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INTRODUCTION TO CRYOGENIC WIND TUNNELS

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16 Abstract

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The principles and advantages of the cryogenic tunnel are outlined, along with guidance on the coolant needs when this is liquid nitrogen, and with a note on energy recovery. Operational features of the tunnels are introduced with reference to a small low speed tunnel.

Finally the outstanding contributions are highlighted of the 0.3-Meter Transonic Cryogenic Tunnel (TCT) at NASA Langley Research Center, and its personnel, to the furtherance of knowledge and confidence in the concept.

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INTRODUCTION TO CRYOGENIC WIND TUNNELS

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SUMMARY

The background to the evolution of the cryogenic wind tunnel is outlined, with particular reference to the late 60's/early 70's when efforts were begun to re-equip with larger wind tunnels. The problems of providing full scale Reynolds numbers in transonic testing were proving particularly intractible, when the notion of satisfying the needs with the cryogenic tunnel was proposed, and then adopted.

The principles and advantages of the cryogenic tunnel are outlined, along with guidance on the coolant needs when this is liquid nitrogen, and with a note on energy recovery. Operational features of the tunnels are introduced with reference to a small low speed tunnel

Finally the outstanding contributions are highlighted of the 0.3m Transonic Cryogenic Tunnel at NASA Langley Research Center, and its personnel, to the furtherance of knowledge and confidence in the concept.

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 Series it is necessary to reflect for a moment on the underlying reasons for the work, which I will first attempt to do. The root cause of us all 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 of the kind represented by 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."(1) This statement was published by a most experienced aircraft designer in September 1971, close to the time of the beginning of construction of the first cryogenic wind tunnel.(2) Since then the two avenues of endeavour, empirical and theoretical, have advanced in healthy competition with improvements in each, which is a recognition that the former was not without weakness.

The birth of the cryogenic wind tunnel was preceeded 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 not the required Reynolds number. The reason for this is that Mach number effects were known to be strong 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 allowed the development of the ventilated test section for transonic testing, satisfying the immediately most pressing needs at reasonable cost. Had Reynolds number effects seemed more important there is no knowing what solutions might have emerged, but quite likely the cryogenic wind tunnel, because the necessary information and technology was around and the route to satisfying Reynolds number by more conventional means is inordinately expensive.

It should be mentioned that throughout almost the whole course 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 satisfied with large unpressurised wind tunnels which were just economically feasible, but the situation became more difficult with the progressive increases particularly in airspeed but also in 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(3) contains 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 for testing 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 also do the same. Mixtures of gases having $\gamma = 1.4$ gave too small rewards.

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On at least two occasions the prospects were discussed for the use of low temperatures in aerodynamic testing. Margoulis[4] in 1920 and Smelt[5] in 1945 published 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 the facing of the practical problems

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 concensus was that mismatch in Reynolds number was the likely cause. From these experiences began compaigns 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 on the subject.

AGARD, through its Fluid Dynamics Panel, first set up the High Reynolds Number Working Group (HIRT) in 1969 which reported on some solutions to the transonic needs of NATO countries in September 1970. 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[6]. These activities represent an interim period, ending in about 1973, when a variety of solutions was actively persued based on the use of normal temperatures but often in otherwise unconventional wind tunnels.

Those involved first set out to define requirements and then to 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 improved 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 U.S.A.) felt that tunnels should match flight 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, including any proposed for Reynolds number, were forced by what was considered economically possible rather than being based on real technical merit.

The tunnel specifications which emerged included minimum run times, Mach number bands, maximum pressure and of course Reynolds number. In Europe it was recognised that this would need to be a multi-national collaborative project because of the capital cost. Several competing schemes emerged for evaluation[6]. A tunnel was separately proposed for the U.S.A. which also had several competing schemes[7,8,9].

Figure 1 compares 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, and it is apparent that tunnel capability is below flight by factors up to 5:1 in the case of larger transonic aircraft. (The picture has changed little in the meantime except for the case of the N.T.F. which is becoming available in the U.S.A.).

