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CRYOGENIC WIND TUNNELS FOR HIGH REYNOLDS NUMBER TESTING

Robert A. Kilgore and Pierce L. Lawing
NASA Langley Research Center
Hampton, VA 23665-5225
U.S.A.

Abstract

This paper begins with a brief review of cryogenic wind tunnels and their use for high Reynolds number testing. Emphasis is on operational experience and recent aerodynamic testing in the NASA Langley 0.3-m Transonic Cryogenic Tunnel (TCT). Since we built the 0.3-m TCT in 1973, it has logged about 8000 hours of running at cryogenic temperatures. The 0.3-m TCT is used for aerodynamic testing and to develop test techniques for cryogenic tunnels.

Specific areas covered in this paper include development of test techniques and aerodynamic testing in cryogenic tunnels. We also give details of our experience in developing model construction techniques, including airfoils as thin as 5 percent. Based on our experience, we recommend using advanced testing techniques to increase the value of cryogenic tunnels to the research community. These include **adaptive wall test sections** using solid but flexible top and bottom walls and **magnetic suspension and balance systems.**

I. Introduction

The ability to simulate the aerodynamics of flight is constantly improving. One area of recent improvement is testing at flight values of Reynolds number in subsonic and transonic wind tunnels. The development of cryogenic wind tunnels makes it possible to test at flight Reynolds number. This paper reviews the state of development of cryogenic wind tunnels and their use for high Reynolds number testing.

II. The World's Cryogenic Wind Tunnels

We begin this section by defining what we mean by *cryogenic*. The U.S. National Bureau of Standards considers the field of cryogenics to involve temperatures below 123 K (-150°C). This definition for *cryogenics* is as good as any. The normal boiling points of the so-called permanent gases (helium, hydrogen, neon, nitrogen, oxygen, and air) all lie below 123 K. Freon refrigerants, hydrogen sulfide, and other common refrigerants all boil above 123 K.

Thus, by our definition, there are at least 12 cryogenic tunnels in use around the world. A recent review article in *Cryogenics* describes most of these cryogenic tunnels.(1) Emphasis in the review article is on the cryogenic engineering aspects of their design and operation. For a variety of reasons, some of the earlier cryogenic tunnels have been abandoned or become inactive. These include the 1 foot and 4 foot Blowdown Cryogenic Tunnels built at Douglas and the T3 adaptive-wall cryogenic tunnel at ONERA/CERT.

There are several cryogenic tunnels in various stages of planning and design. One of the more significant in this category is the European Transonic Windtunnel (ETW).

In this section we briefly describe seven cryogenic tunnels. Each of these tunnels is either of historical interest or of interest because of its actual or potential research capability. These tunnels range from the very simple to the very complex. They are examples of the actual or anticipated use of cryogenic tunnels for high Reynolds number testing.

Subsonic Tunnels

The First. The first cryogenic tunnel was a very simple atmospheric low-speed tunnel. It started as an existing 1/24 scale model of the Langley V/STOL tunnel. We modified this tunnel and successfully operated it as the world's first cryogenic tunnel. It first ran at cryogenic temperatures in January of 1972. Through the spring and summer of 1972 we used this tunnel for a variety of proof-of-concept tests. Figure 1 shows the circuit of the low-speed cryogenic tunnel which is typical of most fan-driven cryogenic tunnels.

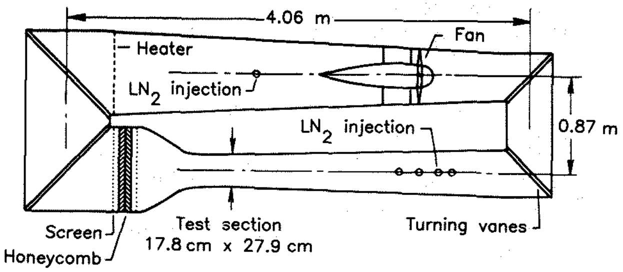


Figure 1- Sketch of Low-Speed Cryogenic Tunnel

One of our major concerns with the low-speed tunnel was finding a simple way to cool the tunnel to cryogenic temperatures. Another concern was finding suitable thermal insulation for the circuit. We had many other concerns. For example, could we really use wooden fan blades in a cryogenic tunnel? With the clarity of hindsight, we now see that most of our early concerns about cryogenic tunnels were unfounded. As wind tunnel engineers, we simply had to extend our experience to lower temperatures. The work at Langley on the low speed tunnel let us discover some the real problems with cryogenic tunnels. It also let us develop solutions to many of the problems on a small scale at low cost.

Once we had worked out operating procedures, we used the low-speed tunnel to confirm the validity of the cryogenic concept. Reference 2 gives details of our work with the low-speed tunnel. Table 1 lists the main conclusions we drew from the aerodynamic experiments and from the day-to-day operation of the Low-Speed Cryogenic Tunnel.

Aerodynamic
- Boundary-layer development with Reynolds number the same for ambient and cryogenic conditions.
- Drive-power and fan-speed found to decrease as predicted.

Operational
- Cooling with LN_2 is practical.
  - Rapid cooldown
  - Automatic temperature control
  - Gas stream is clear, dry, and frost free
- Can use conventional strain-gage balance.
- Trouble-free operation of drive motor and fan.

Table 1 Low-Speed Cryogenic Tunnel Results

The Biggest. Significant because of its size and its research potential is the low speed cryogenic tunnel at DFVLR-Köln, the Kryo-Kanal-Köln (KKK).(3)

Viehweger and his co-workers at the DFVLR Research Center at Porz-Wahn modified a large low-speed tunnel for cryogenic operation. The project started in 1978 with studies of how to modify an existing low-speed 3 m wind tunnel. The studies included modeling the liquid nitrogen injection process and finding ways of fixing internal insulation to the concrete tunnel. They completed the studies in 1979 and got approval to continue the project in 1980. The first cryogenic operation of KKK was in January of 1986.

The KKK is a thoroughly modern low-speed cryogenic wind tunnel. The work by Viehweger and his colleagues is an excellent example of how to modify an existing tunnel for cryogenic operation. By careful study, they understood and solved the problems of liquid nitrogen injection, internal insulation, and automatic controls. They now have an excellent low-speed high Reynolds number tunnel. Reference 3 gives details about the design and operation of KKK. Table 2 gives some of the design and operational characteristics of the KKK.

Type	closed circuit, fan
Material of construction	concrete
Insulation	internal
Cooling	liquid nitrogen
Test gas	nitrogen
Test section size (h,w,l)	2.4 x 2.4 x 5.4 m
Mach range	up to 0.38
Contraction ratio	10.3:1
Stagnation pressure	up to 1.12 bars
Stagnation temperature	100 - 300 K
Running time	several hours
Max. Reynolds number/m	37 million
Drive motor	1 MW
Fan speed	up to 500 rpm
LN_2 tank volume	150 m^3

Table 2 KKK Cryogenic Low-Speed Tunnel at DFVLR - Köln

Transonic Tunnels

The First. The 0.3-m Transonic Cryogenic Tunnel (TCT) at NASA Langley is the world's first transonic cryogenic tunnel. It can operate from ambient to cryogenic temperatures at pressures up to 6 bars. We built and first operated the 0.3-m TCT in 1973 with a 33 cm octagonal 3-D test section. We used the 3-D test section for all of the early experimental proof-of-concept studies.(4)

In 1975 we installed a conventional 20 x 60 cm slotted-wall 2-D test section. In 1978 we increased the operating pressure of the tunnel from 5 to 6 bars. We used the 20 x 60 cm test section for several airfoil studies as well as studies aimed at developing test techniques for cryogenic tunnels.

In 1986 we installed a 33 x 33 cm solid adaptive wall test section. The adaptive wall test section has single curvature top and bottom walls. The solid sidewalls have provision for boundary layer removal. This test section allows us to test airfoils through transonic speeds at flight values of Reynolds number. We use the adaptive wall test section for both 2-D and 3-D testing. Table 3 gives the major design and operational characteristics of the 0.3-m TCT.

