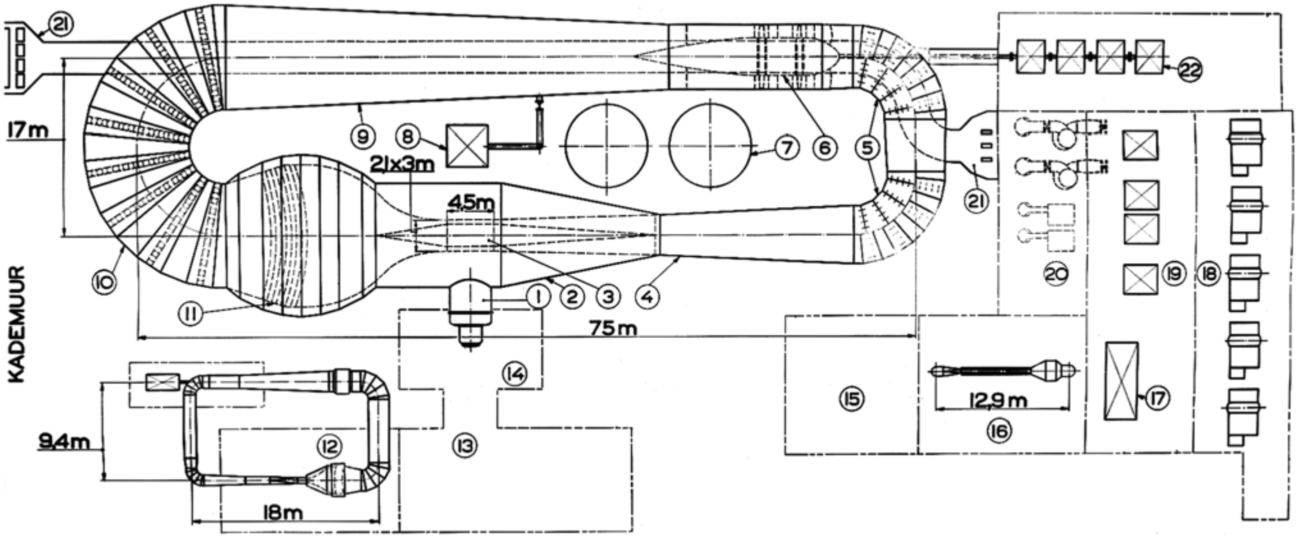
[1-12]

[Figure 1-12]

One of the designs discussed in 1947 with a 'jet-diffusor' to shorten the diffuser length. A similar scheme was considered for the Low Turbulence Tunnel LTT.

It is not clear how the aerodynamic tunnel circuit evolved after this trip. However, the drawing in the report which describes the new NLL tunnel plans[11] (published in September 1948), shows a rather different tunnel circuit [reproduced in figure 1-13], a circuit that is similar to the one shown in the mock-up of the architects Van Tijen en Maaskant [figure 1-7]. This design combines some elements of the NACA Langley 3 x 7½ ft (two-dimensional) low turbulence pressure tunnel [figure 1-14] and the much larger 12 ft variable density high-speed tunnel of NACA Ames. The sketches for

F UNFORTUNATELY, THIS REPORT WAS NOT PRESERVED.



[Figure 1-13]

Design of the High Speed Tunnel HST (1 to 11) together with the Pilot Tunnel PT (12), the (small) Supersonic Tunnel SST (16) and the Power House (17-22) as shown in the new wind tunnel plan of 1948.

[1-13]

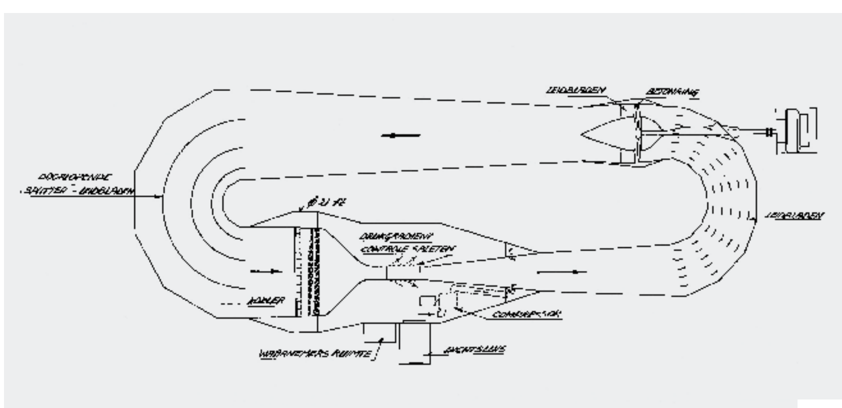
both tunnels can be found in the trip-report of the above mentioned fact-finding tour to the US and indicate rounded corners made up of 5 to 8 segments, similar to the HST drawing at that time.

The sketch of the design, as envisaged around 1948, shows the basic features of the new wind tunnel. To allow the transfer of models from that tunnel to the other facilities, the test section dimensions were kept the same as those of tunnel no. 3 (2.1 x 3 m^2). Not without reason the tunnel was named *high speed* instead of *transonic*. There was a shared view at that time that speeds just below or above the speed of sound (the transonic range) could not be obtained in a wind tunnel due to the problem of 'choking', the occurrence of strong shock waves in the narrowest part of the test section where the model was located (Appendix E). In a test section with closed walls the maximum Mach number that could be obtained was believed to be around 0.95. Another requirement was that at these high speeds, the pressure in the test section should be close to atmospheric. Otherwise valuable time was lost to evacuate the wind tunnel after working inside the tunnel on the model. This, together with the test section dimensions, determined the power that was needed to run the facility. The originally envisaged 8,500 hp was now increased to 20,000 hp. The installations taken from the purchased escort ships and marked on the drawing of figure 1-13, could provide sufficient power to drive four SKA electrical engines made by the Dutch company Heemaf [figure 1-27]. They were to be connected to the shaft of the tunnel fan which, however, was not defined yet. Given the available power, the static pressure in the tunnel circuit could be increased at lower speeds to boost the tunnel Reynolds number, one of the other major requirements for the new facility. A maximum (absolute) pressure of 4 bar was chosen. Although originally a sprinkler installation was envisaged to cool the tunnel, an internal cooler was finally selected to keep the temperature within the tunnel circuit constant.

Building started immediately after the plans had been adapted and in the beginning of 1949 the ground preparation for the HST was finished [see also figure 1-18]. In the ground plan of the HST one can clearly see the rounded corners of the tunnel circuit.

FIRST IDEA'S FOR A SMALL SUPERSONIC TUNNEL

In April 1946 a curious meeting took place[13] with De Lathouder and Wiselius, both involved in the new tunnel plans, and Erdmann. The latter was accompanied by Captain Veenekamp of the Dutch Military Mission in (occupied) Germany. Erdmann was a German scientist, responsible for the testing techniques in the supersonic wind tunnels in Penemünde, where the V2 was developed during World War II (see Appendix D and his memoirs[14]). Through informal family contacts Colonel Michels, head of the Dutch Military Mission in (occupied) Germany, got to know Erdmann and invited him to work in The Netherlands. The idea of the military was to use his knowledge for the development of aeronautical technology. This was the case with many other German scientists who went to work in the UK, France, the US and Russia. At the meeting Erdmann advocated the importance of supersonic flight and suggested some schemes to realise a supersonic tunnel in combination with the high speed facility (e.g. with a supersonic by-pass channel). Shortly after that Erdmann was recruited by NLL. First he studied (at specific request) the possibility of a supersonic addition to the HST[15] but this was apparently not very attractive. About a year later in December



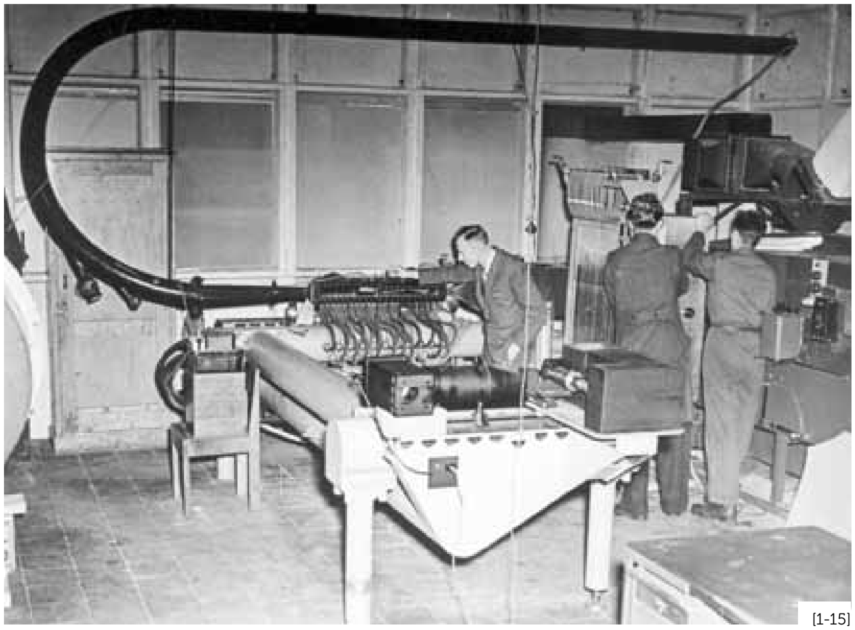
[Figure 1-14]

Sketch of the 3 x 7½ ft Langley two-dimensional low-turbulence pressure tunnel. This sketch was in the report from the trip to the US made by De Lathouder and Wiselius[12].

[1-14]

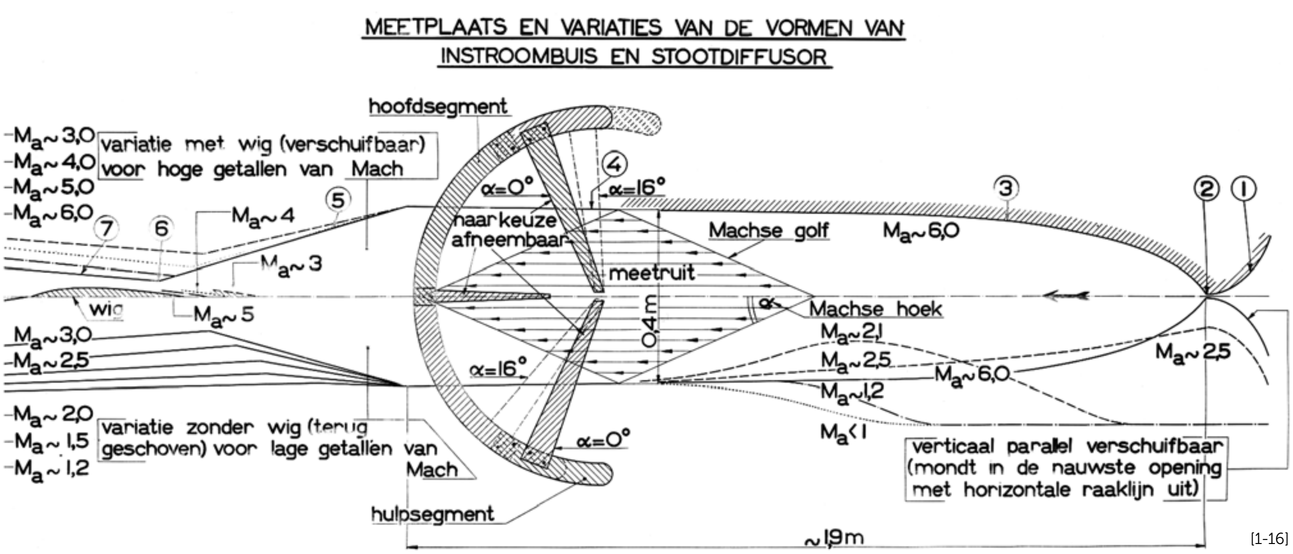
1947 the detailed design considerations of a small 'stand-alone' supersonic wind tunnel with a test section of 0.4 x 0.4 m^2 were described in a report[16]. The test section dimensions were determined by the available power of one of the 6,000 hp turbines that would be installed for the HST. This turbine would be connected to a set of compressors with a total pressure ratio of 1:16. In this way the tunnel could be run as a continuous supersonic wind tunnel. The tunnel had a flexible nozzle with the possibility to increase the Mach number up till 6. An external balance system was foreseen.

In this pre-design report Erdmann also stressed the need to build a small supersonic wind tunnel (with a test section of 4 x 4 cm^2) to get experience with supersonic flows. He wanted to study specifically the efficiency of a 'Stoßdiffusor', a diffusor where the flow is decelerated through a number of oblique shocks generated by a segmented wall with straight elements, each under a particular angle. Such a facility, named for its (somewhat smaller) test section dimensions (in cm!) the '3x3'[G] was designed in the same year and became operational in 1948[17] [see figure 1-15]. Its test section dimensions were dictated by a compressor that had been transferred from Belgium to Holland during the War but had not been used since. This very small wind tunnel is the first supersonic wind tunnel in The Netherlands. The Mach number could be set by fixed nozzle blocks at specific values up to Mach = 4. A special feature was the movable 'Stoßdiffusor' with a second throat that could be adjusted manually by a number of screws. Glass windows along the two-dimensional test section and the diffusor in combination with a schlieren system made it possible to observe the starting process of the supersonic flow in detail. It is interesting to note here that Erdmann used the '3x3' to develop a new interferometer technique to visualize shocks in supersonic flow, a study for which on April 30, 1951 he got his Doctor's degree at the 'Technische Hochschule' in Aachen[80] (see also page 99).
The design of 1947 with a test section 0.4 x 0.4 m^2 formed the basis for the supersonic wind tunnel presented in the new wind tunnel plans by De Lathouder in 1948[11]. In this report it is argued that the tunnel was needed for fundamental research up till Mach = 4. At a later date a larger tunnel might be needed to test complete aircraft configurations to a maximum Mach number of 2. At that time the prospects for supersonic flight for civil applications were not clear. In 1946 Erdmann[13] believed that '*very soon the interest will be in the speed range between Mach = 2 and 4 to 5*'. But Ackeret from the 'Eidgenössische Technische Hochschule' in Zürich, expressed his view[18] that civil applications *might* be possible but certainly not beyond Mach = 1.5. He advocated a high speed facility with a test section area of about 6 m^2 and a supersonic facility with a test section of 0.4 x 0.4 m^2. These figures are very similar to the NLL plans. The layout of the supersonic tunnel as it appeared in the 1948 plans is shown in figure 1-16. ■


[1-15]

[Figure 1-15]

The first supersonic wind tunnel in The Netherlands: the ´3x3´ with a cross sectional area of the test section of 3x3 cm^2 with its designer, Erdmann (in the centre) (around 1948).



[1-16]

[Figure 1-16]

Sketch of the nozzle, the test section and the diffuser of the supersonic wind tunnel as originally designed in 1948. The tunnel was driven by two compressors.

G THIS TUNNEL IS NOW AT THE FACULTY OF AEROSPACE ENGINEERING AT DELFT UNIVERSITY, GIVEN AS A PRESENT TO ERDMANN WHEN IN 1967 HE BECAME FULL PROFESSOR IN DELFT.

1949-1952: A USEFUL TIME-OUT

APRIL 22, 1949: ALL WORK TO BE STOPPED!

The recommendations of the 'Tromp Committee' (page 11) are sometimes considered an outstanding example of industrial policy by the Dutch Government. It can also be regarded as a very pragmatic approach of a small group of highly motivated people to realize their dream to restart aircraft design in The Netherlands in the best tradition of Fokker and other pre-war aircraft designers. Once the recommendations of the 'Tromp Committee' had been accepted by the Government, it became evident that the realization of that dream was rather difficult[19]. The financial situation of Fokker was not very good and there was a permanent problem of cash flow to pay the workers. The track record of the new aircraft developments by Fokker was not very good either. A contract with Diepen, a Dutch business man active in aviation, for the delivery of 100 (!) Fokker F25 'Promotor' air taxis was cancelled due to technical and financial problems. Plesman, founder and director of KLM, was not at all convinced that a national aircraft industry was a good idea and he certainly didn't want to buy Fokker products on forehand. Aircraft production by Fokker under license, such as the Hawker Sea-Fury and the Gloster Meteor, had experienced difficulties and the price was certainly not low. The military was more interested in buying American airplanes, partly motivated by standardisation within NATO. Within the framework of the 'Mutual Defence Assistance Act' American airplanes (such as the Beechcraft 'Navigator', an airplane similar to the new Fokker S13) were 'dumped' on the market out of military stock and almost for free.

After the report of the 'Tromp Committee' was issued, Tromp himself concentrated on the merger of the three still existing aircraft factories: Fokker, De Schelde and Aviolanda. As spelled out in the report such a merger was essential. It was equally important to establish a common production site at an airport. Of course this had significant practical and financial implications. A permanent 'Small Aircraft Committee' ('*Kleine Vliegtuigcommissie*') headed by Tromp was set up to guide the merger process. In 1948 Tromp became President of the yet to be established new 'Joint Dutch Aircraft Factories' ('*NV Verenigde Nederlandse Vliegtuigfabrieken Fokker i.o.*'). Blackstone, the chairman of the Foundation NLL, replaced him in the 'Small Aircraft Committee'. In January 1949 Tromp presented his final proposal for a merger of the three aircraft companies, including the choice for a central site at Schiphol Airport. This was completely unacceptable for Van Tijen[H], the director of Fokker and the merger shattered. Serious problems within the team of directors of Fokker had shown up already before and the position of Van Tijen further eroded. The rather disturbed Government referred the 'merger problem' back to the 'Small Aircraft Committee'. In February 1949 this Committee issued an

[1-17]

[Figure 1-17]

Cartoon in a Dutch Aviation Monthly ('*Vliegwereld*') on proposals by the Dutch Government to reduce the support to the Fokker Company. The Dutch Government demolishes the base ('building of prototypes') of the statue of Anthony Fokker. The other indicated activities are 'building under licence' and 'maintenance and repair'.

[H] He was the brother of the architect that worked with Maaskant on all NLL buildings.

[1-18]

[Figure 1-18]

Aerial view of the site of NLL in April 1952, a situation that must have been identical to the view at the end of 1949 when all activities were frozen. At the rear the big construction hall for the new tunnels. Next to it the lower parts of the unfinished LTT. To the right the ground plan of the HST with 'round corners'.

extremely positive report on the future of the aircraft industry in the Netherlands. This was not accepted by the Government and a new study was requested, to be made by an extended Committee with new specialist members. The Government was also a bit annoyed by the fact that Blackstone (chairman of the Board of NLL) and Van der Maas (chairman of NIV) were prominent members of a Committee that had to advise on their own future. In the same period the Dutch Government had to cope with the decolonization of the former Dutch East Indies leading to the Indonesian Republic in December 1949. The difficult financial and political situation might also have contributed to the hesitation to continue on the road that had been mapped out in 1946. The situation was extremely worrying for NLL. Without Government support for a not yet established joint aircraft industry, it didn't make sense to expand NLL on the scale envisaged in the original 1948 NLL plan.

On April 22, 1949 the Ministry of Transport ordered the freeze of all building activities for the HST. In July 7 a new report of the 'Small Aircraft Committee' appeared, still very positive on the future of a national aircraft industry. The investments for new wind tunnels at NLL were also considered and the original plans were again endorsed, however not by all members. Those with a military background were not at all convinced of a sufficient economic basis for a national aircraft industry, notably because of market perspectives. The representative of the Ministry of Finance was critical as well, notably on the ability of Fokker to organise itself. The Government now had to decide. But pending such a decision, a complete stop of the building activities for all new wind tunnels was issued by the Government on October 31 of the same year. A fierce discussion started, also in the press [figure 1-17] but against all expectations the Government decided on November 30, 1949 to continue the support for a national aircraft industry. The key word was 'industrialization': the expected export of capital goods was important for the Dutch economy. The decision included the continued support of NLL. However, it had to be reassessed whether the original wind tunnel plan could be executed as envisaged. To this end a new Committee was set up, named the 'BDM Committee' after its members Blackstone, Damme and Van der Maas, with the assignment to advice on the organisation, the scope and the financial framework of NLL and more specifically on the new wind tunnel plans. At the end of the first quarter of 1950 this Committee issued a report with the recommendation that the activities should be continued, except for building the LTT, the Low Turbulence Tunnel. The work on the HST, its small pilot facility PT, a small supersonic tunnel as well as the finalization of the Power Plant should continue. Nevertheless, in July 1950 and awaiting the formal decision to support the Dutch aircraft industry by the Parliament ('*Staten Generaal*'), the Ministry of 'Transport, Public Works and Water Management' (the Ministry holding the pen for NLL) demanded an important reduction in NLL personnel. In the same month 59 employees of NLL were discharged. Protests from the Board of NLL had no effect. In August 1950 the members of the Board, Blackstone (chairman) and Damme, stepped down and Van der Maas became the new chairman of the Board of NLL.

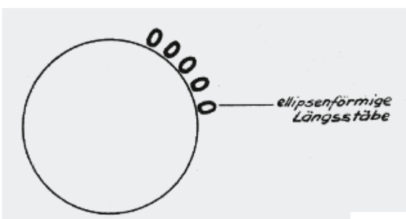
The termination of all activities for the new wind tunnels in 1949 must have come as a complete shock. A train that was running at full speed towards a well defined destination was suddenly stopped. Since NLL was forced to lay off 59 people, many others looked for jobs elsewhere. In 1950 NLL went from 277 to 195 employees with a considerable loss of expertise as a result. Erdmann, who was of invaluably importance for the design of the new supersonic wind tunnel, was nominated at KTU in Stockholm and left NLL as well. All construction activities were frozen and the new situation can be nicely illustrated with figure 1-18. This aerial picture was taken in 1952 and shows the situation exactly as it was in 1949 when all building activities had to stop. The big hall was erected by Stork for all on-site construction work. The power plant building (with the 5 smoke stacks) was ready. One can see the foundation for the LTT[I] and the layout of the HST circuit. Plates of special steel that could stand lower temperatures without loss of strength ordered from a Dutch steel company ('*Hoogovens*') and delivered to NLL were stored outside the gate and remained there for a long time. The area was named the '(metal) sheet park' ('*platenpark*'). See the upper-left corner of figure 1-18.

[I] THE FOUNDATION OF THIS TUNNEL WAS COVERED BY A PLATE OF WOOD AND THE RESULTING STRUCTURE GOT THE NAME 'THE KINGS GRAVE' AFTER THE DIRECTOR AT THAT TIME, KONING. LATER AN OFFICE BUILDING WAS BUILT ON TOP OF THIS FOUNDATION WHEREAS THE AMSTERDAM COMPUTER CENTRE WAS LOCATED IN THE BASEMENT, THE FORMER SETTLING CHAMBER OF THE TUNNEL.

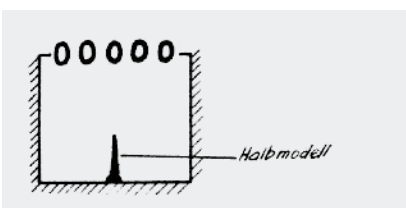
The reluctant way in which the Dutch Government treated NLL was probably partly motivated by the ever increasing costs of the new wind tunnels (see Appendix B). NLL was forced to prepare a new investment plan, which was sent to the Government on April 18, 1951. After many discussions with the Government, the new extension plans of NLL were finally approved. In the meeting of the NLL Board of March 1952 the chairman Van der Maas informed the other board members that the new wind tunnel plans could be continued on the basis of an approved additional budget of 9.43 million guilders. Some board members asked for stricter cost control and a small group was formed to direct all new tunnel activities. This group was made up of the NLL Director Boelen (who fell ill following a motorcycle accident and was replaced by Marx), De Lathouder (the former head of the Aerodynamic Section and already in charge of the new wind tunnel plans), a new young NLL engineer still to be appointed and one external member, Boel of the Sub-Department of Aerospace of the Technical University of Delft (who had been involved in the building activities for the low speed tunnel in Delft). Van der Neut was appointed as an advisor. But it was not until the middle of 1953 that the Parliament formally approved the new budgets. Only now could the work continue at full speed.

[Figure 1-19]

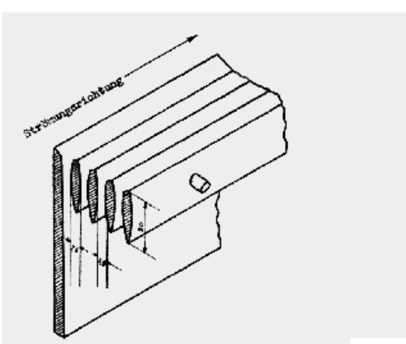
Sketches of the slotted wall configuration according to the 'Swiss solution': a) configuration tested by Busemann[25], b) configuration applied in the wind tunnel of North American Aviation in the US[25] and c) sketch in the test report on the first tests made in Emmen[26].



[1-19a]



[1-19b]



[1-19c]

A MOST SECRET TRANSONIC TEST SECTION

Although all building activities were interrupted, the design work for the HST and PT actually continued between 1949 and 1952. In 1950 the studies for the HST drive system were finalised, the electrical engines were delivered and the turbo-electric drive system taken from the escort ships was properly conserved. In 1951 the detailed design of the PT was finished. Moreover, the performance of various corner vane designs was studied.

The HST was still a high speed tunnel with a maximum Mach number of 0.95. It was believed that truly transonic conditions around Mach = 1 could not be reached due to the problem of 'choking' (see Appendix E). In 1948 a memorandum[20] was written in the US that indicated a possible solution for this problem: longitudinal slots in the test section walls allowed the air to 'escape' and this prevented 'choking' of the tunnel flow. The 'ventilated' test section was enclosed in a confined space, the 'plenum chamber'. This solution was classified. Nevertheless, details must have slowly seeped out.

After it became clear in March 1952 that NLL could resume the construction of the new wind tunnels, it was appropriate for Fokker to assess if the original plans of 1948[11] still met the Fokker requirements. In August 1952 report[21] A-84 was written by Greidanus, the former head of the F-section who had left NLL at the end of 1951 to work at the Fokker company[J]. In the report the importance of the new wind tunnel plans is confirmed. Nevertheless, some recommendations are made. It is argued that very heavy high speed wind tunnel models were needed for the planned test section of 2.1 x 3 m^2. Such big models were expensive and difficult to handle. Moreover, the energy bill for the tunnel would be high. The exchange of models between the LST and the HST was hardly relevant since the high speed conditions required different models anyhow. Since some loss in Reynolds number was acceptable for Fokker, a reduction in size of the test section was proposed. The most important remark of Fokker was concerned with the strong requirement to test at transonic conditions, hence between Mach = 0.9 and 1.3, specifically for military projects. According to Greidanus it is known today that this can be done technically and he continues that a large effort is required to reveal the secret how this can be done ('*...een hoge inspanning [is nodig] tot ontrafeling van het thans nog geheim gehouden procedé.*').

The message was clear. In September 1952 it was learned from Abbot, a leading aerodynamicist at NACA, that Langley had modified their high speed tunnels with transonic test sections. In the same month Van Meerten (Fokker's Chief Engineer) met Fowler in England who worked at Folland Aircraft. He provided information on a slotted test section in a transonic wind tunnel of English Electric. Shortly after that Slotboom of NLL and Greidanus of Fokker visited Fowler[22]. In October 1952 a trip was made to the US by Dobbinga, Slotboom and Boel[23]. They noted that work was ongoing on transonic test sections. The trick seemed to be the shaping of the upper and lower walls and a 'Swiss solution' is mentioned. This 'Swiss solution' was the one that was finally pursued.

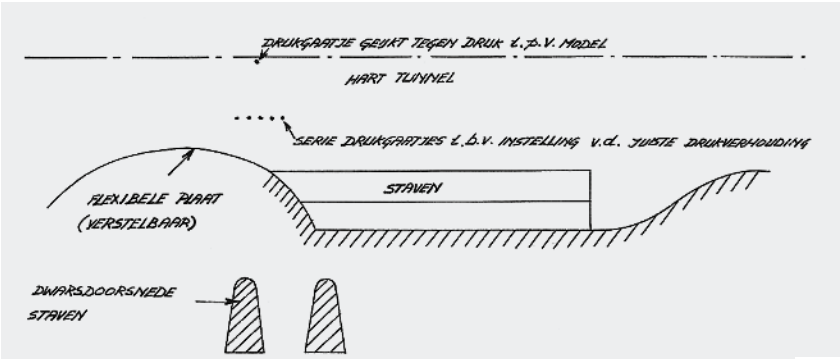
In March 1952 the 'Advisory Group for Aeronautical Development' (AGARD) was founded under the inspiring leadership of Theodore Von Kármán. This transatlantic institution, related to NATO, was set up to facilitate the exchange of information in the field of aeronautics between the armed forces, government laboratories, industry and universities. Through AGARD smaller nations could get access to new developments in the aeronautical world. When Von Kármán learned about the Dutch wind tunnel plans, he remarked that '*it would be a waste to build an expensive obsolete wind tunnel when there was an urgent need on the continent for data in the new speed regime*'[24]. Since the new tunnel wall concept was still classified in the US, he brought the Dutch team in contact with some Swiss engineers who had been working on this principle in the US before the design was classified.

Who were these Swiss engineers? One of them was Hausammann. He worked at the Eidgenössische Flugzeugwerk Emmen and was involved in the design of the N20, an advanced interceptor with a delta wing and four turbofan engines mounted in the wing. In October 1948 Hausammann made a study trip to the US where he met Busemann at North American Aviation Co. Busemann, the inventor of the swept wing, was the Director of the Aerodynamic Institute in Braunschweig during World War II. In 1947 he came to the US where he got a position

[J] AT FOKKER J.H. GREIDANUS BECAME HEAD OF THE AERODYNAMIC SECTION AND THE CHIEF ENGINEER FOR THE FOKKER F28, AN AIRPLANE THAT COULDN'T HAVE BEEN DESIGNED WITHOUT THE HST. THE REGISTRATION OF THE PROTOTYPE PH-JHG REFLECTS HIS NAME.

[K] IUTAM IS THE 'INTERNATIONAL UNION OF THEORETICAL AND APPLIED MECHANICS'; VON KÁRMÁN HAD ALSO A LEADING ROLE IN THE FOUNDATION OF THIS ORGANISATION.

[L] THIS TUNNEL HAD BEEN BUILT INSTEAD OF A LARGER SUPERSONIC FACILITY WITH A TEST SECTION OF 1.2X1.2 M2 THAT WAS CONSIDERED TOO EXPENSIVE.



[1-20]

[Figure 1-20]

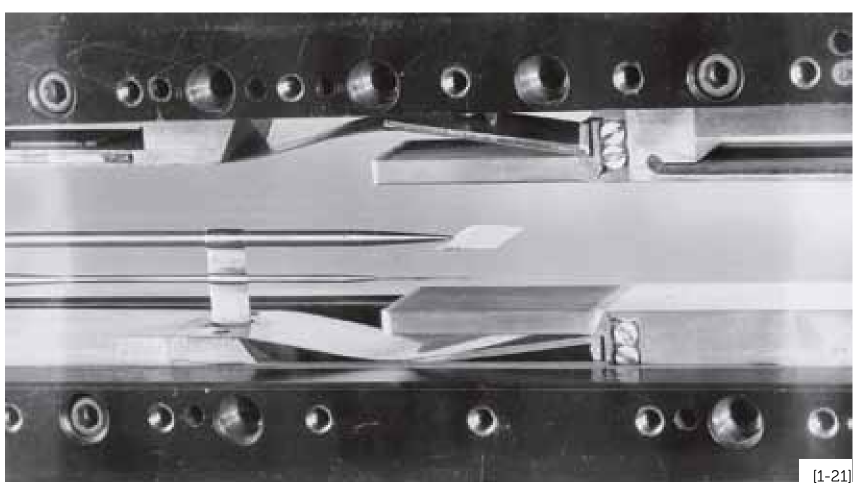
A sketch of the slotted wall test section by Dätwyler and Hausammann as included in the trip report of the visit[27]. Flow direction from left to right.

at NACA Langley. Busemann told Hausammann of a slotted test section to solve the problem of choking and shock reflection. In the trip report[25] Hausammann mentioned that he (Busemann) made his experiments on a cross section (*'Er hat seine Versuche an folgende Querschnitt ausgeführt.'*) as shown in figure 1-19a,b. And he added that North American Aviation applied the same method for 'half model tests'. This concept was further investigated by Hausammann in Emmen in a small tunnel with a cross section of 14 x 16 cm^2. The slotted wall consisted of symmetrical profiles as indicated in figure 1-19c. For more details on this slotted wall concept see Appendix E. Already in June 1949 a report was published[26]. These tests were apparently successful and resulted in a new tunnel with a transonic test section of 0.5 x 0.6 m^2.

In August 1952 Slotboom made the first contacts with Dätwyler, a former colleague of Hausammann, during an IUTAM[K] congress in Istanbul. This was soon followed by a visit in October 1952 by Slotboom and De Leeuw to the Eidgenössische Flugzeugwerk Emmen in Switzerland where Hausammann was operating his small transonic wind tunnel[L]. In the trip report[27] a simple sketch can be found [figure 1-20] with the added description: *'At the transition from nozzle to test section wall, the longitudinal slots begin. In the Swiss tunnel they consist of vertical plates with a rounded top. These plates are not connected to the tunnel wall, but leave a shallow space...'*. The indicated slot configuration is very similar to the one investigated by Eckhaus in 1957 in the '3x3' tunnel [figure 1-21] to validate the slot characteristics in more detail [see Appendix E]. During the same meeting the construction of a multi-manometer and an external balance for the transonic tunnel was discussed with Engler, who represented the instrumentation company Engler & Co. At the end of the visit the NLL representatives asked Hausammann if it was possible to transfer the design drawings for the transonic test section. After consultation with Engler and Dätwyler it was made clear that this would not be possible since the Swiss Military (*'Militär Departement'*) would not allow this. But it would be possible to design and build the test section in Switzerland. In April 1953 the contractual discussions continued during a visit of Boel and Dobbinga[28]. Interestingly enough these discussions focused on three offers made by Engler for the design and construction of a transonic test section for the HST (offered in January 1953), for the design and construction of an external balance for the HST and for the design and construction of a supersonic tunnel, the SST (offered in February 1953). At that time the idea was to build a small supersonic tunnel with a test section of 0.4 x 0.4 m^2 (see also page 15). Part of the discussions focused on the performance guarantees for the HST test section: the Mach number variations should be less than ± 0.003 at the model area whereas the reflected shocks should be reduced to 10 % of their original value.
Apparently the contract to design and build the transonic test section was finally granted to Dätwyler & Hausammann. After the N20 project had failed Hausammann left the Eidgenössische Flugzeugwerk Emmen and started an engineering company[M,29] together with Dätwyler (who provided the capital). Due to the transonic, slotted test section, the maximum Mach number could now be increased from 0.95 to 1.3, a crucial improvement in the performance of the HST. But the available power would not be sufficient for the increased Mach number capability. In fact it was not known at all if and how much additional energy was required for the slotted test section. Fokker had also indicated in report A-84[21] that it favoured smaller wind tunnel models. Since the available power could not be increased (the power plant was almost ready), it made sense to decrease the size of the test section though at the expense of a somewhat lower Reynolds number at low speed conditions (see Appendix A). A suitable compromise was found in a test section of 1.8 x 1.8 m^2 which was later changed into 2 x 1.6 m^2 (width x height) to enable larger wing spans[30]. All recommendations made by Fokker in report A-84 were met.

A summary of the main design decisions for the HST can be found in a report by Dobbinga, Slotboom and Boel[31]. It discusses the requirements and the preferred solutions for the tunnel circuit, the test section, the drive system (including the Mach number control) and the model support including the balance (*'the models will be supported by a strut attached to an external balance; the development of internal balances has to be pursued'*).

It was also decided that the Pilot Tunnel (PT) would be built according to the original plans with closed walls. If needed a transonic test section could be installed at a later date, as was tried between 1957 and 1962. ■

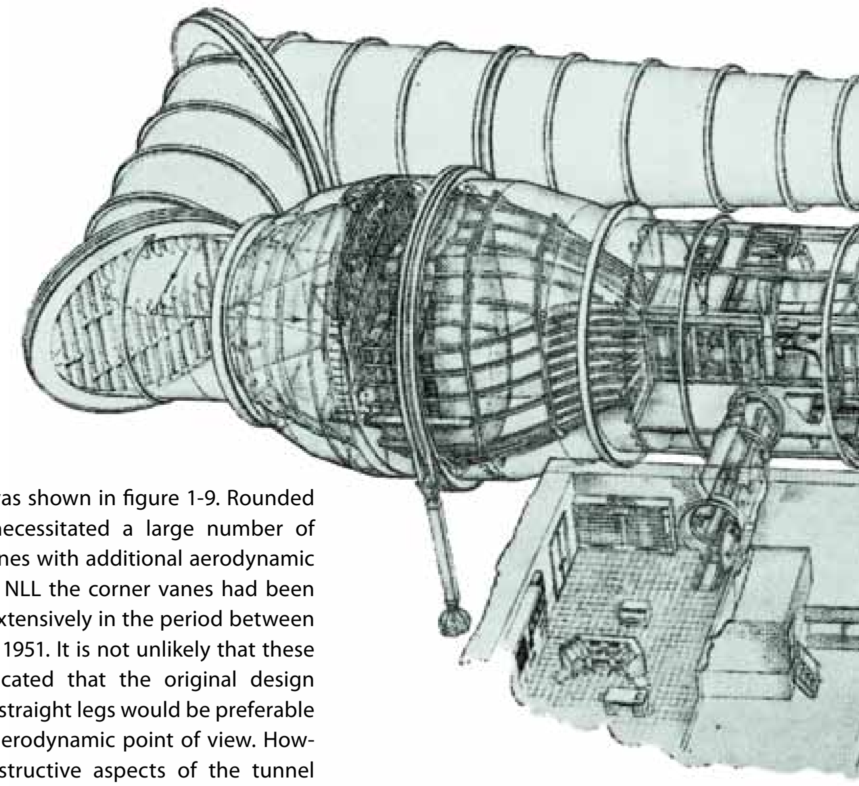


[1-21]

[Figure 1-21]

Scaled model of the slotted wall designed by Hausammann and tested in the '3x3' supersonic tunnel. Flow from right to left.

[M] THE 'EIDGENÖSSISCHE FLUGZEUGWERK EMMEN' STILL CONTINUES UNDER THE NAME RUAG. DÄTWYLER AND HAUSAMMANN HAD TO EXPAND THE COMPANY AFTER THE CONTRACT FROM NLL AND ENGAGED ISLER AS PARTNER. IN 1954 THE COMPANY NAME WAS CHANGED TO 'HAUSAMMANN AND CO' AND IN 1964 INTO 'HAUSAMMANN & ISLER'. AFTER THE DEATH OF W. HAUSAMMANN IN 1977 THE NAME CHANGED INTO 'INGENIEURBÜRO ISLER AG'. THIS COMPANY IS STILL ACTIVE IN WIND TUNNEL DESIGN.

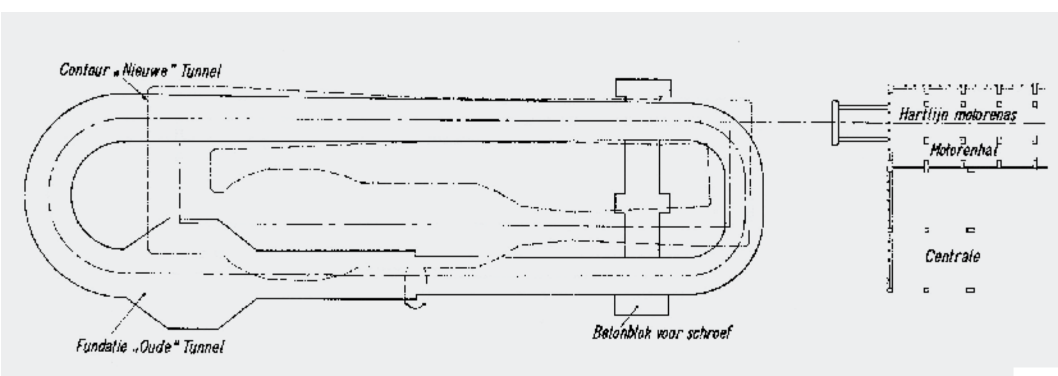


BUILDING THE HST

THE CONSTRUCTIVE DESIGN

As a result of the smaller test section dimensions the aerodynamic and constructive design of the tunnel had to be re-examined. The most important changes are described by Van Asselt[32]. He provided a picture of the foundation of the 'old tunnel' as compared with the new tunnel circuit [figure 1-22]. In 1950, when the building activities were stopped, the foundation of the HST was already finished. One of the requirements for the adapted design was to use as much as possible the existing foundation, notably the heavy foundation for the fan. Also an internal cooler was to be installed in the settling chamber instead of the originally planned cooling by spraying water on the tunnel shell. However, the basin made in concrete and needed to collect the water in the original solution is still present. Another unexpected problem was much more important. In laying out the foundation for the HST in 1948 the wrong measures were used. As a result the location of the tunnel shifted about 10 m away from the power plant[N] in the direction of the canal that bordered on the NLL site. The lost space could be recovered by reducing the total length of the circuit from 75 to 60 m. The reduction in cross sectional area of the test section helped in this respect; the diffusor length could be reduced for the same diffusor efficiency or diffusor angles. Another important change is the replacement of the rounded corners [figure 1-13] by straight corners similar to the 1946 design, as was shown in figure 1-9. Rounded corners necessitated a large number of corner vanes with additional aerodynamic losses. At NLL the corner vanes had been studied extensively in the period between 1946 and 1951. It is not unlikely that these tests indicated that the original design with four straight legs would be preferable from an aerodynamic point of view. However, constructive aspects of the tunnel design were probably the most important reason for going back to a tunnel layout with straight corners. In 1948 it had been agreed that Van der Neut, an external advisor of NLL, would take care of the constructive design in close co-operation with the contractor Stork. In November 1945 Van der Neut, a former employee of NLL, was appointed as professor in aircraft constructions at the Delft Technical University. Wind tunnels were not unfamiliar to him. During the War he wrote, together with Greidanus[33], a detailed and impressive report on the cause and future prevention of the vibrations of the fan of tunnel no. 3, vibrations that in 1941 and 1942 had resulted in the loss of several fan blades.

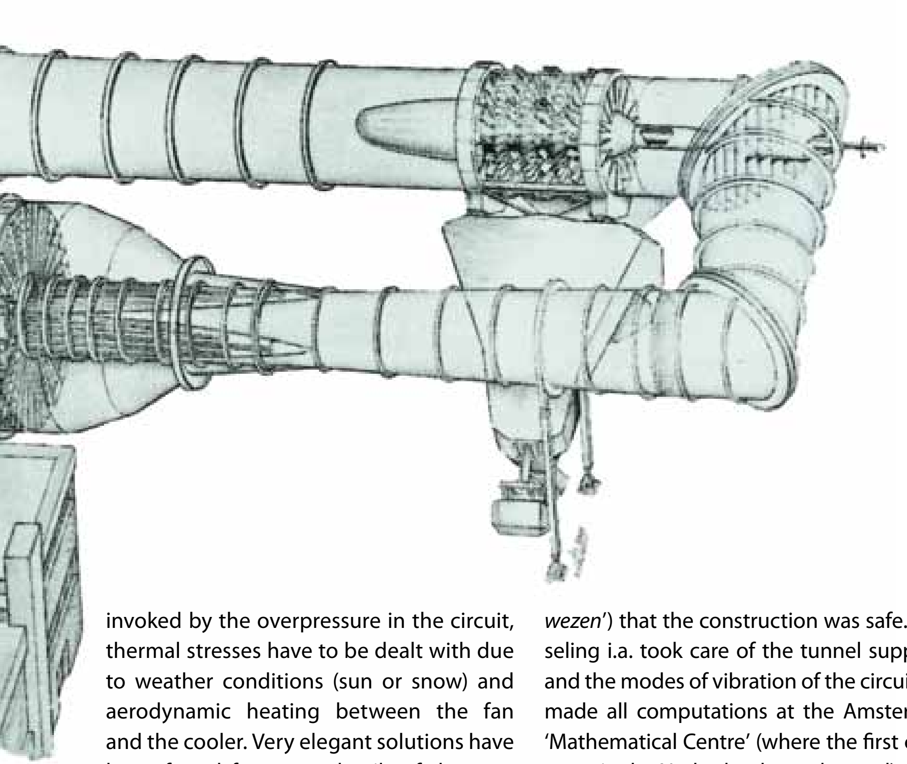
Van der Neut wrote an article[34] for 'De Ingenieur', the Journal of the 'Royal Institute of Dutch Engineers' ('*Koninklijk Instituut van Ingenieurs*' or *KIVI*), after the tunnel was commissioned. This article gives a good overview of the problems that Van der Neut faced in the design of the HST. He remarks that some variable pressure tunnels were built in (loosely coupled) segments '*such that the forces due to the pressure differences on a segment have to be taken by the foundation*'. This will result in a very heavy foundation. In the trip report of the 1946/47 visit to the US[12] it was mentioned that the round corners were required for 'constructive reasons' and figure 1-7 shows that in the original NLL design the tunnel was supported at multiple points. Van der Neut knew about the design of the tunnel in Bedford[35] which had straight corners with locally an elliptical cross section. However, this tunnel was segmented with a very heavy foundation to accommodate pressure differences on the construction. Van der Neut might have followed the idea of the straight corners from the Bedford tunnel but solved the structural stress problem differently. He designed the tunnel as an 'integral shell'. By doing so all stresses due to pressurization and thermal loads will be contained within this integral shell. In a way the shell is 'floating' above the ground, only supported at four cross sections of the circuit (at the settling chamber, the tunnel fan and at two other stations on the long legs of the circuit [see figure 1-23]. This design principle will result in a much lighter construction. In addition to the support loads and the loads



[1-22]

[Figure 1-22]

The foundation of the 'old' tunnel circuit compared with the adapted design of 1952. The length of the circuit was reduced from 75 to 60 m whereas the round corners have been replaced by straight corners[32].



[1-23]

[Figure 1-23]

Drawing of the circuit of the HST as built between 1955 and 1957; the tunnel shell is only supported at four points, with a heavy support at the fan location.

invoked by the overpressure in the circuit, thermal stresses have to be dealt with due to weather conditions (sun or snow) and aerodynamic heating between the fan and the cooler. Very elegant solutions have been found for many details of the construction (such as the joints between the tunnel shell and its supports, the construction of the corners, the air lock towards the testing room), solutions that reduce additional loads as much as possible. The shell thickness is about 15 mm increasing to 25 mm close to the supports. Only above the first diffusor is a small cover visible, mounted to shield that part of the circuit from heat loads by the sun [see figure 1-33].

Normally, the Dutch authorities would require that the complete circuit had to be filled with water and be pressurised till about 2 bar over-pressure for proof of safety of a pressure vessel. Since this is almost impossible for this specific construction, the authorities agreed (already in 1948) that it would suffice to calculate the stresses and to verify these calculations with measurements during the first test with the pressurised tunnel. For the primary calculations of the circuit Van der Neut was assisted in 1952 by van Leest who was his assistant in Delft. He made all calculations required for the contractor to start the detailed design and construction. During the construction of the tunnel Van Leest was responsible for the day-to-day supervision of the construction. Van der Neut also added to his team two of his former students, the engineers Besseling and Zandbergen[O]. Their task was to do the detailed stress calculations required to convince the Dutch authorities ('*het Stoomwezen*') that the construction was safe. Besseling i.a. took care of the tunnel supports and the modes of vibration of the circuit. He made all computations at the Amsterdam 'Mathematical Centre' (where the first computer in the Netherlands was located) using matrix analysis, which would later be called 'finite element computations'. Zandbergen was mainly involved in a stress analysis for the corners of the circuit, again requiring the solution of a large set of equations. His calculations were made at NPL in Teddington, England, but the answers were not satisfactory at all. Fortunately Van der Neut apparently found a way out. The cause of the discrepancies, a misunderstanding in the transfer of data, was found much later.
During final commissioning in 1957[36], stresses were measured with strain gauges at 153 locations, using equipment specifically developed by the NLL Department of Electrical Engineering Services ('*E-lab*'). An overload of 10 % was applied, an acceptable agreement with the predictions was found and the authorities could be convinced of the safety of the design. See also page 50.

Although most of the tunnel circuit was defined by the end of 1953, a very important issue still had to be decided: the question how the forces on the model inside the test section were to be measured. There were two opposing views: either an external mechanical balance (outside the tests section) or an internal strain gauge balance (inside the model). This will be discussed in more detail at page 41. The issue raised a lot of controversy as can be read in a report of November 3, 1954[37]: '*This decision is more or less a gamble. Apparently agreement cannot be reached, but the decision has to be taken now.*' Shortly after that, in a meeting on November 10, 1954 it was decided to go for the internal balance but to keep the possibilities open for an external balance[38]. As history has shown, this was a wise decision. The option for an external balance didn't have serious consequences. The outer wall of the tunnel circuit at the location of the transonic test section (encompassing the so-called 'plenum chamber') had a very big diameter of 9 m. This was done to mount the optical system for flow visualisation (the 'schlieren' system; see page 57) completely inside the pressurized part of the circuit to get rid of optical outline problems due to deformation under load. This large chamber allowed sufficient space for an external balance, if needed, at a later stage.

THE SELECTION OF CONTRACTORS

In the meeting of the NLL Board of March 1952 its chairman Van der Maas announced the continuation of the new tunnel plans and informed the other board members that a special team was to be formed to manage the building activities. A young Delft engineer, Boel, would be part of that team. Boel joined NLL in April 1952 (see Appendix D). In 1953 the existing working group for the new tunnels was replaced by a special department ('*Nieuwbouwdienst*')

[1-24]

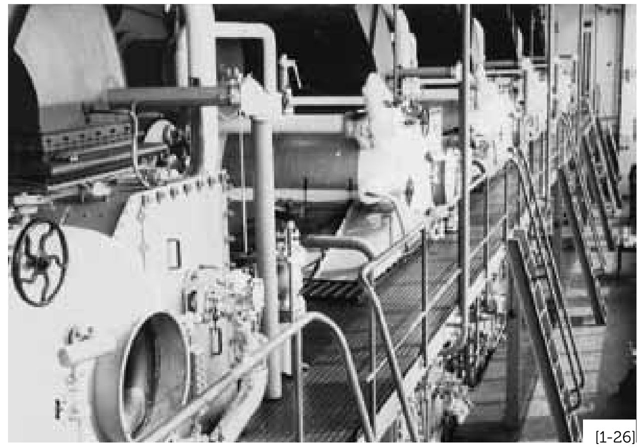
[Figure 1-24]

Transport of a 'short leg' of the HST over water in 1955.

N ACCORDING TO VAN LEEST WHO SUPERVISED THE CONSTRUCTION OF THE HST, THE ERROR HAD A FAVOURABLE SIDE EFFECT. THE LONGER SHAFT BETWEEN MOTOR AND TUNNEL FAN SOLVED THE PROBLEM OF HIGH LOADS DUE TO A POSSIBLE MISALIGNMENT.

O ZANDBERGEN BECAME PROFESSOR IN DELFT AND TWENTE AND WAS ONE OF THE CHAIRMEN OF THE ROYAL ACADEMY OF SCIENCES OF THE NETHERLANDS (KNAW); BESSELING BECAME PROFESSOR IN DELFT AND DID PIONEERING WORK ON 'FINITE ELEMENT METHODS'.

[1-25]



[1-26]

[Figure 1-25]

The first part of the tunnel circuit delivered at NLL in 1955.

[Figure 1-26]

The steam boilers taken from the escort ships are shown here in the Power Plant ('*Centrale*'); the oil-fired furnaces are underneath the walkway.

[Figure 1-27]

The four SKA engines to drive the fan of the HST. Although delivered in 1950 they were used for the first time in 1957 when the construction of the HST was finished.

under supervision of one of the NLL directors to manage all activities related to the construction of the new wind tunnels. De Lathouder, who had been in charge of all new tunnel activities so far, was replaced by Boel to manage this new department of about 10 people. De Lathouder became secretary of the department, but was added to the directors' staff in 1954. He left NLL in 1955. Van Leest was made responsible for the 'on-site' supervision of all aspects of the construction in close co-operation with Van der Neut. Van der Zwaan was made responsible for the development and coordination of the measurement techniques. In 1955 additional support was given by an American Engineering firm, mainly to get access to the newest developments in the US on testing techniques.

In the course of 1952 many trips were made by Slotboom and others to aeronautical laboratories and aircraft industries. In addition to the visit to the Eidgenössiche Flugzeugwerk Emmen in Switzerland where much was learned about the transonic test section, other visits were made to the US, Sweden, England and Belgium. The specific aim was to learn from the experiences elsewhere in building pressurised wind tunnels of big dimensions in order to obtain better cost estimates. In July Boel talked with the 'Bureau of Naval Architecture' ('*Bureau Scheepsbouw*'), an organisation of the 'Ministry of the Navy'. He received information on the price per kilogram steel for naval vessels and submarines in particular[22]. These estimates were used in the price negotiations with Stork, the Dutch company that was already involved in the construction of the tunnel before the stop of all building activities around 1950. Stork argued that the HST case was completely different. The construction of submarines

[1-27]

took place at the contractor's site in a kind of series production and this could not be compared with the building of a single wind tunnel at the NLL site. But Boel and De Lathouder were not convinced. During their trip to England[35] in August 1952 they visited the 8 x 8 ft^2 trans- and supersonic wind tunnel[P] of NAE (National Aeronautical Establishment) in Bedford and obtained detailed information how cost estimates were made. Shortly after that, in October 1952, a big delegation from Stork came to Bedford as well. Their aim was to learn about some specific technical problems but more specifically to get information on the way the costs were estimated[39]. The contact was probably arranged by De Lathouder who was present as well, together with six representatives of Stork, including Busquet who joined the NLL delegation that visited the US in 1946/1947. However, the negotiations between NLL and the Stork Company did not materialise and therefore it was decided to start negotiations with other contractors. At the end of the year 1954 contracts for the tunnel circuit (the pressure shell) were placed at Werkspoor N.V. in Utrecht. Stork intended to concentrate the greater part of the construction activities in the large hall that was erected at the site of NLL [see figure 1-18]. It is quite possible that Werkspoor could offer a much lower price because they envisaged building all parts of the tunnel circuit in their factory in Utrecht. These parts could subsequently be 'sailed' to Amsterdam, a convenient way of transport in the water-rich area around Amsterdam [see figure 1-24 and 1-25]. As mentioned, the transonic test section was built by Dätwyler & Hausammann in Zürich. The same company was involved in the instrumentation such as the multi-manometer and the Mach meter (see page 46). The contract for an external balance with Engler[28]

P THIS TUNNEL COULD MEASURE CLOSE TO MACH = 1 SINCE THE TEST SECTION HAD FLEXIBLE WALLS THAT COULD BE SET TO REDUCE THE BLOCKAGE EFFECTS.

did not materialise since the decision was finally made to go for internal balances. Mid 1954 a contract was placed at Stork for the fan of the tunnel, but at the end of the same year this contractor withdrew. The fan was finally awarded to Dinglerwerke A.G. in Zweibrücken, Germany. The cooler was built by G.E.A. Luftkühler Gesellschaft in Bochum. N.V. Stork and Heemaf became responsible for the steam and electrical installation in the Power Plant ('*Centrale*'). This building contained five 'Foster-Wheeler' steam boilers [see figure 1-26; in 1964 a sixth boiler was added] and four General Electric Turbogenerators that provided the electricity to drive four Heemaf SKA electric motors [figure 1-27] that were coupled to the HST fan [figure 1-28] and a compressor station.

"TECHNICALLY SOUND, WITHIN BUDGET AND QUICK!"

On October 10, 1955 the first parts of the tunnel circuit were erected at the NLL site. The heavy parts could be transported over water [figure 1-24 and 1-25] and the various tunnel parts could be assembled on the site [figure 1-29]. Soon after that the test section built by Dätwyler & Hausammann [figure 1-30 and 1-31] was delivered on site. Progress was not as wanted. On April 15, 1956 a note was written by Boel[40], summarising in a very condensed way (though still 32 pages) all problems with the PT, the HST and the Power Plant. At the end of the Introduction to this note Boel wrote the 'double motto':

- For the building activities: '*technically sound, within budget and quick*'
- For the development of transonic aerodynamics: '*growth of potential, acquisition and planned research*'.

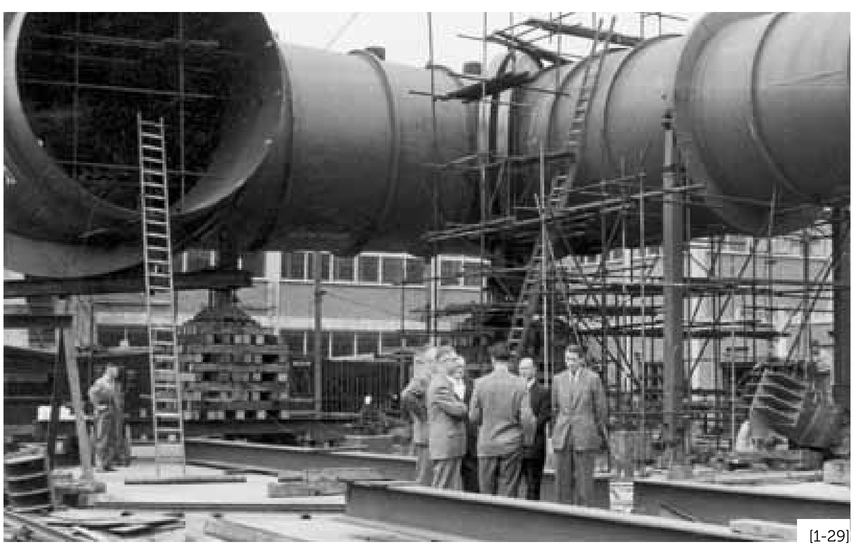
The concern was very understandable: in 1954 NLL had promised to AICMA, the 'European Organisation of Aircraft Manufacturers' (see page 66) that the tunnel would be ready for use in 1956. But the second motto had nothing to do with the construction of the tunnel directly. The message is that to attract customers for wind tunnel testing, it is essential to have a proper theoretical and experimental background of the physics involved. This requires a department with transonic aerodynamics as its 'core business'. At the end of the same year a Section for Transonic Aerodynamics ('*T-sectie*') was created under the leadership of Boel. Another incentive for this organisational change can be found in a confidential addendum to the above mentioned note[41]. In 1954 Erdmann returned from Sweden and soon after that the Section Gasdynamics ('*G-sectie*') was created under his leadership. This section was responsible for building the SST (see page 29), an activity that was formally considered part of the '*Nieuwbouw Dienst*' headed by Boel. In practice the G-Section acted quite independently and Boel proposed to formalise the situation and to create the T-Section, analogous to the G-Section. To co-ordinate all activities for the new wind tunnels a working group ('*Nieuwbouw commissie*') was re-established. This organisational change also reflected the fact that research in the transonic and supersonic speed regimes was gaining momentum, both theoretically and experimentally. In fact supersonic and transonic testing started already in the '3x3' and in the PT, as will be discussed at the pages 69 and 43. The main problems for the HST were related to a serious overrun in delivery times. Several causes were listed. The complexity of the project resulted in a much larger design effort and increased fabrication time. All contractors were very busy with other contracts, as Europe was rebuilding after the devastating war period. But equally important was the lack of sufficient and experienced specialists within NLL. For each item the report points out the best way forward, either by stricter control (on the contractors site), additional subcontracting or claiming higher priorities within NLL.


[1-28]

[Figure 1-28]

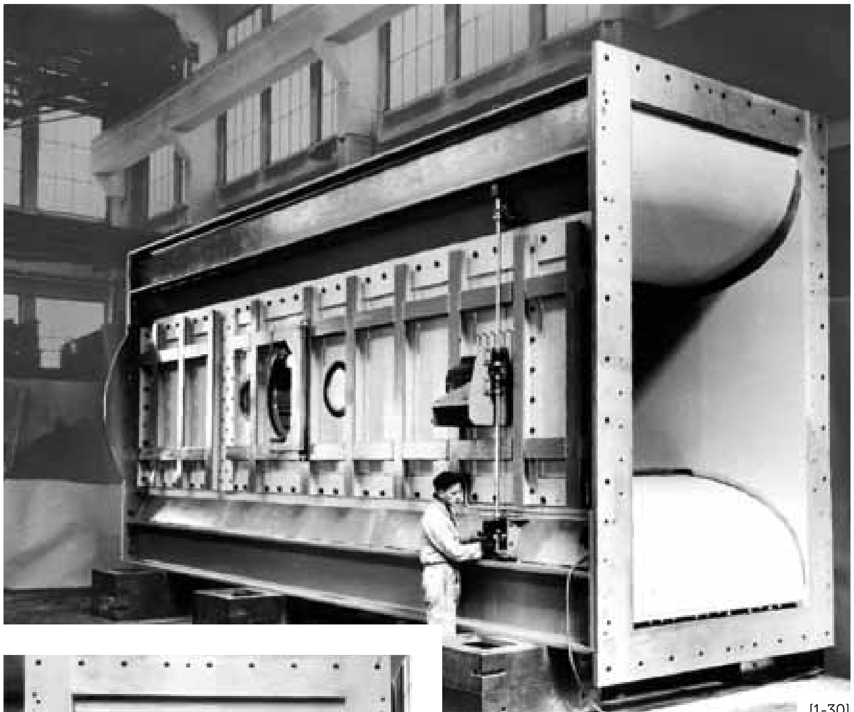
The fan of the HST.

During 1955 the contractor for the test section, Dätwyler & Hausammann, tested in Switzerland the aerodynamic characteristics[42] of the new transonic test section on a scaled model. Based on these data and together with the characteristics of the fan provided by Dinglerwerke, Valk of NLL could update the performance figures of the HST. The new data indicated that the pressure losses in the transonic test section were greater than originally estimated, while also the fan efficiency felt short from the expectations. As a result the new predicted performance of the HST would be less than originally anticipated but still very acceptable: at Mach = 1 the measurements could still be made at atmospheric conditions[43]. (See also Appendix A.)


[1-29]

[Figure 1-29]

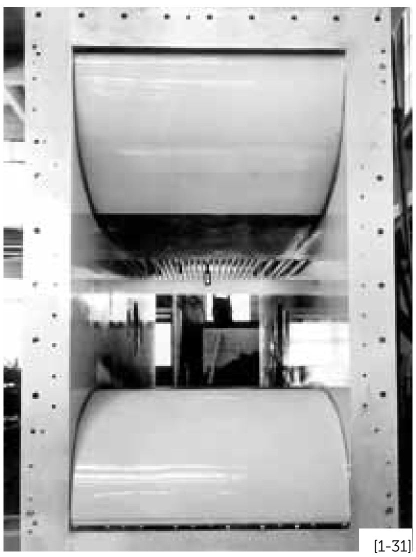
Building of the HST in progress. Visit of Mr. Algera, the Dutch Minister for Transport, Public Works and Water Management in 1955.



[1-30]

[Figure 1-30]

The transonic test section designed by Hausammann at the factory in Switzerland before transfer to The Netherlands.



[1-31]

[Figure 1-31]

Front view of the test section designed by Hausammann. Note the throat and the many longitudinal slots that had to be replaced (due to vibration) by broader slats.

How did the transonic test section look like? At that time this was still a 'secret' for the outside world. In figure 1-31 the presence of many longitudinal slots is clearly visible. Additionally Van der Zwaan mentions in the design report for the HST control desk[44] that due to confidentiality, details could not be given of *'a device required to control the Mach number for supersonic operation'*, a device that was named for simplicity *'an adjustable plate'*. Fortunately, a drawing of a configuration similar to the original test section can be found in a report by Eckhaus[45]. He studied both theoretically and experimentally (in the existing '3x3') the effectiveness of the slotted tunnel walls to cancel shock reflections at supersonic conditions. (See for more details Appendix E.)

In October 1957 a report was written that described the required tests and related instrumentation to establish the aerodynamic performance of the tunnel[46]. These measurements were also needed to check if the requirements for the flow quality in the test sections were met. The requirements, guaranteed by the contractor, stated a maximum Mach number variation less than 0.003 within an area around the model location. The measurements to prove this will be discussed in more detail at page 50.

During 1957 the construction of the HST was completed [figure 1-33]. At the end of 1957 'wind-on' was achieved and the maximum Mach number of 1.3 was reached. The commissioning started with the measurements of the local strength in the tunnel shell by means of strain gauges, as discussed before. Tests were also made to balance the fan. Van Leest reports[47] that this was finally achieved by putting accelerometers at the outer shell of one of the long legs of the wind tunnel. The thin-walled shell construction acted as a kind of amplifier for the vibrations that originated from the tunnel fan, hence providing greater sensitivity to measure these vibrations in order to balance the fan by adding locally weights on the fan blades. Finally very low vibration levels could be achieved: displacements within 35μm anywhere in the circuit and about 4μm at the main bearing of the drive system.

During one of the first runs with 'wind-on' the thin plates that formed the HST throat buckled. The reason was that a beam to fix the nozzle plate had not been installed (although present in the drawing). The problem was fixed, but the shape of the nozzle was not very accurate and had to be repaired. The requirements on Mach number accuracy were not met for supersonic flow conditions and a redesign was required.

Even more important was another constructional deficiency. With 'wind-on' the slats in the transonic test section as built by Dätwyler & Hausammann started to vibrate violently and fractured. This was completely unexpected. The explanation was that the large number of partitions in the slats (to accommodate lamps and cameras to view the model) had an adverse effect on the stiffness of the slats. This was a

[1-32]

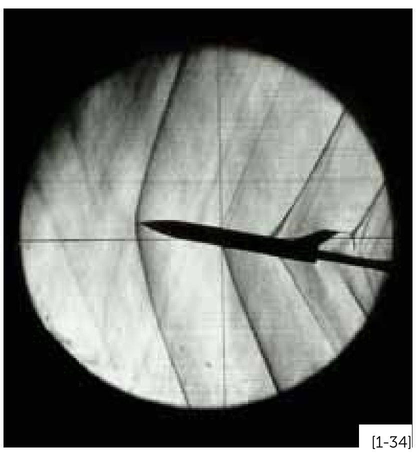
[Figure 1-32]

On January 16, 1960 the HST was officially opened in the presence of representatives of the European aeronautical industry. One of the speakers was Mr. J.N. Adenot, Secretary General of AICMA.

[1-33]

[Figure 1-33]

View of the HST circuit in 1958 still without the building (the '*Overkapping*') around it made for noise insulation. Note the shield above the first diffuser (to the left) to prevent the heat load by the sun.



[1-34]

[Figure 1-34]

Schlieren picture of the flow over the AGARD-C model at Mach = 1.081. A picture similar to this one could be observed by the guests during the opening of the HST in 1960.

matter of urgency and it was decided to replace the large number of narrow slats by a smaller number of broader slats. In these slats provisions were made to mount lamps and cameras without loss of stiffness. In view of the time the first set of slats was made of wood. The 'openess' of the slats (the '*open area ratio*') followed from wall interference calculations made by Loeve[98] in 1959 (see also page 69).

JANUARY 16, 1960: THE OPENING OF THE HST

Early 1959 the first aerodynamic tests in the HST up till Mach = 1.3 were made with the AGARD-B and -C models, a standard configuration defined by AGARD (see page 65). These tests were soon followed by comparative tests performed by Sud Aviation on a Delta wing configuration, named 'Durandal' (also tested in the 'Cornell Aeronautical Laboratories') and on the 'Caravelle' (also tested at Cornell and in the ONERA S-1 tunnel in Modane which had just been finished at that time).

The results of these and similar tests were very positive. When the tunnel became operational in 1959, a special report[48] was published to describe the wind tunnel and related facilities.

On January 16, 1960 the HST was officially opened. The opening ceremony was held in the room adjacent to the HST test hall, now used to store large parts of the HST. The speakers were Van der Maas (chairman of the Foundation NLL), Gieben (Secretary General of the Dutch Ministry of Transport, Public Works and Water Management), Adenot (Secretary General of AICMA; see also page 66) and Marx (director of NLL). Adenot [figure 1-32], gave a speech in which he stressed the importance of the relation with AICMA and the good quality of the test results. The other speakers as well stressed the importance of European co-operation in the aircraft industry. Finally Boel got the floor [figure 1-35] to explain the opening ceremony: the tunnel was run and on television monitors the audience could read the achieved Mach number and watch a schlieren picture of the transonic flow around the AGARD-C model, a flow with shock waves [figure 1-34]. It must have been fascinating after so many years of preparation and hard work to visualize a real transonic flow.

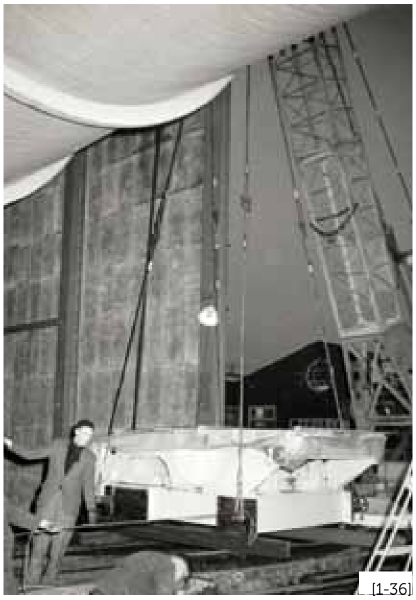
STILL A FEW LEFT-OVER'S

Although the tunnel was running and open for customers, it could only provide the most elementary measurements. There was one support strut and this allowed only a variation of the angle of attack. If the side slip angle needed to be changed, the model had to be rotated over 90° [see figure 3-15 and 3-18] or a specific sting

[1-35]

[Figure 1-35]

Boel, head of the Transonic Aerodynamics Section ('*T-sectie*') and the projectleader for the HST started a small demonstration to mark the opening of the tunnel.


