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# Sensitivity Analysis of Cool-Down Strategies for a Transonic Cryogenic Tunnel

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# SUMMARY

A previously developed computer simulation of the Langley 0.3-Meter Transonic Cryogenic Tunnel and experimental data were used to explore methods for performing efficient tunnel cool-down from ambient to cryogenic temperature (300 K to 100 K). Tests included simulated cool-downs made with procedures normally used by the tunnel operators. Simulated cool-downs were also made at constant Mach numbers, at constant fan speeds, and at constant metal-to-gas temperature differences. The effect of high and low liquid nitrogen ($LN_2$) flow rates on time to cool-down and $LN_2$ consumption were also investigated. Normal cool-downs, used only to show the wide variation in both time and consumption that can occur, were made completely open loop (temperature, pressure, and fan speed) whereas all other simulated cool-downs were made with automatic closed-loop pressure feedback control. The effect of cooling at high pressure rather than low pressure was also investigated. These tests indicate an optimum strategy which was then used in a simulated cool-down.

The data show that open-loop operator cool-down techniques are quite dominant in determining the total nitrogen consumption when manually controlling the cool-down of a cryogenic wind tunnel. In general, relatively low fan speeds (900 to 1200 rpm) or Mach numbers (0.20 to 0.35) during cool-down are much more time and energy efficient when cooling the tunnel from ambient to cryogenic temperatures (300 K to 100 K). These very simple observations result in much less nitrogen being used to overcome the excessive fan-generated heat of compression produced when higher fan speeds or Mach numbers are used during the cool-down phase. Finally, nitrogen savings are realized if cool-downs are performed at low fan speeds and low $LN_2$ flow rates with additional savings occurring if the cool-down is performed at high tunnel pressures. On the other hand, cooling at high pressures when at Mach numbers above about 0.30 is definitely not advocated, because $LN_2$ usage drastically increases.

# INTRODUCTION

The relatively recent introduction of the cryogenic wind tunnel, which uses a gaseous-nitrogen ($GN_2$) flow medium, has added a number of new and unique problems to the operation of wind tunnels. These new problems include the need for highly accurate independent control of tunnel temperature over a very wide range. Another problem is the increased operational costs (as compared with conventional tunnels) associated with tunnel cool-down and testing at high Reynolds numbers. Accurate control of the test variable, however, is possible if high-speed microprocessors together with correctly designed feedback control laws are used. On the other hand, use of manual control of the cool-down process has revealed large variations in both the time required and the amount of liquid nitrogen ($LN_2$) consumed during initial tunnel cool-down prior to commencement of research studies. These variations occur primarily because of the many cool-down conditions and parameter sequencing schemes used by individual tunnel operators. Therefore, identifying an efficient procedure for cool-down would result in cost savings which will inherently permit more research for a given amount of money.

Identification of an efficient cool-down procedure assumes even more importance in light of the fact that more cryogenic wind tunnels are being built or planned throughout the world. One such cryogenic tunnel presently under construction is the

National Transonic Facility (NTF) at the Langley Research Center (ref. 1), which will provide an order of magnitude increase in Reynolds number capability over existing ambient tunnels in the United States when it becomes operational. It is anticipated that initial operation of many of these new cryogenic wind tunnels will be in the manual control mode, which may not be very efficient with regard to time and $LN_2$ consumption for cool-down. Therefore, identifying an efficient cool-down procedure for these tunnels based on closed-loop control is needed. A number of procedures for cool-down from ambient to cryogenic temperatures (300 K to 100 K) were studied and are presented. The procedures suggested herein are for the Langley 0.3-Meter Transonic Cryogenic Tunnel (0.3-m TCT) (see ref. 2 and fig. 1), but they can be extrapolated for use with other cryogenic tunnels that are likely to be operated manually until appropriate automatic control laws can be designed.

## SYMBOLS

| | |
|---|---|
| $A$ | area, $m^2$ or percent |
| $b$ | pressure-loss coefficient, $(r - 1)/M^2$ |
| $c_p$ | specific heat capacity of gas at constant pressure, J/kg-K |
| $K_F$ | fan heat factor, J/sec-atm-$K^{1/2}$ |
| $K_M$ | Mach number factor, rpm/$K^{1/2}$ |
| $M$ | Mach number |
| $\dot{m}$ | mass flow rate, kg/sec |
| $N$ | fan speed, rpm |
| $p$ | total pressure, atm (1 atm = 101.3 kPa) |
| $\dot{Q}$ | heat flow rate, J/sec |
| $r$ | fan pressure ratio, $1 + bM^2$ |
| $s$ | Laplace variable |
| $T$ | total temperature, K |
| $T_m$ | metal temperature, K |
| $t$ | time, sec |
| $y$ | heat-transfer coefficient, J/sec-K |
| $\gamma$ | ratio of specific heats |
| $\Delta T$ | metal-to-gas temperature difference, K |
| $\eta$ | fan efficiency |
| $\tau$ | transport time lag, sec |

Subscripts:

| | |
|---|---|
| a | acoustic |
| F | fan |
| G | gas |
| L | liquid |
| p | plenum |

## LANGLEY 0.3-METER TRANSONIC CRYOGENIC TUNNEL

Since the earliest days of experimental flight research, engineers have been attempting to study the characteristics of airfoil models in conventional wind tunnels to better design wings for full-scale aircraft. The low Reynolds number capability of some of these early conventional facilities, however, greatly restricted the available airfoil testing envelope. Many different strategies and techniques have been attempted to increase the attainable Reynolds number of these testing facilities. Presently, the most widely accepted and least costly idea, originating with a Frenchman named W. Margoulis (refs. 3 and 4), is to cool the test medium to very low temperatures. This ingenious method consists of injecting the tunnel with supercooled liquid nitrogen. When gasified in the tunnel, liquid nitrogen exhibits properties quite similar to air while drastically increasing Reynolds number. In 1971, a small group of researchers at Langley Research Center recognized the advantages of this cryogenic wind tunnel concept and began further research to develop and enhance its application for testing at full-scale Reynolds numbers.

The Langley 0.3-m TCT resulted from this work. It is a closed-circuit, electrically driven tunnel using cryogenic liquid nitrogen for cooling the test medium and removing the generated fan heat of compression. Figure 1 is a schematic of the tunnel as it existed for this study. Pertinent details such as electrical fan power required, tunnel volume, and metal weight are shown. The tunnel can be operated at pressures up to 6.00 atm and at Mach numbers ranging from 0.1 to about 1.0 for any temperature between 320 K to 77 K.

The tunnel pressure shell is constructed of 6061-T6 aluminum alloy. This alloy was selected because of its good mechanical characteristics at both ambient and cryogenic temperatures. Thermal insulation covering the outside of this pressure shell consists of a nitrogen-purged fiberglass layer covered by an impervious vapor barrier.

The tunnel has a fixed-geometry fan system which circulates the gaseous nitrogen through the test section where airfoil models are mounted. The drive fan is powered by a 2000-kW synchronous motor with a variable-frequency speed control. This motor is capable of operating at speeds from 600 to 5200 rpm.

Liquid nitrogen for temperature regulation is injected downstream of the test section just ahead of the tunnel fan section. Injection is accomplished with valves spaced 90° apart around the tunnel circumference. Total pressure is adjusted by means of a control valve located in an exhaust pipe leading to the atmosphere from the low-speed end of the tunnel. Also shown in figure 1 are the sensor locations used for feedback control law implementation. Additional details of this facility can be obtained from reference 2.

## Test Equipment

All the results reported herein were obtained either from the interactive hybrid-computer simulation of the 0.3-m TCT (refs. 5 and 6) or by using the tunnel itself. The tunnel mathematical model used in this simulation is composed of thermodynamic differential-delay/ordinary-differential equations which describe the dynamic behavior of the tunnel gas temperature and pressure, the metal wall temperature, the fan speed, and the free-stream Mach number. Simulator step-response data were shown in reference 5 to agree very well with responses obtained from the actual wind tunnel. As a result of this global model validation, cool-down studies spanning the tunnel operational envelope are expected to yield accurate results.

Figure 2 is a photograph of the analog portion of the simulator along with the recorder and interactive control-display panel used in these studies. Figure 3 is a close-up of the simulator control-display panel.

## Test Procedures

A number of independent quasi-static cool-down tests for both open- and closed-loop conditions were performed on the hybrid-computer simulation of the 0.3-m TCT (ref. 5) in order to explore systematically various tunnel cool-down techniques. These simulated cool-downs were begun by establishing the initial gas pressure and setting both the temperature of the gas in the tunnel and the temperature of the pressure shell (structure exposed to $GN_2$) of the tunnel at 300 K. Constant gas pressure was maintained by using a proportional-integral feedback control law whenever simulated constant tunnel pressure was desired. Cool-down runs were terminated when the simulated metal (pressure shell) temperature reached 100 K. During these tests, gas temperature was continuously reduced but $LN_2$ saturation was not allowed to occur. When approaching the end of cool-down, gas temperature was maintained from about 98 K to 100 K while waiting for the metal temperature to descend to this same final condition. For the normal cool-down data runs, ground rules were established in order to duplicate as accurately as possible the conditions under which the actual tunnel is normally operated. These consisted of avoiding certain fan speeds that are either operationally forbidden or time limited on the actual 0.3-m TCT fan motor. More important, however, was the requirement to cool the simulated tunnel pressure shell at rates no greater than 10 K/min in order to avoid excessive thermal stress and the possibility of structural damage. For some of the simulator tests, the fan speed restrictions were relaxed to preclude discontinuities in the data. The limitation on the pressure shell cooling rate (rate of change of metal temperature) was also relaxed during these same simulation runs but was strictly observed while collecting experimental data at the tunnel.

