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SPECIFIC COOLING CAPACITY OF LIQUID NITROGEN

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ABSTRACT AND SUMMARY

When cryogenic nitrogen wind tunnels are cooled by injecting liquid nitrogen directly into the tunnel, the specific cooling capacity of the nitrogen consists of the heat absorbed in warming and vaporizing the liquid plus the heat absorbed in warming the gaseous nitrogen to the tunnel stagnation temperature. The specific cooling capacity of nitrogen has been calculated for a simplified model based on this method of cooling by using a National Bureau of Standards program for the thermodynamic properties of nitrogen and the results fitted with a relatively simple equation having tunnel stagnation pressure and stagnation temperature as the independent variables. This report describes the assumed cooling process, describes the method used to calculate the specific cooling capacity of liquid nitrogen, gives the simple equation fitted to the calculated specific cooling capacity data, and presents in graphical form calculated values of the specific cooling capacity of nitrogen for stagnation temperatures from saturation to 350 K and stagnation pressures from 1 to 10 atmospheres.

INTRODUCTION

Based on theoretical studies and experience in the United States with the Langley 0.3-meter transonic cryogenic tunnel, the cryogenic wind tunnel concept, using nitrogen as the test gas, has been shown to offer many advantages with respect to attaining full-scale Reynolds number at reasonable levels of dynamic pressure in tunnels of moderate size.[1,2] Because of the advantages offered by cryogenic operation, studies are underway for two large fan-driven cryogenic tunnels.

A cryogenic transonic tunnel, to be known as the National Transonic Facility (NTF) and to be located at the NASA Langley Research Center, will provide test Reynolds numbers up to 120 million* which is an order of magnitude increase in Reynolds number capability over existing U.S. tunnels.[3] Preliminary studies are also being made for a cryogenic transonic tunnel to meet the requirements of the European NATO countries. The proposed Large European High Reynolds Number Tunnel (LEHRT) will provide test Reynolds numbers of at least 40 million at transonic speeds.[4]

In addition to the usual aerodynamic and structural aspects of the wind tunnel, the designer of a cryogenic wind tunnel must also provide for the cryogenic systems which are unique to this new tunnel concept. In order to design properly the cryogenic systems associated with a cryogenic wind tunnel, it is necessary to know fairly accurately the amount of liquid nitrogen that will be required for both cool-down and operation of the tunnel. Also, since a major part of the direct operating cost of a cryogenic tunnel is the cost of the liquid nitrogen, it is essential to know the liquid nitrogen requirements in order to properly assess the operating costs.

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*Reynolds numbers quoted are based on a reference length of 0.1 times the square root of the test section area.

Experience with the Langley 0.3-meter transonic cryogenic tunnel[2] has shown that the amount of liquid nitrogen required for cool-down of the tunnel structure is predicted adequately by the method of Jacobs.[5,6]

The heat to be removed from the tunnel after cool-down and while it is running consists of the heat conducted through the walls of the tunnel from the surroundings, internal sources of heat such as heated actuators or internal strain gage balances, and the heat added to the tunnel circuit by the drive fan. With a knowledge of the design of the tunnel and the properties of the materials used in its construction, the heat conducted through the walls can be calculated with sufficient accuracy in a straightforward manner using standard heat transfer equations. Great accuracy in calculating the heat conducted through the walls is generally not required since, typically, the heat conducted through the walls amounts to only about 10 percent of the total heat to be removed at subsonic speeds and about 1 percent at transonic speeds.[7] The heat to be removed due to internal sources such as heated actuators or balances is generally small enough to be negligible.[8] If, under special circumstances, heat from these internal sources must be known, it may be determined experimentally or estimated from a detailed analysis of each source.

Calculating the heat added by the drive fan can also be done in a straightforward manner by using the method of Adcock and Ogburn[9] who, by taking into account the real gas properties of nitrogen, have determined the drive power required for isentropic compressions of cryogenic nitrogen. Their analysis, which covers stagnation temperatures from 80 to 310 K and stagnation pressures from 1 to 8.8 atmospheres, shows the power required to compress cryogenic nitrogen to be less than that calculated for an ideal diatomic gas by as much as 9.5 percent at the highest pressure. This reduction is, of course, in addition to the basic reduction in drive power with decreasing temperature, that is, power varies as the square root of the stagnation temperature.[1] The reader is thus advised to consult reference 7 for the proper method of calculating the heat added to the stream by the drive fan.

