

CRYOGENIC WIND-TUNNEL TECHNOLOGY

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SUMMARY

As a result of theoretical studies and experience gained during the development and operation of both a low-speed cryogenic tunnel and the Langley 0.3-m transonic cryogenic tunnel, the cryogenic wind tunnel has been shown to be a practical concept and to offer many advantages with respect to achieving full-scale Reynolds number in a moderate size tunnel at reasonable levels of dynamic pressure. After a brief review of the cryogenic concept, this paper presents some of the aspects which must be considered during the development of a cryogenic wind tunnel that uses gaseous nitrogen as the test gas. Based on work by Adcock, it is shown that even though the values of the compressibility factor and the ratio of specific heats of nitrogen depart significantly from their ideal-gas values at cryogenic temperatures, both the isentropic flow parameters and the normal-shock flow parameters are insignificantly affected by these real-gas effects. Based on work by Hall, it is shown that it is possible to operate at stagnation temperatures even lower than those corresponding to the free-stream saturation boundary without encountering condensation effects. Should this mode of operation be possible for arbitrary models, an additional increase in Reynolds number of about 17 percent may be realized at a given operating pressure. Alternatively, for a given Reynolds number, operating at the free-stream saturation boundary temperature will allow testing at reduced pressure, drive power, and liquid nitrogen consumption.

INTRODUCTION

The cryogenic wind tunnel is a relatively new aerodynamic research tool. The first cryogenic tunnel was built at Langley in 1971. Although the demonstrated application to wind tunnels is relatively recent, it is interesting to note that the science of cryogenics, just as the wind tunnel itself, dates back to the previous century. As will be discussed, the technology developed has been very valuable in the present application.

Historically, capital and operating costs have tended to keep transonic tunnels small, while the host of problems encountered at high pressures have tended to keep operating pressures low. The net result has been that existing (ambient temperature) tunnels operate at Reynolds numbers which are too low to insure adequate simulation of the flow experienced in flight - particularly with regard to shock - boundary-layer interactions encountered on modern high subsonic and transonic aircraft. The application of cryogenics to wind tunnels

has thus been brought about by the need for higher test Reynolds numbers in tunnels of reasonable size operating at reasonable pressures.

Although the study which started in the fall of 1971 was directed toward application of the cryogenic concept to increase the Reynolds number capability of a small wind tunnel equipped with a magnetic suspension and balance system, the advantages and possibility of applying the concept to a large transonic tunnel were recognized at that time. In the late 1960's and early 1970's there were several transonic tunnel concepts being studied in the United States which were to provide this country with a greatly increased Reynolds number capability. Because the cryogenic tunnel concept avoided many of the shortcomings of the various competing ambient-temperature tunnel concepts, our efforts for the past five years have been spent full time on the cryogenic tunnel concept and only now are we resuming our work on magnetic suspension and balance systems.

SYMBOLS

a	speed of sound
c	chord of two-dimensional airfoil
\bar{c}	mean geometric chord
l	linear dimension of model or test section
M	Mach number
p	pressure
R	Reynolds number, $\rho V l / \mu$
R	Universal gas constant
T	temperature
V	velocity
v	specific volume
Z	compressibility factor, $Z = pv/RT$
γ	ratio of specific heats
μ	viscosity
ρ	density

Subscripts:

c	based on c
\bar{c}	based on \bar{c}
L	local conditions
max	maximum
t	stagnation conditions
1	upstream
2	downstream
∞	free stream

THE CRYOGENIC CONCEPT

The use of low temperatures in wind tunnels was first proposed as a means of reducing tunnel drive-power requirements at constant values of test Mach number, Reynolds number, and stagnation pressure. Reynolds number, which is the ratio of the inertia force to the viscous force, is given by

$$R = \frac{\text{Inertia force}}{\text{Viscous force}} = \frac{\rho V^2 \ell^2}{\mu V \ell}$$

which reduces to the well-known equation

$$R = \frac{\rho V \ell}{\mu} = \frac{\rho M a \ell}{\mu}$$

As the temperature is decreased, the density ρ increases and the viscosity μ decreases. As can be seen from these equations, both of these changes result in increased Reynolds number. With decreasing temperature, the speed of sound a decreases. For a given Mach number, this reduction in the speed of sound results in a reduced velocity V which, while offsetting to some extent the Reynolds number increase due to the changes in ρ and μ , provides advantages with respect to dynamic pressure, drive power, and energy consumption.