## NORMAL COOL-DOWNS

The first set of cool-downs performed on the 0.3-m TCT simulator was made using the procedures normally used by each individual tunnel operator for cooling the actual tunnel from a 300-K ambient temperature to a preselected operating temperature of 100 K. The four operators were permitted to use any cool-down procedure so long as the 10 K/min maximum cool-down rate was not exceeded. Fan speed ranges operationally forbidden or time limited on the tunnel fan motor were also carefully observed for these tests. During these so-called "normal" cool-downs, the results of which are shown in figure 4, the operators had manual control of fan speed, $LN_2$ valve opening, and $GN_2$ valve opening on the simulator. In other words, the three independent inputs were operated completely open loop. The slopes of the curves in figure 4 are an indication of the $LN_2$ injection rates and the endpoints indicate the total $LN_2$ consumption. The maximum rate of injection which can be realized with the 0.3-m TCT $LN_2$ injection system based on a 1.24-MPa (180-psi) relief-valve setting is 700 kg/min (11.7 kg/sec). Figure 4 is given to demonstrate that without prespecifying cool-down conditions such as Mach number, fan speed, or pressure, wide variations in both consumption of $LN_2$ and time can occur. These variations are known to be dependent on individual technique. In general, the data of figure 4 suggest that higher rates of $LN_2$ injection result in high $LN_2$ consumption. During the cool-down for curve A, the exhaust valve was observed to be at approximately 60- to 80-percent open in order for the operator to maintain his own selected constant pressure (e.g., 2.11 atm) in the simulated tunnel. Consequently, much of the sensible heat capacity of the nitrogen gas was wasted by expelling the cold gas to the atmosphere, thereby requiring much more $LN_2$ for cooling to the 100-K metal temperature. Jacobs (ref. 7) has previously shown that this phenomenon is to be expected and that "a maximum liquid requirement for cool-down would then be the amount that is necessary if all of the latent heat of vaporization is utilized but none of the sensible heat of the vapor is used." Alternately, if the average overall rate of injection is very low, high $LN_2$ consumption and long total cooling time were realized, as shown in curve B of figure 4. In this case, the operator initially began with such a low rate of injection that the majority of the cooling capacity of the $LN_2$ was used to cancel the fan heat of compression and only slightly to reduce the metal temperature of the pressure shell. Extrapolation of this low input slope reveals that the time required to cool to 100 K would certainly be undesirably long. The effect of $LN_2$ injection rate is discussed further in a later section of this paper.

Because of such a long cool-down time, one might suspect that electrical costs for fan operation could become dominant. However, simple calculations show that the unit energy cost of $LN_2$ is much greater than the unit energy cost of electricity, and therefore ignoring electrical operational costs in these analyses is not unwarranted (ref. 8). During this same cool-down (curve B of fig. 4), the operator, after realizing that a large amount of time was being consumed, greatly increased the injection rate. In so doing, he used approximately the same amount of $LN_2$ as was used for the cool-down of curve A.

## COOL-DOWNS AT CONSTANT FAN SPEEDS

Standard operating procedure at the 0.3-m TCT in the past has been to perform cool-downs at constant fan speeds since it is much easier to keep fan speed constant than to maintain constant Mach number because the speed of sound decreases with decreasing temperature. With this background, the simulator was used to generate cool-down data for constant fan speeds of 250, 500, 900, 1200, 1500, 2000, and 3000 rpm using closed-loop pressure regulation for comparison with similar constant Mach number runs performed later. Figure 5 shows experimental data from the 0.3-m TCT and results obtained from the simulator at tunnel pressures of 1.63, 3.00, 4.08, and 5.50 atm for $LN_2$ flow rates of 1.25 and 2.50 kg/sec. As expected, the data of figures 5(a) and 5(b) indicate, in general, that much more $LN_2$ is used when the cool-down is made at higher fan speeds. This is true for both $LN_2$ injection flow rates. Alternately, the simulator shows the fan-speed range of about 900 to 1200 rpm to be the area of minimum $LN_2$ consumption. Several items should be pointed out in these figures, not the least of which is the fact that for low fan speeds consumption decreases as tunnel pressure increases. At 5.50 atm, which approaches the maximum operational tunnel pressure of 6.00 atm, the lowest consumption was experienced. This should not be a total surprise since more efficient heat transfer is expected with increased molecular densities due to high pressure. High-pressure cool-down, however, may present an additional concern in the operation of a cryogenic tunnel if continuous cyclic pressure variations of this magnitude would significantly reduce the structural life of the tunnel. If this variation in pressure is of no concern, it is obvious that high-pressure cool-downs are to be preferred. Additionally, since these tests assumed that the initial pressure condition existed in the simulated tunnel, it is highly unlikely that an $LN_2$ savings would be realized if pressure in the actual tunnel has to be built up to the high-pressure state by $LN_2$ injection for an operational cool-down. Another point of comparison, which confirms the natural unforced-cooling theory of reference 9, is that for 900 rpm and 5.50 atm nearly 8 percent less than $LN_2$ is needed for cool-down when the injection flow rate is 1.25 kg/sec than when the injection flow rate is 2.50 kg/sec. For this same pressure and the 1.25 kg/sec flow rate, figure 5(a) reveals that approximately 2.4 times more $LN_2$ is necessary to cool-down at 3000 rpm than at 900 rpm. This number is very conservative since the 3000-rpm cool-down at 5.50 atm had to be terminated at a gas temperature of 162 K because of insufficient $LN_2$ injection. An explanation of this phenomenon results from examination of the equations for the heat-transfer coefficient, the heat added to the system by the fan, and the relationship between the fan speed and Mach number (refs. 5 and 6):

$$y_G = 8234p^{0.8}T^{-0.22}M\left(1 - 0.67M^{0.65}\right)$$

$$\dot{Q}_F = K_F pM^3 (1 + 0.2M^2)^{-3}\sqrt{T}$$

and

$$M = \frac{Ne^{-\tau_a s}}{K_M\sqrt{T}\left(1 + t_p s\right)}$$

where $K_F \triangleq (6965/\eta)Ac_p b[(\gamma - 1)/\gamma]$ and $K_M \triangleq 597(1 - 0.3M)p^{-0.035}$. Note that both the heat-transfer coefficient and the fan heat are functions of pressure and Mach number. Fan heat is much more strongly influenced by Mach number (directly proportional to fan speed at a given temperature) than is the heat-transfer coefficient. Consequently, for high fan speeds more fan heat must be overcome by the injection of larger amounts of $LN_2$. When fan speed is low and cool-down pressure is high, significantly less $LN_2$ is needed for cool-down. This is because of less fan heat generation and a larger pressure-induced heat-transfer coefficient.

Without any consideration given to tunnel operational constraints such as maximum allowable metal-to-gas temperature difference, the same simulator information of figures 5(a) and 5(b) has been plotted to show the time required for cool-down. Figures 5(c) and 5(d) show the influence of pressure on the cool-down time for constant fan speeds for the same two $LN_2$ injection rates as in figures 5(a) and 5(b). For the 1.25 kg/sec injection rate, minimum time for cool-down occurs at 1200 rpm and 5.50 atm whereas minimum time for the 2.50 kg/sec rate occurs at 1500 rpm and 5.50 atm. For these conditions about 75 percent more time was needed to cool at the lower injection rate. At the higher tunnel pressures, as fan speed is increased beyond 1200 to 1500 rpm, additional time is needed for cooling since less excess $LN_2$ cooling capacity is available in either injection case because of the additional heat added to the stream by the fan.

Experimental cool-downs at constant fan speeds were performed in the 0.3-m TCT to substantiate the above simulator results. Acquiring these data at the tunnel was not easily accomplished because of safety and operational restrictions. The major obstacle to data acquisition was the 10 K/min limitation on pressure shell cooling rate. Liquid-nitrogen flow rates above 1.25 kg/sec could not be explored since this caused the pressure shell to exceed the maximum cooling rate permitted. Two experimental test runs were performed at 1.63 atm for fan speeds of 1200 and 2000 rpm. The $LN_2$ consumption and time to cool-down for these runs are plotted in figures 5(a) and 5(c). Testing at higher fan speeds was not attempted because of the large $LN_2$ consumption expected. For the 2000-rpm cool-down test, a further complication was experienced because of hardware difficulties. Leakage of the $LN_2$ injection valves caused more $LN_2$ to be injected than was commanded. Problems with the $LN_2$ flowmeter also caused the calculation of total $LN_2$ consumption to be inaccurate. Consequently, the $LN_2$ consumption plotted for the 2000-rpm test is in substantial error.

## COOL-DOWNS AT CONSTANT MACH NUMBERS

In order to validate the moderate-cooling-rate philosophy for the 0.3-m TCT, a number of simulated tunnel cool-downs were accomplished for several values of free-stream Mach number. For these cool-downs, the pressures used were the same as those previously used in the runs at constant fan speeds. These cool-downs at constant Mach numbers and constant pressures were accomplished by providing the operator with closed-loop automatic pressure regulation. Control inputs available to the operator during these cool-downs consisted of $LN_2$ injection for control of the cooling rate and fan speed for maintaining constant Mach number. After establishing the correct initial $LN_2$ flow rate, the method involved the continuous reduction of fan speed in order to maintain constant Mach number as temperature decreased. The $LN_2$ flow rate was reduced when the gas temperature reached 100 K. The gas temperature was then maintained at 98 K to 100 K by regulating the flow rate until the metal temperature reached 100 K.

