AGARD-R-812

AGARD-R-812

AGARD

ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT
7 RUE ANCELLE, 92200 NEUILLY-SUR-SEINE, FRANCE

AGARD REPORT 812

Special Course on Advances in Cryogenic Wind Tunnel Technology

(les Avancées en technologie des souffleries cryogéniques)

The material assembled in this report was prepared under the combined sponsorship of the AGARD Fluid Dynamics Panel, the Consultant and Exchange Progam of AGARD, and the von Kármán Institute (VKI) for Fluid Dynamics. It contains the papers presented at a Special Course held in Köln, Germany, 20-24 May 1996.

NORTH ATLANTIC TREATY ORGANIZATION

Published February 1997

Distribution and Availability on Back Cover

AGARD-R-812

AGARD

ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT
7 RUE ANCELLE, 92200 NEUILLY-SUR-SEINE, FRANCE

AGARD REPORT 812

Special Course on Advances in Cryogenic Wind Tunnel Technology

(les Avancées en technologie des souffleries cryogéniques)

The material assembled in this report was prepared under the combined sponsorship of the AGARD Fluid Dynamics Panel, the Consultant and Exchange Progam of AGARD, and the von Kármán Institute (VKI) for Fluid Dynamics. It contains the papers presented at a Special Course held in Köln, Germany, 20-24 May 1996.

North Atlantic Treaty Organization
Organisation du Traité de l'Atlantique Nord

The Mission of AGARD

According to its Charter, the mission of AGARD is to bring together the leading personalities of the NATO nations in the fields of science and technology relating to aerospace for the following purposes:

— Recommending effective ways for the member nations to use their research and development capabilities for the common benefit of the NATO community;

— Providing scientific and technical advice and assistance to the Military Committee in the field of aerospace research and development (with particular regard to its military application);

— Continuously stimulating advances in the aerospace sciences relevant to strengthening the common defence posture;

— Improving the co-operation among member nations in aerospace research and development;

— Exchange of scientific and technical information;

— Providing assistance to member nations for the purpose of increasing their scientific and technical potential;

— Rendering scientific and technical assistance, as requested, to other NATO bodies and to member nations in connection with research and development problems in the aerospace field.

The highest authority within AGARD is the National Delegates Board consisting of officially appointed senior representatives from each member nation. The mission of AGARD is carried out through the Panels which are composed of experts appointed by the National Delegates, the Consultant and Exchange Programme and the Aerospace Applications Studies Programme. The results of AGARD work are reported to the member nations and the NATO Authorities through the AGARD series of publications of which this is one.

Participation in AGARD activities is by invitation only and is normally limited to citizens of the NATO nations.

The content of this publication has been reproduced
directly from material supplied by AGARD or the authors.

Published February 1997

ISBN 92-836-1047-4

Printed by Canada Communication Group
45 Sacré-Cœur Blvd., Hull (Québec), Canada K1A 0S7

Advances in Cryogenic Wind Tunnel Technology

(AGARD R-812)

Executive Summary

This report is a compilation of the edited proceedings of the Special Course on "Advances in Cryogenic Wind Tunnel Technology" held at the DLR Research Center, Köln, Germany, 20-24 May 1996.

The development and use of cryogenic wind tunnels represents a major advance in aerodynamics testing. One advantage of cryogenic tunnels is their ability to achieve full-scale values of Reynolds number in tunnels of moderate size at reasonable operating pressures. Another important advantage is the ability to independently vary temperature, pressure and speed, which lets one separate the effects of Reynolds number, aeroelasticity and Mach number.

This series of lectures, supported by the AGARD Fluid Dynamics Panel and the von Kármán Institute, incorporated a brief review of the development and early uses of cryogenic tunnels, and reports on current operational cryogenic facilities. It then covered the theory and advantages of cryogenic wind tunnels, as well as the special considerations required in their design, construction, and use. Subjects included cryogenic systems, thermal insulation, facility and model design and construction, strain-gage balances, pressure instrumentation, flow visualization, data accuracy, safety, and productivity.

Les avancées en technologie des souffleries cryogéniques

(AGARD R-812)

Synthèse

Ce rapport est une compilation des travaux du Cours spécial sur «les avancées en technologies des souffleries cryogéniques» tenu au DLR Research Center, à Köln, en Allemagne du 20 au 24 mai 1996.

Le développement et l'utilisation des souffleries cryogéniques représente un progrès considérable pour les essais aérodynamiques. L'un des avantages des souffleries cryogéniques réside dans les possibilités offertes pour générer des nombres de Reynolds en vraie grandeur dans des souffleries de dimensions moyennes à des pressions d'utilisation raisonnables. Un autre avantage important est représenté par les possibilités de variation indépendante de température, pression et vitesse, ce qui permet de séparer les effets du nombre de Reynolds, de l'aéroélasticité et du nombre de Mach.

Ce cycle de conférences, organisé conjointement par le Panel AGARD de la dynamique des fluides et l'Institut von Kármán, a inclu un bref résumé du développement et des premières applications des souffleries cryogéniques, ainsi qu'un certain nombre de rapports sur différentes installations cryogéniques en exploitation. La conférence a examiné ensuite la théorie et les avantages des souffleries cryogéniques, ainsi que les considérations particulières régissant leur conception, leur construction et leur utilisation. Les sujets suivants ont été abordés: les souffleries cryogéniques, l'isolation thermique, la conception et la construction des installations et des maquettes, les extensomètres, l'instrumentation de pression, la visualisation des écoulements, la précision des données, la sécurité et la productivité.

Contents

Recent Publications of the Fluid Dynamics Panel

AGARDOGRAPHS (AG)

Turbulent Boundary Layers in Subsonic and Supersonic Flow
AGARD AG-335, July 1996

Computational Aerodynamics Based on the Euler Equations
AGARD AG-325, September 1994

Scale Effects on Aircraft and Weapon Aerodynamics
AGARD AG-323 (E), July 1994

Design and Testing of High-Performance Parachutes
AGARD AG-319, November 1991

Experimental Techniques in the Field of Low Density Aerodynamics
AGARD AG-318 (E), April 1991

Techniques Expérimentales Liées à l'Aérodynamique à Basse Densité
AGARD AG-318 (FR), April 1990

A Survey of Measurements and Measuring Techniques in Rapidly Distorted Compressible Turbulent Boundary Layers
AGARD AG-315, May 1989

Reynolds Number Effects in Transonic Flows
AGARD AG-303, December 1988

REPORTS (R)

Aerothermodynamics and Propulsion Integration for Hypersonic Vehicles
AGARD R-813, Special Course Notes, October 1996

Parallel Computing in CFD
AGARD R-807, Special Course Notes, October 1995

Optimum Design Methods for Aerodynamics
AGARD R-803, Special Course Notes, November 1994

Missile Aerodynamics
AGARD R-804, Special Course Notes, May 1994

Progress in Transition Modelling
AGARD R-793, Special Course Notes, April 1994

Shock-Wave/Boundary-Layer Interactions in Supersonic and Hypersonic Flows
AGARD R-792, Special Course Notes, August 1993

Unstructured Grid Methods for Advection Dominated Flows
AGARD R-787, Special Course Notes, May 1992

Skin Friction Drag Reduction
AGARD R-786, Special Course Notes, March 1992

Engineering Methods in Aerodynamic Analysis and Design of Aircraft
AGARD R-783, Special Course Notes, January 1992

Aircraft Dynamics at High Angles of Attack: Experiments and Modelling
AGARD R-776, Special Course Notes, March 1991

ADVISORY REPORTS (AR)

Cooperative Programme on Dynamic Wind Tunnel Experiments for Manoeuvering Aircraft
AGARD AR-305, Report of WG-16, October 1996

Hypersonic Experimental and Computational Capability, Improvement and Validation
AGARD AR-319, Vol. I, Report of WG-18, May 1996

Aerodynamics of 3-D Aircraft Afterbodies
AGARD AR-318, Report of WG-17, September 1995

A Selection of Experimental Test Cases for the Validation of CFD Codes
AGARD AR-303, Vols. I and II, Report of WG-14, August 1994

Quality Assessment for Wind Tunnel Testing
AGARD AR-304, Report of WG-15, July 1994

Air Intakes of High Speed Vehicles
AGARD AR-270, Report of WG-13, September 1991

Appraisal of the Suitability of Turbulence Models in Flow Calculations
AGARD AR-291, Technical Status Review, July 1991

Rotary-Balance Testing for Aircraft Dynamics
AGARD AR-265, Report of WG11, December 1990

Calculation of 3D Separated Turbulent Flows in Boundary Layer Limit
AGARD AR-255, Report of WG10, May 1990

Adaptive Wind Tunnel Walls: Technology and Applications
AGARD AR-269, Report of WG12, April 1990

CONFERENCE PROCEEDINGS (CP)

Progress and Challenges in CFD Methods and Algorithms
AGARD CP-578, April 1996

Aerodynamics of Store Integration and Separation
AGARD CP-570, February 1996

Aerodynamics and Aeroacoustics of Rotorcraft
AGARD CP-552, August 1995

Application of Direct and Large Eddy Simulation to Transition and Turbulence
AGARD CP-551, December 1994

Wall Interference, Support Interference, and Flow Field Measurements
AGARD CP-535, July 1994

Computational and Experimental Assessment of Jets in Cross Flow
AGARD CP-534, November 1993

High-Lift System Aerodynamics
AGARD CP-515, September 1993

Theoretical and Experimental Methods in Hypersonic Flows
AGARD CP-514, April 1993

Aerodynamic Engine/Airframe Integration for High Performance Aircraft and Missiles
AGARD CP-498, September 1992

Effects of Adverse Weather on Aerodynamics
AGARD CP-496, December 1991

Manoeuvering Aerodynamics
AGARD CP-497, November 1991

Vortex Flow Aerodynamics
AGARD CP-494, July 1991

Missile Aerodynamics
AGARD CP-493, October 1990

Aerodynamics of Combat Aircraft Controls and of Ground Effects
AGARD CP-465, April 1990

Computational Methods for Aerodynamic Design (Inverse) and Optimization
AGARD CP-463, March 1990

Applications of Mesh Generation to Complex 3-D Configurations
AGARD CP-464, March 1990

Fluid Dynamics of Three-Dimensional Turbulent Shear Flows and Transition
AGARD CP-438, April 1989

Validation of Computational Fluid Dynamics
AGARD CP-437, December 1988

Aerodynamic Data Accuracy and Quality: Requirements and Capabilities in Wind Tunnel Testing
AGARD CP-429, July 1988

Aerodynamics of Hypersonic Lifting Vehicles
AGARD CP-428, November 1987

Aerodynamic and Related Hydrodynamic Studies Using Water Facilities
AGARD CP-413, June 1987

Applications of Computational Fluid Dynamics in Aeronautics
AGARD CP-412, November 1986

Special Course Staff

Special Course Director

R.A. Kilgore
C.E.S. - Hampton
359 Marlfield Circle
Hampton Virginia
23669-1733
United States

LECTURERS

L. Badet
European Transonic Wind Tunnel
P.O. Box 906116
Ernst-Mach-Str.
51127 Köln
Gemany

M. Bazin
ONERA BP 72
Avenue de la Division Leclerc
92322 Châtillon Cedex
France

C. Blanchet
BERTIN
144 rue Louis Arnaud
BP 22000/Z.I. les Milles
13791 Aix-en-Provence Cedex 3
France

F. Dupriez
ONERA/IMFL
5, BLD. Paul Painlevé
France

M.J. Goodyer
University of Southampton
Dept. of Aeronautics
10 Randall Road/Chandler Ford
Hampshire SO5 1AL
United Kingdom

H. Rosemann
DLR-Inst. of Fluid Mechanics
SM-SK-HGA
Bunsentrasse 10
37073 Göttingen
Germany

D. Schimanski
European Transonic Wind Tunnel
P.O. Box 906116
Ernst-Mach-Str.
51127 Köln
Germany

A. Seraudie
ONERA-CERT
BP 4025
2 av. E. Belin
31055 Toulouse Cedex
France

J.S. Hill
NASA Langley Research Center
Hampton, Virginia
23681-0001
United States

K. Hufnagel
Technical Univ. of Darmstadt
Windkanal
Flughafenstr. 19
64347 Griesheim
Germany

A. Mignosi
ONERA/CERT
BP 4025
2 av. E. Belin
31055 Toulouse Cedex
France

I. Price
European Transonic Wind Tunnel
P.O. Box 906116
Ernst-Mach-Str.
51127 Köln
Germany

R. Rebstock
Kryo Kanal Köln
DLR Research Center
Postfach 906058
5000 Köln
Germany

G. Viehweger
Kryo Kanal Köln
DLR Research Center
Postfach 906058
5000 Köln
Germany

D.A. Wigley
C.M.& M. Consultants
17 Basset Wood Drive
Bassett, Southampton S016 3PT
United Kingdom

C.P. Young
VIGYAN Inc.
30 Research Drive
Hampton, Virginia
23666-1325
United States

INTRODUCTION TO CRYOGENIC WIND TUNNELS

M J Goodyer
Professor of Experimental Aerodynamics
Department of Aeronautics and Astronautics
The University
Southampton SO17 1BJ
England

SUMMARY

The situation which existed in the era which spawned the cryogenic wind tunnel, the early 1970's, is first explained. The background includes the strong desire felt at that stage to raise Reynolds number in transonic testing, together with the response in the form of the expensive solutions then under consideration. Some paper studies describing the benefits of changing test temperature did exist, mostly older and obscure, but had been ignored up to this time. This situation coincided with the contemporary state of maturity of cryogenic engineering.