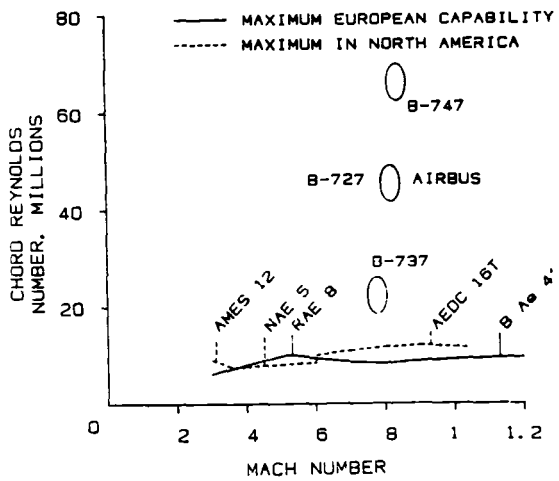

Figure 1: Maximum Reynolds numbers available each side of the Atlantic in conventional transonic tunnels, compared with requirements of some transport aircraft at cruise.

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 that 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 the 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 much thicker sections in the model's structure compared with the aircraft, to the point of many components being solid. With increases in pressure there is an increasing problem arising 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 was 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 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 people at NASA Langley Research Center were faced with a similar kind of problem in relation to a wind tunnel magnetic suspension and balance system, that is much too low a Reynolds number, and 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 elementry misgivings over the concept and also served 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 the cryogenic wind tunnel, fan driven and therefore nominally continuous, capable of reaching full scale flight Reynolds numbers at moderate tunnel size and pressure.

The cryogenic wind tunnel evidently was born out of needs of transonic testing, but is finding wider application as we will hear in due course.

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, 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 in the Series, to cover the familiar intermittent options as well as some novel drives devised to exploit the particular characteristics of cryogenics.

The aims of the remaining part of this paper are to introduce some principles, and this will be by reference to the simple underlying theories and also by reference to two early wind tunnels in order to highlight some design and operational features.

2. PRINCIPLES OF CRYOGENIC WIND TUNNELS

2.1 Fundamentals

While the ideas can be applied to almost any gas, with particular advantage in low speed testing where a wider range of possibilities opens up with the relaxation of a constraint on γ [10], in transonic tests where I believe we are constrained to using diatomic gases there is little if anything to be gained from gases other than air or nitrogen, which the following comments assume.

The basics can be introduced very simply by substituting into the Reynolds number expression

$$\text{Reynolds number } R = \frac{\rho V \ell}{\mu}$$

density ρ in terms of pressure and temperature T from the ideal gas equation of state, velocity V as the product Mach number and speed of sound, and viscosity μ by the approximation $\mu \propto T^{0.9}$. The advantage in terms of Reynolds number of cooling a gas may be conveniently written as a ratio, that is the ratio of the Reynolds number at reduced temperature T to that in the same gas at normal temperature T_1, other factors such as model size ℓ, flow Mach number M and pressure P remaining constant.

The resultant expression is

$$\text{Reynolds number ratio} = \left(\frac{T_1}{T}\right)^{1.4}$$

the value of the ratio depending on the choice of the higher temperature which might be typically about 320K in a continuous tunnel, and on the factors limiting the lower temperature. The lower limit is not necessarily completely defined. It depends on the test Mach number, on the equilibrium saturation boundary of the gas and therefore on the test pressure, but also on the amount of supersaturation permissible in the flow, which may prove to be size- or model-dependent. It should be mentioned that controlled levels of supersaturation have been exploited in hypersonic tunnels for years without adverse effects. During the life of the cryogenic wind tunnel the phenomenon has been the subject of research, because the rewards in terms of Reynolds number and in other respects can be quite useful. There is strong evidence that it is safe to approach the saturation boundary in the free stream ahead of the model. If this is adopted along with a Mach 1 test then the ratio takes the approximate maximum values

6.4 at 1 atmosphere stagnation pressure

5.0 at 5 atmospheres stagnation pressure.

In either case it can be seen that the factor is nicely in accord with the needs outlined in the preceeding section.