[1-36]

[Figure 1-36]

The newly designed throat is mounted in the test section, quite a complicated operation (1965).


[1-37]

[Figure 1-37]

The old smoke stacks of the Power Plant (‘*Centrale*’) were replaced in the late seventies by higher chimneys to comply with an environmental law.


[1-38]

[Figure 1-38]

Building a large hall enclosing the HST tunnel circuit (1966): the beauty of the aerodynamic circuit lost to the eye!

with a pre-set side slip angle had to be used. But in the following years other model support struts were designed and built including the ‘yaw-angle sting support’ that could change angle of attack and side slip angle simultaneously. A half model balance and a subsonic model support were also added. Important improvements in the measurement technique were introduced between 1960 and 1965, greatly increasing the efficiency of the measurements. They will be discussed in the next chapter.

The test section geometry itself was still a problem. The original slats by Dätwyler & Hausammann were (temporarily) replaced by wooden slats of a different geometry. The throat of the test section was repaired provisionally. However the resulting Mach number distribution at supersonic conditions was not good enough. Time was needed to design a new shape, a job done by Nieuwland who worked for the T-Section and started this work in 1961[Q]. The solution for this theoretical problem, a real transonic problem with mixed subsonic and supersonic flow, is not obvious. The throat shape has to be adjusted for each Mach number and it was a constructive challenge to realize this with a simple mechanical construction that would still guarantee a near perfect flow (see Appendix E and figure E-11). In 1965 the new throat was manufactured by Aviatest GmbH and installed [figure 1-36]. Probably at the same time the wooden slats were replaced by metal ones. A last modification of the test section was made in 1967. After an improved yaw sting support had been mounted, the maximum Mach number of the tunnel dropped drastically. Since the new boom had a larger frontal area at the junction between boom and support strut (‘*het zwaard*’), ‘choking’ was believed to be the cause. The problem was solved by extending the slats further downstream with an increased divergence angle between top and bottom slats.

Shortly before that time, in 1966, it was decided to build a large hall around the HST circuit [figure 1-38]. The neighbours of NLL had been complaining about the tunnel noise, a problem that increased in 1963 when the SST became operational (see page 32). Although a muffler was built to reduce the noise during the 45 - 60 sec that a SST run would last, the noise was still irritating when made at regular intervals many times a day. The SST noise could be reduced further by placing the tunnel exit inside the hall. But the beauty of the aerodynamic circuit would be lost to the eye!

A considerable time was used to pressurise and evacuate the tunnel. To keep up with the increased demand (see page 70) the Power Plant (‘*Centrale*’) had to be extended. A 6th steam boiler became operational in 1964 and a second compressor was placed in 1967. An improved water-ring-pump to evacuate the HST till a pressure of 1/8 bar became operational in 1968. When in 1940 NLL was moved to its present site, the area West of Amsterdam was used for farming. But the city expanded and living quarters replaced the green crops. Environmental rules became stricter. Special Dutch fuel with low sulphate content was used from the beginning to fire the steam boilers. This was not sufficient any more. In the late seventies the height of the six characteristic smoke stacks had to be increased and were replaced by two clusters of three pipes each [figure 1-37]. ■

[Q] THESE EARLY TRANSONIC CALCULATIONS CAN BE CONSIDERED AS THE START OF A FURTHER DEVELOPMENT OF THE TRANSONIC THEORY LEADING YEARS LATER TO THE DESIGN OF SHOCK-FREE SUPERCRITICAL WINGS (SEE PAGE 77).

THE PILOT TUNNEL: A LIFE OF ITS OWN

THE ORIGINAL PLANS

In the original wind tunnel plan of 1948 a 1:5 scaled version of the HST was foreseen with a planned date of commissioning mid 1949. In the report describing the original plans[11] the philosophy behind this tunnel is explained. It was to start as a true pilot facility for the HST, intended to reduce the risk for the much larger facility. Hence the name 'Pilot Tunnel' or PT. The test section dimensions were 0.60 x 0.42 m^2 (width x height). After these 'pilot tests' a second test section would be added with dimensions of 0.32 x 0.80 m^2 and adjustable top- and bottom-walls. In this way the tunnel blockage could be reduced and, hopefully, Mach numbers closer to 1 could be achieved. [See also figure 1-39.]

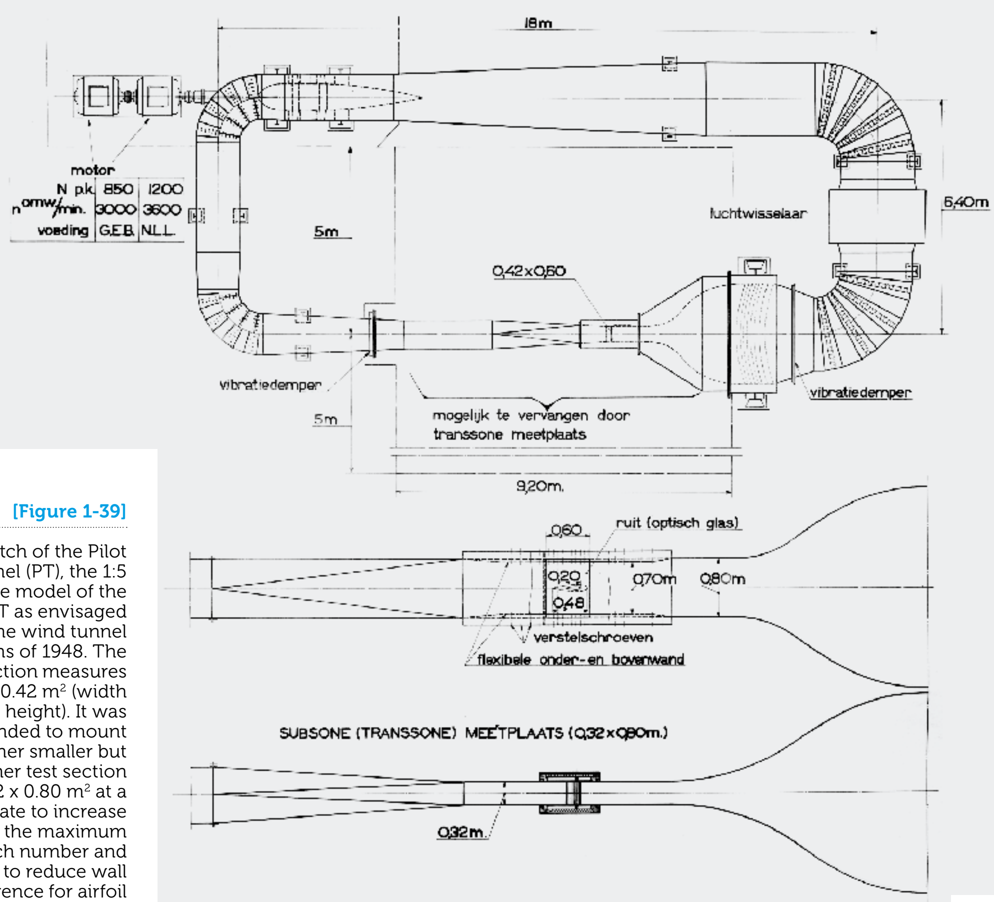
The actual preparatory work for this tunnel had already started in 1947 with Stork as contractor. The foundation was finished in 1948 with the detailed design work still ongoing in May 1949, when the stop on most of the building activities was announced by the Government. Only work on the PT could continue but this activity was finally also stopped in October 1949.

A PILOT FOR TESTING TECHNIQUES

After the green light from the Government for the modified tunnel plans in 1952, the detailed design activities continued. Since it was decided in 1952 to make the test section of the HST a real *transonic* test section with slotted walls, though somewhat reduced in size, a decision on whether the PT had to be changed accordingly was required. Most probably the design and construction was already advanced to the point that such a change was no longer cost effective and it was decided to finish the PT according to the original plans.

The contracts were awarded in 1953 and the PT was commissioned in 1954 [see figure 1-41]. In the first year the tunnel got its power from the public grid, but in 1955 the NLL power plant could be used as well. Problems were reported with the drive system. For the commissioning of the tunnel one of the smaller scale AGARD-C models was used in combination with in-house developed internal strain gauge balances[49]. A schlieren system was built (modified later in 1957) as well as a Mach meter. In this way the PT provided early experience for the development of the testing techniques at high subsonic conditions. Although it was decided in 1952 to limit the flow velocity to high subsonic speeds, a transonic test section with slotted top and bottom walls was added in 1957. A maximum Mach number above 1 could now be reached but the flow quality was not good enough. It is likely that other test section configurations were also investigated. A report on the characteristics of the transonic test section appeared in 1960[50]. In the text of this report the configuration shown in figure 1-40 is referred to as *'type A, the Dätwyler and Hausammann system with 46% open slots'*. Hence, it is likely that this test section resembles the original test section of the HST.

In the report it is also mentioned that adjustable flaps had to be removed because of oscillations. Several times it was considered to increase the maximum Mach number to 1.3 (the same as for the HST) and in 1960 the cooler was even modified to accommodate the higher speeds. However, these plans were dropped in 1963, probably because of other priorities. The first



[1-39]

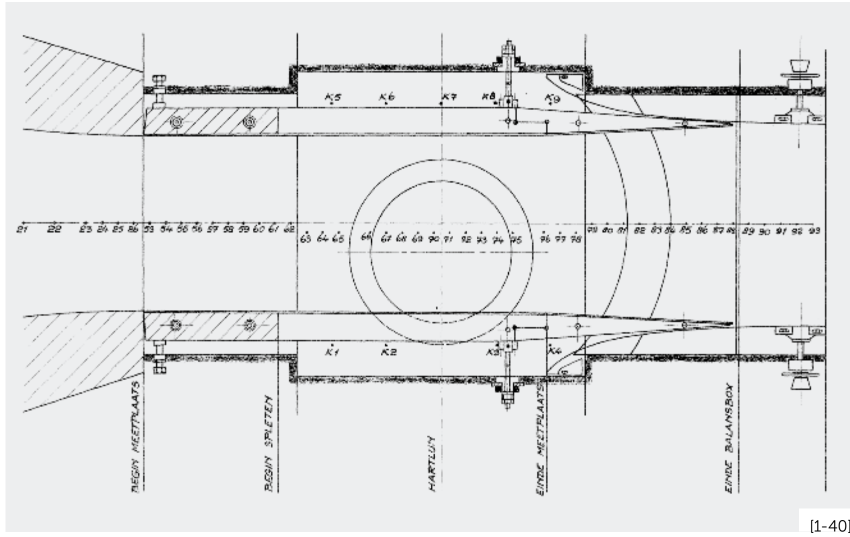
[Figure 1-39]

A sketch of the Pilot Tunnel (PT), the 1:5 scale model of the HST as envisaged in the wind tunnel plans of 1948. The test section measures 0.60 x 0.42 m^2 (width x height). It was intended to mount another smaller but higher test section of 0.32 x 0.80 m^2 at a later date to increase the maximum Mach number and to reduce wall interference for airfoil testing.

measurements with the AGARD-C model in the slotted test section were reported in June 1962[51]. As a result of these tests another change in the test section geometry was made.

Not withstanding the fact that the PT was not a true scaled version of the HST, the tunnel was very important for aerodynamics at NLR. Prior to the use of the HST, various measuring techniques could be developed in the PT such as force balances and schlieren (to visualize transonic flow; see page 43, 57). After that the PT was used extensively for two-dimensional airfoil testing and unsteady measurements (see also page 70, 76f). But it was not till 1984 that the test section of the PT became a true copy of a new HST test section. This modified test section to support the Phase 1 HST modification of 1992 will be discussed at page 35.

When the Phase 2 modification of the HST was finished in 1997, there was no direct use for this facility anymore. Since the test section had been modified, some of the original hardware for specific tests could not be used without adaptation. Also, due to the bankruptcy of Fokker, interest in experimental aerodynamic studies diminished. An option to transfer the facility to Indonesia was shortly considered, but it was finally decided to dismantle this tunnel. ■



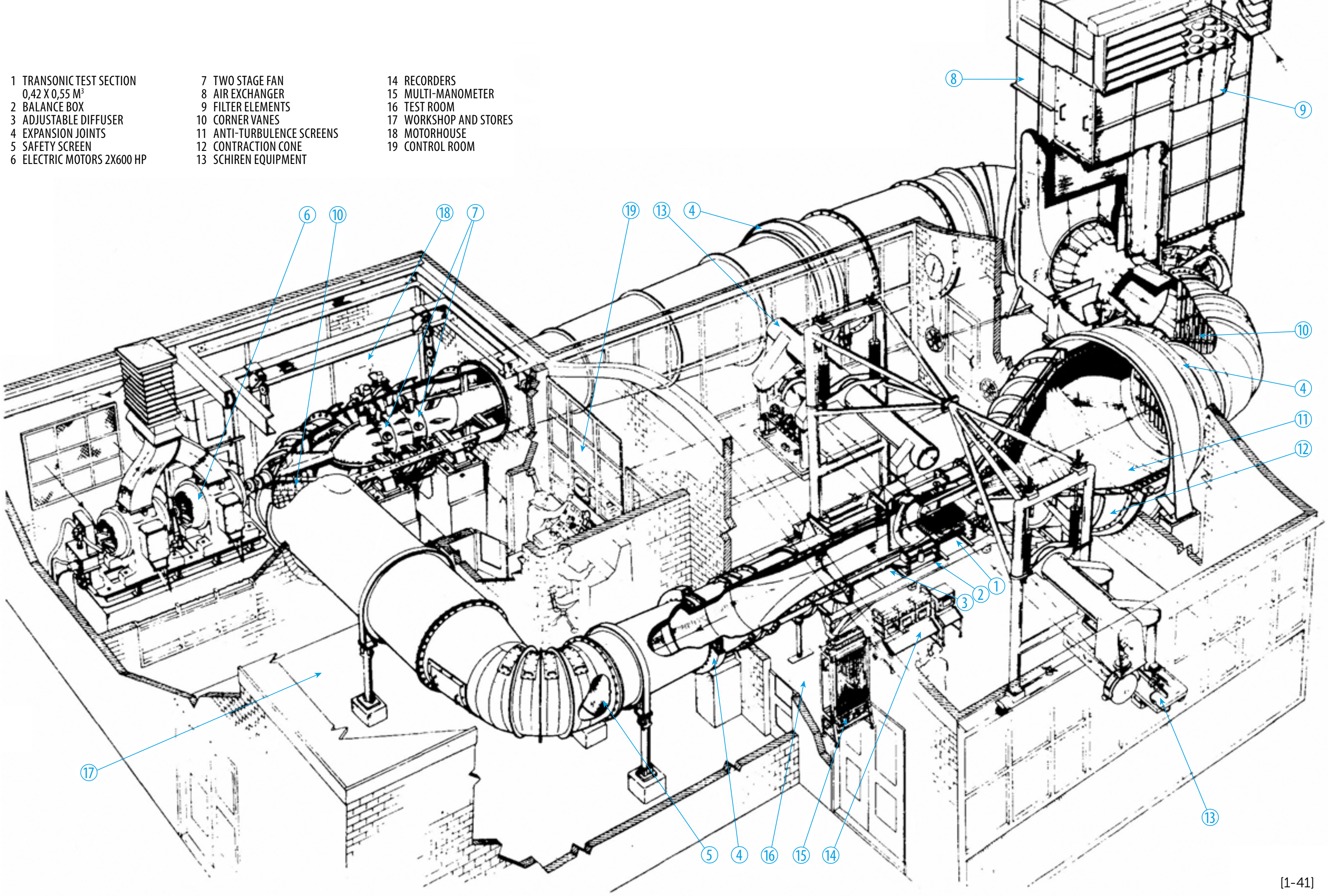
[1-40]

[Figure 1-40]

Drawing of the transonic test section of the PT as tested in 1960; in 1962 this test section was modified.

[Figure 1-41]

Isometric view of the Pilot Tunnel (PT) as built.

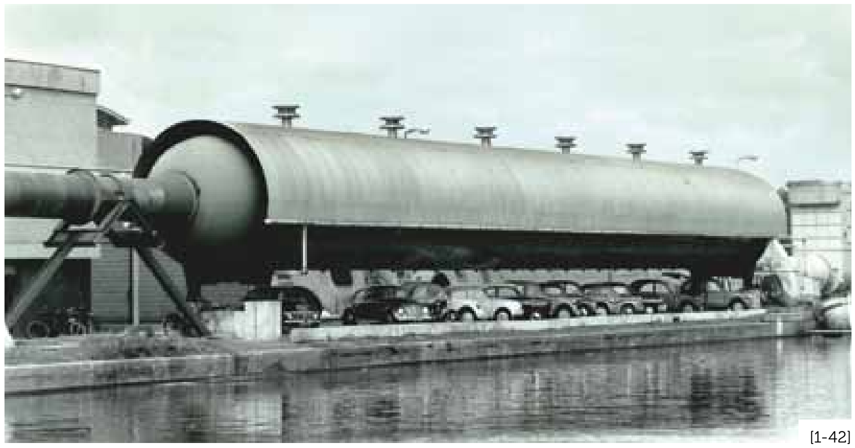


[1-41]

THE SUPERSONIC TUNNELS

A BIGGER TUNNEL

In the original plans of 1948 a small supersonic facility[11], mainly for research purposes, was foreseen with test section dimensions of 0.4 x 0.4 m^2. The freeze of all tunnel plans of 1949 also brought the development of this supersonic tunnel to a hold. Erdmann, who was very eager to continue his supersonic activities, accepted an offer for a position at the KTU, the Technical University in Stockholm. Sweden was very active in the supersonic flow regime with, at that time, seven (!) supersonic facilities. They were also leading in the development of strain gauge balances. However, soon after the decision was made to continue the NLL wind tunnel plans early 1953, Erdmann was approached again by Van der Maas and asked to return to The Netherlands to take the responsibility for the development of a supersonic facility. He returned to NLL in September 1954 and in November the G-Section was established which started with three engineers. The establishment of the G-Section in addition to the much larger Aerodynamics (A) and Flutter (F) Sections was probably part of the deal, as was the promise by Van der Maas that Erdmann would become a part-time professor in Delft in supersonic aerodynamics. It should be noted here that the responsibility for the development of the HST, the PT and the Power Plant (the '*Centrale*') remained formally under the Section '*Nieuwbouw*' headed by Boel, a situation that was only changed in 1957 when the transonic (T) Section was established (see Appendix C).

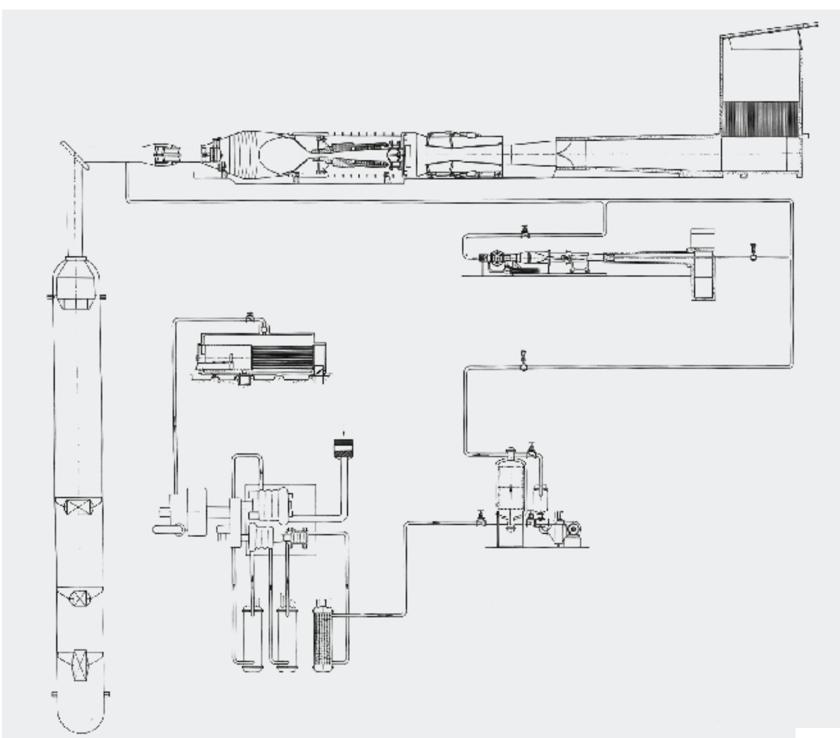


[1-42]

[Figure 1-42]

The pressure vessel, a popular covered parking area.

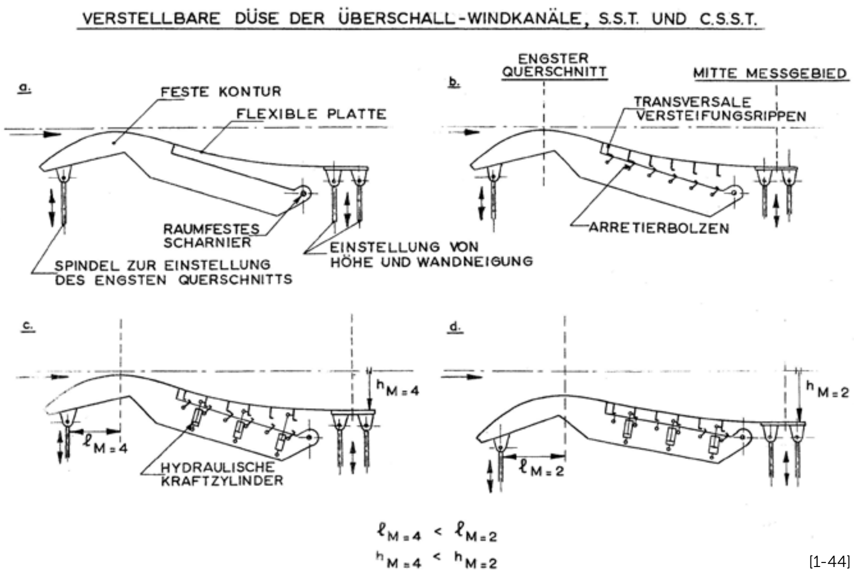
Apparently the option was discussed to outsource the design and construction of the supersonic tunnel as mentioned in the trip report[28] of the visit of Boel and Dobbinga to Switzerland in 1953. But after Erdmann returned various other options for the SST were investigated, including a wild idea from Zwikker, the director of NLL at that time, to use liquefied air instead of compressed air. In July 1954 Von Kármán visited NLL together with a group of advisors, the 'AGARD Travelling Seminar'[52]. They recommended the building of an intermittent or blow down supersonic wind tunnel rather than a continuous supersonic tunnel. In this set-up compressed air, stored in a large pressure vessel, is released through a precisely controlled valve to flow through the test section of the tunnel for a short time (say 45 seconds) only. The change from a continuous to an intermittent facility also allowed an increase of the test section dimensions from 0.4 x 0.4 m^2 to 0.8 x 0.8 m^2. But at that time NLL was still in favour of a continuous supersonic facility



[1-43]

[Figure 1-43]

Sketch of the SST as a blow down facility as actually built around 1960.



[1-44]

[Figure 1-44]

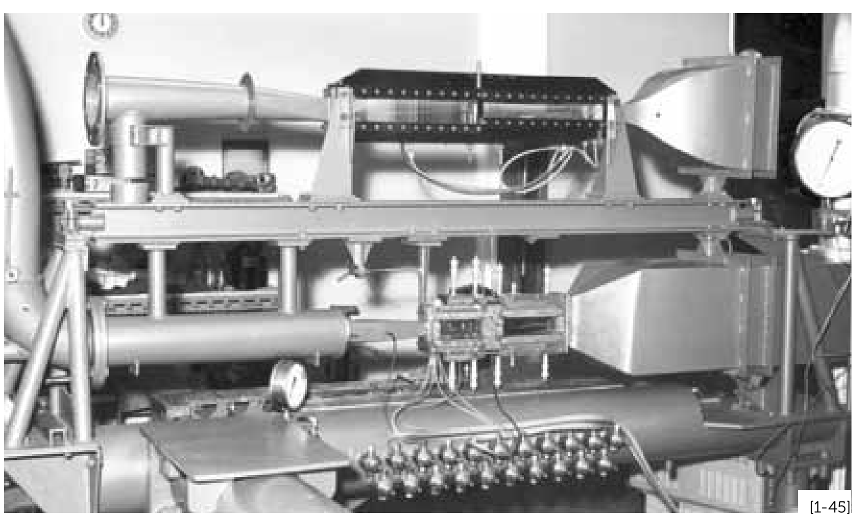
Sketch of the continuously adjustable nozzle of the SST that combined a nozzle block and a flexible plate.

in view of the availability of the compressor and the easier measurement technique. In the summer of 1955 Boel and Erdmann made a trip to the US to visit wind tunnel facilities of NACA and the American industry. A second trip was made by Erdmann in the autumn of 1957 as part of an AGARD meeting. Between Boel, who was in charge of the HST development, and Erdmann the idea was born to increase the dimensions of the SST in such a way that models could be transferred between the two wind tunnels. This would considerably increase the attractiveness of both facilities. Since Boel was convinced that international contracts were essential to exploit the wind tunnels, such a combination would increase the 'market value' of both facilities considerably. Due to a fundamentally different effect of the tunnel walls on the model for subsonic and supersonic flow, test section dimensions smaller than the 1.6 x 2 m^2 test section of the HST would suffice for the SST. In 1956 they were tentatively set at 1.2 x 1.5 m^2 and finally fixed at 1.2 x 1.2 m^2 in 1957. There was an additional advantage to the increase of the test section dimensions. To obtain the same specified Reynolds number, the maximum pressures could be decreased leading to a simpler and cheaper construction. Erdmann, always with an eye on more fundamental research, insisted on adding a small supersonic research facility, the CSST or 'Continuous Super Sonic Tunnel' with a test section of 0.27 x 0.27 m^2, also to be run with pre-heated air for Mach numbers till 6[R]. In spite of a very stringent budget limitation, Van der Maas could be convinced that a larger SST test section, compatible with the HST, would provide better opportunities. Erdmann writes in his memoirs[14] that Van der Maas remarked at the end of the meeting with Boel and Erdmann: *'Mr Erdmann, it is not easy to make me change my mind when I have decided something. But you managed to do so. You have convinced me completely. Go on, but don't forget to make financial commitments only with my written approval.'* Since the total budget for the new wind tunnels was not increased, it is likely that the additional costs for a larger SST were covered by lower costs for the HST due to the change of contractor from Stork to Werkspoor. See Appendix B for more details.

FINAL REALISATION OF SST AND CSST

Once the concept of a blow-down facility was selected, in accordance with the recommendations made in July 1954 by the AGARD specialists, the design of the tunnel could start. The basic layout of the tunnel is shown in figure 1-43. Three major technical obstacles had to be cleared first[53].The pressure vessel (600 m^3, 40 bar pressure) needed for a blow-down facility could be shared with the HST to pressurise the tunnel more efficiently. But during a blow down run it was essential to keep the temperature approximately constant. Solutions for this problem as applied elsewhere were hardly satisfactory and a new scheme was developed. The 46 m long pressure vessel [figure 1-42] was split in compartments separated by 'heat-regenerators' made up of 2 mm thick steel plates at a distance of 2 mm. During a run the air, with a decreasing temperature due to the expansion, had to flow at high speed through the regenerator where it was heated by the available heat capacity of the steel plates. The effectiveness of this scheme was calculated by Van Spiegel[S,54]. In this way the temperature could be maintained at a close to constant level.

The second problem that had to be solved was the control valve. This valve should be capable of reducing the variable pressure of the pressure vessel to a very constant pressure in the settling chamber to keep the Mach and Reynolds number in the test section constant during a run. This problem was finally solved with a clever design of a valve consisting of two elements: a pre-programmed valve (depending on the required pressure and Mach number) for coarse adjustment and a smaller, second valve that could be fine-tuned on the basis of the measured pressures. The control was performed by an analogue system operating in a mixed pneumatic/electric mode. The third innovation was the deci-

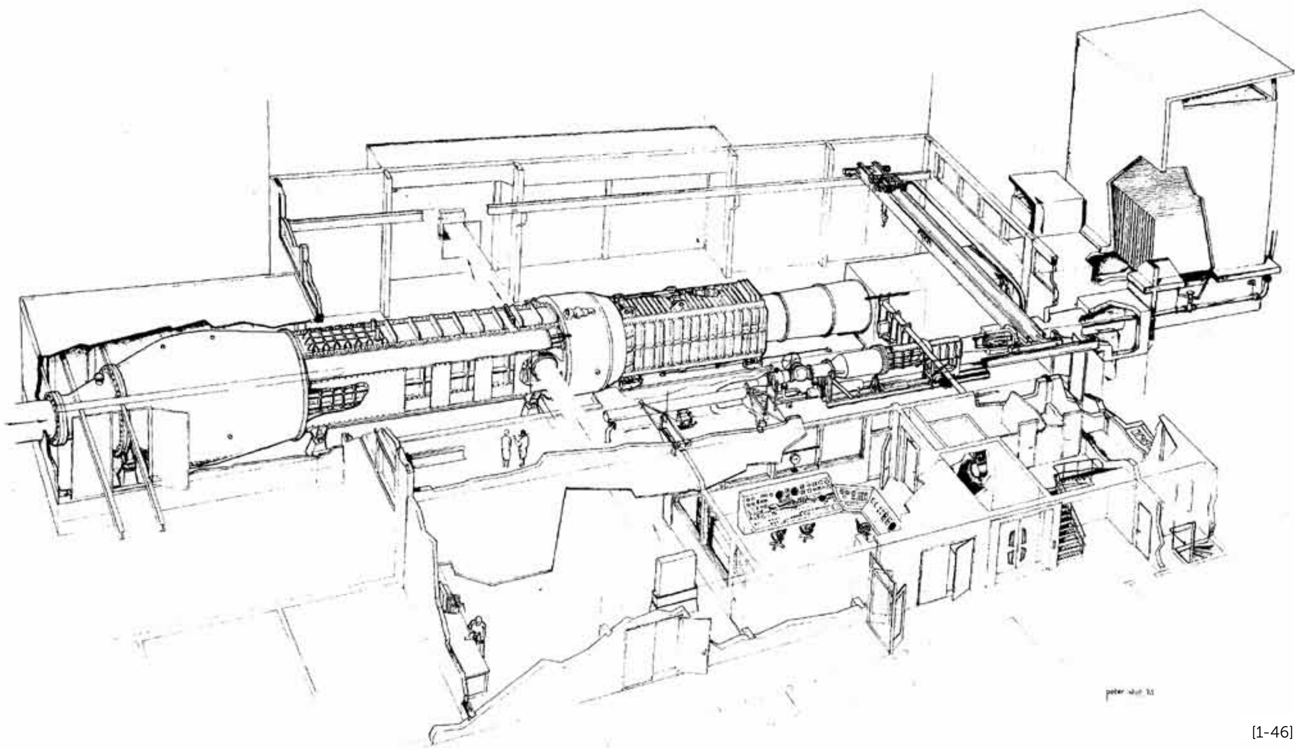

[1-45]

[Figure 1-45]

Photograph of the extension of the original '3x3' cm^2 supersonic tunnel (on top; compare with [figure 1-15]) with a scaled-down model of the SST nozzle and test section of 27 x 34 mm^2 (on the bottom) that was finalised in 1956.

[R] IN PEENEMÜNDE ERDMANN WAS INVOLVED IN THE DESIGN OF A 'SUPER ÜBERSCHALLKANAL' FOR MACH NUMBERS UP TILL 6 OR 7.

[S] VAN SPIEGEL BECAME PROFESSOR IN MATHEMATICS AT DELFT TECHNICAL UNIVERSITY; LATER HE BECAME DIRECTOR-GENERAL OF THE MINISTRY OF EDUCATION.


[1-46]

[Figure 1-46]

Isometric view of the SST and the CSST.

sion to delete the fixed nozzle blocks. In a supersonic wind tunnel the Mach number is determined by the height and the precise shape of the nozzle contour relative to the test section height (see Appendix E). In the Peenemünde supersonic tunnels as well as in the small '3x3' tunnel of NLL, the Mach number was changed by exchanging different nozzle blocks. Adjustable nozzles had been applied elsewhere but they required many (20 to 30) movable jacks that had to be positioned with great accuracy. Erdmann came up with an alternative system, a further development of a system applied in a Swedish tunnel by the tunnel designer Rosen. This design consisted of a movable nozzle block that was attached to a flexible plate that could be held by a maximum of six locks [the number depending on the required Mach number; figure 1-44] that fixed the specific plate contour. A few hydraulic jacks were added for 'fine tuning'. This concept was first investigated on a scaled version of the nozzle and test section (2.7 x 3.4 cm^2) which was added as a module to the already existing '3x3' [figure 1-45].

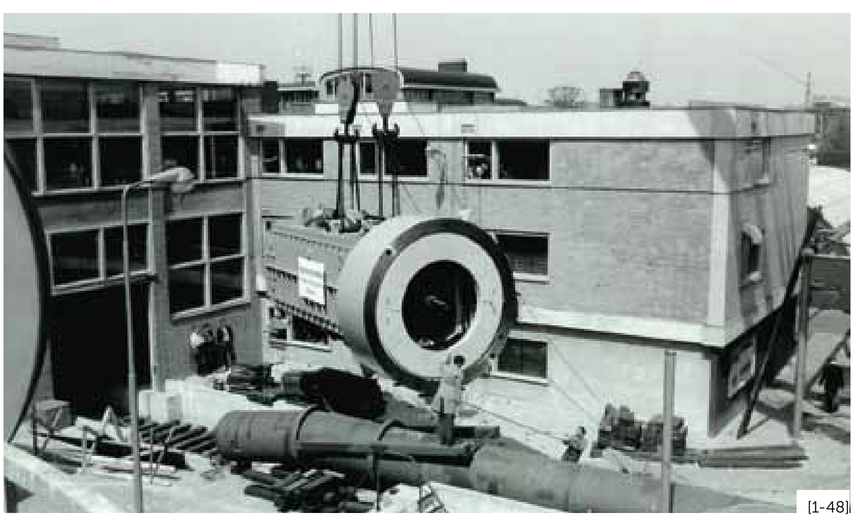
Many internal notes (most of them not preserved) were written during the development of the HST to discuss various technical aspects of the HST design. But for the SST this is hardly the case. As Van der Zwaan[94] remarked: *'it is amazing that we made the HST since we didn't know much about transonic wind tunnels'*. In contrast, Erdmann was very knowledgeable in supersonic wind tunnel design and the related measuring techniques as a result of his work in Peenemünde (see Appendix D). He formed a small group of experts around him. In 1957 the contracts for the SST and the smaller CSST were granted to the Swiss firm Dätwyler & Hausammann, the company that was also responsible for the test section of the HST. A supersonic tunnel with a test section of 1.2 x 1.2 m^2 was designed for Emmen but never built due to lack of money. Instead, the already mentioned smaller transonic tunnel was made. The combination of Erdmann and Dätwyler & Hausammann must have been a very strong one with regard to the available expertise.

The pressure vessel, made by Plaatwellerij Velsen and the compressors, also required for the HST, were delivered early 1958. Zandbergen was responsible for the elaborate stress calculations. Dätwyler &


[1-47]

[Figure 1-47]

The SST and CSST around 1964 and ready to be used for the customers.


[1-48]

[Figure 1-48]

Part of the test section and diffusor of the SST hoisted before the final assembly (around 1959).


[1-49]

[Figure 1-49]

In 1963 the SST was transferred from Hausammann to NLL during a small party in the hall of the SST. From left to right: Hartzuiker (test engineer), Van Leest (in charge of the construction), Erdmann (hardly visible), Isler (the business partner of Hausammann), Hausammann, two waitresses from the restaurant 'Suisse', Marx (director NLL), Dätwyler and Van der Maas (chairman of the Board of NLR).


[1-50]

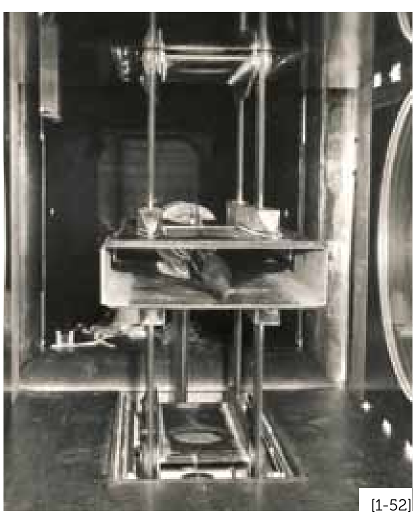
[Figure 1-50]

The 'VIP table' during the informal party at the opening of the SST. From left to right: Isler (?), Hausammann, Dätwyler, Van der Maas, Marx and Erdmann.

[1-51]

[Figure 1-51]

'...and here we will have the sonic wall'. Cartoon in the newspaper '*De Volkskrant*' at the opening of the SST.


[1-52]

[Figure 1-52]

Proximity plates to protect the model during starting and stopping of the flow in deployed position.

Hausammann were responsible for the detailed design and the construction of the supersonic tunnels. The SST and CSST parts were built in Switzerland and transported to the NLL site at Amsterdam. The on-site construction at NLL [figure 1-48] was supervised by Van Leest and Van Straten. The first tests in the CSST were already made in 1959, but required some changes in the construction. The first on-site construction of the SST started in 1960. In 1961 the ultimate strength tests for the pressure vessel and the high pressure parts of the SST and CSST were made by filling the construction with water. In the same year the CSST was finally accepted and calibrated. An isometric view of the SST and the CSST is shown in figure 1-46. A photograph of the SST and the CSST is shown in figure 1-47. Due to the high stagnation pressure very high Reynolds numbers [see figure 1-63] could be achieved, a feature that made this tunnel rather unique in Europe. The maximum Mach number of the SST was 4. Higher Mach numbers can only be achieved when the air is heated. This was possible in the CSST with overheated steam at 200 °C from the power plant. In combination with an 'injector' a Mach number of 6 could be achieved. In 1962 the CSST was extended with a transonic test section.

In early 1963 the SST was handed over to NLR during a small and informal party offered by Dätwyler, Hausammann and Isler (the latter was the business partner of Hausammann). From NLL Van der Maas (the chairman of the Board of NLL), Marx (director) and Erdmann were present, together with some of the engineers. Marx gave a speech [figure 1-49] and toasted to the success of the tunnel. During the open table only the VIPs could enjoy their meal seated [figure 1-50]. In the Dutch newspaper 'De Volkskrant' a cartoon marked the opening of the SST [figure 1-51]. This modest ceremony contrasted with the official opening of the HST three years before in the presence of representatives of the Dutch Government, AICMA and future customers.

Nevertheless, more time was needed before the SST could be used routinely for wind tunnel tests. There were problems with the fixation of the nozzle contour and the control valve had to be improved. An important addition was the installation of the so-called 'proximity plates' [figure 1-52]. These plates, which move out of the top and bottom walls during starting and stopping of the tunnel, form a box to shield the model from high loads as typically encountered during starting and stopping of a supersonic wind tunnel. A similar system was used by Boeing in their supersonic wind tunnel. During each tunnel run the high pressure air was exhausted into the atmosphere. Plates were mounted to deflect the airstream in vertical direction at the end of the supersonic diffusor. They couldn't stand the high loads and were blown to pieces. The noise during a SST run was excessive, but fortunately lasted less than a minute. Only some years later, when the SST could exhaust into the building that enclosed the HST, the noise levels could be reduced to acceptable levels.

The flow quality was another point of concern. As was the case for the nozzle of the HST, the uniformity of the flow in the test section depends directly on the shape of the nozzle. But the theoretical, calculated shape is not necessarily the optimum due to boundary layer effects on the tunnel walls and deformation of the tunnel contour under load. Erdmann realised a very elegant solution to this problem in 1967. He applied the so-called 'method of characteristics' (a mathematical technique to calculate supersonic flow) to derive the optimum shape of the flexible nozzle contour from actual pressure measurements with a calibration rake in the test section. In supersonic flow disturbances propagate along straight lines (the *characteristics* with a Mach number dependent angle). Therefore any deviation in the static pressure or flow direction in the test section could be traced back to a specific jack location of the flexible contour. In this iterative process the setting of a specific Mach number could be quickly realised. In 1973 the jacks to position the flexible plate in the throat were replaced by a much stiffer system ('auto-locks') to further improve the quality of the Mach number setting.

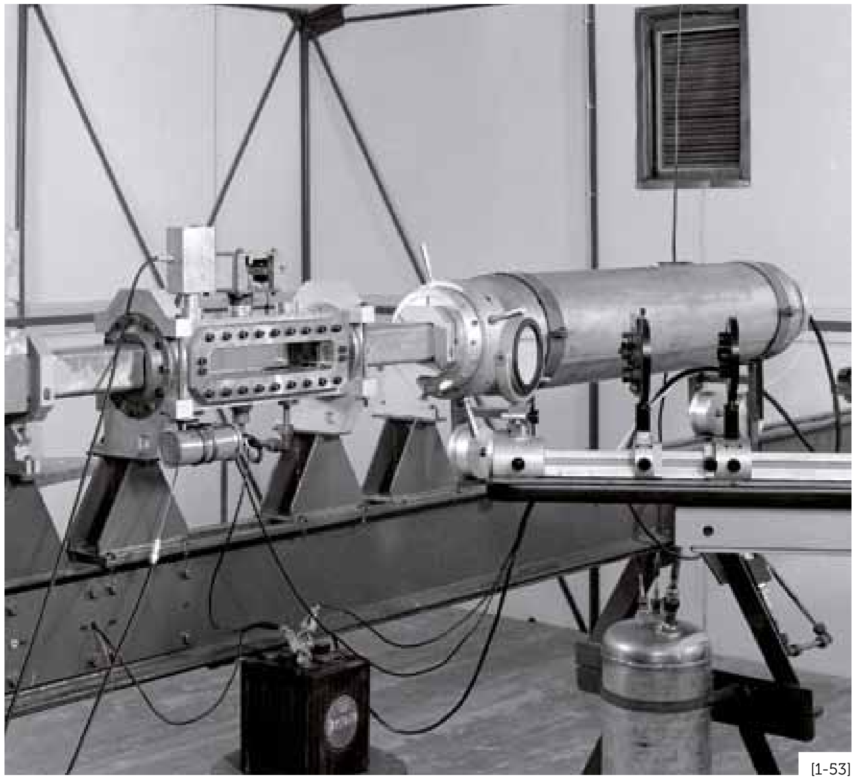
This more or less finalised the development of the SST and CSST. After that most of the effort concentrated on the measurement process as will be discussed in more detail in the next chapter (page 38). After the HST and SST were transferred to the DNW[T] organisation in 1997, it was decided to discontinue testing in the CSST for budgetary reasons. ■

[T] IN 1975 DNW WAS FOUNDED BY NLR AND ITS GERMAN SISTER INSTITUTE DFVLR (NOW DLR) TO JOINTLY BUILD AND OPERATE A LARGE LOW SPEED FACILITY (NOW NAMED LLF) IN THE NOORDOOSTPOLDER.

DEVELOPMENTS AFTER 1960

FROM HYPERSONICS TO PROPULSION AERODYNAMICS

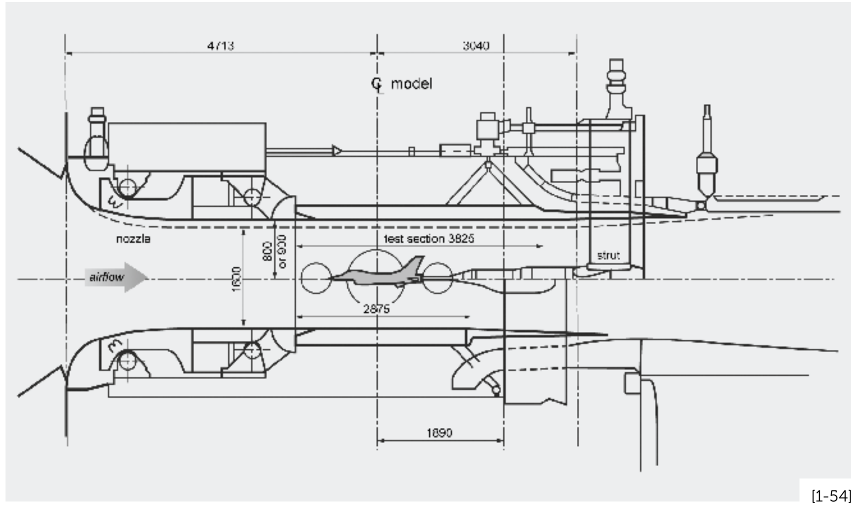
With pre-heated air the CSST could achieve Mach numbers as high as 6, a Mach number at the lower side of the hypersonic flow regime. Hypersonic flows are typically achieved during re-entry conditions of spacecraft. This flow regime is characterized by high stagnation temperatures. At these high temperatures the air and more specific its basic constituents such as oxygen, hydrogen and nitrogen, 'fall apart' and get ionized (lose their electrons). Should NLR be involved in hypersonic flows at still higher Mach numbers?


[1-53]

[Figure 1-53]
The shock tube in the Noordoostpolder in the early sixties.

In the NLL settlement in the Noordoostpolder (since 1957 located in an area of reclaimed land in the north-eastern part of the central lake of Holland), the Combustion Section ('*C-sectie*') studied the ramjet flow for the Dutch Kolibrie helicopter as well as rocket propulsion. This section was later involved in the development of the H_2O_2 system for engine flow simulation in the wind tunnel (see page 84). Some flow phenomena at high temperatures during combustion have a similarity with hypersonic flow. Dynamic effects under these conditions have very small time scales, related to vibration and relaxation phenomena on a molecular and atomic scale. Special equipment was required to measure these dynamic effects. In the early sixties a shock tube was built in the Noordoostpolder to study these phenomena [figure 1-53]. A shock tube is basically a long pipe with two compartments, separated by a membrane. Air (or other gases) at a very high pressure (hundreds of bars) is introduced into one compartment. After breaking the membrane, a shock wave propagates into the other compartment. Behind this moving shock a steady flow is realised with a very high Mach number, though for a very short time only. In 1964 a study was made of a shock tunnel. In such a tunnel a nozzle and a test section are added at the end of the shock tube. For a very short time the high pressure and temperature conditions at the end of the tube just after the reflection of the incoming shock wave provide the proper 'reservoir' conditions to drive a hypersonic flow. These studies evolved into the concept of a 'gun tunnel' where a movable piston is used instead of the shock wave to compress the gas ahead of the nozzle. This movable piston is accelerated by nitrogen gas of 800 bar maximum. The gas ahead of the piston is heated to a temperature of 2700 °C and compressed to a pressure of 1,000 bar, sufficient to realize Mach numbers in the range between 6 and 12 in the test section. In 1970 it was decided to launch a study on the construction of a hypersonic facility based on the gun tunnel concept. This study was conducted by Jaarsma, head of the Department of Hypersonics and Combustion (AH) which became the successor of the C-Section following the reorganisation of the aerodynamic division in 1968 (Appendix C, figure C-1). However, in 1972 all activities for the gun tunnel were halted. One reason for this was the lack of confidence of the intended contractor in the availability of material that could stand the extreme conditions. But the most important reason was a shift in priorities within NLR. A new large low speed facility had to be built and very soon negotiations started with NLR's German counterpart DFVLR ('*Deutsche Forschungs- und Versuchsanstalt für Luft- und Raumfahrt*') leading to a positive decision in 1975 to build the DNW (the 'German-Dutch Wind Tunnel') jointly.

In 1974 'hypersonics' was dropped from the name of the department and AH became AV, the Department of Propulsion ('*Voortstuwing*'). The already existing facilities were expanded to include tests on engine noise, such as the 'Small Acoustic Wind Tunnel' ('*Kleine Acoustische Tunnel*' or *KAT*), an open jet facility within an acoustic room. The specialists of this department supported the engine simulation test in the other NLR wind tunnels. In close co-operation with VFW (Vereinigte Flugzeug Werke, later to become Airbus Deutschland) they introduced the TPS technique for engine simulation ('Turbine Powered Simulators'), first in the DNW and later in the HST (see page 84). With this technique a small fan driven by high pressure air is used to simulate the engine flow. In 1981 a calibration tank was built in the Noordoostpolder to calibrate the TPS engines.



[1-54]

[Figure 1-54]

The modified HST test section (upper part) compared with the original test section (lower part). The length of the test section has been increased by 1.15 m whereas the height can be adjusted to 1.8 m when required. A choice could be made out of three new model supports [figure 1-57].

INCREASED REYNOLDS NUMBER CAPABILITIES

Around 1970 the 'Reynolds number issue' became increasingly important. Till the sixties it was considered sufficient to test at (chord) Reynolds numbers above roughly 2 to 3 million, to have a flow development similar to what could be expected in flight. Transonic flow, where shock-wave boundary layer interaction is of critical importance, changed the traditional picture[55]. This was also triggered by experiences in the US, where the design by Lockheed of a very large transport aircraft (the C-141) had to be modified substantially after the first flight, a problem believed to be caused by Reynolds number effects[56].

Fokker as well felt an urgent need to obtain data at higher Reynolds numbers (see page 79). It was important to see if the Reynolds number capability of the NLR tunnels could be improved. In principle this could be done by adapting the fan. Studies made in 1976 indicated that a 20 % increase in Reynolds number was indeed possible by taking out the second stage (second row of blades) and taking away half of the blades of the third and fourth stage. This however could only be done at the expense of the highest Mach number that could be tested: a reduction from 1.3 to 1.25 (see also Appendix A). This modification was pursued in 1978, leading to the expected change in performance.

[1-55]

[Figure 1-55]

The Pilot ETW was located in Amsterdam near the Power Plant at the location where in 1948 the (small) Supersonic Tunnel was planned.

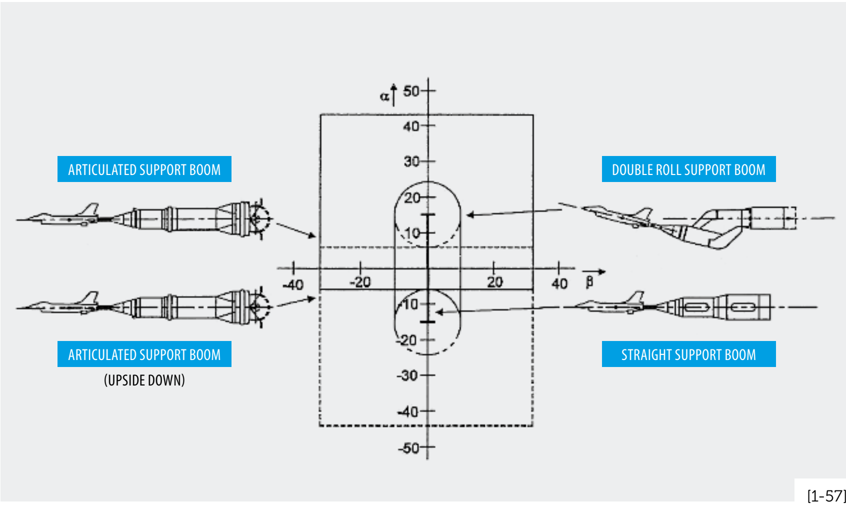
At the same time studies began to use a special insert in the SST to increase the Reynolds number for two-dimensional transonic tests. The idea, proposed by Hartzuiker (head of the Department of Compressible Aerodynamics AC), was to make use of the high stagnation pressures in the SST. The insert was to be mounted in the supersonic flow in the test section of the SST. Transonic flow with a high static pressure could then be generated by a system of oblique shocks, generated by properly shaped and positioned inlet lips at the front of the insert. A model of the insert* was tested in 1978 in the CSST [figure 1-56], but this development was stopped a couple of years later after design studies made by DSMA, a Canadian Engineering Firm which also became involved in the design of the DNW. It was decided to give priority to a new low speed tunnel in the Noordoostpolder to replace the existing LST's in Amsterdam that had been operated since 1940. This new LST was opened in 1984.

[1-56]

[Figure 1-56]

Model of the 'Transonic Insert' tested in the CSST around 1978. The idea was to place a similar (though larger) insert in the SST to generate a high Reynolds number flow to test two-dimensional airfoils.

High Reynolds number testing also became a matter of international co-operation. As early as 1970 an AGARD working group on 'High Reynolds Number Tunnels' (HiRT) was established, followed in 1972 by a second AGARD working group (LaWs from 'Large Wind Tunnels'). As part of this study each of the countries France, England and Germany promoted a specific concept for a 'Large European High Reynolds number Tunnel' (LEHRT). High Reynolds numbers can be achieved by testing very large models or by testing at high pressure levels. Large wind tunnel models require a very large wind tunnel, a very costly affair at transonic flow conditions. Testing at high pressures was believed to be a good alternative. The various concepts differed in the way these high pressures were generated in an energy efficient way to limit the operational cost for such a facility. However, the Reynolds number can also be increased by reducing the temperature of the flow. This can be achieved by spraying liquid nitrogen into the tunnel circuit. This is not easy. Special materials have to be used at these low temperatures and the differences with the ambient temperature cause thermal stresses and instrumentation problems. The idea of cryogenic testing originated in the US, where a pilot facility was successfully tested at NASA Langley. It was concluded that the practical problems could be solved. In the US the decision was taken to build the National Transonic Facility or NTF at NASA Langley. In 1977 agreement was reached in Europe on governmental level between France, Germany, the United Kingdom and



[1-57]

[Figure 1-57]

The three new support booms for the modified HST and the corresponding angle of attack and yaw angle range.

The Netherlands to build such a cryogenic facility, the 'European Transonic Wind Tunnel' (ETW). A special Technical Group was tasked with preparing the construction of such a facility. This group, with members from the contributing countries, was headed by Hartzuiker. In 1978 the group started its activities in Amsterdam. A small pilot facility, the PETW, was built to test various critical aspects such as cooling by spraying liquid nitrogen and its effect on flow quality, tunnel control and instrumentation. This tunnel was actually built in an existing building on the northern side of the HST Power Plant. This building was originally designed to house the small supersonic tunnel that had been planned in 1948. The foundations for this tunnel were prepared in 1948 but the tunnel was never built (see page 29). When it was decided to build the ETW in Germany near Cologne, the ETW Working Group was transferred to Porz-Wahn. In 1990 the first stone was laid for the ETW and this tunnel was opened on June 8, 1993. After a slow start due to the fact that industry had to build confidence in this technically very advanced facility, this tunnel is now running successfully and contributes significantly to the competitiveness of the European aircraft industry.

HST UPGRADE IN THE NINETIES

In 1980 the HST had been in operation for over twenty years. The instrumentation had been modernized continuously (see next chapter, page 38f) but most of the mechanical systems dated from the time of construction of the HST and showed signs of wear and tear, e.g. the fan blades and the model support booms. The tunnel control system was a system with mechanical relays, essentially the same as in 1960. The steam boilers were still older and their second life was limited as well. The requirements of the industry had become more and more demanding over the years. There was an increased interest in high angle of attack aerodynamics for military aircraft. Simulation capabilities, accuracy and productivity became critical aspects in the competition among European wind tunnels. It was about time to think of a major upgrade of the HST.

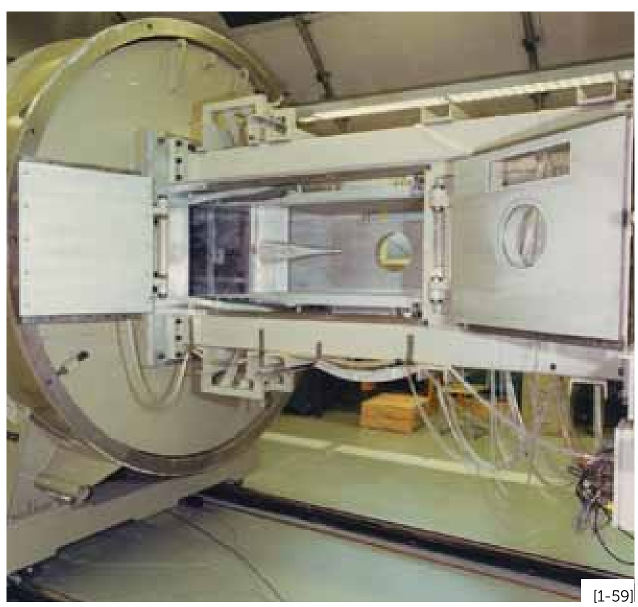
The first plans for such an upgrade originate from 1983. A study was made by Hartzuiker of the possibilities for new model support systems with improved angle of attack and yaw capabilities, following demands from customers. These studies showed that a longer (from 2.5 to 3.65 m) and higher (from 1.6 to 2.0 m; later limited to 1.8 m) test section was essential for these improvements [figure 1-54]. Three new support booms were defined: the 'slender support boom' for accurate drag measurements for transport type aircraft (limited angle of attack range, very low aerodynamic interference), the 'double-roll boom' for all kinds of tests (coupling good angle of attack and yaw capabilities to a low aerodynamic interference) and the 'articulated boom' for high angle of attack (large angle of attack and yaw capabilities) [see figure 1-57].

Replacing the slotted tunnel walls (still based on the 'classified' concept of the fifties: see page 18) by (exchangeable) flexible walls was also considered. Flexible walls were studied in Europe both theoretically and experimentally in the eighties

[1-58]

[Figure 1-58]

The Pilot-HST in 1986, a modification of the Pilot Tunnel (PT) to study the aerodynamic effects of the proposed modifications for the HST test section and model supports (test section closed).



[1-59]

[Figure 1-59]

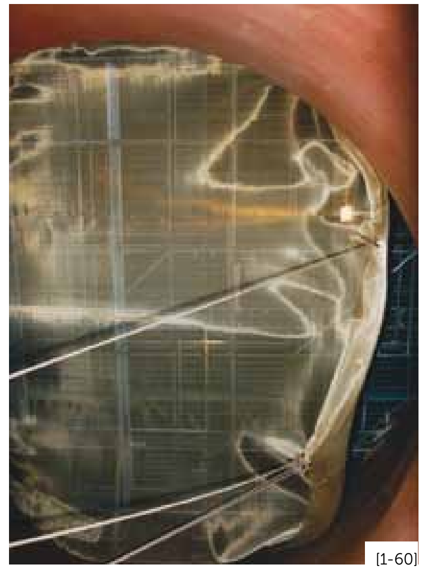
The Pilot-HST in 1986, a modification of the Pilot Tunnel to study the aerodynamic effects of the proposed modifications for the HST test section and model supports (test section open).

(partly within the framework of GARTEUR) as a very convincing method to eliminate substantially wall interference, still a difficult problem in transonic aerodynamics with consequences for accuracy (see page 82). In this concept the upper and lower walls are shaped roughly according to the shape of the streamlines around the aircraft in flight. The trick was that the optimum contour of the walls could be derived from measured tunnel wall pressures by (real time) calculations, without any additional information of the model. For that reason the term 'self adjusting walls' was also used. At NLR Smith was actively involved in the development of this concept. In 1986 and 1987 preliminary studies for the test section modifications were made by DSMA, a Canadian Engineering firm that had also been involved in the DNW design. The companies Comprimo and Holec studied the energy supply and recommended to buy two gas turbines of 15 MW each. The original modernization plans are described in a proposal[57] written in 1987. Total costs were estimated at that time at 44 million Dutch guilders, roughly half of them for the new power supply.
It was decided to test the new tunnel configuration in the Pilot Tunnel. The modified PT was now named Pilot HST or PHST and the test section finally became a real pilot for the 'HST-to-be-modified' [see figure 1-58 and 1-59]. The first tests started in 1986. The engineering contract for the HST modification was granted to DSMA.

Based on these studies the plans for the HST modification evolved. An increase in test section length of 1.15 m could easily be accommodated within the existing HST main structure, but for practical reasons the increase in test section height was limited to 1.8 m instead of the originally planned increase from 1.6 to 2 m. The flexible wall concept was finally not implemented because of its mechanical complexity and a possible negative effect on productivity and reproducibility of test results. The fact that slotted walls were still required at supersonic conditions to eliminate shock reflections from the walls has certainly contributed to this decision.

A new element in the HST modernisation was a completely new set-up of the tunnel control systems and all sub-systems, developed in close co-operation with DSMA. The basic philosophy was the adaptation of a fully automatic operation with 'graceful degradation' to lower control levels if wanted or needed. An increase in productivity of about 30 % was expected.

In 1990 it was decided for budgetary reasons to split the HST modification in two phases. Phase 1 comprised the modification of the test section, the new model support booms and the new tunnel control system. Genius Holding became responsible for the actual construction work. The on-site construction activities started in May 1992 and lasted till the end of the year.

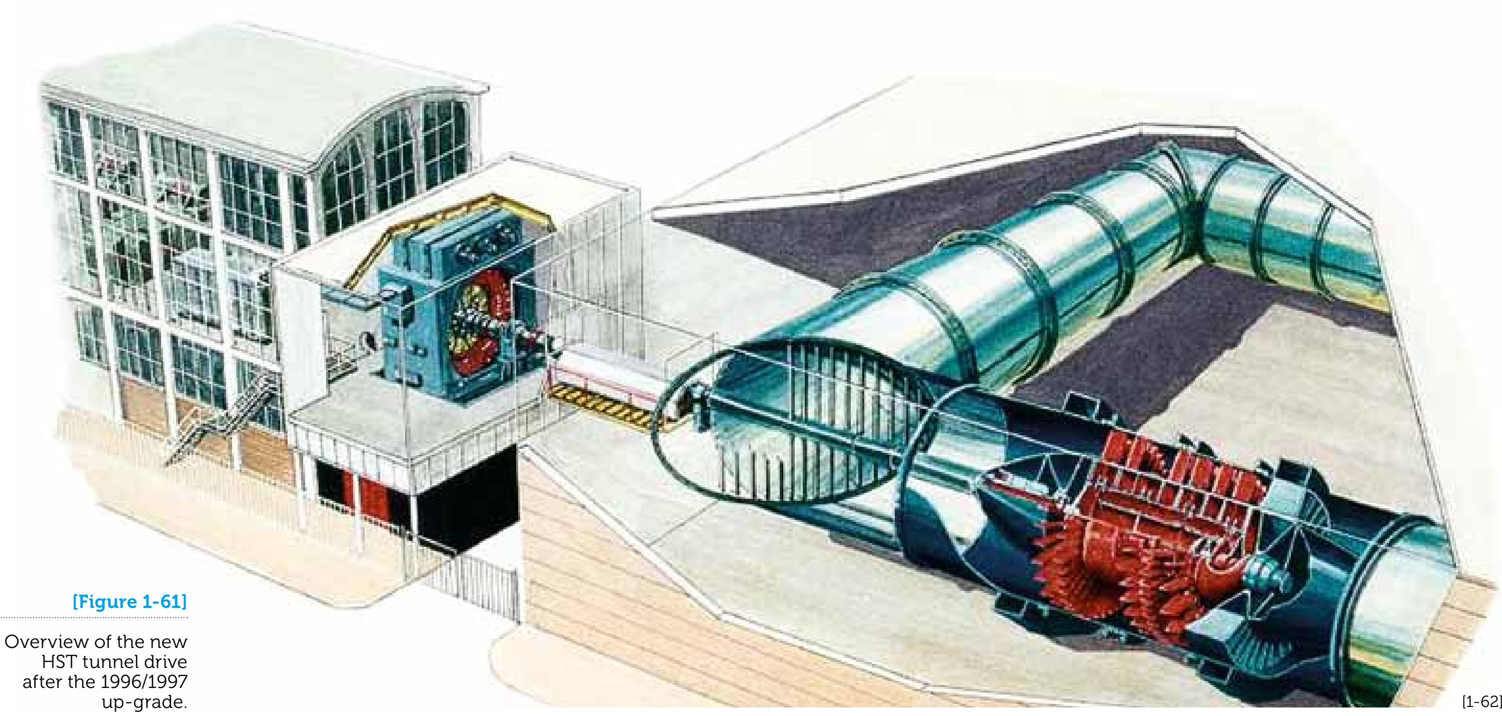

[1-60]

[Figure 1-60]

Mounting new screens in the settling chamber during the modification of the HST in 1996.

In the same period the tunnel control room was completely dismantled, the control desk carried off and all cables renewed. The first calibration and validation tests for the modified HST were made at the beginning of 1993. They showed the expected performance[58] and soon thereafter the tunnel was used again for tests as part of the Fokker 70 program (see page 81).

Hartzuiker was project leader for the phase 1 HST modification. After his retirement in 1993 Jaarsma took over. Jaarsma had been leading the team that designed the 'Guntunnel' (see page 33) and soon after that he became the project leader of the DNW.


[1-62]

[Figure 1-61]

Overview of the new HST tunnel drive after the 1996/1997 up-grade.

[1-62]

[Figure 1-62]

The new drive for the HST fan hoisted into its new position (beginning of 1997)

He subsequently became responsible for the design of the ILST, the Indonesian Low Speed Wind Tunnel of LAGG in Serpong near Jakarta. The Phase 2 modification was his last job at NLR before retirement.

The most important element of the Phase 2 upgrade was the replacement of the Power Plant. This issue came earlier than initially foreseen. In 1993 the Dutch authorities announced that by the year 1998 the smoke emissions of power plants had to meet very narrow limits. Reduction of the NOX emission for the existing Power Plant appeared to be a very hard problem and success could not be guaranteed. In the past a hook-up to the local power grid had been considered but was not attractive due to the high costs for a cable to connect to the closest power plant. But in recent years this situation was changed as a nearby sub-station had sufficient power to serve NLR. Negotiations with the power supplier resulted in attractive power tariffs. An additional advantage was that the starting-up and stopping times in comparison with the steam-driven power plant could be reduced significantly.

The original HST was designed for 25,000 hp (19 MW) but initially only 20,000 hp (15 MW) was installed, divided over four engines of 5,000 hp each [see figure 1-27]. A connection with the public grid now opened new possibilities. A replacement of the existing electric drive motors was required anyhow because of frequency differences and degraded quality of insulation of the engine wiring. And when a new drive was needed it made sense to use the full 19 MW power capabilities. Of course higher power meant higher loads as well and this necessitated a close inspection to find out if and where reinforcements had to be made.

The switch to the public grid and the installation of a new drive system would require a six month shut-down of the HST. This period could be used favourably to upgrade other parts of the tunnel as well. First of all the fan was tackled. The fan blades were mechanically in a poor state. Cracks developed in the blades* (steel sheets welded to a frame connected to a steel spar) and had to be inspected and treated at regular intervals. So it made sense to see if the complete drive-chain could be replaced by a more modern fan design. The German company Turbo Lufttechnik GmbH (or TLT, the successor of the original supplier Dinglerwerk A.G.) executed this study and concluded that the best solution was a three-stage fan that could be operated at max power of 19 MW at variable speed between 470 and 650 rpm. The stator vanes and the drive shaft also had to be renewed. With the additional power this upgrade resulted in a 50 % increase in Reynolds number. This brought the HST performance close to the original plan of 1948! (See Appendix A). In consultation with TLT it was agreed that NLR would produce the fan blades* from carbon-fibre-epoxy composites under supervision of TLT. NLR was experienced in the design and manufacturing of carbon-fibre parts (e.g. as applied for model propellers and large helicopter rotors for models tested in the DNW). Two blades per day were produced for a price less than half of the nearest price proposal.

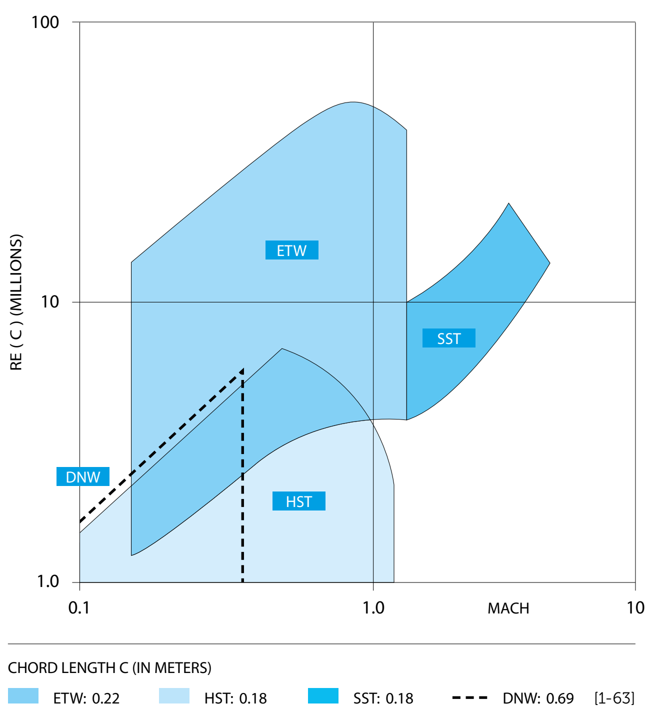
Important changes were also made in the settling chamber. The original cooler was kept but cleaned. A flow rectifier (honey comb panels) was placed just behind the cooler and the five existing anti-turbulence screens were replaced by three new ones [see figure 1-60]. A unique feature of the up-grade is the installation of a smoke injection system in the settling chamber. Some new laser based techniques for flow field measurements such as 'Particle Image Velocimetry' (see page 59) require the addition of smoke particles in the flow. With the new system smoke can be 'delivered' to any part in the test section within a certain area. Other improvements relate to the auxiliary pressure system, safety screens for fan protection, temperature control and Mach number control.

The Phase 2 upgrade started in September 1996 and lasted until April 1997. An overview of the new tunnel drive system as finally installed is shown in figure 1-61 with the new synchronous electric engine from ABB ('ASEA Brown Boveri') put in place [figure 1-62]. With the completion of the second phase upgrade the HST can again be considered as one of the most modern high speed tunnels in the world[59].