The cryogenic wind tunnel evolved in this environment as the way to increase Reynolds number while avoiding undue increase of wind tunnel size or operating pressure. The paper describes the theoretical principles, showing the way in which it achieves its aim. Some cryogenic wind tunnel practice is included, also a description of beneficial features additional to achieving high test Reynolds numbers. These are a rather important reduction of motor power in the case of fan-driven tunnels and the ability for the first time in wind tunnel testing to isolate the separate effects of changes in Reynolds number, Mach number and dynamic pressure. Finally there is an outline of the way in which cryogenic operation affects some representative types of tunnel.

SYMBOLS

a	speed of sound
A	flow area, reference area
c	reference length, wing mean chord
m	mean molecular weight
M	Mach number
n	index in $\mu \propto T^n$
P, P_0	static, stagnation pressure
q	dynamic pressure $\frac{1}{2}\rho U^2$
R	gas constant
R_0	universal gas constant
Re	Reynolds number
Re_c	Reynolds number based on length c
T, T_0	static, stagnation temperature
U	reference velocity
V	specific volume
Z	compressibility factor
α	incidence = angle of attack
γ	ratio of specific heats
λ	drive power constant of proportionality
μ	viscosity
ρ	density

1 BACKGROUND

In any attempt to justify the expenditure of considerable manpower and effort on a project such as that forming the subject of this Course it is appropriate to reflect for a moment on the underlying reasons for the work, which I will first attempt to do. The root cause of us being here is the fundamental weakness of classical mathematics: despite the undoubted brilliance of mathematicians past and present they have not been able to give us the means to forecast by calculation, and with certainty, the behaviour of real life devices such as the products of aerospace industries. This failure reveals inadequacy in the discipline and not in the practitioners. A quotation specifically about our business of aerodynamics is as follows: "The disparity between the designer's need for aerodynamic prediction and the power of his analytic methods seems to be so vast as almost to defy description"(Ref 1). This statement was published by a very experienced aircraft designer in September 1971, close to the time of the beginning of construction of the first cryogenic wind tunnel (Ref 2). Since then the two avenues of endeavour, empirical and theoretical, have advanced in healthy competition with improvement in each, which is a recognition that the former was not without weakness.

The birth of the cryogenic wind tunnel was preceded by a 20 year period spawning almost all of the transonic wind tunnels now in use. During this period the need to provide for the needs of experimental aerodynamics in a reasonably economic way followed the pattern already set, that of matching the required Mach number but in most cases not the required Reynolds number. The reason for this is because Mach number effects were known to be strong, particularly at speeds near the speed of sound, while it was felt that the effects of Reynolds number on performance were rather weak and perhaps systematic and predictable. If the same circumstances existed now and we had to choose between the two parameters there is no doubt that we would still pick Mach number for proper matching. It is perhaps fortunate that background research in Japan and the U.S.A. in the 1930's led to the development of the ventilated test section for transonic testing, allowing the immediately most pressing needs to be satisfied at reasonable cost. Had Reynolds number effects seemed more important there is no knowing what solutions might have emerged, but possibly the cryogenic wind tunnel because the necessary information and most of the technology was around and the route to full scale Reynolds number by more conventional means is inordinately expensive.

It should be mentioned that throughout almost the whole time of aerodynamic testing, the position with regard to Reynolds number was not accepted without question. The needs of the low speeds of the early days of flight were

Paper presented at an AGARD FDP Special Course on "Advances in Cryogenic Wind Tunnel Technology", held at the DLR Research Center, Köln, Germany, 20-24 May 1996, and published in R-812.

satisfied with large unpressurised wind tunnels which were just economically feasible, reaching full scale Reynolds numbers, but the situation became more difficult with the progressive increases in flight speed and aircraft size. To anyone who begins to design a wind tunnel for flight values of Reynolds number at normal values of tunnel pressure and temperature it soon becomes apparent that the cost will be very high. To circumvent this problem searches were made, from about 1920 onwards, for test gases alternative to air which would inherently provide such flows at reasonable size and cost. Pozniak (Ref 3) gives a comprehensive summary and list of references. The searches revealed some gases which were not too toxic and which would provide useful increases in Reynolds number, by factors of up to 4 when compared with air at otherwise the same conditions. However these gases were polyatomic with ratios of specific heats γ much lower than in air and it was felt that in tests at compressibility speeds their behaviour might not always be close enough to that of a diatomic gas. It is no use replacing one system which occasionally and unpredictably gives wrong answers (that is air at low Reynolds number) with another which might do the same but for a different reason. Mixtures of gases having $\gamma \approx 1.4$ gave too small rewards.

On at least two occasions the prospects were discussed for the use of low temperatures in aerodynamic testing. Margoulis (Refs 4,5) in 1920 in open literature, and Smelt (Ref 6) in 1945 in a classified report, gave predictions of the advantages, but the possibilities were largely ignored although from time to time in reports from the period various authors again drew attention to the idea. It is likely that the motivation for producing high Reynolds number flows was not strong enough to encourage facing the practical problems, more serious then because tonnage cryogenics was in its infancy.

While errors can be made of either sign in the prediction of aircraft performance, the cases which cause concern are those where full scale performance is worse than expectation by too large a margin. In the U.S.A. and Europe during the above period there were examples of aircraft projects which performed rather too badly in comparison with predictions based on wind tunnel data. The consensus was that mismatch in Reynolds number was the likely cause. It was decided to reduce the disparity because the state of the art of corrections did not allow their application with confidence. These experiences prompted campaigns on both sides of the Atlantic to provide transonic wind tunnels with Reynolds number capabilities closer to those experienced in flight, and there began considerable activity.

AGARD, through its Fluid Dynamics Panel, set up the High Reynolds Number Working Group (HIRT) in 1969 which in September 1970 offered some solutions to the transonic needs of NATO countries. Following this the same panel set up the Large Wind Tunnels Working Group (the LaWs Group) in 1971 to examine broader needs of aerodynamic testing but including those of transonic testing, and to evaluate the options, although the option of the cryogenic wind tunnel was not evaluated (Ref 7). These activities represent an interim period, ending in about 1973, during which a variety of designs was actively pursued based on the use of normal temperatures, often in otherwise unconventional tunnels.

The procedure followed was first to define requirements and then identify possible solutions. On the subject of requirements it should be mentioned that other inadequacies in flow simulation had also become apparent in the meantime, additional to that simply of low Reynolds number. Notable was the realisation that other measures of flow quality including non-uniformity, noise and turbulence, were often unsatisfactory and would need to be reduced in any new wind tunnel. On the subject of the requirement for Reynolds number there were differences of opinion on the extent to which it was necessary to bridge the existing tunnel-to-flight gap. Some (mostly in Europe) felt that there was a level below which there could be expected to be seen changes in data and above which there would be no significant change. Others (mostly in the USA) felt that tunnels should match flight Reynolds number if at all possible.

There was also disagreement over the minimum practical run time for the new tunnels, but the consensus was that around 10 seconds would suffice for most kinds of test. However in retrospect there is no doubt that such compromises were driven to some extent by what was considered economically possible rather than being based on sound technical merit.

The transonic tunnel specifications which emerged included minimum run time, Mach number bands, maximum pressure and of course Reynolds number. It was recognised in Europe that this would need to be a multi-national collaborative project because of the capital cost. Several competing schemes emerged for evaluation (Ref 7). A tunnel was separately proposed for construction in the U.S.A. which also had several competing schemes (Refs 8-10).

The projected cost of a tunnel varies strongly with its size and therefore all steps are taken to minimise size, including the use of the maximum practical pressure, but there are limits to the pressure than can be used. It is easy to show that in the case where the structure of an aircraft is modelled as well as the aerodynamic envelope, the bending stresses in the wind tunnel model, say in the wing root, in relation to those in the aircraft in flight are factored by the two ratios, tunnel-to-flight, of the static pressures and lift coefficients. The tunnels which offered highest Reynolds numbers used static pressures several times those experienced in transonic cruising flight. Further, particularly in the case of transport aircraft, the range of lift coefficient required to be explored in the tunnel could be much wider than structurally acceptable in the aircraft. The net effect is that models are designed for high loads which demand the use of high strength materials (for example maraging steels) coupled with the use of a much more substantial model construction compared with the aircraft, to the extent that many model components are solid. With increases in pressure there is an increasing problem from support interference. While these comments are on the subject only of stresses, aeroelastic considerations may be even more demanding in terms of model and support stiffness. It became clear that there was insufficient scope for raising Reynolds number, to the levels required, by the sole action of raising the test pressure.

The outcome was a set of designs featuring less than full scale Reynolds number, large test sections (typically 5m, 16 feet) across operating at pressures up to 5 atmospheres or more, with various kinds of intermittent drives. The combination of size and pressure resulted in tunnels projected at rather high cost and requiring also large and expensive models.

At about this stage (in fact in September and October 1971) a small group of engineers at NASA Langley Research Center was faced with a similar kind of problem in relation to a wind tunnel magnetic suspension system, that is much too low a Reynolds number. They proposed the use of a low temperature gas as a means to raise the value. A low speed tunnel was immediately built which served to dispel the most elementary misgivings over the concept and also to draw the attention of the teams working on the large transonic tunnel projects to this alternative approach. In due course the proposals for large transonic tunnels on both sides of the Atlantic narrowed to just cryogenic wind tunnels, fan driven and therefore nominally continuous, capable of reaching full scale flight Reynolds numbers with moderate tunnel size and pressure.

The cryogenic wind tunnel evidently was born out of the needs of transonic testing, but is finding wider application as we will hear in this Special Course. For example achieving full scale Mach and Reynolds numbers in high lift/low speed wind tunnel testing is also important.

The decision to proceed with an investigation of the cryogenic approach for transonic high Reynolds number testing opened up many new lines of endeavour additional to that of just proving the novel aerodynamics. There were the subjects to address of tunnel design and control, cooling, thermal insulation, instrumentation, real gas effects, safety, materials and model making. These and more were first taken on by NASA in relation to the fan driven tunnel. Other organisations have extended the range of tunnel drives as we will hear later, covering intermittent options.

The aims of the remaining parts of this paper are to establish requirements in terms of Reynolds number, to examine briefly the normal-temperature air option, and to introduce the principles of the cryogenic wind tunnel in its practical form. But firstly it is appropriate to discuss some Reynolds number effects.

2 MODELS AND REYNOLDS NUMBER EFFECTS.

The use of small models and therefore low Reynolds numbers raises the question of how the development of the boundary layers affects performance. Boundary layer growth over the model is non-linear and at low Reynolds numbers is disproportionately rapid. Therefore, even when other factors in a tunnel test which might affect performance are correct, such as the model's shape and the airspeed, the boundary layers will not have the correctly scaled thickness or even perhaps the correct character in terms of laminar or turbulent flow, or separations. The force experienced by the model, the net effect of skin friction and pressure distribution, is likely to be incorrect and contain a source of systematic error which cannot be detected whatever the accuracy of the measuring instruments.

Only if an error in a wind tunnel test is large enough will its existence be revealed in subsequent flight tests. Take the example of the Wright brothers. Among the huge amount of work which they did most successfully leading to manned powered flight, work which included learning how best to control and fly several gliders and the design, construction and development of their own engine, they built and used a low speed wind tunnel. This because they had learned from experience not to trust the aerodynamic data of others. Based on their own wind tunnel results they correctly used a high aspect ratio wing planform but incorrectly chose a thin aerofoil section as better aerodynamically compared to thick. This conclusion was a result, it is believed (Ref 11), of using very small models of order 6 inches span compared with the 44 feet span of the aircraft. However the difference in performance between thick and thin did not prevent them from achieving their aim in 1903: the flights did not reveal any significant error even though the Reynolds number of their wind tunnel tests was low by about two orders of magnitude.

In open commercial competition very small differences of performance are now important, often decisively affecting sales and the fortunes of large sections of industry.