The results of performing cool-downs at various constant Mach numbers for constant pressures of 1.63 atm, 3.00 atm, 4.08 atm, and 5.50 atm are shown in figure 6. The curves in this figure consistently indicate that above about Mach 0.25 for a given constant pressure, both $LN_2$ consumption (figs. 6(a) and 6(b)) and time (figs. 6(c) and 6(d)) required for cool-down increase significantly with increasing cool-down Mach number. This increased $LN_2$ consumption is as expected and can be understood by examining the fan heat equation of the simulator (see refs. 5 and 6),

$$\dot{Q}_F = K_F p M^3 (1 + 0.2M^2)^{-3} \sqrt{T}$$

where $K_F \triangleq (6965/\eta) A c_p b[(\gamma - 1)/\gamma]$. As a result of the dominance of the Mach number in the numerator, the additional heat added to the system by the fan with increasing Mach number necessarily means a larger use of $LN_2$. Therefore, in order to conserve liquid nitrogen, it is advantageous to cool the tunnel using very low Mach numbers.

From the standpoint of both $LN_2$ conservation and time required for cool-down, the data of figure 6 in general reveal that less $LN_2$ or less time is used to cool at higher pressures when at low Mach numbers (0.25 or less). This $LN_2$ consumption conclusion, which incidentally was initially predicted by the tunnel operators based on day-to-day tunnel experience, can be seen by directly comparing individual data of figure 6(a) for 5.50 atm with the data for 1.63 atm.

An explanation for this behavior can be obtained by examining the previously given equation for fan heat and the equation for the gas heat-transfer coefficient (refs. 5 and 6),

$$y_G = 8234p^{0.8}T^{-0.22}M(1 - 0.67M^{0.65})$$

It is obvious from the data that at higher Mach numbers and higher pressures, the fan heat is the more dominant factor influencing the amount of $LN_2$ consumed. However, when the Mach number is low but the pressure is high, the heat-transfer coefficient is largely influenced by pressure. The effect is the result of more efficient heat transfer taking place resulting in reduced amounts of $LN_2$ being used for cool-down.

On the other hand, when cooling at high Mach numbers (greater than 0.25), the data suggest that it is better to reduce pressure to conserve $LN_2$ as well as to reduce cool-down time. Here the fan heat term becomes dominant, thereby masking the advantage of the increased heat-transfer coefficient (i.e., high pressure) and ultimately requiring large amounts of $LN_2$.

## OPTIMIZATION OF COOL-DOWN AT CONSTANT MACH NUMBERS

Since it was apparent from previously collected data that progressively decreasing the $LN_2$ injection flow rate at low Mach numbers and high pressures resulted in decreased consumption, it was logical, therefore, to obtain additional cool-downs for a theoretically calculated minimum required $LN_2$ flow rate. This flow rate (1.11 kg/sec) was computed relative to the upper end of the tunnel operation envelope and was just sufficient to overcome the heat generated by the tunnel fan for a Mach number of 0.50, a total pressure of 5.50 atm, and a temperature of 300 K. The idea was to then correlate the influence of Mach numbers less than 0.50 on the $LN_2$ consumption, the time required for cool-down, and the structural stress (maximum metal-to-gas temperature difference) imposed on the tunnel pressure shell using this reduced $LN_2$ injection rate. Subsequently, for the constant injection rate of 1.11 kg/sec, a number of cool-downs at constant pressures were performed from a simulated ambient temperature of 300 K to 100 K for various low constant Mach numbers.

As before for cool-downs at constant Mach numbers, the technique used here was to maintain a constant $LN_2$ injection valve opening which yielded a simulated rate of 1.11 kg/sec throughout most of the cool-down. The valve opening was gradually reduced only when the simulated tunnel temperature approached the lower region so as to preclude saturated conditions. Simultaneously, automatic pressure regulation was used to hold tunnel total pressure constant. As before, Mach number was maintained constant by manually reducing the simulated fan speed to compensate for the increase in Mach number due to the decrease in the speed of sound as temperature was decreased.

An example of the information obtained from these simulator studies is shown in figure 7, which shows the influence of constant Mach number on $LN_2$ consumption, cool-down time, and maximum metal-to-gas temperature difference $\Delta T_{max}$. For this constant $LN_2$ injection rate, both $LN_2$ consumption and cool-down time increase at Mach numbers above about 0.35. This shows once again that cool-down should take place at Mach numbers less than 0.35. However, the metal-to-gas temperature differences indicate that for low structural stress the cool-down should be performed at high Mach numbers, which is contrary to the requirement for minimum $LN_2$ consumption. The arrow on this figure indicates the normal operating point for cool-down based on operational experience with regard to a limit for maximum metal-to-gas temperature difference of approximately 50 K. These simulator studies show that only a small $LN_2$ consumption penalty results from cooling at a Mach number of approximately 0.30 in order to meet the stress criteria, a result consistent with operational experience. Additionally, the data of figure 7 at Mach 0.20 and 5.50 atm imply a rule of thumb of 0.5 kg of $LN_2$ for each kilogram of wetted tunnel metal for cool-down from 300 K to 100 K for the 0.3-m TCT.

The final parameter to be investigated for these cool-downs at constant Mach numbers was the $LN_2$ injection rate. Figure 8 shows that for the given conditions ($p = 5.50$ atm and $M = 0.25$), $LN_2$ injection rates between 1.20 kg/sec and 1.80 kg/sec are about optimum for the 0.3-m TCT. Although cooling within this range may not, upon further study, seem to be best because of the small consumption penalty paid at the highest flow rate, it does provide a metal-to-gas temperature difference safety margin well within the 50 K operational limit for a reasonable amount of time required for cool-down.

## COOL-DOWNS AT CONSTANT METAL-TO-GAS TEMPERATURE DIFFERENCES

The last method of tunnel cooling to be studied was the cool-down at constant metal-to-gas temperature differences. Previously, information was obtained for constant injection flow rates, and consequently it was necessary to discover the advantages, if any, of a continuously varying $LN_2$ injection rate on the process. Because there is an additional $LN_2$ penalty to be paid for initial high tunnel pressure buildup from ambient conditions, only low-pressure cool-downs at constant temperature differences were selected here for study. This is not to imply that high-pressure cool-downs are less efficient, for certainly it is better to use the higher pressure for cooling if cool-down commences at conditions other than ambient, as previous data suggest.

As before, the techniques used on the simulator to acquire these data were to initially establish the same gas and metal temperature (300 K) and then open the simulator $LN_2$ injection valve to a predetermined value. The rate of injection was continuously varied by manually altering the valve opening such that the temperature differences between the gas and metal were maintained at a preselected constant value. This constant temperature difference was held as long as possible during the cool-down. Tunnel pressure was established at the start of each cool-down and kept constant by using closed-loop pressure control. Cool-down was terminated when gas and metal temperature were equalized at 100 K.

It was determined that this technique of constant temperature difference (variable injection rate) was manually unfeasible since it imposed a tedious task upon the operator. The use of a well-designed closed-loop controller, however, could easily alleviate this problem and could continue in such a fashion for an indefinite time period.

The data of figure 9(a) are the result of $LN_2$ consumption tests performed on a digital implementation of the hybrid equations and on the hybrid simulator as a function of the various constant temperature differences. Figure 9(b) shows the corresponding time required for these cool-downs. Both sets of data agree reasonably well except at $\Delta T \approx 20$ K and below. The data show that $LN_2$ consumption tends to decrease as smaller temperature differences (lower injection rates) are maintained. Previous data of figure 8 indicated that consumption increased as injection rates below about 1.20 kg/sec were used. Confusion ensued when the hybrid data of figure 9(a) showed that consumption fell below the line of consumption required for cooling the metal alone. This data point ($\Delta T \approx 20$ K) is in fact in error. It was determined that this trend was because of long-term analog amplifier drift which was of no consequence during the other short-time cool-downs. The digital data are believable since a cool-down for which the cooling energy of the $LN_2$ input only slightly exceeds the fan heat input (small $\Delta T$) should require an inordinate amount of $LN_2$ and time for cool-down. This is the trend predicted by the digital-computer simulation results.

## OPTIMUM COOL-DOWN

Of the various tests performed during this study, data and operator comments indicated that the preferred strategy, both from the standpoint of minimum operator work load and of reduced $LN_2$ consumption, was the cool-down at constant fan speed. Moreover, a high pressure of 5.50 atm and an injection rate of 1.50 kg/sec together with a constant 1200-rpm fan speed should be typically selected for cool-down. Figure 10 shows one such cool-down performed with the criteria suggested above. This cool-down was accomplished using about 18 percent less $LN_2$ and about 17 percent less time than any of the typical operator-controlled cool-downs of figure 4. These savings result from the high cool-down pressure used as compared with the low pressures typically used by the operators.

## CONCLUDING REMARKS

The conclusions of this report apply to the Langley 0.3-Meter Transonic Cryogenic Tunnel. Results and trends, however, can be extrapolated to other similarly constructed cryogenic wind tunnels.

The data of this report show that open-loop tunnel operator technique is a dominant factor influencing both the cool-down time and total liquid-nitrogen ($LN_2$) consumption when manually controlling the cool-down process of a cryogenic wind tunnel. Moderate rates of $LN_2$ injection (1.20 to 1.80 kg/sec), which allow efficient use of both the sensible and latent heats of the injected $LN_2$ preclude excessive $LN_2$ consumption during cool-down. Additionally, it is best to use reduced Mach numbers (0.20 to 0.30) or reduced fan speed (1200 to 1500 rpm) when cooling the tunnel so that less $LN_2$ is required to overcome the fan-generated heat of compression. Because of reduced operator attention required as well as decreased $LN_2$ consumption, it is recommended that cool-downs at constant fan speed of 1200 rpm and $LN_2$ injection rate of about 1.50 kg/sec should be routinely used. Use of this last recommendation will ensure a fairly low metal-to-gas temperature difference while simultaneously allowing cool-down to proceed at an acceptable rate. Cool-down at higher pressures with Mach numbers above about 0.30 is not advocated since $LN_2$ consumption and cool-down time drastically increase with lower metal-to-gas temperature differences occurring. Lastly, because of the additional $LN_2$ penalty to be paid for high tunnel pressure build-up, results indicate that it is better to use existing higher pressures when commencing cool-down.