Once the total heat load is calculated, it is necessary to know the specific cooling capacity of liquid nitrogen in order to calculate the amount of liquid nitrogen required for tunnel operation. Very precise values of the specific cooling capacity can be obtained by suitable manipulation of the data contained in a National Bureau of Standards (NBS) computer program based on the work of Jacobsen.[10] However, because of th large size of the NBS program it is impractical to use for direct calculation of specific cooling capacity with relatively small desk-top programmable computers. Therefore a relatively simple equation which can easily be used with such digital computers has been fitted to the specific cooling capacity data determined from the NBS program.

This report describes the assumed cooling process, the method used to calculate the specific cooling capacity of liquid nitrogen from the NBS program, and gives a relatively simple equation for calculating specific cooling capacity as a function of tunnel stagnation values of temperature and pressure. In addition, the specific cooling capacity of nitrogen is given in graphical form for stagnation temperatures from saturation to 350 K and stagnation pressures from 1 to 10 atmospheres.

SYMBOLS

h	specific enthalpy, kJoules/kgm
p	absolute pressure, atm (1 atm = 101.3 kN/m^2)
q	heat, kJoules
s	specific entropy, kJoules/kgm - ^{o}K
T	absolute temperature, K
β	specific cooling capacity of nitrogen, kJoules/kgm

Subscripts:

a	supercooled liquid (obtained by isentropic compression from $p = 1$ atm), $p = p_t$
b	liquid at the saturation boundary, $p = p_t$
b'	gas at the saturation boundary, $p = p_t$
t	gas at the tunnel stagnation conditions, $p = p_t$, $T = T_t$

SPECIFIC COOLING CAPACITY OF NITROGEN

Assumed Cooling Process

Cooling in the 0.3-meter transonic cryogenic tunnel is accomplished by injecting liquid nitrogen (LN_2) directly into the tunnel circuit. The LN_2 is stored in a large insulated tank kept at atmospheric pressure. A centrifugal pump is used to increase the pressure of the LN_2 to a pressure slightly greater than the tunnel stagnation pressure p_t. The LN_2 is then injected into the tunnel at the diffuser downstream of the test section where it vaporizes. The resulting nitrogen gas absorbs additional heat so that its final temperature and pressure are identical to the stagnation values p_t and T_t. Since this simple and direct method of cooling the 0.3-meter transonic cryogenic tunnel has proven to be satisfactory, the specific cooling capacity of nitrogen will be determined based on this method. The basic assumptions are therefore:

1) Liquid stored at atmospheric pressure
2) Liquid compressed isentropically to $p = p_t$
3) Liquid injected directly into tunnel circuit
4) Warming and vaporization of liquid occurs at $p = p_t$
5) Warming of gas to T_t occurs at $p = p_t$

The basic assumptions which have been made are an oversimplification of the actual cooling process. For example, even for unpressurized LN_2 storage tanks, the head of liquid nitrogen makes the simplifying assumption of storage at exactly atmospheric pressure invalid. Also, in practice the LN_2 may at times be pressurized by the centrifugal pump to a pressure several atmospheres above p_t. The assumption that warming and vaporization of the liquid nitrogen takes place at a constant pressure equal to the stagnation pressure, p_t, is, of course, a great simplification since in practice the liquid is injected in the low-pressure region of the diffuser and the actual warming and vaporization process occurs under conditions of continually changing pressure. The simplifying assumptions not only allow the cooling capacity to be calculated in a relatively simple and straightforward manner, but, more importantly, as can be found from a more rigorous analysis of the cooling process, the simplifying assumptions introduce only negligible errors in the calculated values. From basic thermodynamic considerations it is known that areas in a temperature-entropy diagram represent heat. In order to show the various steps of the cooling process, the temperature-entropy diagram for the heat absorbing process being considered is shown schematically in figure 1. For the process proceeding from point a (supercooled liquid at $p = p_t$ due to isentropic compression from $p = 1$ atm) to point t (gas at p_t and T_t), the heat absorbed by a unit mass of nitrogen is proportional to the area bounded by the curve a b b′ t, the entropy axis, and the vertical lines at s_a and s_t. The total heat absorbed per unit mass, defined as the specific cooling capacity β, is proportional to the sum of the three areas