Later in this paper we will describe in detail some of the work done in the 0.3-m TCT in its first 15 years of operation.

Type	closed circuit, fan
Material of construction	aluminum
Insulation	external, purged
Cooling	liquid nitrogen
Test gas	nitrogen
Test section size (h,w,l)	33 x 33 x 142 cm (solid adaptive walls)
Mach range	0.02 to 1.3+
Contraction ratio	10.7:1
Stagnation pressure	1.1 - 6.2 bars
Stagnation temperature	78 - 340 K
Running time	several hours
Max. Reynolds number/m	400 million
Drive motor	2.25 MW
Fan speed	up to 6500 rpm
LN_2 tank volume	212 m^3

Table 3 Langley 0.3-m Transonic Cryogenic Tunnel (TCT)

The Biggest. Along with the early experimental work on cryogenic tunnels at NASA Langley, there was a parallel theoretical study. Adcock studied in detail the so-called "real-gas effects" of transonic tunnels with nitrogen gas at cryogenic temperatures.(5) We also had experimental proof of the validity of the cryogenic wind tunnel concept at transonic speeds from the 0.3-m TCT.

This experimental proof, combined with Adcock's theoretical studies, had far-reaching effects. As the superiority of the cryogenic concept became more widely recognized, researchers abandoned several proposed ambient temperature high Reynolds number intermittent tunnels.

A direct outcome of our work at Langley was a 1975 decision by the joint Air Force/NASA Aeronautics and Astronautics Coordinating Board (AACB). The AACB recommended a *single* large transonic *cryogenic* tunnel to meet the high Reynolds number testing needs of the United States. Table 4 shows the AACB recommendations for the proposed *U.S. National Transonic Facility* (NTF).

- A single transonic wind tunnel to be called the **U.S. National Transonic Facility**
- **Cryogenic concept**
- Characteristics:

Test section size	2.5 m x 2.5 m
Design pressure	8.8 atm
Design Mach number	0.2 - 1.2
Stream fluid	Nitrogen
Basic drive power	90 megawatts
Productivity/efficiency	8000 polars/year
Reynolds number	120 million ($M_\infty = 1.0$)

- **Located at the NASA Langley Research Center**

Table 4 U.S. National Transonic Facility (NTF) AACB Recommendations

The NTF at NASA Langley is the direct result of the AACB recommendations. The site dedication ceremonies for the U.S. NTF took place on July 19, 1977. The dedication of the completed NTF took place on December 6, 1983. The NTF has brought together for the first time the technology of large transonic wind tunnels and modern cryogenic engineering.

There are many interesting details of the NTF design we could describe. However, most of the information that might be of interest is available in references 6 and 7. Table 5 gives the main design and operational characteristics of the U.S. National Transonic Facility.

Type	closed circuit, fan
Material of construction	304 stainless, aluminum
Insulation	internal
Cooling	
Cryogenic mode	liquid nitrogen
Air mode	air/water heat exchanger
Test gas	nitrogen or air
Test section size (h,w,l)	2.5 x 2.5 x 7.62 m
Mach range	0.2 - 1.2
Contraction ratio	15:1
Stagnation pressure	1 - 8.9 bars
Stagnation temperature	78 - 340 K
Running time	continuous
Max. Reynolds number/m	480 million
Drive motor	94 MW
Fan speed	up to 600 rpm
LN_2 tank volume	946 m^3

Table 5 U.S. National Transonic Facility (NTF)

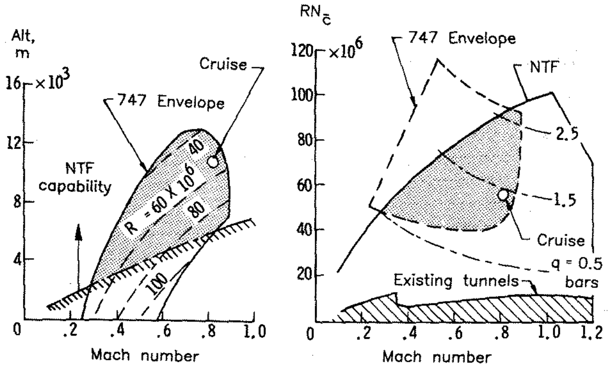


Figure 2- U.S. NTF, Test and Flight Envelopes for B-747 (From Reference 8)

Because of its large test section and high pressure capability, the NTF offers unique high Reynolds number testing capability at transonic speeds. Figure 2 shows the ability of the NTF to test at full scale Reynolds number. The figure compares flight at full scale and test at model scale in the NTF. (For this figure, the reference length for Reynolds number is 0.08 times the square root of the test section area.) The airplane used in this comparison is a large commercial transport, the well-known Boeing 747.

On the left is a plot of the airplane flight envelope showing altitude as a function of Mach number. It shows lines of constant Reynolds number within the flight envelope. On the right, the flight envelope has been superimposed on the NTF test envelope. It shows Reynolds number and dynamic pressure, q, as a function of Mach number for a properly sized model. We can achieve full scale flight Reynolds numbers in the part of the flight envelope covered by the NTF test envelope.

The maximum test boundary of the NTF is also shown on the 747 flight envelope on the left. The NTF will not provide full scale Reynolds number for low altitude flight of the 747. However, the NTF does give correct simulation in the high performance region of the envelope which includes the cruise point. This region around the cruise point is by far the most important region for aircraft design and efficiency.

Heat Transfer Tunnel

Of special interest because of its unusual use of cryogenic temperatures is the Cryogenic Facility at the University of Illinois at Urbana-Champaign (UIUC). Clausing and his colleagues built a low-speed fan-driven cryogenic tunnel. They have used it for studies of forced, natural, and combined convective heat transfer. It excels in these studies under conditions requiring very large values of both Reynolds number and Grashof number.

The need to predict accurately the combined convective losses from large high temperature solar "power tower" receivers prompted the building of the cryogenic tunnel at UIUC. Clausing saw the cryogenic tunnel as the only way to get the required large values of Grashof and Reynolds numbers with the appropriate and near constant Prandtl number.(9)

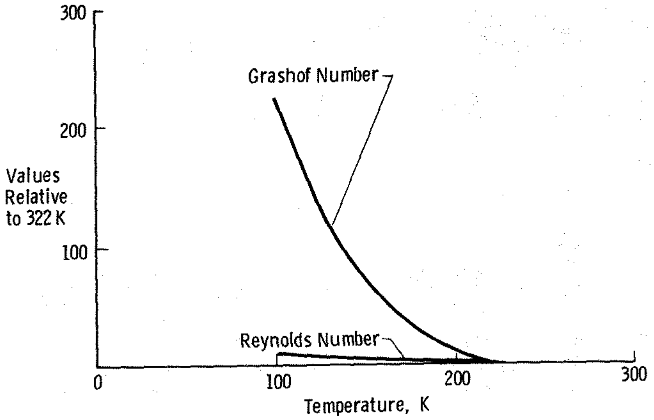


Figure 3- Effect of Temperature on Grashof and Reynolds Number

Figure 3 shows the variation of Grashof number and Reynolds number with temperature. As noted in reference 9, and as you can see in the figure, the use of cryogenic temperatures is a good way to get higher Reynolds number but an even better way to get higher Grashof numbers. Furthermore, the cryogenic environment virtually eliminates the influence of radiative heat transfer. This is a major source of error in natural convection data obtained in conventional facilities.(10) Clausing has reported both the theory and advantages of the cryogenic heat transfer tunnel in more detail in references 10 and 11. The sketch in Figure 4 shows a cross-sectional view of the UIUC Cryogenic Facility.