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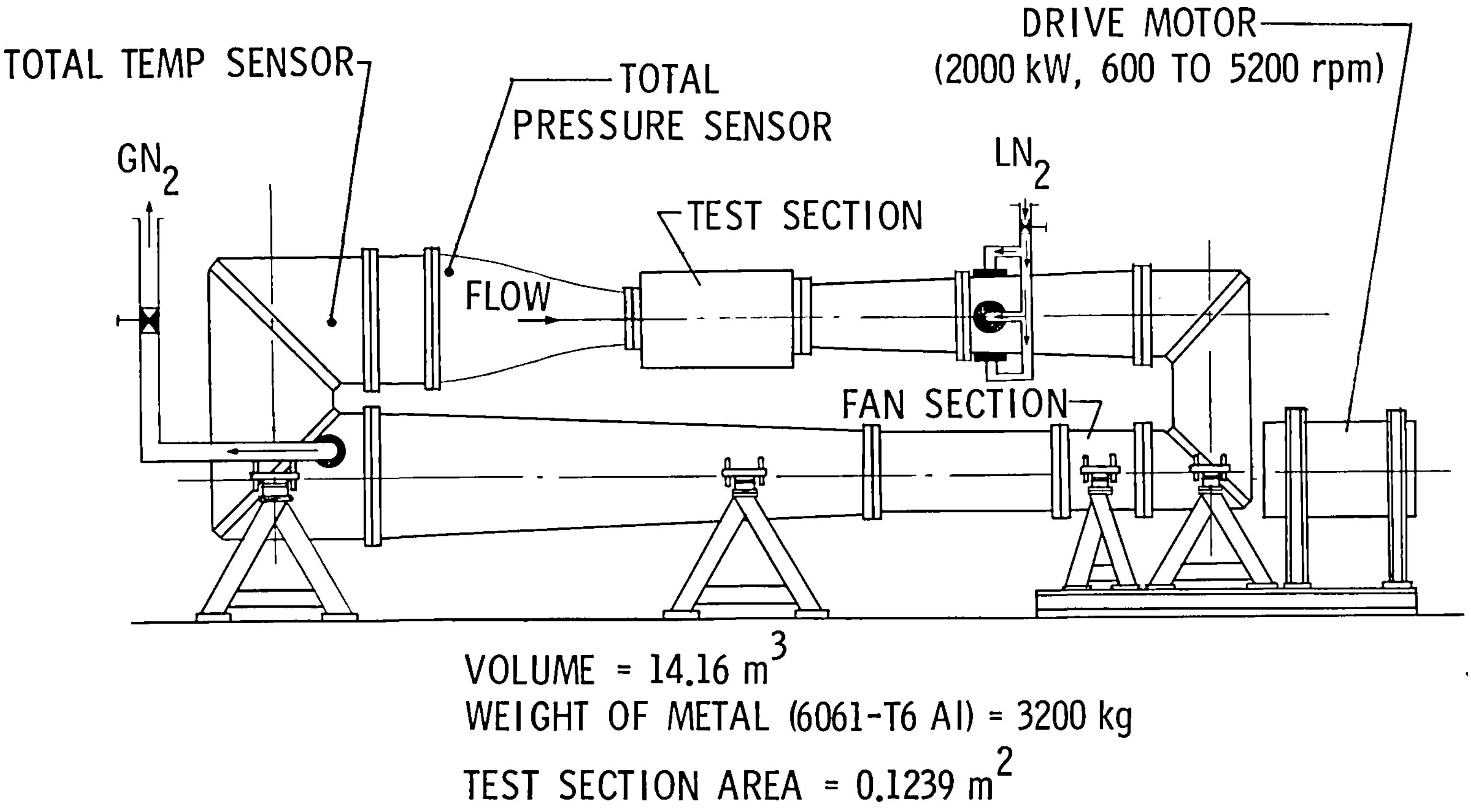

Figure 1.- Schematic of Langley 0.3-Meter Transonic Cryogenic Tunnel.

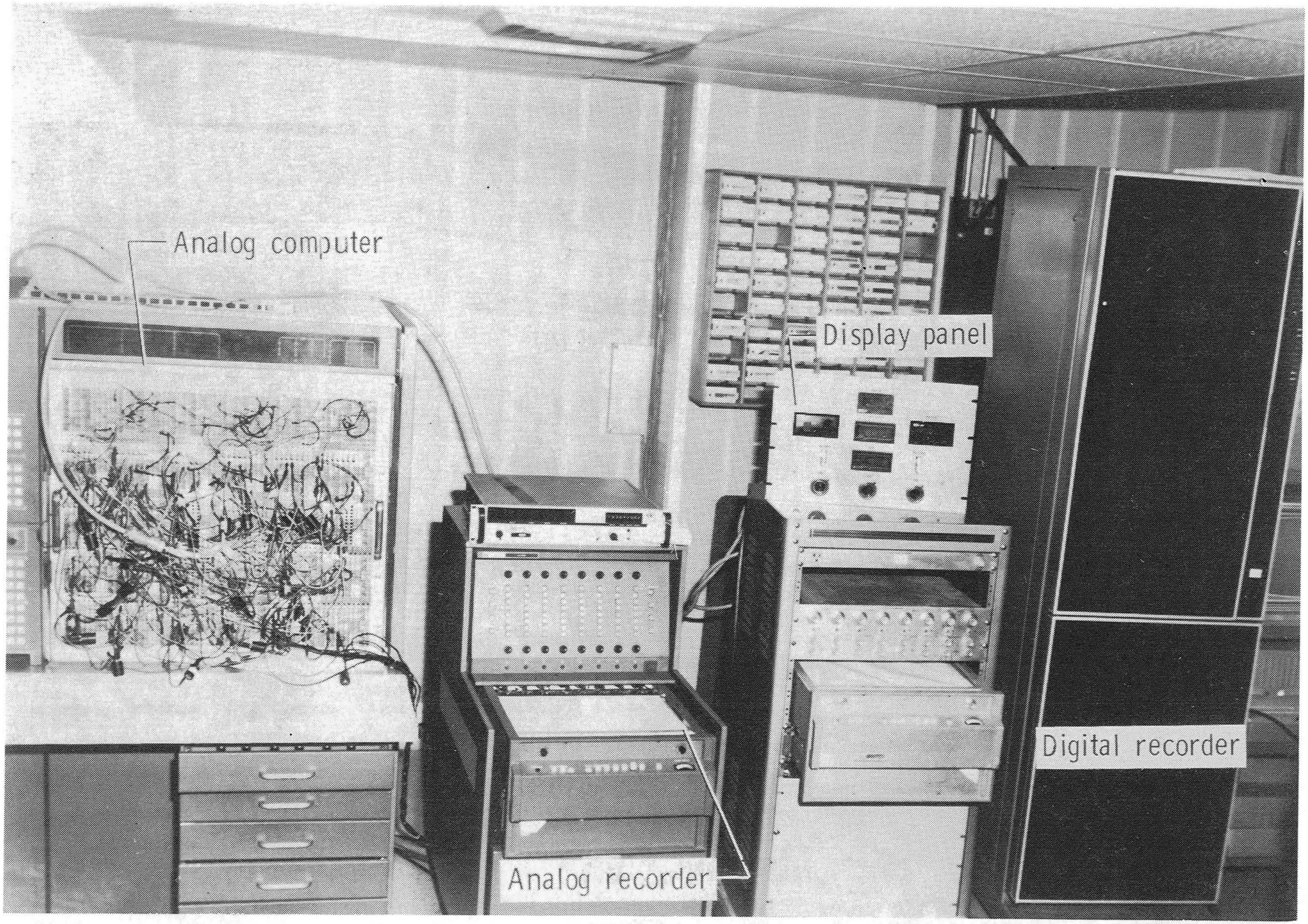

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Figure 2.- Simulator instrumentation.