$$\beta = q_{ab} + q_{bb'} + q_{b't}$$

where q_{ab} = heat absorbed in warming the liquid nitrogen

$q_{bb'}$ = heat of vaporization

$q_{b't}$ = heat absorbed in warming the gaseous nitrogen

Cooling Due to Heat Absorbed in Warming the Supercooled Liquid Nitrogen

The area identified as q_{ab} in figure 1 is proportional to the heat absorbed in warming a unit mass of the liquid nitrogen from approximately the storage temperature at atmospheric pressure to the saturation temperature corresponding to the stagnation pressure p_t. By assuming that the liquid nitrogen is compressed isentropically from its storage pressure to a pressure equal to p_t, the calculation of cooling capacity is greatly simplified. This results from the fact that the heat absorbed between any two points lying on the same isobar is equal to the difference in the specific enthalpy between the two points. (It should be noted that the isobars are so compressed in the liquid region at the saturation boundary that the temperature rise due to the isentropic compression is very small, being only 0.24°K for pressurization from 1 atm to 10 atm.)

Thus, the heat absorbed in warming the supercooled liquid can be calculated as

$$q_{ab} = h_b - h_a \tag{1}$$

where h = specific enthalpy

a = supercooled liquid, $p = p_t$

b = liquid at the saturation boundary, $p = p_t$

Since the boiling point of liquid nitrogen increases with increasing pressure, the advantage of storing the liquid nitrogen at atmospheric pressure rather than at elevated pressure is apparent from figure 1 where it can be seen that the heat absorbing capacity due to warming a unit mass of the liquid, represented by the area q_{ab}, decreases as the long-term storage pressure, and hence the equilibrium storage temperature, is increased. The decrease in cooling capacity with long-term storage pressure will be described in more detail in a later section.

Cooling Due to Vaporization of the Liquid Nitrogen

The area $q_{bb'}$ in figure 1 is proportional to the heat absorbed per unit mass of nitrogen in the change of phase from liquid at b to gas at b′. Again, since this process is assumed to take place along the p_t isobar, $q_{bb'}$ can be calculated directly from the difference in the specific enthalpy of the two phases across the saturation boundary.

$$q_{bb'} = h_{b'} - h_b \tag{2}$$

where b = liquid at the saturation boundary, $p = p_t$

b′ = gas at the saturation boundary, $p = p_t$

Cooling Due to Heat Absorbed in Warming the Gaseous Nitrogen

The area $q_{b't}$ in figure 1 is proportional to the heat absorbed as a unit mass of nitrogen gas is warmed from the saturation temperature corresponding to p_t to the tunnel stagnation temperature T_t.* Since this warming process is assumed to take place along an isobar ($p = p_t$), the heat absorbed per unit mass is again equal to the differences between the specific enthalpies of the gas at the end points. Thus

$$q_{b't} = h_t - h_{b'} \tag{3}$$

where b' = gas at the saturation boundary, $p = p_t$

t = gas at the tunnel stagnation conditions, $p = p_t$, $T = T_t$

Total Specific Cooling Capacity

The three areas in the temperature-entropy diagram of figure 1 were considered separately in the preceding sections in order to describe the three separate heat absorbing processes contributing to the total specific cooling capacity. However, because the entire cooling process is assumed, for simplicity, to take place along the p_t isobar, the total heat absorbed depends only on the difference between the specific enthalpy of the nitrogen at the end points of the heat absorbing process, a and t. That this is true can also be seen by adding the separate contributions from equations (1), (2), and (3) to obtain the total specific cooling capacity

$$\beta = q_{ab} + q_{bb'} + q_{b't} = (h_b - h_a) + (h_{b'} - h_b) + (h_t - h_{b'})$$

or

$$\beta = h_t - h_a, \quad p = p_t \tag{4}$$

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*Failure to properly evaluate $q_{b't}$ resulted in the values of the specific cooling capacity for nitrogen given in reference 7 being too large by about 10 percent at the highest temperatures.