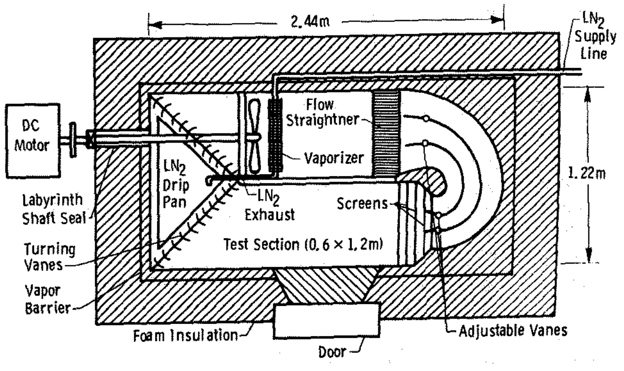


Figure 4- UIUC Cryogenic Facility

They cool the tunnel by passing liquid nitrogen through a heat exchanger/vaporizer located just downstream of twin drive fans. The resultant gas vents into the tunnel circuit. In this way they avoid any problems that might arise from incompletely evaporated liquid nitrogen from direct injection. They maintain a slight overpressure during operation to keep out the room air. Reference 12 gives a complete description of the UIUC Cryogenic Facility. Table 6 gives the basic specifications of the tunnel.

Type	closed circuit, fan
Material of construction	mostly aluminum
Insulation	external, urethane
Cooling	LN$_2$ heat exchanger with GN$_2$ injection
Test gas	nitrogen
Test section size (h,w,l), m	1.22 x 0.60 x 1.0
Speed range	0 - 8 m/s
Contraction ratio	1:1
Stagnation pressure	atmospheric
Stagnation temperature	80 - 300 K
Running time	several minutes
Max. Reynolds number/m	4 million
Drive motor	11.2 kW
Fan speed	0 - 1750 rpm
LN$_2$ tank volume	1 m^3

Table 6 Cryogenic Heat Transfer Tunnel at UIUC

Planned Tunnels

European Transonic Windtunnel (ETW). Originally working through the Fluid Dynamics Panel of AGARD, four European countries have joined to design and build a large fan-driven transonic cryogenic tunnel in Europe. The tunnel will be the European Transonic Windtunnel (ETW). The countries funding the ETW are France, the Federal Republic of Germany, the Netherlands, and the United Kingdom. They expect the ETW to meet their high Reynolds number testing needs at transonic speeds.

Work on the project to date includes building a 0.11-scale pilot tunnel at the National Aerospace Laboratory in Amsterdam. The pilot cryogenic tunnel, known as PETW, has the same operating range as anticipated for the ETW.

The pre-design phase of ETW has been completed. Each of the four countries is doing research in support of the final design. The four countries have approved the construction phase and construction of the ETW is to start in 1988. The ETW will be built on a site adjoining the DFVLR Center in Köln, FRG. Reference 13 gives a complete account of the evolution and early development of the ETW.

Table 7 gives the anticipated major design and operational characteristics of the ETW.

Type	closed circuit, fan
Material of construction	stainless steel
Insulation	internal
Cooling	liquid nitrogen
Test gas	nitrogen
Test section size (h,w,l)	2.0 x 2.4 x 6.9 m
Mach range	0.15 - 1.3
Contraction ratio	12:1
Stagnation pressure	1.25 - 4.5 bars
Stagnation temperature	90 - 313 K
Running time	continuous
Max. Reynolds number/m	228 million
Drive motor	50 MW
Fan speed	up to 1200 rpm
LN$_2$ tank volume	5000 m^3

Table 7 European Transonic Windtunnel (ETW)

Japan. There are many good wind tunnels in Japan. Some of the best are at Japan's National Aerospace Laboratory (NAL) in Chofu, Tokyo. The wind tunnels at Chofu include the 2 m x 2 m Transonic Wind Tunnel and the 5.5 m x 6.0 m Low-speed Wind Tunnel. These are respectively Japan's largest transonic and subsonic tunnels. However, these tunnels cannot achieve the test Reynolds number needed to develop modern aircraft.

To overcome the problem of low Reynolds number, three groups in Japan developed and are now using cryogenic wind tunnels. There are four cryogenic wind tunnels in Japan. Two are low-speed tunnels at the University of Tsukuba.(14) Another is a transonic tunnel at the National Defense Academy in Yokosuka.(15)

The fourth cryogenic tunnel in Japan is a transonic tunnel used regularly by Sawada and his colleagues at the National Aerospace Laboratory (NAL). The NAL 10 x 10 cm Pilot Transonic Cryogenic Tunnel has logged almost 400 hours of testing and development work since first running in 1983. References 16 through 20 describe the tunnel and give some of the aerodynamic and operational results.

There are many possible combinations of size and pressure for a transonic cryogenic tunnel to meet the high Reynolds number testing needs of Japan. Sawada of NAL has suggested one possible scenario for meeting this need.

Based on his experience with the 10 x 10 cm tunnel, Sawada has suggested two new transonic cryogenic tunnels for Japan. The smaller tunnel would have a 0.6 x 0.6 m test section. This tunnel would obviously be useful in its own right for aerodynamic testing. However, its main purpose would be as a pilot for a second transonic cryogenic tunnel having a 3.0 x 3.0 m test section.

The officials at NAL have not officially endorsed Sawada's suggested cryogenic tunnels. In the personal opinion of the authors, however, his suggestion represents a reasoned approach to providing Japan with a world class high Reynolds number transonic tunnel. Tables 8 and 9 give some of the design characteristics of the two cryogenic tunnels suggested by Sawada.

Type	closed circuit, fan
Cooling	liquid nitrogen
Test gas	nitrogen
Test section size (h,w,l)	0.6 x 0.6 x 1.8 m
Mach range	0.2 - 1.2
Contraction ratio	14:1
Stagnation pressure	1.2 - 5 bars
Stagnation temperature	90 - 300 K
Running time	45 min
Max. Reynolds number/m	340 million
Drive motor	5 MW

Table 8 Pilot 0.6 m Transonic Cryogenic Tunnel

Type	closed circuit, fan
Cooling	liquid nitrogen
Test gas	nitrogen
Test section size (h,w,l)	3.0 x 3.0 x 6.0 m
Mach range	0.2 - 1.2
Contraction ratio	14:1
Stagnation pressure	1.2 - 9 bars
Stagnation temperature	90 - 300 K
Running time	60 min
Max. Reynolds number/m	540 million
Drive motor	90 MW

Table 9 3.0 m Transonic Cryogenic Tunnel

Sawada envisions operating pressures up to 9 bars for the 3 m tunnel. The main purpose of the high pressure is to give high Reynolds numbers at Mach numbers below about 0.8.

This will provide a unique high Reynolds number testing capability for take-off and landing studies. Sawada would size the drive motor and nitrogen systems of the 3 m tunnel to operate at reduced pressures above a Mach number of 0.8. Even at reduced pressure, the size of the test section would allow testing at nearly the same Reynolds number as the NTF at Mach numbers up to 1.2.

Reference 20 gives details of the tunnels suggested by Sawada. Reference 20 also describes the specific role the 3 m tunnel might play in Japanese aerodynamic research.

III. Model Construction Techniques

Cryogenic tunnels make it possible to test at flight Reynolds numbers. To use this new capability, we must build models of materials compatible with cryogenic temperatures. Unfortunately, such materials are often unfamiliar to the model maker.

Because of their high Reynolds number capability, cryogenic tunnels have the potential to make major advances in experimental fluid dynamics. To realize this potential, the models must be unusually accurate in contour. The models must also not warp or distort during large swings in temperature and force levels.[21] In addition, to test with free transition at the high Reynolds number, the surface finish of the model must be very good, especially near the leading edge.

In our experience with the 0.3-m TCT, these new and more stringent model requirements led to higher model costs. Even worse, they often led to models that were unfit for testing after construction.

A cryogenic tunnel operating in the production mode will require the construction of several new models each year. At an average cost of $50,000 each for airfoil models for the Langley 0.3-m TCT, 20 new models per year could easily cost $1,000,000. For more complex 3-D models for larger tunnels, whether cryogenic or not, the cost of models will be a major expense. Thus, the money spent on models over the life of a tunnel might exceed the initial capital cost of the tunnel.