After the successful joint operation of the large low speed wind tunnel DNW since 1980, DLR and NLR decided in 1994 on a joint operation of all low speed wind tunnels. In 1997 the high speed facilities were included in this joint operation. From then on the name DNW referred to the extended DNW organisation, whereas the original DNW low speed wind tunnel was renamed 'Large Low Speed Facility' or LLF. The transfer of the HST and SST to the DNW organisation will be discussed in more detail in the Epilogue (page 89). On June 8, 1993 the most advanced transonic wind tunnel in Europe was opened in Portz-Wahn. Both Germany and The Netherlands (through NLR and DLR) remained shareholder in the European Transonic facility ETW, together with France and the United Kingdom. The HST performance is well placed in the centre of the capabilities of some major European wind tunnels: the low speed wind tunnel LLF (still named DNW in this figure), the supersonic tunnel SST and the high Reynolds number transonic wind tunnel ETW [figure 1-63]. ■

[Figure 1-63]

The performance of the HST after the 1996/1997 up-grade in relation with the DNW, the SST and the European Transonic Windtunnel ETW.



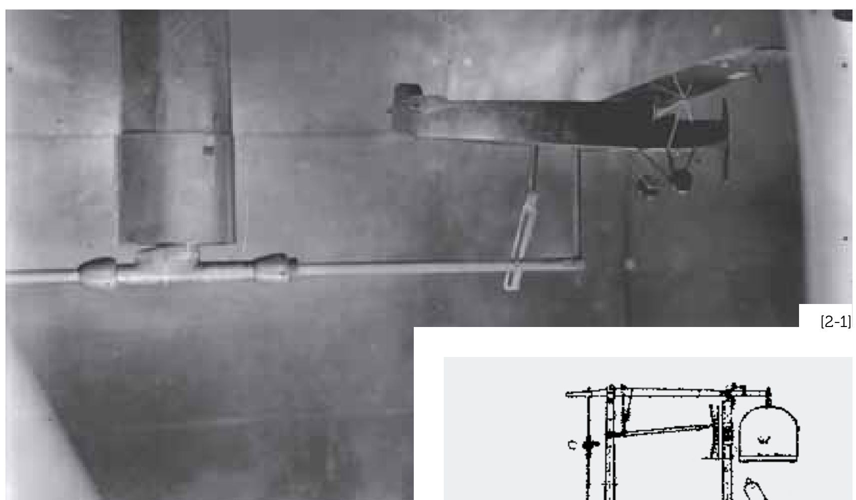
[1-63]

More and more accurate measuring

A NEW FACILITY, NEW TEST TECHNIQUES

CONVENTIONAL WIND TUNNEL TEST TECHNIQUES

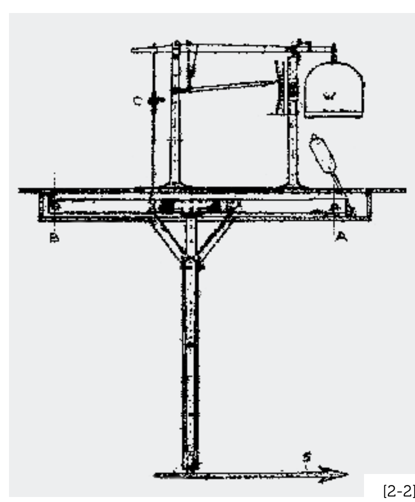
In a wind tunnel the flow around an aircraft is simulated with a sub-scale model to predict what the real aircraft will experience. What is to be learned? Knowledge of the aerodynamic forces and moments that act on the aircraft are of prime interest. By shaping the aircraft, notably the wing and tail surfaces, aerodynamic forces can be generated. Of these the so-called 'symmetrical components', the lift, drag and pitching moment, govern the aircraft motion around the lateral axis in a vertical plane. During stationary horizontal flight the lift acts in a direction perpendicular to the incoming air stream (or flight path) and counterweights the weight of the aircraft. The drag force is pointing backwards, opposite to the direction of flight and is balanced by the propulsive force of the engine. To prevent the aircraft from rotating, the pitching moment around the centre of gravity should be zero. This basic equilibrium has to be maintained at all flight conditions (speed, weight of the aircraft, position of the centre of gravity...). To govern the motion around the longitudinal and vertical axes, such as required for a turn, the three other (a-symmetrical) components, the side force, rolling moment and yawing moment, have to be controlled precisely.



[2-1]

[Figure 2-1]

A model of the Fokker F.II in the test section of the Eiffel tunnel. The model is supported by a sting which is attached to the Eiffel balance (around 1920).

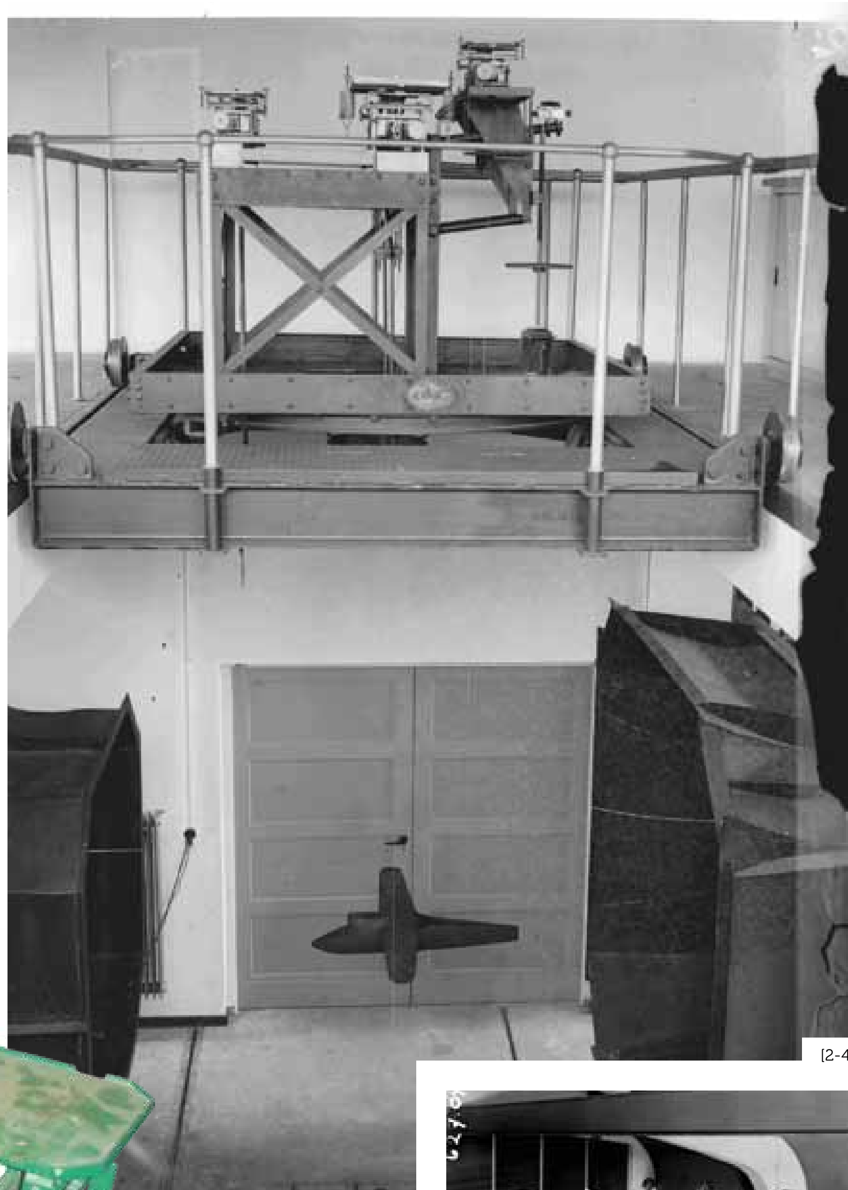


[2-2]

[Figure 2-2]

The 'Eiffel balance' used in the early days of the Eiffel tunnel, the first wind tunnel of the RSL. The model was attached with the sting s to a platform that could pivot around the point A or B (to be adjusted by hand). The force on the model could be balanced by the weight W on a conventional balance.

The aerodynamic forces are predominantly the result of pressure differences in the flow around the aircraft. Generally speaking, when the local flow velocity is higher than the flying speed, the local static pressure will be lower than the ambient atmospheric pressure. A strong curvature of the surface (e.g. at the wing nose) generates a high local velocity and hence a lower pressure. All aerodynamic forces are proportional to the square of the flight velocity. The brothers Wilbur and Orville Wright used their wind tunnel [figure 1-1] to optimize the shape of the wing of the 'Wright Flyer'. Since their wind tunnel was operated at rather low speeds, the forces they measured were low as well. To measure these small forces the test article (most often a section of the wing) was measured relative to a flat plate positioned in the same wind stream: all their tests were relative. Absolute measurements are required to predict from wind tunnel tests the aerodynamic forces on the full scale aircraft. The first wind tunnel of the RSL, the Eiffel wind tunnel [figure 1-2], was equipped with a balance outside the test section (an external balance) to measure the forces on the model* [figure 2-1 and 2-2]. It was a complicated set-up where four measurements (model upright or inverted with the balance platform rotating around one of the two pivot points [see figure 2-2]) were required for one data point. Some years later the model was suspended on wires which transmitted the forces to three conventional ('bascule type') balances* [figure 2-3 and 2-4] placed on top of the wind



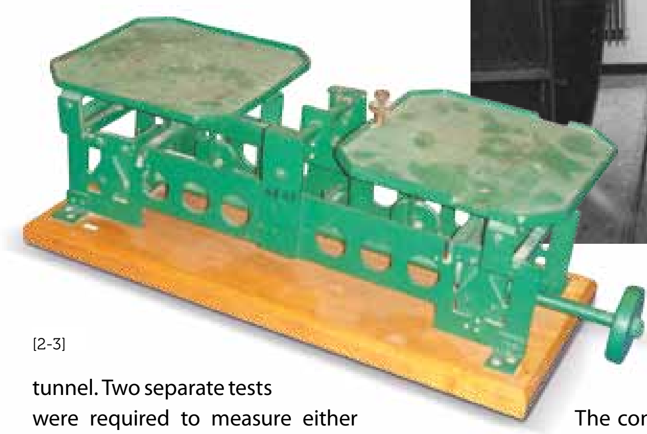
[2-4]

[Figure 2-3]

One of the conventional balances used in the Eiffel tunnel and in the small low speed tunnel (tunnel no. 4) of NLL.

[Figure 2-4]

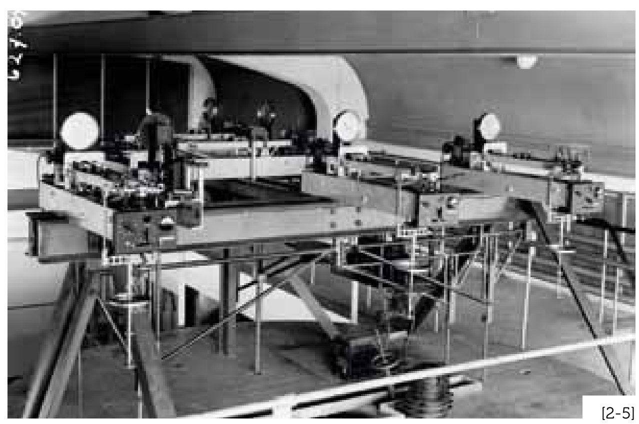
A model tested in the small low speed tunnel (tunnel no. 4) of NLL. The model is suspended on wires attached to an external 'overhead' balance. Each component is measured by a conventional balance. Picture taken during or just after World War II.



[2-3]

tunnel. Two separate tests were required to measure either the symmetric or the non-symmetric components. Taking all balance readings was a time consuming task and a semi-automatic external balance system* was specifically designed for the new low speed tunnel (tunnel no. 3) which was built just prior to World War II. NLL wrote the requirements, but the design was done by the Dutch Engineering firm Vereenigde Ingenieurs en Handelsbureaux A.G.O in Amsterdam. The six components were measured simultaneously. One or more observers were needed to write on paper sheets the actual readings, indicated by two pointers on a clock [figure 2-5].

Another important type of measurements is the measurement of pressure. The conventional way to measure pressures is with a manometer, in its most simple form a glass tube filled with a fluid such as water, alcohol or mercury. The height of the fluid column is proportional to the pressure difference. To increase the sensitivity the tubes could be inclined* [see figure 2-9]. Multi-manometers, a row of glass tubes, were used to measure many pressures, e.g. to measure the pressure distribution on an airfoil. For flight tests a so-called 'automatic observer' was developed. It consisted of a panel with many dial gauge instruments that were photographed by a movie camera. These



[2-5]

[Figure 2-5]

Arrangement of the six external self-adjusting balances above the big low speed wind tunnel (no. 3). The dials had to be read by an observer.

pictures were read out after the flight. In a similar way the pressure tubes of a multi-manometer were photographed to speed up the measuring process.

A very important measurement is the determination of the tunnel reference speed, the speed used as a reference to non-dimensionalize all pressure and balance readings. This speed is determined from the difference in pressure between the total or pitot pressure (the pressure felt by a tube with one open end, positioned in the direction of the flow) and the static pressure (the pressure felt by a hole flush in the tunnel wall or on the side of a tube). Because of its importance, a special more accurate instrument* was used to determine its value [figure 2-8]. The tunnel operator would keep an eye on this manometer to adjust the tunnel speed to the required value.

For a better understanding of the test it was also important to visualize the flow. This was done by gluing small threads of wool ('tufts') to the surface, to 'paint' the model surface with coloured oil or by blowing smoke into the airstream. The patterns formed on the model surface could be observed from outside the tunnel [figure 2-7].

[2-6]

[Figure 2-6]

Till the fifties all scientific calculations and the calculations needed for the processing of wind tunnel data were done by hand at the 'Data Reduction Service' ('*Uitwerkdienst*'). This picture has been taken around 1946.

[2-7]

[Figure 2-7]

Looking at a model in the Eiffel tunnel; picture taken around 1930.

THE NEED FOR NEW TEST TECHNIQUES

It was clear from the beginning that the new high speed wind tunnels required new test techniques. Since the tunnel speeds were much higher than those of the LST, the loads on the model and hence on the balances were much bigger than those experienced so far. Could these loads be measured with an adaptation of the 'conventional' external balance system or was a completely new design required? The pressures were appreciably higher and if conventional pressure tubes had to be used they should be filled with mercury instead of water or alcohol. Or were suitable alternatives available? These issues will be discussed in the next two sections.

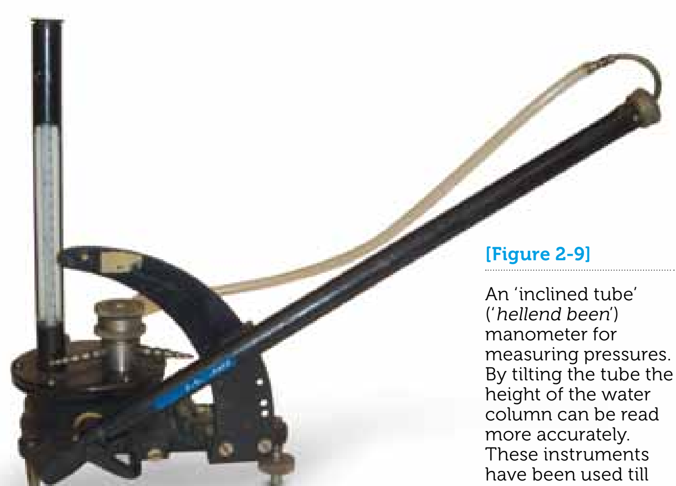
The costs to run the new facilities presented another important difference with the existing tunnels. The tunnels were more complex and this required more personnel. For the low speed tunnels the energy bill could almost be neglected but this was no longer so for the new high speed tunnels. This necessitated a much more efficient measuring process. Instruments were required that could provide electronic data, data that could subsequently be sampled and digitized for automated processing. In the fifties, when the HST and SST were designed, these new developments were only emerging. Through contacts within AGARD NLL could learn about these new developments such as strain gauge balances and electronic pressure transducers.

The recorded data had subsequently be presented in a form suitable for further analysis, most often as coefficients (see Appendix E) and this required additional calculations. Till the early fifties all calculations were made by a group of ladies with hand calculation machines* in the 'Data Reduction Service' ('*Uitwerkdienst*' [figure 2-6]). Numerical calculations were also required in theoretical aerodynamics to calculate the flow around the wing or to determine flutter boundaries. These numerical calculations became increasingly important and developed rapidly into a discipline that would later become known as 'Computational Fluid Dynamics' or CFD. It was clear that electronic calculation meant a significant step ahead. In 1956 the first computer was ordered (see page 51) to be used primarily for the new tunnels and for numerical aerodynamics although this machine was not delivered until 1958. ■

[2-8]

[Figure 2-8]

A Betz precision manometer. This manometer was used in the big LST (tunnel no. 3) to measure the tunnel reference pressure. The pressure could be read on a floating scale that moved up or down with the fluid level inside the manometer.



[2-9]

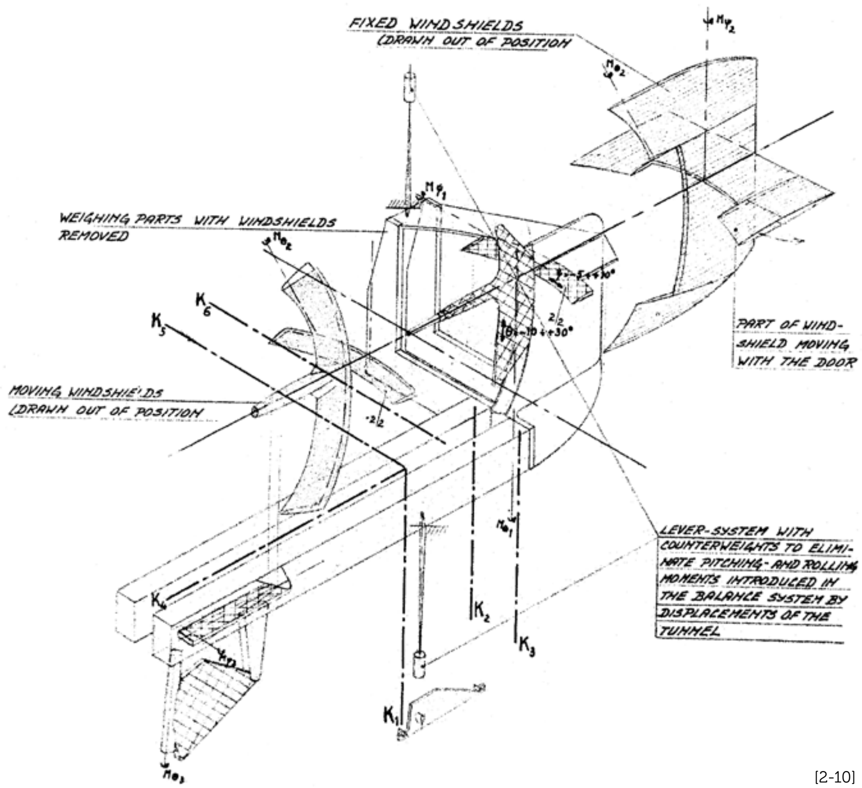
[Figure 2-9]

An 'inclined tube' ('*hellend been*') manometer for measuring pressures. By tilting the tube the height of the water column can be read more accurately. These instruments have been used till the early seventies.

FORCE MEASUREMENTS: A QUESTION OF CONSIDERABLE WEIGHT

BETTING ON EXTERNAL BALANCES

Within NLR experience with force measurements was largely based on the six-component external balance developed for the big low speed tunnel LST (tunnel no. 3). The model was suspended on wires upside-down and attached to a frame that was weighted by six semi-automatic balances [figure 2-5]. For each balance component an electric motor moved a weight automatically to an equilibrium position. That position was displayed on a dial gauge and read by an observer. Dead weights were used to compensate the weight of the model and to shift the range of the balance. The design was such that the six aerodynamic components could easily be derived from the balance readings.



[2-10]

[Figure 2-10]

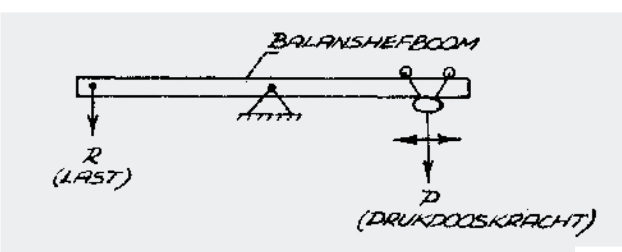
An early drawing of the test section of the HST indicating schematically the external balance (around 1954).

It was clear from the beginning that suspension on wires was not an option for the high speed tunnels due to the much higher loads as a result of the higher dynamic pressures in combination with the increased static pressure. Instead the model had to be mounted on a sting attached to a segment that could be rotated to adjust the angle of attack. The first idea was to attach this segment to an external balance to allow the measurements of all components. In such a set-up the forces on sting and segment were also measured by the balance. Hence covers had to be used to shield the supporting elements from the wind as far as possible [figure 2-10]. Corrections were needed for the remaining interferences (the 'tare' forces). A report of 1947 by Stam[60] mentions that in the US '*indirect force measuring instruments*' are used. This is probably a reference to internal strain gauge balances, as will be discussed more extensively later. Stam concluded, however, that they were not reliable and that direct force measurements were to be preferred. Erdmann[16] was also in favour of an external balance for the 0.4 x 0.4 m^2 supersonic tunnel. This is not unexpected since the supersonic wind tunnels in Peenemünde also used external balances.

As could be expected the design of an external balance for the loads anticipated in the HST was far from trivial. Interestingly enough, a copy was obtained from the Stork Company of a German report[61] on the design of an external balance for a large transonic tunnel (of a size similar to the HST) that was planned to be built in Ottobrun near Münich at the end of the War. The set-up looks very complex: weights were moved by hydraulic cylinders to reach a balanced condition. One of the main problems in the design of such a balance is that it should be accurate for a wide range of load conditions. In 1948 Dobbinga proposed an ingenious balance design named 'the coefficient balance'. In this design the aerodynamic load was balanced by a force proportional to the dynamic pressure in the tunnel. This was achieved with a pressure bellows connected to the dynamic pressure (the pressure in the settling chamber minus the static pressure in the wind tunnel [see figure 2-11]). In a report on the instrumentation for the HST[62] that dates from 1949, it was recommended to use this 'coefficient balance' for the new tunnels. According to the 1951 Annual Report one component of such a balance was actually manufactured [figure 2-12] but there is no information if this was successful. All we know is that in 1949, at the time that the plans for the high speed tunnels came to a sudden stop, an external balance was foreseen.

[Figure 2-11]

Principle of the coefficient balance. The balance arm balances the (aerodynamic) load R against a force P that is proportional to the dynamic pressure sensed by a pressure bellows. The point of application of P can be adjusted (automatically) and its distance to the point of rotation is proportional to the aerodynamic coefficient.



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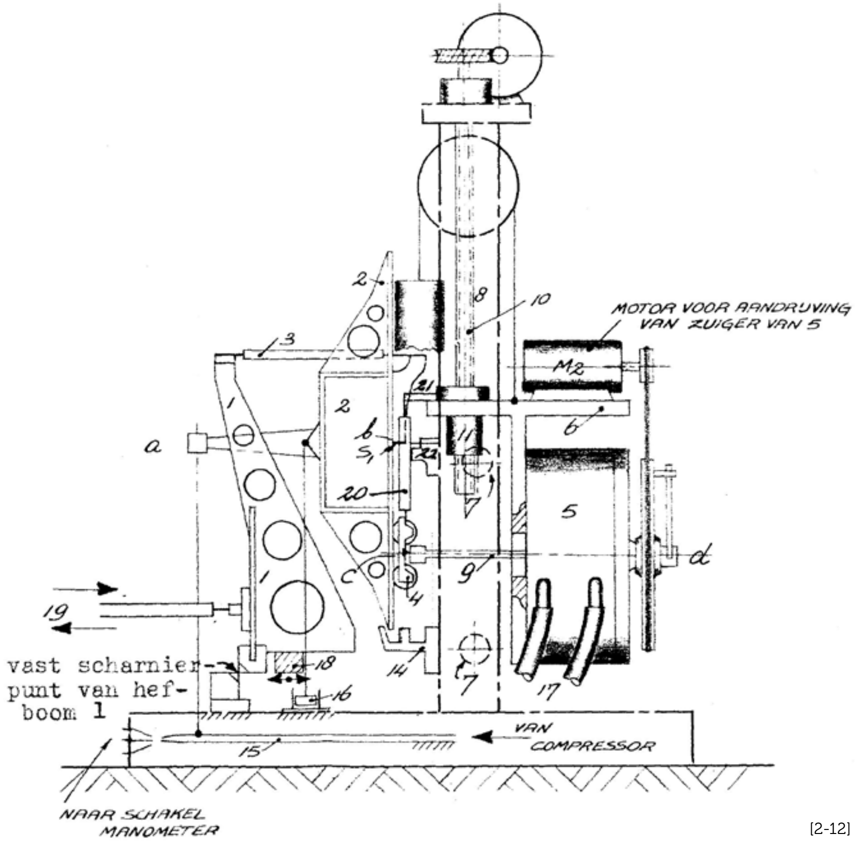


[2-12]

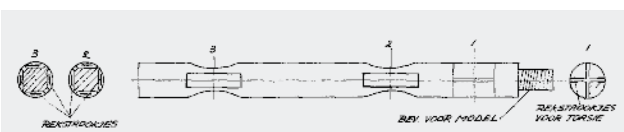
[Figure 2-12]

A drawing of the set-up for one of the components of the 'coefficient balance'. It is possible that this set-up was actually made and tested in 1951 as mentioned in the 1951 Annual Report. A complete six component system was never built and would have been fairly complicated.

FIRST EXPERIENCES WITH STRAIN GAUGE BALANCES

A possible alternative was emerging at that time, the 'strain gauge balance'. The measurement of stresses with strain gauges was a well known technique. A very thin wire is glued onto the surface of the element where the stresses have to be measured. When this surface elongates or compresses due to the applied load, the resistance of the wire changes, an effect that can be measured electronically. The technique had often been applied to measure local tension in structures (and was later used to measure the stresses in the pressure shell of the HST during commissioning; page 50). In 1948 strain gauges were used for the first time at NLL in the big LST (tunnel no. 3) to measure the loads on rudders and ailerons[63]. The concept of the internal strain gauge balance is also based on this technique. A 'flexible' rod (the balance) is mounted between the supporting sting and the wind tunnel model. The rod deforms under load felt by the wind tunnel model and this deformation is measured with strain gauges. The trick is that the 'rod' is shaped such that each of the attached strain gauges is sensitive to a load in a particular direction. After calibration and some data processing the six components can thus be derived from the six strain gauge readings. This technique was still being developed around 1950 in Europe (in Sweden) and in the US (by NACA and some other institutions, e.g. the Massachusetts Institute of Technology or MIT). In 1952, two NLL employees made a visit to Sweden[64] and they met at that occasion Erdmann who moved to Sweden after the new wind tunnel plans came to a sudden stop in 1949 (page 17). On that occasion Erdmann complained that the Swedish strain gauge balances were an '*endless suffering*' and he was '*longing for a good three or better five component balance*'. Much of the information on strain gauge balances was received through the AGARD contacts. In a 1953 trip report[65] of the 'AGARD Wind-Tunnel and Model Testing Panel' various sketches of strain gauge balances can be found (such as the ones from MIT and NACA shown in figure 2-13 and 2-14 respectively). The trip report concludes that '*there is a general feeling that strain gauge balances can be made sufficiently accurate but there is no common view whether the six balance components should be separated by design or that a significant mutual interaction between the components is acceptable*'. Nevertheless, '*... it is essential for NLL to develop and construct strain gauge balances with priority to gain experience*'. The technical problem on 'separation of components' that is mentioned here has to do with the construction of the balance. To keep the calibration and the data reduction manageable, the output of each strain gauge should be determined predominantly by one specific force component. In mathematical terms: the 6 x 6 matrix that relates the balance output to the load components should be diagonally dominant. This makes the calibration process transparent and allows a simple conversion of the calibration matrix, needed to derive the loads from the measured balance output.

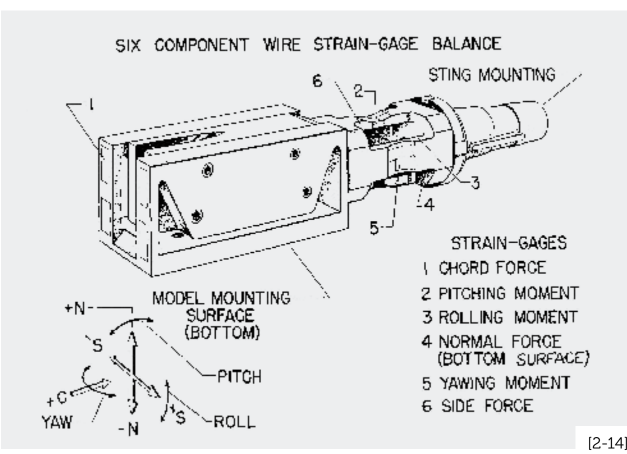
The recommendation for an 'in house' development of strain gauge balances was not new. In November 1952 the main design choices for the HST were listed in a report by Dobbinga, Slotboom and Boel[31]. The report provides a complete overview of all requirements after the adaptation of the wind tunnel plans in 1952 (page 19). One of the paragraphs is concerned with the balance system and it is recommended to purchase an external balance. The Swiss firm Engler had made an offer to manufacture such an external balance[28]. At the same time it was recommended to pursue the development of internal strain gauge balances. The arguments for this choice reflect the hesitation to decide on this important problem. NACA clearly opted for the internal balances to minimize the 'tare' corrections. But the experience and time to build an internal balance for a specific model (NACA claimed 33 weeks on average!) was considered as a real disadvantage. Data reduction and accuracy were



[2-13]

[Figure 2-13]

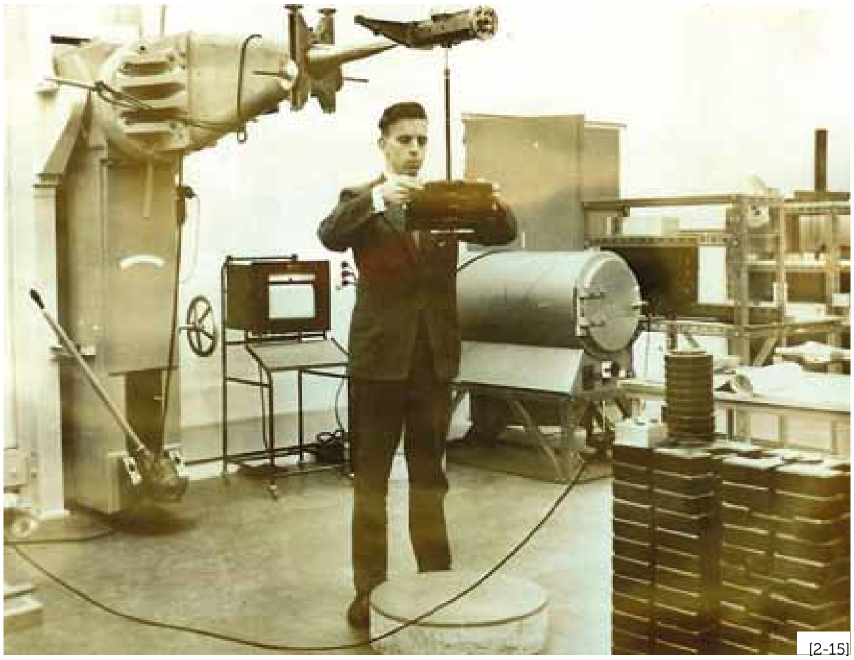
Sketch of a five component balance developed by the 'Massachusetts Institute of Technology' (MIT) in a trip report of an AGARD conference in the US in 1953. With this balance the drag could not be measured.



[2-14]

[Figure 2-14]

Sketch of a six component balance developed by NACA in a trip report of an AGARD conference in the US in 1953. With this balance the drag could be measured.



[2-15]

also problematic. In 1953 a working party on strain gauge balances was set up[66]. In the same year three reports were written on the design of internal strain gauge balances. In 1954 recommendations were made for a calibration facility[67].

THE FINAL DECISION TO GO FOR INTERNAL BALANCES

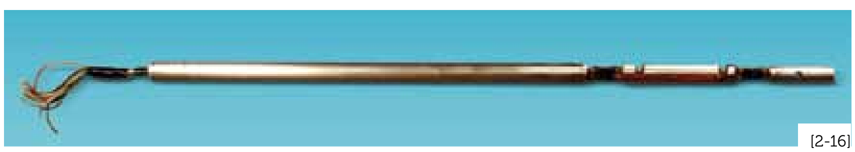
Although in November 1952 a decision was made in principle to proceed with an external balance for the HST, the question did not seem to be fully settled in 1954. It is possible that the offer made by the Swiss company Engler was not acceptable or that the practical consequences of an external balance were underestimated. However, a pre-design of an external balance set-up for the HST was made [figure 2-10]. On November 3, 1954 a Memorandum was written by Prast and Van der Zwaan[37] discussing the pros and cons of the various solutions. In addition to what has been mentioned already, one serious point of concern was the accuracy of the tangential force which is closely related to drag (Appendix E). To measure this force accurately, the balance had to be 'flexible' in the direction of the model axis and this is not easy to realize. Even 'hybrid' solutions were proposed, where drag and rolling moment were measured by an external balance (mounted in the model support sting) whereas the other forces were measured with an internal balance[68]. As explained in the previous chapter (page 21) the decision could not be postponed any longer. Shortly after that, in a meeting on November 10, 1954 it was decided to go for the internal balance but to keep the possibilities open for an external balance[38].

Contacts with the US, Sweden and Switzerland on balance design were intensified, partly through AGARD. Two Swedish balances were purchased and some NLL-made balances were tested in Switzerland in a small transonic tunnel. It was an obvious choice to develop the first balance for use in the Pilot Tunnel (PT), since that tunnel was almost ready in 1954. A six-component calibration facility was completed in 1955 [see figure 2-15] and in 1956 the design and manufacturing started of a balance* for the AGARD-C model* that was tested[U] in the PT in 1957[49] [see also figure 2-16 and 2-17].

Apparently the balance development did not progress as was anticipated. In 1955 Prast wrote a critical evaluation[69] on the advantages and disadvantages of the various balance types in order to select the best balance type for the HST. It was problematic to 'scale up' the sting balances as used in the PT: the sting diameter would be excessive. In the report *'a very complicated balance'*, manufactured by the Sandberg Serrel Corporation, is mentioned. And Prast added that *'due to its complexity the balance might not be suitable to be manufactured for each specific model, but a series of three balances* (with different ranges) *might provide a possible solution.'* Nothing more was heard from this balance but the principle to use a range of balances that can be taken 'off the shelf' was valid and nullified the argument that lots of time were needed to develop specific balances

[Figure 2-15]

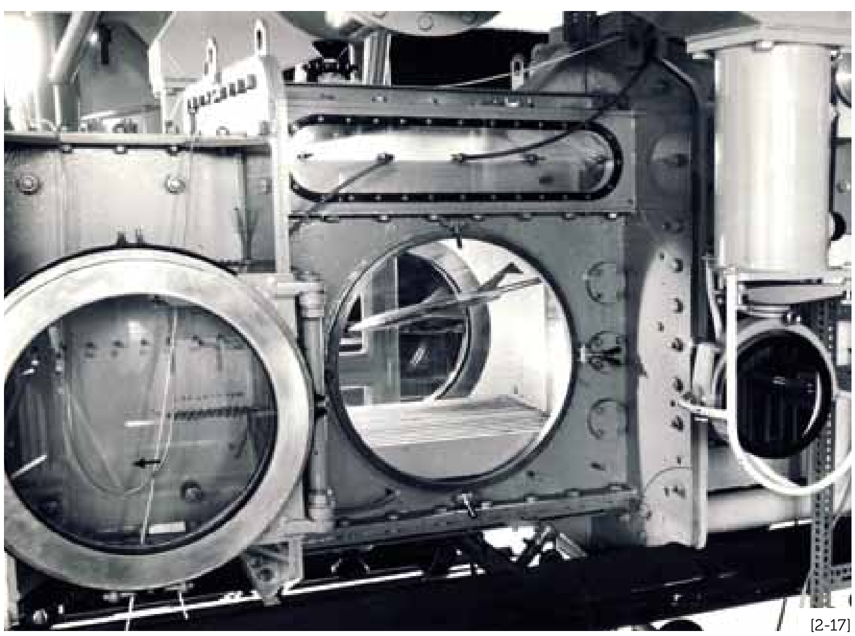
The oldest known picture of the facility for balance calibration at NLL. With a pen recorder of the same type as used in the HST the balance signals were measured. The loads were applied with dead weights (visible to the right). Picture taken before or in 1959.



[2-16]

[Figure 2-16]

A 'sting balance', one of the first internal balances probably used in 1957 for the tests on the AGARD-C model in the PT. The right side was attached to the model whereas the left side acted as sting, to be attached to the model segment (see next picture).



[2-17]

[Figure 2-17]

The AGARD-C model in the PT mounted on a sting balance (around 1957).

U IT IS NOT QUITE CLEAR IF THIS BALANCE WAS A NLL DESIGN OR ONE OF THE BALANCES PURCHASED IN SWEDEN. IT CERTAINLY WAS NOT THE FIRST TEST AT NLL WITH AN INTERNAL BALANCE. THE HONOURS GO TO A TEST MADE IN 1956 IN THE BIG LST (TUNNEL NO. 3) ON A MODEL OF THE FIRST DUTCH PASSENGER CAR AFTER WW II, THE DAF-55 (NLL REPORT A.1439).

for each test. This could be achieved with the balances from the TASK Corporation[70], a company founded by Elmer Ward in 1953. Ward studied at Caltech University where he graduated in 1947 and pursued his Masters degree thereafter. During that time he arranged a partnership with Earl Davies, an engineer from North American Aviation, and took on the challenge of developing an internal balance. In 1951, a 2.50 inch six component, internal balance was manufactured and put into service at the 'Co-operative Wind Tunnel' of GALCIT ('Graduate Aeronautical Laboratories at Caltech Institute of Technology') and to this day that balance is still in use at their facilities.

[2-18]

[Figure 2-18]

NLR developed half-model balance to be mounted in the side wall of the HST test section.

The first reference to a TASK balances can be found in the NLL Annual Report of 1958 where a visit is mentioned to the US to attend an acceptance tests of a balance for the HST. In 1959 an additional set of balances was ordered and again in 1963, bringing the total number of TASK balances to 18 [see figure 2-19] for a total amount of money just over 1.2 million guilders (see Appendix B). It is not clear how the contacts between NLL and TASK started. No reference could be found in the trip reports. It is possible that Von Kármán played a role here as well. Between 1930 and 1949 he was the first director of GALCIT and remained active after that period. He visited NLL in 1954.

The TASK balances are six-component internal strain gage balances of a 'floating-frame type' [figure 2-20]. The main elements are formed by an inner rod, which fastens to the model support sting, and a cylindrical outer case, which is inserted into and attached to the model. Forces and moments are resisted by individually removable elements, employing flexure pivots, connected between the inner rod and outer case of the balance. The balances were specifically designed to be easily exchangeable from one model to the other. The connection between the balance and the model support (the 'earth') was made by a 'standard cone'; the connection to the model by a cylindrical tube or bus that could be fitted inside the model. This type of connection was easy to machine (though it had to be done very accurately) and had the additional advantage that cylindrical inserts could be used to fit a smaller size balance whenever required. The TASK Company (now part of Aerophysics Research Instruments) offered a wide range of balances depending on the expected loads and required accuracy. For repair the balance had to be shipped to the US. The balances became a kind of standard all over the world for wind tunnel testing. This had the additional advantage that models could be easily transferred from one facility to the other.

In retrospect it is likely that the availability of the TASK balances at the right time was quite important for the market position of the HST. It enabled the execution of the wind tunnel tests without delay caused by balance manufacturing. However, the 'in house' development of NLL balances continued (in 1965 the few balances that were manufactured by NLL represented a value of 15,000 guilders) and some of these were used during the first tests in the HST [figure 2-22]. They performed quite well. However, it would have been difficult for the NLL workshop to respond in time to all balance needs in the HST and shortly after that in the SST. The conclusion is that the success of the concept of the TASK balances contributed significantly to the success of the new high speed wind tunnels.

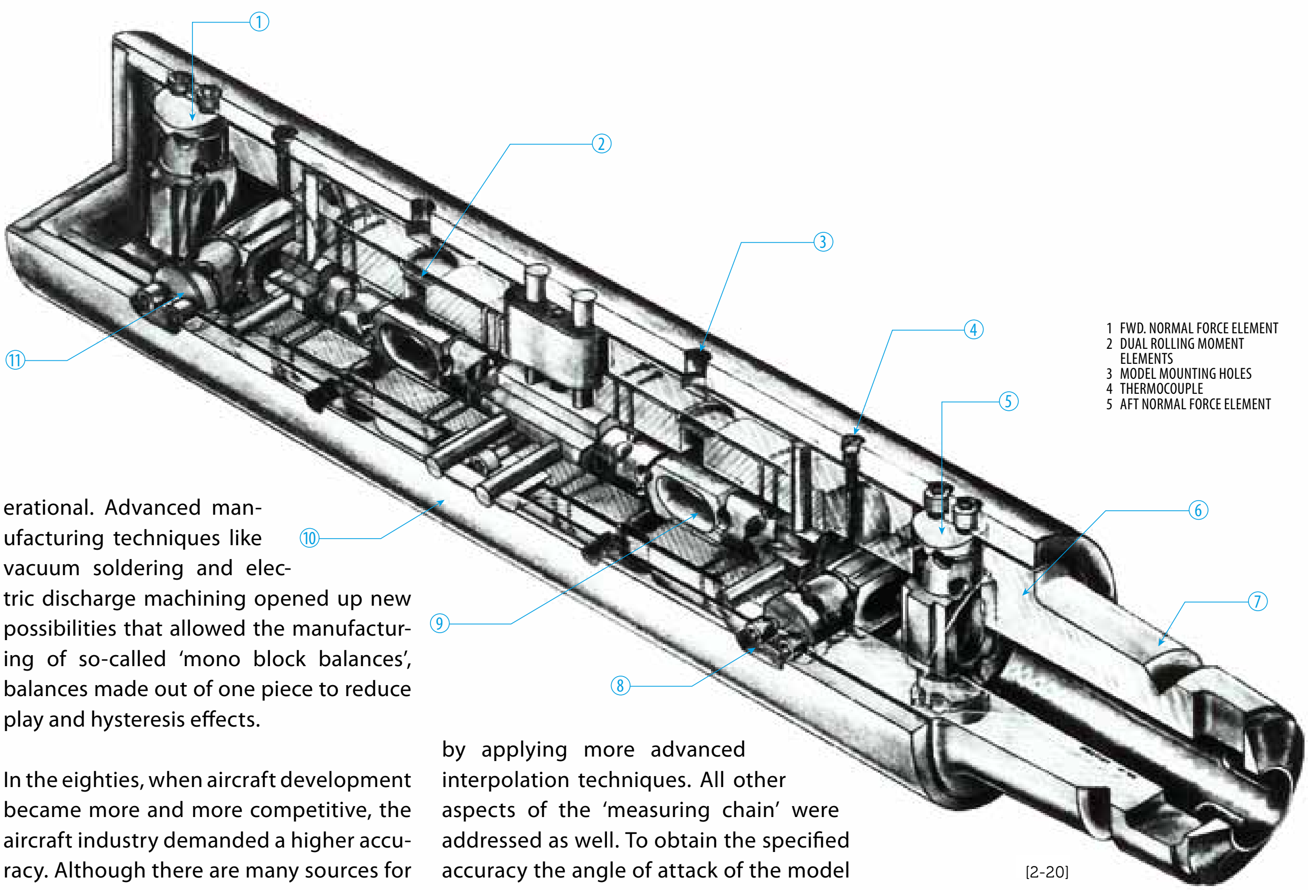
[2-19]

[Figure 2-19]

Some of the TASK balances out of the set of 18 balances purchased around 1960. These balances are the 'working horse' for the force measurements in HST and SST.

FURTHER BALANCE DEVELOPMENTS

For those at NLL engaged in the development of internal balances the purchase of the TASK balances from an outside supplier must have been a disappointment. However, the 'in house' development of internal balances was not stopped. For the tunnels it was very important to have 'hands-on' experience with balance design, calibration and data reduction. Without the development work by NLL itself, it would not have been possible to integrate the TASK balances in the measuring process. This was recognized and in 1960 a special group Models and Balances ('*Modellen en balansen*') was formed as part of the Technical Services ('*Technische Diensten'*). They prepared the wind tunnel models and developed new balances in close co-operation with the workshop*. Some of the tests on the AGARD calibration models (see page 65) were executed with NLL balances [figure 2-22]. The results could be compared with results obtained with the TASK balances. Some of the clients e.g. Sud Aviation and FIAT, brought their own balances for the tests. Sud Aviation was used to testing their models in the transonic wind tunnel of the Cornell Aeronautical Laboratory in the US and the Caravelle model came with a balance developed by Cornell*. This provided another opportunity to learn more about balance design and to compare the NLL developments with other balances. Some specific models required special balances such as the supersonic 'ring-wing' that was tested in the SST (see also page 76 [figure 3-39]). Soon after its opening the HST capabilities were extended with the possibility to test half models with a balance attached to the tunnel side wall. This required the development of a special 'half-model balance' by NLL as well [figure 2-18]. In 1963 a second calibration facility was made op-



[2-20]

[Figure 2-20]

View of the construction of a TASK balance. These very popular balances were used for wind tunnel tests all over the world. The cone (right part) fits into the sting, the (large) cylindrical part (right) is mounted in the model either directly or within a sleeve. In this way balances could easily be exchanged.

erational. Advanced manufacturing techniques like vacuum soldering and electric discharge machining opened up new possibilities that allowed the manufacturing of so-called ‘mono block balances’, balances made out of one piece to reduce play and hysteresis effects.

In the eighties, when aircraft development became more and more competitive, the aircraft industry demanded a higher accuracy. Although there are many sources for inaccuracies (see page 82 and Appendix E) balance accuracy is of critical importance[71]. In the early eighties an extensive program was started to meet these re-

[2-21]

[Figure 2-21]

A new high-accuracy balance developed in the eighties by NLR.

quirements. It was clear that the TASK balances that were used over the years as the ‘working horse’ for force measurements were not good enough when such high accuracies were required. A task group was set up in 1982 to develop new balances and improved balance calibration procedures. As far as the balance was concerned, the stiffness and accuracy of the connection to the model side were significantly improved and the balance itself was optimized with advanced CAD (‘Computer Aided Design’) techniques. See figure 2-21 for one of these new balances. The calibration procedures and corresponding data reduction were improved as well, notably by applying more advanced interpolation techniques. All other aspects of the ‘measuring chain’ were addressed as well. To obtain the specified accuracy the angle of attack of the model has to be known within 0.01 degree, even when the model is deflected under the load and vibrating. The conventional way to determine the angle of attack by measuring the position of the support boom and correcting for sting deflection under load was replaced by an instrument (the ‘Q-flex’) that could be mounted inside the model and that used the direction of the earth gravity field as a reference. In 1987 this system was supplemented by an optical system (named ‘ELOPTOPOS’). Moreover, the Mach number control was improved to allow a constant Mach number during a polar (an angle of attack sweep of the model; see Appendix E). All these improvements were tested and validated on a reference model (one of the ‘old’ SKV models; see page 80).

Finally engine simulation tests demanded very specific requirements. In this case the drag of the wind tunnel model has to be measured with engine simulators running. High pressure air is used to drive ‘Turbine Powered Simulators’ or TPS for the simulation of either propeller or turbo-fan engines [figure 3-61, 3-62]. The high pressure air has to pass the balance without additional reaction forces and specific joints are required to achieve this. To measure the installation effects of propellers, the forces that act on the propeller itself have to be measured in addition to the overall forces on the model (with the running engine). Only in this way can the direct effect of the propeller and the interference effect of the propeller on the aircraft be separated, an essential procedure to understand and minimize the installation effects. This is possible with a ‘rotating balance’, a balance that is mounted in the hub of the propeller. NLR made its first rotating balance in 1990 for tests on the Fokker 50 in the DNW and LST. In this balance only the thrust and torque were measured. Further developments allowed the simultaneous measurements of all six components. Such a balance was also used in the HST during the tests on an isolated propeller as part of the European APIAN program (page 85 and figure 3-63). The rotating balances are a more recent illustration that ‘in house’ knowledge on balance design is essential to respond to specific demands for wind tunnel testing. ■

[Figure 2-22]

One of the first six-component balances made by NLL (AE1013) and used in the early wind tunnel tests, e.g. on the AGARD-C model and the Sud Aviation model with a delta wing ‘Durandal’; shown without strain gauges and wiring.

[2-22]

PRESSURE MEASUREMENTS: THE ART OF MINIATURIZATION

THE TUNNEL REFERENCE PRESSURE

The flow condition in the tunnel should be precisely known during the measurements. These conditions are characterized by the static pressure, the pitot or total pressure and the temperature in the test section. The low speed wind tunnels of NLL (the big and small LST, tunnel no. 3 and no. 4 respectively) were atmospheric: the static pressure in the test section was equal to the atmospheric pressure. The total pressure was measured with a pitot tube located in the flow at the entrance of the test section. The dynamic pressure is the difference between the total and the static pressure. This dynamic pressure is used to non-dimensionalize the forces (and moments) and the pressures (expressed as differences relative to the static pressure) to obtain coefficients like the lift coefficient C_L (see Appendix E). In low speed flow, the coefficients are a function of the model attitude (angle of attack, yaw angle), almost independent of the flow velocity except for a weak dependence on Reynolds number. In the operation of low speed tunnels it is common practice to perform tests at a constant dynamic pressure. This dynamic pressure is readily available from a precision manometer, like the Betz manometer shown in figure 2-8. The tunnel operator watched the small display in the front of the manometer to keep the dynamic pressure constant (by changing the fan speed).

[2-23]

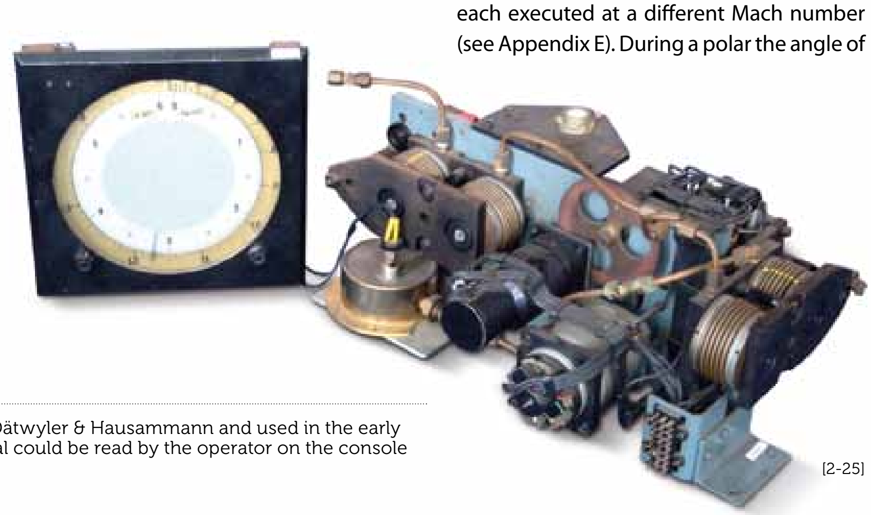
[Figure 2-23]

The control desk of the HST in 1959. To the right the two manometers to measure the tunnel reference pressures [shown in figure 2-24]. Behind the most right operator, the Mach meter [shown in figure 2-25].

[Figure 2-24]

Precision (mercury) manometer made by Dätwyler in Switzerland used in the early days of the HST to determine the reference conditions.

This practice could not be carried over to high speed or compressible flows. The Mach number, which expresses the flow velocity relative to the speed of sound, is now a crucial parameter. The force and pressure coefficients are often strongly dependent on the Mach number and this dependency has to be determined [see figure E-12]. An aircraft at cruise condition flies at a Mach number that is kept accurately constant. Normally a measurement series consists of a set 'polars', each executed at a different Mach number (see Appendix E). During a polar the angle of attack is changed. This causes a variation in the drag of the model and a change in Mach number. It is the task of the operator to keep the Mach number constant during a polar and to adjust the Mach number from one polar to another. The Mach number depends on a pressure ratio: the total pressure divided by the static pressure. To keep the Mach number constant the tunnel operator needs a display of the Mach number. In the early concepts for the HST instrumentation [72,37] precision manometers were foreseen with electrical (analogue) outputs (obtained from the varying resistance of a platinum wire in the mercury column of the manometer) from which the pressure ratio could be derived and presented on a calibrated scale. In the important Technical Note[40] of Boel of April 1956 it is recommended to buy a Mach meter. It is very likely that as a result the Mach meter* as shown in figure 2-25 manufactured by Dätwyler & Hausammann was purchased. It was a mechanical device with several pressure bellows and (digital) position indicators to allow a display of the data at another location. This Mach meter was primarily used to display and control



[2-25]

[Figure 2-25]

Mach meter made by Dätwyler & Hausammann and used in the early days of the HST; the dial could be read by the operator on the console of the HST.

the Mach number. In addition two more conventional precision manometers*, V [figure 2-24] were used to determine the precise value of the pressures. On a photograph of the HST control desk taken around 1959 [figure 2-23], these precision manometers are still visible (on the far right) as well as the Mach meter (on the control desk). The same Mach number indicator can be seen more clearly on a photograph of the HST


[2-24]

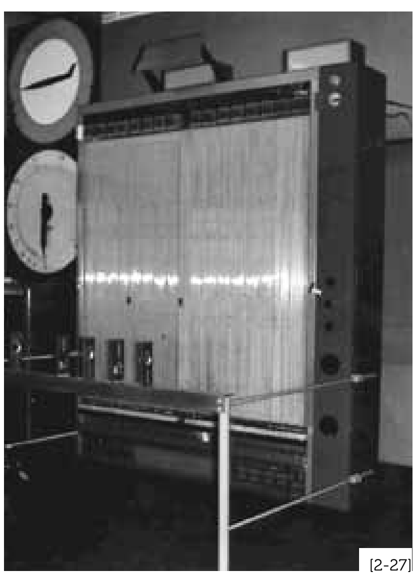
test room probably taken in the mid sixties. [figure 2-39]. At a later date two mechanical precision manometers, known as the Research Engineers Balance* [see figure 2-26] were added. They remained in operation till the HST modernisation program of 1992 when they were replaced by more accurate membrane type pressure transducers (Barocel's of Chell Instruments Ltd, US).

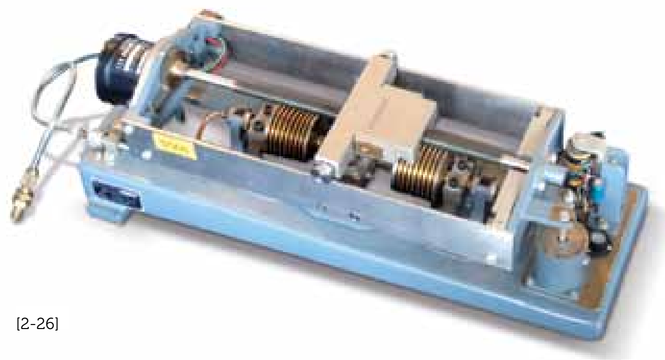
In the HST the Mach number could be adjusted by changing the blade angle of the fan. This was a joint action of the operator in the Power Plant ('*Centrale*') and the operator behind the control desk of the HST. The original idea (of 1955) was to use ships' telegraphs for the communication, but it was more practical to share some instrumentation and to use a special telephone line.

MEASURING MANY PRESSURES

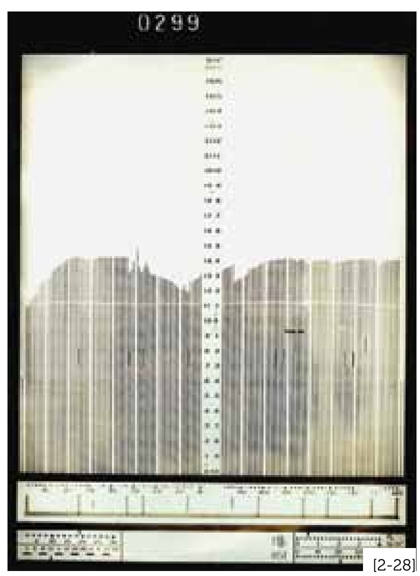
Force measurements with (internal) balances give information to the aircraft designer of the total forces and moments that act on the aircraft. They are used for the prediction of the aircraft performance and to assess the stability and control characteristics. Pressure measurements provide information of the local pressures. In the early days of aircraft development the pressure measurements were predominantly used to derive the local loads, needed as input for the strength calculations. However, with the advance of theoretical calculation methods pressure measurements became increasingly important for the aircraft designer to guide further improvements. Usually pressure distributions on the wing are measured at a number of wing sections. The change of these pressure distributions with the angle of attack and with Mach number provides very useful information on the flow development such as the formation of shock waves or the separation of the flow away from the model surface. The measured pressure distributions can often be compared with calculations. Possible differences with the calculations or unwanted characteristics can be cured in a subsequent design to improve the overall aircraft characteristics.

Typically, 20 to 30 pressures are measured along one wing section. Since usually five to eight wing sections, evenly distributed between the wing root and the wing tip, can be found on the wind tunnel (pressure) model, typically 100 to 250 pressures have to be recorded for a single data point (a specific combination of the Mach number and the angle of attack). These measurements are then made for typically 8 Mach numbers at 10 angles of attack resulting in roughly 8,000 to 20,000 pressure readings. These numbers illustrate the enormous amount of data that has to be sampled.


[2-27]


[2-26]

In the low speed tunnels multi-manometers were used that could measure 100 to 150 pressure points simultaneously. A photograph was taken of all tubes. The height of the water column in each of the tubes indicated the pressure felt by a corresponding hole on the model surface. For each data point a photograph was taken that could be read out on a special machine (named 'OSCAR') where the water level for each of the tubes was measured with a cross hair and subsequently punched in paper tape for further processing. The process was labour intensive, but the measurements could at least be made at an acceptable rate. The same procedure was envisaged for use in the HST. Dätwyler & Hausammann got the order to design such a multi-manometer for the HST with 162 pressures. This multi-manometer was delivered around 1957. Depending on the pressure range mercury or water was used. In the latter case 'Ponceau Red' was added to increase the contrast. The multi-manometer for the HST is shown in figure 2-27 whereas in figure 2-28 a typical photograph can be seen that had to be read out with 'OSCAR' at a later time.



[2-28]

[Figure 2-26]

The 'Research Engineer Balance' used to measure the tunnel reference pressure accurately. It is a real 'balance' in the sense that a small weight is moved by a pressure bellows over the balance arm, counter balanced by a weight driven by an electric step motor. Used till the HST modernisation of 1992.

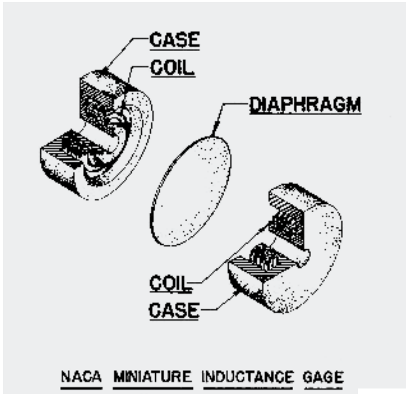
[Figure 2-27]

The multi-manometer made by Dätwyler & Hausammann was used in the first years of the HST to measure pressure distributions.

[Figure 2-28]

Photographic recording for the multi-manometer shown in [figure 2-27]. For each measurement point the tubes of the multi-manometer were photographed and subsequently read-out and punched on paper tape with the 'OSCAR' machine for further data reduction.

V ACCORDING TO STENVERS (RESPONSIBLE FOR THE HST OPERATION) ANOTHER, MUCH TALLER MANOMETER OF A SIMILAR TYPE HAD TO BE USED FOR THE HIGHEST TUNNEL PRESSURES; A STEPLADDER WAS NEEDED TO TAKE THE READINGS.



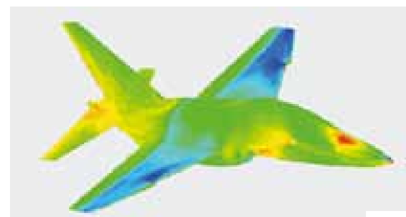
[2-29]

[Figure 2-29]

Sketch of a membrane pressure transducer as shown in a trip report of a 1953 AGARD conference. This particular design was from NACA.

This process was very time consuming and alternatives to take data at a higher rate were about to appear at that time. On an AGARD conference[65] in 1953 a miniature pressure transducer was shown in which the deformation of a membrane under pressure could be measured electronically [figure 2-29]. The analogue signal could then be digitized for computer processing. The second important step was the possibility to scan many pressure holes. In 1958 the first pressure switch* was purchased by the G-Section to find out if it could be used in the supersonic tunnels. The device had to scan very fast because of the small running times (of the order of 30 to 45 seconds) for this blow-down facility. It is not clear if the performance of this scanner was acceptable. At about the same time a multitude of glass tubes were purchased which had to be used in a conventional multi-manometer. However, the intended multi-manometer was never built and the glass tubes remained in their wooden boxes in the hall of the SST for a long time as evidence of the rapid changes in test techniques.

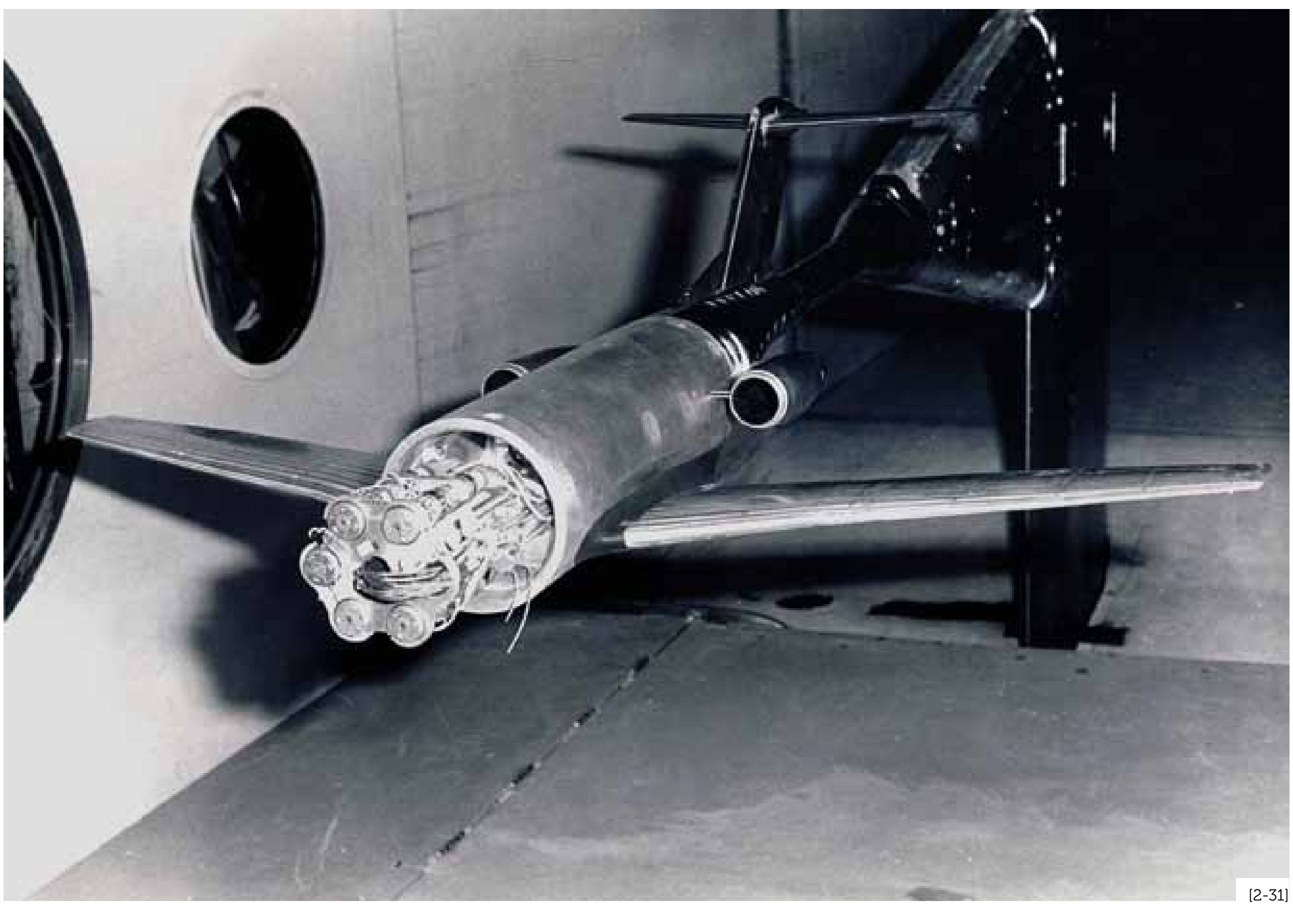
An important and critical step ahead was made by Scanivalve Corporation which had manufactured a much smaller pressure switch. In 1955, J.C. Pemberton[73] left Boeing, the company where he had worked till that time, to start this company. He designed and manufactured a very small mechanical valve that could scan 48 pressures with a small stepping motor. In this way 48 pressure leads could be connected sequentially to a single miniature (electronic) pressure transducer in the centre of the module. The biggest advantage was that these 'scanivalves' could be mounted inside the model. Therefore, only one pressure lead (the reference pressure) and the electronic wiring had to be brought out of the model instead of 48 pressure leads that had to be connected to the multi-manometer outside the test section. The future use of these scanivalves was mentioned already in one of the first Technical Notes[74] which describe the HST and SST in 1959 (hence prior to their official opening). They were introduced in the early sixties in the HST. Van der Zwaan recalls[94] that in the beginning there were quite some difficulties to get them operating properly. Also a control unit was required for the stepping motor as well as a power supply and a (milli)voltmeter. In 1963 with the introduction of the SADIST, as will be discussed in the next section, the scanivalves could be integrated into the data acquisition system of the HST and SST. In 1964 they were used routinely



[2-30]

[Figure 2-30]

Photograph of the Alenia Aermacchi M-346 trainer painted with pressure sensitive paint to measure pressure distributions on the airplane. This test was done in the HST in 2000 in co-operation with DLR.



[2-31]

[Figure 2-31]

Five scanivalves mounted in the nose of a F28 model in 1964.


[2-32a]


[2-32b]

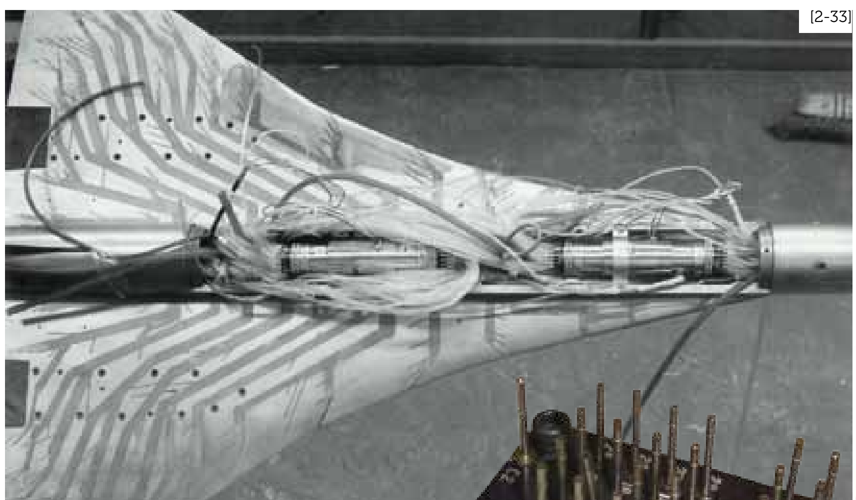
[Figure 2-32]

Two stages in the development of the 'Duplex Scanner' (left picture) compared with the original pressure scanner (utmost left) and an exploded view (right picture) of the final version. The duplex scanner was a modification made by NLR of the original (one-sided) scanner of 'Scanivalve Inc.'

for pressure measurements on the Fokker F28 [figure 2-31]. Five scanivalves could be installed in the fuselage allowing the measurements of 240 pressures.

The maintenance of the scanivalves was done by the NLR workshop and it was realized that the original scanivalves could be improved. Why not drive two pressure scanners with one stepping motor? In a subsequent development even the stepping motor itself could be reduced in size [see figure 2-32]. This resulted in a much more compact and powerful pressure scanner. For the HST and SST these improved 'miniscanners' were an important selling point: double the number of pressures could be measured as compared to other facilities. Hence fewer runs were required with a very substantial reduction of the price per data point. These improved scanivalves came into operation around 1975. See figure 2-33 for an example of duplex scanners mounted in a Concorde model. Some of these devices were also sold to other companies.