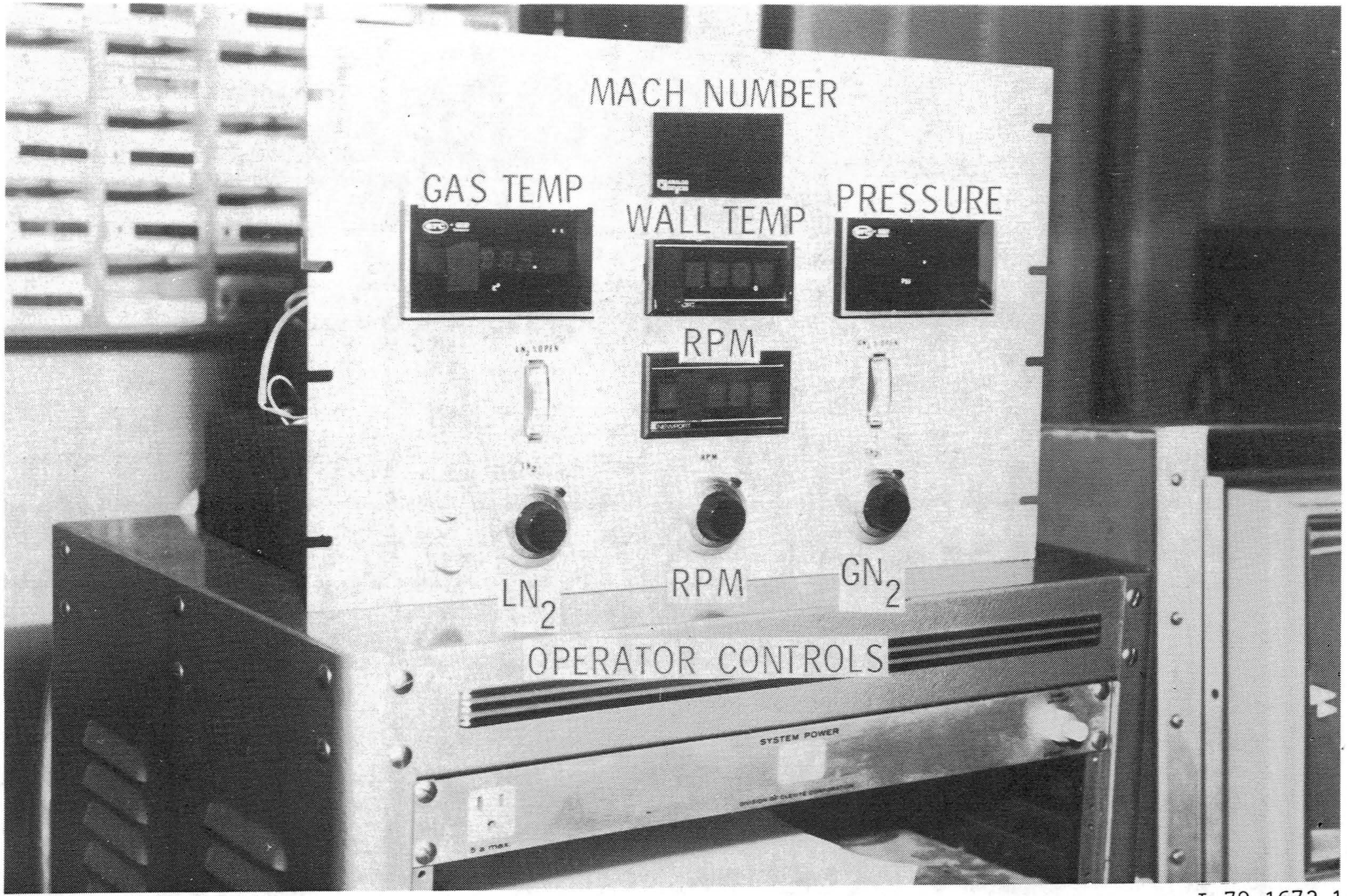

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Figure 3.- Control-display panel for hybrid-computer simulator.

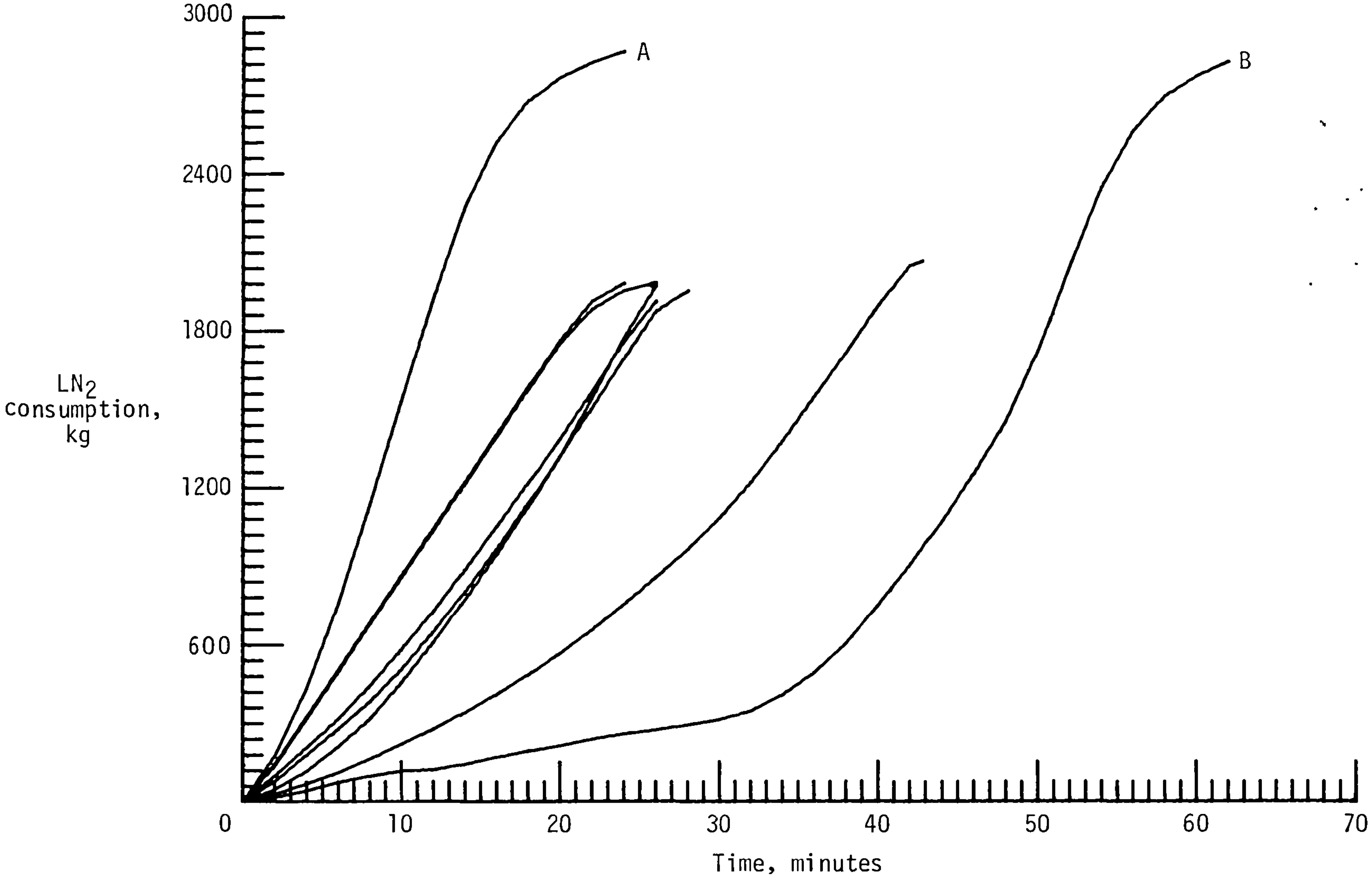
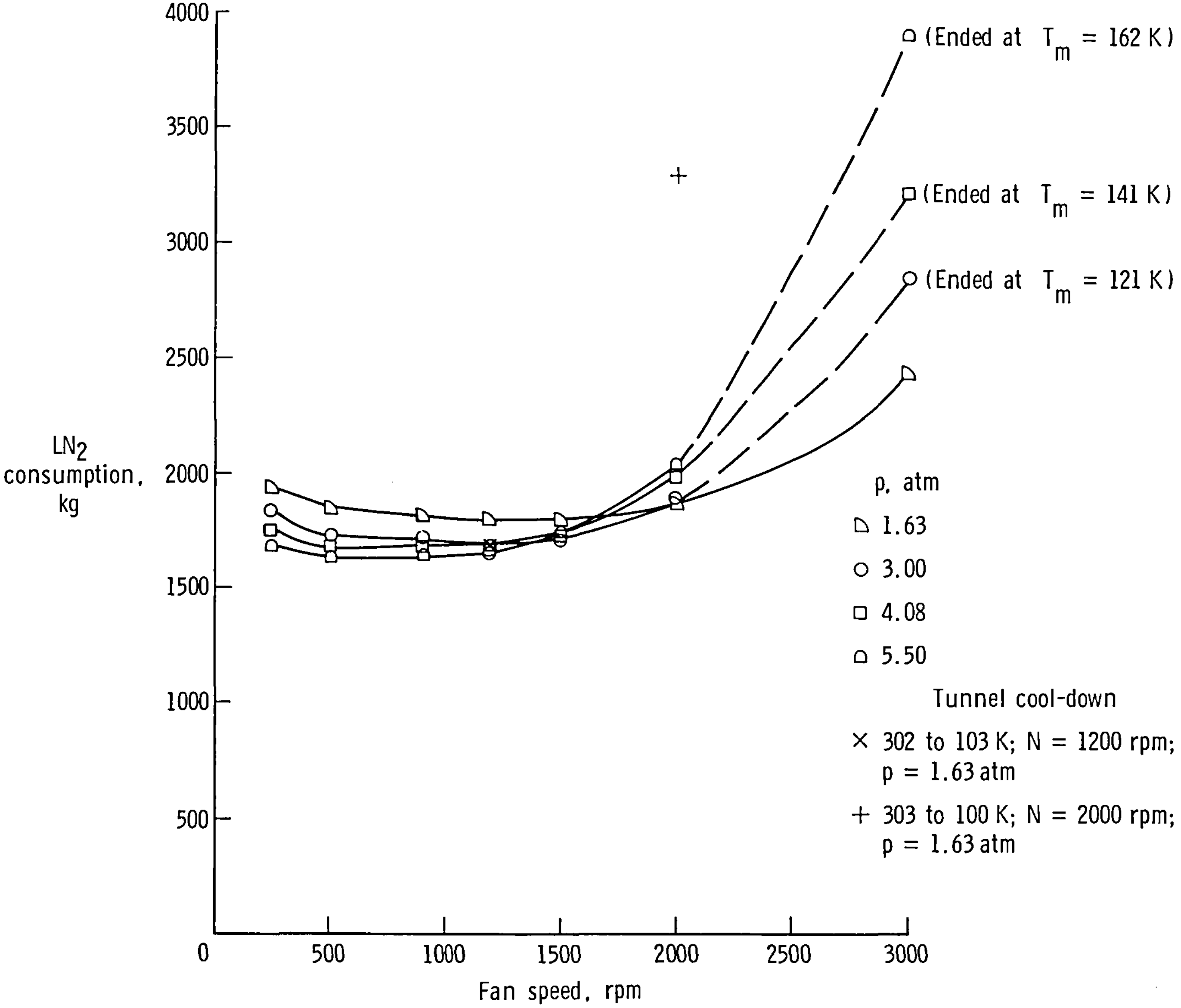
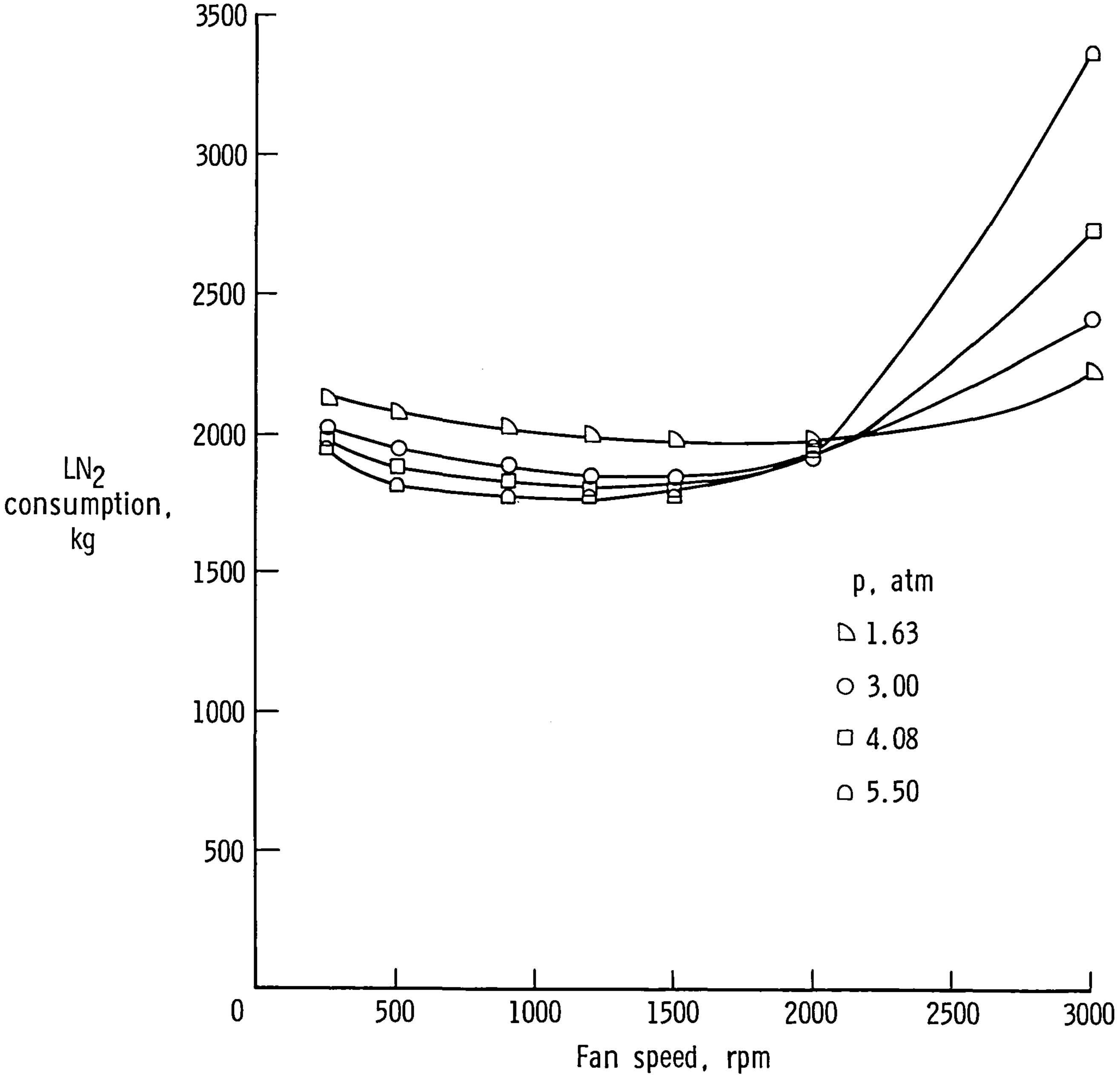