The issue of pressure should be discussed because it has been already in relation to other tunnels. A measure of the effect of test pressure on model aerodynamic loads is the dynamic pressure $\frac{1}{2}\rho V^2$, other factors such as Mach number, size and lift coefficient remaining constant. Similar substitutions as above lead immediately to the expression

$$\tfrac{1}{2}\rho V^2 = \frac{\gamma}{2} pM^2$$

showing that temperature does not affect dynamic pressure. Therefore the increase of Reynolds number which accompanies reduction of temperature is not at the expense of load, at least to a first order.

Particularly if the tunnel is to be driven by a fan there is interest in the influence of temperature on the required power. Fan drive power can be written

$$\text{power } p = \lambda \tfrac{1}{2}\rho V^3 A$$

where A = test section flow area and λ is a coefficient which varies primarily with the tunnel design and the flow Mach number.

For a given tunnel, Mach number and pressure, this simplifies to

$$p \propto \sqrt{T}$$

showing that fan power reduces as Reynolds number is increased by means of reduced temperature.

2.2 Cooling

There are two basic methods open for exploitation. One is the near-isentropic expansion of a gas from high pressure storage to the test stagnation pressure. The gas may be fairly cool in storage but is further cooled in the expansion process, and then used in the tunnel. The expansion pressure ratios required in isentropic processes are easy to calculate. With a diatomic gas beginning at room temperature a pressure ratio of 40 is required to expand to 100K. Several projects fall into this category and will be discussed in Paper 16.

The alternate is to inject a cryogenic liquid (perhaps produced in plant separate from the tunnel, but stored alongside) into the test gas, using the latent heat of the coolant and in some circumstances an appreciable component of sensible heat. It is common to use liquid nitrogen although combinations of nitrogen and oxygen could be used, at the cost of some complication, if there was a strong need to retain an air mixture. The quantity of liquid nitrogen needed as a coolant may be calculated with reasonable precision from the approximate expression

$$\text{cooling effect of } LN_2 \simeq 100 + 1.2\, T_0 \text{ kJ/kg}$$

where T_0 is the tunnel stagnation temperature. A more precise expression is available[11].

This 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. For tunnels operating at 100K, in the former case the exchange rate, LN_2 flow rate to fan power, is 0.0045 kg/sec per kW., and in the case of the induced flow tunnel supplied with air at 300K the ratio of LN_2 flow rate to inducing air flow rate is about 0.9. There is also the need to account for the cooling of at least a proportion of the tunnel structure, the proportion depending on the thermal insulation scheme and on run time. However the exchange rate, expressed as the ratio of LN_2 mass to structure mass, in cooling from 300K to 100K is about 0.25.

Additional coolant is required to absorb heat inflow through insulation. The quantity required is strongly design- and run-time dependent and it is difficult to provide very general information. However the specific example of the Langley 0.3 Meter Transonic Cryogenic Tunnel(12) may be cited for guidance. In this recent reference the proportion of LN_2 consumption estimated as attributable to heat inflow is 1½% of the total. While the authors naturally are guarded about the general applicability of the information, as I must be, it is nevertheless a useful guide to expectations for fan driven transonic tunnels. One estimate for low speed tunnels(13) attributes up to 10% of the LN_2 consumption to heat leakage.

While the total 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 cryogenic wind tunnel is appreciably less than a conventional tunnel when comparisons are made on the basis of equal pressure, Mach and Reynolds numbers.

2.3 Controlled Variables

The cryogenic wind tunnel has, in contrast to a conventional tunnel working at essentially constant temperature, the new controllable variable of temperature which can be exploited in a way which is not always immediately apparent. The last comment is made with confidence because those of us who were involved in the earliest days did not see the point for a while.

The cryogenic pressure tunnel has the three independently controllable test variables of speed, pressure and temperature. These may be used in various combinations to control the Mach and Reynolds numbers of the test. In principle only two of the variables are needed and therefore the third is free to be used to control some other feature of the test conditions. The potential usefulness of this freedom is in controlling the loads on a model and its consequent aeroelastic deformation, because in some testing the variations of data due, say, to Reynolds number effects can be clouded by the aerodynamic consequences of the deformation. It is usual therefore to regard the three variable test conditions as controlling the Mach number, the Reynolds number and the dynamic pressure. Through the independent control of dynamic pressure there is independent control of model shape (at least to a first order) which is a unique feature of the cryogenic wind tunnel and is particularly important in transonic tests where stresses and deflections can be large.