It is informative to examine the underlying mechanism through which changes in pressure and temperature influence Reynolds number. To the first order μ and a are not functions of pressure whereas ρ is directly proportional to pressure. Thus, increasing pressure produces an increase in Reynolds number by increasing the inertia force with a commensurate increase in model, balance, and sting loads. Also, to the first order, $\rho \propto T^{-1}$, $V \propto T^{0.5}$, and $\mu \propto T^{0.9}$. Thus, decreasing temperature leaves the inertia force unchanged at a

given Mach number because of the compensating effects of temperature on ρ and V^2 . The increase in Reynolds number with decreasing temperature thus is due strictly to the large reduction in the viscous force term as a result of the changes in μ and V with temperature.

The effect of a reduction in temperature on the gas properties, test conditions, and drive power are illustrated in figure 1. For comparison purposes, a stagnation temperature of 322 K (120° F) for normal ambient temperature tunnels is assumed as a datum. It can be seen that an increase in Reynolds number by more than a factor of 6 is obtained with no increase in dynamic pressure and with a large reduction in the required drive power. To obtain such an increase in Reynolds number without increasing either the tunnel size or the operating pressure while actually reducing the drive power is extremely attractive and makes the cryogenic approach to a high Reynolds number transonic tunnel much more desirable than previous approaches.

ASPECTS CONSIDERED DURING CRYOGENIC TUNNEL DEVELOPMENT

Planning for the design of a cryogenic wind tunnel falls into two basic areas. First is the area of fluid dynamics. There is a question as to whether the test gas at cryogenic temperatures will provide data from the wind tunnel (e.g., forces, moments, and pressures on the model) which can be used to predict the loads and aerodynamic characteristics of the full-scale vehicle in free flight. The second area includes the design of the tunnel and its operation at cryogenic temperatures. Figure 2 lists the items under the areas of "Fluid Dynamics" and "Design and Operation."

Fluid Dynamics

The first item under Fluid Dynamics is "Knowledge of gas properties." Its obvious that one needs to know such things as the speed of sound and the viscosity of the test gas. Although nothing thus far in the operation of the low-speed cryogenic tunnel (ref. 1) or the Langley 0.3-m transonic cryogenic tunnel (ref. 2) has indicated that existing values for any given property of nitrogen are not sufficiently accurate, the magnitudes of some of the probable errors are somewhat larger than one would like, especially at the high pressures proposed for the NTF. In order to be sure there are no problems in this area, Langley is funding work at the Cryogenics Division of the National Bureau of Standards (NBS) in Boulder, Colorado, which will improve our knowledge of the properties of nitrogen, especially at the higher pressures, and at the same time provide a simplified equation of state limited to the range of temperatures and pressures of interest for cryogenic wind tunnels.

Jerry Adcock is in charge of the area of "Proper flow simulation" which, as indicated in the figure, includes both analytical and experimental work. The early experimental work was done in the low-speed tunnel at atmospheric pressure whereas the recent work has been done at pressures up to 506.5 kN/m² (5 atm) in the Langley 0.3-m transonic cryogenic tunnel.

Typical of the analytical studies being made (ref. 3) are those related to isentropic expansions and normal-shock flows in nitrogen. First, the thermodynamic properties for nitrogen were obtained from an NBS program based on work by Jacobsen (ref. 4). The NBS program was then modified so that isentropic expansions could be made. The various ratios which describe an isentropic expansion were then calculated by using the real-gas properties of nitrogen and were compared with ratios derived from ideal-gas equations and ideal values of the compressibility factor ($Z = 1$) and the ratio of specific heats ($\gamma = 1.4$) for a diatomic gas. An example of the results is presented in figure 3, where the ratio of the real and ideal pressure ratios necessary to expand isentropically to $M = 1.0$ is presented as a function of tunnel stagnation temperature and pressure. As can be seen, the real-gas effects are extremely small and, for $R_{\bar{C}} = 50 \times 10^6$ at cryogenic temperatures, the real-gas pressure ratio differs from the ideal-gas pressure ratio by only about 0.2 percent. It is interesting to note that the real-gas effect at cryogenic temperature is actually less than the real-gas effect at ambient temperatures, where for the same size test section a considerably higher stagnation pressure is required to obtain $R_{\bar{C}} = 50 \times 10^6$.