Figure 4.- Liquid-nitrogen consumption for normal cool-downs.



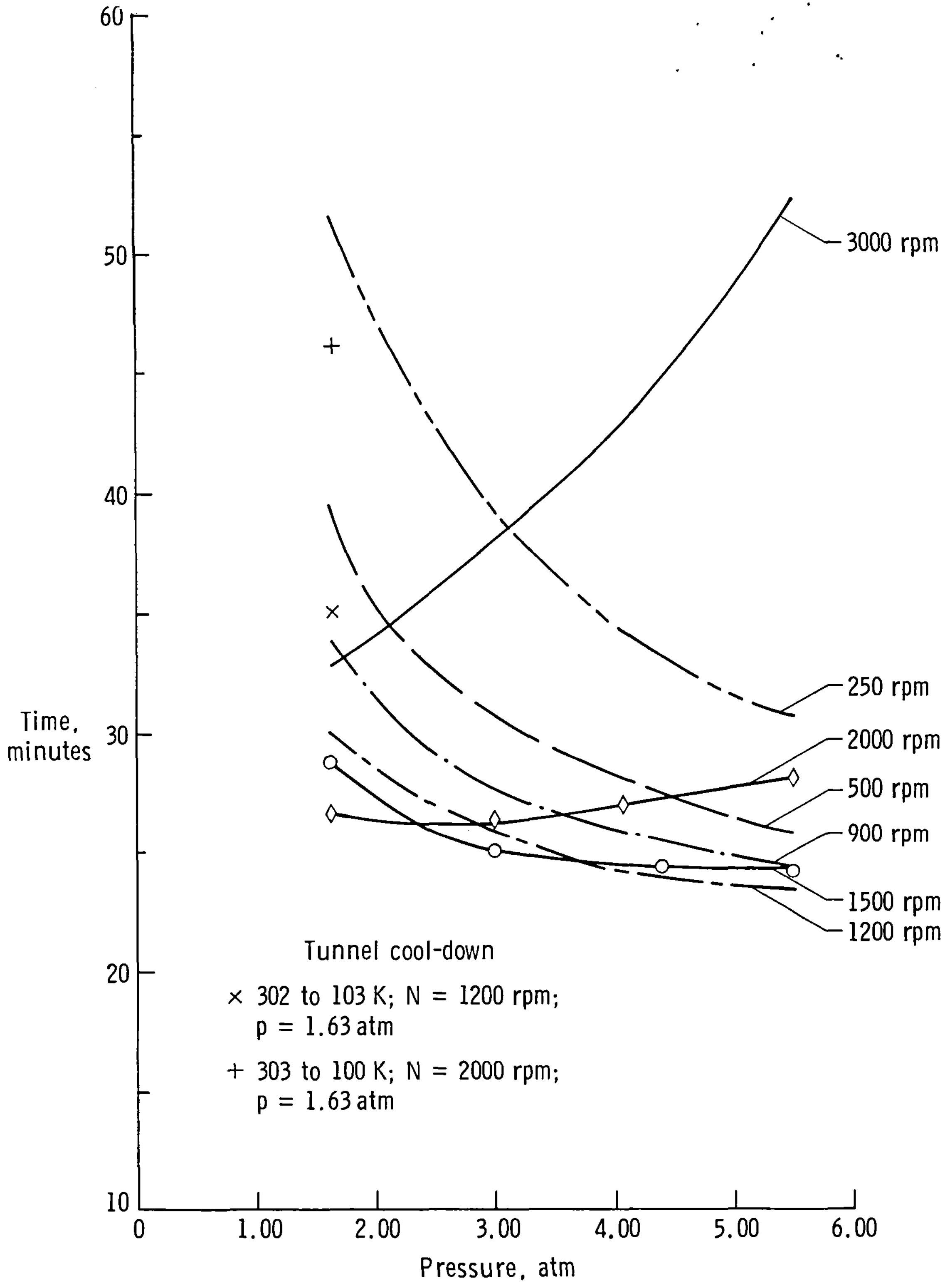
(a) $LN_2$ consumption for 1.25 kg/sec $LN_2$ injection rate.

Figure 5.- Cool-downs at constant fan speeds for various closed-loop pressures.