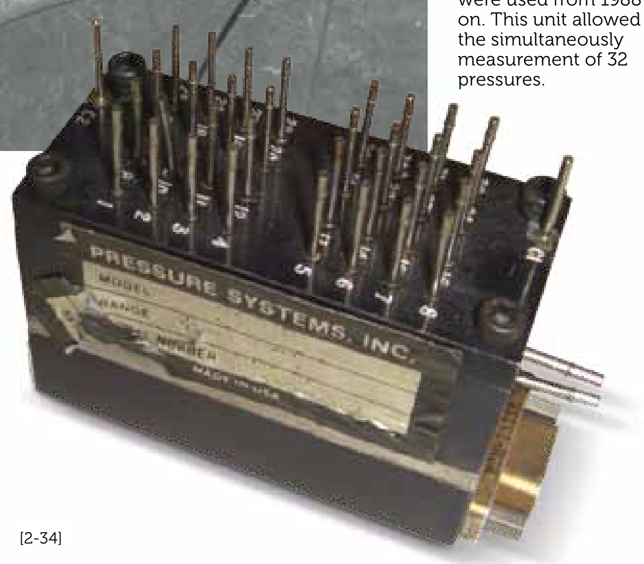
This was not the end of the development of pressure measurements. In the mid eighties Pressure Systems Incorporated (PSI) offered the market a new ' multiport' system based on 'Electronic Pressure Scanning' [EPS; see figure 2-34]. In this system, each pressure lead was connected to its own pressure transducer, a solid state device. Consequently many pressures (32 in the standard system) could be measured simultaneously. Although the electronic signal was multiplexed (one signal for all transducers), the scanning rate was so high that after de-multiplexing a continuous signal resulted for all 32 pressures. The first system was bought in 1988, but it took several years to adapt, in close co-operation with PSI, the original device for use in pressurized wind tunnels. The big advantage was that the usual step-by-step measurement procedure could be replaced by a continuous sweep procedure with a considerable reduction in testing time and even an increase in the number of data points. A particular nice and very efficient application of these multiport transducers was the online measurements of wakes by means of a wake rake. In fact these transducers triggered a development in 1990 of a new pressure rake with 18 'five-hole pressure probes' to map entire flow fields (see page 59).


[2-33]

[Figure 2-33]

Duplex scanners mounted in the fuselage of a model of the Concorde. The wing is full of pressure holes that are connected to the duplex scanners.

At about the same time the first useful results were obtained with 'pressure paint'. In Europe this fascinating technique was developed by DLR (the German sister institute of NLR) in Göttingen [see figure 2-30] whereas in the US the Boeing team from St Louis (former Lockheed) was leading in this field. In this technique the wing surface is painted with a special kind of paint that changes colour depending on the local pressure (in fact the local oxygen content is indicated). Rather than discrete pressure data for a limited number of pressure holes on the wing surface, a complete, continuous map of the pressure distribution could now be obtained. This technique is particularly useful for the determination of detailed wing loadings for a large range of flow conditions. However, it requires the installation and calibration of a number of special cameras and hence an extra effort. Depending on the requirements of the client pressure paint can be considered an alternative of or complementary to more conventional pressure measurements with pressure holes. ■



[2-34]

[Figure 2-34]

Solid state multiport transducers of 'Pressure Systems Incorporated' (PSI) were used from 1988 on. This unit allowed the simultaneously measurement of 32 pressures.

HANDLING ALL TEST DATA

CALIBRATION AND COMMISSIONING

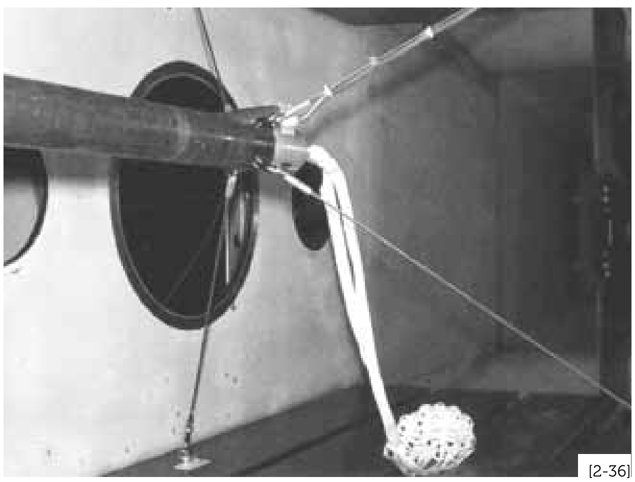
The first measurements during commissioning and calibration of the HST were still made in a conventional way. They involved three types of tests: the stresses in the tunnel shell, the performance of the fan and the tunnel calibration.
The measurement of the stresses in the tunnel shell was mandatory to convince the Dutch authorities that the construction was safe (see page 21). Altogether 150 strain gauges were glued onto the HST shell. Each strain gauge required proper balancing and this presented a formidable task. To handle this problem the Electronic Laboratory of NLL ('*E-lab*') developed the first large scale data acquisition system named SARA or 'Semi Automatic Strain Gauge Scanner' ('*Semi Automatische Rekstrook Aftaster*'). Although this scanner was not completely successful due to problems with the switches (parts originally designed for use in a telephone installation malfunctioned[36]) this development pointed already in the direction of future automation to speed up the measuring process.


[2-35]

[Figure 2-35]

ZEBRA, the first computer of NLL used for the data reduction of the HST (1958). Photo from the manufacturer.

The balancing of the fan and the final check-out of the fan performance was a responsibility of the producer of the fan, Dinglerwerke GmbH. Their tests were combined with pressure measurements[75] to derive the aerodynamic performance of the circuit. This involved measurements in the test section, at the first corner of the tunnel (after the test section), just before and aft of the tunnel fan and in the settling chamber. For these tests a temporary barrack was placed in the middle of the tunnel circuit to house the engineers from Dinglewerke and NLL. Multi-manometers were used to record all pressures. They were photographed and read out on the 'OSCAR' machine. Breman[76], one of the observers at that time, recalls that Van der Zwaan, who supervised these measurements, blew a whistle before each data point was taken. This was essential since the floor was not very stable and all those present had to stand still during the photographic recording.


[2-36]

[Figure 2-36]

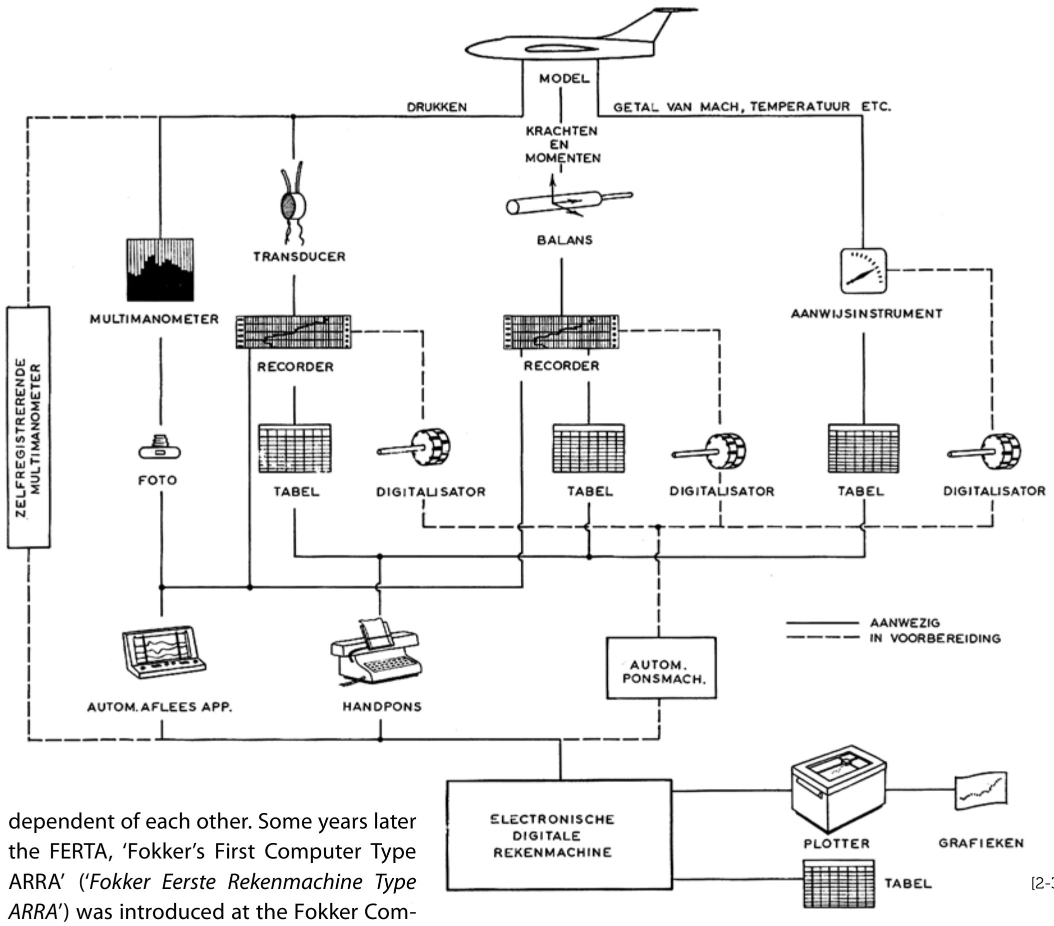
Calibration tests in the test section of the HST with the 'long static pipe' (1959).

To judge the quality of the flow in the test section the tunnel had to be calibrated. The measurements of the static pressure distribution along the tunnel centre line were specifically important. They were made with the so-called 'long static pipe', a tube with 40 static pressure holes. This tube was attached by wires to the tunnel walls [figure 2-34]. Additionally, a rake with a variety of interchangeable probes (total pressure, static pressure, flow direction) was used to measure the flow in the area where the model would be located. Close to 200 pressures were measured at the tunnel walls. Dätwyler & Hausammann which designed and manufactured the test section, guaranteed Mach number variations smaller than 0.003 for all Mach numbers. Apparently, this requirement was not met for the higher Mach numbers and this later necessitated a redesign (by NLL) of the contraction (page 26).

To perform these measurements twelve observers were needed, most of them 'borrowed' from the LST's ('*A-sectie*'), the '3x3' ('*G-sectie*') and the PT. Of course the new multi-manometer, designed and manufactured by Dätwyler & Hausammann was used for these tests. The 162 glass tubes were filled with either water or mercury, depending on the type of measurements. But this was not sufficient. Five other multi-manometers to measure an additional 220 pressures were borrowed from other NLL departments. According to the original plans a total of 1,400 data points had to be taken involving an estimated 47 'wind-on' tunnel hours[46].

A BLUE PRINT FOR DATA ACQUISITION

It was realised from the beginning that such an expensive tunnel required an automated data acquisition system and computerized data reduction to limit the testing times. However, when the HST was designed, these new technologies were just emerging. It was clear that one of the key issues was the digitalisation of the measurement data to ensure a smooth flow of data from the instruments to the computer. An illustrative example of the state of the art at that time can be found in an internal report by Prast[77] from 1955. On a symposium of the 'Dutch Physical Society' ('*Nederlandsch Natuurkundige Vereeniging*' or *N.N.V.*) it had been demonstrated how an encoder could be added to a standard Honeywell Brown pen recorder to provide digital output. The resolution of this system was only 1 on 200, whereas 1 on 500 was required for the balance measurements. A better design was proposed, built and demonstrated at NLL.



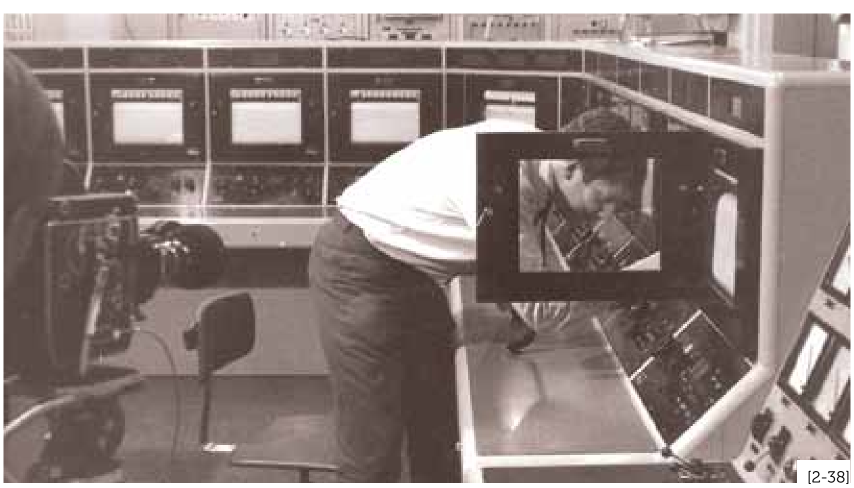
[2-37]

[Figure 2-37]

The 'blue print' of the data acquisition system as viewed in 1960. The solid lines indicate what was available in 1960, the dotted lines show the automated system as envisaged for the near future.

An equally important issue was the availability of a digital computer. The first computer in The Netherlands was developed in 1952 by the Mathematical Centre ('*Mathematisch Centrum*') in Amsterdam. It got the name ARRA, 'Automatic Relais Calculator Amsterdam' ('*Automatische Relais Rekenmachine Amsterdam*'). At that time the calculations at NLL, either mathematical calculations or data reduction from wind tunnel or flight tests, were done at a special department, the Data Reduction Service ('*Uitwerkdienst*') by a group of ladies [figure 2-6]. They used table calculators to perform specified calculations on data written down in tables. To prevent errors each calculation was done twice by two ladies independent of each other. Some years later the FERTA, 'Fokker's First Computer Type ARRA' ('*Fokker Eerste Rekenmachine Type ARRA*') was introduced at the Fokker Company to support the development work for the Fokker Friendship. NLL considered purchasing a similar computer, but the machine was too slow in floating point operations. After an evaluation[78] of a new development at the Dutch mathematical centre (the ARMAC) and of an English computer (the ELLIOTT-402) it was finally decided in 1956 to buy a machine developed by the Dutch Postal Services (PTT), the ZEBRA or 'Very Simple Binary Calculation Machine' ('*Zeer Eenvoudig Binair Reken Apparaat*'). It was claimed that the computer was 300 times as fast as the 'calculating ladies'. The production of this machine by Standard Electric in England proved to be a bit problematic and the computer was finally delivered in 1958 by Standard Telephones and Cables (Stantec), also in England [figure 2-35].

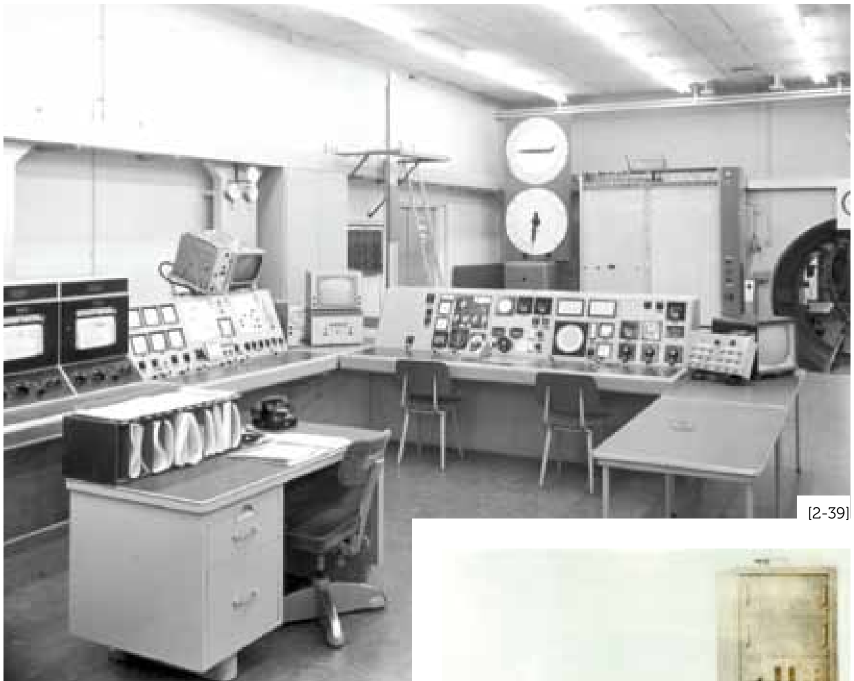
At the opening of the HST in January 1960, a completely digitized measurement chain was not yet ready, although some key elements were available. In a description of the HST at that time the 'blue print' of the HST data acquisition system is given[74] [figure 2-37]. The figure reflects that the data acquisition system is still being developed, though with a clear vision where to go. The solid lines relate to the actual situation in 1960. All data were read from dials and written by hand in tables (balance readings) or recorded on photographs (pressures). The photographs were read out on a semi-automatic machine, named OSCAR, which provided punched paper tape. For the balance output Honeywell-Brown pen recorders were used [figure 2-38]. In the next step the paper tape was fed into the computer for the data reduction. In the blue print a dotted line shows the future perspective.



[2-38]

[Figure 2-38]

View of the Honeywell-Brown recorders for the balance measurements. Just visible against the wall behind the recorders the units to record the scanivalve pressures. The picture was taken during the shooting of a movie to promote the HST at the end of 1968.



[2-39]

[Figure 2-39]

The control room of the HST probably around 1965. On the right side the entrance via the 'sluice' to the plenum chamber and test section. To the left of the 'sluice' the multi-manometer and the indicator for the model position (top) and the Mach number (bottom). On the control desk the tunnel control to the right side and the controls for the schlieren system to the left. The model inside the test section could be viewed on the television screen. Pen-recorders to record the balance signals are still visible to the left.

[2-40]

[Figure 2-40]

The first plotter ('*grafiekenmachine*') used to make graphs of the HST test results (around 1959).

Figure 2-39 shows the control room of the HST around 1965 with some of the Honeywell-Brown pen recorders visible on the left and the multi-manometer behind the control desk in the centre. A large crew was required during the early measurements: one man for the tunnel control, one man to record the reference pressures, one man for the multi-manometer, two men behind the pen recorders for the balance readings, one man for the model position and one man for the cameras and the schlieren system. Each observer had a red or green light in front of him to indicate that the flow was stabilized. This could take as long as seven minutes[79].

Once the data had been recorded and punched on paper tape, they could be processed on the ZEBRA computer. Already at that time two types of output were foreseen. All processed data were printed on paper in tables. To visualize the test data plots could also be generated automatically. To this end a plotter was purchased, known as the 'graphics machine'[48] ('*grafieken machine*') [figure 2-40].

AUTOMATIC DATA ACQUISITION

How would a typical measurement cycle look like? After the installation of the model or a change of the model configuration the tunnel was closed and pressurized. The measurements started (and ended) typically with a zero-reading to compensate for drift in the electronic equipment. The operator then started the tunnel fan to achieve a particular Mach number. When the Mach number was reached, a so-called 'polar' could be made: the model was subsequently set at a range of angles of attack, typically of the order of 20. For each data point (angle of attack) the pressure or balance data were recorded as well as the tunnel flow conditions. When the last point on the polar was taken the next Mach number would be set and so on for 10 to 15 Mach numbers. Recording all data by hand was of course very time-consuming and required many observers. It provided a strong incentive to automate the process. One of the first steps was the addition of encoders to the Honeywell-Brown pen recorders [figure 2-41], later followed by a (mechanical) system to change automatically the range and zero shift of the recorder, a NLL development. A next important improvement was the introduction of the Scanivalves for the measurement of multiple pressures (page 48). This necessitated elaborate control and measuring units. A stepping motor had to scan the 48 pressures and return to a 'home' position before the next sequence could be started. When more scanivalves were used, as was normally the case, each scanivalve had its own pressure transducer and all these readings had to be recorded during each step. In 1963 this whole system was integrated in a system named SADIST, a 'Quick Scanning Digital Information System for the Tunnels' ('*Snel Aftastend Digitaal Informatie Systeem Tunnels*' [figure 2-42]). The process was controlled by a 'patch panel' which determined the order by which the data had to be taken. An important further addition was the recording of a great number of essential parameters (named 'pre-cycle' or '*voorcyclus*') required for the data reduction such as the number of scanivalves, identification of the type of pressure transducers and balances, selection of the channels that measured the tunnel conditions, the balance and transducer signals etc. All data were punched on paper tape [figure 2-43] and fed into the

[2-41]

[Figure 2-41]

Control room of the SST with the control panel to the right. To the left the Honeywell-Brown pen recorders with the additional encoders (on top and bottom) to digitalize the recorder readings. Probably around the mid sixties.

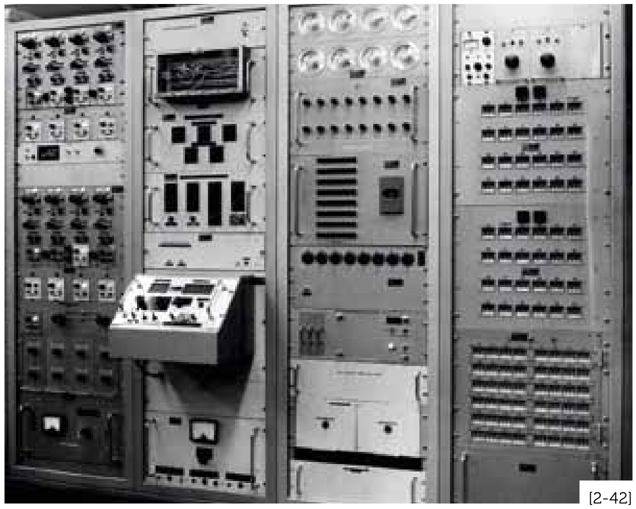
computer for data reduction. The system, based on technology developed for the first digital flight data recorder, was developed by NLL at the Electronic Laboratory ('*E-lab*'). In 1963 the system was first installed at the HST and later at the SST. To the SST system a memory was added to store 4,000 values during a run. This was essential since a run in this blow down facility would typically take 30 to 45 seconds. The, at the time, very advanced data acquisition system has probably been decisive in obtaining the contract for the wind tunnel tests on the ELDO launcher and the Concorde (page 69). In 1964 this contract was awarded after a fierce competition with the supersonic tunnels of ONERA in Modane, France and the tunnel of the British Aircraft Corporation (BAC) in England, a competition involving comparative tests in the three facilities[123].

In 1965 a quick look system named 'Quick Analogue Automated Registration' or SAAR ('*Snelle Analoge Automatische Registratie*') was added, first to the SST and later to the HST system. With light sensitive paper the individual traces of the signal outputs could be visualized for inspection just after a run. In the same year the external balance of the low speed tunnel LST was modified. The arm of the semi-automatic balance (discussed on page 39) was fixed and the rods that connected the balance to the frame to which the model was attached, were modified to accommodate a one-component strain gauge balance ('wheel balance' or '*spakenwielbalans*'*). This enabled the integration of the balance measurements in the data acquisition system of the LST similar to what had been achieved for the HST and SST, all based on the SADIST layout.

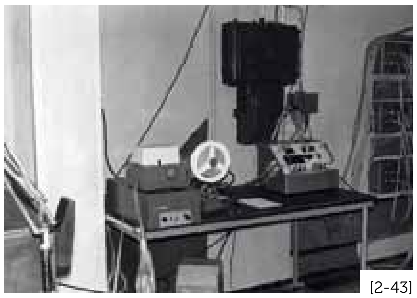
As a result in the mid sixties the data acquisition for the three major wind tunnels of NLR (HST, SST and LST) was automated and based on one and the same data acquisition system, the SADIST. Basically with a single button the whole measuring cycle could be initiated and all data punched on paper tape for the subsequent data reduction on a central computer.

CENTRALISATION OF DATA PROCESSING

As mentioned, the ZEBRA was the first computer used to process all wind tunnel data. Though located in the HST building, the ZEBRA was not exclusively used for the tunnels. Numerical aerodynamics was also developing rapidly. It is of some interest to note that at the end of the evaluation report[78] that resulted in the purchase of the ZEBRA (written in 1956) it is mentioned that the Mathematical Centre ('*Mathematisch Centrum*') had announced that within a couple of years a next generation computer would be 100 times faster due to a much improved memory technology. The author commented though that still higher speeds were only important if the computer couldn't handle the work load anymore, '*not very likely on a short term*'. The ZEBRA was delivered in 1958 and only two years later, in 1960, two (!) new computers were ordered: a replacement for the ZEBRA, the ELLIOTT 803B, an English computer and a second computer, the Electrologica X-1, a Dutch design, to be located in the Noordoostpolder. These replacements were justified because of the very heavy work load for the ZEBRA. Both computers were delivered in 1962. Only four years later a Control Data CDC 3300 was acquired to replace the X-1. This CDC 3300 was running an ELLIOT-simulator for the wind tunnel data processing (named ELSI). The programming was still based on machine code. The demand for computing power was rapidly increasing. With the introduction of the strain gauges in the balance of the low speed tunnel LST, the data of three wind tunnels now had to be processed. At the same time the Fokker F28 was flight-tested with a considerable workload for NLR and the emerging discipline of numerical aerodynamics was advancing rapidly. A contract was made with CDC to use the CDC 6600 in Rijswijk. This very fast computer was considered the first 'Super Computer'. Remote calculations were made possible by the increased possibilities for data transfer over telephone lines. Within NLR the very awkward paper tape (it broke easily and could only be repaired by gluing an aluminium foil to the tape*) was replaced by a cable which connected the wind tunnels directly to a CDC 1700 computer (later the MODCOMP II) which transferred the data either to Rijswijk or to the CDC 3300 in the Noordoostpolder. Still later, in 1972, the Cyber 72, also from CDC, was ordered and this provided enough capacity to do all calculations in house again. Figure 2-44 gives a view of the computer infrastructure at that time. As a result of this development the data reduction and processing that started very close to the wind tunnel in 1960, became more and more centralized and physically separated from the wind tunnels in the mid seventies.



[2-42]



[2-43]

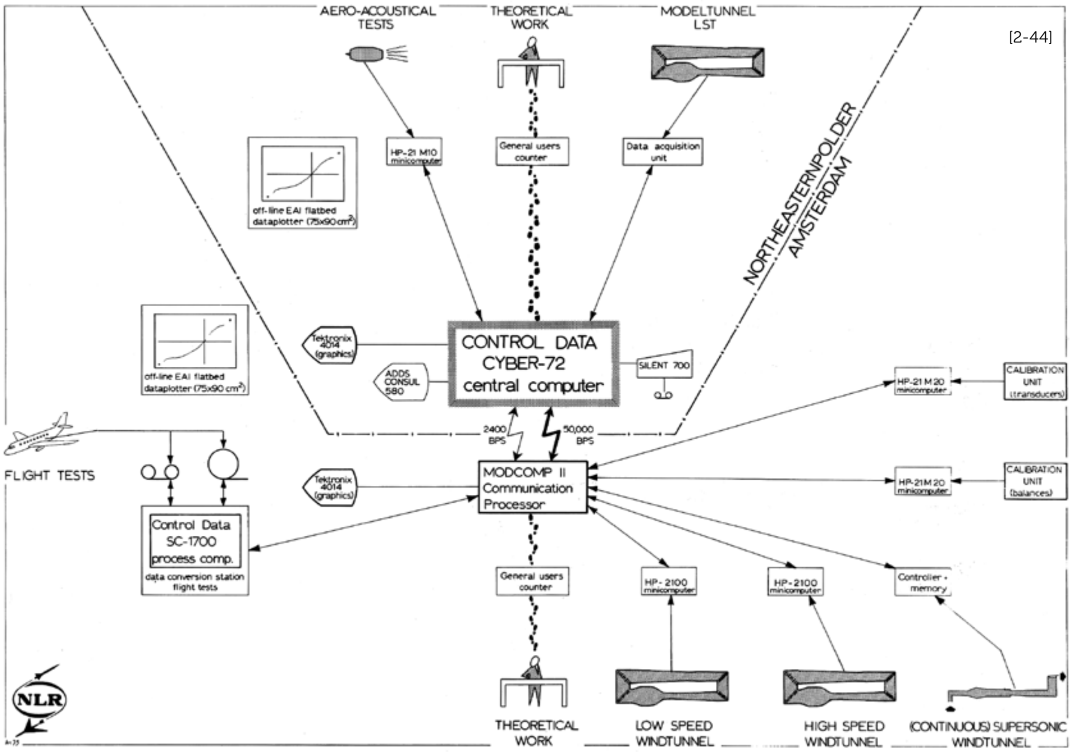
[Figure 2-42]

The SADIST ('quick scanning digital information system tunnels') in 1963. This was the first automated data acquisition system of the HST and SST. From left to right: panel 1: the conditioning units for the pressure transducers; panel 2: the control panel with the patch panel (top) to control the order of the data acquisition and the console (middle); panel 3: the scanivalve panel with the subscanner home indicators on the top and panel 4: a panel with many dials to be set by hand before each run with all constants required for the automatic data processing (the so called '*voorcyclus*').

[Figure 2-43]

Paper tape unit used in connection wit the pressure scanning system and SADIST (picture taken around 1963).

This centralisation could also be observed in the computer program that was used for the data reduction. In the early sixties (Henk) Valk prepared a 'formulae package' that contained all expressions for the processing of the recorded data. This involved the determination of the tunnel reference values (dynamic pressure, Mach number, Reynolds number) as well as the calculation of the pressure coefficients and force coefficients for drag, lift etc. from the balance readings. Rather extensive calculations had to be made. From the balance readings the actual forces and moments had to be calculated with the help of the balance calibration and these in turn had to be expressed in the proper axis system (aligned with the incoming airstream) for the aerodynamic coefficients (see Appendix E). These calculations involved many angles such as the angle of attack and yaw angles, the rolling angle, the up-flow in the empty test section and the deflection angles of the model support under load. All these formulae, over 100 expressions in total, were hand written in a specific Technical Note, nicknamed 'Uncle Henk's stories' ('*Ome Henk vertelt*'). This set of notes formed the basis of a 'General data reduction program for wind tunnel measurements' or APVW ('*Algemeen Programma Verwerking Windtun-*



THE CYBER-72 AS A CENTRAL COMPUTING FACILITY WITHIN THE NLR NETWORK

[Figure 2-44]

The computer infrastructure around 1977. All computing activities are centralized on a main frame computer, the CDC Cyber-72.

nelmetingen') which could be used for the processing of all wind tunnel data from the three major wind tunnels. A working group was formed to make the specification for this program. The program itself was written by the department that handled the computer and related programming ('*W/N sectie*'; see Appendix C). The control of the program was partly achieved by the setting of the parameters contained in the wind tunnel data (the '*voorcyclus*' as mentioned before). Another set of parameters was punched on cards to provide parameters for additional calculations (for secondary balances, for the integration of pressures etc.) and for the type of output that was required (tables, plots). The program was 'universal' for all wind tunnels although there were important differences between the tunnels due to the local hardware and the way they were operated. Any addition to the program required more control parameters and the development continued till the point that the complexity became the enemy of the improved efficiency by standardisation and centralisation. Errors in the input, notably in the control parameters, could only be detected after the tables and plots had been inspected and this involved a walk between the tunnel and the computer centre in Amsterdam or even a trip by car to the Noordoostpolder. The fact that the computer was no longer in the HST building was a clear disadvantage. The wind tunnel project-engineers became as result of this more and more involved in data handling and inspection of the processed data, at the expense of their original task, the orchestration of the wind tunnel measurements. The blue-print of the computer infrastructure in the mid seventies illustrates the much more centralized position of the data processing. The original notion that the computer was the end of the measurement chain, as illustrated in figure 2-37, was gradually replaced by a situation shown in figure 2-44 where the computer was in the centre with the wind tunnels as one of the elements to provide the data to run the computer. This is also reflected in the NLR organisation. The Data Reduction Service ('*Uitwerkdienst*') in the fifties evolved over the years into the Informatics Division ('*Hoofdafdeling Informatica*'), established in 1980 on the same organizational level as the other NLR divisions for aerodynamics, flight or structures. See also Appendix C.

POST PROCESSING

All foreign customers of the NLR wind tunnels got their (final) results on computer tape for a further analysis at home (the so-called '*Tape-OUT*' or '*TOUT tape*'). The analysis of the wind tunnel test results was a 'company owned' activity, a part of their own organisation. However, the research programs on airfoil and wing development sponsored by NIVR (page 76) required a detailed analysis of the wind tunnel data by the NLR staff itself. This was essential to guide the future theoretical developments in consultation with Fokker and NIVR. It necessitated a careful analysis of many wind tunnel data involving curve fitting, interpolation, the determination of increments and so on. Spread sheets were not available at that time and the Department of Applied Mathematics and Data Reduction ('*Toegepaste wiskunde en data verwerking*') initiated the development of a data analysis program. In 1977 the development of such a program started in close co-operation with CDC, based on a new concept for 'relational data base management'

[2-45]

[Figure 2-45]

Overview of the control room around 1975 after the EGOIST (the 'online instrumentation system tunnels' on the left side) was installed. The whole system was controlled by a HP2100 computer (behind the teletype). On the right side the 'quick-look' units. The control desk was also modified.

named 'Evolutionary Data-Base Management System' (EDMS). The resulting program was named ADIPAS: 'Aerodynamic Data Interactive Presentation and Analysis System'. For more general applications it was later changed into EDIPAS with the E for Engineering. On NLR level and after the creation of the Informatics Division in 1980 a centralized steering group for 'Computer-Aided Research and Development' (CARD) was set up to guide these developments and to make sure that they were done to the benefit of NLR as a whole. The first CARD activities were related to the ADIPAS development, computer-controlled manufacturing by the workshops and COLAS, a higher level Command Language System to couple data and programs from different sources. In spite of a very substantial effort EDIPAS was not very successful. Since it was far ahead of its time, the necessary infrastructure with high resolution displays (the first IBM personal computer dates from 1981) was not available yet. In the HST building one or two displays were located in a separate room. Very few users sufficiently advanced on the learning curve to use the most important features of the program efficiently.

The philosophy behind this development was to couple information retrieval (data base management) and post-processing in one program. In the data base information from different sources was stored such as the results of the computations and experimental data from various aircraft configurations. In the analysis these results had to be compared. This merger of data from different sources was never successful, partly because it necessitated an agreement on formats in an environment in which test techniques and computations were changing all the time. And most importantly, the plotting of all kinds of data in various ad-hoc formats could soon easily be done with commercially available spread sheet programs such as LOTUS 1-2-3 introduced in 1982 followed by EXCEL around 1990, both for Personal Computer applications. For very specific applications more professional commercial programs such as PV-WAVE became available. The introduction of the Personal Computer and very powerful work stations soon enabled a decentralisation of most of the data storage and analysis. 'Floppy disks' and 'Diskettes' enabled flexible, distributed data storage. There was no technical necessity anymore to store all data on a central computer.


[2-46]

[Figure 2-46]

Front plate of the first generation 'measurement conditioning units' or MCU's, an essential part of the data acquisition system EGOIST (around 1975).

LOCAL INTELLIGENCE AND DISTRIBUTED PROCESSING

Was the SADIST, the acquisition system located near each wind tunnel, well suited to operate in an environment with data processing on a central computer? To answer this question a study was initiated resulting in the development of a new data acquisition system with the name EGOIST, the 'First Completely Online Instrumentation System Tunnels' ('*Eerste Geheel Online Instrumentatie Systeem Tunnels*') which became operational in 1973 [figure 2-45]. Fuykschot, who started at the Electronic laboratory ('*E-lab*') before he became head of the Wind Tunnel Instrumentation Section ('*Windtunnel Instrumentatie*', AW) was the driving force behind this and many other instrumentation developments. This system consisted of two unique features. The first one was a set of new 'Measurement Conditioning Units'* or MCU's, necessary to replace the pen recorders for the balance measurements (and other transducers) and to provide the proper digital output for the central computer [figure 2-46]. The second one was the replacement of the 'patch panel' by a small process computer, the HP2100, to control the whole process of data acquisition, some data reduction and data transfer.

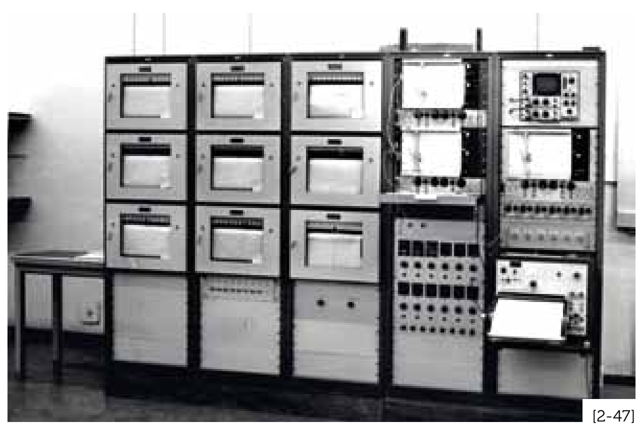
The presence of 'local intelligence' allowed a significant step forward in the existing 'quick-look' system. Already in 1965 X-Y pen recorders were coupled to the SADIST to display some relevant graphs notably for the presentation of pressure distributions and polars. Later several display units, such as conventional pen recorders, X-Y plotters and a UV-recorder and oscilloscope for dynamic signals were combined in a quick-look system [figure 2-47].

During the installation and related testing of the EGOIST, experiments were carried out with data-processing routines on the CDC-1700/MODCOMP II-computer. This, combined with the experiences of the HP2100-computer of the EGOIST, resulted in a dedicated real-time HP1000-computer system for the listing of raw-data and the real-time presentation of calculated results by a sub-set of the 'Valk formulae package'. This development was initiated by De Moes of the Department of Compressible Aerodynamics (AC) [figure 2-48]. In 1978 this local computer, an HP1000/45, was programmed to perform data reduction for the on-line display of all relevant data. The demands of the companies Aérospatiale and Aviation Marcel Dassault contributed to this development.

In 1980 further developments of the local data processing led to the introduction of an 'Operational Local Information Processing Unit Windtunnels' named OLIVE ('*Operationeel Lokale Informatie Verwerkings Eenheid Windtunnels*'). All details of the wind tunnel test could now be followed by the customer in real-time. Prints as well as plotted data were provided. The latter as graphs on 6 A3 multicolour HP-plotters. This graphical system was a NLR-development. After that it was only a small step towards implementing the complete data processing, including the output-tape 'TOUT', on a local HP computer, a task performed till that time centrally by the APVW-program. On CRT monitors ('BARCO') the results of the measurements could be displayed. Graphs were produced during or immediately after the measurements by electrostatic plotters ('Versatec'). It also became possible to compare results (e.g. lift curves or drag polars) with past results stored in the system during a previous test, an option very much welcomed by the customers.

[Figure 2-47]

'Quick-look' system in the HST. To the left pen-recorders now only used for visualization, at the right 3 X-Y plotters. Also at the right side at the bottom a UV-recorder to check dynamic aspects of the measurements. The pen recorders were later replaced by X-Y plotters (see figure 2-48) and still later by screens ('BARCO').


[2-47]

[2-48]

[Figure 2-48]

Bert de Moes behind the HP1000/45 computer for the on-line reduction of the wind tunnel data. On the left six X-Y plotters to visualize the results according to the needs of the customer. In the middle the printer.

For those who could read the signs it was quite clear that the use of local computing power was more efficient and opened the way for new developments in terms of process control. In the following years the (C)SST and the PT, all equipped with EGOIST data-acquisition systems, were connected to the OLIVE-computers for data-processing and data-presentation. The same OLIVE-concept was later applied at the LST in the Noordoostpolder.

Local intelligence made it possible to initiate further improvements in the measuring process. The control desk was adapted to enable the new possibilities. Till that time the Mach number was controlled manually during an angle of attack sweep of the model. Without this additional control the Mach number would normally change during an angle of attack sweep as a result of the increased drag of the model. In a new development the setting of the Mach number (hence the deflection of the fan blades) could be adjusted automatically, based on the measured tunnel pressures. In 1976 this development, combined with real time data processing, opened the way for 'continuous sweep' measurements instead of the usual 'pitch and pause' mode of operation. During the angle of attack sweep the measurement data for a polar could be taken continuously. This system was further refined with the implementation of one of the first Apple II computers in The Netherlands in the automated control loop. As a result the productivity of the tunnel improved significantly. For pressure measurements the conventional 'pitch and pause' mode still had to be used. The fact that a constant Mach number could be maintained during an angle of attack sweep was extremely attractive for the customers who otherwise had to take many more data points to interpolate towards a constant Mach number during a run. This was a real advantage in the competition with other tunnels, notably with the ONERA S2 tunnel where interpolation between polars was always required.

In the early eighties it became more and more evident that the transfer of data from one facility to the other was increasingly important. For the simulation of model engines on wind tunnel models, calibration tests had to be performed in the Noord-Oostpolder and the same equipment was used subsequently in HST or LST. It was not unusual to exchange models between the tunnels, not only between HST and SST but also between HST and LST. This development triggered a proposal to set up a new modular local data processing system based on the OLIVE-principles for all wind tunnels. The idea was to combine local data processing with a modular set-up to facilitate the common use of data-acquisition hardware and software by all test engineers from either the high speed, low speed or propulsion facilities. This proposal, however, was blocked by the higher management. It was not believed to be compatible with a centralized information structure as pursued by the Informatics Division. De Moes, who played a crucial role in this development, left NLR.

However, the trend towards local data processing could not be reversed any more. In 1988 a new further improved data acquisition system was introduced in the HST. This was soon followed by an improved data processing system to replace the OLIVE system. This system named 'APROPOS', meaning 'Aerodynamic PROcessing and Presentation Open-ended System', was soon introduced for all wind tunnels, though with a core software packet that was derived from the APVW. A local area network was installed for the data transfer. Also a new generation conditioning unit was developed. At the same time 'Programmable Logical Computers' or PLC's were introduced. They allowed local control over specific equipment such as the 'Probe Traversing Mechanism' or the 'Traversing Wake Rake' (see page 59).

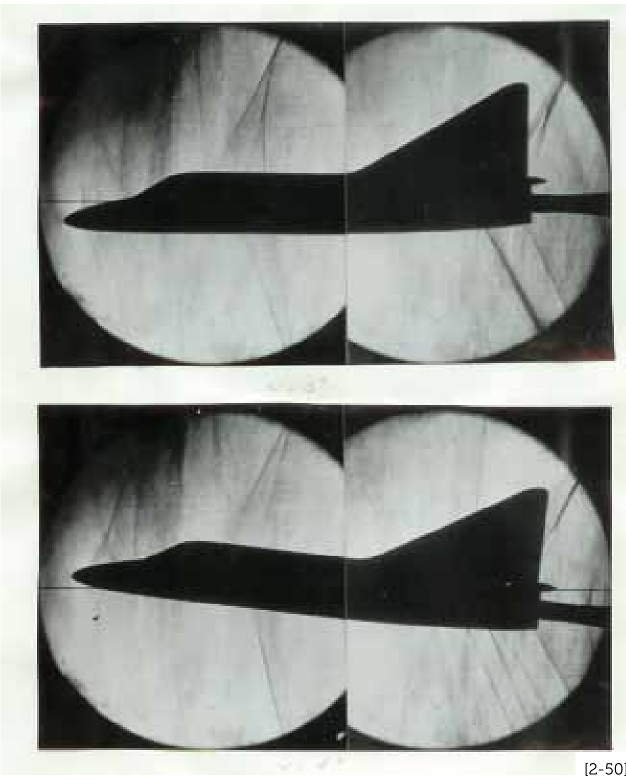
With the Phase I modification of the HST in 1992/1993 the complete architecture of the HST tunnel controls was redesigned to fully exploit the improved capabilities of the data acquisition and tunnel control systems. The data acquisition system and the control desk [figure 2-49] were completely renewed. The data reduction program also had to be adapted. The 'formulae package' by Valk could no longer be used for the new more versatile model support systems, notably for the 'articulated boom' [see figure 1-57]. Instead of the lengthy and not very transparent goniometric expressions a more structured approach was followed, based on 'homogeneous transformations', a technique developed for robot kinematic applications. This new set-up allowed a much greater flexibility in the test execution, also in the sense that the conditions for taking data could now be controlled by the actual measurements. It opened new possibilities in controlling the measurements and speeding up the tests, possibilities that were fully exploited in the decade following the HST modification. ■

[Figure 2-49]

A recent picture (2010) of the control room of the HST. To the left the Signal Conditioning Units. All controls on the control desk with digital displays.

[2-49]

MAKING THE FLOW VISIBLE



[2-50]

THE FIRST PRIORITY: SCHLIEREN

[Figure 2-50]

Schlieren photograph of the Sud Aviation 'Durandal' around Mach=1. This was one of the first models tested in 1959 in the HST at transonic conditions.

[Figure 2-51]

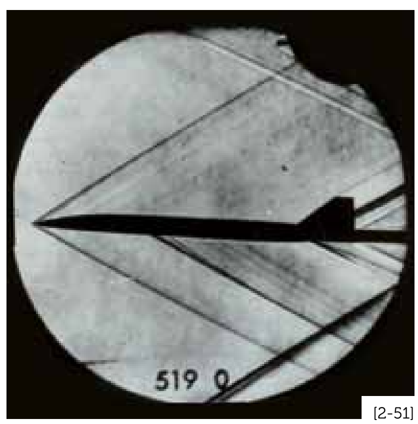
Schlieren photograph of the Concorde in the SST made between 1963 and 1975 during the extensive test program for 'Sud Aviation'.

The importance attributed by the test engineers to a 'quick-look' system as discussed in the previous section reflects a more general interest to see what has been measured. The most direct way is to visualize the flow itself. This can be done by blowing smoke in the flow, by gluing threads of wool to the model surface ('tufts') or by painting the model with oil, oil that will align itself with the local flow direction at the model surface. All these techniques were already used in the old Eiffel tunnel of the RSL [figure 2-7]. The application of these techniques was not straightforward for the HST and SST. For the HST as well as for the SST, the test section is completely enclosed and the model can only be observed through television cameras. Smoke could not be used anymore since the smoke would disperse rapidly in the high speed flow. Tufts on the model surface would be blown away. Fortunately flows at high speeds are compressible and this opened the way to optical techniques such as 'schlieren', 'shadow graphs' and 'interferometry'. These techniques are based on the principle that due to density variations in the compressible flow, the light is deflected depending on the density distribution, resulting in an interference pattern of light and dark lines and area's. In reference 31 it was already remarked that, following NACA experience, a schlieren system was very valuable.

At transonic conditions the flow is dominated by shock waves. A shock wave can be seen as a discontinuous change in the flow velocity and the pressure when the flow is forced to decelerate from local supersonic to subsonic speeds. Not without reason the phrase 'breaking the sound barrier' [figure 1-51] was used to pass the speed of sound, reflecting the problems that were encountered and mastered on October 14, 1947 for the first time by Chuck Yeager in the Bell X-1. The technique of schlieren to visualize density variations in air was well known (the invention was already made in 1864) and used extensively in the Peenemünde wind tunnels where the V2 was tested during WW II. The small '3x3' supersonic wind tunnel built by Erdmann (see page 15) was also meant to obtain experience with these optical techniques. In fact, the experiments by Erdmann in this small wind tunnel formed the basis for his dissertation[80] on April 30, 1951 at the Technical University of Aachen ('*Fakultät für Machinenwesen und Elektrotechnik der Rheinisch-Westfalischen Technische Hochschule Aachen*'). Based on these experiences the schlieren/schadowgraph system for the PT had been constructed with a beam diameter of 0.45 cm. The decision was taken to use a similar system for the HST. To prevent tunnel vibrations from spoiling the quality of the pictures, the whole system was suspended on very flexible springs. The size of this traversable schlieren system roughly determined the diameter of the plenum chamber. In the Note on the construction of the HST from 1956[40], Boel remarked that the schlieren system had top-priority. This was also caused by the long delivery times for the special mirrors in the optics. The schlieren system was designed by NLL, but finally built by Dätwyler & Hausammann in Switzerland. At the opening of the HST the schlieren system was operational [figure 2-50], followed some years later by a similar system for the SST [figure 2-51]. Since that time the system has been used routinely. In the seventies the schlieren system was extended with the possibility to make colour pictures. Very 'picturesque' photographs were obtained, but these hardly contributed to a better understanding of the flow.

OIL FLOW VISUALIZATIONS

This technique, routinely applied in the low speed tunnels, had to be slightly adapted for use at transonic speeds. Instead of 'lamp black' or 'day glow' suspended in petroleum, a more viscous oil seeded with titanium dioxide had to be used. It was somewhat problematic to mount the cameras to view the model. They were located in the slats of the upper and lower tunnel walls (behind glass windows) or behind the windows in the side walls. These cameras, the so-called 'robot cameras' purchased in Germany, could be remotely controlled. The appropriate lighting of the model had to be developed by trial and error. This technique allowed the visualization of a



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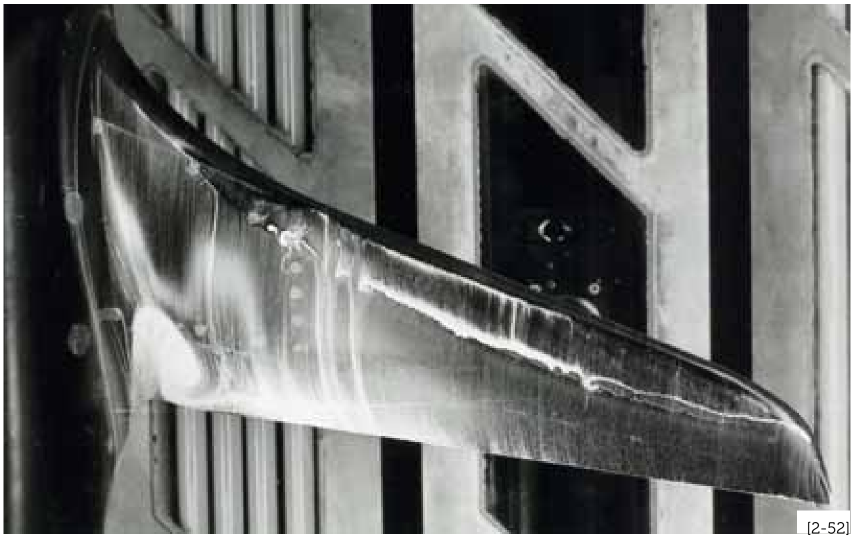


[2-52]

[Figure 2-52]

Oil flow picture of the flow over the wing of the first supercritical wing SKV-1. The thick white line in the middle of the wing is indicative of a shock wave that extends from the wing root to the tip. Note also the vortex at the wing root, indicating flow separation.

very detailed ‘footprint’ of the flow over the surface of the model. It was an art, or almost a science (related to the mathematical discipline of topology) to reconstruct from these surface patterns the three-dimensional flow field around the model. Figure 2-52 gives a nice example of such an oil flow picture for the flow over the first supercritical wing designed by NLR in close co-operation with Fokker (see page 78). From this picture the position of the shock wave on top of the wing is visible as well as an unwanted flow separation at the wing root[W]. This technique is still applied routinely to understand the flow on wind tunnel models. Another nice example is presented in figure 2-53 for the Hermes space vehicle, a study made for ESA around 1988.

[2-53]

[Figure 2-53]

An oil flow picture of the fllow over a Hermes configuration in the SST made around 1988.

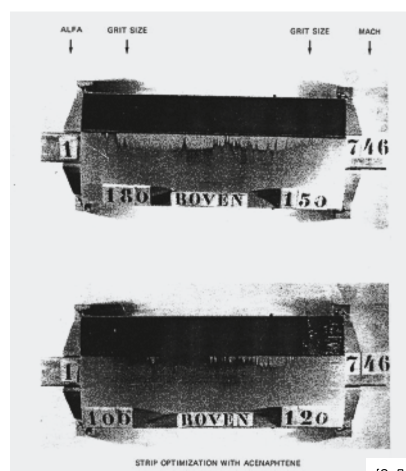
BOUNDARY LAYER TRANSITION

In the region close to the wing surface the flow is decelerated due to viscous friction and a so-called boundary layer is formed. The boundary layer is responsible for the (viscous) drag and can also be the origin of flow separation, the situation that the flow breaks away from the model surface (as was shown in figure 2-52 at the wing root of the SKV-1 model). The boundary layer can obtain two states, depending on the pressure distribution, the roughness of the wall and the Reynolds number. These two states are laminar (‘smooth’ flow) or turbulent (with a ‘chaotic’ turbulent motion). At low Reynolds numbers the flow is most often laminar, whereas at flight Reynolds numbers the boundary layer is generally turbulent. To simulate the flow over an aircraft configuration in the wind tunnel at a low Reynolds number, it is common practice to force the boundary layer flow on the model to become turbulent. This can be achieved with a so-called ‘transition strip’ a small roughness band, generally made of carborundum grains (the grains used in ‘sand paper’) glued onto the wing at a fixed percentage of the local chord (normally 5 to 10 %). To know the location of the transition line and/or to make sure that the transition strip has actually provoked transition, a sublimation technique is used. On the model a thin and smooth layer of a chemical substance is sprayed. This layer has the property that it transforms directly from a solid to a gaseous state (it ‘sublimates’). Due to the action of turbulence this transformation is faster in a turbulent boundary layer compared to a laminar boundary layer. After a short time (in the order of minutes) the not yet sublimated material is left behind on the model as a witness that the flow is locally laminar [figure 2-54]. For high speed conditions acenaphtene is normally used as the sublimating material. This test is a very important one, notably to assure an accurate determination of the drag and of the off-design characteristics. Also the choice of the size of transition strip is more an art than a science and is based on considerable experience. Mastering the techniques for the application of transition bands and the related transition detection, was one of the requirements of Sud Aviation to execute their wind tunnel tests at NLL.

For each transition strip a new test has to be made. This makes these tests rather time consuming and hence expensive and other more time and cost-efficient methods have been tried. Since the state of the boundary layer, laminar or turbulent, also affects the local wall temperature, it is in principle possible to measure the temperature by optical means, either with temperature sensitive paint or with an infrared camera. But since the temperature differences are very small (in the order of one degree) the model surface should be non-heat conducting. First experience with the infrared technique was obtained with tests in the HST on a natural laminar flow airfoil designed and tested by NLR in 1986. In that case the model was coated with a thin insulating layer. The technique has been used since, depending on the model surface properties. The big advantage is, of course, that the transition characteristics can be monitored continuously during a test without additional costs.

FLOW FIELD MEASUREMENTS

The techniques for flow visualization with schlieren, oil or acenaphtene have hardly changed over the years of operation of HST and SST. However, quantitative flow field measurements with the objective to determine the magnitude and direction of the flow in the neighbourhood of a wind tunnel model have shown considerable improvements. One of the earliest examples of flow field measurements, related to the F28 development program



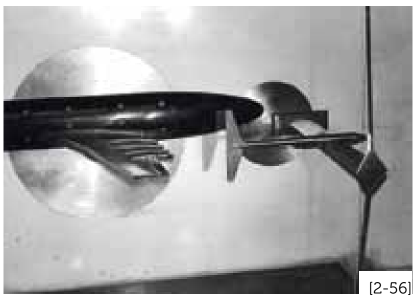
[2-54]

[Figure 2-54]

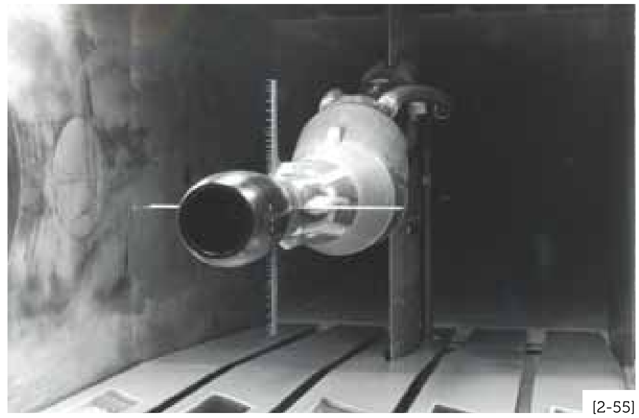
Two examples of the application of the acenaphtene technique to visualize boundary layer transition behind a transition strip on a two-dimensional airfoil. The flow direction is from top to bottom. The smaller carborundum grains on the top figure leave a larger white area, indicative of laminar flow. The largest grain (indicated by the smallest carborundum number 100) makes the boundary layer fully turbulent.

[W] THIS SEPARATION AT THE WING ROOT WAS NOT INTENDED BUT IT HAD BEEN PREDICTED FROM THREE-DIMENSIONAL BOUNDARY LAYER CALCULATIONS. IT WAS THE FIRST APPLICATION OF A CALCULATION METHOD FOR THREE-DIMENSIONAL VISCOUS FLOWS AND THOSE THAT WERE ENGAGED IN THIS DEVELOPMENT WERE THE ONLY ONES WHO LIKED THIS RESULT.

in 1964, is shown in figure 2-56. The F28 wing is mounted as a half model on an external half model balance against the side wall of the HST. This balance measures the overall forces, including the drag. The question may be asked: are there regions on the wing that contribute excessively to the overall drag e.g. due to premature shock wave formation or flow separation? To answer this question the wake behind the wing can be measured. To this end a so-called 'wake rake', a row of many total pressure tubes spaced in vertical direction, is translated in span wise direction behind the wing. This rake measures the total pressure loss due to the boundary layer on the wing or behind shock waves. Similar wake rake measurements have been made for


[2-56]

Sud Aviation on the Concorde and the Airbus A300 to investigate the flow conditions for the turbofan engines. Since the inlet conditions of turbofan engines depend on the Reynolds number, in 1980 during the F29 development program a special inlet test rig was made to study the inlet characteristics on a larger scale [figure 2-55]. With an ejector the mass flow through the inlet duct could be controlled. A rotating rake inside the inlet duct and four fixed external rakes were used to determine the viscous and shock wave losses for a wide range of mass flows and flow conditions (Mach number and angle of attack/yaw angles).
In the eighties the validation of Computational Fluid Dynamics became increasingly important (see page 86). To check the quality of the computer codes there was a need to measure the flow velocity in certain regions of the flow field. The conventional way to do this makes use of a 'five-hole probe', a small probe with a spherical head. From five tiny holes in the probe head the magnitude and direction of the flow velocity can be derived after the probe has been calibrated. In 1985 a special mechanism was manufactured to position this probe anywhere in the flow field, the so-called 'Probe Traversing Mechanism' ('*Sonde Traverseer Mechanisme*' or *STM* [figure 2-57]). This set-up has been used to measure the boundary layer development of wings and two-dimensional airfoils as well as to probe the vortex flow field above a delta wing. The mechanism had four degrees of freedom controlled by a special computer-controlled unit. Various types of probes could be positioned very accurately in vertical direction to measure the thin boundary layers (thickness order of 10 mm) on wing surfaces.
At about the same time a wake rake was manufactured with 18 five-hole probes. This was done to enable detailed measurements of the slipstream behind a propeller, an investigation made on behalf of Fokker to study the interference of a high speed propeller with the wing. The design of this new wake rake was made possible by the electronic pressure scanners (see page 49), which could measure many pressures simultaneously and continuously. The pressure tubing was designed in such a way that delay times were minimized and this allowed a continuous displacement of the rake. And last but not least, the data acquisition was so fast that a large amount of data could be sampled and processed in real time. In 1986 this rake was used to measure a two-dimensional laminar flow airfoil (NLR8602) in the HST. In addition to the traversing five-hole probe rake, the pressures on the model were measured as well in real time with the electronic pressure scanners. It constituted the first example of 'continuous' pressure measurements in the HST instead of the more conventional 'pitch and pause' testing, a development similar to what had been achieved about ten years before for the force measurements. This five-hole probe rake was a great success due to its high productivity and the rake was used extensively in the 'Large Low Speed Facility' LLF of DNW to investigate wake vortex development behind the wing, an important issue during the Airbus A380 development program.
The probe traversing mechanism (for detailed local measurements) and the five-hole probe rake (for flow field mapping) are probably as far as one can go with mechanical systems. In the eighties new possibilities for flow field measurements were offered by optical techniques. 'Laser Doppler Velocimetry' or LDV was very suitable for local flow field measurements and this technique was applied a number of times in the HST to measure the flow behind propeller blades. It is based on measurement of the Doppler effect, a change in frequency of a light signal when reflected from a moving particle. Mapping entire flow fields was possible with 'Particle Image Velocimetry' or PIV [figure 2-58]. In this technique two 'snapshots' are made with a laser light sheet of very small particles moving with the flow. With correlation techniques the displacement of these particles and hence the velocity can be derived from the two pictures. This is a very powerful and promising technique. To apply this technique, it is essential to distribute micron particles in the flow. In 1996, with the Phase 2 modification of the HST, this has been achieved by the permanent installation of a traversable smoke dispenser in the settling chamber of the HST.
Finally, pressure sensitive paint as already discussed at page 48 has to be mentioned as well as a very powerful tool to visualize the local pressures on the model surface. [see also figure 2-30]. ■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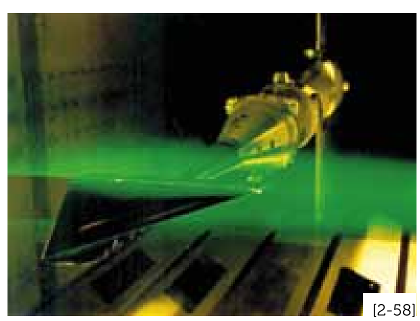
[Figure 2-55]
Wake rakes around the nacelle during inlet simulation tests for the nacelle of the Fokker F29. From the rake measurements the external nacelle drag can be derived for a range of flow conditions of the engine, simulated by a variation in mass flow through the nacelle (around 1980).

[Figure 2-56]
Wake rake measurements in 1964 behind the wing of a half model of the Fokker F28 used to evaluate the drag characteristics.


[2-57]

[Figure 2-57]
The Probe Traversing Mechanism above a delta wing in the HST around 1985.

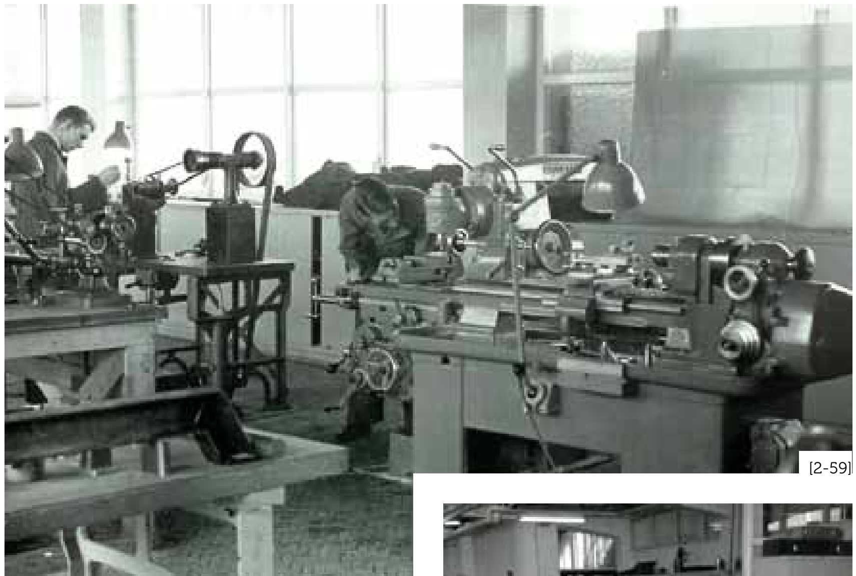

[2-58]

[Figure 2-58]
A laser light sheet above a delta wing (part of the IEPG program) to measure the flow velocity with Particle Image Velocimetry (PIV).

MODEL MANUFACTURING

FROM WOOD TO METAL

Before World War II all aircraft models for the RSL wind tunnel were manufactured in the workshops of the laboratory. The models were generally made out of wood. Wood can easily be shaped in the required form by cutting and chiselling, followed by sanding to obtain a very smooth surface. The skills needed were similar to those required for ship building or furniture making. A problem, though, was the dimensional stability of the models. Temperature and moisture could change the shape considerably. To reduce these effects the models were often built up of layers of wood glued together. In some special cases, such as the manufacturing of small model propellers, flaps and control surfaces, wood was not strong enough and metal had to be used.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[Figure 2-59]

View of the metal workshop around 1950.

During World War II some craftsmen of the laboratory workshop went to Göttingen in Germany to learn about other production techniques applied at AVA, the 'Aerodynamic Research Institute' that supervised the NLL activities at that time. The Germans used a metal skeleton filled with plaster. After the War a similar technique was tried at NLL using resin instead of plaster. But in general the wind tunnel models for the LST were still made of wood [figure 2-61].

It was soon realised that wooden models would not be adequate for tests in the high speed wind tunnels mainly due to the much higher loads, a factor of 10 compared with the low speed tunnels. Moreover, the required accuracies for high speed models could not be achieved in wood. The workshops were fully equipped to machine specific metal parts for wind tunnel models and related instrumentation and to support the activities of other departments [figure 2-59]. However, manufacturing aluminium or steel wind tunnel models with curved surfaces necessitated the development of new production techniques. Note that in 1950 the first transonic model of Fokker, the S14 jet trainer*, was manufactured in France (see page 65). Time was needed to develop these techniques.


[2-60]

[Figure 2-60]

Wooden template of the nose of the Concorde used in the 'rotating barrel machine' for the manufacturing of metal Concorde models for tests in HST and SST (around 1970).


[2-61]

[Figure 2-61]

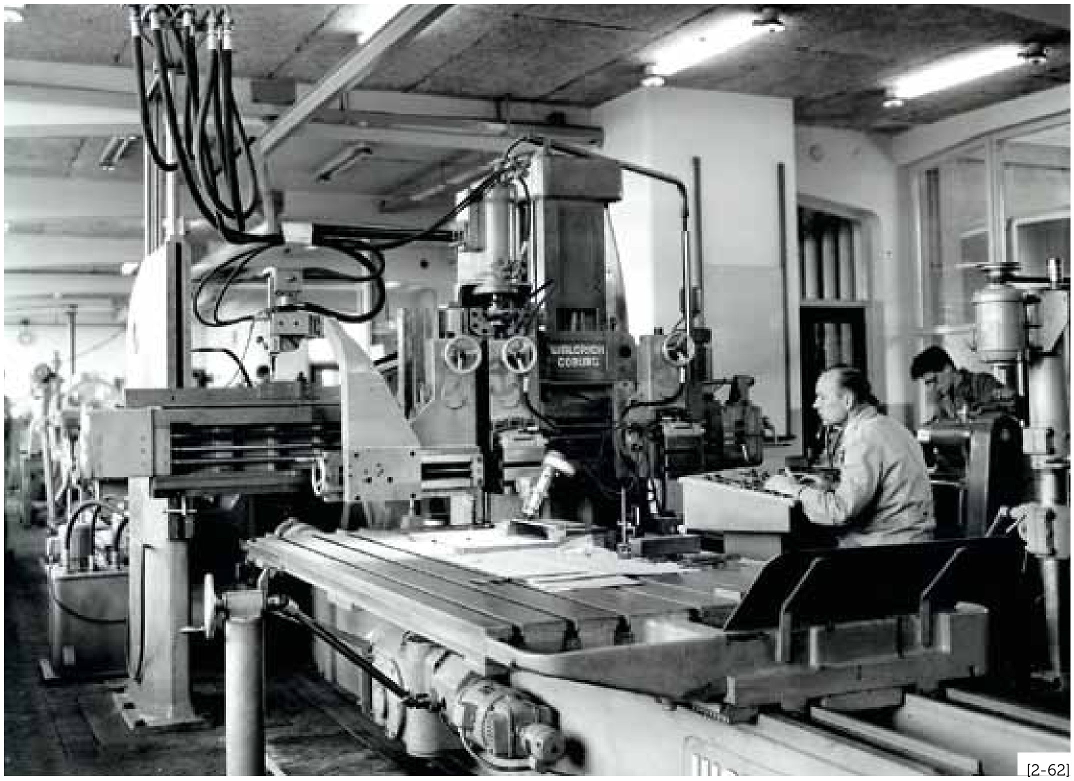
Manufacturing a tail model for the F27 in the wood workshop (around 1950).

Conventional metal cutting machines were restricted to circular or linear movements. In a lathe the material is centred between two pivot points and turned around whereas the chisel that cuts the material remains fixed. In the long planing machine the work piece is reciprocated in linear motion, during which the cut is made in one direction by lowering the tool before each cutting stroke. In a routing machine the piece of metal that has to be worked on can be moved in a plane in two dimensions underneath a revolving chisel (milling cutter).

In 1954 Baljeu[81] developed a 'copier routing machine', a machine where the movement of the milling cutter was guided by a template. This template was made out of wood or sheet metal with a contour sawing machine. An available pantograph was used to copy the shape of the template onto the metal that had to be cut. This technique was first applied to the manufacturing of model propellers. The same principle was applied later in the so-called 'rotating barrel machine' which was purchased in 1958. Three dimensional shapes could be copied and cut in metal on this machine, which was used intensively for a long period. A nice example of this technique is the manufacturing of the fuselage nose of a Concorde model with the help of a six times larger mock-up* made out of wood in the conventional way [figure 2-60 and 2-63]. Straight wings were produced differently. In 1954 the Waldrich 'long planing/routing copying machine' was purchased to this end [figure 2-62]. This machine could manufacture straight wings with a constant cross section such as two-dimensional airfoil sections for e.g. tests in the low speed tunnel LST or the PT. This machine could also be used to duplicate shapes [figure 2-64]. In that case the position of a special routing head was directed by a feeler in such a way that a three dimensional template could be copied one-to-one onto a piece of metal. This technique required an accurate shaping of the template. As an alternative the shape of the wing could be cut approximately 'by hand' on the 'Waldrich'. Numerous small holes were drilled into the oversized material according to the coordinates of the wing surface. Then the superfluous material was removed by painstaking filing and polishing. During the campaigns for the Concorde* the NLL workshop had to make many extra hours to get the models ready in time.