The other real-gas ratios used to describe an isentropic expansion in nitrogen also differ from the ideal-gas ratios by this same small percentage. In many cases, such as the determination of tunnel Mach number, the real-gas equations can be used to avoid even this small error of 0.1 percent to 0.2 percent. However, errors of such magnitude are of the same order as the uncertainty in measurements and would be considered insignificant in most wind-tunnel work.

For the normal-shock flow studies, Adcock modified the NBS program so that the various ratios which describe normal-shock flow could be calculated by using the real-gas properties, and compared these with the corresponding ideal-gas ratios. An example of the results is shown in figure 4 where the ratio of the real to the ideal static pressure ratio across a normal shock is shown as a function of tunnel stagnation temperature at stagnation pressures of 101.3 and 506.5 N/m² (1 and 5 atm). As in the case of isentropic expansions, the effects are extremely small, and for $R_{\bar{C}} = 50 \times 10^6$, the real pressure ratios differ from the ideal-gas pressure ratio by only about 0.2 percent. The other real-gas ratios associated with normal-shock flow in nitrogen also differ from the ideal ratios by this same small percentage. As in the case of isentropic expansion, even in those situations where the real-gas equations cannot be used to take these effects into account, an error of this magnitude would usually be considered insignificant. Thus, even though the values of Z and γ for nitrogen depart significantly from their ideal-gas values at cryogenic temperatures, both the isentropic flow parameters and the normal-shock flow parameters are insignificantly affected by these real-gas effects.

Design and Operation

In figure 2, under the heading "Design and Operation", are listed several areas which, depending on the type of cryogenic tunnel being considered, will receive various amounts of attention. Each of these areas has been covered to some extent in previous publications so it will not be necessary to consider

them here. The one area that will be discussed briefly is "Condensation," which is being studied here at Langley under the direction of Robert Hall.

As shown in figure 5, the test Reynolds number increases rapidly as temperature is reduced. Marked on the curve of Reynolds number against temperature are three "boundaries" which, for the conditions of this example are set by a maximum local Mach number over the model of 1.2, a free-stream Mach number of 0.85, and a settling chamber Mach number of 0. As reported in detail by Hall (ref. 5), effects of condensation were not seen on the airfoil used for these tests until the tunnel was operated at temperatures below those associated with free-stream saturation. His results indicate that for a given size tunnel and model and for a constant tunnel pressure, an additional increase in test Reynolds number of about 17 percent may be realized by operating at temperatures corresponding to those of the free-stream saturation boundary.

Another way to take advantage of being able to operate beyond the local saturation boundary would be to reduce the operating pressure for testing at a given Reynolds number. This should be of considerable practical importance for the NTF with its extremely high (by present standards) operating pressures. If the minimum operating temperature in the NTF can be reduced from the present arbitrary limit (corresponding to a saturation boundary based on an assumed local Mach number of 1.4) to a lower temperature without condensation effects occurring, then the tunnel operating pressure can be lowered correspondingly. And, of course, when the operating pressure is reduced, both drive power and LN₂ consumption are also reduced.

As can be seen from figure 6, if operation is possible at temperatures corresponding to free-stream saturation, tunnel pressure can be reduced by about 15 percent (from 895.5 to 760.8 kN/m² (8.84 to 7.51 atm)) and LN₂ flow rate, which is directly related to operating costs, is reduced by about 16 percent.

SOURCES OF INFORMATION

Relative to the cryogenic tunnel development areas listed in figure 2, several sources of information have been found useful and are generally available. Since there is familiarity with the design of ambient temperature tunnels, sources related to the aerodynamics of tunnel design are not listed. The problem is really one of applying good cryogenic engineering to the type of tunnel required.

In the United States the best source of information by far on the cryogenic aspects of a cryogenic tunnel are the publications and people of the Cryogenics Division of the National Bureau of Standards. Although the cryogenic wind tunnel is a recent application of cryogenic technology, most of the information needed on materials, insulation, instrumentation, liquid nitrogen systems, safety, and so forth has been documented by the NBS and is readily available. If there is need to know something that is not documented, the chances are excellent that the NBS Cryogenic Division can be of help.