2.4 Energy Recovery

Despite the quite enormous savings in capital costs and significant reductions in energy consumption offered by the cryogenic wind tunnel in relation to competing continuously-running designs, viewers of the cryogenic wind tunnels now in operation quite often look at the exhaust plume and ruminate on the possibilities of recovering in some way the "cold" and the energy so represented. The notion is as old as the cryogenic wind tunnel and it is quite proper for it to be kept in mind. There is much scope for inventiveness and there are many possible recovery schemes.

An essential feature must be practicality in the light of the duty cycle of the tunnel. Typically the tunnel is used only intermittently, rather unpredictably and then with strongly varying conditions. The user will not want to have a test compromised significantly by the recovery scheme. These considerations eliminate some possibilities. In particular I think those which aim to recover cold gas or liquid from a pressurised tunnel for recycling, either of which are possible in principle, are impractical for application to wind tunnels.

However, to illustrate the possibilities, the following is an outline of one scheme which might offer useful energy savings while having the necessary responsiveness. The notion, applicable perhaps to the fan driven pressurised tunnel, is merely to expand the exhausting nitrogen gas through a turbine. Calculations using idealised thermodynamics and neglecting flow losses are summarised on Figure 2, where the power output available from the turbine is shown in relation to the tunnel's fan power as a function of tunnel temperture and pressure. The LN_2 flow rate into the tunnel is assumed just that required to absorb fan power. The recovery expressed in this way is independent of test Mach number. There are two sets of curves, the lower full curves assuming the exhausting gas to be expanded directly from the tunnel, the other broken curves assuming the gas to be first heated to ambient temperature in a heat exchanger before expansion. It can be seen that quite a large proportion of the motor power is recoverable under some conditions, perhaps 30% with the gas warmed to room temperature at high pressure. While the maximum proportion of recoverable power

rises as tunnel temperature falls, in fact the absolute value of turbine power for a particular tunnel, pressure and Mach number is roughly constant. Idealised calculations usually are expected to overestimate, but in this case there is the additional factor of LN_2 flow for heat leakage and for cooldown which would raise flows and perhaps leave the power forecasts on Figure 2 not too far from realistic.

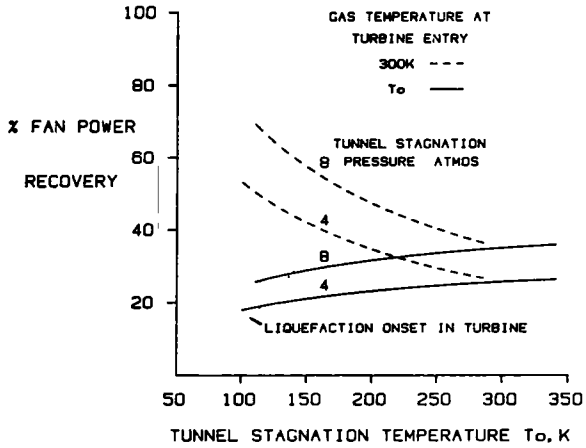

Figure 2: Energy recovery by expansion of tunnel exhaust gas in a turbine, relative to tunnel drive power. Ideal expansion from a fan driven tunnel.

There are of course many practicalities to be considered alongside thermodynamic cycles, in this scheme these include the control of flows and turbines, and the effects of re-liquefaction near the outlet of the turbine. The costs and complexities of the additional hardware must be weighed against any reduction in the direct running cost and motor and land-line capital costs. These comments will apply to any such energy recovery scheme.