TOWARDS NUMERICAL CONTROL

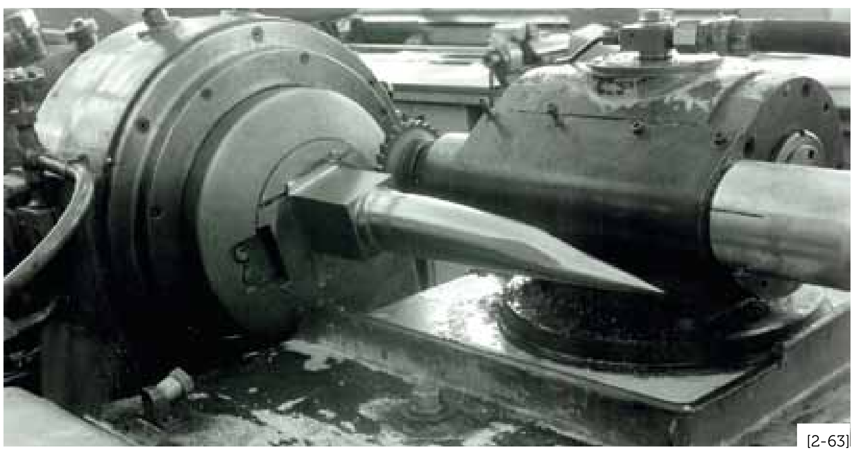
At the end of the sixties the chairman of the Board of NLR, Van der Maas, on leaving the NLR offices, met Dröge, the head of the workshop and told him that in the US he had seen a machine which manufactured wind tunnel models numerically[82].



[2-62]

[Figure 2-62]

The Waldrich long planing/routing copying machine (since 1954). The templates, hardly visible, are located in the portal.


[2-63]

[Figure 2-63]

Manufacturing the Concorde nose (scale 1:60) on the 'rotating barrel machine'.


[2-64]

[Figure 2-64]

Copying a Fokker F28 wing on the Waldrich routing copying machine.

[2-65]

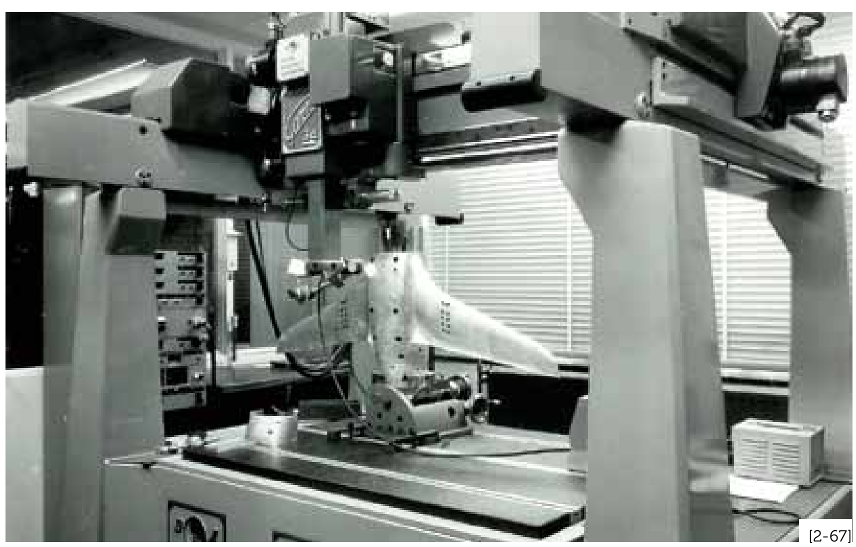
[Figure 2-65]

The Bohle, the first numerical controlled routing machine.

[2-66]

[Figure 2-66]

Wing centre piece machined numerically on the Bohle.



[2-67]

[Figure 2-67]

The DEA coordinate measuring machine with the SKV-1 supercritical wing.

The complete cutting process was under control of a set of instructions punched in numerical form on a paper tape. *'Could this also be done at NLR?'* was the question. A small study group was formed with Baljeu, Dröge, Van Benthem (head of the Applied Mathematics and Numerical Section) and Cool (from the Technical University in Delft as an advisor). They visited the US, France, Germany and England and it was finally decided to buy a numerically controlled German milling machine, the Bohle, equipped with an American Bendix control unit. This machine was delivered in 1969. It was a 'four axis machine', allowing a numerically controlled freedom of movement in three orthogonal directions in addition to a rotating platform to which the 'routing head' was attached [figure 2-65, 2-66]. This new numerically controlled machine (N/C, in house named the NuBe for '*Numerieke Besturing*') was located in the new workshop in the Noordoostpolder. To check the actual geometry of the model a three-dimensional coordinate measuring machine, the DEA, was acquired. With this machine the coordinates of the model surface could be measured and digitized and the outcome compared with the specified geometry [figure 2-67]. With the introduction of the numerically controlled machines, the Design Office ('*Constructiebureau*' or *TO*) had to adapt its way of working as well. This office combined expertise in the design of all kind of constructions in response to specific demands from the various departments within the laboratory or from external customers. The activities were most often related to fine mechanical constructions as required for instrumentation development and model design. Its design activities resulted in a set of drawings for the workshops. A smaller group of people in the Department for Technical Projects (TP) took care of the coordination between the NLR customers, the NLR departments, the Design Office and the workshops. The combined expertise and know how of the Design Office and the workshops enabled the NLR departments to do research on the edge of what was possible. When the first N/C machine was introduced, the construction office had a staff of about 20 people, whereas the workshops counted over 50 employees. In the early days of the Numerically Controlled Machining special computer programmers wrote the instructions for the machine in the language APT (or 'Automatically Programmed Tool'), a time consuming activity. Since, as a result of the aerodynamic design process, the actual model shape was numerically available, it made sense to use this digital model geometry directly for the numerical machining process. In the early eighties the geometry package SIGMA, developed by the French aerospace company SNIAS, performed this task at NLR. Although this package was very convenient for the aerodynamicists, it was not very practical for model manufacturing applications. At that time Fokker was experimenting with two other programs, the commercially available CADAM packet for general 'computer aided design and manufacturing' and CATIA, a program developed by another French aerospace company with the name Dassault and marketed by IBM. Around 1990 and after some tests at the Fokker factories, NLR decided to buy CATIA as the standard tool for model design and numerical manufacturing. Special work stations with graphic displays were purchased replacing the conventional drawing boards [figure 2-69]. Model design and manufacturing were finally completely digitized.

[2-68]

[Figure 2-68]

Making grooves for pressure tubing in the wing of a Concorde.

The precise reproduction of the external shape of the model is one issue, but it is equally important to accommodate the required instrumentation within the confined space of the model. Pressure holes had to be drilled and pressure tubes had to be installed [figure 2-68, 2-70] and connected to the pressure scanners. The pressure scanners themselves were modified and miniaturized as described at page 49. Sometimes

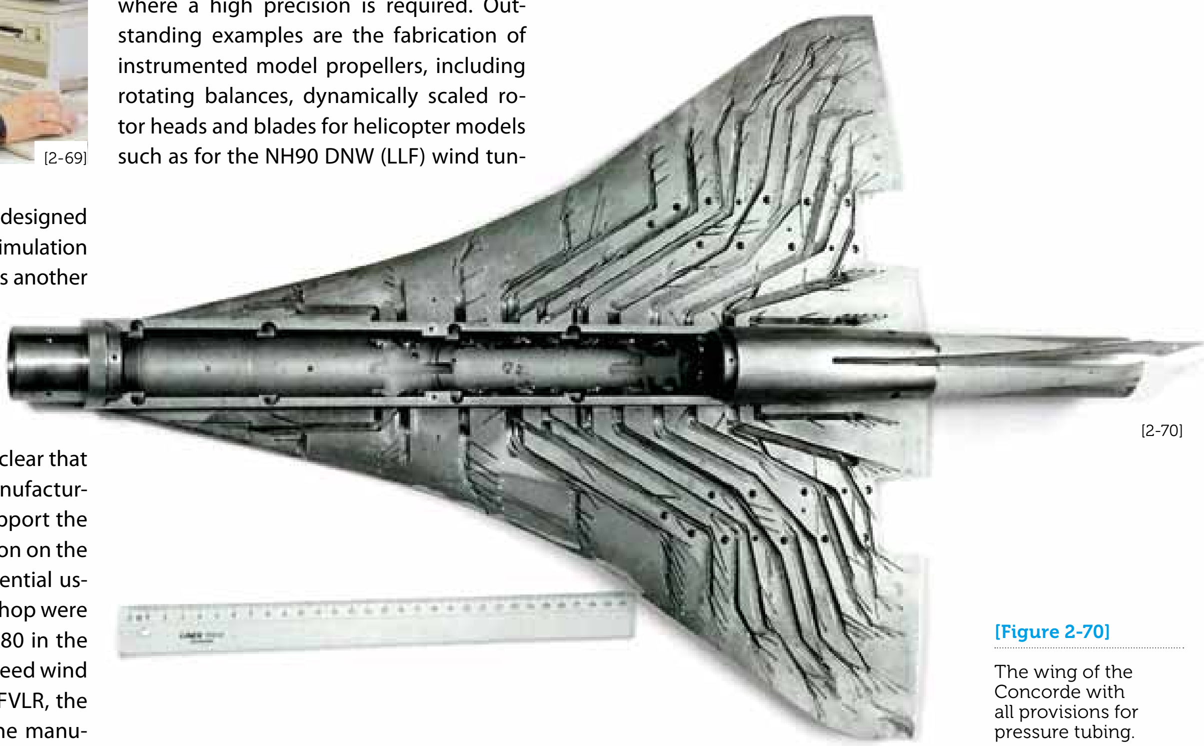
[2-69]

[Figure 2-69]

A designer working with the CATIA system (around 1990).

special force balances had to be designed and manufactured. Propulsion simulation as will be described at page 84 was another area where the design office and workshop were working on the edge of what was technically feasible.

For the NLR directors it was quite clear that a specialized, in-house model manufacturing capability was essential to support the wind tunnels. In the first publication on the HST of 1959 intended for the potential users[48], the capabilities of the workshop were explicitly mentioned. When in 1980 in the Noordoostpolder the large low speed wind tunnel was built together with DFVLR, the German sister institute of NLR, the manufacturing of very large models for this tunnel signalled a new challenge for the NLR model design capabilities. These models are so large that the use of remotely controlled wing surfaces (such as ailerons and spoilers) to speed up the measuring process is cost effective. In 1996, after the bankruptcy of Fokker and the transfer of all wind tunnels to the DNW organisation, the design office and workshop remained as separate departments within the NLR organisation. As in the past, they specialize not only in wind tunnel model design and manufacturing, but in the manufacturing of fine mechanical systems in general where a high precision is required. Outstanding examples are the fabrication of instrumented model propellers, including rotating balances, dynamically scaled rotor heads and blades for helicopter models such as for the NH90 DNW (LLF) wind tunnel model, remotely controlled ailerons and the installation of miniature dynamic pressure transducers in wind tunnel models to measure fluctuating loads on model surfaces. Most of the wind tunnel models to be discussed in the next chapter have been designed and manufactured at NLR. It is fair to say that demands from customers for testing in the high speed wind tunnels PT, HST and SST contributed substantially to these capabilities. Similarly, the NLR capabilities for model manufacturing have stimulated many customers to execute their tests in HST or SST. ■



[2-70]

[Figure 2-70]

The wing of the Concorde with all provisions for pressure tubing.

Contributions to the aerospace industry

GETTING STARTED

A TUNNEL FOR THE DUTCH AIRCRAFT INDUSTRY

Just after World War II the Dutch Government agreed that it was very important to re-establish an independent Dutch aeronautical industry. Already in September 1945 the 'Tromp Committee' (page 11) was tasked to make recommendations as to how the Government could support these intentions and their report appeared in March 1946. In the first years after the War Fokker was involved in the maintenance of military aircraft (such as the North American Harvard Trainer) and refurbishing military DC-3's on behalf of KLM and other airlines. Some years later military aircraft were built under license such as the Gloster Meteor and the Hawker Sea Fury. For new projects the 'Tromp Committee' recommended that Fokker would build military trainers, under contract of the Royal Netherlands Air Force, and a new passenger aircraft financed by the revolving fund of the newly established 'Netherlands Institute for Aircraft Development' (NIV). It was also suggested that Fokker cooperated with other partners, notably in England and the US, for the development of advanced military aircraft. Fokker was also involved in the design and production of an air taxi, the F25 'Promotor'* which however never became a success due to technical and financial problems. The first successful trainer was the Fokker S11 followed by the Fokker S13, a twin-engined bomber/trainer. A prototype was built but before the production could start the American Beechcraft 'Navigator', a similar type of aircraft, was offered by the US almost for free to various European air forces within the framework of the 'Mutual Defence Assistance Act'. It was the time of the Cold War. Fokker also considered a new passenger plane named project P275, intended as a replacement for the DC-3, which would later become the F27. All these new Fokker developments did not require high speed testing. But Fokker had plans as well for aircraft at higher speeds such as the jet trainer S14 and the F26 'Phantom'. This last aircraft was a civil aircraft with jet engines for 16 passengers. A number of design studies for jet fighters may be considered as design exercises for the future Fokker-Republic D-24 Alliance (see page 68). Of these aircraft only the S14 was manufactured. The first ideas for the S14 dated from 1947 and since not very much was known about transonic aerodynamics, information was retrieved from German war reports, notably on the Messerschmitt 262, which had become available through the allied forces[83]. In 1950 wind tunnel tests on a small model of the S14 were made in France at the Institute Aérotechnique at St. Cyr[84] since the HST was not available yet. The model* was also manufactured in France by R. Dupont in Anbervilliers. The tunnel in St. Cyr had an almost circular test section with a diameter of about 1 m. The model was mounted with struts on an external overhead balance. Representatives of NLL visited the tunnel in St. Cyr because the results had to be compared with the low speed data obtained in the LST.

It is interesting to note here that, when between 1945 and 1948 the first ideas on the HST were formulated, there were hardly any Fokker projects that required transonic testing. In the report of the 'Tromp Committee' it was suggested that NLL would look for international co-operation in research, notably with England. This remark foreshadows the active NLL contribution to AGARD, contacts with the French aeronautical industry within AICMA and activities as part of the 'Anglo-Netherlands Co-operation Program' ANCP which was so important for the development of Computational Fluid Dynamics as will be discussed in the next sections.

AGARD, THE ADVISORY GROUP FOR AERONAUTICAL RESEARCH AND DEVELOPMENT

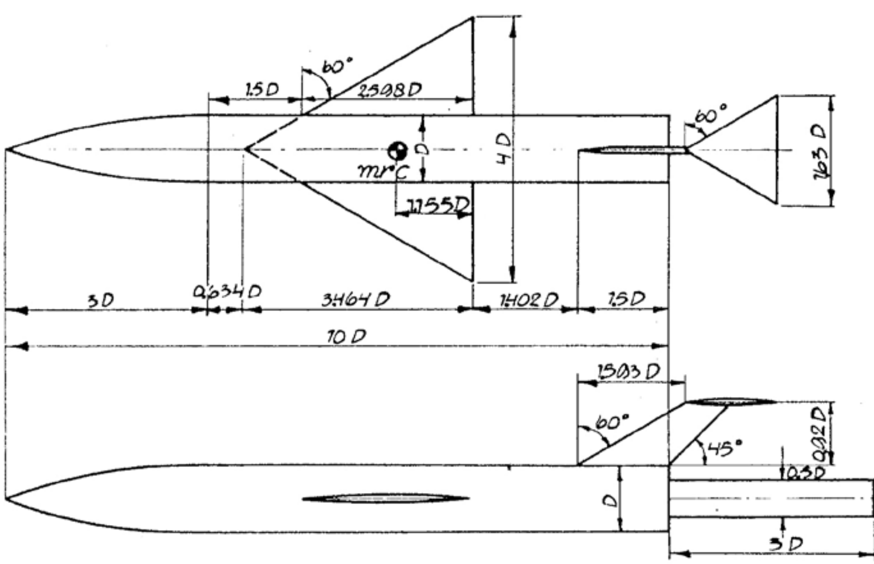
In the Cold War atmosphere after World War II, the 'North Atlantic Treaty Organisation' NATO was set up as a defence alliance for the Atlantic partners. Exchange of research was considered an essential part of this alliance. Theodore von Kármán was a Hungarian scientist who got his PhD under Prandtl in Göttingen and, after emigrating to the United States, became a leading consultant for the United States Air Force on aeronautical technology development. As a member of a special committee he investigated just after the War the German aeronautical achievements. As he stated himself: *'progress in technology was so swift that only a pool of nations could properly utilize scientific advances for mutual protection.'* And he moved decisively to set up a scientific advisory board for NATO which became known as AGARD[85]. In May 1952 the first AGARD general assembly took place in Paris. The Netherlands were represented by Van der Maas (chairman of the NLL Board) and Koning (Director of NLL). An Executive Committee was formed which had its first meeting a week later in London. This committee had five members, one of them Koning. The NLL leadership realised very well that, after five years of isolation during the War, AGARD provided a small country like The Netherlands with the best opportunities to establish scientific contacts abroad. As early as September 1952 the 'Wind Tunnel and Model Testing Panel' (later to become the 'Fluid Dynamics Panel' or FDP) had its first meeting in Farnborough. Van der Maas himself and Dobbinga became the first Dutch members. In May 1954 the fourth general assembly meeting took place in Scheveningen and the audience was welcomed by His Royal Highness Prince Bernard who mentioned in his welcome speech that *'AGARD has grown into something more substantial and important even than optimists originally thought.'* This illustrates the importance attached to AGARD in The Netherlands. And understandably since the concept of the slotted wall test section for the HST was communicated through AGARD as well as many other suggestions and recommendations for test techniques, notably balance design and the concept for the supersonic wind tunnel (see page 42 and 29).

One of the initiatives of the 'Wind Tunnel and Model Testing Panel' was the definition of a number of 'Standard Calibration Models'. The models had a very simple, well-defined shape that could easily be manufactured by each laboratory. The AGARD-B model had

[3-1]

[Figure 3-1]

A very 'shiny' AGARD-C model used to validate the HST; probably end of 1958.



Wing and tail profile: symmetrical circular arc section thickness ratio = 0.04.

Nose profile: length 3D. Equation of curve $r = \frac{x}{3}\left[1 - \frac{1}{9}\left(\frac{x}{D}\right)^2 + \frac{1}{54}\left(\frac{x}{D}\right)^3\right]$.

Radius of nose and wing leading edges should be D/500.

[3-2]

[Figure 3-2]

Drawing of the AGARD-C standard model. The geometry was very simple and easy to manufacture to ensure that each tunnel could make its own model.

[3-3]

[Figure 3-3]

The cover of the contract with AICMA.

[Figure 3-4]

The first wind tunnel test for a customer was made for Sud Aviation on a delta wing configuration named the 'Durandal' SE-212.

a cylindrical fuselage with an ogive nose and a small delta wing. A horizontal tail was added for the AGARD-C model [figure 3-2]. Although slotted tunnel walls were meant to reduce the effects of the tunnel walls, it was not clear at all to what extent they were successful. A comparison of results for one configuration built at different sizes (model scales) and tested in various wind tunnels would give confidence in the results of transonic wind tunnel tests.
NLL manufactured four AGARD-B/C models* with fuselage diameters of 22, 40, 70 and 100 mm. In 1957 the first measurements in the PT of the 40 mm diameter model [see figure 2-17] were reported by Zwaaneveld[49]. The highest tested Mach number was 0.8 since the PT with solid walls could not measure close to Mach = 1. The results were compared with data obtained from AEDC in the US. In 1962 these data were supplemented with results from tests in the recently installed slotted test section of the PT, including tests with the smaller 20 mm diameter model[50].

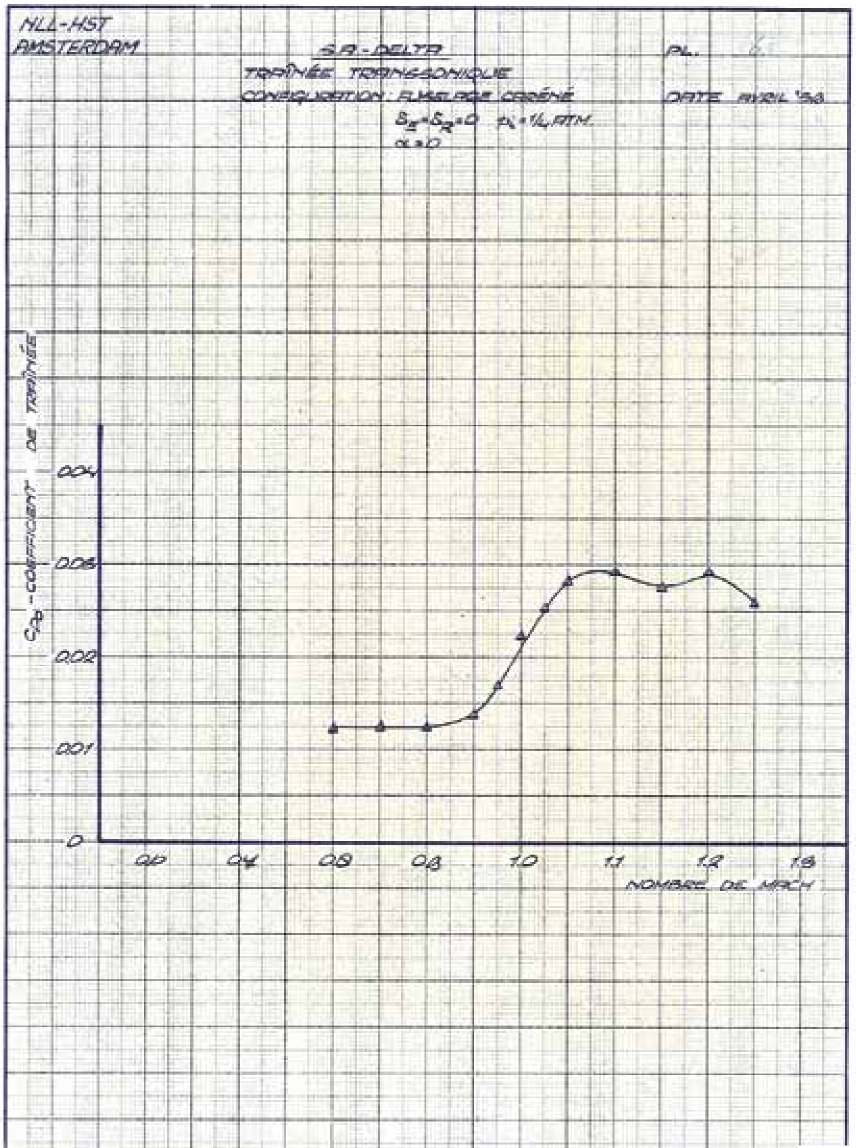
[3-4]

The larger AGARD models were extensively used for the first tests in the HST [figure 3-1] and later in the SST. In fact, NLL got a contract from AGARD to assess the available data for the AGARD-B and -C models tested in many other facilities in the NATO countries. In total three reports were written: for transonic tests on the AGARD-B model[86] (1960) and the AGARD-C model[87] (1961) and supersonic tests on the AGARD-C model[88] (also 1961). Only the second report contained data for the HST. These measurements constituted a very elaborate set of data since all four model sizes were investigated, some of them at different stagnation pressures (Reynolds number). In this way effects of model size (wall interference related) and Reynolds number could be separated. The spread in tests results is great, notably for the transonic drag results. But there is no doubt that this rather unique compilation of test results has stimulated a critical evaluation of the test techniques for all wind tunnels involved and with a specific benefit for the HST.

The importance of the many contacts that were established through AGARD extended far beyond the period of the design and early tests in the HST. Throughout its entire life, hence till 1996 when AGARD and the 'Defence Research Group' (DRG) merged to form the 'Research and Technology Organisation' RTO, AGARD has proved to be crucial for the development of the aeronautical sciences within The Netherlands.

THE AICMA CONTRACT

The HST and SST were built to support the aircraft industry of The Netherlands. But in view of the costs to run a facility as big as the HST it was quite clear that it would be important to attract work from abroad. In the so-called BDM report (see page 17) issued in March 1950 during the stop of all building activities at NLL, an interesting remark can be found. Contacts with Willaume, director of ONERA, the sister institute of NLL in France, revealed that '*the French Government didn't want to build a pressurized high speed tunnel with a test section of 3 m in diameter, since a similar facility was built already in The Netherlands*'. The suggestion was made that the French would be prepared to do their tests in the HST whereas in return the Dutch industry could use the large (atmospheric) transonic facility[X] (9 m diameter) that was almost finished at that time at Modane in France. Of course neither NLL nor the Dutch Government could speak on behalf of Fokker but there were other ways to put the HST on the European map. On the initiative of the Fokker director Vos part of the European aeronautical industry in Europe had organised itself in AICMA, the 'Association Internationale des Constructeurs de Matériel Aéronautique' (England didn't join this organisation). In April 1952 Vos wrote a letter to the NLL director Koning explaining that the AICMA members were favourable to the idea of making national wind tunnel capacity available to all other AICMA members[89]. He asked NLL to send a letter to AICMA to explain the willingness of NLL to accept work from other AICMA members, as was done already for the S1 wind tunnel in Modane. Vos added that he proposed this only now since he was afraid in the past that the Dutch Government would cancel the Dutch wind tunnel plans if such an agreement was in place. The idea of a European arrangement was further elaborated in an AICMA note 'Terms for a contract between a wind tunnel and its users.' ('*Dispositions principales proposées pour l'étude d'un contrat-type entre une soufflerie et les utilisateurs.*'). In March 1954 another Dutch AICMA member, Van de Velde, director of Aviolanda, organised a meeting between AICMA and NLL (Vos had passed away). At that time a subcommittee within AICMA, the 'Permanent Wind Tunnel Committee' or C.I.S.P. ('*Comité International Permanent des Souffleries*') had inquired among the AICMA members which facilities would be needed. As a result of this inquiry two types of facilities were proposed: a transonic tunnel with test section dimensions of 2.10 x 2.80 m^2 (0.85 < Mach < 1.4) and a supersonic tunnel for engine studies at Mach = 3 with a test section of 2.80 x 3.00 m^2. For the latter facility a pilot tunnel was envisaged. However, it was far from clear how the cost sharing between the AICMA members had to be arranged. Van der Maas, who participated in this meeting on behalf of NLL, of-



[3-5]

fered 'just on time' the willingness of NLL to take all costs for the transonic facility, provided that '*NLL would not be deprived from its soul*'[90]. Although NLL even shortly considered the possibility to build a supersonic 'engine tunnel' with test section dimensions of 1.5 x 1.5 m^2, the offer of a transonic facility with a test section of 1.6 x 2.0 m^2 was already sufficiently attractive for AICMA to start more detailed negotiations for a contract. The basic elements of this contract were that NLL reserved 50% of the HST tunnel time for AICMA members with a minimum occupancy of 10% guaranteed by AICMA. The tariff structure was based on depreciation over ten or twenty-five years for the installations and the buildings respectively, whereas the exploitation costs were based on 250 occupancy days. Non-AICMA members had to pay an extra 10%, whereas AICMA members obtained a preferred right to test in the remaining 50% testing time (this was explained as 'a right of first refusal'). The negotiations progressed rapidly and on February 23, 1955 the contract was signed [figure 3-3]. Practical details had to be arranged later in a specific agreement ('*Réglement*'). In September 1955 AICMA asked when the first test could be done, since many AICMA members showed interest. Van der Maas answered that the first tests could be made at end of 1956, a rather optimistic view. In February 1956 Boelen, the adjunct NLL director, informed Van der Maas about serious problems with nearly all aspects of the construction of the HST and he concluded that the opening of the HST at the end of 1956 had to be ruled out. AICMA was informed of this new situation on March 12, 1956 and an expected introduction was now foreseen in the spring of 1957. Only a couple of days later NLL had to inform Van der Maas of a new delay, announced by Werkspoor, the contractor for the HST.

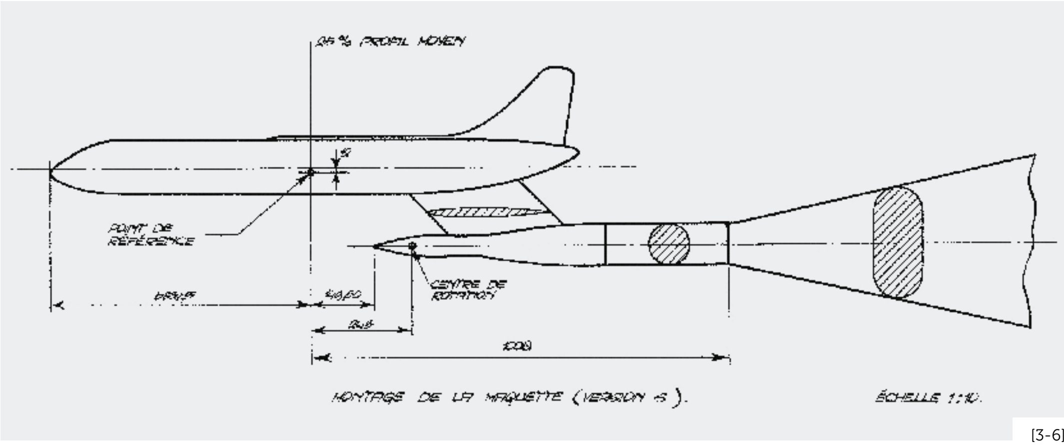
Against this background the notes by Boel of April 15, 1956[40,41] have to be understood. These notes (discussed in more detail on page 23) analyse in a systematic way the lack of progress in building the HST and in developing the required equipment. Even the date of spring 1957 was far too optimistic, since it was not until March 1959 that the first tests for AICMA[91] were made on a delta wing configuration named the Durandal SE-212 [figure 3-4]. The first flight test for this interceptor had been made in 1956 and the development by Sud-Aviation had already been terminated in 1958. For these reasons this configuration was probably a good candidate for comparison with flight test results and other wind tunnel data, notably results obtained in the 4 x 3 ft transonic wind tunnel of Cornell Aeronautical Laboratory in the US for Mach numbers between 0.8 and 1.25. The forces were measured with a NLL balance (AE1013 [see figure 2-22]). These tests clearly showed the typical drag-increase around Mach = 1, illustrating convincingly that the HST with its slotted wall test section was fully capable of transonic wind tunnel testing [figure 3-5].

In about the same period (also March/April 1959 with a second tunnel entry in July) a model of the Caravelle, scale 1:25, also of Sud-Aviation, was measured[92,93]. These tests were made with 2½" and 2" TASK balances and the results could be compared with data from the 12 x 8½ ft wind tunnel of Cornell Aeronautical Laboratory in the US and the S1 tunnel in Modane, France. The model was supported in the HST by a straight sting and a so-called Z-sting [figure 3-6], a sting support that later became a standard in the HST, also for Fokker tests. Tests in the HST were made with and without the horizontal tail [figure 3-7] and, as noted by Van der Zwaan, Sud-Aviation was very pleased with the results since for the first time the drag increase due to the horizontal tail could be measured systematically[94]. Not without reason Mr Adenot mentioned in his opening speech in January 1960 '*it is good to underline the good results obtained*' ('*il est bon de souligner à l'occasion les résults heureux obtenus*'). Many more tests on the Caravelle followed in later years [figure 3-8].

[Figure 3-5]

The drag measured on the Durandal presented in the first measurement report of the HST. One can clearly see the drag increase when entering the 'sound barrier' Mach = 1.

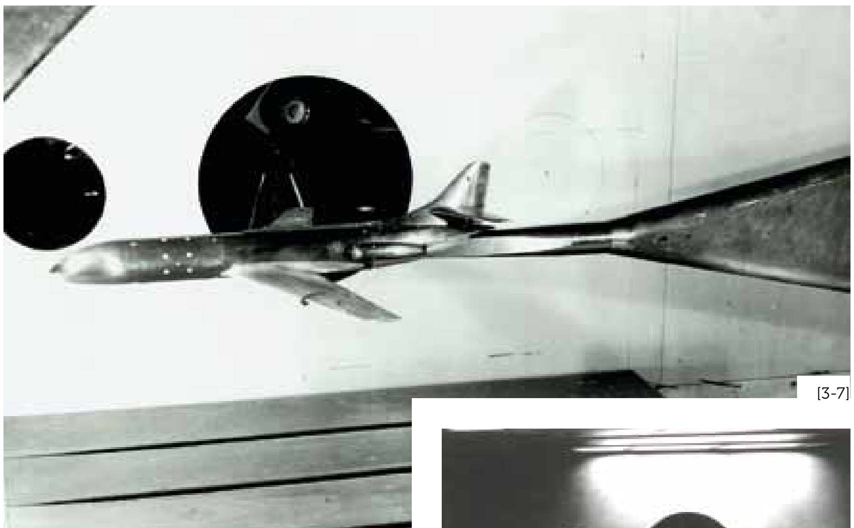
[x] THIS TUNNEL, THE S1 IN MODANE, WAS JUST AFTER THE WAR TAKEN FROM GERMANY WHERE IT WAS ERECTED IN THE ÖTZTAL NEAR MUNICH AS PART OF AN AERODYNAMIC RESEARCH CENTRE TO REPLACE THE WIND TUNNEL FACILITIES AT PEENEMÜNDE THAT WERE TOO VULNERABLE FOR ALLIED BOMBING.



[3-6]

[Figure 3-6]

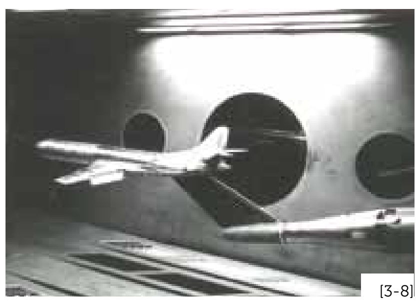
Drawing of the Sud Aviation Caravelle model on the so called 'Z-sting'. This sting type became one of the standard support configurations generally with the sting under a small pre-set angle. Note the 'area ruling' on the sting.



[3-7]

[Figure 3-7]

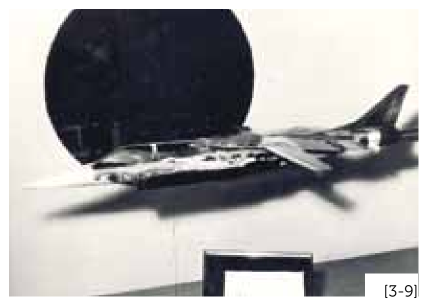
Photograph of the model of the Caravelle, tested in April 1959 in the HST.



[3-8]

[Figure 3-8]

The first AICMA tests on the Caravelle were followed by numerous test campaigns in the period between 1959 and 1964. The photograph shows the aircraft in landing configuration illustrating the Reynolds number capability of the HST for low speed research in addition to tests in the transonic regime.



[3-9]

[Figure 3-9]

The Fokker D-24 'Alliance' in the HST with the wings extended.

models could be used for this purpose. The first comparisons of the AGARD model were made with results from tests at AEDC and indicated a very acceptable agreement[87]. An impressive agreement with another wind tunnel was obtained from comparative tests on the Fokker/Republic D-24 Alliance [figure 3-9], which was also tested in the 8 ft transonic wind tunnel of NASA Langley. Van der Zwaan recalls[94] that NASA stated that there were only two good transonic wind tunnels: the 8 ft tunnel of NASA Langley and the HST! Apparently Fokker/Republic agreed that NLR was allowed to make a publication with some results[96].

For rockets or launcher-type models a comparison with free flight data could be made for the MO-3 configuration. Since 1954 NLL had been involved in launches of small rockets in co-operation with the Royal Netherlands Army. There was also an interest in getting free flight data in the transonic regime in view of the expected problems around Mach = 1. The first field tests were made near Petten (on the Dutch coast) on the NACA RM-10 configuration (also adapted as an AGARD standard model). This configuration was followed by the MO-3 [figure 3-13] which had its first launch in 1960, now on the coast of the island of Texel. Wind tunnel tests in the HST were made in 1963 [figure 3-12] and a comparison with flight test data was reported in 1965[97]. It is possible that the experience obtained with these tests has contributed to the involvement of NLL in the ELDO development a couple of years later.

In spite of these favourable results, AICMA used the delay in the availability of the HST (originally promised in the course of 1956!) to change the contract with NLL. The guaranteed minimum occupancy was reduced from 10 to 5%. However, the duration of the contract was extended from February 1962 till June 1964.

French companies were not the only ones to make measurements in the HST under the umbrella of the AICMA contract. German companies (such as Bölkow and HFB or Hamburger Flugzeugbau) and Italian companies (FIAT) did measurements as well. The contract with AICMA lasted till June 1, 1964 and was not extended. In fact, there was no reason to do so. The AICMA tariff was kept after that period and there was no reason to give the HST a preferred status. The S-2 transonic wind tunnel of ONERA, with test section dimensions similar to the HST though equipped with perforated instead of slotted walls, provided a French alternative for Sud Aviation as well as for other aircraft companies. But the AICMA contract had resulted in excellent relations with the European industry as noted in the Annual Report of NLR in 1964.

OTHER COMPARISONS

As early as April 1959 a note on the first test results of the HST, summarising the tests on the AGARD-C model, 'Avion I' (the Caravelle) and 'Avion II' (the Durandal) was issued[95]. However, the results of the comparisons with other test results for the Durandal and Caravelle configurations were not communicated (officially) with NLL and consequently it was not possible to share these results with other potential customers as a proof of quality for the HST. The data obtained with the AGARD-B and -C

EARLY WORK ON WIND TUNNEL CORRECTIONS

A comparison with other test data is not the only argument to convince customers of the quality of a wind tunnel. At an early stage theoretical calculations were made for two of the most important wind tunnel corrections: wall interference and support interference.

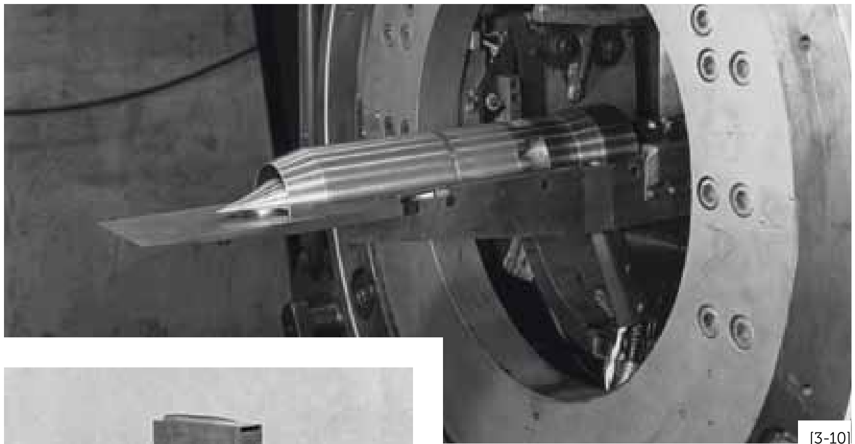
Y AROUND 1960 THE EGYPTIAN PRESIDENT NASSER STARTED A MISSILE AND FIGHTER DEVELOPMENT PROGRAM IN EGYPT AND HIRED GERMAN SCIENTISTS (E.G. EUGEN SÄNGER) TO THIS END. THE ISRAEL SECRET SERVICE ACTIVELY SABOTAGED THESE ACTIVITIES BY KIDNAPPING PEOPLE AND MURDER ATTEMPTS. SEE 'DER SPIEGEL', NO 19 (1963).

The flow over a model in the confined space of a wind tunnel differs from the flow in free air. Such differences are caused by 'wall interference' and there has always been an interest to estimate the magnitude of these effects from calculations. Wall interference calculations were reported by Loeve[98] prior to the opening of the HST in a report that was published in November 1959. In his approach the model is represented by 'singularities' (mathematical elements that jointly describe a particular aerodynamic shape) and the slotted tunnel walls are modelled with a so-called 'homogenous boundary condition' (an evenly distributed out- or inflow at the slotted walls depending on the local pressure difference). In the report a (unclear) reference is given to work of Davis and More and to work done in 1957 at AEDC in Tullahoma in the US by Chen and Mears (AEDC TR 57-20) and Göthert (AEDC TN 55-56). In the latter report values of practical interest are deduced for the so-called 'permeability factor', a constant that describes the specific wall characteristics in relation to the slot geometry. These calculations have been used to determine the optimal slot width for the HST after it was decided to modify the original Dätwyler & Hausammann test sec-

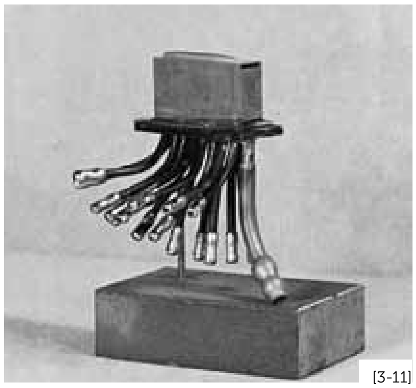
[3-12]

tion (see page 24). The method provided estimates of both blockage (Mach number) and angle of attack interference corrections and is truly impressive, given the uncertainty in transonic wall behaviour at that time.

The second important correction is related to support interference, the effect of the model support on the flow over the model. Spee used the method of singularities as well to calculate the support interference for a straight sting support[99]. The disturbance at the model location in magnitude and direction of the flow velocity at the model centre has been calculated and compared with measurements. It is concluded that the interference effects are small and suggestions are made to decrease these disturbances even more by decreasing the cone angle.



[3-10]



[3-11]

Both examples indicate that from the very beginning a theoretical approach to tunnel corrections was pursued, an approach that was feasible since theoretical work on transonic aerodynamics had become an essential part of the activities of the newly established Transonic Section ('*T-sectie*').

THE FIRST SUPERSONIC TESTS

Erdmann made the very first wind tunnel tests at supersonic speeds in the small '3x3' supersonic wind tunnel (page 15). Just before he left NLL in 1951 to work in Sweden Erdmann wrote a report[100] summarizing the main characteristics of this facility including some examples of wind tunnel tests. One of the models described was a tiny half model of a V-2 [figure 3-11], a model too small to make useful measurements. Useful supersonic tests could only be made after the CSST and SST were operational.

In 1961, as mentioned before, NLL was involved in the analysis of test data obtained with the AGARD-B and -C models in various supersonic wind tunnels[86,87,88]. At that time the SST was not ready yet. The AGARD configuration was of course measured later and a detailed analysis of the drag results was reported in 1964[101].

The first measurements in the CSST took place in 1962 when this tunnel was just about ready. It was an order from the English Company Hawker Siddely for intake tests at Mach numbers as high as 6[102]. The test was not a success since the tunnel could not be started with the model installed at the highest Mach numbers. It triggered the development of an ejector to extend the operational envelope. From a technical point of view a second measurement campaign in August 1963 was more successful. The tests were related to pressure measurements on a side-inlet configuration [see figure 3-10] for a Swiss firm 'Motoren, Turbinen und Pumpen A.G.', located in Zürich[103]. It soon became clear that this firm worked for an Egyptian company, staffed by German engineers[Y] and these contacts were discontinued.

In 1963 the SST got really good exposure in comparative tests with two other European wind tunnels, the S-2 from ONERA and the supersonic tunnel of BAC (British Aircraft Corporation, later British Aerospace) in Preston. The SST came out as the best facility, partly because of the high data rate of the SST. This was the result of a further development of the SADIST (see page 52), a data acquisition system jointly developed for the HST and SST and extended for the SST with a memory unit that could store 4,000 quantities in the limited time of a test run. Due to this favourable comparison the SST was selected for measurements on the Concorde as well as for the development of the ELDO launcher. One of the requirements for these tests was that NLR mastered the technique of boundary layer transition detection (the point where the boundary layer changes from a laminar to a turbulent state[94] (page 58)). ■

[3-13]

[Figure 3-10]

One of the first models tested in the CSST in 1962: pressure measurements on a side inlet configuration for the Swiss firm MTP. This company appeared to work under cover for an Egyptian company and the tests were not continued.

[Figure 3-11]

A half model of a V-2 mounted on a block for tests in the small '3x3' supersonic wind tunnel.

[Figure 3-12]

Model of the MO-3 tested in 1963 in the HST. The results of the test have been compared with free flight data obtained by NLL in 1960 on its test range in Texel.

[Figure 3-13]

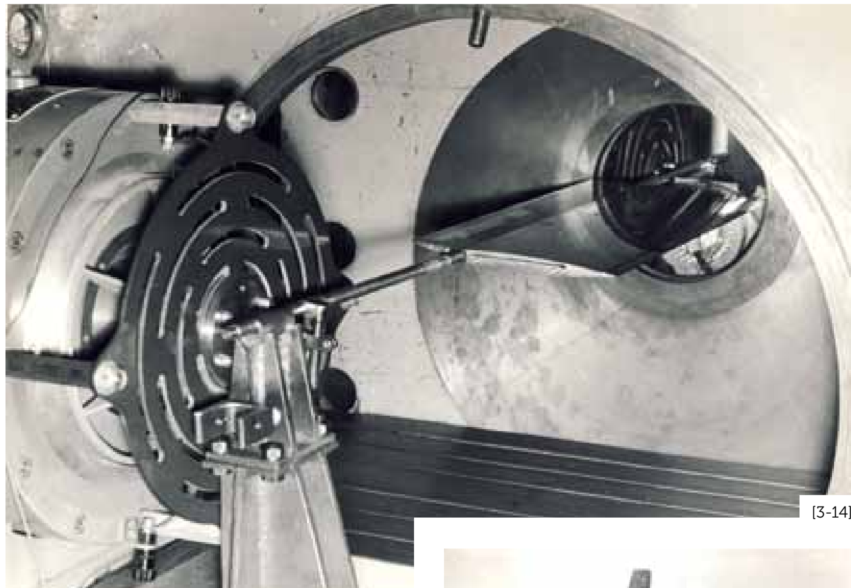
Around 1960 NLL launched a number of sounding rockets as a test bed for telemetry and guidance systems. Another objective was to compare the aerodynamic characteristics between wind tunnel and flight in the so difficult transonic regime.
This photograph shows the MO-3 rocket. A scale model was tested in the HST in 1963.

THE FIRST 15 YEARS OF HST AND SST

A VERY HEAVY WORKLOAD

The new tunnels were extremely busy in the sixties. The high workload resulted from a combination of work for Fokker (the already mentioned D-24 Alliance and the Fokker F28) and external orders (predominantly for Caravelle, Concorde and the ELDO launcher). The Annual Report of 1963 notes that the productivity of the HST needs to be increased urgently. During certain periods personnel had to work 12 hours a day. The neighbours of NLR started to complain over the noise that the tunnels generated and an isolating building around the circuit was considered. Such a building was built in 1966 (see page 26 and figure 1-38). The high work load is also reflected in the data taken from a graph in the Annual Report of 1966 [figure 3-16] which proudly indicates the growth in income after 1960 mainly from wind tunnel work for the F28 development and contracts from abroad for Caravelle, Concorde and ELDO.

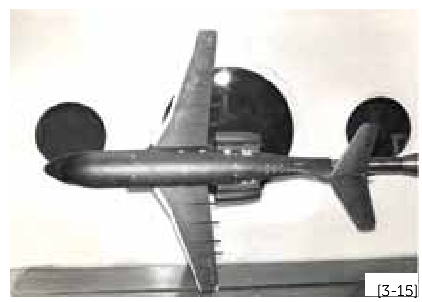
This high work load had to be combined with important additions to the measuring capabilities. At the opening of the HST in 1960 only a very simple model support was available, the so-called 'straight support boom' that could be used in combination with the 'straight sting' or the 'Z-sting'. The data acquisition system was hardly automated and this necessitated a large number of people in the control room during the measurements. There were clear ideas on how to improve the situation but till 1960 running the facility itself had the highest priority. After that, and parallel to all wind tunnel testing for customers, a significant effort was made to increase the productivity and to extend the measuring capabilities. In 1961 the 'subsonic model support' (a sting that protruded from the lower tunnel wall), a 'ground plane' (to measure low speed configurations in ground effect) and provisions for 'half model mounting' (for tests with big half models to increase the model Reynolds number) were introduced. The 'yaw support boom', required to measure models in side slip, followed some time after this. Till that time yaw or side slip could only be simulated with (a number of fixed) cranked stings or by rotating the model over 90° such that the angle of attack mechanism could be used for a continuous yaw variation [see figure 3-15]. The new yaw support boom allowed simultaneous variations in angle of



[3-14]

[Figure 3-14]

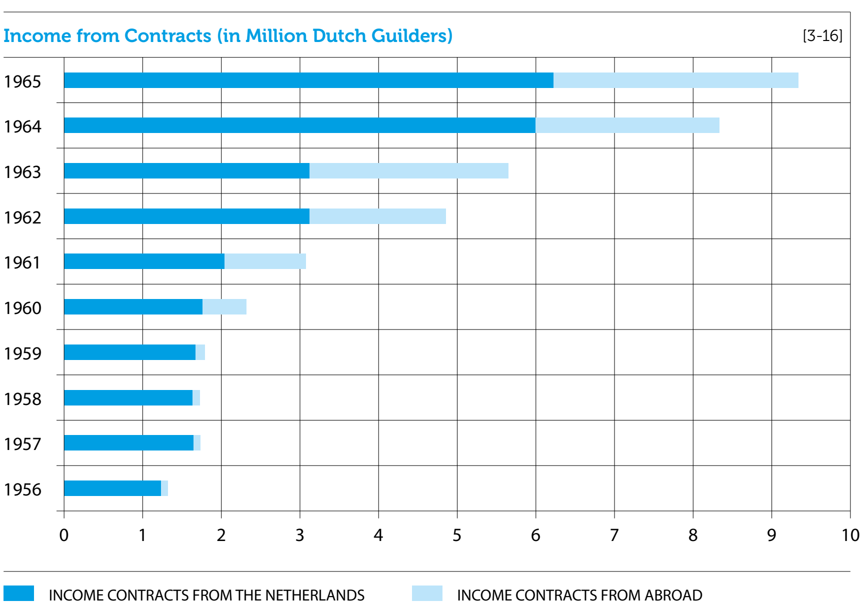
A two dimensional model mounted in the test section of the Pilot Tunnel (PT), visible through the open door. The PT was used extensively by Fokker in the early sixties to develop a suitable transonic airfoil for the F28 wing.



[3-15]

[Figure 3-15]

Model of the F28 in side slip. Since the yaw support boom was only introduced in 1963, the model had to be rotated over 90° to use the incidence mechanism for yaw variation. Picture probably taken around 1962.



[Figure 3-16]

Data taken from the NLR Annual Report 1966 indicating the income from national contracts and from contracts abroad. The growth after 1960 is mainly due to wind tunnel testing in HST and SST (notably Fokker F28, Caravelle and Concorde).

attack and yaw angles. The automatic data acquisition system 'SADIST' was introduced in 1963 together with the introduction of scanivalves that replaced the very time consuming and elaborate use of the multi-manometer (see page 52). A significant increase of productivity was the result.

The staff required to do the tests was another problem. Boel noted already in 1956 in his confidential note to the NLL Direction[41] (page 23) that it was difficult to acquire good engineers and that NLL should make the work more attractive. He advocated that university graduates should be much more involved in discussions of the NLR 'Workplan' '*to give them the feeling that their work was useful*'. And he noted that NLR '*had a negative image among the wives of the young graduates since there was no support to assist in finding suitable housing*' (there was a shortage in housing at that time). Nevertheless, he managed to attract a group of very capable graduates from Delft that were involved in all aspects of transonic aerodynamics: theoretical work, the development of test techniques and also the wind tunnel testing for customers. Some of them got international recognition for their theoretical work or got leading positions in the NLR organisation and quite a few later became professor at a university. The heavy work load in the mid sixties necessitated that test engineers were even hired before their graduation from the Department of Aeronautical Engineering in Delft. They got the title of 'candidate engineering graduates' ('*adspirant ingenieurs*') and worked for a salary a bit less than that of a graduated engineer, though with the promise that they could devote part of their time to writing their master's thesis.

FOKKER-REPUBLIC D-24 'ALLIANCE'

The Fokker-Republic D-24 Alliance was a joint project between Fokker and the Republic Aviation Corporation in the US. The interest on the part of Republic to work with Fokker was motivated by the fact that 'The Netherlands Air Force' was looking for a replacement for the F-84 fighter/bomber. The D-24 was an answer to a NATO tender for a supersonic VTOL interceptor. With its VTOL capability and movable wings it was far too advanced and the project didn't last long. A D-24 configuration was tested in 1962 in the HST with straight and swept-back wings [figure 3-9]. Since the same configuration was also tested in the NASA Langley 8 ft tunnel, a comparison could be made for both configurations which came out extremely well[96]. These tests also triggered the development of jet simulation based on the decomposition of H_2O_2, a technique that was known in the US. Since the development of this technique for engine simulation took more years than the D-24 project lasted, the technique was used many years later in a joint project with Airbus and later for noise reduction studies for Fokker in the small acoustic wind tunnel KAT.

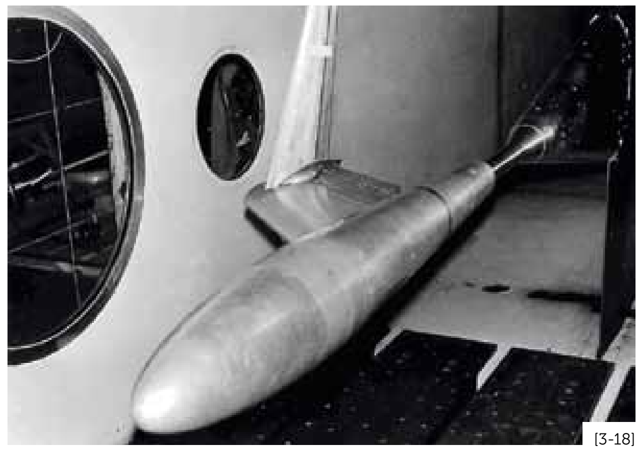
FOKKER F28 DEVELOPMENT

A much more important and successful project was the development of the Fokker F28 'Fellowship'. The first pre-design studies for this successor of the F27 'Friendship' date from 1961 and the first tests on two-dimensional transonic airfoils were made in the PT in the beginning of 1962 [figure 3-14]. Also in 1962 a comparison was made in the HST between straight and swept wings to mitigate the transonic effects. Many more tests followed, notably between 1962 and 1965.

Figure 3-19 shows the distribution of wind tunnel testing hours for the F28 development in LST, PT and HST respectively. In the beginning of the project the tests in the HST were mainly related to the optimization of the wing plan form and the profile shape. The effect of various modifications of the wing nose on the (transonic) drag characteristics was investigated in much detail to obtain the optimal wing shape by trial and error. Subsequent investigations were concerned with Reynolds number effects on low speed stall and the effectiveness of flaps, ailerons and rudders. These tests were made with complete 'full' models scale 1:20 [figure 3-17] and large-scale partial models such as a 1:12 scale half model [figure 2-56] and a 1:10 scale model of the tail [figure 3-18].

The development of a transonic wing was a challenging exercise. Fokker had obtained its first experience in the transonic flow regime with the development of the S14 mili-


[3-17]

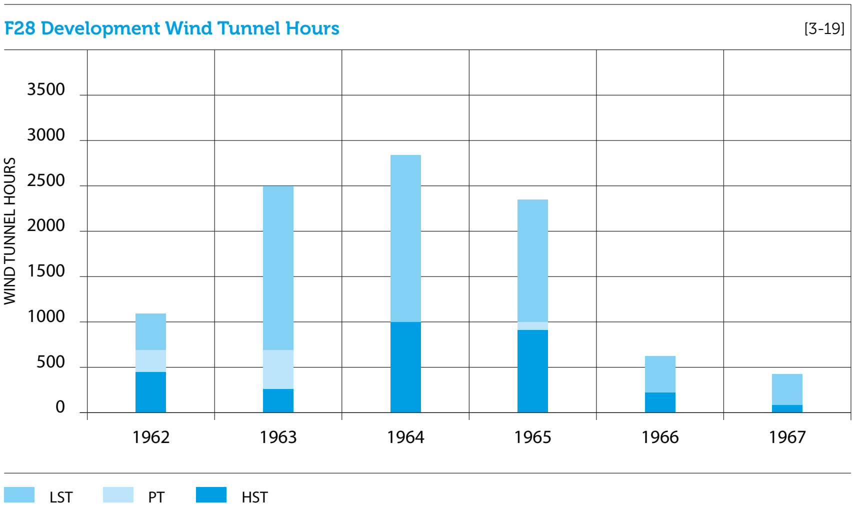

[3-18]

[Figure 3-17]

Model of the F28 in landing configuration.

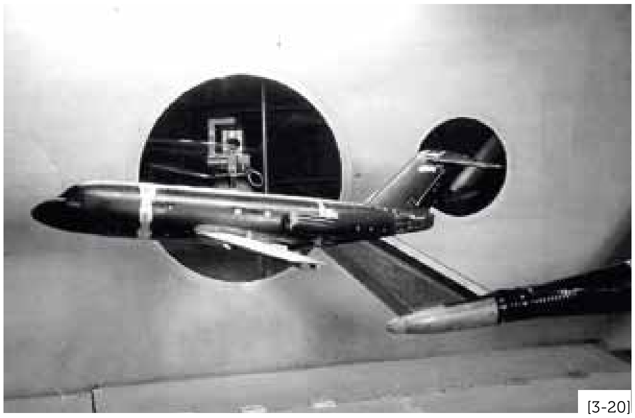
[Figure 3-18]

The rotated tail model of the F28 to study the rudder characteristics in side slip.



[Figure 3-19]

Distribution of wind tunnel hours for the F28 development.



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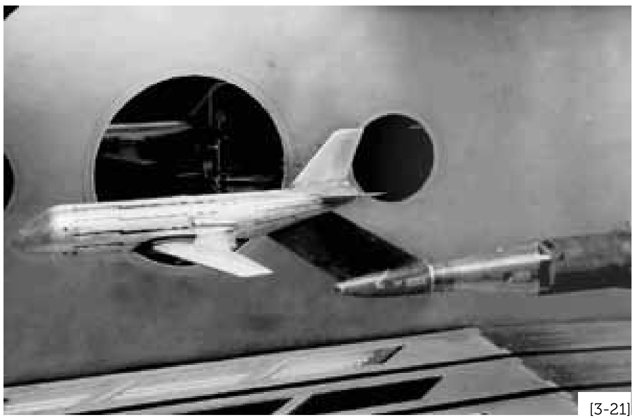


[3-21]

[Figure 3-20]

Model of the FH-228 in the HST around 1968; this was a shortened version of the F28 intended as a co-production with Fairchild-Hiller.

[Figure 3-21]

VFW-614 pressure model in the HST (around 1966).

tary trainer, tested in the wind tunnel of St. Cyr in France in 1950 (page 65). During the F28 development many different wing configurations were tested in the HST and the best one was selected and used as a starting point for further developments. In the NLR Annual Report of 1963 it is remarked that the calculation of wings for transonic conditions is still very problematic, '*notably the prediction of the position and strength of the shock waves*'. It is argued that in this speed regime a close interaction between theory and experiment is necessary.

In an internal report[104] of June 1966, so at the end of the F28 wing development, the question was raised again if theoretical calculations could be used to assist the optimization process of a transonic wing. The application of the so-called 'Weber-Küchemann method' for the calculation of the wing pressure distributions appeared to be rather successful. The lifting surface theory of Multhopp provided a reasonable prediction of the lift distribution as well (see page 76). An attempt was made to modify the nose section of the wing to obtain a so-called (supercritical) 'peaky pressure distribution'. The attempt was not successful, but it reflects an ongoing development within NLR at that period: the development of 'shock free supercritical airfoils' by Nieuwland (see page 76). However, in 1966 it was far too early to exploit the benefits of the 'supercritical wing technology' in favour of the F28 development. Nevertheless, in the above mentioned report some recommendations were given to improve the drag characteristics based on a comparison between the measured and calculated wing pressure distributions. As such it marks the beginning of a development in which the wing shape is derived primarily from calculations and in which the wind tunnel is used to verify these designs for all conditions within the flight envelope.

In 1968 also a derivative of the Fokker F28 was tested: the Fairchild-Hiller FH-228 [figure 3-20]. Following an agreement with Fairchild-Hiller on the production of the F27 and a stretched version of the same aircraft for the US market (the FH-227), a similar deal was discussed in 1967 for the F28. In this case, however, the idea was to shorten the F28. This program was dropped because the commercial prospects were not good.

VFW-614

In 1961 Weser Flugzeugbau, Focke-Wulf and Hamburger Flugzeugbau merged to form the Vereinigte Flugtechnische Werke VFW. These three companies were already engaged in the development of a 40 to 44-seat passenger plane with short take-off performance. Go-ahead was given in 1968 and the development continued in 1969 when Fokker and VFW merged. The wind tunnel program in the HST was executed under supervision of VFW. Three models were made: a force-model*, a pressure model* [see figure 3-21] and a half model. During flight tests problems with tail flutter were encountered which caused the loss of one test aircraft. The VFW-614 was certified in 1974 but didn't become a commercial success and the production was terminated in 1977 after the delivery of 16 aircraft.

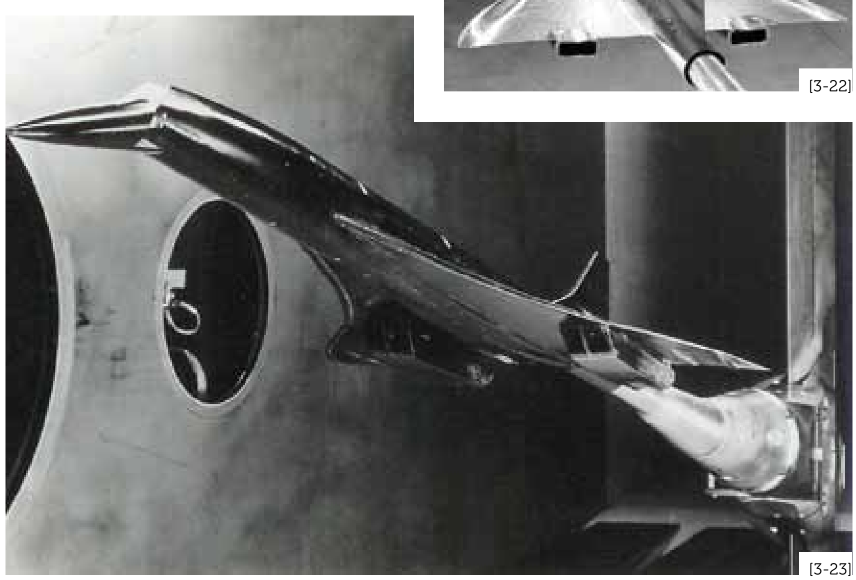
CONCORDE

On November 28, 1962 the British Aircraft Corporation and the French Company Aérospatiale signed a draft agreement on the common development of a supersonic transport aircraft. The construction of the two prototypes started in 1965 and the first flight took place in 1969. French and English wind tunnels were of course heavily involved in the development of the Concorde, but the NLL wind tunnels played an important role as well. The first test in the HST was made by Aérospatiale in 1963, the first tests in the SST in 1965 following comparative tests between the ONERA S-3 and the BAC supersonic tunnel in Preston. These tests initiated a very intensive test campaign that lasted till 1975. Many models with various scales (e.g. 1:45, 1:60 and 1:75) were tested. The HST was also involved in low speed tests [figure 3-23] including oil flow studies [figure 3-22] partly due to its good Reynolds number capability. The SST

[3-22]

[Figure 3-22]

Oil flow picture of the Concorde taken during low speed tests; traces left by oil flow show the surface stream lines, indicative of the flow development on the wing.

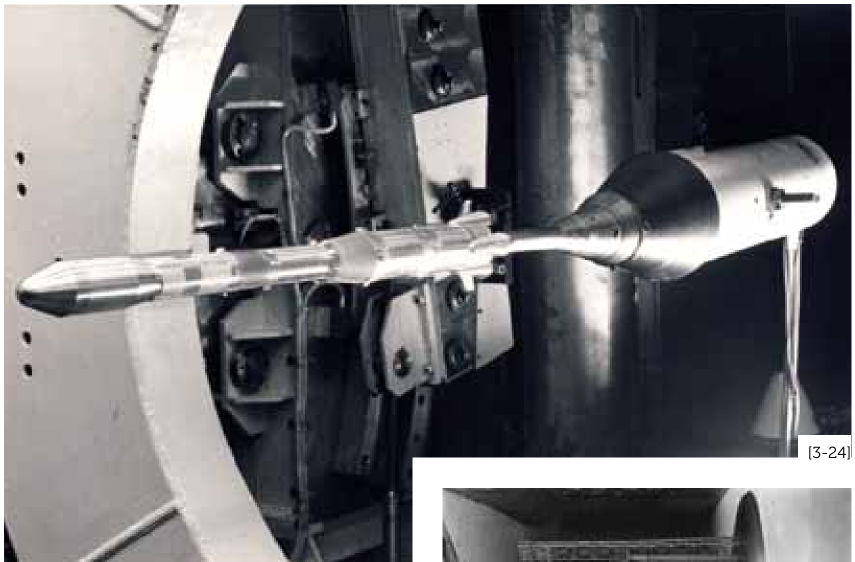


[3-23]

[Figure 3-23]

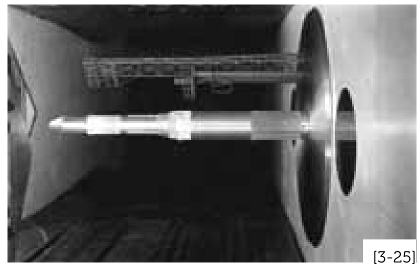
Low speed tests of the Concorde in the HST (around 1965).

was selected because of its productivity and the high quality of the drag measurements. Since the Concorde had a problem with its range due to a higher than expected drag, many investigations followed in the SST [figure 3-27] to investigate means of reducing the drag. The optimal position of the pitot-static reference tube on the nose* of the Concorde was derived from tests in the SST (*'anémomètre'* tests). Tests in the HST, SST and CSST were also made to measure the mass flow through the engine inlets, the so-called *'débitmètre'* tests [figure 3-29]. During this period from 1962 till 1975 the Concorde was tested for 1200 (!) days, about one-third in the HST and two-third in the SST. This illustrates very well the importance of the Concorde for the exploitation of the new wind tunnels.


[3-24]

EARLY WORK ON LAUNCHERS: THE ELDO PROGRAM

In 1960 England and France started discussions on a European co-operation for the development of rocket launchers to bring a pay-load into orbit. In April 1962 these discussions resulted in the signing of a Convention between England, France, Germany, Italy, Belgium, Australia and The Netherlands to establish the 'European Launcher Development Organisation' ELDO. The first wind tunnel tests in the HST for ELDO were performed in 1962 and these tests were followed in 1964 by tests in the SST. During the ELDO development program NLR was given the 'Aerodynamic Authority for Aerodynamics'. Erdmann himself, with his background in Peenemünde (between 1939 and 1944 involved in the stability and control of the V-2 and the anti-air rocket 'Wasserfall'; Appendix D) was of course an expert on rocket aerodynamics (see also [105]). It is not clear if this played a role in the decision to give NLR the aerodynamic authority. But the good flow quality and the high data rate of the tunnels certainly were of crucial importance. The wind tunnel measurements consisted of various types of tests. Force measurements for 'stability and control' were done both in the HST [figure 3-28] and the SST for Mach numbers up till 4. The Flutter Section (the *'F-sectie'*, later the Department of Aeroelasticity AE) was involved in the measurements of the unsteady loads on the surface in area's of flow separation [see figure 3-30] whereas unsteady loads due to the wind on the launch platform were measured in the HST [figure 3-25]. In the latter case a more fundamental study was launched around 1970 of the unsteady flow over a cylinder at high Reynolds numbers [figure 3-26]. Another department of NLR was responsible for the 'Attitude Reference and Program Unit' during the EUROPA-I development, an activity that required a detailed knowledge of the aerodynamics, knowledge that was close at hand.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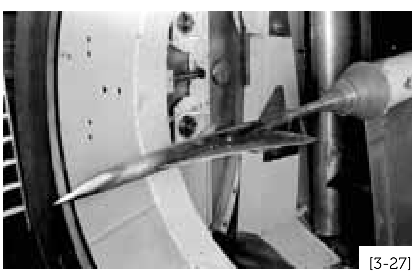
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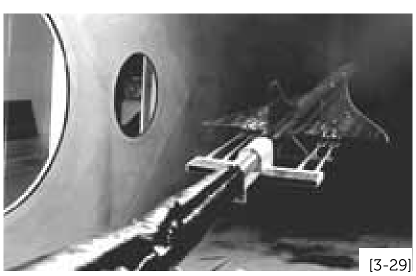
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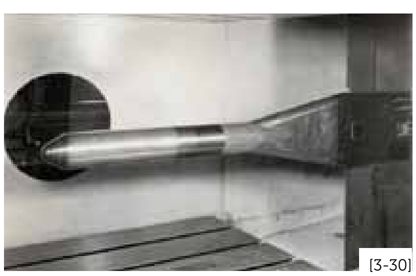

[3-30]

In 1973, due to the rather poor performance of ELDO (there was no completely successful launch between 1962 and 1973) ELDO and ESRO merged to become the 'European Space Agency' ESA. The EUROPE-III configuration of ELDO became the basis for the first ARIANE launcher, ARIANE-1 [figure 3-24]. However, the specific relation between NLR and ESA, built upon the expertise for 'stability and control' and 'unsteady measurements' remained till the ARIANE 5 development in the nineties and beyond.

[Figure 3-24]

One of the first ARIANE models in the SST. The configuration is similar to the last ELDO configuration (EUROPA-III). Test made around 1973.

[Figure 3-25]

The ELDO model with the launching tower used to measure the loads on the launching platform due to winds (1964).

[Figure 3-26]

A fundamental study for ELDO of the unsteady loads on a cylinder at high Reynolds numbers (around 1970).

[Figure 3-27]

A model of the Concorde in the SST. The high Reynolds number and the excellent flow quality enabled detailed drag evaluation studies.

[Figure 3-28]

The ELDO-A (later named EUROPA-I) in the test section of the HST (around 1964).

[Figure 3-29]

Set-up with pressure rakes to measure the flow through the nacelles to optimise the inlet configuration (*'débitmètre tests'*).