In addition to the NBS and the work being done here at Langley in the 0.3-m transonic cryogenic tunnel and on the NTF design, there are several other places where cryogenic tunnels are being designed and built. Figure 7 lists the various tunnels and provides information about each of the projects such as the size of the test section, the type of tunnel, the location, and the actual or anticipated date of operation. As one can see, there is considerable activity going on around the world related to the development and use of cryogenic wind tunnels. Since this is such a new field, one must keep informed as to what is going on, not only on his own projects, but around the world, if duplication of effort is to be avoided and the full potential of the cryogenic wind tunnel is to be realized as quickly as possible.

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5. Hall, Robert M.: An Analysis of Data Related to the Minimum Temperatures for Valid Testing in Cryogenic Wind Tunnels Using Nitrogen as the Test Gas. NASA TM X-73924, 1976.

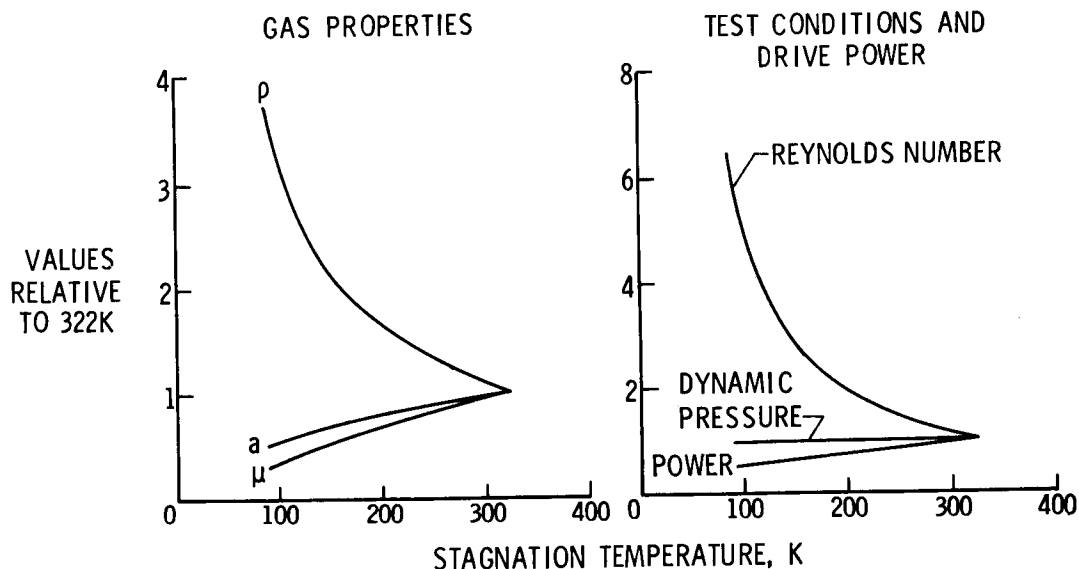


Figure 1.- Effect of temperature reduction on gas properties, test conditions, and drive power. $M_\infty = 1.0$; constant stagnation pressure and tunnel size.

- Fluid dynamics
 - Knowledge of gas properties
 - Proper flow simulation
 - ➔ ● Analytical
 - Experimental
 - Low-speed tunnel
 - Transonic tunnel
- Design and operation
 - Materials of construction
 - Drive system
 - Insulation
 - Method of cooling
 - Vent system
 - Models
 - Instrumentation
 - Operating procedure
 - Tunnel dynamics
 - ➔ ● Condensation
 - Safety

Figure 2.- Some aspects considered during cryogenic tunnel development.