Many of our difficulties with the early airfoil models had a common source in the plumbing needed to access the surface pressure orifices. We decided that an effort aimed specifically at better integration of the plumbing into the model structure would solve many of the problems. Reference 22 records some of the schemes we tried. One of the better schemes is to groove a flat plate and then bond on a second plate to form pressure channels.(23,24) The resulting sandwich of plates is then contoured to form an airfoil. It is this scheme that appears most promising. In this section we describe its development and potential.

Construction of Samples

Working through a contract with Wigley, a specialist on materials at cryogenic temperatures, we built many small samples to study the bonding technology necessary to seal the integral pressure channels.(25) Figure 5 shows an example of the bonding study. The sample is cut to show a bond obtained using brazing foil and a vacuum brazing oven. Also of interest in this figure are the triangular pressure channels cut in the face of each plate.

Because we laid the sandwich of plates flat in the brazing oven, this became a test of gravitational effects. We would expect the bottom channels to fill with metal if gravity is a big factor in the flow of the melted braze foil. As shown in the figure, this does not happen. The dominant force is the capillary attraction from the narrow gap between the plates. This belief is reinforced when we realize that the brazing foil was a single thin sheet which also covered the grooves. Close examination shows that the foil covering the grooves partially melted and flowed into the adjacent narrow gap.

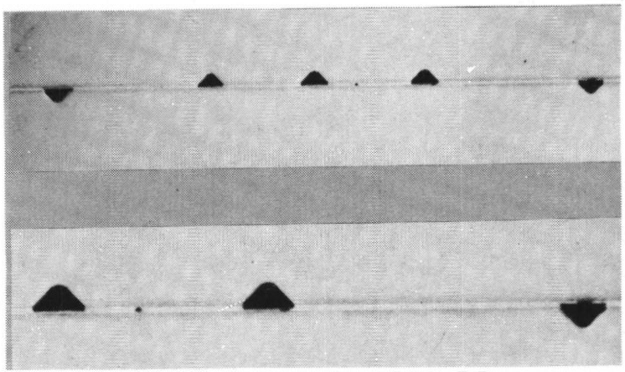

0.010 inch Channels, 0.003 inch Brazing Foil

Figure 5- Example of the Bonding Study

Construction of Airfoil Model

After we identified a successful bonding technique, we decided to build an airfoil model suitable for testing in the 0.3-m TCT. The airfoil chosen was a 12-percent thick symmetrical supercritical shape. The main reason for building this model was to discover the unanticipated problems. Therefore, we used a very ambitious pressure orifice layout for this first airfoil model. It fully exercised the new capabilities offered by this construction method.

Figure 6 is a photograph of the two halves of the model showing the surfaces ready for bonding. The channel layout shown is for 94 orifices. Most of the orifices have been pre-drilled at the proper angle and depth to penetrate the model surface during contour machining. At the ends of the model, where the channels are parallel, alternate channels end in a hole drilled normal to surface. The other half of the channels end at holes drilled in the mating plate.

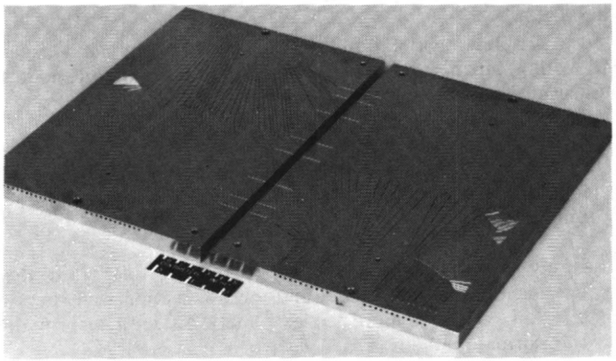


Figure 6- Photograph of Two Halves of Model

Each of the normal holes intercepts a connector hole drilled from the end of the plate. Tubes brazed in these connector holes provide the connection with the wind tunnel pressure measuring system. We use this method to avoid overcrowding, since the larger connector holes would be too closely spaced if drilled side-by-side in the bond plane.

Figure 6 shows the plates arranged with the channels matching at the trailing edge of the model. In this case the two channels combine to form the orifice. There are eight trailing edge orifices shown. The left and right hand edges of the plates will become the model leading edge. The right hand edge is the upper model surface. The fan shaped channel configurations are the top and bottom leading edge pressure tap rows. The second, smaller, fan is a row of orifices to be one half the diameter of the normal orifices. This will let us determine the effect of orifice size near the leading edge. Also visible on the lower right hand corner are 4 orifices which will be at the junction between the model and the tunnel wall.

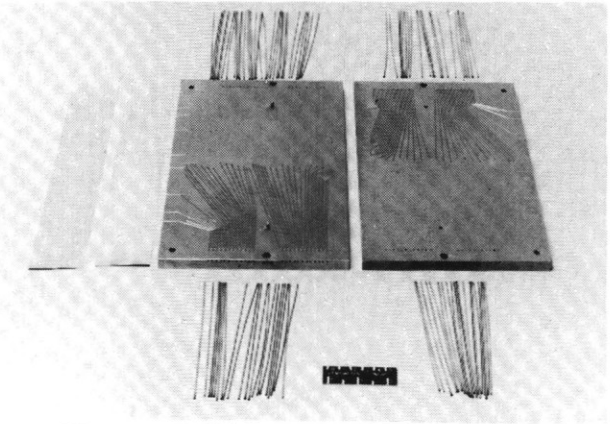


Figure 7- Model Components Ready for Brazing

Figure 7 is a photograph of the model halves, two of the four sheets of brazing foil, two of the alignment dowels, and all of the connector tubes. Figure 8 shows the model as completed and ready for test.

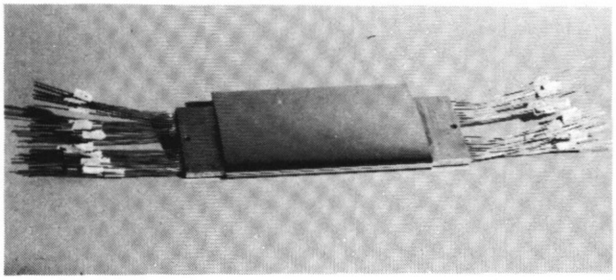


Figure 8- Model Ready for Test

This new model building technique offers advantages and testing capabilities not usually available on airfoil models built using conventional methods.

1. A spanwise row of trailing edge pressure orifices is easy to install. Installing even a single trailing edge orifice was difficult with previous methods, and often impossible on thin airfoils.

2. A row of orifices at the wing stagnation line or at the junction between the model and the test section wall is easy to install. This capability is extremely difficult to provide with normal methods.

3. The new method uses less than 0.1 percent of the model volume for pressure passages. There are no large voids in the model to cause structural irregularities during mechanical or thermal stress. Also, the models inherently have higher strength and can take larger loads.

4. Bonds of near parent metal strength and toughness offer improved margins of safety. The bond line acts as a crack stopper. Failure in one half of the model will not easily propagate to the other half.

5. The expense due to fabrication failure is less since we can check all of the pressure channels for leaks and blockage before any contour machining.

6. Construction costs are less because of the reduction in time to install pressure orifices and related internal tubing.

Aerodynamic Data on Airfoil Model

Figure 9 shows pressure coefficient data at transonic conditions and a moderate lift coefficient. This data shows the presence of a shock wave on the upper surface between 30 and 38 percent chord.

We show two sets of data. One is for the model at an angle of attack, α, of 2°, corresponding to a lift coefficient of 0.31. The other is for $\alpha = -2°$, lift coefficient of -0.31. Since this is a symmetrical airfoil, the pressure distributions at positive and negative angle of attack should match with the upper and lower symbols changing places.