In recognising the influence of scale, organisations built as large tunnels as they could reasonably afford during the 60 years or so following the Wright brothers flight, with the largest allowing low speed testing of full scale smaller aircraft such as fighters and light training aircraft as has been mentioned. However as the cost of a tunnel rises with airspeed partly because of a sharp increase in tunnel drive power, no wind tunnel has ever been built to accommodate complete full scale aircraft at transonic or supersonic speeds, speed ranges which became of interest from about 1940 on.

Wind tunnel test data, in the form of dimensionless force and moment coefficients, are functions of a lengthy list of tunnel/model parameters of various levels of importance in terms of their influence on aerodynamic behaviour. Some have been mentioned. Singled out as being of particular relevance to the subject matter of this Course are the three parameters of model shape and the Mach and Reynolds numbers. The wind tunnel test must reproduce closely the environment of flight in these and in other respects.

It is so obvious a requirement to correctly reproduce the shape of the aircraft that it might seem fair to question its inclusion in the above list. However the issue is not simple. The word shape is used here to include all geometric factors, some subtle in nature, which can influence the pattern of airflow around the model. Subtleties include surface finish, pressure tappings, small gaps through which air can or should flow, the deflections of parts of the model under load and the modification of the external flow by engine flows. A more obvious way in which a model can differ from the aircraft is any alteration to accommodate a mechanical support. The alteration can take two forms: alteration of the shape of the model for the support, while the support itself can disturb airflow and interfere with the model, modifying its aerodynamic behaviour. Once the question of shape is examined in detail it is seen to become a complex issue.

Assuming that all else in a test is correct then reproducing the flight Mach number ensures that compressibility effects are modelled properly. Reproducing the Reynolds number should ensure proper modelling of viscous effects.

It is usual now to derive Reynolds number using dimensional analysis although Osborne Reynolds (Ref 12) used just physical reasoning to derive the group which is, with his symbols,

$$\frac{c\rho U}{\mu} \text{ ----- } (1)$$

where c is an appropriate length scale, ρ, U and μ are respectively fluid density, speed and viscosity.

It is common practice to evaluate Reynolds number in relation to aircraft by using the mean chord of the wing as the length scale c, while the fluid's properties are evaluated at its undisturbed state. For an aircraft in flight the appropriate state is the ambient air density and viscosity at that altitude, and the flight speed. In the tunnel test these properties are estimated from airflow measurements in the entrance region of the test section reasonably far upstream of the model, away from the strongest effects of its disturbances.

Table 1 allows comparisons between the requirements of cruising flight with the Reynolds number capabilities of tunnels each side of the Atlantic. A representative selection of transport aircraft is shown. They all cruise in the Mach number band 0.7 to 0.9. It is apparent that flight requirements are above tunnel capability by large factors, a situation which was only likely to get worse with the passage of time. Reynolds number needed to be raised to around 70 millions in the wind tunnel to match large transports in cruise, perhaps more to allow for future needs. Therefore about a ten-fold increase in capability was needed from the new facilities, bearing in mind the likelihood of long lifetimes.

Table 1. Reynolds numbers of a variety of aircraft and projects of the 1960's compared with the capabilities of contemporary tunnels.

Reynolds numbers (millions) based on wing mean chord and cruising flight:

Boeing 737-200: 23.
Airbus A300B: 41.
Lockheed C-141: 50.
Lockheed C-5A: 63.
Boeing 727-200: 38.
Lockheed L-1011: 49.
DC 10-10: 54.
Boeing 747: 71.

Transonic tunnel maximum capabilities for tests on complete transport aircraft models at Mach 0.9 in

Europe:
B.Ae. (Warton) 1.2m tunnel, DRA 8 foot, and ONERA Modane S1, ~8.5 millions
the USA:
typically NASA Ames 11′ and AEDC 16T, ~10 millions.

As far as the speed requirement of the new tunnel was concerned it will be noticed that the band of cruising speed of the aircraft listed, as indicated by Mach number, is rather narrow. This is because for aircraft such as these, which are required to cruise efficiently, there is in effect a barrier inhibiting the use of slightly higher flight speeds. Of course this is not an absolute speed barrier but one of economics: drag rises sharply when Mach number is allowed to rise from these general levels.

The shortfall in Reynolds number needs to be linked with indications of some effects of Reynolds number on aerodynamic behaviour in order to begin to form a picture of possible consequences. The first examples are the classic cases of low speed flow around a circular cylinder and a sphere. In each case the pressure distribution and drag vary widely with Reynolds number, with particularly strong variations in one rather narrow Reynolds number band. Figure 1 shows empirical data on the dependence of drag, in its non-dimensional form drag coefficient, on Reynolds number. It is seen that the coefficient rises by a large factor on moving down through Reynolds numbers around 10^5.

Clearly a test carried out at the wrong Reynolds number on a shape which had a similarly strong sensitivity to Reynolds number could yield very misleading results. Extrapolating

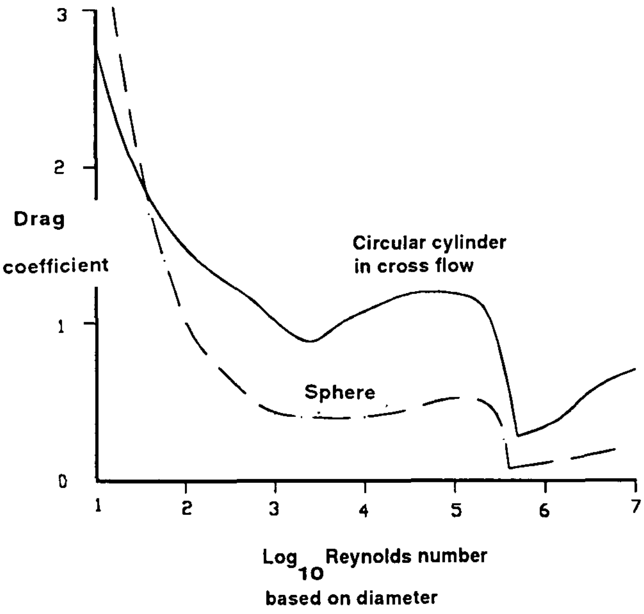

Fig 1. Drag coefficients of a sphere and circular cylinder in cross flow. Reynolds number is based on diameter.

data which was obtained in one range of Reynolds number for use at another can be unsafe. Examples of flows around aircraft which have a general similarity to that of a cylinder in cross flow include high incidence flows around rear fuselages of almost any aircraft and across the noses of fighters, and flows across undercarriage components.

The next three examples relate to two-dimensional aerofoil tests. Figure 2 shows lift coefficient for one section as a function of angle of incidence, measured at two values of Reynolds number at low speeds. At low incidences there is little difference between the two data sets. However the maximum lift coefficient is very sensitive to Reynolds number.

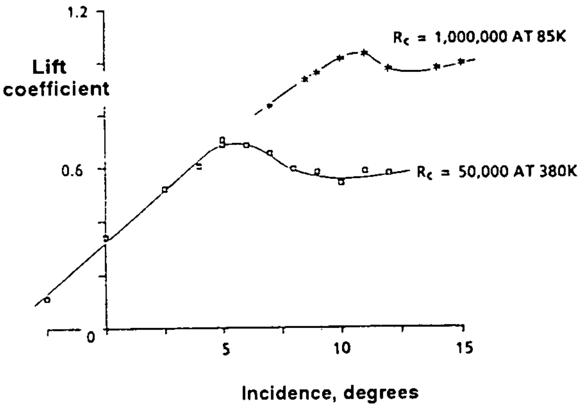

Fig 2. Illustration of the sensitivity of the maximum lift of an aerofoil to Reynolds number.

Therefore the dependence on Reynolds number varies from little to large depending on incidence, but the importance of using the correct Reynolds number for the correct overall picture is very apparent. The Reynolds numbers in this example are very low for the flight of normal aircraft although the higher value, 1 million, corresponds roughly to that of a glider's wing at stalling speed. There is plenty of empirical evidence showing that maximum lift coefficient can continue to rise (Refs 13-15) with further increase in Reynolds number.

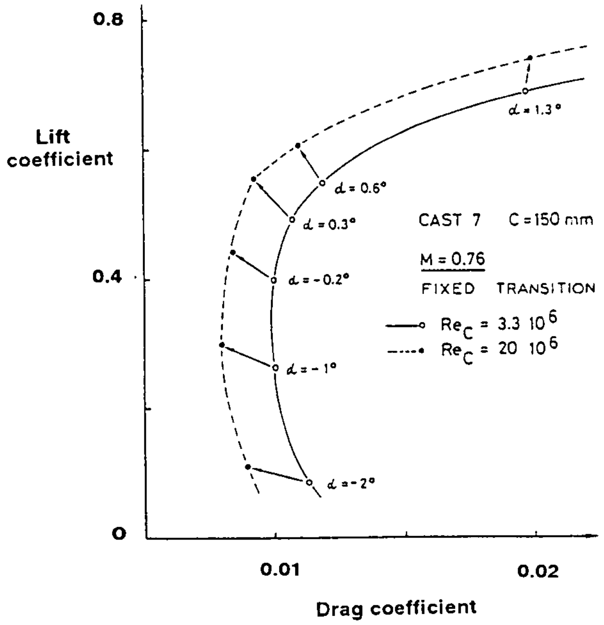

Fig 3. Polars from transonic aerofoil tests showing Reynolds number effects on lift and drag.

Figure 3 shows experimental data, taken by ONERA (Ref 16) in a cryogenic wind tunnel which will be described in a later lecture, for an aerofoil section at Mach 0.76. Lift and drag coefficients are shown as functions of incidence for two values of Reynolds number. The lower value is typical of those used in much aerodynamic testing in the past. The higher value approaches those experienced in some transport aircraft. Through the incidence range there is seen to be a varying dependence of lift and drag (in magnitude and sign) on Reynolds number, effects large and different enough to be of definite concern to planemakers. One measure of the aerodynamic effect of change of Reynolds number is the ratio of lift to drag. The maximum values differ by about 28% in this case.

Finally an example of Reynolds number effects in data taken by NASA in their 0.3m Transonic Cryogenic Tunnel (Ref 17) on an aft-loaded section also over a band of Reynolds numbers spanning those attainable in conventional tunnels and, in this case, the flight of a fairly large aircraft. Near the design Mach number and lift coefficient the drag coefficient is shown to decrease by about 18% on raising Reynolds number from about 7 millions to about 48 millions, with the trend evidently continuing.

In summary, the evidence available to aerodynamicists on Reynolds number effects, derived from wind tunnel tests such as in the examples above and also from tunnel-flight comparisons, led the wind tunnel community to seek new generations of tunnel which could solve the problem.They were uneasy making such large extrapolations and corrections as typified by these examples. The disparity in Reynolds number was greatest for large transonic transports because of their size and speed. When the needs of all types of aerospace products are taken into account, the speed range of concern could extend from the low range associated with takeoff and landing, upwards at least to supersonic flight. This range is covered by a variety of designs of wind tunnel, but there was a firm opinion held that the need for bridging the Reynolds number gap was felt most strongly in the aerodynamics of flight at transonic speeds. Therefore attention became focused on the search for a high Reynolds number transonic wind tunnel. According to the data in table 1 and the discussion following, the need was for roughly a tenfold increase in the highest wind tunnel Reynolds number capability in order to cover anticipated flight values. Some designs of tunnel which were receiving serious consideration before the emergence of the cryogenic option in the early 1970's are now reviewed, partly to highlight some of the appeal of the cryogenic tunnel but also to remind researchers of what they might now have been preparing to use, in other circumstances, for their high Reynolds number tests.

3. Raising Reynolds number by conventional methods

The shortfall in Reynolds number can be bridged in several ways. Equation (1) shows that the options for change are through the properties of the test gas, namely its density, speed or viscosity, and by changing c the length scale of the model. The options are made clearer in the context of aerodynamic testing by substituting

(i) for density using the ideal gas equation of state

$$\rho = \frac{P}{RT} = \frac{Pm}{R_0 T} \text{ ----- (2)}$$

where P and T are the reference static pressure and temperature of the test gas, R and R_0 are the particular and universal gas constants respectively and m is the mean molecular weight,

(ii) for the velocity U as the product Mach number and speed of sound now written for convenience as

$$U = Ma = M\sqrt{\gamma R_o \frac{T}{m}} \text{ ----- (3)}$$

where γ is the ratio of specific heats and a the speed of sound,

(iii) finally for the viscosity of the gas as a function of temperature $\mu(T)$.

These are combined in (1) to give

$$\textit{Reynolds number } Re = \frac{PMc}{\mu(T)}\sqrt{\frac{m\gamma}{R_0 T}} \text{ ----- (4)}$$

an expression which shows all options available for influencing Reynolds number.