EQUATION FOR SPECIFIC COOLING CAPACITY AS A FUNCTION OF p_t AND T_t

Values of the specific cooling capacity of nitrogen, β, were calculated from the National Bureau of Standards computer program for pressures from 1 to 10 atm and for temperatures from saturation to 350 K. The calculated values of β were then fitted with an equation of the form

$$\beta = B_0 T_t + B_1 + B_2 \frac{1}{T_t} \tag{5}$$

where $B_0 = 1.0379 - 3.9157 \times 10^{-3} p_t$

$B_1 = 1.2125 \times 10^{2} + 2.1577 p_t$

$B_2 = 6.6585 \times 10^{1} - 3.9122 \times 10^{2} p_t$

T_t = stagnation temperature, K

p_t stagnation pressure, atm

The dimensions of β calculated from equation (5) are kJ/kgm. The values of β calculated from equation (5) agree well with the values of specific cooling capacity of nitrogen calculated using the NBS program and the method described in the preceding section (eq. (4)) for absolute pressures from 1 to 10 atm and absolute temperatures from saturation to 350 K. The average error in β is less than 0.3 percent with the maximum error being 0.9 percent for values of β calculated at the higher pressures with T_t at the saturation boundary.

The specific cooling capacity of liquid nitrogen, β, as a function of tunnel stagnation temperature for various values of tunnel stagnation pressure was calculated using equation (5) and is presented graphically in figure 2 The conditions covered are likely to cover all practical wind tunnel designs, namely, stagnation temperatures from saturation to 350 K and stagnation pressures from 1 to 10 atm. As can be seen from figure 2, the specific cooling capacity of liquid nitrogen is a weak function of stagnation pressure and a fairly strong nearly linear function of stagnation temperature.

As previously noted, the cooling capacity of liquid nitrogen is reduced if the liquid is stored at elevated pressures and the bulk temperature of the liquid rises. The decrease in cooling capacity due to storage of the liquid nitrogen at elevated pressures is shown in figure 3 as a function of storage pressure. The values of $\Delta\beta$ are based on the assumption that the temperature of the liquid is equal to the saturation temperature corresponding to the storage pressure. For long-term storage at pressures above 1 atm the values of β given by equation (5) or in figure 2 are <u>reduced</u> by the value of $\Delta\beta$ given in figure 3 for the actual storage pressure.

As an example of the reduction in cooling capacity due to storage at elevated pressures we can consider cooling a tunnel with stagnation conditions of $p_t = 5$ atm and $T_t = 100$ K. From figure 2 (or eq. (5)) we find $\beta = 215.2$ kJ/kgm based on storage at 1 atm (T = 77.35 K) with isentropic compression to 5 atm (resulting in a supercooled liquid at T = 77.45 K). Had the liquid nitrogen been stored at 7 atm we find from figure 3 that the reduction in cooling capacity, $\Delta\beta$, is 45.0 kJ/kgm Under the conditions, cooling capacity is reduced by 21%.

CONCLUDING REMARKS

The specific cooling capacity, β, of nitrogen has been calculated for a simplified cooling model based on the cooling method developed for the Lengley 0.3-m transonic cryogenic tunnel. Calculations of β were made by using a National Bureau of Standards program for the thermodynamic properties of nitrogen and the results fitted with a relatively simple equation of eight coefficients having tunnel stagnation pressure and stagnation temperature as the independent variables. The equation can be used with relatively small desk-top computers to calculate the specific cooling capacity of nitrogen for tunnel stagnation temperatures from saturation to 350 K and tunnel stagnation pressures from 1 to 10 atmospheres. The values of β calculated from the relatively simple equation generally agree with the more precise calculations made directly from the National Bureau of Standards program to within 0.3 percent with a maximum difference of only 0.9 percent for values calculated with tunnel stagnation temperature near the saturation boundary.