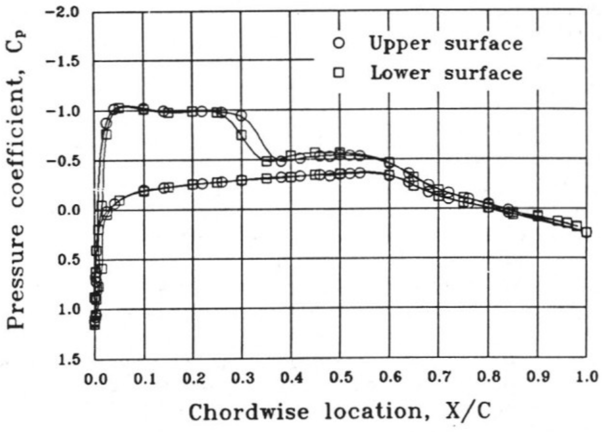


Figure 9- Aerodynamic Data on Airfoil Model

The pressures coefficients are very nearly the same. This agreement demonstrates good top and bottom symmetry of model construction. It also demonstrates good testing technique and shows that any possible cross-leaks between channels do not cause significant errors. Reference 26 gives additional aerodynamic data for this airfoil.

Current Research

The previous section described the success of the bonded plate technique in producing a useful airfoil model to test. Research is under way to further advance this construction technique. The effort is based on our desire to produce thin airfoil models not possible with current methods.(27)

We consider an airfoil model *thin* and possibly difficult to build if it has a thickness to chord ratio of less than 10 percent. However, many airplanes and missiles are flying with wings and fins much thinner. Thus, our goal was to build a model of a 5 percent thick airfoil to test in the 0.3-m TCT.

New Bonding Technology

A persistent problem met during this program is the lack of reliable vacuum brazing methods. This problem has many facets.

For the present program the main problem is control over the gap between the two plates being brazed. The gap changes as residual machining stresses in the plates relieve themselves as we heat the plates in the brazing oven. One possible solution is brute force loading to suppress any relative movement between the plates.

Another approach is to use stacked thin sheets rather than the two relatively thick plates.(28) In theory, the thin sheets would require only light loading to overcome warpage, since each sheet experiences the entire load.

Photoetched Channels

An early advance in this model construction technique was using photoetching rather than milling to form the pressure channels. We first draw the desired channel layout at a conveniently large scale and then photographically reduce it to the size of the model. Figure 10 shows chemically etched channels on a stainless steel surface. We drill the orifice holes at the end of the channel. Note the dimples etched at the end of the channel to help locate the drill bit.

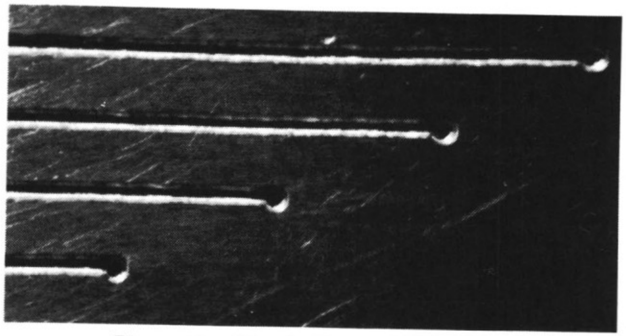


Figure 10- Chemically Etched Channels

Curved Bond Planes

Figure 11 shows the results of using the photoetching technique on curved surfaces, in this case one convex and one concave. An electrical discharge milling machine cuts the matching surfaces. The machine uses a small wire as the electrode, somewhat in the fashion of a wire cheese slicer.

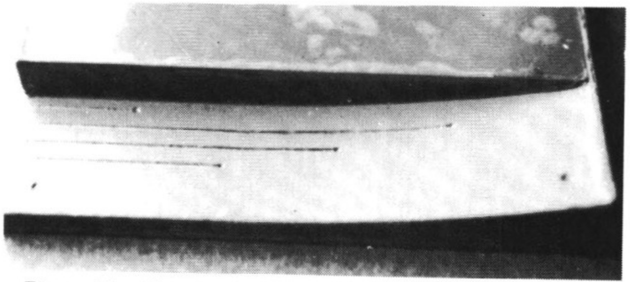


Figure 11- Chemically Etched Channels on Curved Surface

This process is known as wire cutting. After brazing the matching surfaces together, the wire cut process was once again used to cut upper and lower contours. The sample shown is the aft section of a 6 percent supercritical airfoil. The left side of figure 12 shows various size orifices as exposed by the wire cut. It also shows a trailing edge orifice. The right side shows magnified views of 1.0, 0.5, and 0.32 mm diameter orifices. This figure clearly shows the high quality of the orifice after being machined by the wire cut technique.

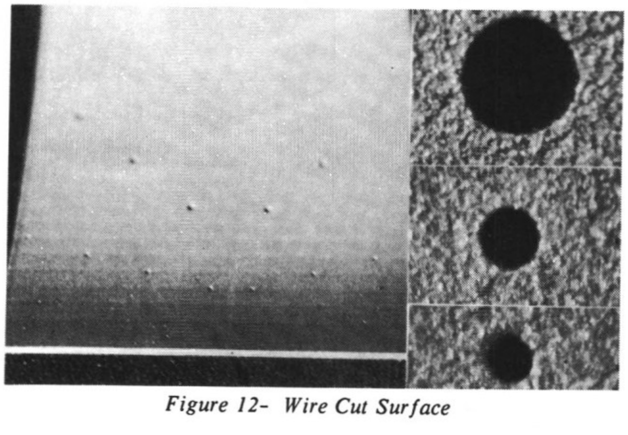


Figure 12- Wire Cut Surface

Three-Dimensional Models

The multilayer concept sketched in figure 13 is one way of providing more room for pressure channels.(28) This concept may be especially useful for models of high aspect ratio wings where a row of orifices is needed at many spanwise stations. In this case, each plate would provide one spanwise row.

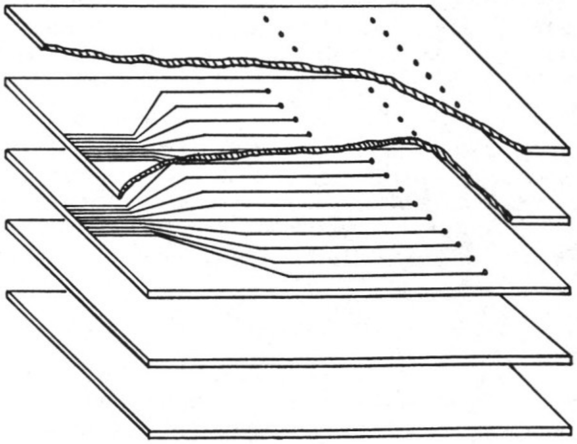


Figure 13- Multilayer Model Construction

A typical airfoil used in supersonic fighter aircraft has a lift coefficient of 0.1 and a thickness of 5 percent. One such airfoil section is the NACA 64A-105. Building such a thin airfoil model for cryogenic testing is very difficult using conventional techniques. However, the stacked thin plates method seems ideal for building a model of such a thin wing.

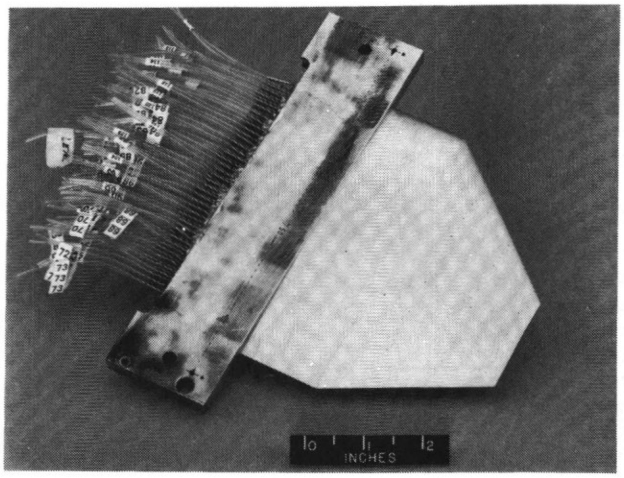


Figure 14- Pressure Model of X29A Canard

Figure 14 is a photograph of a pressure model of the X29A canard. There are three rows of orifices with a total of 56 orifices on the upper surface. Six thin plates form the upper surface of the airfoil. The outcrop of the five bond planes is clear on the photograph. There are 37 additional orifices on the bottom surface.