First consider increasing c by using larger complete models, with the same wind tunnel gas properties as at present. As the model cannot be increased in size significantly relative to the tunnel, in order to satisfy the Reynolds number needs established in section 2 both the model and tunnel would be scaled up linearly by a factor of 10 relative to the largest existing transonic tunnels. Implications in terms of costs are immediately available. Firstly tunnel fan drive power. To a first order the power is proportional to the flux of kinetic energy in the air passing through the test section

$$\textit{Power} = \lambda \frac{1}{2} \rho U^3 A \text{ ----- (5)}$$

where A is the flow area of the test section, U and ρ are flow reference values of velocity and density, and λ is an empirically determined proportionality factor usually in the region of 1/3. Similar substitutions in this expression may be made giving

$$\textit{Power} = \frac{\lambda}{2} P M^3 \gamma^{1.5} \sqrt{\frac{R_0 T}{m}} A \text{ ----- (6)}$$

A tunnel 10 times larger than the largest would have a flow area A 100 times larger and absorb 100 times the power. This becomes around 20 million horsepower.

Secondly the cost of the shell of the tunnel. Various sources relate the cost approximately to its surface area which again varies as the square of the scale. Therefore the two major components of capital cost, motors and structure, would be higher by a factor of around 100 than the largest transonic wind tunnels. Further considerations would be the time and cost of making models upwards of 100ft, 30m span.

Difficulties are apparent.

The expressions for Reynolds number (1) and power (5) show each increasing in proportion to density. One way of raising density is by pressurisation, an idea probably first published by Margoulis (Refs 4,5) and put into practice by Munk (Ref 18). A tunnel providing full scale Reynolds number would have to withstand a pressure differential of more than 10 atmospheres and therefore would be expensive. However the indications are that this might be a more economical option than that of just increasing size, partly because, from (6), pressurisation would raise the drive power by a factor of only 10 compared with existing wind tunnels.

The aerodynamic loads acting on a model in a particular attitude relative to the airflow vary to a first order with the dynamic pressure $q = \frac{1}{2}\rho U^2$ which increases directly with pressure. Models of transport aircraft can experience very high loads when tested at transonic speeds as was established in section 1, dominated by the lift force component. Opinions vary, but studies (Refs 7,19) have set the maximum stagnation pressure at around 6 atmospheres for complete models of transport aircraft, the limit being influenced also by considerations of the size of the model's support sting. Existing high Reynolds number tunnels operate at 1 atmosphere or above, therefore it was not possible to advocate increased pressure alone to bridge the Reynolds number gap. When confined to using normal air temperatures, moderately higher pressure must be combined with increased size. Within these constraints the tunnel would have a test section about 40 feet, 12m across, operate at up to 6 atmospheres stagnation pressure and for transonic speeds would require about 3 million horsepower for its fan.

The costs, capital and running, were still too high to contemplate and the designers resorted to compromise. Among the options for economy were (additional to the use of alternative gases), designing for values of Reynolds numbers below full scale and the use of a variety of different tunnel drive systems all exploiting intermittent operation of the tunnel in contrast to the continuous operation available with a motor driven fan. The latter compromises are now discussed briefly.

The temptation to design for sub-full-scale Reynolds numbers was strong because with the other factors held constant the power and construction costs vary strongly with the targeted Reynolds number (Ref 20). Engineers studied the possibility of aiming low because of the rewards for even modest reductions, and came up with justifications. Both in the USA and Europe the targeted Reynolds number based on mean-wing-chord was set at around 40 millions

(Refs 7,21), low by a factor of about 2 compared with the full scale requirements even of large contemporary aircraft, and by a larger but unknown factor in relation to future needs. A supporting argument was that the variation of aerodynamic performance at Reynolds numbers beyond these compromise values would be small, systematic and predictable.

Wind tunnel capital costs can be further reduced if the run-time is restricted. Opinions were again divided but the consensus was that times of 2 to 10 seconds were adequate. The tunnel would then remain idle for a period before another run, for example to allow compressed air to be stored. These run-time and Reynolds number figures were adopted and quite a variety of design schemes emerged under this influence on both sides of the Atlantic (Refs 8-10,22-29). These included various drive schemes including induction, blowdown, the Ludweig tube, hydraulics and more. Just two are selected for illustration and brief description in order to show what might have been in use if cryogenics had not come along.

The projects shared an operating envelope like that shown on figure 4, because of an almost-common specification. In constructing this figure it has been assumed that the minimum operating pressure would have been atmospheric although technically it could have been lower in some designs.

The highest Reynolds number boundary on the figure is given by the maximum pressure, 6 atmospheres in this example. This envelope boundary would extend across to the maximum Mach number of the wind tunnel, here 1.4, had sufficient power been available. The peak power demand is in the top right corner. The minimum Mach number might be set by fan speed or difficulties in resolving small forces or pressures. Lines of constant dynamic pressure q are superimposed, along with broad arrows showing examples of two test sweeps which are possible with this type of tunnel. One, Y, at constant Mach number where Reynolds number is varied, is aimed at showing Reynolds number effects, while sweep X is intended to show just Mach number effects. In both cases the arrows cross iso-dynamic-pressure lines showing variations of aerodynamic load with the possibility that varied aeroelastic distortion of the model might corrupt its aerodynamic performance.

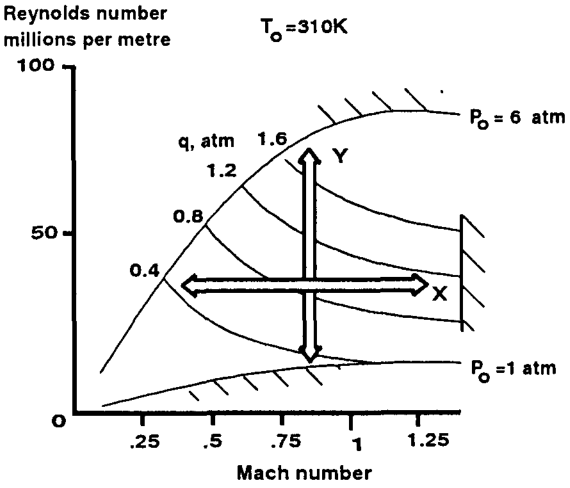

Figure 4. A representative operating envelope of the normal temperature pressure tunnels being considered before the advent of the cryogenic wind tunnel.

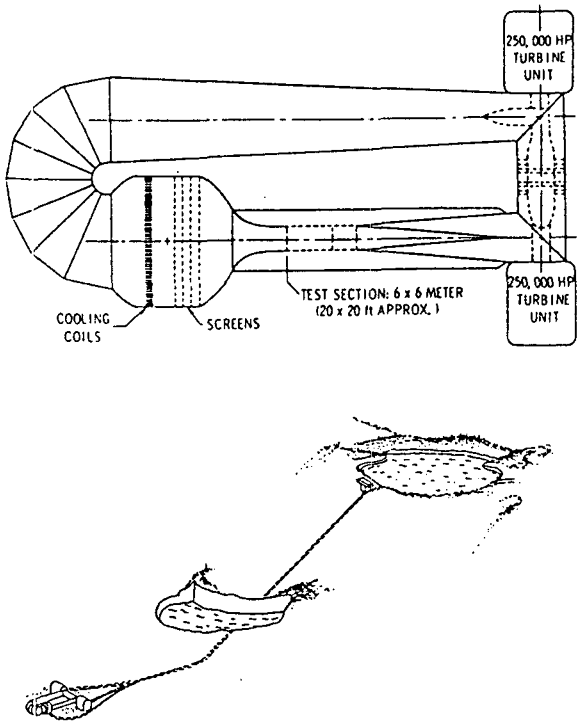

Figure 5. A NASA project where the power demands of the large tunnel would be met hydraulically by a pumped storage scheme.

Figure 5 is a sketch of one NASA normal-temperature project (Ref 8) of the early 1970's. An outline of the tunnel, comprising a closed circuit around which the pressurised air would be driven by a fan, is in the upper half of the figure. This was a transonic tunnel project for speeds up to just over the speed of sound and the tunnel demanded considerable drive power for the fan. Two motors are shown totalling half a million horsepower. Usually electric motors are used in fan-driven tunnels but in this project it was proposed to avoid the cost of building and feeding such large motors and instead site the tunnel in the mountainous region of West Virginia where a pumped water storage scheme could be built to supply hydraulic turbines coupled to the fans. In the site layout, below, the wind tunnel is on the left. The tunnel operators would drain water relatively quickly during a run, then smaller electric motors would pump back the water over a much longer period. Altogether this was a large mechanical and civil engineering project, but capable only of reaching the compromise value of Reynolds number.

An example of a European project of the same era (Refs 28,29) is shown on figure 6. For capital economy this project used the Ludweig Tube principle, in which stored compressed air, approximately at normal temperature in this case, is released by a quick-acting valve to flow for a period through the test section. The tunnel also would have reached the compromise Reynolds number for a 10 second run. Its most striking feature is its length: over 2½ miles, 4.1 km.

There were many other design schemes but these two will serve as illustrations. Quite clearly the capital costs of such projects were high but it is almost certain that two would have been built. Agreement to proceed was close when the successful demonstration of the small cryogenic wind tunnel (Ref 2) introduced the alternative method of raising Reynolds number, avoiding the need to build these very large conventional temperature tunnels. In the intervening years the cryogenic wind tunnel has been further researched, then brought into mainstream transonic aerodynamic testing with, in the cases of the largest facilities, Reynolds number capabilities somewhat above those of the normal temperature alternate schemes which they have displaced.

4. Cryogenic wind tunnels - introduction.

The cryogenic wind tunnel emerged because of the powerful effect of air temperature on Reynolds number. The relevant background comprises the early studies by Margoulis and Smelt (Refs 4-6), and the mix of experimental/theoretical cryogenic tunnel project work at NASA Langley Research Center in 1971/2. An incubation period spanning 50 years.

Cooling the test gas raises its density and reduces its viscosity, both of which contribute to an increase in Reynolds number as is clear from equation (1). In the case of transonic testing we are not free to change Mach number in assessing the effect of temperature. Probably this is also true in typical low speed testing in aeronautics. This restraint results in the velocity of the gas varying as the square root of temperature which, on cooling, is an effect which reduces Reynolds number.

Smelt carried out a comprehensive review of the effects of temperature and choice of test gas and showed in some cases very substantial advantages in terms of tunnel size and drive power. From among the diatomic gases cryogenic hydrogen showed the best promise with a size of 6.3% and a power demand of 0.5% of a normal temperature air tunnel. Aside from any safety issues, the use of hydrogen gas is now judged questionable because of a real-gas behaviour rather far removed from the nearly ideal-gas behaviour of atmospheric air (Ref 30).

The best of the remaining diatomic gases for use in a cryogenic wind tunnel are nitrogen, carbon monoxide and air, offering tunnel sizes in the order of 25% to 30% of that of normal temperature air. Because of the small differences the choice of working fluid is dictated by practical issues and the most commonly used working fluid has become nitrogen.

In comparing the cryogenic wind tunnel with conventional tunnels it is useful to take the Reynolds number expression (4) a stage further with the approximation that viscosity varies with temperature according to

$$\mu \propto T^n \text{ ----- } (7)$$

where for nitrogen $n \approx 0.9$. Adopting this value and omitting constants

$$\textit{Reynolds number} \propto \frac{1}{T^{1.4}} \text{ ----- } (8)$$

for particular values of Mach number and pressure. This shows more clearly the effect of temperature on Reynolds number and is illustrated on figure 7.

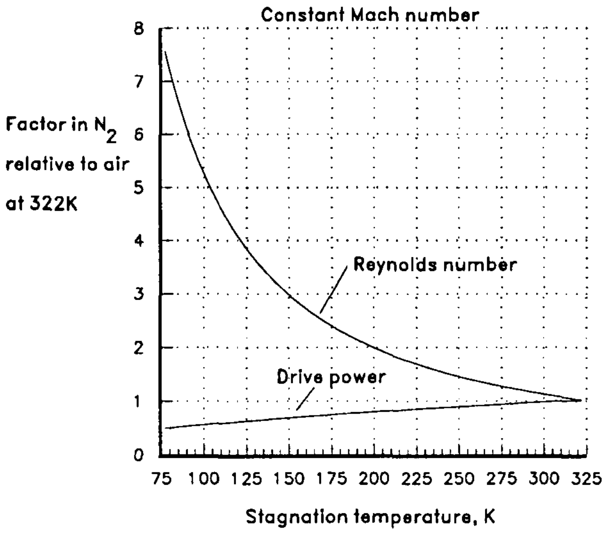

Figure 7. The influence of temperature on the test Reynolds number and tunnel drive power in a nitrogen wind tunnel compared with air at a normal temperature.