[Figure 3-30]

One of the first tests for ELDO to study the pressure fluctuations in the region just downstream of the nose cone (around 1963). Note the short 'old' wooden slats mounted in the test section that were replaced around 1964.


[3-31]

[Figure 3-31]

A very early test of the Airbus A300 in the HST (February 1968). Note the tail that differs substantially from the final configuration.

[Figure 3-32]

Model support interference is an important issue in wind tunnel testing. On this 1:38 scale model of the Airbus A300, mounted on the so called subsonic sting, the interference effects of a dummy Z-sting are investigated.

[Figure 3-33]

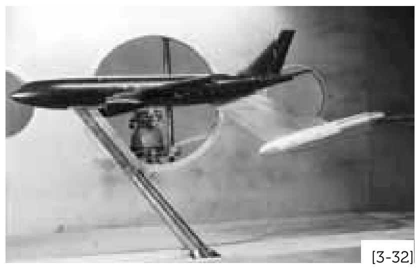
The Dassault Mercure tested in 1971.

[Figure 3-34]

The SAAB Viggen tested in 1979.

AIRBUS

Airbus was formally established in December 1970 as a co-operation between aircraft industries from France, Germany and England, joined later by Fokker-VFW and CASA in Spain. However, Sud Aviation started the development of the Airbus A300 as early as 1967. In view of the very intensive contacts between Sud Aviation and NLR for the Caravelle and the Concorde, one of the first versions of the Airbus A300 was measured in February 1968 in the HST [figure 3-31]. Wind tunnel tests continued since that time and a very fruitful relation with Aérospatiale (following a merger between Sud Aviation and Nord Aviation) resulted, leading to co-operation on specific topics such as support interference and engine simulation. Since economy in cruise (to lower the fuel costs and to increase the range) was one of the key issues for a new transport aircraft an accurate prediction of the drag was very important. Support interference introduced an unknown effect that had to be quantified. In support interference tests the model was mounted on the 'subsonic sting' (or 'ventral sting') and the difference in drag was measured by placing a dummy model support (representative of the usual model support) close to the model, but not touching it [figure 3-32]. These measurements were accompanied by theoretical calculations with the NLR 'panel method' (see page 78) in which model and support could be accurately modelled. The simulation of the engine jet was another crucial issue. Since NLR had invested considerably in jet simulation with H_2O_2, both parties had an interest in applying this technique


[3-32]

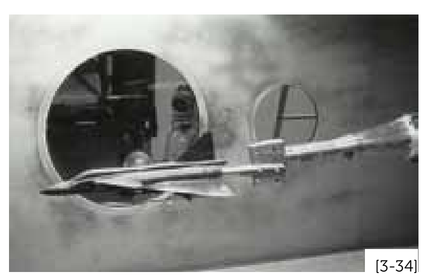
for a transport type aircraft [see figure 3-57]. This rather complicated technique was later abandoned in favour of 'turbine powered simulators' or TPS, introduced in the HST by Airbus-Deutschland (see page 84).

These examples show that there was a very good relationship between Sud-Aviation, later Aérospatiale and NLR. This relation came to an end for two reasons. First of all, the French Government was not happy that Aérospatiale, a partly state owned company at that time, was doing its wind tunnel testing in The Netherlands rather than in the S-2 wind tunnel of ONERA, a tunnel with roughly the same size. Aérospatiale was urged to carry out the transonic test programs in France[106]. When Fokker pulled out of the Airbus program in 1980[Z], the HST lost its preferred status as an Airbus tunnel as laid down in 'Chapter 6' of the Airbus document concerned with the 'Work Sharing' between the Airbus partners. This resulted in a considerable loss of orders from Airbus, a loss that was only partly compensated with development work done for Airbus Deutschland as part of their own development programs. This will be discussed further on page 84.

OTHER AIRCRAFT PROJECTS

Many other customers found their way to the HST. In the early sixties FIAT, Hamburger Flugzeugbau (HFB) and Piaggio executed wind tunnel tests in the framework of the AICMA contract. Dassault as well became an important customer, first with the Mercure that was tested in 1971 [figure 3-33] and later with various versions of the Mirage. Since the French Governement didn't allow Mirage development outside France, only export versions could be tested in the HST. SAAB was also a regular customer with the Draken and Viggen [figure 3-34] and (much later) the small passenger aircraft SAAB 2000. Another important project was the 'Multi-Role Combat Aircraft' MRCA, a joint European project for a fighter. The Netherlands supported this program and Fokker was made responsible for the development of the high lift devices [figure 3-36]. However, when in 1970 The Netherlands pulled out of the project, no more work was granted to the HST. Other companies that may be mentioned are Aermacchi, Israeli Aircraft Industries, Dornier, General Dynamics (as part of the F16-Agile test campaign), MBB-München, CNES. This list of customers is far from complete but illustrates very well the interest in HST and SST from the international aeronautical industry in the sixties, the seventies and beyond. Most of these companies remained regular customers up till the point that they merged with other companies or terminated their activities altogether.
Figure 3-38 illustrates the occupancy of the HST in the period between 1960 and 1986[57]. It shows that very busy periods al-


[3-33]


[3-34]

[Z] PARTICIPATION FOR FOKKER IN AIRBUS WAS FINANCIALLY OPEN-ENDED (REF. 19). WHEN IN 1978 SWARTTOUW BECAME THE NEW DIRECTOR OF FOKKER HE SOON REALIZED THAT PARTICIPATION IN AIRBUS AND THE DEVELOPMENT OF NEW FOKKER PRODUCTS COULD NOT BE COMBINED. HE OPTED FOR NEW FOKKER PRODUCTS.

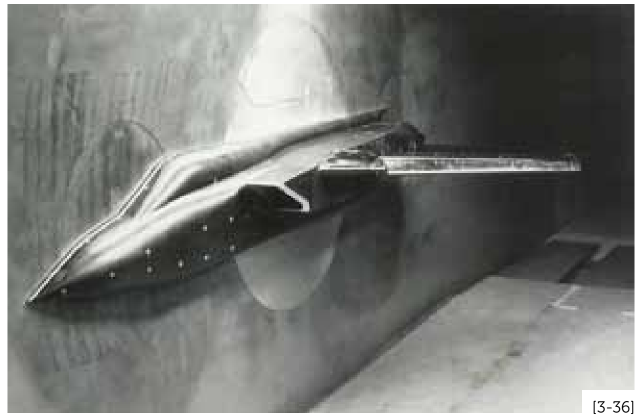
[3-35]

ternate with quiet periods. Fortunately periods with a low Fokker activity were compensated by an increased demand of other aircraft companies. The average occupancy is about 100 tunnel days a year, roughly half the available capacity. Over the years the decrease in the number of projects and in the number of independent aircraft companies contributed to the fall in the number of test entries relative to the 'heydays' in the sixties. Also, since testing became more and more efficient, the number of days needed to execute a certain test program (e.g. the requested polars) decreased as well. This trend was partly compensated by increased activities for technology programs on behalf of Fokker, as will be discussed in the next section. In addition to this a small part of the tunnel time was devoted to research, either under contract with NIVR or, although rarely, paid for out of the NLR's own research budget.

When the plans for the SST and the HST took shape, it was realised that these facilities would be too expensive for fundamental research. For that reason Erdmann wanted, in addition to the much more expensive SST, a small supersonic facility, the CSST, where research could be done at lower costs. And Boel, in his confidential note of 1956[41] worried about the high costs of fundamental research in the HST. Of course the PT could be used for some of these tests, which was the case in the following years for advanced wing profile development and the study of unsteady flow around oscillating airfoils. Fortunately, as further developments showed, experimental studies on advanced wing designs were made in the HST as part of a collaborative research program with Fokker, funded by NIVR, the 'Netherlands Agency for Aircraft and Space Development'. These studies will be discussed in the next section.

NON-AERONAUTICAL TESTS

The HST was used occasionally for non-aeronautical tests, generally to establish the wind loads on structures such as buildings, trains, road signs etc. Such tests are usually done in low speed wind tunnels that are relatively cheap to use. However, sometimes these loads depend critically on the Reynolds number. This is typically the case for flows over circular cylinders as was already mentioned in relation with the ELDO tests [see figure 3-26]. The drag of structures with cylindrical elements might go down substantially when a certain critical value of the Reynolds number is exceeded. The explanation is that the flow in the boundary layer passes beyond the critical Reynolds number from a laminar flow regime into a turbulent flow regime with different characteristics. The dynamic behaviour might as well be quite different. Since at low speed conditions the pressure can be increased fourfold in the HST, a fourfold increase in Reynolds number can be achieved, for some applications sufficient to pass this critical Reynolds number. For this reason non-aeronautical tests are sometimes made in the HST and the higher costs are accepted. Two examples are shortly discussed here. One is the so-called 'Shell Tulip', a large oil container that was intended to collect oil from the bottom of the sea for the exploration of off-shore oil wells. Figure 3-35 shows the configuration that was tested. Threads of wool have been glued onto the surface to give an indication of the flow separation. Another example is given in figure 3-37. It represent elements of a large barrier, that was planned as part of the so-called 'Delta Works' that were executed to protect the 'Low Countries' (below sea level) after the big flood in The Netherlands in February 1953. This barrier is normally open but may be closed in case of extreme high water conditions. It was feared that the unsteady shedding of vortices behind the thick pillars would result in high dynamic loads on the structure when water flowed through the openings due to tidal motion. Both of these tests were done by the Department of Aeroelasticity (AE) which was specialised in experimental and theoretical investigations of unsteady flow phenomena. ■



[3-36]

[3-37]

[Figure 3-35]

The 'Shell Tulip', a model of a large structure to be used by Shell as a sea oil container.

[Figure 3-36]

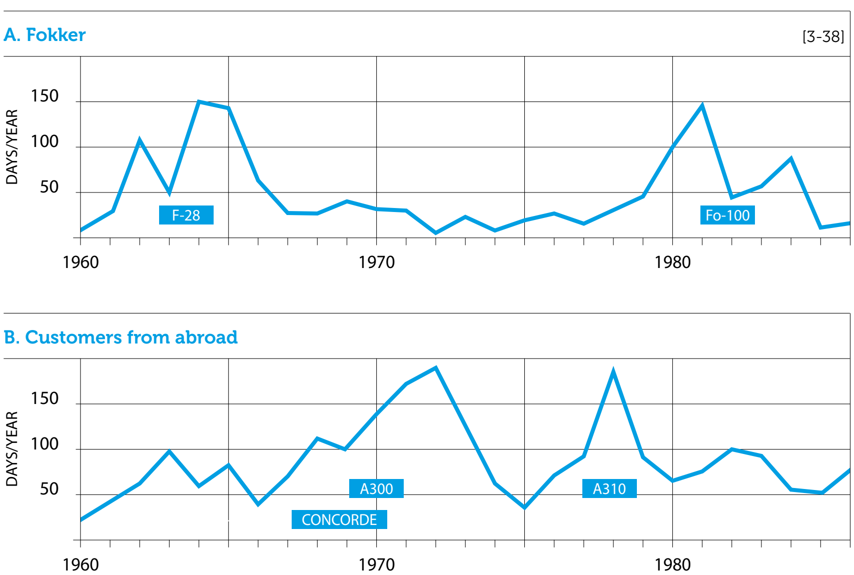
Half model of the Multi Role Combat Aircraft (MRCA) tested in 1969.

[Figure 3-37]

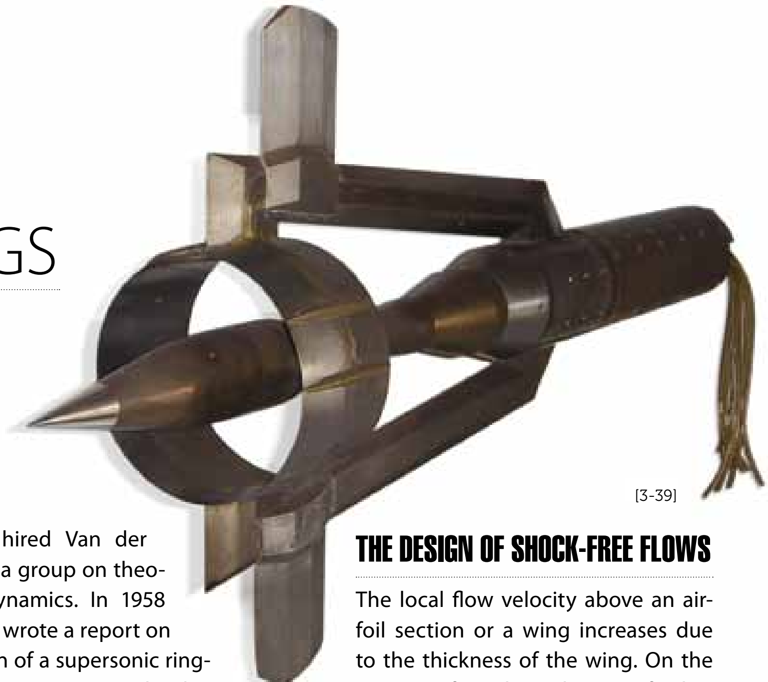
In 1975 a sub-scale model of locks was tested in the HST for the Dutch Ministry of Transport, Public Works and Water Management ('*Ministerie van Verkeer en Waterstaat*'). These locks were envisaged as part of the 'Delta Works' to protect the Southwest part of The Netherlands.

[Figure 3-38]

Occupancy of the HST (days per year) In the period 1960 - 1986. Fokker development tests (F28, Fokker 100) at the top, customers from abroad at the bottom.



RESEARCH MAKES BETTER WINGS



[3-39]

THEORETICAL WORK ON WINGS

[Figure 3-39]

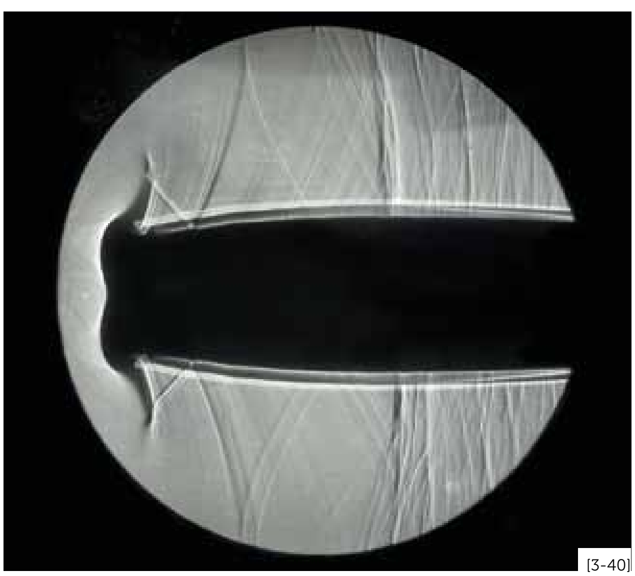
The 'ring-wing', a configuration for a supersonic airplane with minimum drag. This model was tested in the CSST in the late sixties to validate the design method.

[Figure 3-40]

A 'schlieren' picture of the (near) shock free flow over a 'quasi ellipse'. The lines that are visible on both sides of the airfoil are caused by weak shock waves.

Just after the War a Section on Flutter and General Aerodynamics (*'F-sectie'*) was established under the leadership of Greidanus (who joined the Fokker Company later to become the head of the Design Office (*'Constructie Bureau'*) and the chief-designer of the F28 Fellowship). This section concentrated its activities on theoretical aerodynamics and specifically the prediction of flutter. The much older Aerodynamics Section (*'A-sectie'*) focussed on experimental work and the design of new facilities. The theoretical work for steady aerodynamics in the F-Section was concerned with problems such as the prediction of wing loading, the drag of airfoils and wings and three-dimensional boundary layer calculations. Also an 'inverse method' for the design of airfoils and wings was developed. In this type of method the wing shape is calculated for a specified pressure distribution on the wing. This is the opposite of a 'direct calculation' which calculates the pressure distribution for a specified wing geometry.

In 1954 another aerodynamics section was added: the Gasdynamics Section (*'G-sectie'*), probably because Erdmann wanted his own section when he returned from Sweden. He hired Van der Walle to start a group on theoretical gas dynamics. In 1958 Van der Walle wrote a report on the calculation of a supersonic ring-wing configuration using the linearized method of characteristics. This was based on an article written by Erdmann and Oswatich in 1955. Supersonic flight was seriously considered but the high drag due to shock waves remained problematic. With a ring-wing configuration [figure 3-39] the supersonic wave drag can be reduced substantially. The conical shock wave generated by the fuselage is reflected from the circular wing around the body and is even further reduced by interaction with expansion waves at the rear of the fuselage. Theoretical research on ring-wings was pursued for nearly a decade by Van der Walle and later by Zandbergen resulting in a successful validation of the optimum design for the ring-wing* in the CSST [figure 3-39].



[3-40]

In his confidential note of 1956[41] Boel questioned the relation between theoretical and transonic aerodynamics. Was the theoretical work for transonic flows a task for the F-Section? How to relate theory and experiment? These issues were apparently resolved when the T-Section was established in 1957. From the names of those who wrote the first reports of the T-Section it becomes clear that many members of the T-Section were involved in wind tunnel testing as well as in theoretical work. Theoretical work on wall and support interference was already mentioned in this respect (page 68). But the most important issues were understanding the formation of shock waves on airfoils and wings and calculating compressible flows around complete aircraft configurations.

THE DESIGN OF SHOCK-FREE FLOWS

The local flow velocity above an airfoil section or a wing increases due to the thickness of the wing. On the upper surface this velocity is further increased with increasing lift. When the speed of the aircraft itself is a substantial part (say 70 %) of the speed of sound (hence when the flow Mach number is around 0.70) the flow velocity above the wing might locally exceed the speed of sound to become supersonic. Near the rear of the airfoil the flow has to decelerate again to reach the downstream subsonic free stream conditions. This deceleration is normally accompanied by a shock wave, a discontinuous change in the local flow velocity. The shock waves contribute significantly to the drag of the aircraft and, when sufficiently strong, might lead to flow separation and all kinds of unwanted dynamic effects (referred to as 'buffeting'). Around 1960 subsonic flow over wings could be calculated reasonably accurately but it was not possible to calculate flows with shock waves. An even more difficult challenge was the design of high speed airfoils with local supersonic flow, but without the detrimental effect of shock waves. It was even questioned if this could be done at all. In two other places in the world, at the NASA Langley Research Centre in the US by Dick Whitcomb and at the National Physics Laboratory NPL in the UK by Herbert Pearcey, work was ongoing to solve this problem with semi-empirical design methods.

How did NLR get involved in this development? After the first tests during the commissioning of the HST it was decided to redesign the nozzle. There were problems with the construction (see page 24) and it was desirable to improve the flow quality, notably at transonic and supersonic conditions where the risk of unwanted shock wave formation was real. Nieuwland, a mathematician who worked for the T-Section, got this job. He used the so-called 'hodograph method' (a theoretical approach that maps the flow in velocity space) to solve this problem. After its successful application the idea evolved to use these methods for the design of (shock free) airfoils[107]. He extended some existing theories (notably those by Chaplygin and Cherry & Lighthill) and managed to design airfoil shapes with supercritical flow but without shock waves. The family of airfoils that resulted from his work got the name 'quasi-ellipse'. Some of these airfoil sections were tested in the PT [see figure 3-40] and showed the predicted behaviour. It was not generally accepted at that time that shock-free flows were of practical interest since it was feared that small disturbances might spoil the benefits. Subsequently, a number of experimental studies were initiated to see if shock-free supercritical flows were stable for small disturbances due to noise or variations in the ideal airfoil shape. From a study by Spee[108] (also described in his dissertation[109]) it could be concluded that these flows were indeed stable.

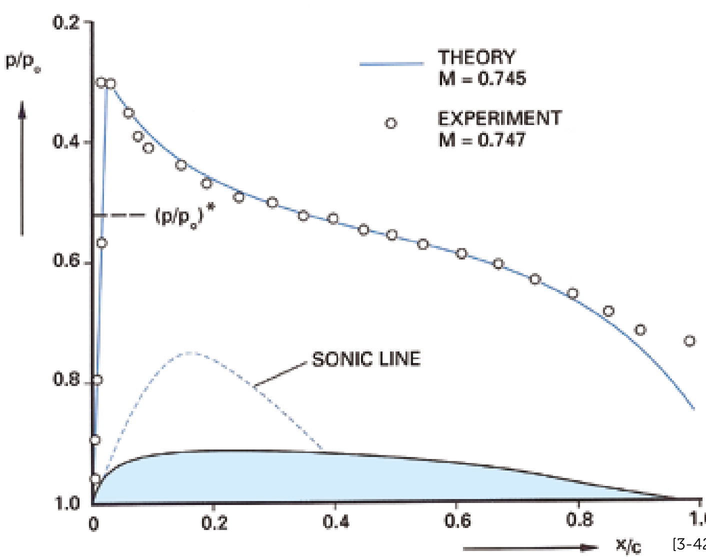
The first supercritical airfoils designed in that way had a suction peak at the nose ('peaky pressure distributions' [see figure 3-42a]) and showed some characteristics that were not attractive for use on airplanes. The work of Whitcomb was concerned with a different type of airfoil which showed a prolonged region of supersonic flow, terminated by a weak shock ('rooftop pressure distributions' [see figure 3-42b]). At NLR the work by Nieuwland was further extended by Boerstoel to include rooftop pressure distributions. In 1971 the first airfoil* with such a pressure distribution, named NLR 7101, could be tested in the PT, soon followed by the well-known and rather thick (airfoil thickness/chord length = 16.5 %) airfoil section NLR 7301 [figure 3-42b].

The first real application of a NLR-designed supercritical airfoil was made for Bell Helicopters in Fort Worth in the US. Meijer Drees, the man behind the Dutch Kolibrie helicopter, got to know about the NLR work on supercritical airfoils and asked NLR to design an airfoil specifically for helicopter applications, named by Bell 'NLR-1'. After wind tunnel tests in the US the airfoil was tested on a full-scale Cobra helicopter, resulting in substantially improved rotor performance[110].

THE CALCULATION OF FLOW OVER WINGS

A successful airfoil is not yet a wing and this requires a wing design method. Before World War II the wing loading for aircraft design purposes or strength calculations at NLL was estimated by a German method developed by Lotz. After the War these methods were further extended in the F-Section. However, the calculation of the flow over a wing for transonic conditions was beyond the possibilities. In the design for high speed wings supercritical flow can be postponed by sweeping the wings[AA]. In England a group of researchers from RAE, ARA and NPL was actively involved in the development of methods to calculate the flow over swept wings at transonic conditions. One specific method, based on idea's by Weber (a German scientist who settled in England after the War), was documented in the 'Transonic Data Memorandum' TDM 6312, issued by the 'Royal Aeronautical Society'. There was a great interest in validating these methods and it was decided to make this topic part of the existing joint 'Anglo-Netherlands Co-operation Program' (ANCP).


[3-41]



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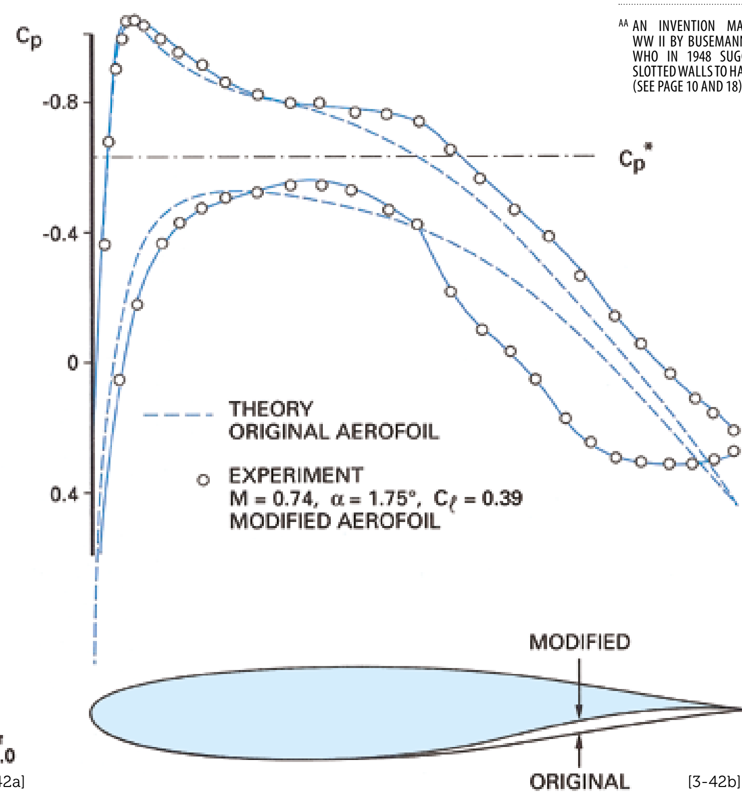


[3-42b]

[Figure 3-41]

The C9A wing, the result of a joint design by RAE, ARA and NLR. This wing was tested in the HST as part of the 'Anglo Netherlands Cooperation Program' (ANCP). Around 1967.

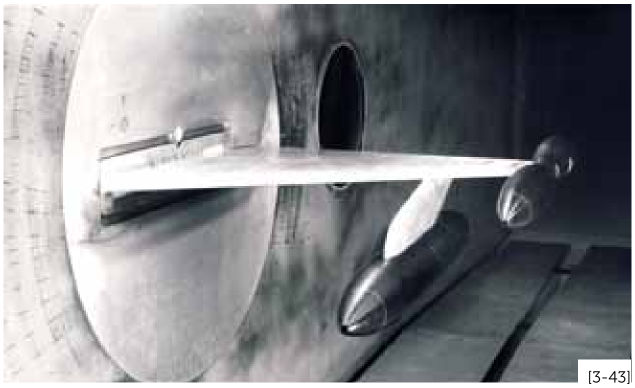
[Figure 3-42a]

A 'peaky pressure distribution' of the flow over a 'quasi-ellipse'. Near the leading edge of the airfoil the flow is locally supersonic.

[Figure 3-42b]

One of the first practical shock-free airfoils (NLR 7301) exhibits a combination of 'shock-free supercritical flow' over the front part of the upper surface and 'rear loading' at the rear of the airfoil. Both effects increase the lift and hence the performance of the airfoil. The pressure distribution above the line noted with c_p*, the region where the flow is locally supersonic, has a gradual slope, hence the name 'rooftop pressure distribution'.

[AA] AN INVENTION MADE BEFORE WW II BY BUSEMANN, THE SAME WHO IN 1948 SUGGESTED THE SLOTTED WALLS TO HAUSAMMANN (SEE PAGE 10 AND 18).



[3-43]

[Figure 3-43]

The NF-5 configuration in the HST. First used to validate the NLR panel method (around 1971) and subsequently used for flutter investigations.

NLR made calculations on a standard configuration of an arrow wing (the Warren 12 wing) and tested another configuration in the HST, a configuration that had already been tested in one of the RAE wind tunnels. At a later stage a new Mach = 1.2 wing was designed in a joint effort by RAE, ARA and NLR, using an inverse design method[111]. This wing (designated C9A) had a rooftop pressure distribution. A model* was manufactured by ARA and tested in the HST [see figure 3-41]. In this co-operation NLR learned a lot about the design of advanced transonic wings, a very valuable experience indeed.

In one of these common exercises an American method for the calculation of the pressure distribution on a wing by Hess and Smith from Douglas participated. In 1967 the original method by Hess and Smith was modified by Rubbert from Boeing in the US to include lift and compressibility effects. This latter method was further developed by NLR[112] to include an improved compressibility correction and a more efficient numerical procedure to solve the large system of equations on the computer. This method, known as the 'NLR Panel method' soon became the 'work horse' for the calculation of the flow over three-dimensional wing-body configurations. To validate this method calculations were made for the wing of the NF-5 (the interceptor of the Royal Netherlands Air Force at that time), including configurations with under-wing mounted pods or stores*. The results of these calculations could be compared with test results obtained in the HST around 1971 [see figure 3-43].

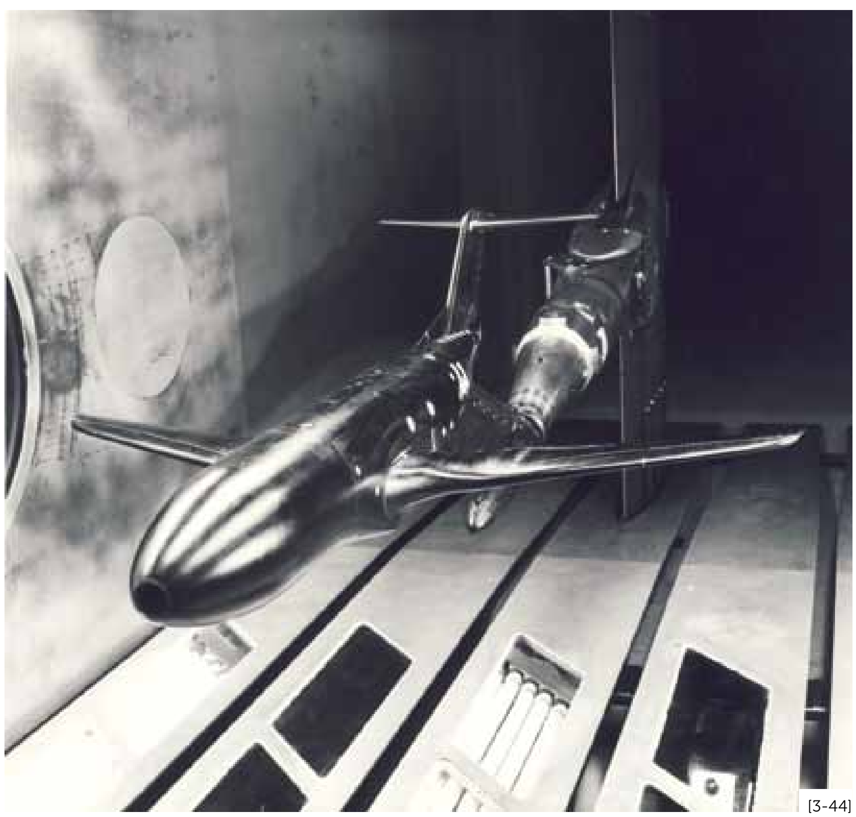
THE SUPERCRITICAL WING DEVELOPMENT

In the early seventies Slooff, head of the Department of Theoretical Aerodynamics (AT), held a presentation in the 'Purple Room' at NLR on new developments in transonic design methods at NLR. In the first row quite a few staff-members of the aerodynamics department of Fokker were seated, including Blom, head of the aerodynamics department, who later became professor in Delft in Aircraft Design. Slooff spoke about the tools that could be used for wing design such as the hodograph method for the design of shock free airfoil sections, the NLR panel method to calculate pressure distributions and an inverse method for the design of the wing. He concluded his presentation with an example of how, by elimination of the kink in the leading edge and in combination with a modified airfoil section, the drag performance of the F28 wing could be improved considerably. The Fokker participants were not altogether positive, but Blom realised the potential of these methods for the design of a next generation Fokker aircraft. The first idea's for a successor of the F28 started to take shape in 1974. NIVR, the 'Netherlands Agency for Aerospace Programs', could be convinced of the prospects of such a development. In the same year a research program named 'Preparations for New Projects' or ANP ('*Aanloop Nieuwe Projecten*') was started. An essential part of this program was the 'Supercritical Wing' or 'SKV-project' ('*SuperKritieke Vleugel*'). In this project engineers from Fokker and NLR worked closely together to exploit the aerodynamic benefits of the new transonic developments. The pre-design group of Fokker specified the overall characteristics for a new wing, whereas NLR was involved in the detailed design of the wing shape. During joint meetings the progress was discussed, new requirements were formulated and specific tasks given to various working parties. For the NLR engineers this joint approach was very educative, since they got insight into practical constraints in aircraft design related to structural and operational issues. Although the exercise concentrated on the design with shock-free flow at the design condition, off-design characteristics such as low speed maximum lift, buffet boundary and buffet penetration (Appendix E) soon appeared to be essential issues that had to be addressed as well.

In the design procedure as established by Slooff, various calculation methods were loosely coupled to cope with some of the inherent limitations of the particular theoretical calculation methods at that time. The procedure was based on 'inverse design', meaning that the wing shape had to be calculated from a specified pressure distribution, the 'target pressure distribution'. This 'target pressure distribution' was derived from the two-dimensional

[Figure 3-44]

SKV-1 was the first supercritical wing designed by NLR as part of a collaborative study with Fokker financed by NIVR (1975).



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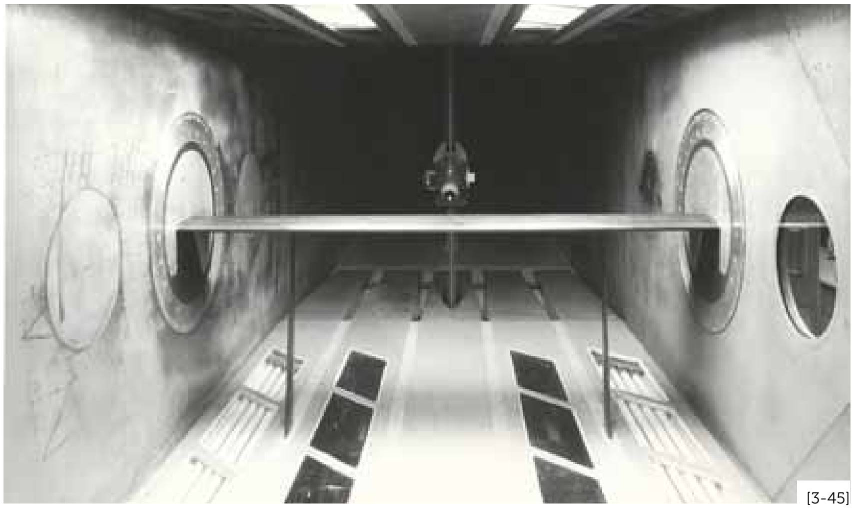


[3-45]

[Figure 3-45]

The figure shows a two-dimensional wing spanning the HST test section. The span was so large that support struts were needed to reduce the stresses on the model. This set-up was used for high Reynolds number testing in the HST.

supercritical airfoil section designed by the above-mentioned hodograph method. This two-dimensional pressure distribution was adapted subsequently to include (in a rather approximate way) compressibility and wing sweep effects to yield a three-dimensional target pressure distribution. With the inverse method the wing shape could now be derived. Finally, the wing pressure could be calculated with the NLR panel method to check if the result agreed with the target pressure distribution. The first three-dimensional supercritical wing*, named SKV-1, was tested in 1975 in the HST [figure 3-44]. This wing had an extremely thick inner wing section (about 20%) due to the fact that the inverse calculation appeared to be an 'ill posed problem'. This means that for one specified 'target pressure distribution' many different wing shapes can be derived. In later designs geometrical constraints were added to the procedure to cure this problem. The SKV-1 wing was the first in a sequence of many wings that illustrate the development from a research wing to the actual wing for the F29, the project that Fokker defined around 1980 [see figure 3-49].

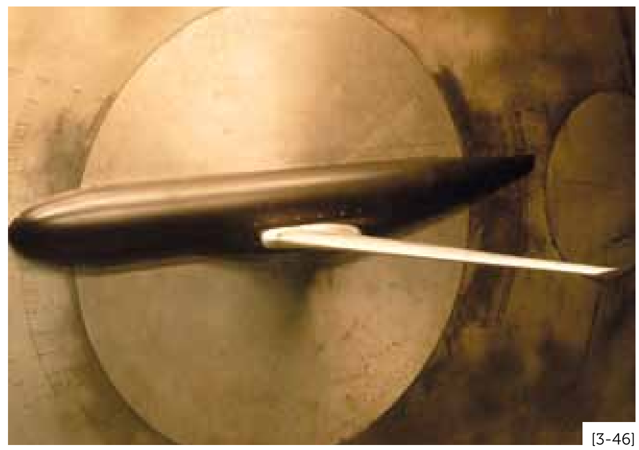
THE REYNOLDS NUMBER ISSUE

In 1963 the C-141, a transport aircraft built by Lockheed for the USAF, made its first flight. It soon became clear that the pitching moment of the flying aircraft differed substantially from what was anticipated and so-called 'scale effects' were to blame. The C-141 was a very large aircraft (with a fuselage length and wing span of about 50 m) and it was questioned if wind tunnel results obtained for a model at a much smaller scale would be representative for the actual flight values. It was also noted by other aircraft manufacturers (e.g. Airbus) that so-called 'pitch-up' at Mach numbers beyond the design Mach number, was Reynolds number dependent. Other differences between wind tunnel and flight had been observed in the past. Although scale effects were not necessarily the cause of these problems it was feared that some wings and airfoil designs might be very sensitive to a variation in Reynolds number. Would advanced wings with a high wing loading at transonic conditions be particularly sensitive?

Fokker wanted to know this for the new supercritical airfoils. Therefore airfoil NLR-7301 (a basic section of the SKV-1 wing) was tested in the 'Compressible Flow Facility' (CFF) of Lockheed Georgia in Atlanta in the US. Indeed, this airfoil turned out to be rather Reynolds number sensitive. Fokker subsequently wanted to extend the possibilities to test in the HST at Reynolds numbers as high as possible. In 1976 a study was initiated by NLR to see if the Reynolds number could be increased for the HST (see page 34). In 1978 preparations also started to test a large half model in the HST, again with the intention to increase the Reynolds number. In an effort to push the Reynolds number as much as possible, this half model was a bit 'oversized' for the HST and extensive studies were made to quantify the corrections for half model mounting and tunnel wall interference. Detailed drag information could be derived from wake rake surveys. The importance of Reynolds number effects also triggered the development of a new test set-up in the HST to test two-dimensional models with a chord length of 0.5 m and a span of 2 m [figure 3-45], a set-up that became operational in 1981.

UNSTEADY AERODYNAMICS AND AERO-ELASTICITY

Unknown Reynolds number effects were not the only concern for Fokker. Unstable coupling between aerodynamics and the aircraft structure known as flutter is a crucial item in aircraft design. Aileron flutter had already been investigated and cured by the RSL (the predecessor of NLL and NLR) in 1923 for the Van Berkel WB aircraft[113]. The VFW-614 had a very serious problem with tail flutter. Next to theoretical aerodynamics, flutter was one of the main research topics of the Flutter Section ('*F-sectie*') that later changed its name into the Department of Aeroelasticity (AE).



[3-46]

[Figure 3-46]

A half model of the SKV-5 wing. The model could be oscillated in pitch and from the results the aerodynamic input for flutter calculations could be derived.

At transonic conditions the problem of flutter is dominated by complex interactions between shock-induced separations and shock wave motion. Unsteady transonic aerodynamics was studied extensively in the seventies in the PT on two-dimensional airfoils with an oscillating flap* and on airfoils that could be forced to oscillate in pitch. In these tests the unsteady lift and pitching moment could be derived from unsteady pressure measurements at the model surface[BB]. Experimental results were essential to validate approximate theories to model the aerodynamic part in the flutter calculations (which are based on an interaction between aerodynamics and deformable structures). Later the theory was extended to three-dimensional wing configurations (using local two-dimensional characteristics as an input), also necessitating an experimental validation. Such an experiment was executed in the HST in 1979 on a half model of one of the SKV configurations named SKV-5. The half model could oscillate in pitch [figure 3-46]. A so-called

[BB] NLR PIONEERED IN THE DEVELOPMENT OF A SPECIAL MEASURING TECHNIQUE IN WHICH STANDARD PRESSURE HOLES ON THE MODEL SURFACE WERE CONNECTED WITH CONVENTIONAL TUBING TO AN UNSTEADY PRESSURE TRANSDUCER OUTSIDE THE MODEL. A THEORETICAL MODEL WAS USED TO MAKE CORRECTIONS FOR THE EFFECTS OF THE FINAL TUBE LENGTH.


[3-47]

[Figure 3-47]

Dynamic tests on the F-16 to study 'Limit Cycle Oscillation' at transonic conditions. This was part of a cooperative program with AFWAL and Lockheed (around 1991).


[3-48]

[Figure 3-48]

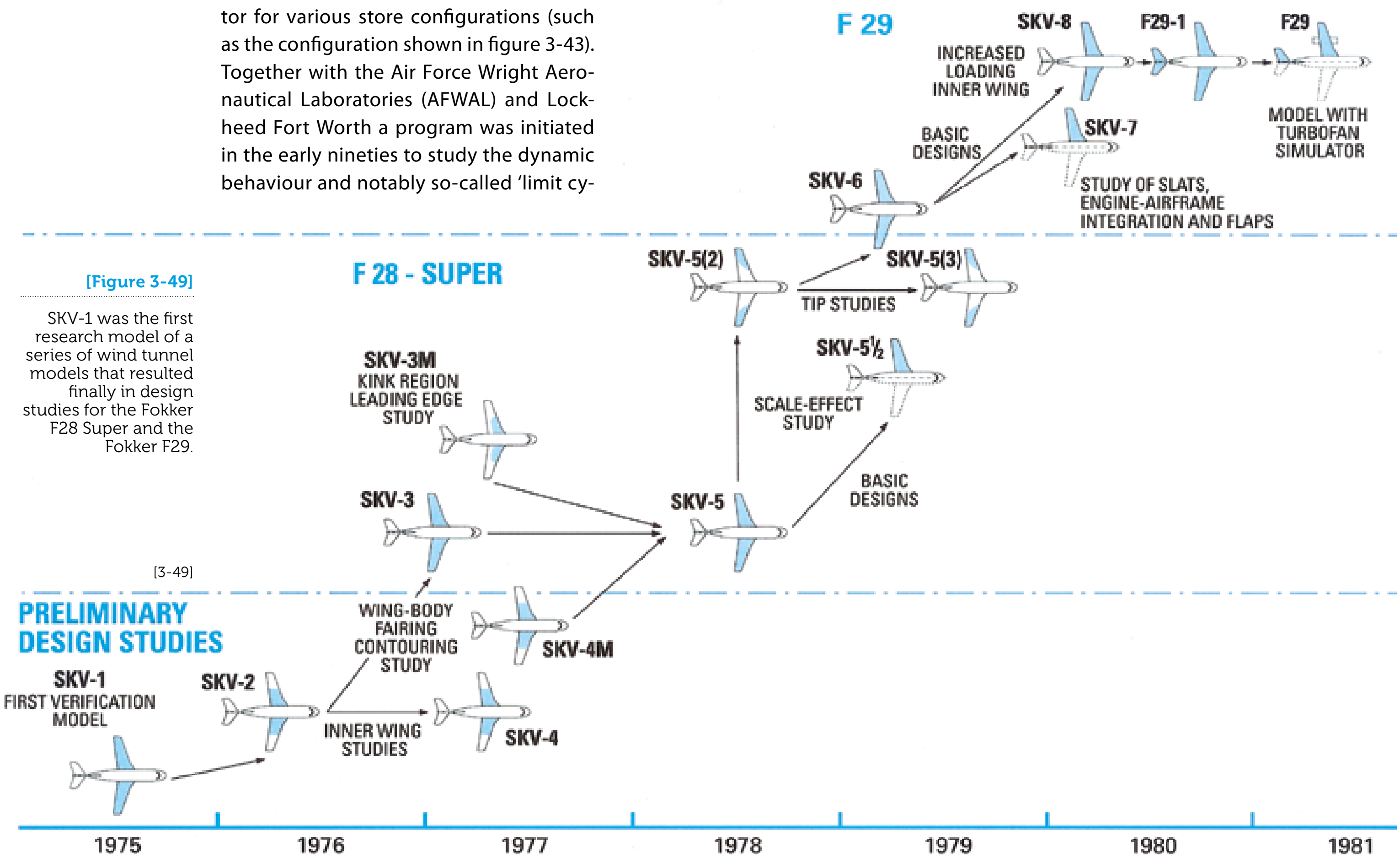
The F29 in low speed configuration in the HST (around 1980).

'transonic dip' was observed (a lower flutter margin at transonic conditions) and this experiment proved to be very useful for the further development of methods that could predict the flutter boundaries at transonic conditions.

The experience obtained for unsteady transonic flows during the SKV project appeared to be very valuable, not only for civil aircraft design but also for military applications. In the HST NLR studied the unsteady behaviour of the NF-5 interceptor for various store configurations (such as the configuration shown in figure 3-43). Together with the Air Force Wright Aeronautical Laboratories (AFWAL) and Lockheed Fort Worth a program was initiated in the early nineties to study the dynamic behaviour and notably so-called 'limit cycle oscillations' for the delta wing of the F-16 [see figure 3-47]. NLR was also extensively involved in tests to study unsteady flow at the base of the ARIANE-5 launcher [figure 3-68].

IN SUPPORT OF NEW FOKKER AIRCRAFT

In the SKV-project many different configurations were tested. The program started with elementary studies to address specific design questions (the form of the inner wing, the wing tip shape, off-design studies...) but gradually the program developed into the design of a real airplane: the F28 Super, an improved F28. Figure 3-49 illustrates this development. The ANP-program 'Preparations for New Projects' ('*Aanloop Nieuwe Projecten*') continued in 1978 within the 'Interim Program' or IP in anticipation of a new Fokker project. Such a project was launched in 1979 with the F29, a completely new design with a T-tail and underwing mounted engines for 132-150 passengers [figure 3-48].
The close co-operation between Fokker and NLR in the SKV, ANP and IP programs during the period between 1974 and 1980 has been of invaluable importance for the development of aerodynamics at NLR, both theoretically and experimentally. Key elements were the interactions between NLR as a research laboratory and Fokker as the aircraft builder, as well as a very fruitful interaction between theory and experiment. But it was inevitable that the role of NLR would be a different one as soon as a real Fokker project emerged. The time of close co-operation to prove the limits of a new technology was to be followed by



[Figure 3-49]

SKV-1 was the first research model of a series of wind tunnel models that resulted finally in design studies for the Fokker F28 Super and the Fokker F29.

[3-49]


[3-50]

[Figure 3-50]

The MDF-100 configuration in the HST (1981).

a period in which Fokker was in the lead of the development and NLR contributed in providing (and improving) the tools for wind tunnel testing and theoretical calculations. This point in time was reached with the F29.

The F29 was the largest airplane that Fokker had envisaged so far. The risks were too big for Fokker and a partner had to be found. Boeing and Japanese companies were approached but in May 1981 the MDF-100 was announced, a joint project between McDonnell Douglas and Fokker. This co-operation started a very busy period for the HST since a large part of the tests was to be made in the HST [figure 3-50]. In February 1982, within a year, this joint venture was terminated, mainly because of the weak market outlook at that time. To survive Fokker needed to return to less ambitious projects: improvements of the existing F27 and F28 aircraft. For the HST the improved F28, named the Fokker 100, was the most important one. The capacity of the F28 was increased from 79 to 107 seats, necessitating a longer fuselage and modified wing. The design lift coefficient was increased and so was the wingspan. The kink in the leading edge was almost eliminated and the wing nose section modified. These latter changes made it possible to incorporate some specific supercritical airfoil characteristics, based on the knowledge acquired in the preceding years. The fact that the existing wing box should be maintained was a serious constraint. Nevertheless, the aerodynamic performance came close to a completely new designed supercritical wing. The Fokker 100 development provided the HST with a lot of work [figure 3-53]. In November 1986 the first flight of the Fokker 100 was made. The supercritical wing technology in The Netherlands was finally airborne [figure 3-51].

This was not the end of the Fokker family of aircraft. In 1992 it was decided to build a smaller version of the Fokker 100, the Fokker 70. As far as the wind tunnel tests were concerned, that decision was taken at a rather inconvenient time: the first phase of the HST modification started in 1992. The new test section had to be installed and all tunnel control systems had to be renewed. At the beginning of 1993 Fokker was the first customer to test the Fokker 70 in the new test section, right after the NLR validation program to prove that the modified tunnel gave reliable results.

In October 1992 Fokker was taken over by DASA, Deutsche Aerospace AG, the company that resulted in 1989 from a merger between all German aircraft industries. DASA wanted to bring a new aircraft to the market, a regional jet in size just below the Airbus A320. The Fokker engineers wanted to extend the Fokker 100 family with a new, larger member, the Fokker 130, to reduce the costs for such a new development. Studies were made for a so-called ‘root plug’ between the existing Fokker 100 wing and an enlarged fuselage [figure 3-52] to accommodate the increased aircraft weight. At the same time a completely new wing was designed as an ‘ideal reference’. DASA proposed a completely new configuration, derived from the MPC-75 program that had already been studied for some time. Wind tunnel tests were made in the HST to compare the various configurations. But when DASA dropped Fokker in January 1996, leading to the bankruptcy of Fokker in March, the Fokker family had really ended. ■

[3-51]

[Figure 3-51]

A Fokker 100 in flight.


[3-52]

[Figure 3-52]

The fuselage of the last Fokker model: the Fokker 130, an enlarged version of the Fokker 100. On this figure the key players in the Fokker wind tunnel test programs: leaning on the table Jack van Hengst (Fokker, head aerodynamics), behind him to the right Karl Möller (NLR, wind tunnel testing) and further to the right Klaas Breman (NLR, model manufacturing).


[3-53]

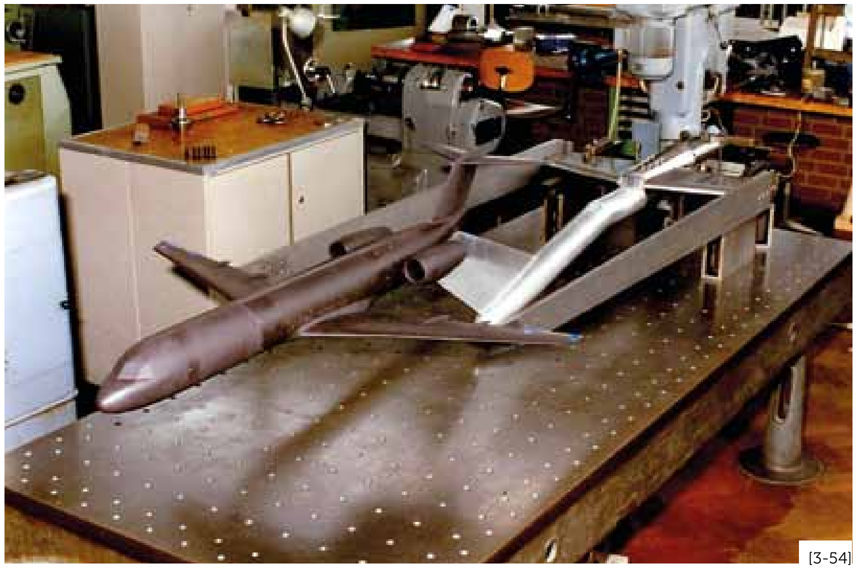
[Figure 3-53]

The improved wing for the Fokker 100 in the HST (1983).

THE EIGHTIES AND BEYOND

IMPROVING ACCURACY

During the short time of the joint development program for the MDF-100, the McDonnell-Douglas and Fokker wing designs were compared in the HST. One of the quantities of interest in this comparison was the drag creep: the increase in drag at the design lift coefficient between a subsonic condition (say Mach = 0.5) and the design Mach number (around Mach = 0.8). The results of the tests showed that the drag creep for the McDonnell-Douglas design was one drag count less than for the Fokker design: a difference in drag coefficient of 0.0001. This was a small difference. Nevertheless, it was a serious argument in the discussions on how to proceed with the wing designs. The question may be asked: *'Are the measurements accurate enough to measure such small differences?'*



[Figure 3-54]

A Fokker model with the twin-sting support. With a dummy sting (the metal coloured Z-sting near the rear of the model) the interference effects can be determined (1995).

[3-54]

In the table below the accuracies claimed in the early sixties by the various transonic wind tunnels in operation at that time have been compared with the demands of industry in the early eighties.

This table focuses on the accuracy in drag since this is the pacing item to reduce fuel costs. The accuracies listed in the left column have been taken from the report on the comparison of the AGARD-B and -C models, measured in various wind tunnels[86] (page 66). They relate to tests in the transonic regime at Mach ≈ 0.8. The last column lists the requirements 25 years later to indicate what industry wanted and expected in 1985. During those 25 years a continued effort was made to increase the accuracy. Better instrumentation, automatic data handling and improved tunnel controls greatly contributed to this end. But in spite of these improvements some customers were not satisfied with what was achieved. This was particularly true for MBB (later to become Airbus Deutschland as part of DASA). MBB used the HST intensively for their pre-development work which often resulted in proposals brought to the table of the Airbus consortium. Their achievements had to be compared with results obtained by other partners in other facilities. Notably ARA (the Aerodynamic Research Association in Bedford that operated a slightly larger atmospheric wind tunnel) claimed a drag repeatability of one third of a count. The requirement on drag is particularly severe, as can be illustrated by the following example. The design lift coefficient C_L of a transport type aircraft is of the order of 0.5. If an accuracy in drag coefficient C_D of 0.0001 (one count) has to be achieved it should be possible to measure a force difference of 0.02 % of the lift value! This issue and the consequences for the balance development are addressed in more depth in Appendix E and at page 45.

	range of accuracies as listed around 1960 by various wind tunnels	accuracies required by the aircraft industry around 1985
Mach number (around 0.8)	0.002 - 0.006	0.001
angle of attack (degrees)	0.03-0.3	0.01
drag accuracy (counts)	3-30	1

WALL AND SUPPORT INTERFERENCE

Instrumentation is not the only issue for accuracy. Wall and support interference are important as well and may introduce unwanted bias effects in the data. This problem manifests itself when results from different wind tunnels are compared. This was already clear from the comparison made around 1960 for the AGARD-B and -C models. In 1980/1981 a similar comparison was made within the framework of GARTEUR for a typical transport type wing (the DLR F-4 model) measured in the transonic wind tunnels of ONERA Modane, RAE Bedford and NLR. This comparison showed an acceptable agreement (a couple of counts differences). No tunnel wall interference corrections were applied to the HST data in accordance with the theoretical work by Loeve[98] in 1959. He optimised the HST slot width theoretically for negligible interference effects. From several comparisons with other wind tunnels there were no clear indications that questioned the assumption that the HST is almost interference free for complete models of the usual size. For large half models or two-dimensional models this is not longer true. Serious attempts have been made later to quantify the remaining wall interference. The method of Loeve was based on so-called 'homogeneous boundary conditions' which describe the slotted walls mathematically. To improve this method the concept of the 'measured boundary condition' was introduced and pursued by Smith. In this concept the (mathematically expressed) boundary condition at the tunnel walls in the wall interference calculations is replaced by actual pressure measurements at the tunnel walls in combination with a mathematical representation of the model (based on the actually measured forces on the model). This method was applied successfully in the HST for two-dimensional models, for which wall interference corrections were essential. However, for the half models this method was not accurate enough and empirical corrections were derived. For full models of the usual size, corrections could be derived, but they turned out to be small and these small values could not be validated independently. In fact, the optimum wall configuration for the modified test section in the nineties (see page 36) was derived rather conventionally by measuring a small model (named TWIG, 'Transonic Wall Interference Generator') in the Pilot HST (PHST) for various slot geometries and comparing these results with virtually wall interference free results from the same model tested in the HST [see figure 3-55].

Sting interference, the direct effect of the model support on the measured forces on the model, appeared to be an equally difficult problem to tackle. A first theoretical estimate of sting interference effects was made by Spee in 1961[99] (see page 69). The first sting interference tests were done in co-operation with Aérospatiale in the seventies, using dummy supports [figure 3-32]. The NLR panel method was applied to supplement these measurements. The results were not entirely satisfactory. A similar exercise was done in co-operation with Fokker in the eighties. Three different supports were compared: the Z-sting, a straight sting and the subsonic sting. For each of these cases support corrections on lift, drag and pitching moment could be derived from measurements with dummy stings and compared with calculations. Also in this case the final comparison of all corrected results was not entirely satisfactory. In the nineties it was subsequently decided in close consultation with Fokker, to manufacture a so-called 'enhanced twin-sting support' [figure 3-54]. With this


[3-55]

set-up, following a concept by ARA[CC], the wing of the model is supported by a twin sting. Balances in each of the supports measure the total forces on the model with and without a dummy rear sting. The difference between these measurements is a measure for the interference effects of the rear sting. If the customer wants to achieve a high absolute accuracy in his results, this is still the recommended practice.

QUALITY ASSURANCE

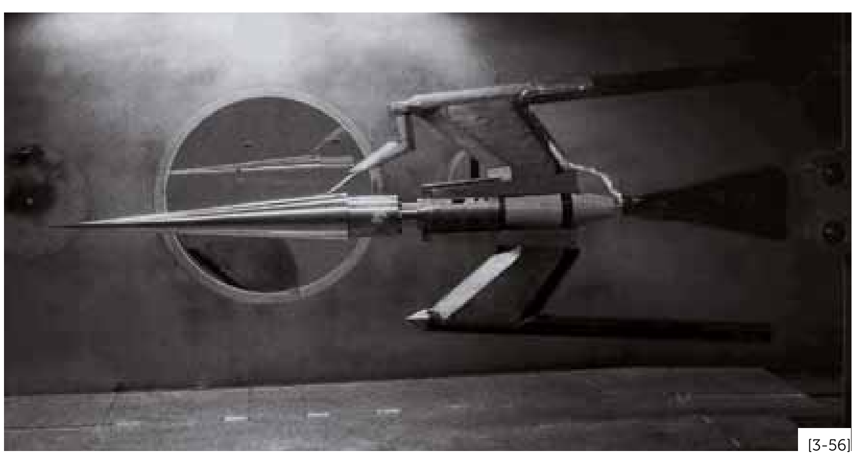
At the end of the eighties, during the ARIANE-Hermes tests (page 85), the French company Aérospatiale (Les Mureaux), responsible for the development of the ARIANE 5 launcher, requested error estimates for all wind tunnel test data obtained in the HST and the SST. This question followed directly from safety assessment procedures for the Hermes space plane. Till that time balance accuracies had usually been listed, but these are not sufficient for an overall error estimate. The effect on the aerodynamic coefficients of all instrumentation errors, errors that are usually known, can be derived by standard techniques. These uncertainties typically have a random nature. The problematic parts in the measurement accuracy are the not precisely known effects such as sting and wall interference or uncertainties in transition location. They cause a non-random 'bias' in the test results. For these effects upper limits can sometimes be estimated, though with appreciable uncertainties. For that reason test data are often evaluated on a relative basis, relative to a previous design for which flight test data are available. This procedure is sometimes called the 'delta method'.

Aérospatiale also requested 'Quality Assurance Procedures' or more precisely, they required that the wind tunnels would comply with their procedures. They prescribed the format of a pre-test document, procedures for non-conformities during the test execution, the format of the final test report and guide lines for the test evaluation. Moreover, the maintenance and calibration of the instrumentation had to be traceable. Their recommendations were clearly improvements on the already existing procedures and it was not too difficult to implement these.

This specific request from Aérospatiale in fact reflected an increased interest in quality control. In 1987 ISO, the 'International Organisation for Standardisation', issued guidelines for Quality Assessment known as ISO 9001. These guidelines were derived from military standards known as MIL-Q-9858, which go back to 1959. Customers of NLR requested the implementation

[Figure 3-55]

The TWIG model ('Transonic Wall Interference Generator') in the HST. Since the model was relatively small for the HST, the so obtained interference free results could be compared with results for various slotted wall configurations obtained with the same model tested in the Pilot HST (the modified Pilot Tunnel with a scaled HST test section). Around 1985.


[3-56]

[Figure 3-56]

A low noise level is essential for the quality of the tests; this can be measured with the so-called Q-lite cone.

[CC] AROUND 1970 AÉROSPATIALE ALSO USED A TWIN STING FOR THE TESTS ON THE CONCORDE NAMED 'BIDARD'. THIS STING WAS ATTACHED TO THE UNDERWING MOUNTED ENGINES OF THE CONCORDE AND THE TEST SET-UP WAS USED TO MEASURE THE AFTERBODY DRAG.

of ISO 9001 to ‘stamp’ the test results. A NLR wide group was set up headed by Te Boekhorst and Ross to introduce the ISO 9001 procedures. In 1993 the Informatics Division and the Space Division were the first within NLR to obtain a quality certificate from KEMA (the Qualifying Organisation that started in 1927 as the Electrical Engineering Equipment Testing Company) soon followed by the wind tunnels. NLR as a whole was certified in 2001.

ENGINE SIMULATION

Measurement accuracy is an important issue in wind tunnel testing, but is the wind tunnel model sufficiently representative for the aircraft in flight? The Reynolds number is important here (page 79) as is the representation of the engine. Engine simulation has always been an important aspect of wind tunnel testing. In most cases the (turbofan) engines are represented by a so-called ‘through flow nacelle’, an open nacelle in which the inlet mass flow can be changed to some extent. In the F28 development program an oil-fired burner was used in the LST to simulate the hot jet flow, but this technique was never applied in the HST. The development of engine simulation with H_2O_2, initiated because of the D-24 Fokker Alliance Interceptor (page 71), never made it to routine use in the HST. In the early seventies tests were done with H_2O_2 on a small rocket shaped research model* in the CSST [figure 3-60]. In co-operation with Aérospatiale tests were made in the HST at the end of the seventies to simulate the engine flow with H_2O_2 [figure 3-57] but this development was not continued. The fact that Fokker was not interested in this technique may have played a role here. Fokker preferred the use of a blown nacelle [figure 3-58], although this required a separate support strut to bring the compressed air into the (blown) nacelle*. The inlet configuration was either tested on a through-flow nacelle or on the special inlet rig [figure 2-55, 3-59] that allowed large variations of inlet flow conditions.

[3-57]

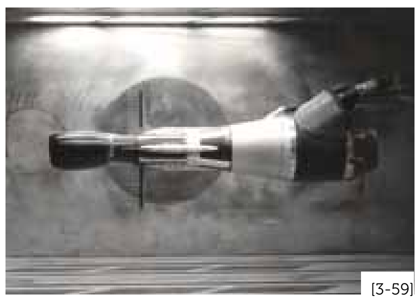
[Figure 3-57]

A test made in cooperation with Airbus on a half model for the development of the technique to simulate the engine jet with H_2O_2 (1979).

[3-58]

[Figure 3-58]

A half model with a blown nacelle tested in the HST as part of the NIVR sponsored VTP technology program. A rake is used to measure the exhaust jet (around 1994).



[3-59]

[Figure 3-59]

Rig specifically made to test the engine intake for variable mass flow conditions. The suction through the inlet is obtained by means of a downstream placed ejector. This set-up allowed high Reynolds number inlet testing for a wide range of flow conditions.

[3-60]

[Figure 3-60]

Model to test jet simulation at supersonic conditions with the H_2O_2 technique in the CSST (around 1972).

In 1980 the DNW, the large low speed tunnel in the Noordoostpolder which had been developed jointly by DFVLR and NLR, came into operation. This tunnel was used extensively by MBB (Airbus Germany) for the final testing of low speed configurations. MBB had its own subsonic wind tunnel in Bremen and in this tunnel their first experience with ‘Turbine Powered Simulators’ or TPS was obtained. This technique was pioneered in Europe by ARA in Bedford. With this technique compressed air drives a small turbine, which is coupled to the fan to move the by-pass air. Inlet and outlet flow conditions can be simulated, though with some limitations as far as the precise flow conditions are concerned and for a cold jet only. MBB was determined to use this technique in the DNW for Airbus testing. NLR was willing to invest in a calibration facility necessary to calibrate the model engines. MBB also wanted to use the TPS technique in the HST. One half of the low speed models that were tested in their low speed wind tunnel could be used as a half model in the HST. This provided an efficient use of wind tunnel models for both the low speed and high speed development. In this scheme it was only a small step to test a TPS engine at transonic conditions in the HST, as was done for the first time in 1986 [figure 3-61]. For the HST it meant the development of a half model balance with special provisions to bring the high pressure air into the model without affecting the balance readings. This was successful and the experience obtained with TPS testing in the calibration facility and in the DNW provided a firm base for TPS testing in the HST for MBB and also for other companies such as Dornier.

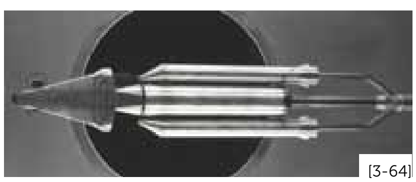
As an alternative to turbofan engines, propfans were considered many times, notably when fuel prices were rising. In 1991 Fokker tested a small propfan mounted on a separate strut underneath the wing in the HST. These exploratory tests were also made to validate calculation methods for the wing/slipstream interactions. Also in 1991 Deutsche Airbus tested a counter


[3-61]


[3-62]

rotating propfan in the HST [figure 3-62]. Although this test was successful, it was never followed by additional tests, possibly also because the interest in propfans dwindled again some years later. An isolated high performance propfan was tested in 1998 as part of the European APIAN technology program. This was basically intended as technology development for the application of high speed propellers such as considered for the Airbus A400. The drive of this system was borrowed from elsewhere. The very detailed measurements included the measurement with a rotating balance of the three forces and three moments (including the torque) that acted on the propeller. Additionally the flow field (swirl) in the slipstream, the radiated noise field and the deformation of the blades under load (with the 'Moirée' technique) were measured. It presented an altogether very complicated test. Based on the experience obtained in this test, the design of the rotating balance was improved [figure 3-63].


[3-63]


[3-64]


[3-67]

SPACE FLIGHT

When ESA was founded in 1973 ARIANE was to become the new launching vehicle for Europe. The ARIANE development started with ARIANE 1, still partly based on the EUROPE III configuration and continued up till ARIANE 5. Most of the tests in the HST and SST were made to determine the stability and control characteristics as had also been the case for the ELDO launcher. Of these measurements the ARIANE 5 wind tunnel tests were the most comprehensive. Go-ahead for the ARIANE 5 development was given in November 1987 and already in the same year the first tests were made in HST and SST by Aérospatiale. These tests comprised the 'version automatique' [figure 3-67] as well as a configuration with the 'Hermes Space Vehicle' mounted on top of the main rocket [figure 3-64]. The contract for Hermes [figure 3-65], a European alternative for the US Space Shuttle, was given in 1985 by CNES (Centre National d'Études Spatiales, the French space organisation)


[3-65]


[3-66]

to Aérospatiale in a fierce competition with Dassault. In the Phase I 'Detailed Design', which lasted between 1988 and 1990, more countries became involved, including The Netherlands. Following the Space Shuttle accident of the Challenger in January 1986, it was decided to include in the design an escape possibility: the Hermes Escape Cabin [figure 3-66]. The Hermes development was stopped in 1992 although it took many more years before the program was terminated officially.

[Figure 3-61]
The first MBB half model with a 'Turbine Powered Simulator' (TPS) for engine simulation (1986).

[Figure 3-62]
Test of a counter-rotating prop fan in the HST by Deutsche Airbus in 1991.

[Figure 3-63]
The APIAN isolated prop fan in the HST. Note the traversing mechanism, here used to measure the acoustic field (1997).

[Figure 3-64]
ARIANE 5 with Hermes in the HST (around 1986).

[Figure 3-65]
The Hermes model in the HST (around 1986).

[Figure 3-66]
Escape cabin for the Hermes configuration (around 1986).

[Figure 3-67]
The ARIANE 5 configuration in the SST (around 1986).

[3-68]

[Figure 3-68]

ARIANE 5 nozzle equipped with dynamic pressure transducers to test the fluctuating loads in the base area (around 2000).

A very challenging test for ARIANE 5 was the measurement of the acoustic loads. To protect the pay load and the equipment in the ARIANE 5 the intensity of the pressure fluctuations on the ARIANE 5 upper part and booster noses had to be known. For these measurements about 80 tiny pressure transducers, named 'q-lite transducers'*, with a high frequency response up to 80 kHz, had to be mounted in the sensitive areas. The signals from these transducers were recorded simultaneously to allow post-processing after the test e.g. to determine frequency spectra (for up-scaling to flight conditions) and space correlations. These very expensive and complex tests were executed successfully in the early nineties.

Unfortunately the first launch of ARIANE 5 in June 1996 was a failure due to software errors. But after the third flight with ARIANE 503 in October 1998, ARIANE 5 became operational and ready for use by customers. A problem with the base flow still needed attention. The highly unsteady flow at the launcher base caused unwanted deformations of the nozzle. A special model was made by NLR and tested in the HST to measure these pressure fluctuations in detail [figure 3-68].

[Figure 3-69]

The X-38 configuration, tested by CNES/ESA in a joint US/European project as 'Crew Transfer Vehicle' (CTV) for the 'International Space Station' (ISS).

[3-69]

On board ARIANE 503 was a 'non-paying guest': the 'Atmospheric Re-entry Demonstrator' ARD. The contract for this vehicle, in shape rather similar to the Mercury capsules launched by the US around 1960, was granted in 1994 to Aérospatiale. But the ARD was unmanned and only built with the intention to test new technologies for a next generation re-entry vehicles. The ARD configuration was tested extensively in the HST and SST to determine its stability during descent. The final test during re-entry was a success. At about the same time NASA and ESA decided on a joint program for the X-38 development, the 'Crew Transfer Vehicle' or CTV. This re-entry configuration was intended to be used as a 'lifeboat' for the 'International Space Station' (ISS) in case of a quick emergency evacuation. The X-38 configuration was extensively tested as well in the HST [figure 3-69], but the project was stopped in 2002.

Two other rather unusual tests were related to the above mentioned space activities. In the early nineties a special test set-up was made on the lower wall of the test section of the HST and SST respectively for testing various types of heat protection materials to be used in a re-entry shield. The intention of the tests was to see if these materials could stand a highly fluctuating pressure field. This was achieved in the tunnel by placing the test specimen in a highly fluctuating flow field underneath a big vortex. Another unusual test was done for Fokker Space in the mid nineties. Fokker Space had obtained a contract to recover a booster of ARIANE 5 to study the status of the booster after the launch, also for a possible re-use. A system of parachutes had to be deployed after the boosters were pushed off. To make sure that this system would work, data were required on the stability characteristics of the booster and to this end tests were made to measure the aerodynamic forces on the booster for all possible model orientations in the SST. After the third ARIANE test (503) one of the boosters was indeed safely recovered.