3. NOTES ON A CRYOGENIC LOW SPEED AND A CRYOGENIC TRANSONIC WIND TUNNEL

3.1 As an introduction to cryogenic wind tunnel design and operation, subjects which will be expanded upon in later lectures, I am using the example of the 0.1m cryogenic wind tunnel at Southampton University[14]. This was built originally for an investigation into the possibilities for surface flow visualisation at low temperature. It ran in 1977 and was used successfully for that task[15]. Since then it has been further developed (with material help from NASA under Grant NSG-7172) and used in a series of Undergraduate final year projects (titles appear in the Appendix), the most recent aimed at bringing the tunnel to the point where it is suitable for the teaching of fundamental aerodynamics, in particular the demonstration of Reynolds number effects.

I believe the existence of this size of tunnel represents a double need, a need for economical instruction in cryogenic testing, and for the economical development of instrumentation and other devices for use in other larger tunnels.

The tunnel is closed circuit, unpressurised, fan-driven and cooled by liquid nitrogen sprayed into the circuit just downstream of the test section. At low temperature the test gas is therefore nitrogen; at room temperature and above it is usually air. There is a chimney to carry exhaust gas out of its building. The test section is 4 inches (102mm) square, and the overall dimensions are 7½ feet (2⅓m) long by 3½ feet (1.1m) high, with the circuit centreline in the vertical plane. The drive motor of 4kW has a variable frequency power supply driving the fan at up to 7,200 r.p.m. The principal materials of construction are aluminium and fibreglass.

Aside from the obvious differences between a cryogenic tunnel and one of similar design for use at normal temperature, such as the need for circuit insulation and a sensible choice of materials, the only significant difference in this tunnel lies in the design of a bearing housing. The bearing is inside the circuit and supports the fan. The housing, sketched on Figure 3, is thermally insulated and heated with two 250W cartridge heaters, the temperature being controlled at a 50 deg. C set point by a thermocouple-activated relay. The tunnel has other heaters in its circuit to warm it more quickly following a cryogenic run and incidentally allowing the tunnel to run at elevated temperature.

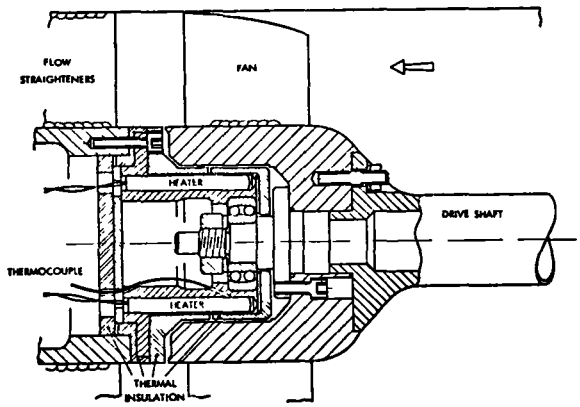

Figure 3: 0.1m low speed cryogenic wind tunnel at the University of Southampton. Fan and heated bearing.

The available variations of fan speed and gas temperature provide test Mach numbers up to 0.4 and unit Reynolds numbers up to 50 millions per metre. Of value in teaching is the wide range of Reynolds number, the ratio of the maximum to the minimum usable values being close to 100:1. The operating envelope, which is in most respects typical of a low speed atmospheric pressure cryogenic tunnel, is shown on Figure 4.

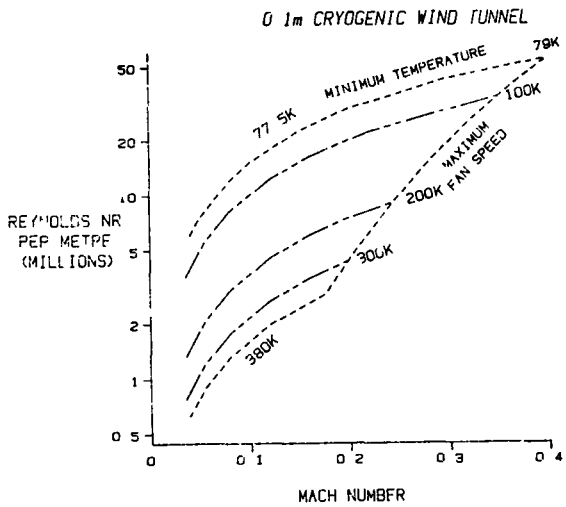

Figure 4: Operating envelope.