Also shown on this figure is tunnel drive power which, from (6), actually falls in these circumstances with the increase in Reynolds number. Not shown is that dynamic pressure is invariant as is clear from its expression $q=\frac{1}{2}\rho U^2=\frac{1}{2}\gamma PM^2$. This is an example of one important aerodynamic parameter,

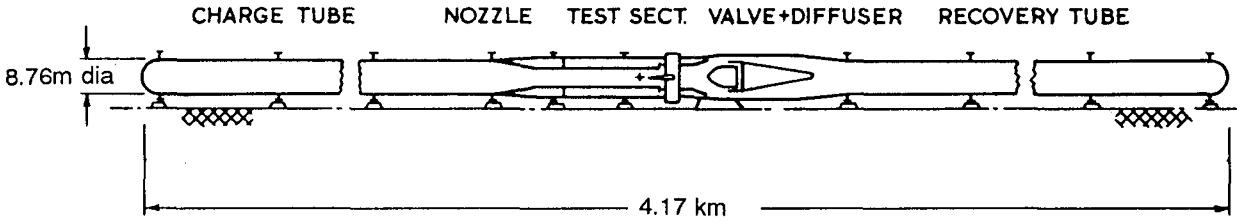

Figure 6. A European proposal for reaching full-scale Reynolds number at normal temperature

in this case the Reynolds number, being varied over a wide range by means of a change in temperature while both Mach number and dynamic pressure both are constant, a test not possible in a normal temperature variable pressure tunnel. The curves on figure 7 are taken down to 77K but the question arises immediately as to the minimum permissible operating temperature because of the advantageous slopes of both curves at low temperature. One limit is set by the need to avoid any effects of liquefaction of the test gas. The equilibrium saturation boundary is first reached at the point in the tunnel where the pressure and temperature are lowest. While this could be in the region of the fan inlet or over its rotor blades, the prime concern is condensation affecting the model. The saturation boundary is reached first where the Mach number is locally the highest which will be somewhere close to the model's surface, likely regions being the outer edge of a boundary layer or close to the core of a vortex. Take for example a test at about Mach 1. The highest local Mach number probably would not exceed about 1.7 and for this example the minimum pressure existing in a tunnel operating at 1 atmosphere stagnation pressure would be about 0.2 atmospheres. Figure 8 is the saturation curve for nitrogen from which it is seen that a minimum static temperature of 66K is permissible. This leads to a minimum stagnation temperature of 104K for such a test.

From figure 7 it is seen that at 104K the Reynolds number advantage in comparison with normal tunnels is about 5, an advantage insufficient in itself to satisfy the needs of the high Reynolds number transonic wind tunnel. It is still necessary to use elevated pressure. For the test conditions adopted in the paragraph above and the stagnation pressure limit of 6 atmospheres the minimum stagnation temperature becomes 125K where the Reynolds number advantage attributable to low temperature reduces to 3.8. More generally applicable data is that shown on figure 9 where the minimum useable temperature (giving the maximum Reynolds number) is shown as a function of the local maximum Mach number and stagnation pressure.

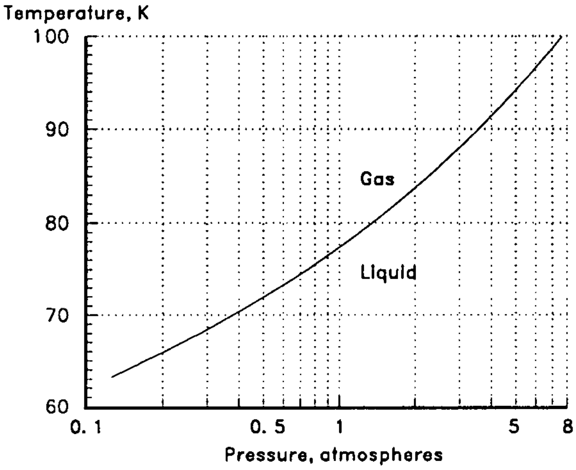

Figure 8. The liquid-gas saturation curve for nitrogen.

The impact of the smaller factor, 3.8, on the full-scale Reynolds number tunnel discussed in section 3 is still quite profound: the required size of the test section is reduced to about 10.8ft, 3.3m, smaller that many existing high speed tunnels. The full scale Reynolds number transonic tunnel was no longer necessarily an impossibly large tunnel.

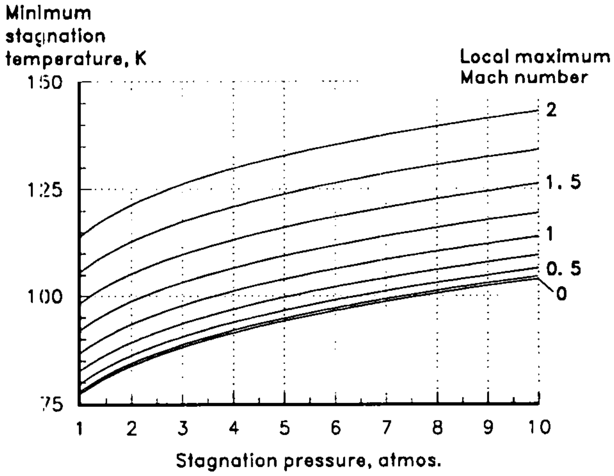

Figure 9. The minimum operating temperature of a cryogenic nitrogen tunnel set by isentropic expansion of the gas from stagnation conditions to the local minimum pressure/maximum Mach number.

Following the demonstration of the low speed atmospheric pressure cryogenic wind tunnel and the associated studies NASA immediately constructed the 0.3-meter Transonic Cryogenic Tunnel, an excellent wind tunnel which quickly yielded some very important experimental results. Among these were demonstrations (Refs 31,32) that the flow could in some circumstances be taken over the saturation boundary leading to supercooling. On occasion the tunnel could be operated with the saturation point being reached in the free stream ahead of the model without affecting performance to any detectable extent. The advantages in terms of Reynolds number, drive power and operating cost were predicted to be up to 22%.

Further, it was also almost immediately realised that the cryogenic wind tunnel offered a unique testing capability. The cryogenic pressure tunnel can be considered to have the three controllable parameters of speed, pressure and temperature. These are each variable over a usefully wide range and can be used to control independently the test Mach number, Reynolds number and dynamic pressure. This versatility is not available in any other tunnel. The significance is that for a model in a given attitude, each of these parameters can affect aerodynamic performance (through Mach number, Reynolds number or aeroelastic effects) but the cryogenic pressure tunnel allows each to be independently varied and their individual effects determined.

As any new high Reynolds number transonic wind tunnel would be required to set new standards in terms of the test environment, this unique test feature of the cryogenic pressure tunnel may have been decisive in its adoption as the preferred solution.

5. Operating envelopes for cryogenic wind tunnels.

5.1 Atmospheric-pressure cryogenic tunnels.

Guidelines for the minimum operating temperature of a cryogenic nitrogen tunnel have now been established. The maximum temperature is probably unimportant but will depend on the cooling method used near room temperature, the power of the tunnel and the temperature tolerance of its structure and is usually somewhat above ambient. In the general charts which follow a fixed maximum of 310K has been assumed as being fairly representative of maximum temperatures attained in typical tunnels over a wide band of Mach number.

The first chart shows the operating envelope of a subsonic cryogenic wind tunnel designed to operate only at ambient stagnation pressure. The chart, figure 10, applies to the original cryogenic wind tunnel (Refs 2,33,34) as well as to several current types (Ref 35) in most respects except coverage of Mach number. Unit Reynolds number is shown as a function of Mach number for the available temperature range using a nitrogen test gas.

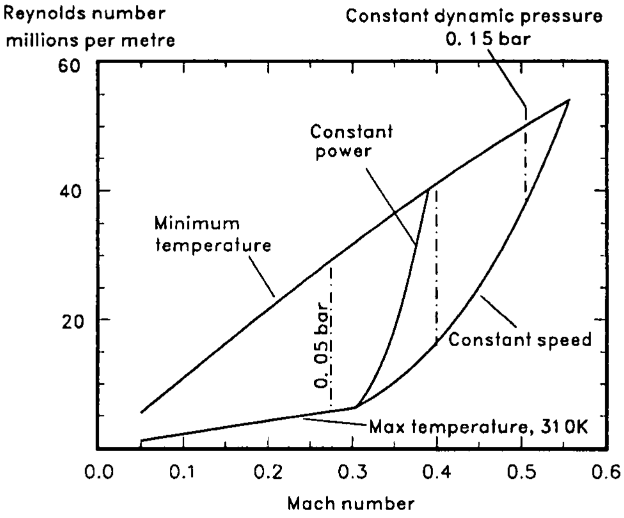

Figure 10. The operating envelope of subsonic cryogenic nitrogen wind tunnels operating at atmospheric pressure.

Lines of constant dynamic pressure are superimposed at intervals of 0.05 bar and are seen to be vertical which shows that traverses may be made in Reynolds number at constant Mach number without affecting dynamic pressure or therefore, to a first order for a model at fixed attitude, affecting aerodynamic loads and therefore model shape. A traverse at constant Reynolds number does involve variations of dynamic pressure. However they are lessthan experienced in normal temperature pressure tunnels. At Mach 0.3 the derivative $\partial q/\partial M=0.375$ bar in the ambient pressure cryogenic wind tunnel at all available Reynolds numbers. The derivative is about half of that which would exist in normal temperature pressure tunnels at similar conditions. In the latter case, for example at Mach 0.3 and a unit Reynolds number of 20 millions per metre, the derivative is 0.62 bar.

Two of the boundaries comprise the maximum temperature (310K stagnation) and a minimum temperature which here is set at 95.7K by reaching saturation in an isentropic expansion to Mach 1.4 which is a representative local high Mach number for subsonic testing. With this type of wind tunnel a variety of factors can restrict the right-hand boundary, depending on how the tunnel is driven and what limits speed. Arbitrary examples are shown here, of power and fan rotational speed limits for the case of a motor and fan drive.

Figures 2 and 10 serve to highlight another feature of the atmospheric pressure cryogenic wind tunnel, that is the wide dynamic range of Reynolds number which is available without change of model. The data of figure 2 was taken in such a tunnel and the ratio of maximum to minimum Reynolds number is seen to be 20:1 in this example. This is rather a wide range, obtained by combining the useable band of airspeed, similar to that available in any wind tunnel, with the effects of change of temperature. In the case of a fan-driven tunnel the speed band is determined by the maximum speed of the fan and the minimum practical dynamic pressure at which aerodynamic data can be obtained with acceptable resolution. The ratio of maximum to minimum Reynolds number given by this band is multiplied in the case of the cryogenic wind tunnel by the ratio of maximum to minimum Reynolds number conferred by change of temperature, which is the temperature-dependent factor shown on figure 7.

5.2 The cryogenic pressure tunnel.

This tunnel is more complex because of the pressure variable and therefore it is regarded as having an operating volume. A universal operating volume may be constructed in the form of a three-dimensional figure having axes of test dynamic pressure, Mach number and Reynolds number. This is shown on figure 11 for nitrogen. It has six faces and is drawn for the following operational limits:

a) stagnation pressure range 1 to 6 atmospheres. The minimum pressure in a cryogenic tunnel is limited to about 1 atmosphere by the frequent need to exhaust gas from the tunnel and it is convenient, in that it saves on plant costs, to have the tunnel at least slightly pressurised,

b) Mach numbers 0.2 to 1.4. This represents typically the range covered by transonic wind tunnels,

c) temperatures from 310K to the minimum reached in isentropic expansions to local Mach numbers varying from 1.4 to 1.85 depending on free stream Mach number according to the "High maximum local Mach number" on figure 3 of reference 33.

The viewpoint of the operating volume on figure 11 places a vertical Mach 1.4 plane close to the reader and the vertical Mach 0.2 plane at the far end. The left and right vertical boundaries are curved in single curvature and represent tunnel operation at stagnation pressures of 1 and 6 atmospheres respectively. The remaining boundaries at the top and bottom represent the minimum temperature and 310K stagnation temperature respectively. The tunnel may be operated anywhere inside the volume which serves to highlight the freedom to vary test parameters in isolation or, if desired, in combination to follow a flight locus. There is particular freedom for manoeuvre within the volume at the higher Mach numbers, say 0.5 upwards. The top right corner of the volume will be clipped in the case of a power-limited fan driven tunnel.