This is the 3-D airfoil tested in the 0.3-m TCT and discussed later in this paper. Based on our experience with this model, we are satisfied with this method of model construction. Plans are under way to extend this technique. We plan to build additional thin airfoil models. We also plan to further increase the total number of pressure orifices to give even more surface pressure data.

IV. The 0.3-m TCT - The First Fifteen Years

Earlier we gave some of the design and operational characteristics of the Langley 0.3-m TCT. In this section we describe some of the work done in the 0.3-m TCT during its first 15 years of operation.

We can arbitrarily divide the work in the 0.3-m TCT into three broad categories. The first category includes studies to improve the efficiency, safety, and performance of cryogenic tunnels. The second category is the development of test techniques for cryogenic tunnels. The third category is aerodynamic research. We discuss each of these categories in turn.

The majority of the work done in the 0.3-m TCT is reported in the open literature. Rather than cite individual references to the work, we refer the reader to reference 29, a recent bibliography on cryogenic tunnels. The subject index of reference 29 gives ready access to published papers giving details of work listed in this section.

Efficiency, Safety, and Performance

Most cryogenic tunnels use large quantities of liquid nitrogen for cooling. Therefore, cryogenic tunnels are more expensive to operate than the same size and pressure ambient temperature tunnel. This is the price we must pay for high Reynolds number testing.

We must make our high Reynolds number cryogenic tunnels as efficient as possible if we are to take full advantage of their research capability. During the past 15 years we have worked to make the 0.3-m TCT an efficient wind tunnel. Most of the lessons we have learned in the 0.3-m TCT are usable in other cryogenic tunnels.

Safety is another important consideration, especially with pressurized cryogenic tunnels. Again, in using the 0.3-m TCT for almost 8000 hours of testing, we have tried to develop safe operating procedures. Table 10 lists some of the work done with the 0.3-m TCT related to **efficiency, safety, and performance.**

A contract study of ways to recover energy from the cold tunnel exhaust does not show up in the table. However, if preliminary studies(30) warrant, we will connect the 0.3-m TCT exhaust to an especially designed expansion engine. Depending on test conditions, this expansion engine would deliver LN_2 to be re-used in the tunnel. We expect recovery rates to be about 10 percent of the exhaust mass flow. This recovery scheme should let us recover some of the energy presently wasted in the cold tunnel exhaust during high Reynolds number testing.

Good automatic controls contribute directly to tunnel efficiency, safety, and performance. Being able to hold test conditions constant also improves the quality of the aerodynamic data. From our first day of operation, we have worked toward fully automatic controls for the 0.3-m TCT. We are in the process of installing our third generation automatic control system at the 0.3-m TCT.

Balakrishna has recently made substantial improvements in tunnel control using a system based on a dedicated microcomputer.(31) From operator keyboard inputs, the computer automatically controls the three primary tunnel variables of Mach number (fan speed), total pressure, and total temperature. Another mode of operation allows constant Reynolds number operation. The successful development of automatic controls for the 0.3-m TCT is one of our major accomplishments.

Automatic Controls
- Tunnel conditions
  - Mach number
  - Pressure
  - Temperature
- Adaptive-wall test section
- Side-wall boundary layer removal

GN_2 exhaust
LN_2 injection
- Location
- Nozzle design

LN_2 storage and supply
Operating procedures
- Optimum purging and cooldown
- Minimum energy test direction

Performance
- Condensation boundaries
- Digital valves

Safety
- Organization
- Procedures
- Training

Thermal insulation

Table 10 Work in the 0.3-m TCT related to Efficiency, Safety, and Performance

Test Techniques

The minimum goal of any cryogenic tunnel is to be able to do the same types of tests offered by a comparable ambient temperature tunnel. In addition, the cryogenic tunnel should offer some unique testing capability made possible by having temperature as an independent variable. In the early days of operation, almost every new test in the 0.3-m TCT forced us to work on test techniques. We could use some of our ambient tunnel techniques directly without modification. However, many of them needed modification before we could use them successfully at cryogenic temperatures.

Adaptive-wall test section
- 2-D and 3-D models

2-D Testing
- Surface pressures (static and dynamic)
- Wake surveys
- Oscillating airfoil
- Non-adiabatic airfoil (LN_2 cooled)
- Side-wall boundary layer removal

3-D Testing
- Surface pressures
- Internal strain-gage balances (heated and unheated)

Flow angularity probe
Flow visualization
- Holographic Interferometry
- Shadowgraph
- Vapor-screen technique

Laser techniques
- LDV
- Seeding schemes
- Two-spot

Model construction techniques
Orifice size effect
Skin-friction measurement
Temperature measurements
Transition detection
- Fluctuating pressure measurement
- Hot film gages

Turbulence measurement techniques

Table 11 Test Techniques Studied in the 0.3-m TCT

Table 11 lists in rather arbitrary order the major types of test techniques studied in the 0.3-m TCT. The main purpose of this list is to show the wide range of techniques studied during the past 15 years in the 0.3-m TCT.

Not all of the work listed in Table 11 was successful. For example, we have used several methods of seeding the flow for laser work. One method that worked was a small inadvertent oil leak into the tunnel. Frozen oil does a good job of seeding the flow. However, it also eroded the models. For a variety of reasons, none of the methods we purposely tried were satisfactory.(32)

We are still working toward developing test techniques for cryogenic tunnels. As noted in a recent paper by Wolf,(33) much of our effort at the 0.3-m TCT now goes toward developing and using our adaptive wall test section. Work also continues in the area of flow visualization techniques with emphasis on transition detection. Recently, we have started studying how to do propulsion simulation in cryogenic tunnels.

As noted earlier, building models for cryogenic tunnels is an important area. Without good models it is impossible to take advantage of the testing capability of cryogenic tunnels. Fortunately, we have had considerable success in this area. Because of its importance, we will describe our work on Model Construction Techniques in more detail later in this paper.

Aerodynamic Research

For aerodynamic research, the most significant capability of the 0.3-m TCT is the high unit Reynolds number. We can test at unit Reynolds number up to 400 million per meter. Another extremely important testing capability of the 0.3-m TCT is the very wide range of Reynolds number. This wide range in Reynolds number is a direct result of the wide ranges of operating temperature and pressure. In incompressible flow (below $M_\infty = 0.4$) we can cover a 500 to 1 range of Reynolds. number. In compressible flow, where Mach number is not an independent variable, we can cover at least a 30 to 1 range.

The range of aerodynamic research in the 0.3-m TCT is fairly broad. Proving the validity of the cryogenic wind tunnel concept at transonic speeds was the aim of the earliest aerodynamic research. Most of the recent aerodynamic research has been on 2-D airfoils.

- 2-D Testing
  - Effect of Reynolds number on performance
  - Circular cylinder
  - Non-adiabatic wall effects (LN_2 cooled)
  - Surface roughness effects
- Semi-span Testing
  - Buffet (delta wing and NPL 9510 airfoil)
  - Flutter (NACA 64A010 airfoil)
  - X29A canard
- 3-D Testing
  - Shuttle Orbiter
  - Boattail models
  - Wing-body interference
- Special Testing
  - NTF cooling coils
  - Oscillating airfoil
  - Tunnel wall boundary layer

Table 12 Types of Aerodynamic Research in the 0.3-m TCT

Most of the aerodynamic research done in the Langley 0.3-m TCT is reported in the literature.(29) Therefore, we will not go into the details of the work in this paper. However, we will describe some of the work to illustrate the research capabilities of the 0.3-m TCT. Table 12 lists the major types of **aerodynamic tests** made in the 0.3-m TCT.