Test conditions can be manoeuvred to any point inside the envelope, to the high temperature boundary by use of the circuit heaters. The tunnel has a microcomputer-based control and data logging system. The computer is a Commodore PET with a multi-function interface (A-D, D-A and relay switching), acquiring temperature, pressure and other data, and providing closed-loop control of the tunnel and the experiment through relays and D-A. The cycle time of the controller is approximately 4 seconds. A block diagram of the complete system is shown on Figure 5, together with an outline of the tunnel circuit.

The operator can select one of a variety of control modes. For example he can select a Mach number hold (say while temperature is being changed: in this case a decrease in temperature is accompanied by a decrease in fan speed in proportion to the decrease in the speed of sound) or select constant Reynolds number or constant temperture, all within the confines of the envelope of Figure 4. Temperature may be controlled manually, or automatically by switching the circuit heaters. An example of the locus of a typical one hour run is on Figures 6. Figure 6(a) shows temperature and fan speed, the controlled variables, changing through the run in apparent disorder. However for much of the run time they were in fact varying in response to the operator's demands (which were changed from time to time) for certain constant values of Mach or Reynolds numbers, or for constant temperture.

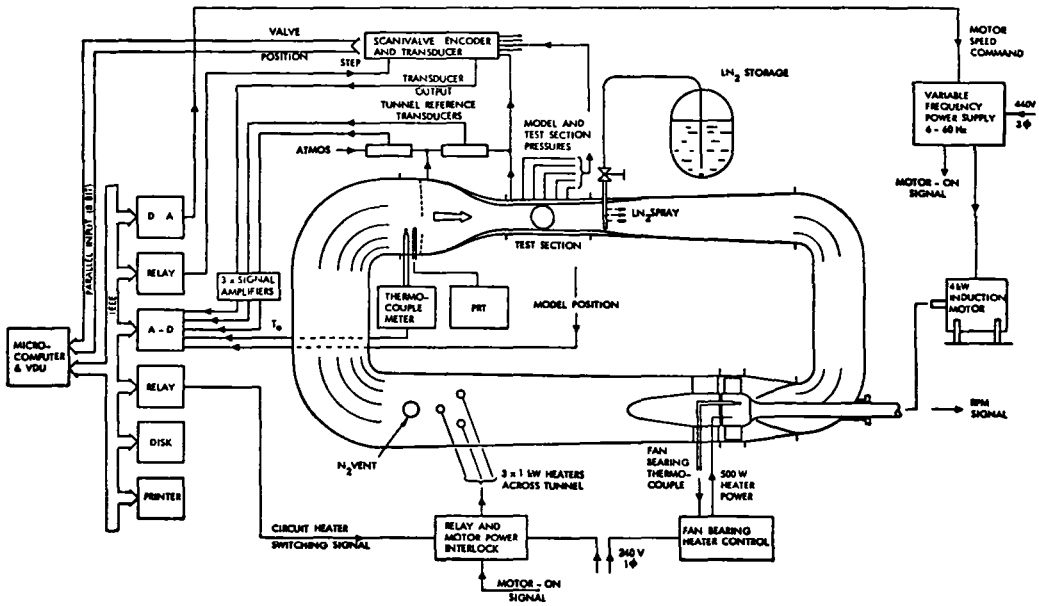

Figure 5: Cryogenic wind tunnel systems block diagram.