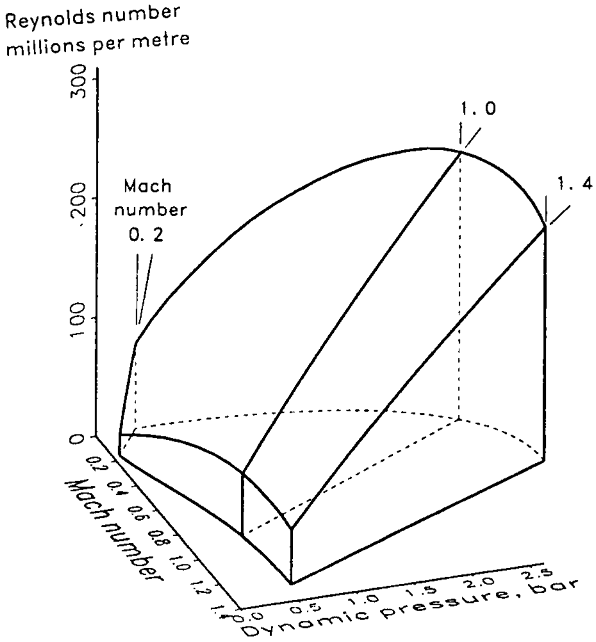

Figure 11. The generalised operating volume of a transonic cryogenic pressure tunnel.

The point on the operating volume, figure 11, where the maximum unit Reynolds number is reached is not clear. It can be seen to lie on the minimum temperature/maximum pressure line but at an indistinct Mach number. In the case of constant stagnation pressure and temperature the product ρU in the Reynolds number expression, equation (1), is a maximum precisely at Mach 1 as in nozzle flow. However the viscosity is falling steadily with increase of Mach number and this postpones the peak in the value of unit Reynolds number ρU/μ to a Mach number above 1. From (4) and for a given gas the Reynolds number varies with Mach number as

$$Re \propto M\left(1+\frac{\gamma-1}{2}M^2\right)^{n-\frac{\gamma+1}{2(\gamma-1}}$$

where n is the index in the temperature-viscosity relationship equation (7). For diatomic gases and n=0.9 this reduces to

$$Re \propto \frac{M}{(1+0{\cdot}2M^2)^{2\cdot 1}}$$

which, on differentiation, shows a maximum unit Reynolds number at Mach 1.25.

6 COOLING THE CRYOGENIC WIND TUNNEL

While mechanical refrigeration to the desired temperatures is possible in principle, the plant costs are too high. In place of this method there appear to be two other methods available for cooling a wind tunnel, each intermittent in its own way.

One is the near-isentropic expansion of a gas from high pressure storage to the test stagnation pressure. Demonstrations have shown that cryogenic temperatures can be reached at expansion pressure ratios above about 20:1 (Refs 36-38).

The second and most common method comprises cooling by means of injecting liquid nitrogen LN_2 directly into the circuit as a coolant which then becomes also part or all of the test gas. Nitrogen is used because it is relatively cheap and has low levels of contaminants. This cooling method is also intermittent in that the liquid is produced in continuously-running plant, stored and used relatively rapidly during wind tunnel tests.

The liquid, on evaporating in the tunnel, cools by latent and sensible heat absorbtion and on doing so reduces or displaces, for induced flow or fan-driven tunnels respectively, the air contents of the tunnel circuit. This reduces or removes oxygen, CO_2 and water vapour with advantage in each case. The cooling capacity of LN_2 is well established (Ref 39) and is dissipated in several ways. There is a requirement to absorb fan power or, in the case of the induced flow tunnel, to cool the inducing air. There is also the need to account for cooling at least a proportion of the tunnel structure, the proportion depending on the thermal insulation scheme and on run time. The exchange rate, expressed as the ratio of the mass of LN_2 to mass of cooled structure, in cooling from 300K to 100K is about 0.25 for steels.

Additional coolant is required to absorb heat inflow through the thermal insulation. The quantity required is strongly design-dependent and it is difficult to provide very general information. However the proportion of LN_2 consumption quoted as attributable to heat inflow ranges from 1½% up to 10% of the total LN_2 flow under typical steady running conditions at 100K.

While the requirements of a cryogenic wind tunnel for coolant and therefore cooling power depend on its design and operating cycle, studies have shown that the total energy consumption of a well insulated fan driven cryogenic wind tunnel (taking into account fan drive power and the power to generate the LN_2) is appreciably less than that required for a conventional tunnel compared on the basis of equal pressure, Mach and Reynolds numbers. Other factors in determining the coolant costs are the times required to get the tunnel to an operating condition and be held there during a test, which are pointers to the need for efficient operating procedures, instrumentation and controls.

The exhausting gas needs careful treatment except perhaps for the smallest tunnels where all that may be required is to exhaust outdoors away from people. Pure nitrogen gas must not be allowed to accumulate as could easily happen if the cold gas was simply allowed to discharge at ground level. Typically in large tunnels the cold gas is mixed with air in a ratio which renders the mixture very safe in terms of oxygen content while warming it to reduce the tendency of the plume to fall. The mixture is discharged to the atmosphere (from whence it came in the liquefaction plant) using a chimney.

7 REAL GAS EFFECTS

Analyses of flows and the test data from wind tunnels usually assume the working fluid to behave as a perfect gas, that is one obeying the equation of state for an ideal gas while having constant specific heats. Examples of departures from perfect gas behaviour are: (1) a thermal imperfection where, in the equation of state $PV = ZRT$, the compressibility factor Z is not unity (V=specific volume), (2) a caloric imperfection where the ratio of specific heats γ departs from the ideal diatomic gas value of 1.4.

Each varies several percent from its value at room temperature for the ranges of pressure and temperature experienced in cryogenic wind tunnels. These were thought to introduce more stringent restrictions to operating temperatures than set by liquefaction (Refs 2,33) in a tunnel required to behave as air at room temperature. The effects were examined by Kilgore, Adcock, Albone and Johnson (Refs 34,40-43), analytically and by experiment in the 0.3m Transonic Cryogenic Tunnel. Representative isentropic, shock and boundary layer flows were studied. The conclusion was that a cryogenic wind tunnel can be operated at conditions very close to saturation without these real gas effects becoming apparent, a very useful discovery.

Another real gas effect is condensation, mentioned already in connection with the choice of operating temperature.

8 REVIEW

The aim of this final section is to describe some of the broad impacts which cryogenic operation has on tunnels with drives other than the fan, and to highlight some general reference sources. Cryogenic techniques might be applied to most types of tunnel drive, for all speeds up to supersonic, with a view to raising unit Reynolds number and in most cases there are authoritative accounts in lectures to follow. The hypersonic tunnel is an inappropriate application of cryogenic technology because of the low static temperature which already exists in the test section under normal circumstances.

The Cryogenic Ludweig Tube. A reduction of the temperature of the gas stored in the Ludweig Tube results in increases both of Reynolds number and run time. Run time varies approximately inversely with $\sqrt{T_o}$. The permissible temperature reductions from normal are modified by the reduction of stagnation temperature which occurs during the passage of the expansion wave along the tube, a feature of this tunnel drive. Model precooling generally would be required. By injecting a cryogenic fluid directly into the tube for the purpose of cooling, the pressure recharging process might be simplified and shortened.

The Cryogenic Induced-Flow Tunnel. The cryogenic mode of operation is applicable to the closed-circuit induced-flow facility. The inducing gas must be cooled in order to maintain a constant test temperature. Precooling of the model could be carried out simultaneously with the tunnel, depending on the design and method of operation of the tunnel (but please note the different technique used by ONERA and described later). If a test in air was deemed desirable then suitable proportions of liquid oxygen and LN_2 could be evaporated within the circuit or inducing airstream.

The Cryogenic Blowdown Tunnel. One mode of operation of this tunnel might be to store air at normal temperature, to precool the model, and during a run to hold a constant test temperature by injecting and evaporating coolant in the region of the settling chamber. As an example of some of the changes to facility design which would result from operation at cryogenic temperatures, a comparison can be made between a normal-temperature blowdown-tunnel and an equivalent cryogenic tunnel which operates at the same Reynolds number, stagnation pressure (3 atmospheres) and transonic Mach number. The test section of the cryogenic tunnel would be about 24% of the size of that for the normal tunnel when designed for the minimum practical temperature in a nitrogen-air mix. When operating from the same-sized air storage bottles the cryogenic tunnel would run 20 times as long. However the consumption of LN_2 is high, comprising almost half of the gas flow rate through the test section, and therefore this type of tunnel must be considered only for intermittent operation.

To close, I recommend references 35,44 and 45 as sources which the reader might consult for more detailed and specialised information on cryogenic wind tunnel and related technologies, in many cases the citations supplementing the material of this Course.

9 REFERENCES

1. Allen, J E. "The Future of Aeronautics - Dreams and Realities." The Aeronautical Journal, Vol 75, No 729, pp587-609, September 1971.

2. Goodyer, M.J., Kilgore, R.A. "The high Reynolds number cryogenic wind tunnel." AIAA paper 72-995, 7th Aerodynamic Testing Conference, September 1972.

3. Pozniak, O.M. "Investigation into the use of Freon 12 as a working medium in a high speed wind-tunnel." College of Aeronautics Note 72, 1957.

4. Margoulis, W. "Nouvelle Methode d'essai de Modeles en Souffleries Aerodynamiques." Competes Rendus Acad Sci., vol 171, 1920.

5. Margoulis, W. "A new method of testing models in wind tunnels." NACA TN-52, 1921.

6. Smelt, R. "Power economy in high speed wind tunnels by the choice of working fluid and temperature." R.A.E Report Aero 2081, 1945.

7. LaWs Working Group. "The need for large wind-tunnels in Europe." AGARD Advisory Report 60, December 1972.

8. Baals, D.D., Stokes, G.M. "A facility concept for high Reynolds number testing at transonic speeds." Paper 28, Facilities and techniques for aerodynamic testing at transonic speeds and high Reynolds number. AGARD CP 83, 1971.

9. Whitfield, J D. et al. "Higher Reynolds Number Transonic Tunnels - Blowdown or Ludweig Tube?" Paper 29, AGARD CP83, April 1971.

10 Schueler, C J. "Experimental studies in a Ludweig tube transonic tunnel." AGARD Report 615, December 1973.

11. R. T. Jones. "Highlights from the history of airfoil development." Sport Aviation, June 1978.

12. Reynolds O. "An experimental investigation of the circumstances which determine whether the motion of water shall be direct or sinuous, and the law of resistance in parallel channels." The Philosophical Transactions of the Royal Society, 1883.

13. Abbott, I. H. and Von Doenhoff, A. E. "Theory of wing sections." Dover, 1959.

14. J. L. Jones. "Problems of flow simulation in wind tunnels." AIAA paper 69-660, June 1969.

15. Hoerner, B. "Fluid dynamic lift." Hoerner Fluid Dynamics.

16. Dor, J-B. "The T2 cryogenic induction tunnel in Toulouse." Paper 9, Special Course on cryogenic technology for wind tunnel testing, AGARD Report no. 722, 1985.

17. Jenkins, R V. "Reynolds Number Tests of an NPL 9510 Airfoil in the Langley 0.3-Meter Transonic Cryogenic Tunnel." NASA TM 85663, 1983.

18. Munk, M. M., Miller, E.W. "The Variable-Density Wind Tunnel of the National Advisory Committee for Aeronautics." NACA TR 227, 1926.

19. Evans, J.Y.G., Taylor, C.R. "Some factors relevant to the simulation of full-scale flows in model tests and to the specification of new high Reynolds number transonic testing." Paper 31 in AGARD CP 83, 1971.

20. Heppe, R.R., O'Laughlin, B.D., Celniker, L. "New Aeronautical Facilities-We Need Them Now." Aeronautics and Astronautics, March 1968, AIAA.

21. Igoe W. B., Baals D. D. "Reynolds number requirements for valid testing at transonic speeds." Paper 5-1, AGARD Cp 83, April 1971.

22. Agard report number 603. "Aerodynamic test simulation: lessons from the past and future prospects." Editor J.Lukasiewicz. December 1972.

23. "Facilities and techniques for aerodynamic testing at transonic speeds and high Reynolds number." AGARD CP 83, Göttingen, 1971.

24. Schueler, C.J. "Experimental studies in a Ludweig tube tunnel. Paper 3, Large Windtunnels: Required Characteristics and the Performance of Various Types of Transonic Facility." AGARD-R-615, 1974.

25. Nelander, C., Overby, B. "Application of the gasometer storage concept to a transonic windtunnel meeting the Laws specification." Paper 4, Large Windtunnels: Required Characteristics and the Performance of Various Types of Transonic Facility. AGARD-R-615, 1974.

26. Evans, J.Y.G. "A scheme for a quiet transonic flow suitable for model testing at a high Reynolds number." RAE Technical Report 71112, 1971.

27. Pugh, P.G., Beckett, W.A., Gell, T.G. "The ECT drive system : a demonstration of its practicability and utility." Paper 2, Windtunnel Design and Testing Techniques, AGARD-CP-174, 1976.

28. Ludweig, H., Grauer-Carstensen, H., Lorenz-Meyer, W. "Project study of a large European transonic Ludweig tube windtunnel." Paper 2, Problems of Wind Tunnel Design and Testing, AGARD Report R-600, 1973.