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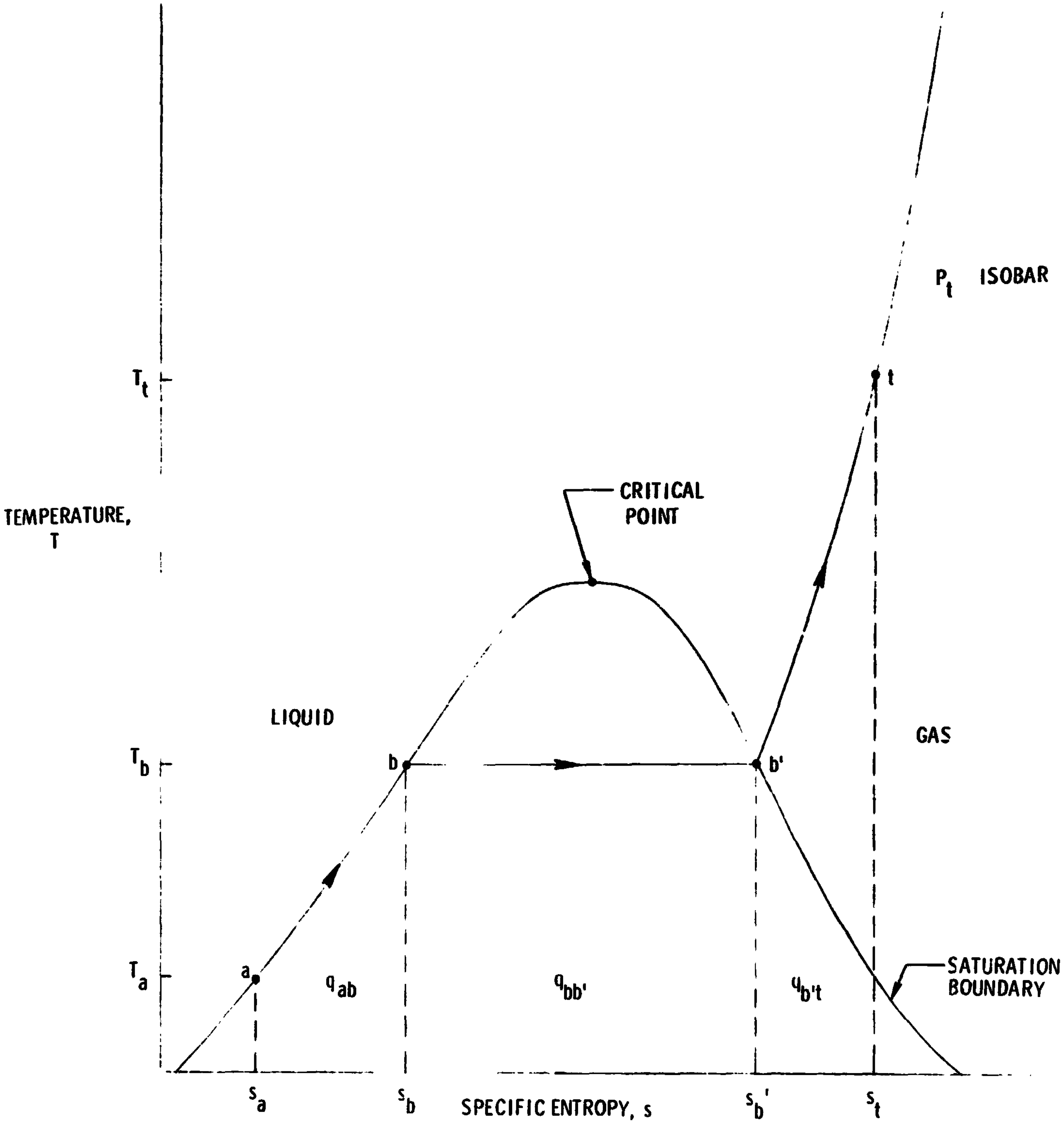

Figure 1.- A schematic temperature-entropy diagram for the heat absorbing process being considered.