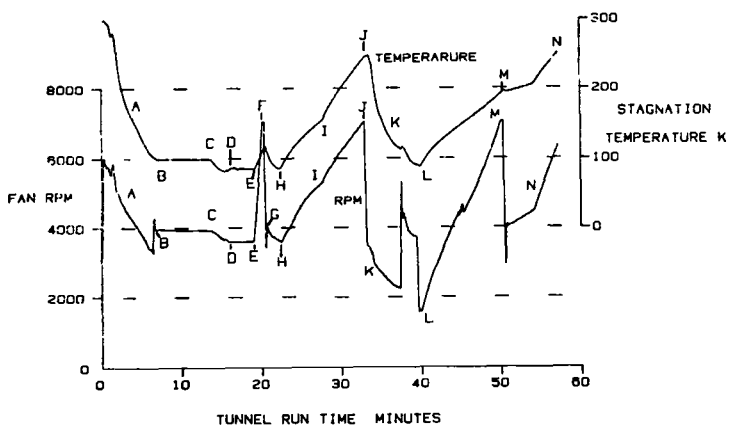

Figure 6(a): The variations of fan speed and stagnation temperature during a typical one-hour run, in response to the pattern of demands from the operator, illustrated in Figure 6(b), for changes in Mach and Reynolds numbers.

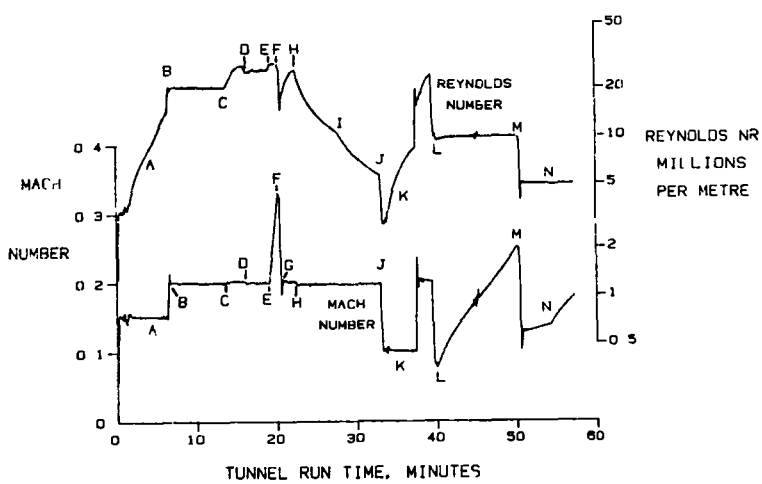

Figure 6(b): Mach and Reynolds numbers selected by tunnel operator.

Features of the traces on Figure 6(a) are labelled. These may be related to the labels on Figure 6(b) which shows the corresponding variations of Mach and Reynolds numbers. The traces (plotted from the run data file, complete sets of data having been sampled about every 4 seconds) have been analysed statistically in selected areas. Table 1 summarises events and, where a parameter is being held constant, shows the standard deviation of that parameter through the period.

Table 1: An outline of events during the one-hour run illustrated on Figure 6, with the standard deviations of controlled parameters

Activity	Period			Value of controlled parameter			Standard deviations		
	Label	Seconds	**	Mach no	Reynolds no *	Temperature K	Mach no	Reynolds no *	Temperature K
7 minute cooldown, 299K-99K at constant Mach no	A	366	82	15	-	-	0 0024+	-	-
Steady tunnel conditions	B-C	401	89	.2	20 4	99	0 0005	0 115	0.274
Period of constant demanded Mach no	B-E	724	156	2	-	-	0 0009	-	-
Steady tunnel conditions	D-E	185	54	2	25 9	85	0.0007	0 372	0 707
Warmup, LN_2 off, 85K to 111K at constant Reynolds no.	E-F	59	14	-	28 5	-	-	0.127	-
Cooldown to 85K at constant Mach no.	G-H	97	22	2	-	-	0 0009	-	-
Warmup, LN_2 off, 85K to 245K, constant Mach no (circuit heaters on at 1)	H-J	639	141	.2	-	-	0.0008	-	-
Constant demanded Mach no during temperature changes	G-J	736	162	.2	-	-	0 0017	-	-
4 minute cooldown, 247K-113K at constant Mach no	K	246	54	1	-	-	0 0013	-	-
Warmup, LN_2 off, 89K-190K at constant Reynolds no	L-M	619	140	-	9.9	-	-	0.171	-
Warmup, LN_2 off, 195K-250K at constant Reynolds no	N	359	81	-	5.0	-	-	0.023	-

** Number of samples analysed
* Millions per metre
\+ 0.0009 from 2 minutes into cooldown

This evidence shows that indicated Mach number can be held constant for useful periods of up to 10 minutes or more (long enough for the requirements of most aerodynamic tests at one tunnel condition) to a standard deviation of better than 0.001, rising only to about 0.002 during relatively rapid temperature changes. When Reynolds number was being controlled the standard deviation was 0.5% to 2% of the absolute value, which may be good enough. The limited information given in Table 1 on the constancy of temperature when under automatic control indicates a standard deviation of about 0.5 degrees. This is confirmed by other test data from 80K to 380K, which also shows that when temperature is manually controlled the standard deviation is worse, at 1 to 1.5K.