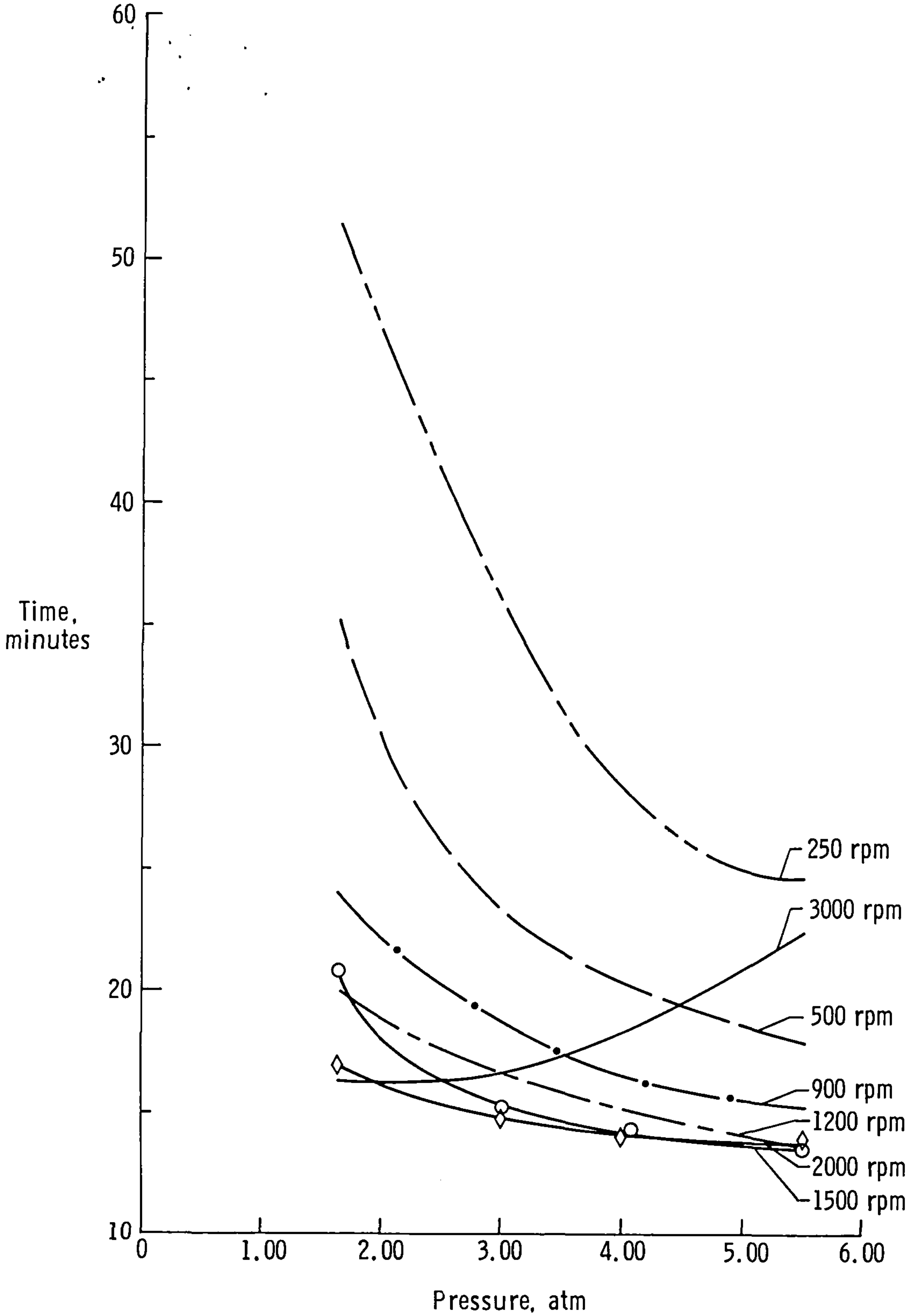
(b) $LN_2$ consumption for 2.50 kg/sec $LN_2$ injection rate.

Figure 5.- Continued.



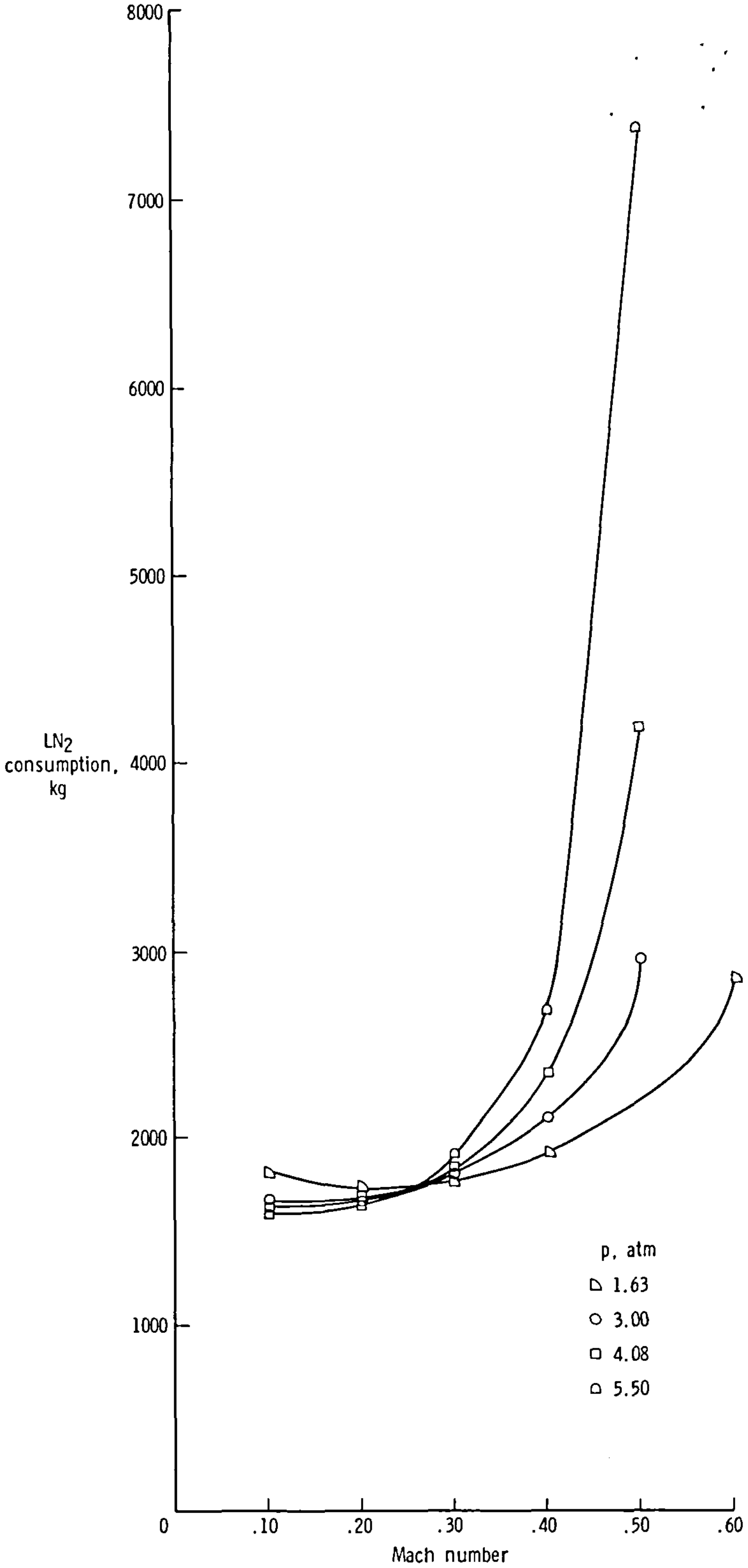
(c) Cool-down time for 1.25 kg/sec $LN_2$ injection rate.

Figure 5.- Continued.



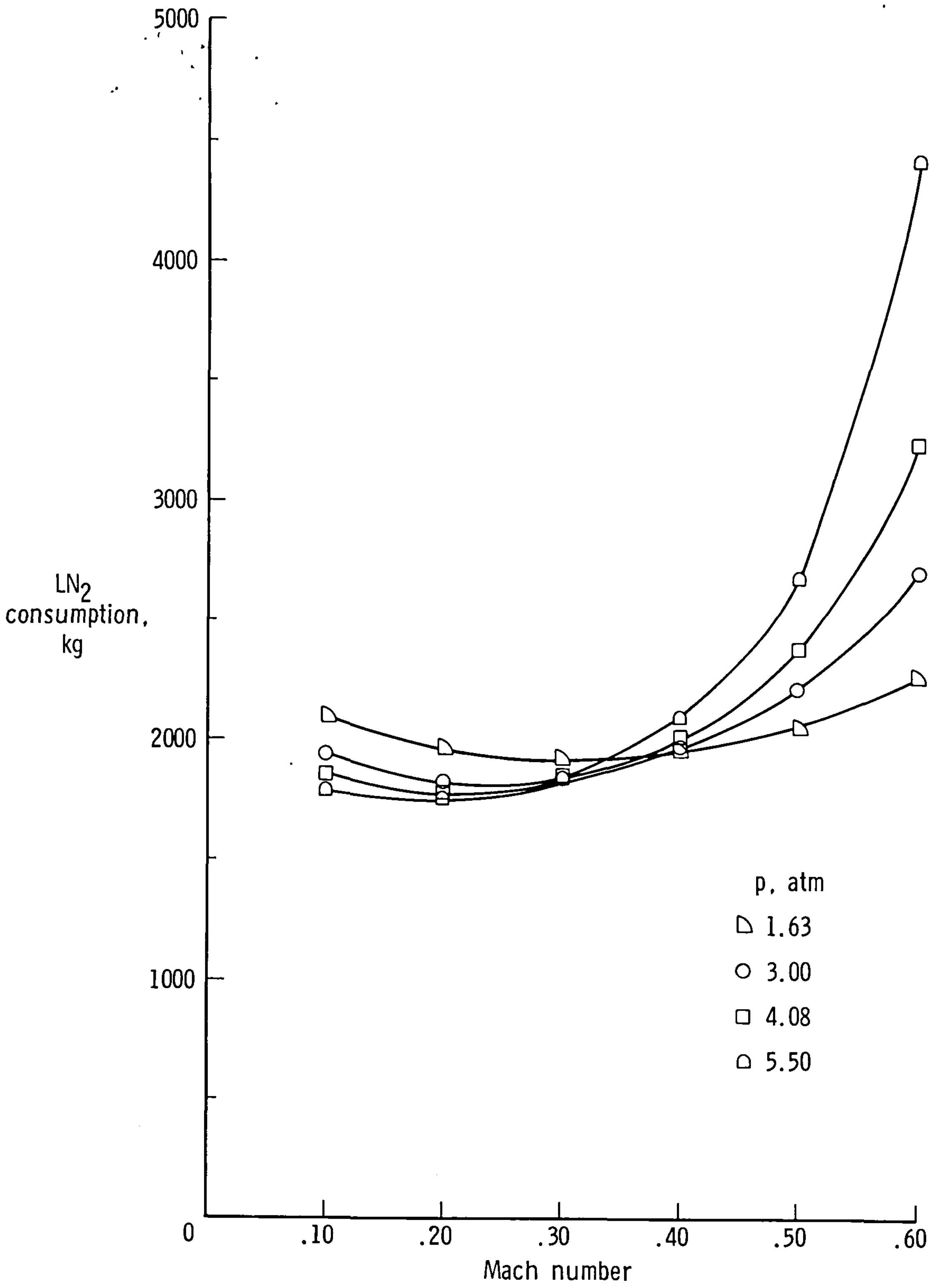
(d) Cool-down time for 2.50 kg/sec $LN_2$ injection rate.