29. Ludweig, H., Grauer-Carstensen, H., Lorenz-Meyer, W. "The Ludweig tube - a proposal for a high Reynolds number transonic windtunnel." Paper 3, Windtunnel Design and Testing Techniques, AGARD-CP-174, 1976.

30. Haut, R.C. "Evaluation of Hydrogen as a Cryogenic Wind Tunnel Gas." NASA CR-145186, April 1977.

31. Hall, R.M., Ray, E.J. "Investigation of minimum operating temperatures for cryogenic wind tunnels." AIAA paper 76-89, 14th Aerospace Sciences Meeting, Washington, 1976.

32. Hall, R.M. "Studies of Condensation Effects on Airfoil Testing in the Langley 0.3 Meter Transonic Cryogenic Tunnel." NASA TP 2509, 1986.

33. Kilgore, R.A., Goodyer, M.J., Adcock, J.B., Davenport, E.E. "The cryogenic wind-tunnel concept for High Reynolds number testing." NASA TN D-7762, 1974.

34. Kilgore, R.A. "The Cryogenic Wind Tunnel for High Reynolds Number Testing." Southampton University, Ph.D. Thesis, 1974.

35. Kilgore, R.A. (editor). "CRYO Newsletter", PO Box 4006, Hampton, VA 23664-0006, U.S.A.

36. Stollery, J.L., Murthy, A.V. "An Intermittent High-Reynolds Number Wind Tunnel." Aeronautical

Quarterly, vol. 28, 1977.

37. Hutt, G.R., East, R.A. "Preliminary Studies of a Free Piston Expander for an Intermittent Cryogenic Wind Tunnel." Paper 8, First International Symposium on Cryogenic Wind Tunnels, Southampton University, 1979.

38. Edmundson, I.C. The generation of cryogenic temperatures by high pressure expansion." Paper 12, First International Symposium on Cryogenic Wind Tunnels, Southampton University, 1979.

39. Kilgore, R.A., Adcock, J.B. "Specific Cooling Capacity of Liquid Nitrogen." NASA TM-X-74015, 1977.

40. Adcock, J.B. "Real-Gas Effects Associated With One-Dimensional Transonic Flow of Cryogenic Nitrogen." NASA TN D-8274, 1976.

41. Albone, C.M. "An investigation into the real gas effects of cryogenic nitrogen in inviscid homentropic flow." Paper 17, First International Symposium on Cryogenic Wind Tunnels, Southampton University, 1979.

42. Adcock, J.B., Johnson, C.B. "A Theoretical Analysis of Simulated Transonic Boundary Layers in Cryogenic-Nitrogen Wind Tunnels." NASA TP-1631, 1980.

43. Johnson, C.B., Adcock, J.B. "Measurements of Recovery Temperature on an Airfoil in the Langley 0.3-m Transonic Cryogenic Tunnel." AIAA Thermophysics Conference, Palo Alto, June 1981.

44. Goodyer, M.J., "The Cryogenic Wind Tunnel." Progress in Aerospace Sciences, vol 29 no 3, 1992.

45. Tuttle, M.H., Kilgore, R.A., Moore, D.L. "Cryogenic Wind Tunnels. A Comprehensive, Annotated Bibliography." NASA TM 4273, 1991.

CRYOGENIC ENGINEERING AND MATERIALS.

David. A. Wigley.
Cryogenic, Marine and Materials Consultants Ltd
17 Bassett Wood Drive, Bassett,
Southampton, SO16 3PT, UK

SUMMARY

The following aspects of cryogenic engineering and basic properties of materials are considered:
- The oxygen-nitrogen binary phase diagram and the formation of liquid oxygen in unsealed insulation systems.
- The large liquid/gas volume expansion and the dangers inherent in the pressure created in closed containers.
- Nucleate and film boiling in liquid nitrogen, the different heat transfer rates in between solid/liquid and solid/gas, operation of liquid nitrogen level sensors and of electric immersion heaters used to evaporate liquid nitrogen.
- Safe working practices for handling liquid nitrogen, the physiological effects of oxygen deficiency, anoxia and asphyxiation, the use of oxygen monitors, breathing apparatus, condensation clouds and nitrogen concentration, escape routes and victim rescue.
- The cause and avoidance of cold burns by good working practice and the use of protective clothing.
- Storage of liquid nitrogen and its transfer using bare and insulated transfer lines over long and short distances.
- Selection of materials for their LOX compatibility and for the avoidance of moisture desorption.
- Thermal contraction of metals and non-metals, problems caused by temperature gradients and the use of materials with mis-matched expansion coefficients.
- Thermal conductivity and insulation, heat capacity, thermal response times and thermal shock.

1. INTRODUCTION

This paper might well be described as a "foundation level" course on those aspects of cryogenic engineering and materials technology that underlie the design and operation of High Reynolds' Number Cryogenic Wind Tunnels (abbreviated in this paper as HRNCWTs). There are parallels with the foundations of a building in that both are often taken for granted, but necessary in order to give a solid base for the subsequent structure. In particular, an understanding of the safe use and handling of liquid nitrogen is of extreme importance if accidents are to be avoided. Cold burns or asphyxiation are just two of the hazards that needed to be prevented, while a working knowledge of the storage and transfer of liquid nitrogen is essential for those handling this cryogenic fluid. Control of moisture desorption important to maintain very low dew point atmospheres needed to avoid formation of ice on the surface of a cold model. An understanding of physical properties such as thermal contraction is important for the correct design of equipment operating at cryogenic temperatures, while an appreciation of thermal conductivities can avoid unnecessary heat influxes.

2. GENERAL PROPERTIES OF LIQUID AIR, ARGON, NITROGEN AND OXYGEN

The basic properties of liquid air and its constituents are given in Table 1 and discussed in the next few paragraphs.

Table 1. Properties of Liquid Nitrogen, Air, Argon and Oxygen.

Property	Nitrogen	Air	Argon	Oxygen
Molecular Weight	28	28.8	40	32
Critical Pressure (Atm.)	33.5	38.7	48.3	50.1
Critical Temperature (K)	126	132	151	154
Normal Boiling Point (K)	77.4	Bubble 78.8 Dew 81.8	87.3	90.2
Freezing Point (K)	63.2	-	84	54.8
Liquid Density @ Normal Boiling Pt, (kg/m^3)	808	876	1402	1138
Specific Gravity of Gas at 288 K and 1 Atm.	0.97	1	1.38	1.10
Vol.Gas @ 288 K, 1 Atm,/Unit Vol.Gas @ B.P.	683	730	823	843
Latent Heat of Vaporisat'n (kJ/kg)	199	205	161	213
Specific Heat of Liquid, C_p, (J/kg.K)	2.038	1.967	1.138	1.699
Liquid Viscosity, (microPascal.sec)	158	163	256	188
Paramagnetism	None	Oxygen / 5	None	Strong
Colour	Colourless	Light blue	Colourless	Blue
Oxidising Power	None	Moderate	None	High

Paper presented at an AGARD FDP Special Course on "Advances in Cryogenic Wind Tunnel Technology", held at the DLR Research Center, Köln, Germany, 20-24 May 1996, and published in R-812.

2.1 Binary Phase Diagram for Oxygen-Nitrogen Mixtures.

For simplicity, gaseous air is assumed to contain 21% oxygen and 79% nitrogen, neglecting the minor constituents such as argon, neon, krypton and carbon dioxide. The binary phase diagram between pure oxygen, boiling point 90.3 K (-183 °C) and pure nitrogen, boiling point 77.3 K (-196 °C), is shown in Figure 1.

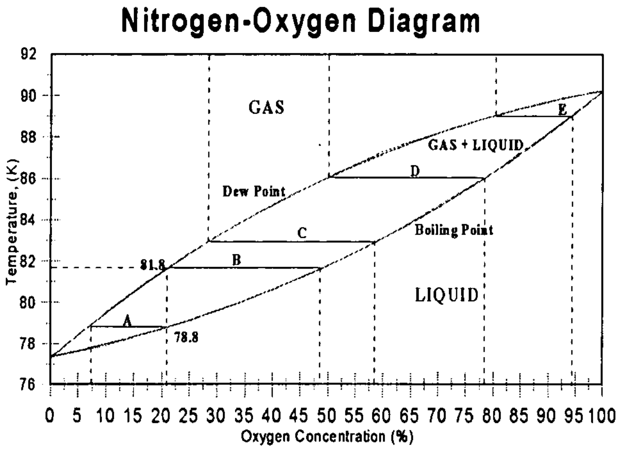

Figure 1. Nitrogen/Oxygen Binary Phase Diagram.

The dew point temperature is the temperature at which droplets of liquid start to condense from saturated vapour. For air this is 81.8 K (-191.4 °C), as may be seen from the vertical dashed line at a composition of 21% oxygen. The bubble point temperature of air, where bubbles of gas start to form from the saturated liquid, is 78.8 K (-194.4°C). Consider now the horizontal tie line, A, drawn at 78.8 K, the bubble point temperature of liquid air. It can be seen that the evaporating gas contains only about 7% oxygen and 93% nitrogen, thus the gas is enriched in nitrogen. In commercial air separation this composition difference between the liquid and gas is exploited by arranging a series of trays in the column on which the liquid is re-evaporated. The liquid descends and becomes progressively richer in oxygen, while the gas rising up the column contains more and more nitrogen.

A similar mechanism gives rise to inadvertent liquid oxygen formation where air can come into contact with a surface cooled by liquid nitrogen, as indicated schematically in Figure 2. This assumes that air can migrate through the insulation and condense on the surface at its dew point of 81.8 K. As can be seen from tie line B, the liquid that condenses is enriched to a concentration of almost 50% oxygen. The droplets of liquid then fall into the insulation and the liquid warms up in the temperature gradient within the insulation. The composition of the evaporating gas is given by the dew pint line and that of the gas by the bubble line. Thus, when the droplet is at position C and a temperature of 83 K the evaporating gas will contain 29% oxygen and the remaining liquid 58% oxygen. At 86 K, position D, the liquid contains 78% oxygen, while at position E, 89 K, it is enriched to about 95%. Depending on the actual conditions within the insulation it is possible that almost pure liquid oxygen will be created within the insulation, or even drip from it.

It is this mechanism that gives rise to potential hazards if combustible material such as grease, most plastics and even some metals come into contact with the liquid oxygen or oxygen-enriched gas.

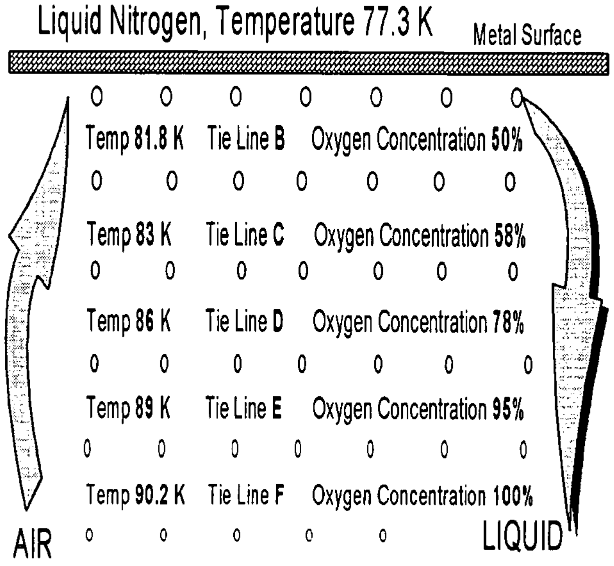

Figure 2. Schematic View of the Mechanism of Liquid Oxygen Enrichment

2.2 Liquid-Gas x 683 Volume Increase.

As may be seen from Table 1, when unit volume of liquid nitrogen evaporates at 77 K, it produces 683 unit volumes of gas at atmospheric pressure at room temperature. As PV = RT, the volume of gas at 77 K is 683 * 77 / 288 = 183 unit volumes. Thus 1 cc of liquid at 77 K evaporates to give 183 cc of gas at 1 atmosphere pressure at 77 K. Alternatively, if the liquid is unable to evaporate freely, a large pressure is generated in the trapped volume. Thus,

NEVER CLOSE A PIPE OR ENCLOSURE CONTAINING LN$_2$ UNLESS IT IS FITTED WITH A PRESSURE-RELIEF SYSTEM!

By law, all vessels operating at pressures above ½ an atmosphere must be fitted with relief valves and bursting disks. The effective operation of relief valves must be checked periodically.

2.3 Effect of Pressure on Boiling Point.

Figure 3 shows the Vapour Pressure - Temperature relationship for nitrogen. The triple point, at which liquid, solid and gas co-exist is at a temperature of 63.2 K and a pressure of 0.012 MPa. Although unlikely to be of much interest for HRNCWT applications, in research laboratories temperatures between 77.3 K and 63.2 K are obtained by pumping off the evaporating gas using rotary pumps and thus lowering the boiling point.