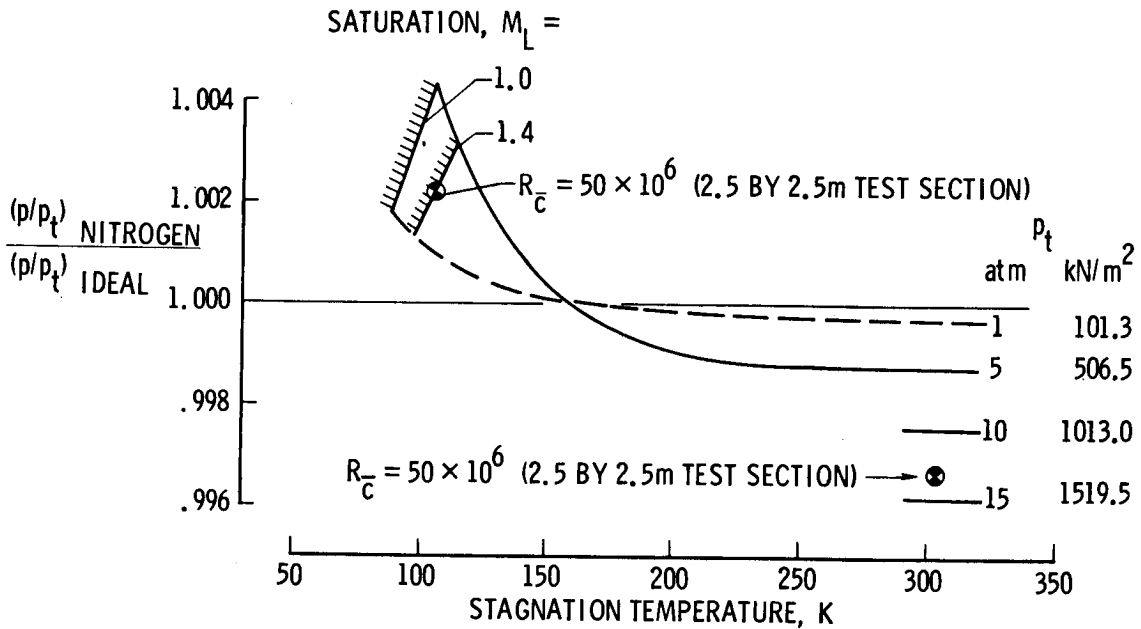


Figure 3.- Isentropic expansion pressure ratio of nitrogen.
Pressure ratio p/p_t ; $M_\infty = 1$.

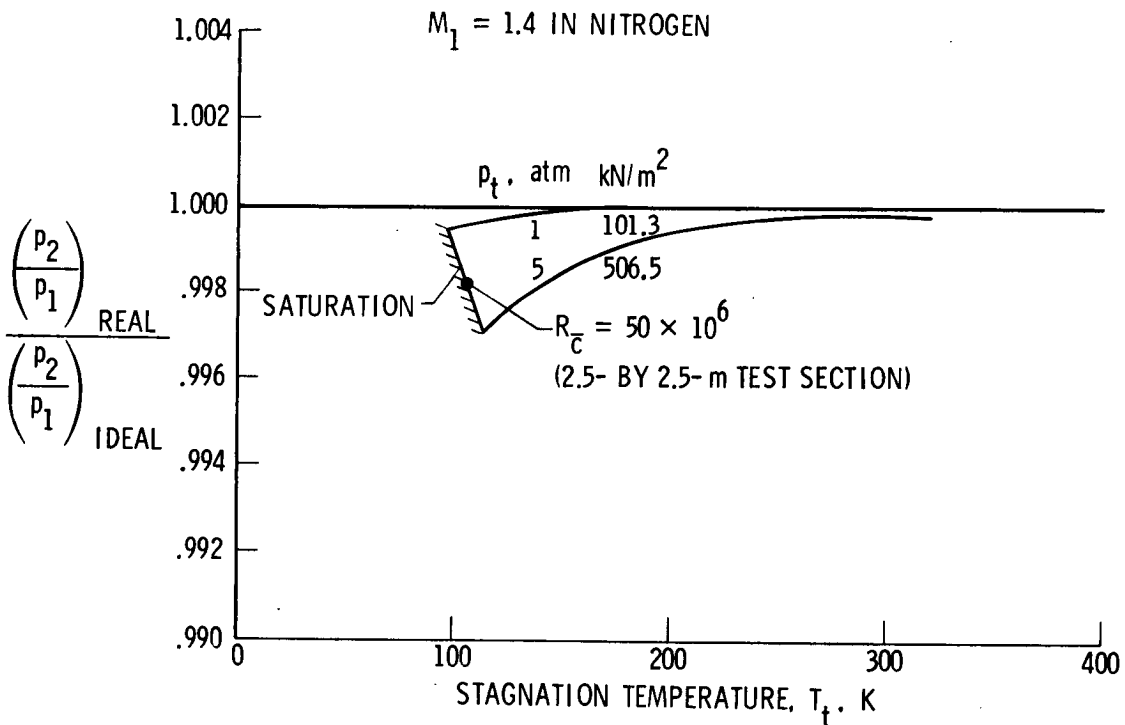


Figure 4.- Normal shock pressure ratio in nitrogen.