VALIDATION OF COMPUTATIONAL FLUID DYNAMICS

In the previous sections examples were shown of some early experiments in support of theoretical developments. The supersonic ring-wing experiment [figure 3-39] and the arrow wing of the ANCP program [figure 3-41] are typical examples. At that time theoretical design methods were still in their infancy. Actual wing designs, such as the wing for the F28, were largely based on a process in which various wing designs were measured in the wind tunnel in comparative tests to select the best one for further development. During the supercritical wing development in the seventies (the SKV program; page 78) the optimum wing shape was determined from an inverse design method: the wing shape was calculated from a prescribed pressure distribution, the so-called 'target pressure distribution'. A wind tunnel model was made to see if the target pressure distribution was approximately met and to determine if the required aircraft characteristics at the design condition (notably drag and pitching moment) and at off-design conditions (e.g. maximum lift and buffet boundaries) were acceptable. If not, the target pressure distribution was to be modified and the sequence was to be repeated.

At that time the results of the 'direct methods' (calculate for a specific wing shape the corresponding pressure distribution for an angle of attack and Mach number combination) were only approximate. In the NLR panel method, compressibility effects were approximately accounted for, shockwaves could not be calculated at all and viscous effects were neglected. The precise characteristics of the wing at the design point could only be obtained from a wind tunnel test. But as a result of the ever increasing computing power, new numerical methods such as 'finite difference methods' advanced rapidly. In these finite difference methods the complete flow field around an aircraft is divided into a large number of 'cells' (the 'numerical grid') and in each of the corner points the flow conditions can be calculated by solving the appropriate flow physics expressed as 'finite difference equations'. The first finite difference code, for airfoil sections only, was written in the mid seventies by Garabedian and Korn from the Courant Institute (NYU) in the US. A copy was obtained at NLR and flows with shock waves could now be calculated and compared with data from two-dimensional airfoils measured in the PT. Some years later the VGK code was obtained from RAE in England as part of an exchange of computer codes. VGK stands for 'Viscous Garabedian Korn' and included viscous effects, essential for the evaluation of the airfoil drag. This code was also validated against results from two-dimensional airfoils and played an important role in the wing development program. The first three-dimensional method that could calculate flows with shocks (a so-called 'full potential method') was obtained in 1979. This code, named FLO22, was developed by Jameson of Princeton University in the US. The code was immediately modified by NLR to include the effects of a fuselage (XFLO22; X stands for the cross flow that was added as a boundary condition to simulate the fuselage) in order to use it for the Fokker wing designs. To tests its abilities, comparisons were made with test results obtained in the HST as part of the F29 and MDF-100 development.


[3-70]

[Figure 3-70]

The wing of the 'International Vortex Flow Experiment' (IVFE), used to validate Euler methods.

The new discipline of simulating the complete flow around an aircraft on a computer is named 'Computational Fluid Dynamics' or CFD. The CFD methods improved rapidly in the eighties. NLR developed its own finite difference full potential method ('MATRICS') and this code was further extended to include viscous effects ('MATRICS-V'). It was extensively used to calculate the detailed drag characteristics of new wing designs. At about the same time, in the mid eighties, the first Euler codes appeared such as FLO57, also developed by Jameson. With Euler codes, flows with vortices, as can be found on the upper surface of fighter airplanes with delta wings, could be calculated. This is an important improvement since similar flow phenomena can also occur on transport type wings when flow separation occurs at off-design conditions. It was only one final step further to add the viscous terms resulting in the solution of the (time averaged) Navier-Stokes equations, an exact representation of the actual flow except for the details of flow turbulence. The resulting computer code developed by NLR in a co-operation with CIRA (the Italian sister institute of NLR) was named ENFLOW.

These computer codes became so powerful that the question was sometimes asked: '*Will the computer replace the wind tunnel*?'. Before the wind tunnel can be replaced, one has to make sure that the computer codes give accurate results and it makes sense to use the wind tunnel to validate the calculated results. The validation of these new codes was a common interest of aeronautical research laboratories. It stimulated a close co-operation within organisations such as AGARD, GARTEUR (a European co-operation that The Netherlands joined in 1977), various Technology Programs of the European Commission (Brite/Euram and the subsequent Framework Programs) or IEPG (the Independent European Programme Group, a military co-operation). The HST was involved in many of these programs. The first finite difference codes were validated in GARTEUR against a number of well-known wings such as the M6 wing of ONERA and the DFVLR-F4 wing that was tested in the HST in 1980. In 1985 a delta wing was tested in the HST [figure 3-70] as part of an 'ad-hoc' co-operation between NLR, AFWAL, FFA and DLR. These parties agreed to this experiment to prove that the new Euler codes were capable of capturing vortices of the type that can be found above delta wings. This co-operation was rather successful and a nice example of a close interaction between theory and experiment. It was exciting to see for the first time how a computer code could calculate a vortex 'out of the blue'[DD], giving excitement similar to the first calculation of shock waves about 10 years earlier. In 1988 ICAS (The International Council for the Aeronautical Sciences) decided to award the participants the 'Von Kármán Medal' [figure 3-71].

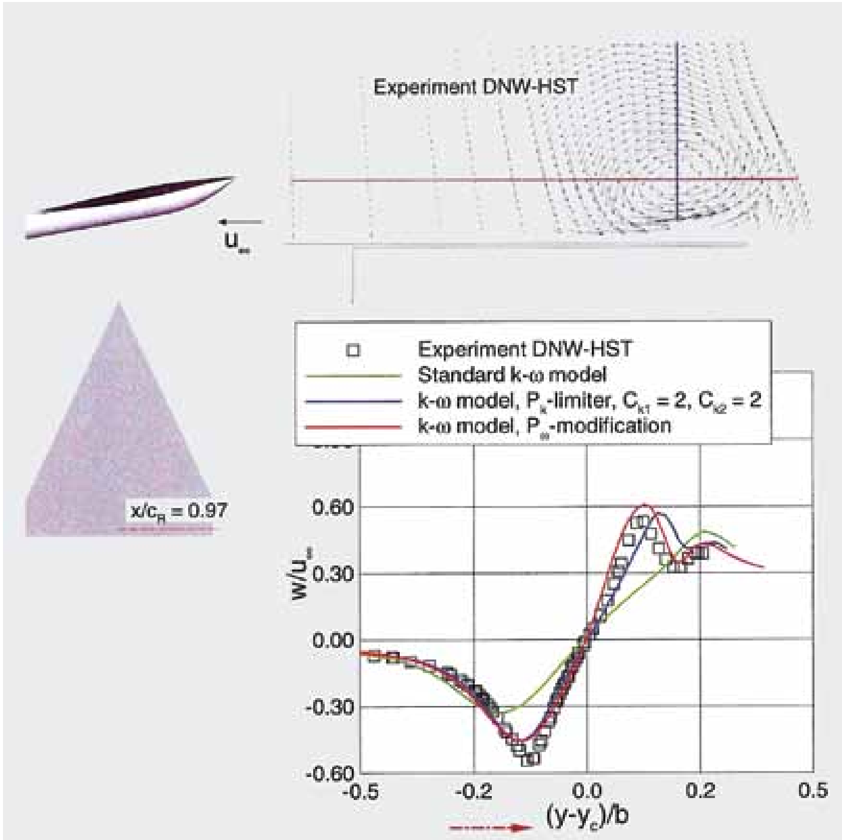

[3-71]

[Figure 3-71]

The 'Von Kármán Medal', an award given by ICAS for the 'International Vortex Flow Experiment' (1988).

In some cases detailed information was required to validate and improve the CFD methods. Around 1986 a very extensive study was also made within GARTEUR (by the Action group AD-AG08) of the viscous effects on a (two-dimensional) airfoil section with high lift devices (with slat and flap). It was specifically required to make detailed measurements of the boundary layer on the airfoil surface. A special mechanism was designed to move the tiny probe through the thin boundary layer (discussed at page 59). The same mechanism was used later to probe the vortex flow above a delta wing (the same geom-

[DD] VORTICES ARE THE RESULT OF FLOW SEPARATION, CAUSED BY THE EFFECTS OF VISCOSITY. EULER CODES ARE BASICALLY INVISCID SO WHY CAN THEY CALCULATE THE VORTEX FORMATION? THE REASON IS 'PSEUDO VISCOSITY' INTRODUCED BY NUMERICAL ARTEFACTS. MOREOVER, THE EULER CODE AT THAT TIME COULD ONLY CALCULATE CONDITIONS WITH MACH NUMBERS ABOVE 0.8 DUE TO NUMERICAL STABILITY. THEREFORE THE EXPERIMENT COULD NOT BE DONE IN A SUBSONIC TUNNEL BUT HAD TO BE DONE IN A TRANSONIC FACILITY.

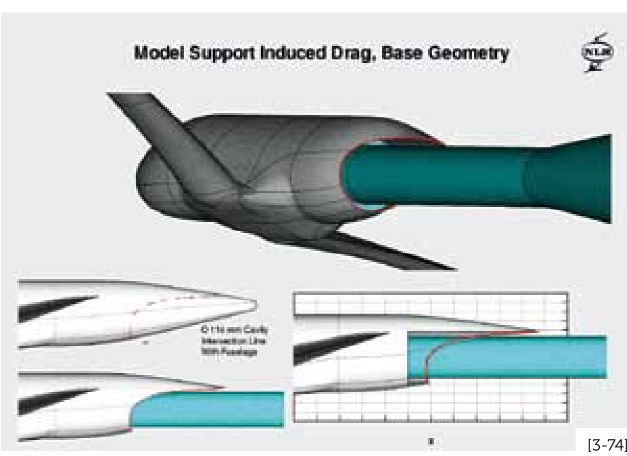


[3-72]

[Figure 3-72]

Example of the flow field measured with the 'Probe Traversing Mechanism' above a delta wing (see figure 2-57). The measurements of the vortex above the wing could be compared with computed results using various expressions to model the turbulence in the vortex.

etry as the wing of the 'International Vortex Flow Experiment') as part of the IEPG-TA-15 project [figure 2-57], a field study that was repeated some years later with 'Particle Image Velocimetry' or PIV, a new optical technique to measure flow fields [figure 2-58]. Results of these tests were compared with computational data. They were used to assess the quality of the computational models for turbulence, still one of the uncertainties in CFD calculations [figure 3-72]. In the early eighties Fokker was hardly involved in CFD validation since all effort was concentrated on the Fokker 100 and 50 development. Support was given by NIVR for the MATRICS-V and ENFLOW development as part of the 'General Research Program' ('*Algemene Research Programma*' or *ARP*). In 1986 the NIVR sponsored 'Airplane Technology Program' or *VTP* ('*Vliegtuig Technologie Programma*') started, was stopped again in 1987 and restarted in 1990. This 'hop on, hop off' situation reflected the delicate financial situation of Fokker and its troubled relation with the Dutch Government at that time. The VTP program was meant to provide Fokker with concepts and tools for a new aircraft type. Wing design was an essential part and a number of different wings were designed with the help of CFD, extensively tested in the HST and compared with the new CFD methods to see where improvements were possible. The MATRICS-V code played a very important role in this respect since it provided the means to analyse in great detail the origins of the various drag contributions. This in turn opened the way for improvements. Later the same code was used to assist the Indonesian Aircraft Company IPTN and the Brazilian Company EMBRAER in the development of new transonic wings, resulting in wings that were also tested in the HST.



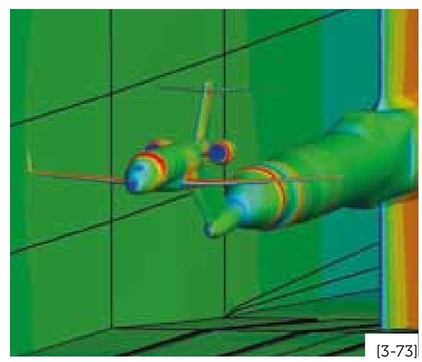
[3-74]

[Figure 3-74]

Computer simulation of the flow near the rear of a wind tunnel model with and without sting mounting. In such calculations detailed information can be obtained of the interference effects, including the pressures in the gap between the sting and the model (2003).

THE WAY AHEAD: WIND TUNNELS AND COMPUTERS WORKING TOGETHER

'Will the computer replace the wind tunnel?' It is obvious that the computer has radically changed the design process of aircraft. This was already the case before the computer provided a full simulation of the flow, as was illustrated at page 78 with the Supercritical Wing Project (SKV). In the mid-nineties the point was reached that the full time-averaged Navier Stokes Equations could be solved on the computer. This meant that the 'real flow' including the effects of compressibility, vorticity and turbulence could now be simulated. Developments in wind tunnel test techniques progressed to the point that aircraft configurations could be measured in the wind tunnel in great detail, including the presence of turbofan engines or propellers. The measurement data also showed much more detail. At the start of transonic testing in the sixties force and pressure measurements formed the core of nearly all measurement campaigns. But later developments allowed much more detailed pressure information on the model and in the flow field such as wake rake surveys for drag and flow field assessment.


[3-73]

[Figure 3-73]

A computer simulation of the flow around a model in the wind tunnel. Note the detailed representation of the tunnel geometry including the slots on the tunnel wall (2009).

This in turn allowed a more extensive validation of the numerical simulations. If CFD is used to simulate the flow over entire aircraft configurations in great detail, why not use CFD to simulate the flow in the wind tunnel itself?

The European sponsored HiReTT program, which covered the period between 2000 and 2003, focussed on high Reynolds number testing including a substantial effort to quantify wind tunnel corrections such as support interference, wall interference and wing deformation. This was done to enhance the validation process. Are differences between CFD calculations and wind tunnel tests caused by flaws in the CFD method or errors in the wind tunnel measurements? Figure 3-74 gives an indication of the amount of detail that can be achieved in CFD to represent the sting support of a wind tunnel model. In this way various elements of the sting interference corrections can be separated and compared with the corresponding parts obtained from wind tunnel procedures (such as base pressure measurements and sting interference tests). Figure 3-73 provides another example of the flow calculated inside the slotted test section of the HST. The flow in and out of the slots, the most critical element of the wall interference, can be quantified in this way. And the results can be compared with pressures measured on the tunnel walls. As noted before some wall interference assessment methods are based on measured wall pressures to derive the corrections by computation. By confronting the CFD results with detailed wind tunnel data both approaches can be validated.

Although the Navier-Stokes equations represent the 'real flow', a fundamental weakness is still the so-called 'turbulence modelling', the representation of the turbulence in boundary layers, wakes and vortices. These effects are approximated in the time averaged Navier Stokes equations by 'turbulence modelling', since it would take unrealistically long computing times to solve the full, time-accurate Navier-Stokes equations (the time scales for turbulence are very small). Wind tunnels represent the real flow (though most often at a lower than flight Reynolds number) and somewhat 'contaminated' by wall and support interference effects. Wind tunnels have the additional advantage that many flow situations (in terms of Mach number and model orientation) can be measured rapidly once the model is available. Numerical simulation of all these conditions will take a long time and will be expensive. Model changes, however, are easier made on the computer. Both techniques have their pros and cons. They supplement each other.

For decades aircraft manufacturers have used CFD and wind tunnel testing in a joint approach to obtain the best answer in the shortest possible time. If the accuracy and reliability of the aerodynamic data are to be increased even further, CFD and the wind tunnel should work closely together to understand the limitations of each approach and to improve the CFD and wind tunnel methods wherever possible. ■

Epilogue

The history of the HST and SST has been documented in this publication for the period between 1945, the end of World War II and March 1996, the end of Fokker. Both tunnels, the HST and SST, continued to operate after that, but it is too early to write the history of the more recent time. In March 1996 the Fokker Company went bankrupt. It might be argued that Fokker was too small anyhow and that Fokker missed the opportunities to integrate within Airbus. Or that a well managed industrial policy by the Dutch Government, as exampled just after World War II by the foundation of NIV and the support for the new wind tunnel plans, was replaced by an attitude of non-involvement. Or that the leadership within Fokker failed. But the final result was the same: the dream of the 'Tromp Committee' in 1946 and of Van der Maas, the visionary chairman of the Foundation NLL during the construction of the HST and SST, the dream of an aircraft industry with a '*full design and development capability*' shattered.

Of course this had great consequences for NLR. Not only Fokker as the main customer disappeared, but also the incentives to develop new technologies, to improve the measurement capabilities to meet the Fokker requirements, the sensation to be part of the fierce competition in aircraft development. These incentives no longer originated from a company that was even literally close to NLR and its predecessor RSL right from the beginning in 1919.
It was realised at that time that NLR had to find a new way, a way that was based on the NLR capabilities that were developed over the years and that could match those elsewhere in Europe. Of course, Fokker was the main customer but on average, roughly one third of the wind tunnel testing time was devoted to tests for Fokker and the other two thirds came from customers abroad. Technology development was, of course, not exclusively owned by Fokker. Through AGARD and GARTEUR the playing field for technology development was already enlarged from a national to a European scale. Moreover, the European Commission actively supported technology development, starting with the Brite-Euram program in 1989 and continuing in Framework Technology Programs that grew bigger and bigger every year. And to bridge the gap after the fall of Fokker, the Dutch Government acted swiftly to announce support for two major aircraft programs, a Dutch participation in the Airbus A380 development and in the Joint Strike Fighter (JSF).

In 1997 NLR went through a process of 'reorientation'. Basically, NLR shifted its attention more towards aircraft operations, including air traffic management and safety. Research activities related to aircraft design were cut back, though less so for structures and materials (to support Stork that had taken over part of the Fokker capabilities to build aircraft parts for the A380, the JSF and other aircraft types). Nevertheless, the basic organisation remained roughly the same and it was not until 2004 that the NLR organisation reflected a new approach, also in management style. In this new organisation Aerodynamics moved closer to Structures and concentrated on Computational Fluid Dynamics (CFD), all within the Division Aerospace Vehicles.

When the new tunnels were conceived just after the War, Van der Maas, the chairman of the Foundation NLL at that time, realised that wind tunnels such as the HST and SST had to operate across the border. As a result the AICMA contract promoted the use of the HST on a European scale. When a new large low speed tunnel had to be built, NLR and its German counterpart DFVLR (now DLR) decided to join their efforts in a large low speed facility, the German-Dutch Wind Tunnel DNW. This tunnel was built at the NLR site in the Noordoostpolder and inaugurated in 1980. Right from the beginning, this tunnel became one of the Airbus wind tunnels. This joint operation triggered a closer co-operation between DLR and NLR, notably on all aspects of wind tunnel testing. In 1994 it was decided to incorporate into the DNW organisation the smaller low speed wind tunnels as well, the NWB in Braunschweig and the LST in the Noordoostpolder[EE]. After a period of two years a full integration took place. There was an important contractual clause: when the occupancy of a particular facility was below a certain percentage (the 'Z-factor', expressed as the ratio between income from the customers and exploitation costs) that facility could be handed back to the parent institute. This clause gave the incentive to actively attract new customers and to operate the facilities as efficiently as possible. Following these steps, it made sense to incorporate the HST and SST as well into the DNW organisation. In July 1997 agreement was reached with DLR to extend the DNW organisation with the big transonic and supersonic facilities in Germany and The Netherlands, notably the TWG (the Transonic Wind tunnel of Göttingen), the HST, the SST as well as the Engine Calibration Facility (ECF). The Pilot Tunnel (PT or PHST) had to be closed and the CSST was closed some time later. The name of DNW (German Dutch Wind Tunnels) was kept for this much expanded organisation after a 's' had been added. The big tunnel that was originally named DNW was renamed 'Large Low Speed Facility' or LLF. The parent institutes remained responsible for new investments in the DNW wind tunnels and a certain volume of research support had to be guaranteed by the parents.

In 1997 the HST and SST became the Amsterdam Business Unit within the DNW organisation. Somewhat later for reasons of efficiency the organisation was simplified into two Business Units, GUK and NOP/ASD with HST and SST as part of the latter. DNW expanded considerably its acquisition activities. European companies, e.g. Dornier with the Dornier 728 regional aircraft, Aermacchi with the military trainer M-346 and EADS with the refuelling boom for the tanker version of the A330, found their way to the HST. New customers could be attracted from outside Europe like CESSNA, Bombardier, EMBREAR and various Chinese aircraft companies. In view of the Dutch involvement with the Joint Strike Fighter, the Boeing configuration was tested in the HST at the time that Boeing and Lockheed were still in competition for the final contract[FF]. As part of some European programs like EUROSUP (for the development of a new generation supersonic aircraft) and HiReTT (for High Reynolds number Testing) tests were executed in the HST and SST involving research groups from NLR and DLR. The development of new measuring techniques, like pressure paint and the integration of data acquisition and computer controlled wind tunnel operation continued now by joining the DLR and NLR capabilities. In this way all DNW tunnels could remain competitive. And today the HST and SST are still among the first in transonic and supersonic wind tunnel testing.

One might wonder why these facilities have kept their rather unique position although the market for wind tunnel testing has changed considerably over the years. The most obvious explanation is that it was realised from the beginning that wind tunnel testing needs an international environment to maintain a leading international position. AGARD, the AICMA contract, DNW, an active participation in GARTEUR and European programs and finally the further development of DNW have been crucial in this respect. Another reason has been and still is the active involvement of the parent institutes in support of wind tunnel testing. The development of electronic equipment, the workshops for model manufacturing and mechanical systems for the tunnel and the close relation with CFD are crucial in this respect. The fact that the essential knowledge can now be drawn from two research institutes provides an added value. Of these, the interaction with CFD has to be stressed specifically. Aerodynamic theory, later followed by CFD, went hand in hand with wind tunnel testing. The theoretical design of the throat for the HST in 1960 marked the starting point for the design of shock-free transonic flow a decade later. The HST slots were optimised by aerodynamic theory. Many experiments in the wind tunnel have supported the development of new computational methods and their validation. The point has been reached that wind tunnels and CFD have a comparable capability to model very fine flow details, though each with its own limitations. If the two are combined, if CFD is used to master the wall and support interference effects, if the wind tunnel is used to check and validate CFD calculations for new, unusual configurations, both approaches will benefit from each other. In this way the reliability and accuracy of both wind tunnel testing and CFD can be improved further. To this end the parent institutes of DLR and NLR work closely together with the DNW organisation. There is still a bright future ahead for wind tunnel testing. ■

[EE] THIS NEW LOW SPEED TUNNEL IN THE NOORDOOSTPOLDER WAS COMMISSIONED IN 1983 TO REPLACE THE OLD LOW SPEED WIND TUNNELS NO. 3 AND NO. 4 IN AMSTERDAM THAT WERE WORN OUT COMPLETELY.

[FF] FINALLY THE LOCKHEED CONFIGURATION WAS SELECTED AND EXTENSIVELY TESTED IN THE LLF OF DNW.

Appendices

APPENDIX A
THE PERFORMANCE OF THE HST OVER THE YEARS

In a wind tunnel the flow around an aircraft is simulated on a small scale model of the aircraft. The results obtained for the smaller model are valid for the aircraft in flight provided two characteristic numbers are duplicated: the Reynolds number and the Mach number.

The Reynolds number is the ratio between the inertial forces (acceleration and deceleration of the flow due to pressure differences in the flow) and the viscous forces (effects of viscosity that lead to turbulence and wall friction). It is defined as:

$$Re = \frac{V.\rho.\ell}{\mu}$$

with V the reference flow velocity (or speed of the aircraft), ℓ a typical length scale (e.g. the mean wing chord defined as the average length measured between the leading edge and the trailing edge of the wing), ρ the density and μ the dynamic viscosity of the air. Pressurization of the tunnel, as can be done in the HST, increases the density and hence the Reynolds number.

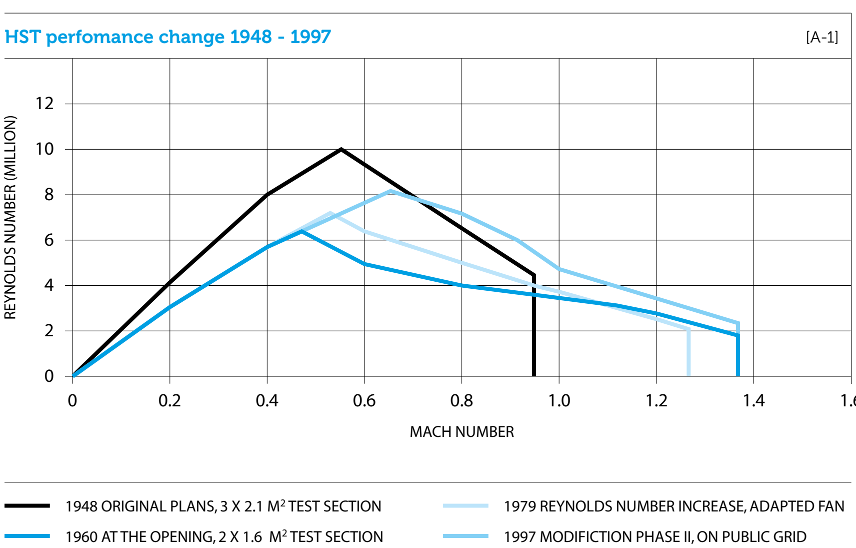
For aircraft the value of the Reynolds number is typically 10 to 50 million, depending on size and speed. This indicates that the frictional forces are generally small. But even these small frictional forces are important, since they determine the separation of the flow over the surface: when the Reynolds number becomes too small the flow breaks away from the surface and this situation is no longer representative for flight conditions. In the low speed tunnel LST of NLL the Reynolds number based on the mean chord was typically 2 million. In the report that described the plans for the new wind tunnels[11] a rather challenging requirement of 10 million is mentioned. It is not necessary that the flight Reynolds number is exactly duplicated. The remaining differences can be accounted for by 'Reynolds number extrapolation', specific procedures to 'scale up' the wind tunnel test results.

The Mach number is the ratio between the flow velocity (speed of the aircraft) and the speed of sound, defined as:

$$Ma = \frac{V}{a}$$

with V the reference flow velocity and a the speed of sound. Contrary to the Reynolds number the Mach number should normally be duplicated exactly in the wind tunnel tests. This is even more critical for higher Mach numbers. The 'sound barrier' is attained for Ma = 1. On October 14, 1947 Chuck Yeager broke the sound barrier with the experimental airplane Bell X-1. At that time breaking the sound barrier in a wind tunnel was still very problematic due to a phenomenon called 'choking'. This is the result of the formation of shock waves in the test section when the flow velocity locally exceeds the speed of sound.

The performance of a wind tunnel is conveniently expressed in the Reynolds number - Mach number plane [figure A-1]. The Reynolds number is always related to a characteristic length. Since the model size depends on the dimensions of the test section it is common practice to use the length ℓ defined by $\ell = 0.1\sqrt{A}$ (with A the cross sectional area of the test section) as a typical measure. Due to the anticipated problems of choking around Ma = 1, the maximum



[Figure A-1]

Evolution of the HST performance over the years.

Mach number in the original design of the tunnel was set at 0.95. The operational envelope of the tunnel is bounded by two other constraints. For low Mach numbers the strength of the tunnel shell limits the maximum tunnel pressure, for the HST set at 3 bar over pressure. The power required to move the air around is proportional to the third power of the velocity in the test section. So with increasing tunnel velocity or Mach number the performance of the tunnel is limited by the available power. This happens for the HST roughly beyond Ma ≈ 0.6. At supersonic conditions the achievable Mach number is determined by the shape of the (adjustable) nozzle upstream of the test section and the fan characteristics. See also Appendix E.

In the original design of the HST the option to exchange models between the big low speed tunnel LST (test section 3 x 2.1 m²) and the high speed tunnel was an important requirement. By pressurizing the HST, the Reynolds number could be increased significantly, also at low speed conditions (with typically Ma ≈ 0.2). In this way a much better Reynolds number could be realized for take-off and landing conditions. The idea was that most of the low speed development work could be done in the (cheaper) LST. The model could then be transported to the HST for complementary tests at higher Reynolds numbers. For the high Mach number end Fokker required that the tunnel pressure should still be atmospheric to avoid that valuable time would be lost during the evacuation of the tunnel. This latter requirement in combination with the cross sectional area, set the required power at 20,000 hp. The power plant was built according to this specification which resulted in a performance envelope as indicated by the black line in figure A-1.

Around 1952 it became clear that a transonic test section could be made with ventilated tunnel walls (see page 18). As a result the maximum Mach number could be increased till Ma = 1.35 to create some overlap with the planned supersonic tunnel. With the available power (the power plant was almost ready, the steam and turbo-electrical installations had already been bought) the tunnel pressure would fall below atmospheric at the highest Mach number. Fokker also indicated in report A-84[21] that it favoured smaller wind tunnel models and was prepared to drop the compatibility with the LST models. Test section dimensions of 1.6 x 2 m² were finally selected. This also meant a decrease in Reynolds number at lower Mach numbers since the models were reduced in size. In the figure the performance, after the tunnel had been built, is shown with the dark blue line.

Around 1975 there was a strong wish from Fokker to increase the Reynolds number at the anticipated cruise Mach number of about 0.8 for the next generation aircraft. A 20% increase in Reynolds number was feasible by modifying the tunnel drive system. The tunnel drive system consisted of four rows ('stages') of 22 fan blades each, with stator blades in between. This configuration was optimized to have the best efficiency at the highest Mach number. The optimum could be shifted to lower Mach numbers by taking out the 2nd stage (second row of blades) and taking away half of the blades of the 3rd and 4th stage. However, this reduced the highest Mach number that could be tested: a reduction from 1.35 to 1.25. See the light blue line in the figure.

Not until 1997 with the Phase II modification the maximum operating Mach number could be increased again, even in combination with a significant increase in Reynolds number capability. First of all, since all fan blades had aged and needed replacement anyhow, the entire tunnel drive system could be redesigned for improved efficiency. This new drive system consisted of three stages with 22 blades each, made 'in house' out of carbon fibre. Secondly, the steam boilers and turbo-electric installations became obsolete for a number of reasons (environmental restrictions, flexibility, availability of a nearby power station). A new engine could now be coupled directly to the public grid. The four original engines for the HST could deliver 5,000 hp (3.8 MW) each. But since the HST was originally designed for a maximum of 25,000 hp (19 MW) this full capability could now be used, giving a further boost in maximum Reynolds number as indicated in figure A-1. ■

APPENDIX B
THE COSTS OF HST AND SST

In the report of the 'Tromp Committee' of March 20, 1946 indications were given of the investments necessary to enable aeronautical research at NLL to support the Dutch industry. At that time the estimate amounted to 3 million guilders for NLL as a whole, including new buildings, the plans for new wind tunnels and a laboratory aircraft. It was estimated that the high speed tunnel (HST) required an investment of 1.6 million with the remark '*that NLL is working on a more accurate cost estimate*'.
It is clear that this first estimate was far too optimistic. Subsequent estimates for the HST only (but including part of the costs for the power plant) showed a rapid increase of the costs (in millions of Dutch Guilders HFl) [shown in table B-1].

In 1949 the total costs for the new wind tunnel plans amounted to 16 million including the costs for the Low Turbulence Tunnel LTT, the Pilot Tunnel PT and a small supersonic tunnel SST. These estimates were also used in the report of the 'Small Aircraft Committee' that was issued on February 19, 1949. In spite of the increased costs the Committee concluded that the new wind tunnel plans should be executed as planned. As noted at page 17 the Government was not at all pleased with this advice and asked the Committee to reassess the situation. In the meantime all building activities for the new wind tunnels were put on hold. It is quite possible that the rapid increase in investment costs over a period of about three years played an important role

[Table B-1] Cost increase for the HTS only (between 1946 and 1949)

	Cie 'Tromp' March 1946	November 1946	February 1947	February 1948	February 1949
total costs for the HST (million HFl)	1.6	4.7	7.5	10.6	12.4

[Table B-2] Cost summary in BDM report (Spring 1950)

	HST	Power Plant	PT	SST	LTT	Total
total costs (million HFl)	11.25	4.19	0.71	1.00	2.88	20.03
ready	3.42	2.41	0.35	0.02	0.59	6.79
ready (%)	30%	57%	50%	2%	21%	34%
still to be done	7.83	1.78	0.36	0.98	2.29	13.24

[Table B-3] Costs as approved by the Government (March 1952)

	HST	Power Plant	PT	SST	Terrain Provision	Total
total costs (million HFl)	10.00	4.00	0.71	0.82	0.10	15.63
ready	3.42	2.41	0.35	0.02		6.20
to be done	6.58	1.59	0.36	0.80	0.10	9.43

in this decision. Even after the commitment by the Dutch Government in November 1949 to continue the support of the Dutch aeronautical industry, NLL was not allowed to continue the new wind tunnel plans and was forced to lay off 59 people. In the spring of 1950 the Government requested a reappraisal of the investments and the exploitation costs. This was done by the 'BDM Committee' (so named after Blackstone, Damme and Van der Maas), which issued a report in March 1950. In the Appendix of this report the financial situation was summarized as follows[114] [table B-2].

The estimated total costs of 20 million exceeded the 1949 estimate by another 4 million HFl. It was probably realized that some kind of cost reduction was inevitable. The Committee advised to drop the Low Turbulence Tunnel LTT but even in that case an amount of 11 million was required to complete the (adapted) new wind tunnel plan. New negotiations started with the Government and this finally resulted in a commitment of the Dutch Government to provide an additional 9.43 million HFl.

NLL was forced to reduce costs as described in a note[115] [table B-3]. In the meeting of the NLL Board of March 1952 chairman Van der Maas informed the other Board members that the new wind tunnel plans could be finished on the basis of an additional budget of 9.43 million HFl. Some Board members asked for a strict cost control. A small group was formed, under the direct guidance of one of the NLL directors, to achieve this. Unfortunately detailed records of the cost development up till the point in time that the tunnels became operational are not available. Table B-4 below gives a low and very tentative estimate of the costs at the moment the tunnels were finished. These estimates are partly based on information provided to the NLL Board (balance sheets of December 1959 and 1960).

It should be noted here that for various reasons these numbers cannot be compared directly to the estimates of March 1952. Since that time the wind tunnel plans had been adapted: a smaller test section with slotted walls for the HST, a much larger SST combined with the CSST instead of the originally planned small supersonic tunnel. Note also that the contract for building the HST was granted to a new contractor, costs being the main incentive. The complete test section was sub-contracted to the company Dätwyler & Hausammann and the external balance was dropped. Moreover, the high pressure system (pressure vessel and compressor) served both the HST and the SST. Its costs have been included here in the Power Plant costs, but originally they might have been partly included in the HST costs. Moreover, the table does not include all costs, e.g. the costs for instrumentation were taken from a special instrumentation budget. These were not minor expenditures: between 1958 and 1963 18 external balances were purchased for 1.2 million HFl. NLL probably wanted to show to the Government that the costs were well in hand. The figures suggest that this was indeed the case.

In the above referenced note[115] the future exploitation of the new wind tunnels was also addressed. In fact some of the specific recommendations had already been suggested by the BDM Committee. They clearly reflect the view that NLL existed for the customers, (nearly) all of them represented in the Board of the Foundation NLL. The tariffs for the work done under contract were based on a balanced exploitation with a total yearly expenditure of about 1.6 million HFl (year 1955). On the income side roughly 1/3 came from subsidies provided by the Government and the remaining 2/3 followed from contracts with customers. The estimated income from these clients can be specified as follows (also taken from a 1950 prediction for the year 1955) [see table B-5].

Note that these figures relate to all the work done by the various NLL departments for the external customers, including the work done in the wind tunnels. Who paid for the investment costs of the new wind tunnels? An estimated 1.8 million HFl had to be paid yearly to cover the interest on and instalments for the 'loans' obtained by NLL for the new wind tunnels. In the BDM report it was recommended that the Gov-

[Table B-4] Tentative estimates of final costs (1960)

	HST	Power Plant	PT	SST	Total
total costs (million HFl)	7.70	4.70	0.70	3.50	16.60

[Table B-5] Predicted total NLL income from contracts (made in 1950 for the year 1955)

	NIV	Fokker	Air Force	Navy	RLD	KLM	Other	Total
total income (million HFl)	0.500	0.035	0.145	0.090	0.090	0.035	0.025	0.920
interest and instalments to be paid on investments								1.800

ernment would provide this money to NLL as a subsidy. NLL would then return this to the Government as a payment for interest and instalment. In other words, the Government was asked to cover all investment costs. To assure continuity in the exploitation it was also suggested to enforce that each customer would yearly guarantee a specified amount of money for contract work. This amount still had to be paid even when there was less work to do. In that case it was allowed to 'trade' this deficiency with other customers. It is not clear if these recommendations were effectuated, but it seems highly unlikely.

The proposed arrangement is neither very practical nor very effective in controlling the costs and income. In hindsight it is quite clear that the tariffs for using the wind tunnels should be based on the actual costs made for doing the wind tunnel tests rather than a kind of 'general tariff' for all activities. The AICMA contract (see page 66) might very well have provided the incentive to adopt a more transparent way to calculate the tunnel tariffs. In [table B-5] contracts from the European (non-Dutch) aircraft industry are part of the 'other customers' estimate and represent less than 3% of the total income. But due to the AICMA contract the income side changed completely. The AICMA members were willing to pay a fair price for use of the HST and SST and the contract that resulted reflects some of the elements discussed above. NLL reserved 50% of the HST tunnel time for AICMA members with a minimum occupancy of 10% guaranteed by AICMA. The true exploitation costs had to be paid based on 250 occupancy days. The tariff structure was further based on depreciation over 10 and 25 years for the installations and the buildings respectively. Non-AICMA members paid an additional 10%. And, most attractive for the Dutch customers, customers that were represented in the NLL Board (such as Fokker and NIV) did not have to pay the depreciation costs at all. For the first 10 years of HST and SST this was a very good deal indeed: the foreign customers paid a large part of the investment costs for the tunnels [see also figure 3-16]. This became less obvious in later years. For various reasons the number of occupancy days for foreign customers decreased, whereas the investment costs for the tunnels increased steadily, notably for the ongoing modernisation of the tunnels and related equipment. ■

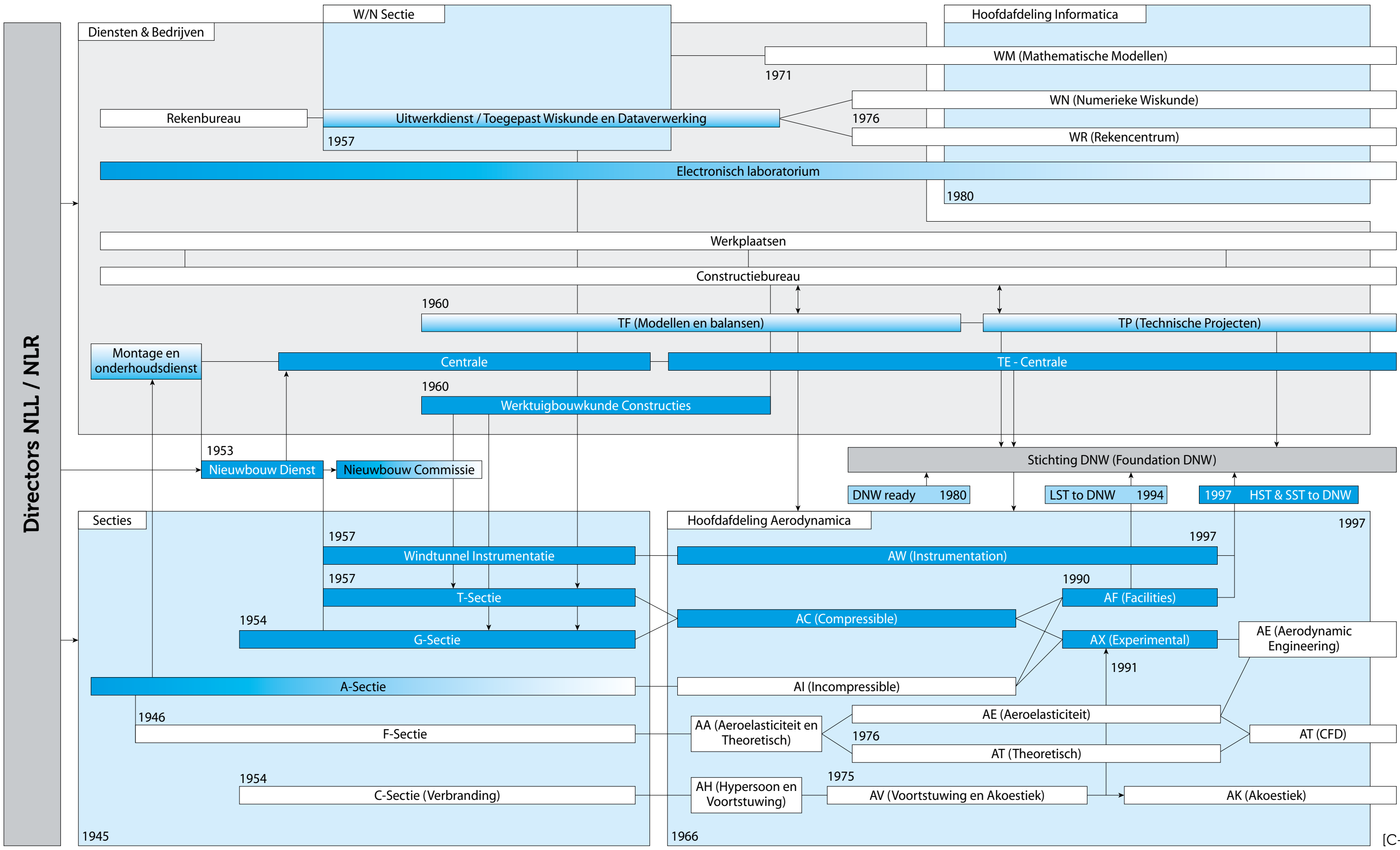
APPENDIX C
HST AND SST WITHIN THE NLR ORGANISATION

Just after World War II NLL had 138 employees. The new role of NLL as envisaged by the 'Tromp Committee' in 1946 clearly required a rapid expansion. The new wind tunnels were only a part of these expansion plans. The development of the NLL and later the NLR organisation as far as relevant for the development of the high speed wind tunnels has been depicted schematically in figure C-1. This rather complex figure shows that the organisation had to be adapted permanently to respond to the needs at that time. During the period between 1945 and 1997 the number of NLL/NLR employees increased from 138 to about 900. Of course this had a big impact on the organisation. With the new wind tunnel plans the interaction between wind tunnels and other disciplines such as electronics, data reduction, instrumentation, power generation, model design and manufacture also became more and more important and necessitated organisational changes.

In 1945 NLL had organised itself along two lines: the Main Department ('*Hoofdafdeling*') grouped around 24 university graduates ('*ingenieurs*') and the supporting Sub-departments ('*Onderafdelingen*') with technical and administrative personnel to support the Main Department. The Main Department was split in 4 sections: Aerodynamics, Aircraft, Strength and Materials. The expansion of NLL in 1947 concentrated on an increase of the office space (the West wing and the Middle wing were added to the existing building) and on the design and construction of the new wind tunnels. Rotgans, head of the Technical Services ('*Technische Diensten*') was made responsible for all expansion plans and these activities were delegated to the Construction and Maintenance Department ('*Montage en Onderhoudsdienst*'). A number of aerodynamicists in the Aerodynamic Section ('*A-sectie*') guided by De Lathouder, worked on the aerodynamic design of the new wind tunnels. At that time De Lathouder, as deputy head of the Aerodynamic Section, replaced the section head Boelen, who was called for military service in the Dutch East-Indies. Boelen returned in 1948 and De Lathouder became fully responsible for the design of the new tunnels. At the end of 1948 the report on the new tunnels[11] was issued. At that time NLL had 305 employees and of these about 50 worked in aerodynamics. However in 1950, as a result of the Government ordered stop, 59 people had to leave NLR.

When the work on the new wind tunnels was picked up again in 1952, the organisation was changed drastically. In the NLL Board meeting of March 12, 1952 it was announced by the new chairman, Van der Maas, that a team would be formed for the new tunnel activities ('*De Nieuwbouw Dienst*') headed by the NLL Director Boelen. But since Boelen was severely injured in a motorcycle accident, he was replaced by Marx. De Lathouder would be part of this group as well as the young engineer Boel (who came from the Department of Aeronautics of the Technical University Delft). Soon after that Boel became responsible for all new tunnel activities. In the same year De Lathouder got a special position close to the NLL Directors. He left NLL in 1954. As mentioned in Appendix B it is likely that this change was made because the NLL board was not satisfied with the large cost overruns for the new tunnels.

In 1954 the number of sections within the 'Main Department' had increased from 4 till 8 with more than 80 employees. At that time the total number of NLL employees, including all supporting Sub-departments amounted to 230. This reflects an increased diversity in NLL activities. Already in 1946 a Section for Flutter and Theoretical Aerodynamics ('*F-sectie*') was split off from the Aerodynamic Section. In 1946 when Erdmann joined NLL, he became part of the F-Section. Other Sections for Helicopters, Combustion and Free Flight Models followed. Erdmann left NLL in 1951 to work in Sweden (see Appendix D) and when he



[C-1]

[Figure C-1]

The position of the High Speed Tunnels (dark blue) in the NLL / NLR organisation.

returned in 1954, a new section, the Gasdynamics Section ('*G-sectie*') was formed starting with a staff of three. Apparently Erdmann developed the plans for a new supersonic wind tunnel very much on his own, as Boel noted in his confidential note[41]. Boel also suggested to formalize this situation and this was finally realized in 1957 with the formation of a Transonic Section ('*T-sectie*') headed by Boel. A working group ('*Nieuwbouw*') was set up to coordinate all activities between the various sections and technical services.

Other services were organised around the G- and T-Section to support the new activities. During the design and construction phases of the new wind tunnels specific expertise was needed to assess the constructive designs, to prepare contracts with the contractors and for on-site inspection during the construction. This was provided by an Engineering Group (*WeCo* or '*Werktuigbouwkundige Constructies*') headed by Van Leest. In 1954 the operation of the Power Plant was delegated to a separate unit as part of Services ('*Diensten*'). But the operation of the high speed wind tunnels remained at the T- and G-Section.

The new wind tunnels required new instrumentation and its development was pursued at various locations. Specific expertise on wind tunnel test techniques was developed in the A-Section. The Electronic Laboratory ('*E-lab*') was very much involved in electronic measurement techniques and new developments in digitalization. The expertise on strain gauge balances had to be built up almost from scratch. A new group was created for models and balances (TF or '*Modellen en Balansen*') as part of the Technical Services ('*Technische Diensten*') and positioned very close to the construction office and the workshop. Other instrumentation developments were done by a group on Wind Tunnel Instrumentation (WI or '*Windtunnel Instrumentatie*') which operated within the G- and T-Section. This group combined expertise on mechanical, electronic, optical and computer systems. The basic organisational question here is: do the services have to be centralized to form a pool of knowledge for all of NLL or should they operate very close to the 'end-user', a dilemma already noted by Boel in his confidential note [41]. At the end the development of wind tunnel instrumentation was concentrated around the tunnels.

A similar dilemma existed for the processing of all wind tunnel data. In the NLL organisation the Calculating Service ('*Uitwerkdienst*'; a group of mainly women with hand-calculating machines), was tasked with the data reduction for all departments. This group was placed under supervision of the Aircraft Section ('*V-sectie*'). In 1957, with the decision to buy a digital computer, it was decided to concentrate the data processing and the related computer programming and supporting mathematics into a new Applied Mathematical and Numerical Section (W/N or '*Toegepaste Wiskunde en Dataverwerking*'). As a result all data reduction at NLL and later NLR remained centralised in one group W/N. Later this section became part of the Informatics Division. In the seventies, as described at page 54, the advantages of local data processing close to the wind tunnel outweighted the advantage of a centralisation of hardware and expertise within the W/N Section and the data processing was subsequently concentrated around the wind tunnels. However, specific expertise could be provided by the Informatics Division whenever required.

In 1966 the number of employees had increased to about 560. Half of them worked in ten Sections, while the other half was part of the Services ('*Diensten*'). In the T-Section, the G-Section and the Power Plant ('*Centrale*') respectively 44, 36 and 16 people were employed. The organisation had grown beyond its limits of effectiveness and NLR as a whole was reorganised in three Divisions ('*Hoofdafdelingen*') for Aircraft (V), Aerodynamics (A or '*Hoofdafdeling Stromingen*') and Structures & Materials (S). In 1970 the Space Division (R) was added and in 1980 the Informatics Division (I). Within the Aerodynamics Division the low speed wind tunnel activities were concentrated in the Department of Incompressible Aerodynamics (AI) while the high speed wind tunnels were managed by the Department of Compressible Aerodynamics (AC). The instrumentation activities for all wind tunnels were concentrated in the Department for Wind Tunnel Instrumentation (AW). Other departments within the Aerodynamics Division were concerned with Theoretical and Numerical Aerodynamics (AT) and Unsteady Aerodynamics and Flutter (AE). The Department of Hypersonics (AH) changed its activities some time later into Propulsion (AV).

In 1980, the new large low speed tunnel DNW, a joint activity of NLR and its German sister institute DFVLR (later DLR) became operational at the NLR site in the Noordoostpolder. This hardly affected the NLR organisation since DNW could use the existing infrastructure of NLR and DLR. DNW organised its own services for design, instrumentation and data reduction for the day-to-day wind tunnel testing. A few years later, in 1984, another low speed wind tunnel was opened in the Noordoostpolder. This tunnel replaced the low speed tunnels no. 3 and no. 4, which had been operational in Amsterdam since 1940 and were technically worn out. This didn't affect the organisation, except that the department AI had to move to the Noordoostpolder.
In 1982 a photograph was made of all 'inhabitants' of the HST-building [figure C-2]. This picture was presented to Marie Dekker, the lady serving the coffee in the HST building, when she retired from NLR. Nearly all people on the picture worked for the Departments of Compressible Aerodynamics AC (47) and Wind Tunnel Instrumentation AW (21).

For the wind tunnels an important reorganisation was made in 1990. It was felt that the synergy in the operation of the wind tunnels could be improved by concentrating the operation of all facilities in one department ('Facilities' or AF). In this way it was much easier to share equipment among the various facilities. Also the procurement of new instrumentation could be rationalised in this way. The group of wind tunnel test engineers and the research group that made use of these facilities were also combined in one department ('Experimental Aerodynamics' or AX).

Some years later talks were initiated between DLR and NLR on a further integration of all low speed facilities. This integration was made effective in 1994, originally for a period of 2 years and extended later. This started with the operation and the maintenance of the facilities and the related equipment. Although DNW had its own group of test engineers, the test engineers of AX generally remained responsible for the tests in the LST in the Noordoostpolder. In 1997 it was finally decided to include the high speed facilities HST and SST in the DNW organisation. The full operational responsibility was taken over by the DNW organisation, including all test engineers. The parent institutes DLR and NLR provided research support through the existing departments, in particular for the development of equipment and the design and machining of tunnel hardware and wind tunnel models. ■

[C-2]

[Figure C-2]

The 'inhabitants' of the HST-building in 1982. The picture has been taken in front of the main entrance to the building. Nearly all people shown were part of the Departments of Compressible Aerodynamics AC or Wind Tunnel Instrumentation AW.

APPENDIX D THE 'BUILDERS': DE LATHOUDER, BOEL AND ERDMANN

DE LATHOUDER

Ir. J.A. De Lathouder was born in 1911. He studied Mechanics and Shipbuilding at the Technical University in Delft. He joined the Government Service for Aeronautical Studies ('*Rijksstudiedienst voor de Luchtvaart*' or *RSL*) in 1936, just before RSL was split into a regulatory part, the Government Department of Civil Aviation and a research part, the National Aeronautical Laboratory ('*Nationaal Luchtvaart Laboratorium*'). He joined the Aerodynamics Section headed by Boelen. At that time 52 employees worked at the RSL, nine of them university graduates ('*ingenieurs*'). De Lathouder became involved in the design of the new low speed wind tunnels needed to replace the existing Eiffel tunnel. In 1938 it had been decided to build two new low speed wind tunnels of the Göttinger type (tunnel no. 3 and no. 4) and a small pilot facility (tunnel no. 2) to evaluate the aerodynamic design of the larger tunnels. In April 1939 the actual construction started at the new site of NLL, on the outskirts of Amsterdam. A few days after the beginning of World War II, even before the tunnels were finished, NLL decided to move to this new area. In June (tunnel 3) and November (tunnel 4) operation started. De Lathouder led the commissioning and calibration tests which were reported in great detail during the War. He was further involved in the development of measuring techniques and the design of small scale wind mills for local energy production.

In an interview given in 2003[116] De Lathouder mentioned that he was active in a resistance group that operated from the basement of the NLL buildings. He was also a very social man within NLL, involved in many activities of the Employees Society ('*Personeels Vereniging*') notably by leading a Theatre Group. On social evenings he could be seen playing the guitar.

Just after the War he became deputy head of the Aerodynamics Section to replace Boelen during his military service in the Dutch East-Indies. When at the end of 1948 Boelen returned, De Lathouder could concentrate fully on the new wind tunnel plans. He made many trips to various European countries and the US to learn from experiences elsewhere. The trip made in 1946/1947 to the US, together with Wiselius[12], was particularly important. During this trip the new wind tunnel plans were shown for comments. De Lathouder was also the author of the report A.1136[11] that appeared in 1948 and summarized all new wind tunnel plans. De Lathouder himself gave all the credits for the HST design to Wiselius who was already involved in the design of a high speed tunnel during the War[8,9]. Other engineers from the Aerodynamic Section that contributed to the new wind tunnels and related test techniques were Slotboom, Loos, Dobbinga, Wijker, Stam and Zwaaneveld. It is difficult to get a clear picture of the individual contributions of these men, but it is very likely that De Lathouder played an important role in coordinating all new wind tunnel plans. His contribution is certainly impressive considering what was achieved in the short period between 1946 and 1949. The actual construction of the tunnels was well underway in 1949 (see also the table in Appendix B).

In March 1946 De Lathouder and Wiselius were present when Erdmann visited NLL to share information on the design of supersonic wind tunnels[13]. This resulted in the engagement of Erdmann at NLL soon after that. He became responsible for the design of a small supersonic wind tunnel that was included in the new wind tunnel plans.

After the freeze of all building activities ended in 1952, a new team was formed to manage all activities for the new wind tunnels ('*De Nieuwbouw Dienst*'). Formally Boelen, who became one of the NLL Directors, headed this group, while De Lathouder acted as its secretary (Annual Report 1953). This meant effectively that De Lathouder was responsible since Boelen was seriously injured in a motorcycle accident. Boel, who came from Delft Technical University where he had been involved in the design and building of the low speed tunnel, was appointed by Van der Maas to join this group. Within a year Boel became fully responsible for the new tunnels and in 1954 De Lathouder joined the Direction Staff as Engineer in Civil Service ('*Ingenieur in Civiele Dienst*'). He left NLL about a year later on the first of January 1956 and got a position at the 'Dutch Laboratory for Water Quality'. The move to make Boel rather than De Lathouder the responsible manager for the new tunnel plans must have been difficult to accept for De Lathouder. In retrospect it is good to realize that building the HST was an order of magnitude more complex than the building of the two low speed tunnels just before the War. All experience within NLL was based on low speed wind tunnel testing. In his farewell speech of 1956 De Lathouder spoke about the significant 'brain drain' as NLL had to lay off people in 1951. And he told the audience: '*Give us the brains and give us the experience and we'll do the job.*' Part of the problem was that the operation of the HST was so much different from the low speed tunnels that the experience was not available at NLL. Van der Maas must have realized that when he got the chair of the Foundation NLL. By appointing Boel he betted on a new generation of Delft engineers. And Boel, after he got the job, was eager to build such a group of young Delft graduates around him to work on the HST.

De Lathouder died in 2009

BOEL

Ir. J. Boel was born in 1925. He graduated at the Delft Technical University where he was involved in the design of the low speed wind tunnel of the (Sub) Department of Aeronautics. In 1949 Van der Maas asked him to join the Office of the Foundation NLL ('*Bestuursbureau*') as his assistant. He most likely played a role in preparing the report made by the BDM Committee, named after its members Blackstone, Damme and Van der Maas. This committee had to advise on the organisation, the scope and the financial framework of NLL and more specifically on the new wind tunnel plans. In the meeting of the NLL Board of March 1952 its chairman Van der Maas informed the other board members that a special team was to be formed to manage the new wind tunnel plans. Boel was to be part of that team. In April 1952 he joined NLL in Amsterdam and got directly involved in the design of the new tunnels. In November 1952 he wrote a report on the high speed tunnel[31] together with Dobbinga and Slotboom. In the same period he visited aeronautical laboratories in England, Switzerland and the US. In 1953 he became head of the team for the new tunnels ('*Nieuwbouwdienst*').

The year 1956 was apparently a critical phase in the HST design. In that year a Technical Note[40,41] was issued by Boel which summarized what had been achieved so far and what still had to be done (see page 23). This Note described in bullet points what was required. As Besseling, responsible for the strength calculations, noted[117]: '*with Boel things started to move again'*. In a confidential addendum to the Technical Note Boel[41] sketched his view on some more sensitive issues for the higher management. He proposed to make an 'acquisition plan' and a 'research plan'. In the latter plan a distinction was made between 'free research' and 'applied research'. He also realised that the HST would be far too expensive for research and that the PT would be needed in this respect, possibly with an increased Mach number capability beyond Mach = 1. Since it was difficult to obtain professional staff, especially graduates from Delft Technical University, he wanted to invest in people by 'talent scouting', 'traineeships' elsewhere (e.g. at Cornell Laboratories in the US) and participation of the young engineers in defining the research plan. He also noted that NLL had a bad reputation among the young wives of the Delft graduates: NLL didn't help sufficiently in finding proper housing, a difficult problem since there was an extreme shortage of housing. And finally, Boel realised that the organisation had to be changed.
The team that was leading the new wind tunnels was in principle responsible for all new wind tunnels including the supersonic tunnel. However, in practice Erdmann, assisted by his staff in the newly formed Gasdynamics Section ('*G-sectie*'), just developed his own plans. Boel proposed to formalise the existing situation with a subsonic (A-), a transonic (T-) and supersonic (G-) Section and to co-ordinate all building activities for the new wind tunnels in a working group ('*Nieuwbouw commissie*'). This was actually done in 1957. Looking at the future, he raised the question if

these three different sections should remain separated or incorporated in a larger aerodynamic department. He also raised the question how theory and experiment should relate to each other and wondered if it would be wise to concentrate all equipment development into a 'physics' department. To take some work off the shoulders of the section chiefs he advised to appoint group leaders in each section. In a similar way, the operation of the wind tunnels should be left to a separate group ('*het tunnelbedrijf*'). In fact, what is stated in the confidential document is very close to a blue print of the organisation that was effectuated 10 years later in 1967. Boel was a man with real vision in research management.

Boel's star was rapidly rising. In 1967 NLR was reorganised, roughly along the lines that he had already described in 1956. In the same year he became 'adjunct director', next to Marx as 'general director' and Viveen as 'controller'. Part of his assignment was the responsibility for the Scientific Services ('*Wetenschappelijke Diensten'*) including the Electronic Laboratory, the Applied Mathematics group (with the data reduction group) and the Library. He was very active in promoting space research and exploration in The Netherlands as part of a larger European effort at a time that the benefits were not clear at all[118]. As early as 1967 he initiated a department for Space Exploration as part of the Scientific Services. In 1970 that department became a Division ('*Hoofdafdeling*') for Space Exploration.

In the course of 1971 and just prior to the retirement in May of Van der Maas as chairman of the Foundation NLR, a conflict developed between Boel and the general director Marx. As a result of this conflict Boel was removed from active service in April 1971. He left NLR formally in September 1972, very much regretted by many NLR employees, in particular those working in the Aerodynamics Division. For them Boel was the representation of a new *élan* at NLR.

Boel continued to work as an advisor in research management e.g. for the Technical University Delft. He died in 1989.

ERDMANN

Prof. Dr.Ing. Siegfried F. Erdmann was born in Berlin in 1916 (see his memoires[14]). His father was a specialist in the army on ballistics and machine guns and ended as an officer in the Army Weapon Division ('*Heereswaffenamt*'). Erdmann studied at the Technical University of Berlin-Charlottenburg where he graduated (as '*Diplom Ingenieur*') in September 1939 at the time that World War II broke out. A few days later he got an offer to join the Army Research Establishment at Peenemünde ('*Heeresversuchs-Anstalt Peenemünde*' or *HVA-Peenemünde*) and accepted. HVA-Peenemünde was established in 1936 by Dornberger and Werner von Braun on a sealed-off area of the peninsula Usedom in the North-Eastern part of Germany bordering on the Baltic Sea. It was established in great secrecy following promising launches of liquid fuel rockets at the army test site of Kummersdorf-West[119] near Berlin. The most important activity in Peenemünde was the development of the ballistic missile V2, which could carry a load of 1,000 kg over a distance of 300 km. HVA-Peenemünde was a huge complex with well over 10,000 employees. The site had its own power station of 30 MW. There were all kinds of workshops, laboratories, production facilities, a liquid gas plant and many launch sites. A dedicated S-Bahn type public transportation system with a total length of 70 km transported the employees from the small towns along the sea shore to the military site.

In 1939 Erdmann started to work at the 'Aerodynamic Institute' where he became responsible for the measurement techniques in the supersonic wind tunnel that was already in operation[120]. Rudolf Hermann, an aerodynamicist who started his career in supersonic aerodynamics at the University of Aachen under Wieselsberger, led the institute. The tunnel had a cross section of 0.4 x 0.4 m^2 with different fixed nozzle blocks (each set for a specific Mach number) and a vacuum sphere to suck the air through[121]. In the winter of 1941/1942 a big measuring campaign was started to determine the aerodynamic loads on the V2 missile and Erdmann was in charge. The measurements were done on a half model equipped with 121 pressure holes. In total about 100,000 test points were taken, involving 15,000 hours of work for 35 people: no doubt the largest supersonic experimental program executed at that time. The first successful launch of the V2 took place in October 1942. Industrial production of the V2 started in 1944 at the concentration camp Dora after HVA had been taken over by the SS. During the last year of the War about 1,400 V2s were aimed at Britain with 500 strikes at London, causing the loss of life of well over 2,500 people. Technically the V2 was an enormous achievement with many advanced solutions for the rocket engine and the guidance and control aspects. But these achievements are completely overshadowed by the brutality of the production process at the concentration camp Dora and the loss of civilian lives following the deployment of the V2.

After 1942, when the aerodynamic work for the V2 was finished, Erdmann was in charge of the research group II ('*Versuchtstrupp II*') under Lehnert who reported to Hermann directly. He got engaged in two projects. An air-to-ground rocket named 'Wasserfall' and the development of a supersonic wind tunnel for a still higher Mach number (the 'Superschallkanal'). This tunnel was basically a hypersonic facility. Erdmann studied specifically how a Mach number of 8.8 could be achieved and he succeeded in solving the technical problems. At that time there were 200 employees at the Aerodynamic Institute. The planned hypersonic facility was to be built in Kochel, near Münich, where hydro-energy was readily available as part of a new research complex. Kochel was selected after an air-raid on Peenemünde in August 1943. Erdmann visited Kochel in May 1944. In July of the same year he wrote on request of Werner von Braun an internal confidential memorandum suggesting the postponement of the transfer of the existing Peenemünde wind tunnels to Kochel to enable the continuation of aerodynamic testing on the 'Wasserfall'. This memorandum was regarded by Hermann as an act of insubordination. Erdmann was fired and drafted in the army to fight on the Eastern front. He managed to stay away from the front line by teaching ballistics to the new soldiers in Augsburg. Just before the end of the War he was rehabilitated by the army and formally had to work in Braunschweig but gathered with his family and his brother's family in a mansion that belonged to the family. There he awaited the end of the war.

Almost by accident and through contacts with his family (his brother's sister-in-law was married to a Dutchman) he was noticed by Michels, head of the Dutch Military Mission in Germany. Michels asked Erdmann if he was willing to work for the allies. Erdmann agreed and in September 1945 was transferred to Wimbledon, England, for inquiries on his involvement in the War effort. There he met former colleagues, including Werner von Braun, who were interrogated to assess their specific involvement in Nazi Germany and to determine their 'scientific value'. Von Braun asked Erdmann to join him to the US, but Erdmann declined and returned to Germany after his release. In January 1946 he was contacted again by Michels and invited for talks in The Netherlands. He talked with Fokker representatives who showed no interest. In April 1946 he visited NLL to talk with Koning (the director at that time), De Lathouder and Wiselius[13,14]. In May 1946 he started to work at NLL in the F-Section, where he shared a room with van der Vooren. His wife followed in April 1947 and the family settled in Amsterdam.

How did the NLL organisation react to the arrival of a German scientist who spent most of his life on arms development? Erdmann himself writes that he was rather isolated during the first weeks at NLL. One day the lady who served him coffee in his room at NLL asked him if he was a guest, an employee or a prisoner-of-war. And when Erdmann told her that he was an employee of NLL she left the room showing signs of incomprehension. Soon after that Erdmann was approached by representatives of the 'Employees Society' ('*Personeelsvereniging*') to explain in a meeting his view on Nazi Germany and his involvement during the War. Most likely De Lathouder, who was a member of a resistance group during the War and active in this society, was present as well. After that meeting he was accepted by his colleagues.

Erdmann was a scientist. During the first years at NLL he wrote detailed reports on measuring techniques and supersonic aerodynamics[122] to transfer his detailed knowledge to NLL. He had scientific contacts outside The Netherlands, e.g. with Oswatich and with former German colleagues at the Institute St. Louis in France. The theoretical work with Oswatich on supersonic flows resulted in the study of the ring wing configuration (see page 76). The very small supersonic wind tunnel he built (the '3x3') was also used for his experimental work on a simplified interferometer. For this he got his Ph.D. at Aachen University on April 30[GG], 1951. Of course he was very much involved in the plans for a supersonic wind tunnel at NLL. But when in 1949 these plans were put on hold, Erdmann accepted an offer made by Sweden to work at the Technical University in Stockholm and 10 days after he got his Ph.D. he left NLL. Early 1953 he got a letter from Van der Maas asking him if he was willing to return to NLL. At about the same time he was also offered a position in supersonic aerodynamics in Göttingen in Germany by Betz (director of AVA, the laboratory that supervised the NLL activities during the War). The offer by Van der Maas was finally accepted, probably also because he would become a part-time lecturer in Delft. On November 1, 1954 he returned to NLL, where he started to work on the new supersonic wind tunnel. At the end of 1957, at a Space Transportation Congress in Amsterdam, he met again his former Peenemünde bosses Von Braun and Dornberger. On August 7, 1961 he was inaugurated as extra-ordinary professor at the Delft Technical University. Following the reorganisation of the Aerodynamics Department which combined the Transonic and Gasdynamic Sections[123], he became a special advisor in 1967. He left NLR in September 1969 to become full-time professor in Delft. Erdmann died in 2002. ■

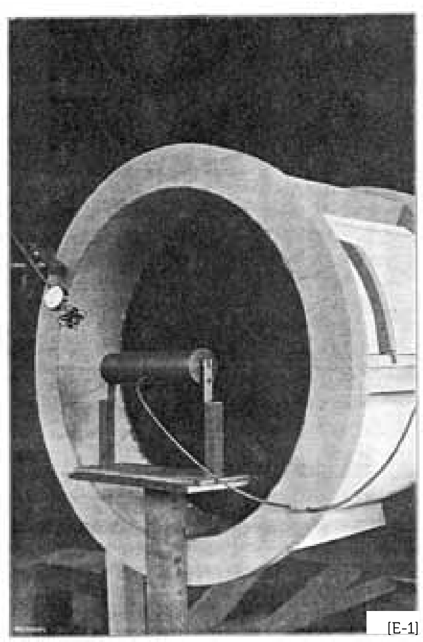
[GG] ON THE QUEENS BIRTHDAY, AS SUGGESTED BY THE NLL DIRECTOR KONING, OTHERWISE HIS DUTCH COLLEAGUES HAD TO TAKE A DAY OFF!

APPENDIX E SHORT COURSE ON WIND TUNNEL DESIGN AND TESTING

THE EIFFEL TUNNEL OF THE RSL

In a wind tunnel a precisely controlled airflow is generated around a subscale model of an airplane to study the aerodynamic forces that act on the aircraft. In 1871 the first wind tunnel was built in England by Frank H. Wenham. It was a simple, straight wooden channel with a fan driven by a steam engine. In 1901 the Wright Brothers also built and used a simple wind tunnel (a straight channel) to determine the lift and drag of the airfoil sections and to optimize the wing planform. Around 1910 members of the Dutch Society for Aeronautics at the Delft Technical University (among them Von Baumhauer who later worked at RSL) built the first wind tunnel in The Netherlands [figure E-1]. It was a rather simple device with a circular cross section and a fan at the end. In Amsterdam the first wind tunnel of the RSL (the precursor of NLL and NLR) was built in 1918 before the official opening of the RSL in 1919. It was designed by Pigeaud and was inspired on a design by Gustave Eiffel, who had founded an aeronautical laboratory near Paris in 1907. This type of wind tunnel is hence named the 'Eiffel tunnel'[HH]. As with the other early wind tunnels, it was a duct with an open front and rear end while the air returns through the room in which the tunnel is located. The first wind tunnel of the RSL will now be described in more detail [figure E-2].