2-D Airfoils. As an example of testing in the 0.3-m TCT, we show some airfoil drag data as a function of Mach number and Reynolds number. Figure 15 shows the drag data for three airfoils tested in one of our early airfoil test programs.(34) We used a traversing wake survey mechanism to measure the pressures in the wake. These pressures give us the momentum deficit in the wake which in turn gives us the section drag coefficient. We picked this example because it clearly shows the ability of the 0.3-m TCT to test over a wide range of Reynolds number and Mach number.

At the lower Mach number, the drag is constant with Mach number for the NACA 0012. The SC(3)0712A shows a continual gradual rise. We also see this rise (or drag creep) for the BAC 1 at the lower Reynolds number. There is little effect of Reynolds number on the drag rise Mach number of the two advanced technology airfoils.

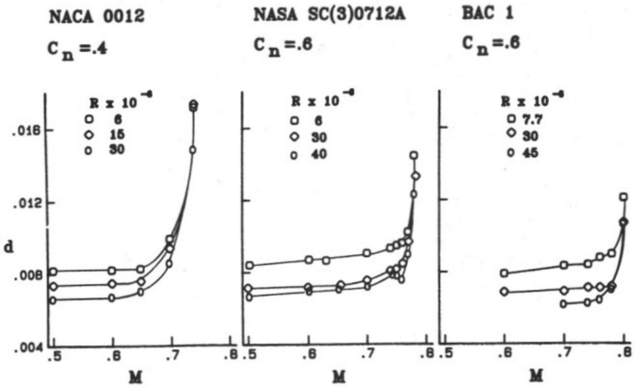


Figure 15- Effect of Reynolds Number on Drag Coefficient

3-D Airfoil. In May of this year we tested a semi-span 3-D airfoil model in the adaptive wall test section of the 0.3-m TCT. The airfoil is a model of the X29A canard and is only 5 percent thick. We built the model using the new construction technique described in detail in the previous section of this paper. The model has an 14.5 cm root chord, a 4.6 cm tip chord, and span (b/2) of 7.0 cm. We fitted the airfoil with a total of 93 pressure orifices divided between three chordwise rows on both the upper and lower surfaces. Figure 16 shows a photograph of the 3-D airfoil model and the mounting block used to fit it to the turntable.

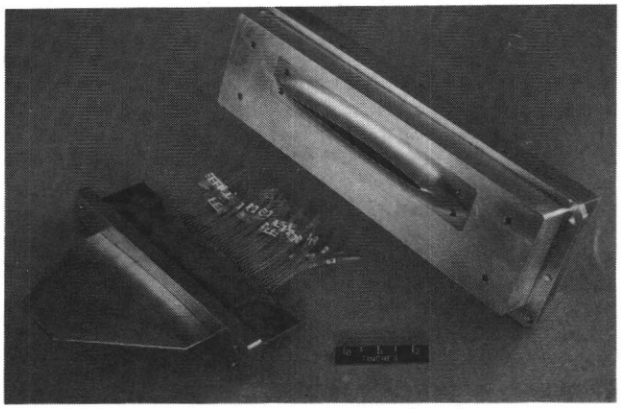
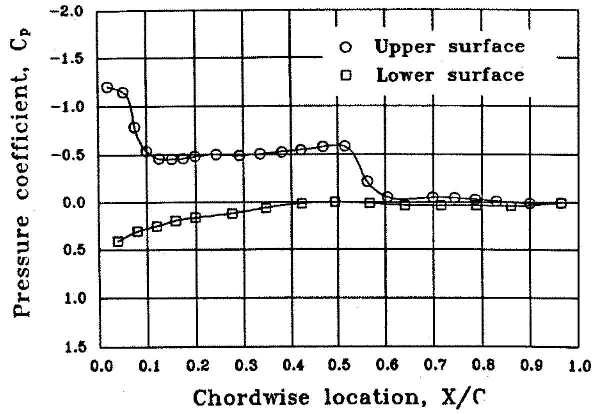


Figure 16- Model of X29A Canard

The main purpose of the test was to verify the model construction technique. However, the test also let us take some aerodynamic data and exercise the solid adaptive wall test section for 3-D testing.

We tested this 3-D airfoil over nearly the full range of conditions available with the adaptive wall test section. This included both ambient and cryogenic operation at pressures up to 6 bars at Mach numbers up to 1.3. We took aerodynamic data for the airfoil (surface pressures and wake survey) at Mach numbers from 0.3 to 1.2. The tests covered angles of attack from - 4° to + 15°. At most Mach numbers we covered a 10 to 1 range of Reynolds number and could easily get flight values of Reynolds number.

For testing this semi-span 3-D model, we used the method of Rebstock to adapt the solid test section walls for minimum interference.(35) Figure 17 shows an example of the airfoil data at an angle of attack of 8°, a Mach number of 0.9, and a Reynolds number (based on root chord) of 43 million.



Orifice row at 28-percent span

Figure 17- Data for X29A Canard, $M_\infty = 0.9$

As we had hoped, the model construction method proved satisfactory in every respect. In addition, the model gave us an abundance of useful aerodynamic data. The test was also another successful demonstration of using solid adaptive walls for 3-D testing through transonic speeds.

V. Advanced Testing Techniques

Cryogenic tunnels let us test at full-scale Reynolds number. However, full-scale Reynolds number is usually a *necessary* but not always a *sufficient condition* to insure usable data from our wind tunnels. Wall interference and support interference effects can make the data useless by completely masking any Reynolds number effect.

Also, some of our conventional testing techniques introduce problems of their own. One example from the Langley 0.3-m TCT is the wake survey rake we use in airfoil testing. The survey rake becomes a lifting surface in the presence of the downwash from a lifting airfoil. This can cause serious interference effects.

Fortunately, advanced testing techniques exist to solve most of our serious problems. We need to take advantage of these advanced testing techniques to increase the value of cryogenic tunnels to the research community.

Adaptive Wall Test Sections

To reduce or eliminate wall interference we need to use **adaptive wall test sections.** Although we include adaptive walls under advanced techniques, British researchers first used them 50 years ago.(33) Adaptive walls address the problem of wall interference at its source, the test section walls. We can use analytical techniques to correct any wall induced errors left after wall streamlining.

For the 0.3-m TCT we have chosen an adaptive wall test section with solid but flexible top and bottom walls. We have had success with both 2-D and 3-D models through the transonic speed range. We and other researchers have demonstrated the practicality of adaptive wall test sections for transonic testing.

Magnetic Suspension and Balance Systems

We need to use **magnetic suspension and balance systems** (MSBS) to eliminate completely support interference. The French at ONERA first used magnetic suspension for wind tunnel tests in the mid 1950s. The early success at ONERA led several other researchers to build small systems, mostly for hypersonic research.

In 1979, Britcher demonstrated the combination of a 6-component MSBS with the low-speed cryogenic tunnel at the University of Southampton.(36) Britcher took data on a body of revolution with tunnel temperatures below 100 K.

Advances in technology make it possible to build large MSBSs for large wind tunnels. Recent design studies confirm the feasibility of building systems for 2 or 3 m test sections. Further, testing experience at several laboratories has demonstrated the research potential of MSBS.

Laser Techniques

The use of laser techniques to eliminate intrusive measurement methods is a logical and essential step if we are to take full advantage of the high Reynolds number capability of cryogenic tunnels.

Taken together, we have solutions to most of the problems with subsonic and transonic wind tunnels. As we continue to develop and apply these solutions, we will enter a new era of experimental aerodynamics. Improved experimental data will lead inevitably to improvements in computational fluid dynamics techniques. Likewise, improved computational techniques will lead to better experimental data. This symbiotic relationship will help aerodynamics move with confidence into the 21st century.

VI. Conclusions

1. Cryogenic tunnels are in regular and productive use around the world.
2. The first 15 years of operation of the 0.3-m TCT has been safe, productive, and a cryogenic engineering success.
3. Model building techniques are improving rapidly. We have had success with both 2-D and 3-D models using a bonded plate construction technique.
4. The use of advanced testing techniques, such as adaptive walls, MSBS, and advanced instrumentation techniques, will allow us to take full advantage of cryogenic tunnels.
5. The use of cryogenic tunnels should increase dramatically as we begin to use high Reynolds number data to develop and verify advanced CFD codes. Cryogenic wind tunnels will join with supercomputers as our basic tools as we move the aeronautical sciences into the 21st century.