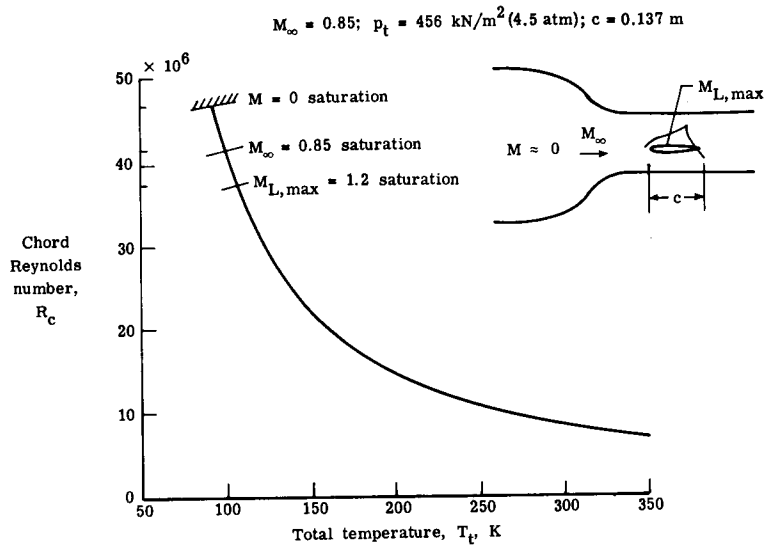


Figure 5.- Potential benefits of operation below saturation temperature.

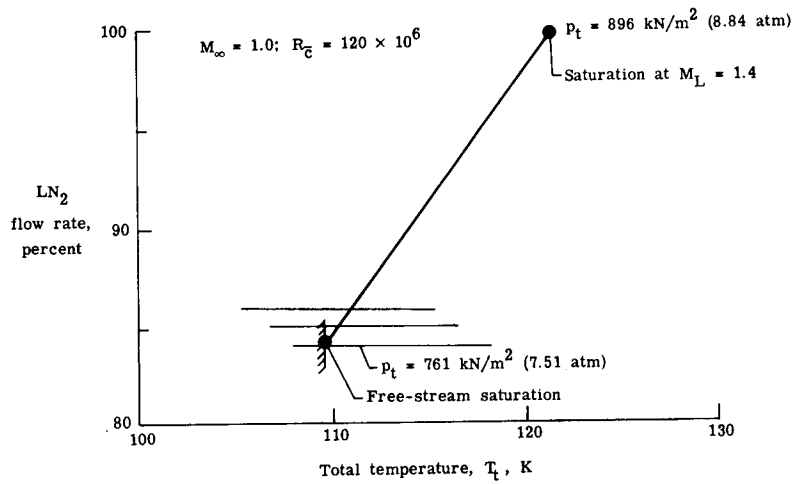


Figure 6.- LN_2 consumption as a function of temperature.

● <u>Initial</u>				
	0.178 × 0.279 m	Low-speed/fan	NASA-LRC	1972
● <u>Present</u>				
	0.3 m	Transonic/fan	NASA-LRC	1973
	0.10 × 0.10 m	Low-speed/fan	University of Southampton	1977
● <u>Studies of conversion of existing tunnels</u>				
	0.30 × 0.30 m	TWT/blowdown	McDonnell - El Segundo	1977
	1.22 × 1.22 m	TWT/blowdown	McDonnell - El Segundo	1978
	1.22 × 1.22 m	Transonic/blowdown	British Aircraft Corp.	----
● <u>Design of new cryogenic tunnels</u>				
	2.5 × 2.5 m	Transonic/fan	NTF (Langley)	1981
		Transonic/Ludwig tube	DFVLR - AVA (Holland)	----
	1.4 × 1.4 m	Transonic/blowdown	FFA (Germany)	----
	1.6 × 2 m	Transonic/fan	LEHRT (AGARD)	----

Figure 7.- Some sources of cryogenic tunnel design and operational experience.