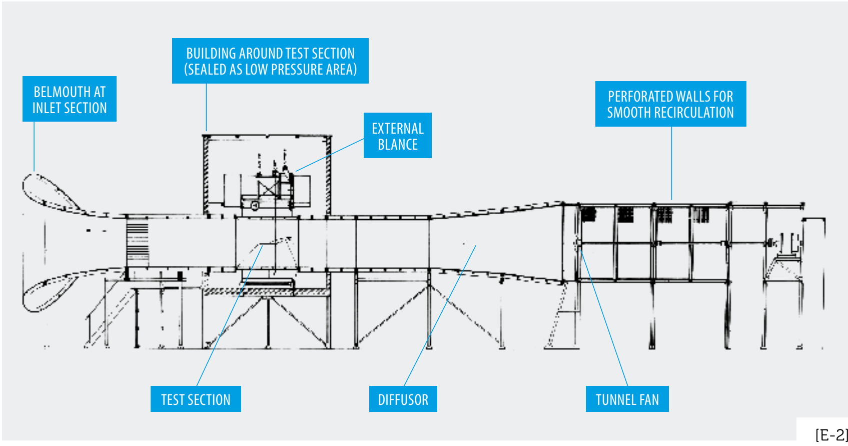
The circular test section (diameter 1.6 m) is located in the centre of the tunnel where the model is attached to an external balance mounted on top of the tunnel. To assure a smooth air flow the inlet section is shaped as a bell mouth. This part of the tunnel was modified extensively in the early years of operation, since the flow


[E-1]

[Figure E-1]

Photograph of the entry section of the first wind tunnel ('*de blaastunnel*') built around 1910 in the Netherlands.

[HH] IN A LETTER DATED MARCH 28, 1919 EIFFEL REQUESTED THAT A PLAQUE SHOULD BE FIXED TO THE RSL TUNNEL MENTIONING: 'SYSTÈME G. EIFFEL (PARIS)'.



[Figure E-2]

The Eiffel tunnel, the first wind tunnel of the RSL (1919)

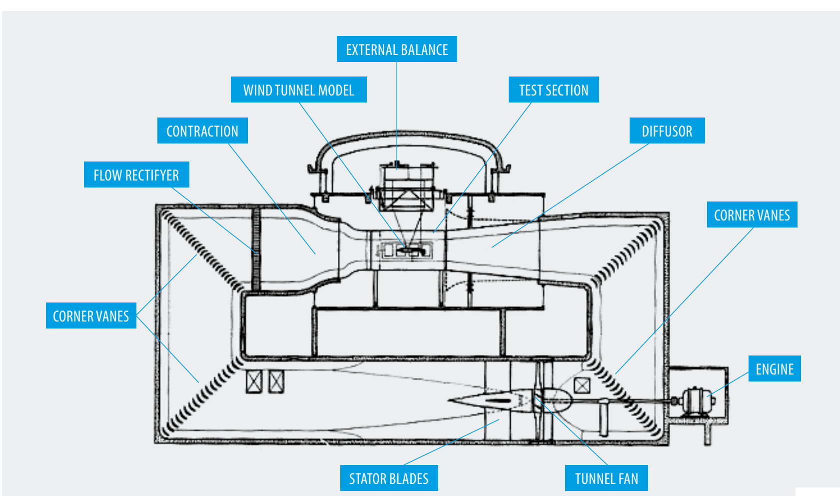
quality with the original inlet section was not acceptable. Because of the bell mouth, the cross sectional area at the entrance is appreciably larger than the cross sectional area at the test section. According to the law of Bernoulli this will result in a lower than atmospheric pressure in the test section. For that reason an air-tight test room was erected around the test section. The test section is followed by a diffusor section where the flow velocity decreases and the pressure increases again till atmospheric. At the end of the diffusor a fan sucks the air through the tunnel. Downstream of the fan the air can flow out of the tunnel through perforated walls to recirculate inside the building and back into the inlet section. On the drawing the test section is closed by the circular tunnel wall, but it was also possible to remove the wall to create an open jet to make the model better accessible during the tests. This tunnel was extensively used until World War II. In 1938, in view of the heavy work load, it was decided to build two new wind tunnels at a new (the present) location just outside Amsterdam.

THE BIG LOW SPEED TUNNEL LST

The main disadvantage of an Eiffel tunnel is that the flow quality in the test section is somewhat problematic due to the fact that the return flow through the building cannot be controlled. Therefore it was decided to make the new tunnels of the 'Göttinger type': the flow goes around in a closed circuit. The design of this tunnel was inspired by a similar tunnel in Zürich designed by Ackeret. The main elements of this wind tunnel, which became operational in 1940, will be described on the basis of a sketch of the big LST (tunnel no. 3) [see figure E-3].

As for the Eiffel tunnel the model was mounted in the test section on wires that are attached to an external balance which measures the forces on the model. To keep the flow going a fan is required. Basically, the power to drive the fan balances the power lost in the circuit due to friction on all tunnel walls and on the model. The loss of power due to friction is proportional to the third power of the local flow velocity. Hence, when the (average) tunnel speed is twice as high, the fan power has to be increased by a factor 8. That explains why a high speed tunnel such as the HST needs a lot of energy. The LST was designed for a maximum speed of 80 m/sec in the empty test section. To reduce the losses in the circuit as much as possible the cross sectional area of the tunnel circuit was increased immediately after the test section, since a larger area means a lower local velocity (the local speed is inversely proportional to the local cross sectional area). This part, the diffusor, is one of the most critical parts of the circuit. If the cross sectional area increases too rapidly, the tunnel flow can no longer follow the walls and the flow separates (breaks away from the wall) with extra losses as a result. After the diffusor the cross sectional area of the tunnel circuit is roughly constant. Corner vanes are needed to turn the flow efficiently.

The fan that drives the tunnel generates a swirl in the flow. This is detrimental to a good flow quality in the test section and for that reason stator blades are mounted close to the fan to take out the swirl.
To recover the high flow velocities when the flow returns to the test section the cross sectional area has to decrease again just upstream of the test section in a part of the tunnel that is named contraction. The precise shape of the contraction is another critical element of the tunnel: everywhere in the (empty) test section the flow velocity has to be uniform to a high accuracy (generally much better than 1 %). However, the tunnel wall boundary layers, the fan, the stator and corner vanes generate turbulence in the tunnel flow. This has to be suppressed for a good flow quality in the test section. In the LST this was achieved by a flow straightener or rectifier, a honeycomb structure that restricts the transverse flow velocities.

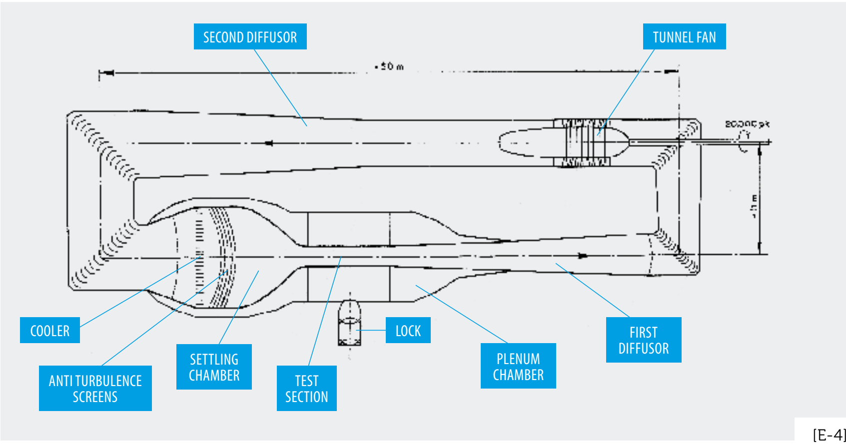


[Figure E-3]

Sketch of the big LST or tunnel no. 3 that became operational in 1940.

THE HIGH SPEED TUNNEL HST

The circuit of the HST is in principle similar to the one of the LST. However, due to the much higher speeds the detailed aerodynamic design is more advanced [figure E-4]. More power is needed to drive the tunnel. Whereas a single fan was sufficient to drive the LST, a four-stage fan is required for the HST, driven by four 5,000 hp electric engines. The frictional losses in the circuit are further reduced with a second diffusor after the fan. To reduce the turbulence levels in the test section as much as pos-



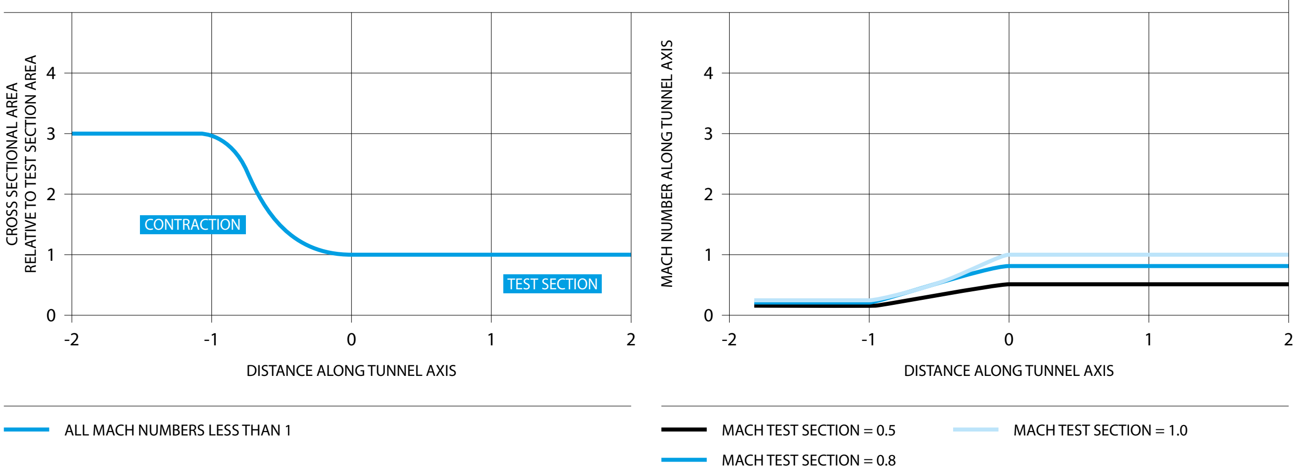
[E-4]

[Figure E-4]

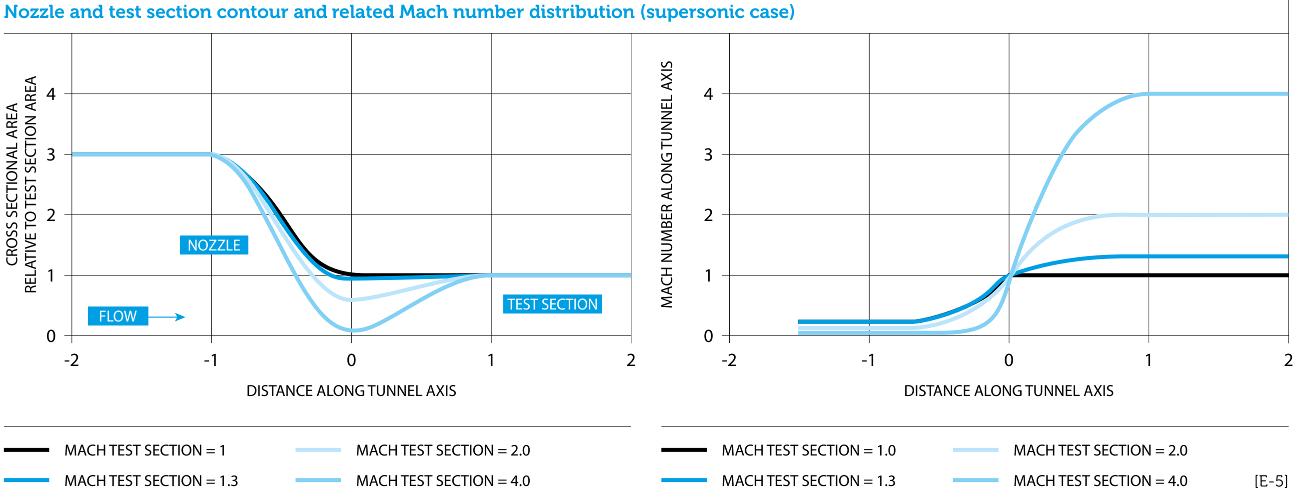
Sketch of the High Speed Tunnel HST.

sible a so-called settling chamber is used instead of the much simpler contraction of the LST. Just after the last corner the cross sectional area increases rapidly to form a kind of sphere (in the original design of the low turbulence tunnel LTT this was named the 'anti turbulence sphere'). 'Screens' (similar to screens used to keep the flies out of one's house [see figure 1-60] are needed to prevent the flow from separating at the entrance of the settling chamber. However, the most important effect of these screens is to damp the longitudinal flow variations. In the settling chamber of the HST a (water) cooler is installed, since otherwise the temperature of the flow would increase too much. The HST has a very high contraction ratio: the ratio between the maximum cross section in the settling chamber and the cross sectional area in the test section. For the HST this ratio is as high as 25 as a consequence of a decision made after the original design to reduce the test section area. This decision was a result of the introduction of slotted walls in the test section to prevent choking of the flow at transonic speeds (see page 18). This was favourable from an aerodynamic point of view: the higher the contraction ratio the lower the turbulence level. Since the whole tunnel circuit could be pressurized till 3 bar (over pressure), the HST tunnel circuit had to be made of steel, like a pressure vessel. The settling chamber and the test section were surrounded by a pressure shell of a larger diameter, the plenum chamber. The shell of the plenum chamber took the larger part of the loads instead of the more complicated and vulnerable parts of the contraction and test section. It had the additional advantage that more space

Contraction and test section contour and related Mach number distribution (subsonic case)



Nozzle and test section contour and related Mach number distribution (supersonic case)



[E-5]

[Figure E-5]

Schematic view illustrating the difference between subsonic and supersonic test sections.

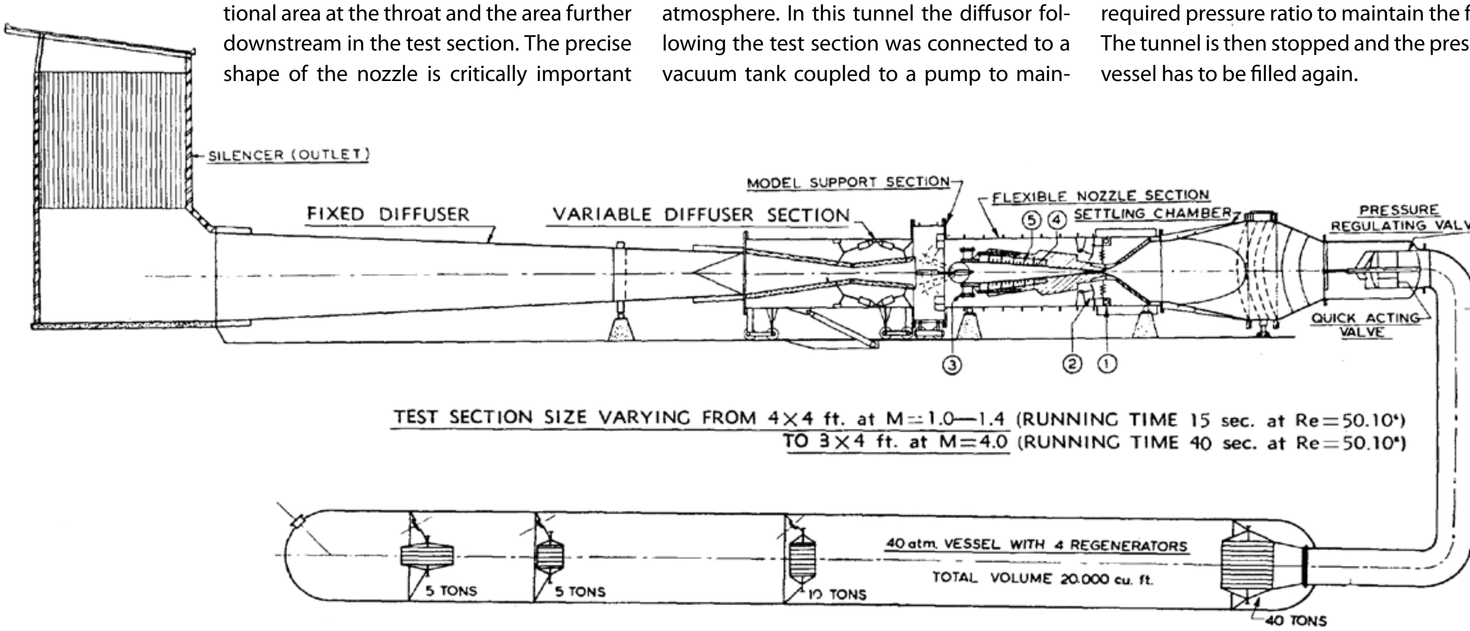
was created around the test section, space that could be used to accommodate equipment (e.g. the optical schlieren system) and as a working area. A lock connected this plenum chamber to the test section hall. More details of the transonic test section will be discussed further below.

THE SUPERSONIC WIND TUNNEL SST

When the cross sectional area of the tunnel decreases the flow velocity increases [see figure E-5]. This is the case up to the point that the local flow velocity reaches the speed of sound at the smallest cross section. Normally a shock wave will be formed at that point. Behind the shock wave the flow returns to subsonic conditions: the flow is said to be 'chocked' and this restricts the mass flow. In 1888 the Swedish inventor Gustaf de Laval discovered that in a carefully shaped channel with an area that first decreases (converges) and then increases (diverges), the flow velocity downstream of the smallest cross section can further increase to supersonic speeds. Such a geometrical arrangement is called a 'Laval nozzle', the smallest cross section the 'throat'. At the smallest cross section the flow reaches the speed of sound. Further downstream the flow becomes supersonic: the local flow velocity exceeds the speed of sound. This principle is used in the design of a supersonic wind tunnel. Downstream of the throat the test section is located. The flow velocity in the test section (expressed as the Mach number, the ratio between the local flow velocity and the local speed of sound) depends on the ratio between the cross sectional area at the throat and the area further downstream in the test section. The precise shape of the nozzle is critically important to obtain uniform flow. This implies that for each particular Mach number in the test section a specific shape of the nozzle is required [see e.g. figure 1-15]. This can be realized by different nozzle blocks that have to be exchanged whenever the Mach number has to be changed (as was the case in the Peenemünde supersonic wind tunnel) or with a flexible nozzle that can be adjusted continuously. This latter solution was finally chosen by Erdmann in the design of the SST [figure 1-44].

To initiate the flow in a supersonic wind tunnel the ratio of the pressure at the entrance of the tunnel and at the end of the test section should be sufficiently large. During starting and stopping of the tunnel shock waves are formed that travel in upstream and downstream direction through the tunnel. For that reason a still higher pressure ratio is required to get the tunnel started. A (supersonic) diffusor downstream of the test section is an essential element in this respect. The very small '3x3' supersonic wind tunnel [figure 1-15, 1-45] was also built to investigate the performance of such a supersonic diffusor. The high loads on the model during starting and stopping of the tunnel might cause an overload on the model, a problem that can be solved with proximity plates [figure 1-52]. The model itself can be mounted in the test section on a sting attached to a segment to position the model in the flow.

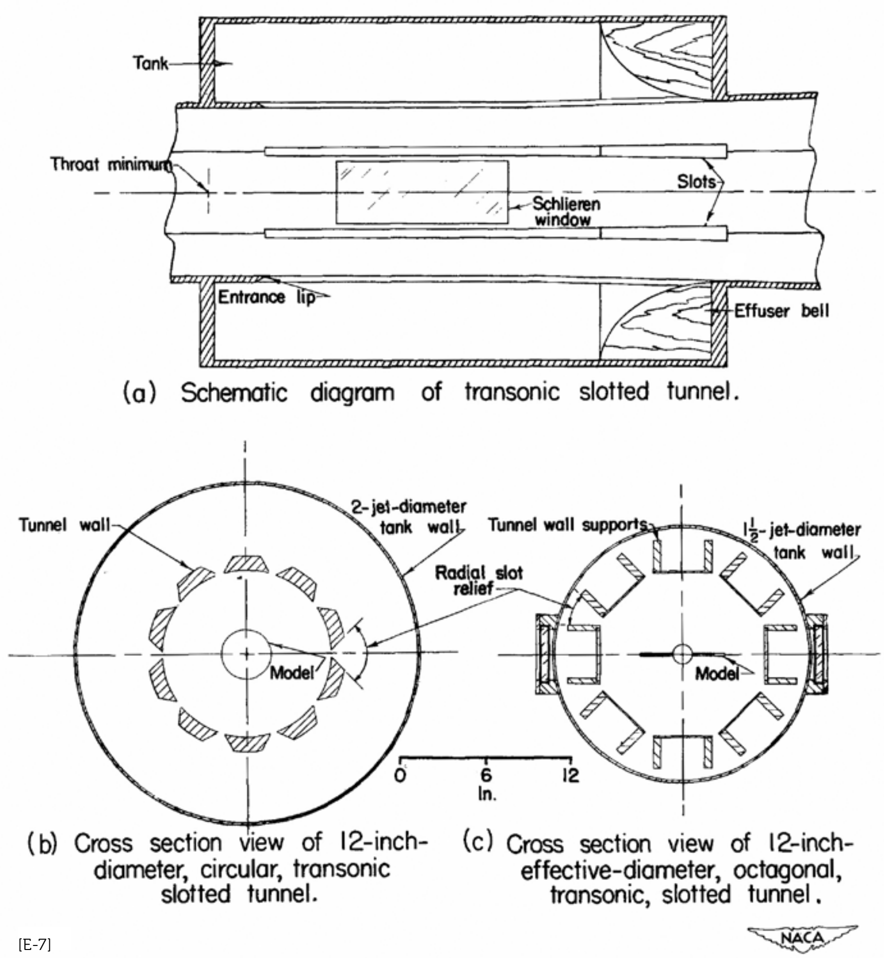
Various solutions are possible to generate the required pressure ratio for a supersonic tunnel. The '3x3' sucked air from the atmosphere. In this tunnel the diffusor following the test section was connected to a vacuum tank coupled to a pump to maintain a low pressure. In the original design of the small supersonic tunnel (0.4 x 0.4 m^2 test section) a big compressor was used at the entrance of the tunnel to generate high pressure. In both cases these tunnels could be run continuously. Due to the required power consumption this solution was no longer attractive for the much larger facility with test section dimensions of 1.2 x 1.2 m^2 which was envisaged in 1956. Instead, a blow down operation was intended [figure E-6]. At the upstream side the tunnel is connected to a very large pressure vessel that can be charged till 40 bar maximum. In the pressure vessel so-called regenerators are used, steel plates that keep the temperature roughly constant during the expansion process. By opening a valve between the pressure vessel and the tunnel, high pressure air flows into the test section. This valve, the 'control valve', is operated automatically to maintain a constant pressure in the test section. The control valve for the SST was based on a clever design by Erdmann. The valve had two shutters, a large one and a small one. The movement of the large shutter was pre-programmed whereas the smaller shutter could be positioned automatically according to the measured pressures. As for the subsonic tunnel a settling chamber with screens is located upstream of the test section (between the control valve and the nozzle) to reduce the turbulence level in the test section. Downstream of the test section the flow is decelerated through a diffusor and exhausts finally into the atmosphere. The tunnel can be operated for 15 to 40 sec, depending on the Mach number, till the pressure in the vessel has fallen below the required pressure ratio to maintain the flow. The tunnel is then stopped and the pressure vessel has to be filled again.



[Figure E-6]

Sketch of the supersonic blow-down tunnel SST with the pressure vessel.

[E-6]



[E-7]

THE TRANSONIC TEST SECTION AND THE PROBLEM OF CHOKING

The circuit for a high speed wind tunnel as discussed above resembles that of a subsonic wind tunnel. In the original design of the high speed tunnel [figure 1-9] the maximum speed was limited to a value of 0.9 or 0.95 times the local speed of sound to prevent choking of the tunnel. Depending on the size of the model the cross sectional area decreases when the model is mounted in the test section. Choking is the result of the formation of shock waves (between the model and the test section walls), when locally around the model the speed of sound is exceeded. These shock waves would not be present in the absence of tunnel walls (hence in free flight) and prevent wind tunnel tests just below Mach = 1. At supersonic speeds a second problem occurs. An aircraft (or model) flying at supersonic speeds will generate shock waves. However, in the confined space of a wind tunnel, these shock waves will reflect from the tunnel walls back to the model, spoiling the tests as well.

The first problem is similar to the wall interference problem at high subsonic speeds. In a tunnel with closed (solid) tunnel walls the reference speed is usually derived from the total pressure in the settling chamber and the static pressure some distance upstream of the wind tunnel model. However, due to the presence of the model the average flow velocity close to the model increases and the model will feel a somewhat higher reference velocity than the one indicated by the tunnel reference speed. This effect is called 'wall interference'. In an open test section (no tunnel walls) the opposite occurs and the reference speed will decrease relative to the indicated tunnel reference velocity. It seems to be a sensible idea that the wall interference can be eliminated in a test section with mixed open and closed tunnel walls. In 1942 a theoretical solution to this problem was found by Carl Wieselsberger, professor at Technische Hochschule in Aachen[124]. He calculated that with closed top and bottom walls and open side walls (with an area ratio of 1.17) the wall interference would be nullified. This publication was referenced by Wright and Ward of NACA Langley in the US[20] who made a similar calculation for a tunnel with slotted walls in a circular cross section. They calculated that an open area ratio (the ratio between the slot width and the total periphery) of 0.125 would be needed to eliminate the wall interference. This and another configuration [figure E-7] was actually tested and they claimed almost interference-free flow up to Mach = 1.1. To prevent the flow from leaking away, the slotted test section is surrounded by the plenum chamber [see also figure E-7]. It is important to note here that the configuration of the walls shown here is somewhat different from those applied in 'the Swiss solution' by Hausammann in 1949 [see page 18 and figure 1-19]. This will be discussed in more detail below.

The second problem, preventing the reflection of shocks from the walls, can be solved with porous walls, walls with evenly distributed holes[125]. The holes will result in a succession of expansion and compression waves that cancel the reflected shock wave altogether. In 1956 Eckhaus, who at that time was working at NLL, studied the problem of shock reflection both theoretically[126] and experimentally[45]. Although he could not treat the porous wall with holes, he managed to find a theoretical solution for walls with transverse slots and reached the conclusion that an open area ratio of about 0.5 would be needed for shock cancellation. In 1956 Eckhaus discussed the various concepts for transonic test sections[127] and noted the conflicting requirements of a small open area ratio to minimize wall interference and an open area ratio of about 0.5 for the cancellation of the reflected shock waves. He also noted a way out: a slotted wall with 'deep slots' as shown in figure E-8. Due to the shape of the slots, viscous effects on the sides of the slots will decrease the flow through the slots, whereas at the inner wall an open

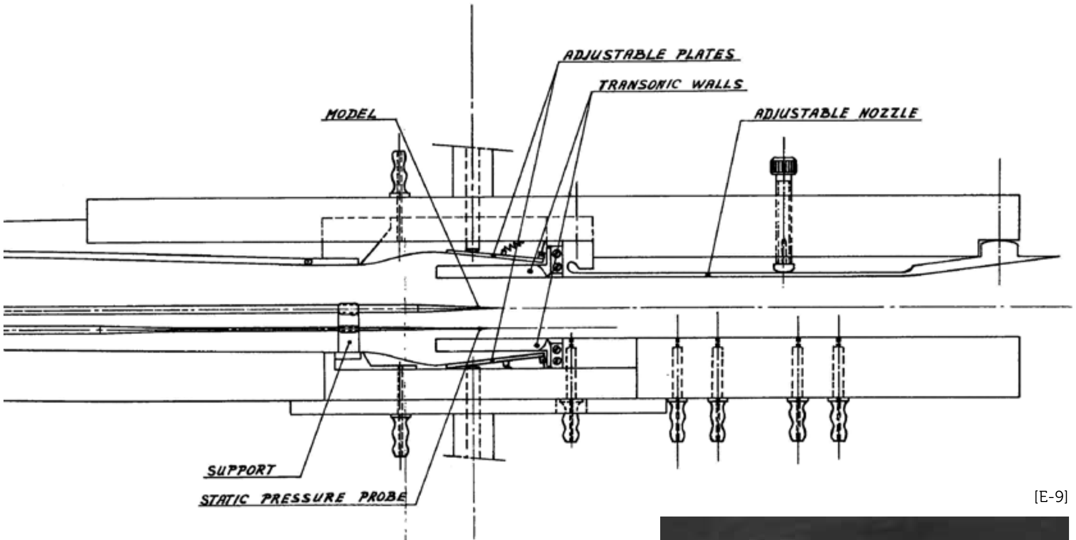
[Figure E-7]

Slotted wall configuration tested in 1948 at NACA Langley by Wright and Ward[20].

[Figure E-8]

Slotted wall discussed by Eckhaus[127]. Viscous effects in the deep slots will reduce the flow through the slots for a better compromise between the elimination of wall interference and shock reflection. This slot geometry is very similar to the one of Hausammann [see page 18 and figure 1-19].

[E-8]



[E-9]

[Figure E-9]

Drawing of the scaled model of the slotted wall configuration designed by Hausammann as tested in the small '3x3' supersonic tunnel by Eckhaus[45] in 1957.

[Figure E-10]

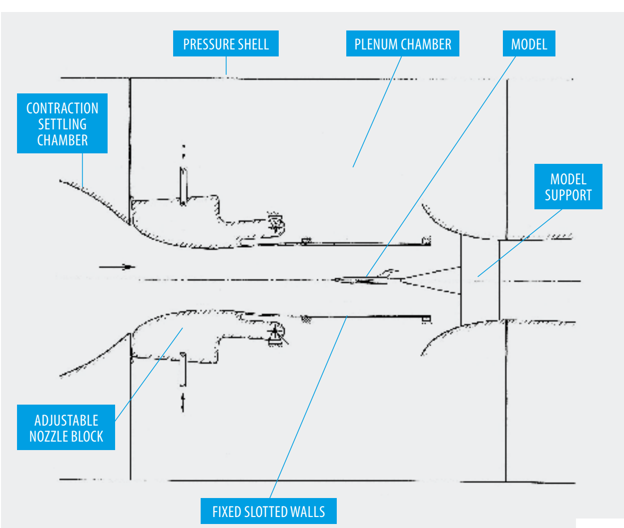
Schlieren pictures of the shocks and shock reflections from the walls of the scaled model of the HST transonic tests section as shown in figure E-9.

[Figure E-11]

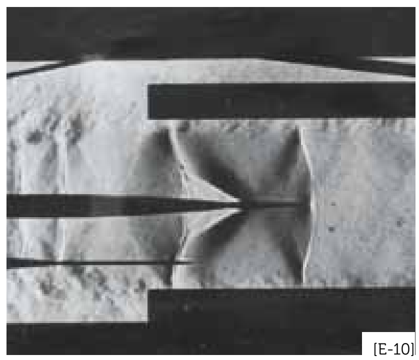
Nozzle design for the HST required for low supersonic Mach numbers.

area ratio of about 0.5 can still be maintained. Eckhaus suggested that by experimentally optimizing the shock width and the slot heights, both requirements could be met. He actually performed tests in the small '3x3' supersonic wind tunnel to investigate the ability of the slotted walls to cancel shock reflections[45] [see the figures E-9 and E-10]. However, these tests were not conclusive mainly due to the very thick boundary layer on the tunnel walls in this small wind tunnel. The wall geometry in this experiment is most likely identical to the one applied by Hausammann for the HST test section.

As mentioned the slotted wall geometry designed by Hausammann was not successful (see page 24) for mechanical reasons and was replaced by a much simpler slot geometry, similar to the NACA solution as already shown in figure E-7.



[E-11]



[E-10]

The slotted walls were optimized for high subsonic speeds just below Mach=1. For supersonic conditions NACA claimed that the Mach number could be changed by adjusting the power of the fan. Nevertheless, the slot geometry had to be tapered[128] to obtain a constant Mach number distribution in the test section. Apparently Dätwyler & Hausammann envisaged an adjustable plate in the plenum chamber to control the Mach number[45] [figure E-9]. A more elegant way is the use of a real supersonic throat, as was realized in the test section for the HST. As can be deduced from figure E-5, only very small changes in the contour are required to obtain Mach numbers just in excess of 1. For that reason the nozzle can be kept relatively simple [figure E-11] though its shape has to be very accurate. As mentioned at page 26 Nieuwland made the calculation for this nozzle shape[129].

Finally it should be remarked that there is another solution to eliminate wall interference at high subsonic conditions: the flexible wall. Its principle is to deform the tunnel walls in such a way that they are similar in shape to the streamlines away from the model at the wall location. In this way the walls are 'not felt' by the flow and choking will be prevented. The shape of the tunnel walls will depend on the flow around the model and hence on the model geometry. How to shape the walls? Wall interference studies made in the eighties by GARTEUR[130] showed an elegant solution to this problem. In an iterative process the optimal wall shape could be deduced from the pressures measured on the tunnel walls without any knowledge of the model itself[II]. This principle was successfully applied in a small wind tunnel at the Technical University in Berlin and at DFVLR in Göttingen. This solution was seriously considered for the HST modification in the nineties, but soon abandoned for practical reasons. The solution requires many jacks to position the wall and it was feared that it would hamper the reproducibility of the test results. Moreover, for supersonic conditions shock reflections will not be eliminated, requiring exchangeable tunnel walls, as was indeed foreseen in the original plans[57].

A TYPICAL TEST PROGRAM

The aerodynamic forces and moments that act on the aircraft can be derived from wind tunnel tests, notably the overall forces (e.g. lift, drag and pitching moment for the symmetrical components) or local forces (e.g. on the flaps, rudders and the ailerons). The overall forces or moments can be measured with an internal or an external balance. From the pressures measured on the model surface the local aerodynamic loads can be derived.

The overall forces and moments can be expressed as coefficients, made non-dimensional with the wing area S, a reference length ℓ (e.g. the length of the mean chord of the wing) and the dynamic pressure in the tunnel $q = \frac{1}{2}\rho V^2$ with ρ the air density and V the tunnel (or aircraft) speed. As an example the symmetrical components lift (L), drag (D) and the pitching moment (M) can be written as:

$$L = C_L \tfrac{1}{2} \rho V^2 S$$
$$D = C_D \tfrac{1}{2} \rho V^2 S$$
$$M = C_M \tfrac{1}{2} \rho V^2 S \ell$$

The non-dimensional coefficients are used to transfer the aerodynamic information from the wind tunnel model to the real aircraft: e.g. the lift for the real aircraft can be calculated by multiplying the coefficient C_L measured in the tunnel with the dynamic pressure q and the wing surface

S for the real aircraft. This is exactly true when the Reynolds number is the same for the real aircraft and the wind tunnel model. When there are differences in the tunnel and flight Reynolds number a correction is required as a result of viscous effects that will be slightly different for wind tunnel and flight conditions. This process is called 'Reynolds number extrapolation'.

The aerodynamic performance of an aircraft is most conveniently expressed in the so-called 'Lift-Mach number plane'. This plot shows some of the aerodynamic characteristics in terms of the lift coefficient C_L as a function of the Mach number [figure E-12].

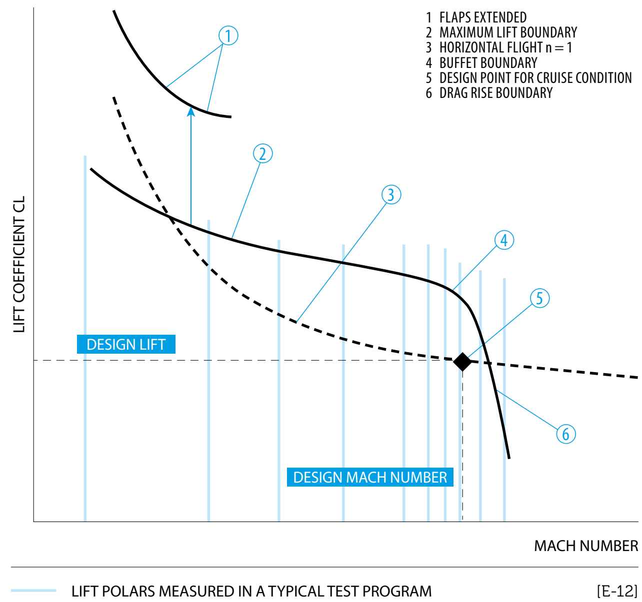
An aircraft is designed to carry its own weight and an additional load (passengers, cargo and fuel) at a certain cruise Mach number. This condition represents the design or cruise condition of the aircraft. For this condition the shape of the wing is optimized for minimum drag. For a stationary flight the lift is constant and the lift L equals the aircraft weight W. But since, as indicated in the formula, the lift of an aircraft is proportional to the square of the velocity, a higher lift coefficient is required at speeds below the cruise condition. The variation of the lift coefficient with the Mach number for horizontal flight is indicated in the figure by the dotted line denoted 'horizontal flight n=1'.

More general the lift can be expressed as:

$$L = n.W$$

with n the load factor. In a stationary, horizontal flight the lift balances the aircraft weight and the load factor n = 1. For non-steady conditions, when the aircraft is manoeuvring, (e.g. pull-up or a horizontal turn) n is no longer equal to 1 and other points in the C_L-Mach plane can be reached. A boundary ('envelope') can be drawn in the C_L-Mach plane that limits the aircraft movement from an aerodynamic point of view. This envelope has also been indicated in the figure and represents different aerodynamic phenomena. When the Mach number is increased the drag-rise boundary is met. It marks the region, where due to the formation of shock waves on the wing, the drag increases rapidly such that economic flight is not possible anymore. Normally the drag divergence is very close to the design condition: the aircraft has to fly precisely at a constant cruise Mach number. When at the design Mach number the lift (and hence the lift coefficient) is increased, e.g. by making a manoeuvre such as a pull-up, the buffet boundary can be met. At this boundary the shock waves that are formed on the wing are so strong that local flow separation occurs: the flow breaks away from the wing surface. This results in a violent movement of the aircraft called buffeting. The regulations describe that this buffet boundary should be sufficiently far away from the cruise condition (n=1.3). When the speed of the aircraft is decreased the maximum lift boundary (in fact a maximum lift coefficient boundary) might be reached: the wing of the aircraft can no longer provide the required lift. At this point the n=1 curve crosses the boundary for the maximum lift coefficient. To fly at still lower speeds the lift coefficient of the wing has to be increased by changing the wing shape e.g. by deploying flaps and slats.

An important part of wind tunnel tests is concerned with studies to optimize the aircraft for the cruise condition. But the designer also wants to know the location of the off-design boundaries as described above. This can be done by measuring polars for a range of Mach numbers. During a polar the angle of attack of the model is varied at a constant Mach number and hence the lift coefficient C_L will also change. At many discrete angles of attack the forces and sometimes pressures as well, are measured. In this way all possible flow conditions in the C_L-Mach plane are covered. From these measurements the off-design boundaries can be derived. Near the cruise condition the polars are measured at small Mach number increments to determine the drag divergence boundary accurately. A special low speed model with flaps that can be set at different angles is needed to measure the take-off and landing characteristics at low speed. Typically a measurement program consists of 10 to 20 polars. In the early days of the HST a polar was measured by setting the Mach number and taking the data step by step for a range of angle of attack angles α. Later with the improved data acquisition, all data could be obtained in a single sweep during which the angle of attack was increased continuously. During such a sweep the automated tunnel control kept the Mach number constant.



[E-12]

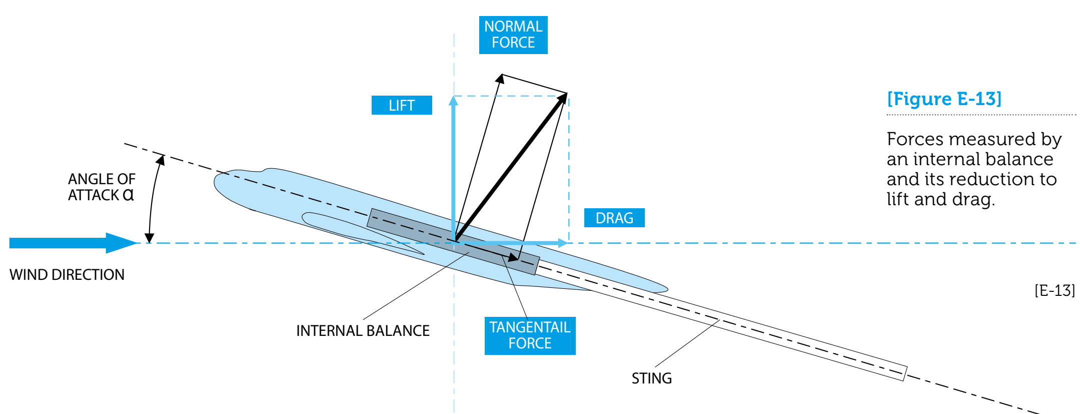
[Figure E-12]

Main aerodynamic characteristics shown in the Lift-Mach number plane.

AN ACCURACY PROBLEM

An internal balance [see figure E-13] measures the overall loads on the model. This load is measured in the balance axis system: the normal force N perpendicular to the balance axis, the tangential force T in the direction of the balance axis and the

II THIS SOLUTION IS BASED ON AN INTERESTING APPLICATION OF GREEN'S THEOREM.



[E-13]

[Figure E-13]

Forces measured by an internal balance and its reduction to lift and drag.

moment M around the balance centre. The forces and moments measured by the balance can also be expressed in a non-dimensional way, similar to what has been shown already for the lift and the drag:

$$C_N = N/qS$$
$$C_T = T/qS$$
$$C_M = M/qS\ell$$

The measured balance forces N and T have to be resolved in the lift force L (perpendicular to the flow direction that balances the weight of the aircraft) and the drag force D (in flow direction, balanced by the propulsive force of the aircraft). These forces and the corresponding coefficients can be derived by rotating the balance axis system over the angle of attack α of the model, here defined as the angle between the balance axis and the wind direction [see figure E-13]:

$$C_L = C_N \cos\alpha - C_T \sin\alpha$$
$$C_D = C_N \sin\alpha + C_T \cos\alpha$$

These expressions can also be used to assess the effect of possible measurement errors. In the cruise condition of the aircraft typically $C_N \approx 0.5$ and $C_T \approx 0.03$ whereas α is small, of the order of some degrees (or $\alpha \approx 0.1$ in radians). It is now possible to write approximately:

$$\Delta C_L \approx |\Delta C_N|$$
$$\Delta C_D \approx |\Delta C_T| + |C_N \Delta\alpha|$$

to show how the error in the balance readings ΔC_N, ΔC_T and the error in the angle of attack Δα is reflected in the error for the coefficients ΔC_L and ΔC_D. The formulae indicate that the accuracy of the lift and drag is (of course) directly related to the accuracy of the balance reading ΔC_N and ΔC_T. Since the balance accuracy is normally expressed as a percentage of the maximum balance load (percentage full scale or % FS; typically 0.3%) it is important in a wind tunnel test to choose the balance such that its full balance range is used. That explains why around 1960 so many balances of different sizes were bought by NLL. In this way for each test the optimum balance could be selected. For the accuracy of the drag component an additional term $C_N\Delta\alpha$ appears. Since industry is interested to know the drag C_D to an accuracy of 0.0001 (called one drag count) the angle of attack should be known to an accuracy of 0.0001/0.5 radians or 0.01 degree. That illustrates the importance of an accurate measurement of the angle of attack α. First of all the balance should be fixed in a very rigid and reproducible way to the model. Moreover, due to the loads on the model the balance-sting combination deflects during the wind tunnel test. This effect can be dealt with in the calibration of the balance-sting combination. For a range of different dead weights the output of the balance and the deflection is recorded and consolidated in the balance calibration. This calibration is subsequently applied in the data reduction of the wind tunnel measurements where the loads and the deflection can be derived from the balance readings. Still more accurate is the in situ measurement of the angle of attack of the model by an instrument mounted in the model (such as the so-called Q-flex) or by optical means. The fact that the model is also vibrating somewhat under a fluctuating load, adds to the accuracy problem.

A third source of error relates to the wind direction. Basically the direction of the flow should be measured at a large distance ahead of the model. But in the confined space of the wind tunnel this is not possible. Since the presence of the tunnel walls restricts the flow as compared with the free air situation, the reference flow direction is also effected by the walls. This effect is a critical part of the wall interference and it presents an important problem in wind tunnel testing. For solid tunnel walls the wall interference effects can be derived theoretically. In the case of well optimized slotted tunnel walls the wall interference effects are much reduced compared to the solid wall case, but it appears to be very difficult to quantify the still remaining effect up to a desired accuracy of 0.01 degree. Often semi-empirical corrections are applied that have been derived from and/or have been verified with comparative tests. ■

APPENDIX F
GLOSSARY OF TECHNICAL TERMS

AEDC	'Arnold Engineering Development Center', founded just after World War II for research and development on behalf of the US 'Department of Defence' near Nashville, Tennessee.
AFWAL	'Air Force Wright Aeronautical Laboratory' at Wright-Patterson AFB, Ohio.
AGARD	'Advisory Group for Aeronautical Research and Development': established in 1952 by Theodore von Kármán within the framework of NATO ('North Atlantic Treaty Organisation') to promote the exchange of aeronautical technology between the member states.
AICMA	'Association Internationale des Constructeurs de Matériel Aéronautique': European organisation of aircraft manufacturers (not including England).
ANCP	'Anglo-Netherlands Co-operation Program': a program between the Air Forces of England and the Netherlands on military research.

angle of attack	The angle between the flight velocity and a reference line of the model or of the aircraft (often the mean aerodynamic chord of the wing). The lift coefficient increases with increasing angle of attack till a maximum (the maximum lift coefficient) is reached [figure E-12].
ARA	'Aerodynamic Research Association': the aerodynamic research institute in Bedford, England, jointly established in 1952 by the English aircraft industry.
AVA	'Aerodynamische Versuchs Anstalt': the aeronautical laboratory in Göttingen, Germany founded in 1907. During World War II AVA supervised the NLL activities. In 1969 AVA was integrated within DFVLR.
boundary layer	The region of the flow very close to the surface (e.g. of the wing or the fuselage) where viscous effects are dominant. The effect of the boundary layer is felt as friction force on the surface causing viscous drag. The boundary layer can have a laminar or a turbulent state (see transition).
buffeting, buffet boundary, buffet penetration	Buffet appears in flight as a violently shaking of the aircraft due to the separation of boundary layers on the wing surface, often caused by the interaction with shock waves.
CAL	'Cornell Aeronautical Laboratory' in the US. They operated several transonic wind tunnels.
choking	Choking occurs when the flow velocity in a channel locally exceeds the speed of sound due to an obstruction in the channel (e.g. a model in the test section of a wind tunnel) or at the smallest cross section (the throat or nozzle). A shock wave is formed that separates the upstream supersonic region from the downstream subsonic region. In transonic test sections choking is avoided by longitudinal slots or perforations in the tunnel walls.
CIRA	'Centro Italiano di Ricerche Aerospaziali': the Italian aeronautical research institute in Capua near Naples.
CNES	'Centre National d'Études Spatiales': the French space organisation.
contraction	Part of the wind tunnel circuit between the setting chamber and the test section where the cross sectional area decreases in a very precise way to create a uniform flow in the test section.
contraction ratio	The ratio between the maximum cross sectional area in the settling chamber and the cross sectional area of the test section.
corner vane	Vanes or curved plates in the corner of a wind tunnel circuit to force the flow around the corner with minimal losses.
cruise condition	The combination of lift coefficient and Mach number for which the aircraft is designed to fly in cruise with minimum drag.
DFVLR / DLR	'Deutsche Forschungs- und Versuchsanstalt für Luft- und Raumfahrt', later abbreviated as DLR ('German Aerospace Research Institute'). DLR is the sister organisation of NLR in Germany.
diffusor, diffuser	Part of a wind tunnel circuit downstream of the test section where the cross sectional area increases to reduce the speed to minimize frictional losses in the circuit.
DNW	'Deutsch-Niederländischer Windkanalen' / 'German-Dutch Wind Tunnels'. Started in 1980 as a large low speed wind tunnel, jointly built and operated by DLR and NLR in the Noordoostpolder in The Netherlands. When in the nineties other wind tunnels were added to the DNW organisation, the low speed tunnel was renamed LLF (Large Low-speed Facility).
DSMA	'Dilworth, Secord, Marr & Associates': a Canadian consulting company for wind tunnel engineering. DSMA was involved in the design of the ETW and the modification of the HST.
dynamic pressure (q)	The pressure felt at the end of a tube pointing in the direction of the flow (total pressure) minus the internal pressure (static pressure); defined by $q = \frac{1}{2}\rho V^2$ with ρ the air density and V the flow velocity.
ejector	A device to suck air through a pipe or a channel by blowing high pressure air in the direction of the flow.

ELDO	'European Launcher Development Organisation', a multinational consortium formed in the 1960s to build a European space launch vehicle. Members were Belgium, Britain, France, Germany, Italy and the Netherlands, with Australia as an associate member.
ESA	'European Space Agency': established in 1975 as a merger between the European Space Research Organization (ESRO) and the European Launcher Development Organisation (ELDO).
ESRO	'European Space Research Organization', an organisation founded by 10 European nations with the intention of jointly pursuing scientific research in space. It was founded in 1964.
ETW	'European Transonic Windtunnel', a high Reynolds number transonic wind tunnel, built and operated by Germany, France, England and the Netherlands in Porz-Wahn near Cologne. In this facility free flight Reynolds numbers can be obtained by cooling the air with nitrogen till temperatures as low as 120° Kelvin (-150° Celsius). Inaugurated in 1993.
FDP	' Fluid Dynamics Panel': one of the first AGARD panels that started in 1952 as the 'Wind-Tunnel and Model Testing Panel'.
FFA	'Flygtekniska Försöksanstalten': the aeronautical research institute of Sweden, later to become part of FOI, the ' Swedish Defence Research Agency'.
flutter	An unstable oscillation of the construction due to a coupling between the aerodynamic forces and the deformation of the structure.
GALCIT	'Graduate Aeronautical Laboratories' at Caltech Institute of Technology, California USA.
GARTEUR	'Group for Aeronautical Research and Technology in Europe': co-operation on government level between European countries with a common interest in aeronautical research. Joined by France, Germany, England, The Netherlands, Spain, Italy and Sweden. Founded in 1973.
ICAS	'International Council of the Aeronautical Sciences'. An international, non-government, non-profit scientific organization founded in 1958 with the mission to advance knowledge and facilitate collaboration in aeronautics.
IEPG	'Independent European Program Group': a European co-operation on defence.
intake	Front part of the engine or the duct towards the engine to capture the air.
interferometer	Optical system to visualize density differences in the flow by interference between a light beam that passes the test section and an undisturbed reference light beam.
inverse design	A design in which the shape of the wing is derived from a specified (the 'target') pressure distribution. This as opposed to a 'direct design' where the wing geometry is derived in subsequent steps, each step involving the calculation of the pressure distribution for a given wing shape.
KAT	'Kleine Acoustische Tunnel': a small wind tunnel in the Noordoostpolder to measure aerodynamic noise (built in 1975).
Mach number	The Mach number is defined a $Ma = \frac{V}{a}$ with V the air speed and a the speed of sound. The flow is said to be subsonic when Ma<1, supersonic when Ma>1 and transonic when M≈1. It is essential in wind tunnel testing to duplicate the flight Mach number since many flow phenomena are critically dependent on the Mach number.
maximum lift coefficient	See angle of attack.
NACA, NASA	'National Advisory Committee for Aeronautics', established in the US in 1915 for aeronautical research; after 1958 continued as the 'National Aeronautics and Space Administration'.
NIV, NIVR	'Nederlands Instituut voor Vliegtuigontwikkeling', later 'Nederlands Instituut voor Vliegtuigontwikkeling en Ruimtevaart' ('Netherlands Agency for Aerospace Programs'); established in 1946.

off-design boundaries	Boundaries in the flight envelope of an aircraft that mark specific flow phenomena such as maximum lift, drag rise (a sudden increase in drag due to shock waves), buffet (flow separation in combination with strong shock waves). See also figure E-12.
ONERA	'Office Nationale d'Études et de Recherches Aérospatiales' : ONERA is the sister organisation of NLR in France. Founded in 1946 as a merger of several already existing aeronautical research institutes.
open area ratio	The ratio between the open area (slots, perforation holes) and the total area of the wall for a test section with a ventilated wall (slotted or perforated).
plenum chamber	A confined space surrounding a (ventilated wall) test section. A plenum chamber is needed when the static pressure in the test section differs from the atmospheric pressure.
pitot pressure	See total pressure.
PIV	'Particle Image Velocimetry': an optical technique to measure flow velocities in magnitude and direction in a plane. In the flow two images are made of the distribution of very small particles, illuminated by two subsequent laser pulses that generate a light sheet. By correlating the position of the particles in the two images, the local flow velocity can be derived.
polar	A set of data points obtained for an increased angle of attack at constant Mach number; each data point consists of the measured pressures and/or balance forces and the reference flow conditions. Also used to denote the graph that shows the lift coefficient as a function of the angle of attack or the lift coefficient versus the drag coefficient.
PSP	'Pressure Sensitive Paint': a way to measure pressures by painting the model surface with a special kind of paint that changes its colour depending on the local pressure (basically the local oxygen content). See figure 2-30.
RAE	'Royal Aircraft Establishment': the sister organisation of NLR in England. Established in 1918 as a continuation of the Royal Aircraft Factory. In 2001 partly privatised to become part of QinetiQ.
Reynolds number	The Reynolds number is defined by $Re = \frac{V.\rho.\ell}{\mu}$ with V the flight velocity, ρ the air density, ℓ a reference length such as the mean chord of the wing and μ the dynamic viscosity. It is a measure for the relative importance of the viscous forces, the pressure forces and the inertial forces. The flow in flight and on a wind tunnel model is similar when the Reynolds number is the same. However, some difference between tunnel and flight Reynolds numbers is generally acceptable. The ETW was built to duplicate the flight Reynolds numbers.
schlieren	An optical technique to visualize the density variations in the flow. When a light beam passes a flow with density variations (e.g. due to shock waves) it will be deflected according to the density gradient to form lighter and darker areas on a photograph. See figures 1-34, 2-50 and 2-51.
separation, flow separation	Flow separation occurs when the flow in the boundary layer breaks away from the surface of the wing or the fuselage. Normally, once the flow is separated on a wing, the drag increases and the lift decreases, typically leading to maximum lift or buffet boundaries. See figure 2-52.
settling chamber	Part of the tunnel circuit just upstream of the test section to 'calm down' the flow. In the settling chamber the speed is reduced as a result of a large cross sectional area (relative to the cross section of the other parts of the tunnel circuit). Screens or a flow rectifier can be installed to break up the turbulence.
shock wave	Shock waves will generally occur when the flow is decelerated from supersonic to subsonic flow velocities. They manifest themselves as discontinuities in the flow field such as a sudden pressure rise. The best known example is the sonic boom for an aircraft that flies faster than the speed of sound. At transonic conditions shocks most often terminate pockets of supersonic flow above the wing. They are the cause of extra drag. In a supercritical design the wing is shaped in such a way that regions of supersonic flow are terminated by weak shocks.

shock wave boundary layer interaction	Interaction between a shock wave and the boundary layer. When the shock is sufficiently strong flow separation will occur with an adverse effect on the aerodynamics causing e.g. a rapid drag increase, maximum lift or buffeting.
SKV	'Super Kritieke Vleugel' or 'Super Critical Wing': name of a research project at NLR between 1974 and 1980 funded by NIVR to develop supercritical wing technology. See also shock wave.
slotted walls	Longitudinal openings ('slots') in the walls of a transonic test section to prevent choking.
stagnation pressure or total pressure	The pressure felt by a tube pointing in the direction of the flow. In the tube the flow is brought to rest hence the name stagnation pressure. The total pressure is the sum of the static and the dynamic pressure.
stagnation temperature	The temperature of the flow when brought to rest. It is the sum of the static temperature in the flow and a contribution that increases rapidly with flow velocity. For high supersonic and hypersonic conditions the stagnation temperature can be very high.
static pressure	The 'internal' pressure of the flow. It can be measured with a pressure hole in a surface which is aligned with the flow (e.g. the tunnel wall, the side of a pressure probe).
sting, sting support	The sting is the bar or rod that holds the wind tunnel model in the test section. It is often streamline shaped in order not to disturb the flow over the model. For force measurements an internal balance can be inserted between the model and the sting.
subsonic	See Mach number
supercritical flow	The flow at high subsonic flight conditions when the speed of sound is locally exceeded. Shock waves are generally formed to terminate local supersonic pockets. This can be avoided by a special design for shock free conditions ('supercritical designs').
supersonic	See Mach number.
total pressure	See stagnation pressure.
TPS	'Turbine Powered Simulators': small engines driven by high pressure air used to simulate the turbofan engines on a wind tunnel model.
transition	Transition occurs in a boundary layer when the flow changes from a laminar into a turbulent state. It depends on the local flow conditions and the surface roughness and its location changes with Reynolds number. Transition influences the downstream development of the boundary layer and possibly flow separation.
transonic	See Mach number.
wake	The wake is the continuation of the boundary layer flow behind the wing or aircraft. The total pressure in the wake differs from the total pressure outside of the wake and is a measure of the viscous drag of the aircraft.
wake rake	A device with a row of total pressure probes to measure in detail the total pressure distribution inside the wake. From wake rake measurements the viscous drag can be derived.
yaw angle	The angle between the model or aircraft axis and the flow velocity when the aircraft is rotated around its top axis (the axis vertical to the plane defined by the aircraft axis and the wing). ■

APPENDIX G
OBJECTS RELATED TO HST AND SST ON DISPLAY IN THE NLR MUSEUM

This table provides an overview of the objects that are preserved by the Foundation Historical Museum NLR. These objects have been discussed in the text (marked with an *) or they are otherwise of interest for the history of the wind tunnels at NLR and high speeds testing in particular. Most of the objects are part of the exhibit. Contact http://www.nlrmuseum.nl.

Page number	Museum number	Figure number	Description
9	-	1-2,3	From the original Eiffel tunnel only the fan to drive the tunnel has been preserved; it is on display against the wall at the entrance hall of the main NLR building in Amsterdam (1919).
9	X0037	-	Fan of tunnel No. 2 designed by Burgers. This tunnel was designed as a pilot facility to test the aerodynamic circuit of the low speed wind tunnels no. 3 and no. 4 that became operational in 1940.
11	X0563	-	Demonstration model of a wind tunnel. Displayed on exhibitions to show to the public the principle of a wind tunnel together with an explanation of the new wind tunnel plans (around 1950).
13	X0090-1 X0090-2	1-11	Nameplates of one of the escort ship, HMS Duff; the power plant for the HST and SST used the turbo-electric installation of this ship (around 1950).
23 27	X0500 X0501	1-28	One of the original blades of the fan of the HST (around 1958) and a carbon fibre blade made by NLR during the Phase 2 modification of the HST (1996).
27	X0274	-	Temperature sensor of the Pilot Tunnel (1954).
34	X0564	1-56	The 'transonic insert' tested in the CSST to find out if high Reynolds number transonic flow could be generated with an insert in the SST (1978).
35	X1050	-	Counter for the actual 'wind-on' hours of the HST, used until the Phase 2 modification of 1996.
35	X1650 X1651	1-57	Sub-scale models of the model support booms ('double roll boom' and 'articulated boom') measured in the PHST (the modified Pilot Tunnel) to optimise the design for the new HST supports (1986).
36	X1072	-	Indicator of the 'allowable rate of change' for the pitch angle of the tunnel fan. The operator of the HST had to increase the tunnel speed gradually, depending on the rate at which more energy could be delivered by the power plant (used till 1996).
38	X0320	2-1	Fokker F.II wind tunnel model measured on the Eiffel balance (around 1920).
39	X0244-2	2-3	One of the conventional balances used with the Eiffel-tunnel and later with tunnel no. 4 (the small LST); all weights to be placed manually (used till 1965).
39	X1740-2	2-5	One component of the external balance of the big Low Speed Tunnel LST, tunnel no. 3 (in use till 1984).
40	X0153-1 X0154	2-6	Table calculator used by the ladies of the 'Calculation Service' ('*Uitwerkdienst*') (used till around 1960).
9 40	X0290-1	2-8	The 'Schildknecht' Betz-manometer in use by the big LST to measure the tunnel reference pressure (till around 1975).
40	X0001 X0014	2-9	Water / alcohol manometer; to increase the resolution, the tube could be inclined (in use till about 1965).
43	X0148	2-16 2-17	One of the first NLL made balances AE1037; it is a 'sting balance' used to test the AGARD-C standard calibration model in the PT (around 1960).

Page number	Museum number	Figure number	Description
44 68	X0550	3-8	Balance made by Cornell Laboratories in the US, probably used for early tests in the Caravelle model for Sud Aviation (around 1960).
44 45	X0271	2-19 2-20	One of the TASK balances (the smallest one and not in use any more) (around 1963).
45	X0553	2-22	Large demonstration model of an NLR designed internal balance for use in HST and SST (around 1970).
45	X0286	2-22	The NLL made 6 component strain gauge balance AE1013 used for the AGARD calibration models (around 1960).
46	X0260	-	Barometer used in the PT.
46	X0024	-	Mach number dial mounted on the wall of the PT to indicate the actual Mach number.
46	X1049	-	P_o meter used as an indicator on the control desk of the HST till the Phase 1 modification of 1993.
46	X0460 X0961	2-25	The Mach meter from Dätwyler & Haussammann to indicate the Mach number on the tunnel console (used till 1970?).
47	X0185	2-24	Precision manometer by Dätwyler used in the early days of the HST (around 1960).
47	X0565	2-26	The 'Engineering balance', a precision instrument measuring reference pressures of the HST and providing a digital output (used till 1992).
48	X0142	-	Parts of a large pressure scanner (pressure switch), probably purchased in 1958 for an intended use in the supersonic tunnels.
49	X0603 X0020	-	Parts of a 'Scanivalve' pressure scanner (used since 1963).
49	X0578	-	Inclined multi-manometer used in the PT to measure the pressure distributions of two-dimensional airfoils (1960-1980).
49	X1134	2-32	Model of the NLR developed duplex-scanner (1975).
49	X0602	2-34	A solid state PSI pressure scanner (introduced around 1985).
53	X0093	-	Unit to repair paper tapes (1960-1973).
53	X1064	-	The so-called 'wheel-balance' (a strain gauge balance) enabled on-line balance readings in the low speed tunnel LST. The balance was mounted in the connecting rod between the old external balance and the platform to which the wind tunnel model was attached (1965-1984).
55	X1538	2-46	First generation Measurement Conditioning Unit (MCU) used by all wind tunnels of NLR (1973).
60 61	X0645	2-60 2-63	Wooden mock-up of the nose of the Concorde, used in the 'rotating barrel machine' for the manufacturing of metal Concorde models for tests in HST and SST (around 1970).
61 63	X0278	-	Test specimen of a Concorde wing from the NLR Workshop (around 1970).
64	X0935	-	Wind tunnel model of the Fokker F25 'Promotor'.
64	X0517	-	High speed wind tunnel model of the Fokker S14 manufactured and tested in France (1950).
43 65	X0249 -1 to 4	2-17 3-1 3-2	Set of four AGARD-C standard calibration wind tunnel models used for wall interference studies and comparative tests in various facilities (1955-1965).
69	X0484	-	Wind tunnel model of the NLL sounding rocket GS/1 (around 1963).
69	X0547	3-12	Wind tunnel model of the MO-3 experimental rocket of NLL (1962).
69	X0010	3-13	The experimental rocket MO-3 (1960)
72	X0937	-	HST wind tunnel (force) model of the regional transport aircraft VFW-614 (1970).

Page number	Museum number	Figure number	Description
72	X0936	3-21	HST wind tunnel (pressure) model of the regional transport aircraft VFW-614 (1970).
73	X0502	-	Wind tunnel model of ARIANE-1 with launch platform (1976).
73	X0054	3-24	Wind tunnel model of the EUROPE-3 launcher (1971).
73	X0648	3-25	Wind tunnel model of the ELDO-A launcher with simulated launch platform (around 1964).
76	X0273	3-39	The ring wing configuration designed by the group of Erdmann and tested in the CSST (around 1965).
77 79	X0381 X0382 X1067	-	Two-dimensional supercritical airfoils tested in the PT: i) NLR 7101 with oscillating flap, ii) NLR 7301, a 16.5 % thick supercritical airfoil and iii) the Quasi-Ellipse QE-1, the first shock-free design (around 1970).
78	X0632	-	'The supercritical wing of NLR', a souvenir offered by the 'workers council' to the general director Marx when he retired in 1976 from NLR.
78	X0560	3-41	The transonic wing designed within the framework of the ANCP program, a co-operation between England and The Netherlands; this model was built by ARA and tested in the HST (1967).
78	X0744 -1 to 5	3-43	Various stores used with the NF-5 HST model to validate the NLR 'panel method'; later used for flutter investigations (1971).
78	X1069 X1070	3-44	HST wind tunnel models of SKV-1 and -4, the first supercritical research wings developed at NLR together with Fokker (tested in 1975).
84	X0545	-	Model to simulate the rear part of the engine for the F29 / MDF-100. The jet was simulated with compressed air (1980).
59 84	X0546	2-55 3-59	Intake model for the F29 / MDF-100; this model was mounted on the Inlet Test Rig in the HST to simulate various intake conditions (mass flow ratio's) (around 1980).
84	X0272	3-57	Rotating rake used for tests on the nozzle of the engine of an Airbus A300 wind tunnel model in the HST (around 1979).
84	X0562	3-60	Test set-up for the CSST to develop the hot jet simulation technique with H_2O_2 (around 1975).
85	X0483	3-64	Wind tunnel model of ARIANE-5 with Hermes space plane (1988). ■

Index of names

On the author

Bram Elsenaar with a wind tunnel model of the Fokker S.13.

Bram Elsenaar (1943) studied aeronautical engineering at Delft Technical University. In 1967 he finished his master thesis at NLR with a study on heat transfer in supersonic boundary layers. The experimental work was executed in the small 3x3 cm^2 supersonic wind tunnel of NLR under supervision of Prof. S.F. Erdmann and Prof. J. Steketee. For two years through contacts of Steketee he studied at the Institute for Aerospace Studies at the University of Toronto (UTIAS) where he obtained his Masters Degree in Applied Sciences in 1969. After returning to the Netherlands, he got a position at NLR where he was part of a small group to develop and validate a calculation method for three dimensional turbulent boundary layers. Within this group he was responsible for the measuring techniques as part of a large scale experiment in the big low speed wind tunnel LST (tunnel no. 3). In the early seventies he was transferred to the Department of Compressible Aerodynamics (AC) to co-ordinate the experimental work in the HST and the PT on the development of supercritical airfoils and wings, the SKV program. This program, financed by NIVR, was executed in close co-operation with Fokker. After that, until 1990, he guided the research on transonic aerodynamics and wind tunnel testing within the Department of Compressible Aerodyamics (AC). In 1990 he became head of the newly formed Department of Experimental Aerodynamics (AX), responsible for all wind tunnel testing in the low speed, transonic and supersonic wind tunnels of NLR. In 1982 he became involved in GARTEUR, a European co-operation on aeronautical research. In 1988 he joined the AGARD Fluid Dynamics Panel, of which he became an active member. After the reorganisation of NLR following the bankruptcy of Fokker, he was involved in different research projects in the NLR wind tunnels, most often as part of GARTEUR or the European Framework Programmes. Between 1999 and 2001 he worked on the aerodynamic development of the A380 at AIRBUS Large Aircraft Division in Toulouse on behalf of STORK Fokker Aerostructures. He retired in 2004. Soon after that he became active in the Foundation Historical Museum NLR, concentrating mainly on the aerodynamic collection. ■

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50 years high speed wind tunnel testing
in The Netherlands

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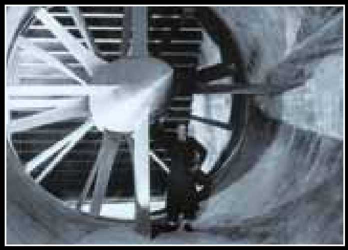
50 YEARS HIGH SPEED WIND TUNNEL TESTING IN THE NETHERLANDS describes the fascinating story of the transonic and supersonic wind tunnels of the National Aerospace Laboratory NLR. Wind tunnels are used to optimize the aerodynamic shape of the aircraft. The high speed tunnels were built after World War II to support the Dutch aircraft industry. The Fokker F28 Fellowship, the Fokker 100 and the Fokker 70, were tested here prior to their first flight. Many other European projects such as the Concorde, Airbus and the Ariane launchers (to name a few) found their way as well into these wind tunnels. Therefore this book on the history of high speed wind tunnel testing also provides a reflection on the development of aeronautics in the Netherlands and abroad.



In 2010 the 50th anniversary of these tunnels was celebrated and this event marked the beginning of a study into the origin of these wind tunnels by the Foundation Historical Museum NLR. It is the mission of this museum to preserve the aerospace heritage of the Netherlands, notably specific aspects related to research and development in support of the aerospace industry and the aircraft operators. To achieve this a dedicated group of volunteers makes the museum archives accessible, retrieves relevant photographs and collects instruments, equipment and wind tunnel models that are on display in the museum exposition hall. Without this information it would not have been possible to document the history of the high speed wind tunnels as described in this book. Moreover, many of the objects discussed in this book have been preserved and can still be seen as an interesting illustration of an innovative technological development. This collection can be visited (on request). The recently published book "Waypoint NLR 90YR" on the history of NLR provides an interesting view of the activities of NLR since its foundation in 1919. More information can be found on the museum website: www.nlrmuseum.nl. The museum is located in the former low speed wind tunnel complex at the NLR site, Anthony Fokkerweg 2, 1059 CM AMSTERDAM. Mail to museum@nlr.nl.

Foundation Historical Museum NLR