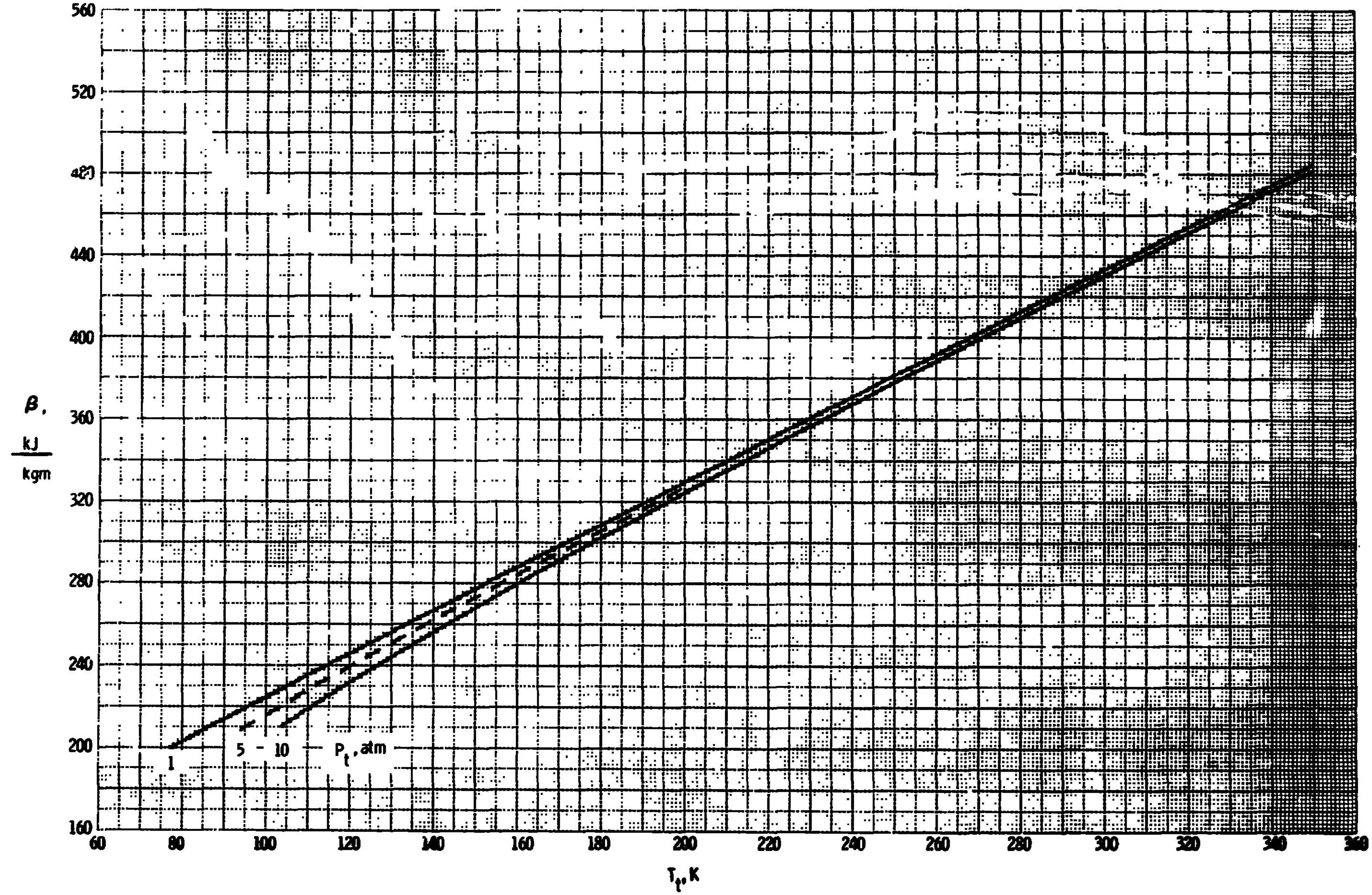

Figure 2. - Specific cooling capacity of nitrogen as a function of tunnel stagnation temperature for various values of tunnel stagnation pressure.