This example of a fairly typical run is intended to show several features:

1) the rapidity with which test conditions can be changed. This is not a feature of the control system in the case of this tunnel,

2) the versatility of digital control in allowing control over several selected test parameters. It should be mentioned also that automatic control is useful in easing considerbly the workload of the operator,

3) the quality of control, which is seen to be good despite the fact that no attempt has been made to optimise the control algorithms.

There is one procedure which is carried out with ease under automatic control but which is probably quite difficult to do manually (although it has not been attempted manually on this wind tunnel). That is the holding of constant Reynolds number by continuously adjusting the fan speed while temperature is ramped slowly up or down. This is the way in which variations of test Mach number are introduced at constant Reynolds number. The example is presented because as yet there are so few fan-driven cryogenic tunnels in service for which analyses of such information is available.

A final point on temperature and its control. It is fairly natural that this should be an emotive subject in relation to the cryogenic wind tunnel. However it should be noted that the precision with which the long-term (and possibly the short-term) variations of stream temperature are now being controlled is much better in the case of the cryogenic wind tunnel than is possible in most conventional transonic or subsonic wind tunnels. This is probably as it should be, and the precision which was demanded is just another consequence of the cryogenic wind tunnel being born into an age when new standards are being set.

3.2 The 0.3m Transonic Cryogenic Tunnel at NASA Langley Research Center

This wind tunnel is singled out for special mention because of the outstanding record of the tunnel and those people associated with it, in promoting the acceptance of the concept of cryogenic testing.

First some historical facts. the tunnel was designed, built and run inside a year with the vigour characteristic of the US nation, with a main objective of proving the concept by demonstrating at transonic speeds what we now accept, and which with the benefit of hindsight even seems odd to question, that Reynolds number obtained by temperature is the same as Reynolds number obtained by other means. The evidence was quick to arrive, leading also in a short time to the decision by the U.S. to adopt the concept for their large high Reynolds number transonic tunnel which is now running and known as NTF. Since its proof-of-concept days 0.3m has been fitted with a two-dimensional test section and for years has been used for routine testing at chord Reynolds numbers up to 70 millions. The tunnel is run two shifts a day and at the time of writing is still the only cryogenic wind tunnel which has been used on a routine basis for production aerodynamics. The total running time is now in excess of 5000 hours, a large proportion of which has been at cryogenic temperatures. During this time it has pioneered the art and science of testing, of control, instrumentation, model making, safety and construction of the fan-driven transonic pressure tunnel. 0.3m has done more than any other tunnel to convince the world of the merits of the cryogenic concept, while at the same time providing a mass of aerodynamic and operational data. This achievement is in my opinion a fine tribute to the engineers who evolved the concept, to the administrators who backed the venture, to the designers and to the engineers who have since come along and carried out the day-to-day operating, maintenance and updating of the tunnel.

Now to close, a cautionary note. The aim of the cryogenic wind tunnel is to make a step forwards in the quality of aerodynamic testing by bridging the Reynolds number gap. In doing so we must be sure that we do not introduce inadvertently some feature which tends to degrade the potential for improvement in quality. We are here to learn, from experts in the field, of the measures being taken around the world to introduce the tunnel into more general use following the lead of 0.3m, measures ensuring the proper contribution of the cryogenic wind tunnel to a general trend towards excellence in the discipline of experimental aerodynamics.

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APPENDIX

UNDERGRADUATE PROJECTS WITH THE 0.1M CRYOGENIC WIND TUNNEL AT THE UNIVERSITY OF SOUTHAMPTON

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