In contrast, if the pressure over the liquid is increased, the boiling point is increased up to the Critical point, where there is no distinction between liquid and gas. This occurs at a temperature of 126 K and a pressure of 33.5 Atm. (~3.4 MPa) If high pressure nitrogen gas is cooled to below 126 K, liquid can be created by expansion through a small orifice, the so-called Joule-Thompson effect.

The effect of increasing the pressure over liquid nitrogen can be demonstrated using an un-silvered glass Dewar and covering the top with a balloon. If the balloon is compressed to raise the pressure, gas bubble formation ceases as boiling is quenched.

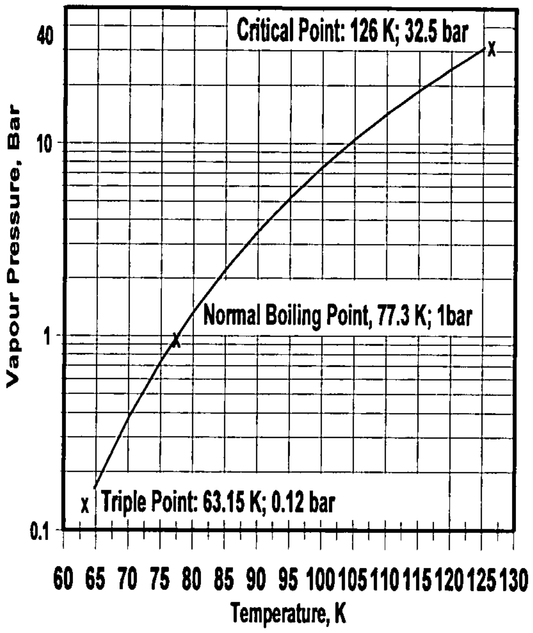

Figure 3. Vapour Pressure-Temperature Curve for Nitrogen

2.4 Heat Transfer in Liquid and Gaseous Nitrogen.

2.4.1 *Difference Between Heat Transfer Rates in Liquid and Gas.*

Heat can be transferred at a much greater rate between a solid and a surrounding liquid than between a solid and surrounding gas. This effect can be used to make a simple liquid nitrogen level detector by attaching a thermocouple junction to a small electric resistor through which a current is passed. When immersed in liquid nitrogen, the power dissipated in the resistor is set to give a thermocouple reading a few degrees above the liquid temperature of 77 K. If the resistor is then raised above the liquid, its temperature will rise quite rapidly and stabilise a temperature that can be sustained by heat transfer to the cold gas. Thus, when immersed in liquid, ΔT is a few K, surrounded by gas ΔT is 10's of K. This effect is shown in Figure 4.

A relevant example of the restriction on power dissipation in LN_2 by the onset of film boiling is that of heaters used to evaporate liquid nitrogen. Commercially available water heaters, rated at 3 kW were tested in liquid nitrogen and it was found that a maximum of 720 W could be dissipated by nucleate boiling. This was equivalent to a dissipation rate of about 3 W / cm^2, significantly lower than the 10 - 12 W / cm^2 obtained under ideal conditions. At the maximum rate of heat transfer, the temperature of a thermocouple taped to the surface of the heater coil showed a ΔT of a few K above the liquid temperature. The tests also showed that the surface temperature of the upper heater coil increased very rapidly as soon as the liquid nitrogen level dropped to allow it to be partially uncovered by the boiling nitrogen, a further indication of the much lower heat transfer rate between the heated surface and gaseous nitrogen.

It is also possible to demonstrate the effect of surface condition by comparing the time for bubble formation to stop on a series of otherwise identical specimens of copper, lead or aluminium that are polished, tarnished, and coated with a clear lacquer, white, or black paint. The most striking result is that the lacquer-coated specimen cools most rapidly, as the insulating effect of the lacquer layer allows nucleate boiling and its characteristically high heat-transfer rate to be established more rapidly.

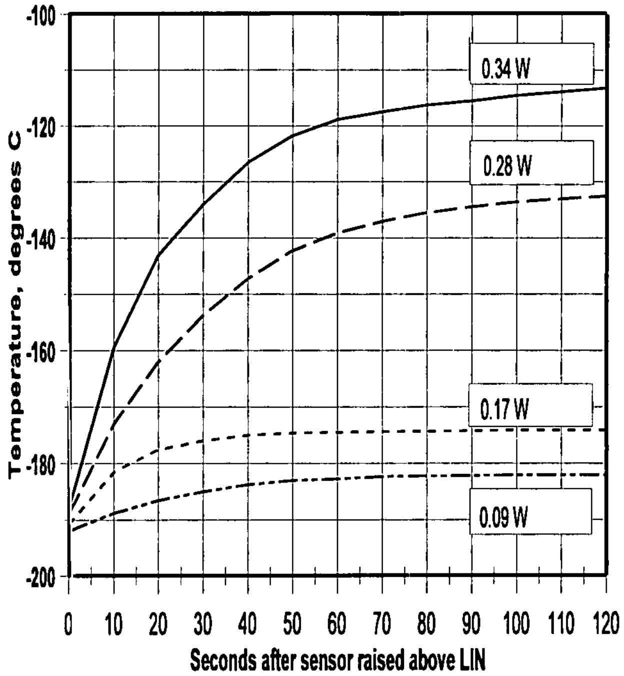

Figure 4. Temperature of Thermocouple / Heater After Removal from Liquid Nitrogen.

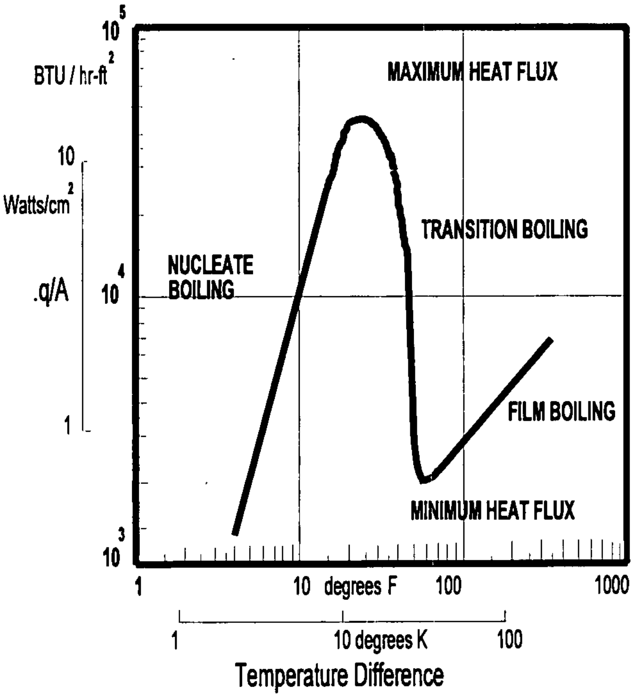

Figure 5. Typical Pool Boiling Characteristic Curve.

3. SAFETY: OXYGEN DEFICIENCY, ANOXIA, ASPHYXIATION.

Safe handling of cryogenic fluids and solids is discussed in the British Cryogenics Council "Cryogenics Safety Manual - A Guide To Good Practice". Suitable training in these topics should form a natural part of training of operatives by the contractor. Advice and assistance is also available from suppliers of cryogenic liquids.

3.1 Physiological Effects of Nitrogen.

Liquid nitrogen evaporates to produce a gas that is potentially liable to cause asphyxiation. It is only necessary for the oxygen content of air to fall a few percent below its normal value of about 20% for bodily functions, both mental and physical, to be adversely affected. Gradual asphyxiation occurs if the oxygen concentration decreases slowly. Reduction of the oxygen level towards about 14% causes anoxaemia, characterised by an increase in pulse rate, laboured breathing and difficulty in concentration. At oxygen levels between 14 and 10% the victim is still conscious but muscular effort causes rapid fatigue and mental processes such as co-ordination and judgement deteriorate.

When the oxygen concentration falls below 10% there is a severe risk of asphyxiation and possibly permanent brain damage. By the time the victim realises that something is wrong it may be too late for him to save himself as his muscles will be unable to function and allow his escape. If the oxygen level falls below 6% death is virtually inevitable - apparently painless, but nonetheless permanent! These effects are summarised in Table 2.

Table 2. Signs and Symptoms of Gradual Asphyxiation.

O_2 % at 1 Atm. Press.	Victim at rest, signs and symptoms of O_2 deficiency
12-14	Respiration deeper, pulse faster, coordination poor
10 - 12	Giddiness, poor judgement, lips blue.
8 - 10	Nausea, vomiting, unconsciousness, ashen face
6 - 8	After 8 min., 100% die; 6 min., 50% die and 50% recover with treatment; 4 - 5 min., all recover with treatment.
4	Coma in 40 sec., convulsions, respiration ceases

Sudden asphyxia occurs by inhalation of a gas that contains little or no oxygen and the victim often falls as if struck by a blow on the head. It is surprisingly easy to produce such low oxygen levels. Inhaling just a few breaths, or even one deep breath of pure nitrogen, or any other inert gas, can flush the oxygen out of the lungs and the loss of muscle function can prevent them refilling even if the victim is removed from the inert atmosphere. Death can occur in a few minutes and some form of rapid resuscitation is necessary to restore oxygen to the lungs and allow possible recovery. A typical scenario for such an accident is where someone opens an inspection hatch in a nitrogen-purged vessel, puts his head inside to "take a quick look" and collapses within a few seconds because his lungs have become filled with nitrogen. Unlike the gradual loss of breathable air that takes place in a sealed volume when the oxygen is not replaced, little or no warning is given by the body of this form of anoxia. Use of liquid nitrogen in, or near, pits and ducts is particularly hazardous as cold gases tend to sink and accumulate at low levels. Positive air flow is required to prevent dangerously low levels of oxygen in such locations.

One of the few fatal accidents involving liquid nitrogen that have occurred in the UK involved pipe freezing in a pit. One operator went down to investigate a leak in the freezing jacket and collapsed due to anoxia. Unfortunately, he was not wearing a safety harness or rope, neither was a colleague who attempted to rescue him. When he also collapsed, a third colleague also attempted rescue, also without wearing appropriate equipment. Ultimately, the first two operatives died, while the third recovered. There are a number of ways in which the effects of anoxia can be avoided, including ensuring a supply of fresh air and the use of oxygen monitors, both of which are discussed in paragraph 3.1.3.

3.1.1 *Rescue of the Victim and Treatment of Oxygen Deficiency and Anoxia.*

If a serious accident is not to be compounded into a tragedy, rescue personnel must ensure that they are adequately equipped with breathing apparatus, air line, etc. **before** entering the zone in which the victim of an oxygen-deficient incident lies. As noted earlier, it was the failure to observe this precaution that increased the number of casualties in the pipe freezing related incident. The victim should be removed immediately to a normal atmosphere. If he is not breathing it is vitally important to start artificial respiration at the first opportunity, preferably by the use of an automatic resuscitator employing oxygen gas, or alternatively by the mouth or other unaided method.

3.1.2 *Oxygen Monitors*

In order to avoid anoxia, it is necessary to be able to detect the presence, and extent, of regions of low oxygen concentration. Oxygen monitors are used for this purpose and used correctly they are invaluable. There are a number of types of monitor available, but the most useful are the small portable types. Care is needed in the appropriate placing of oxygen monitors. If, for example, they are placed too high up they will not register a dangerous loss of oxygen at working head height. Placed directly over a nitrogen vent or on the floor below an outlet they will trigger prematurely. Such false alarms are likely to lead to distrust or complacency that could prevent operatives from reacting to a truly dangerous situation. Small, portable monitors can be worn high up on the body to give a rapid warning if the head is moved into a potentially dangerous location. It is important that oxygen monitors are serviced and re-calibrated regularly, as their efficiency decreases over periods of about 6 to 12 months.

3.1.3 *Safe Methods of Working with Liquid Nitrogen.*

Fresh Air Supply

When using liquid nitrogen It is essential to maintain a flow of fresh air to prevent the build up of an inert gas. Often this is simply a matter of opening appropriate doors and windows, in other cases it is necessary to provide air movers to ensure an adequate air flow.

Condensation Clouds

When a cold gas comes into contact with moist air, water vapour is condensed to form a cloud, the conditions for which depend on factors such as the temperature of the gas and the dew point of the air. It should be assumed that the fog could contain a high proportion of nitrogen gas and a correspondingly low amount of oxygen. It should, therefore, not be entered. It is also possible for the clear air beneath a cloud to be oxygen deficient as the cold nitrogen gas will sink to the lowest level. A dense cloud can cause a loss of visibility and create a hazard to personnel in the area, especially in the event of a large spillage.