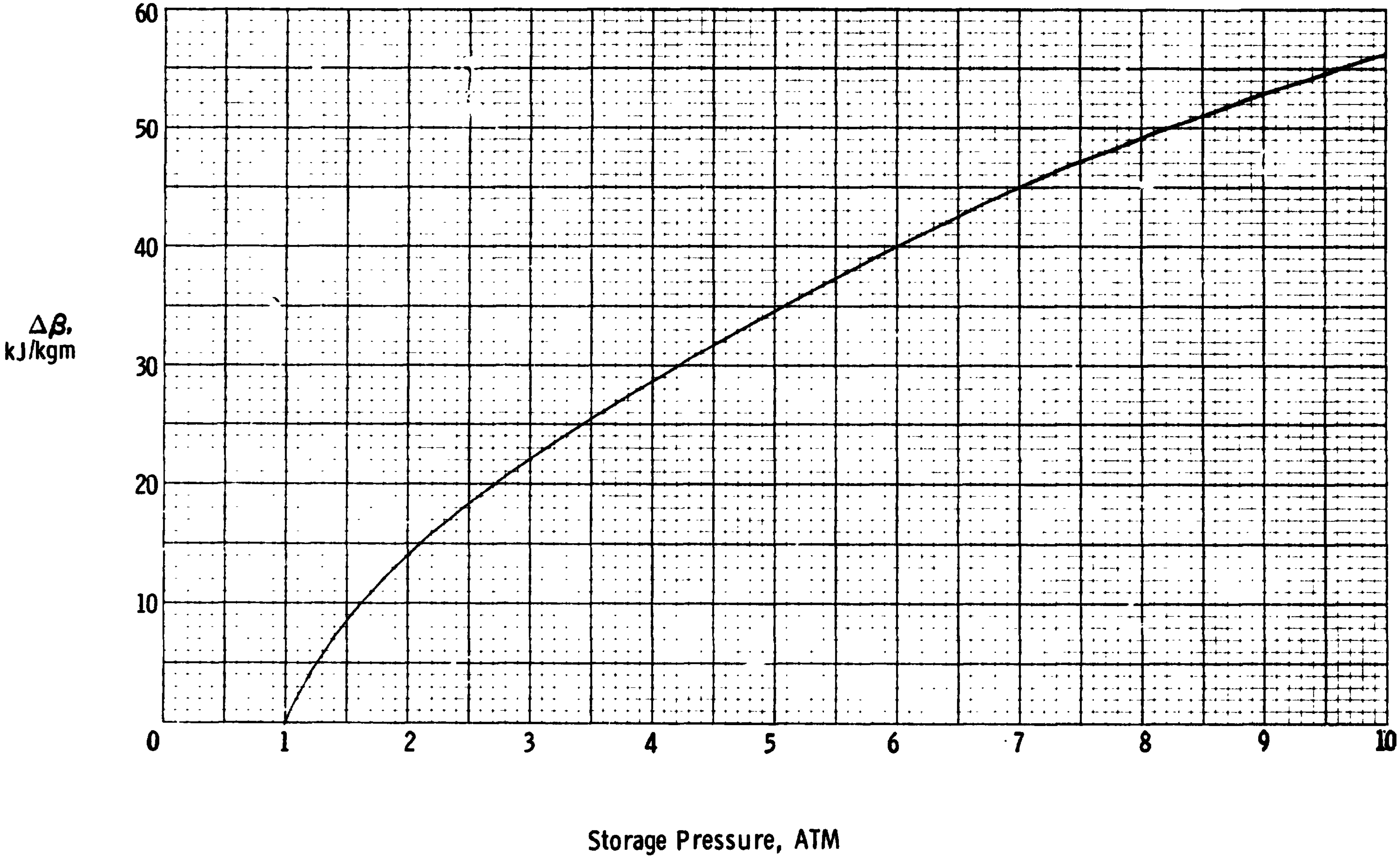

Figure 3.- Reduction in cooling capacity of liquid nitrogen due to storage at pressures greater than 1 atm.