VII. References

1. Dress, D.A.; and Kilgore, R.A.: **Cryogenic Wind Tunnels - A Global Perspective.** *Cryogenics*, vol. 28, Jan. 1988, pp. 10-21.

2. Kilgore, R.A.; et al.: **The Cryogenic Wind Tunnel Concept for High Reynolds Number Testing.** NASA TN-D-7762, Nov. 1974, 96 pp.

3. Viehweger, G.: **The Kryo-Kanal-Köln Project, KKK.** AGARD R-722, July 1985, pp. 11-1 through 11-20.

4. Kilgore, R.A.; Adcock, J.B.; and Ray, E.J.: **Simulation of Flight Test Conditions in the Langley Pilot Transonic Cryogenic Tunnel.** NASA TN-7811, Dec. 1974, 24 pp.

5. Adcock, J.B.: **Real-Gas Effects Associated With One-Dimensional Transonic Flow of Cryogenic Nitrogen.** NASA TN-D-8274, Dec. 1976, 272 pp.

6. Anon: **Cryogenic Technology.** NASA CP-2122, Parts I and II, March 1980, 441 pp.

7. Bruce, W.E., Jr.; Fuller, D.E.; and Igoe, W.B.: **National Transonic Facility Shakedown Test Results and Calibration Plan.** AIAA Paper 84-0584, 13 pp.

8. Howell, R.R.: **The National Transonic Facility: Review and Status Report.** Paper in *High Reynolds Number Research - 1980.* NASA CP-2183, 1981, pp. 1-24.

9. Clausing, A.M.; et al.: **The Cryogenic Heat Transfer Tunnel - A New Tool for Convective Research.** Presented at ASME Meeting, San Francisco, CA., 1978, pp. 73-78.

10. Clausing, A.M.: **Experimental Studies of Forced, Natural and Combined Convective Heat Transfer at Cryogenic Temperatures.** Paper 24, 1st International Symposium on Cryogenic Wind Tunnels, Southampton, U.K., 1979, 8 pp.

11. Clausing, A.M.: **Advantages of a Cryogenic Environment for Experimental Investigations of Convective Heat Transfer.** International Journal of Heat and Mass Transfer, vol. 25, no. 8, 1982, pp. 1255-1257.

12. Mueller, M.H.; et al: **Description of UIUC Cryogenic Wind Tunnel Including Pressure Distributions, Turbulence Measurements and Heat Transfer Data.** University of Illinois Technical Report ME-TN-79-9180-1, 1979, 82 pp.

13. Tizard, J.A.; and Hartzuiker, J.P.: **The European Transonic Windtunnel Project ETW.** AGARD R-722, July 1985, pp. 12-1 through 12-23.

14. Adachi, T.: **Cryogenic Wind Tunnel and its Activities in University of Tsukuba.** June 1987, Personal Communication.

15. Yamaguchi, Y.; Kuribayashi, N.; and Kaba, H.: **Characteristics for ambient condition of NDA Cryo-tunnel and an attempt on its automatic cryogenic operation.** Proceedings of the 19th Annual Meeting of JSASS, April 5-6, 1988, pp. 73-74.

16. Takashima, K.; Sawada, H.; Aoki, T.; and Kayaba, S.: **Trial Manufacture of NAL 0.1m x 0.1m Transonic Cryogenic Wind Tunnel.** NAL TR-910, 1986, pp. 58.

17. Sawada, H.: **NAL TCWT Status - Cryogenic Operation.** NAL News, 1984-3, No. 229, pp. 2-4.

18. Sawada, H.: **Automatic Operation of the NAL Cryogenic Wind Tunnel.** NAL News, 1986-1, No. 321, pp. 2-4.

19. Sawada, H.: **Heated External Balance for Cryogenic Wind Tunnel.** NAL News, 1987-1, No. 333, pp. 2-3.

20. Sawada, H.: **Cryogenic Wind Tunnels.** Journal of JSASS, June 1987, pp. 285-293.

21. Wigley, D. A.: **The Problem of Dimensional Instability in Airfoil Models for Cryogenic Wind Tunnels.** NASA CR-16603, 1982.

22. Lawing, P.L.; and Kilgore, R.A.: **Model Experience in the Langley 0.3-m Transonic Cryogenic Tunnel.** NASA CP-2183, Sept. 1981, pp. 53-73.

23. Lawing, P.L.; Sandefur, P.G., Jr.; and Wood, W.H.: **A Construction Technique for Wind-Tunnel Models.** NASA Tech Brief, LAR-12710, Fall 1980.

24. Wigley, D.A.; Sandefur, P.G., Jr.; and Lawing, P.L.: **Preliminary Results on the Development of Vacuum Brazed Joints for Cryogenic Wind Tunnel Aerofoil Models.** ICMC, San Diego, CA, August 10-14, 1981.

25. Wigley, D.A.: **The Structure and Properties of Diffusion Assisted Bonded Joints in 17-4PH, TYPE 347, 15-5PH and Nitronic 40 Stainless Steel.** NASA CR-165745, July 1981.

26. Mineck, R.E.; and Lawing, P.L.: **High Reynolds Number Tests of the NASA SC(2)-0012 Airfoil in the Langley 0.3-Meter Transonic Cryogenic Tunnel.** NASA TM-89102, July 1987, pp. 56.

27. Wigley, D.A.: **Technology For Pressure-Instrumented Thin Airfoil Models.** NASA CR 3891, May 1985.

28. Lawing, P.L.: **The Construction of Airfoil Pressure Models by the Bonded Plate Method: Achievements, Current Research, Technology Development and Potential Applications.** NASA TM-87613, Sept. 1985. 31 pp.

29. Tuttle, M.H.; Kilgore, R.A.; and Cole, K.L.: **Cryogenic Wind Tunnels - A Selected, Annotated Bibliography.** NASA TM-4013, Sept. 1987, 89 pp.

30. McIntosh, G.E.; Lombard, D.S.; Martindale, D.L.; and Dunn, R.P.: **Cost Effective Use of Liquid Nitrogen in Cryogenic Wind Tunnels--Final Report.** NASA CR-178279, April 1987, 62 pp.

31. Balakrishna, S.; and Kilgore, W.A.: **Microcomputer Based Controller for the Langley 0.3-m Transonic Cryogenic Tunnel.** Proposed NASA Contractor Report.

32. Lawing, P.L.; and Johnson, C.B.: **Summary of Test Techniques Used in the NASA-Langley 0.3-m Transonic Cryogenic Tunnel.** AIAA Paper 86-0745, March 1986, 11 pp.

33. Wolf, S.W.D.; and Ray, E.J.: **Highlights of Experience with Flexible Walled Test Section in the NASA Langley 0.3-meter Transonic Cryogenic Tunnel.** AIAA Paper 88-2036, May 1988.

34. Ladson, C.L.; and Ray, E.J.: **Status of Advanced Airfoil Tests in the Langley 0.3-Meter Transonic Cryogenic Tunnel.** NASA CP-2208, Sept. 14-15, 1981, pp. 37-53.

35. Rebstock, R.; and Lee, E.E., Jr.: **Capabilities of Wind Tunnels with Two Adaptive Walls to Minimize Boundary Interference in #-D Model Testing.** Paper given at the *Transonic Symposium*, NASA Langley, April 19-21, 1988, 26 pp. Symposium Proceedings to be published as a NASA CP.

36. Britcher, C.P.; and Goodyer, M.J.: **The Southampton University Magnetic Suspension/Cryogenic Wind Tunnel Facility.** Paper 10, 1st International Symposium on Cryogenic Wind Tunnels, Southampton, U.K., 1979, 9 pp.