Figure 5.- Concluded.



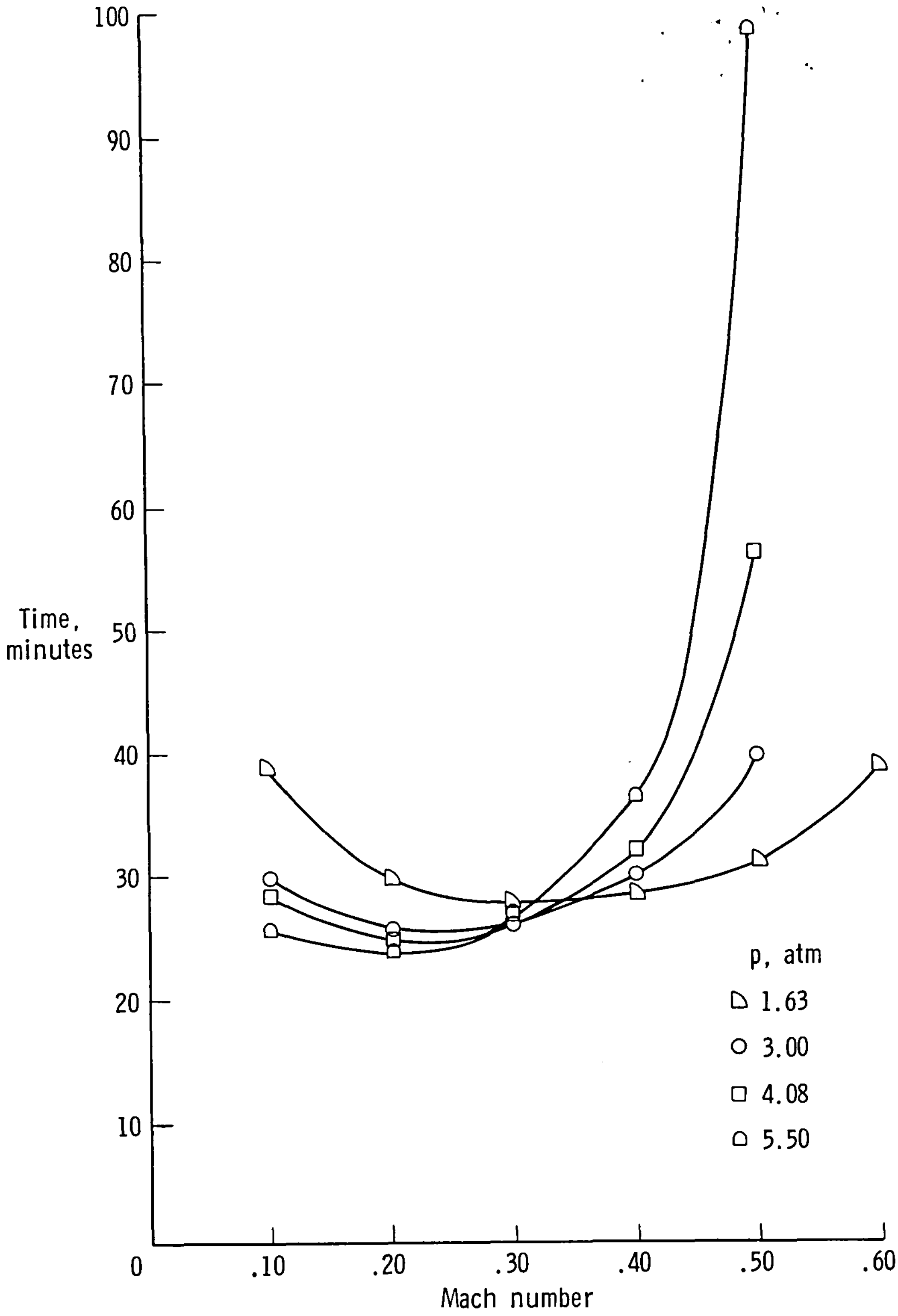
(a) $LN_2$ consumption for 1.25 kg/sec $LN_2$ injection rate.

Figure 6.- Cool-downs at constant Mach numbers for various closed-loop pressures.



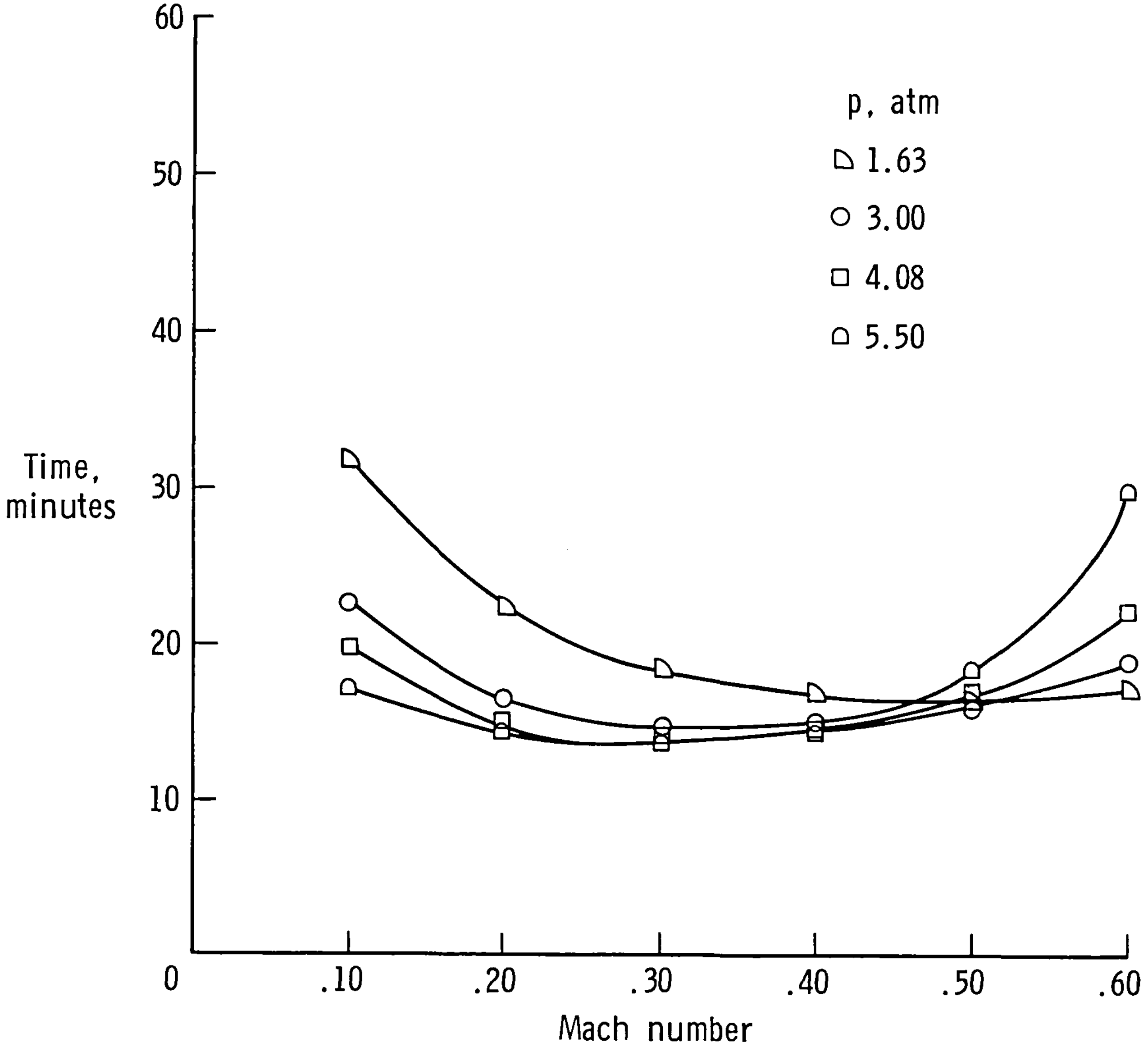
(b) $LN_2$ consumption for 2.50 kg/sec $LN_2$ injection rate.

Figure 6.- Continued.



(c) Cool-down time for 1.25 kg/sec $LN_2$ injection rate.

Figure 6.- Continued.



(d) Cool-down time for 2.50 kg/sec $LN_2$ injection rate.

Figure 6.- Concluded.

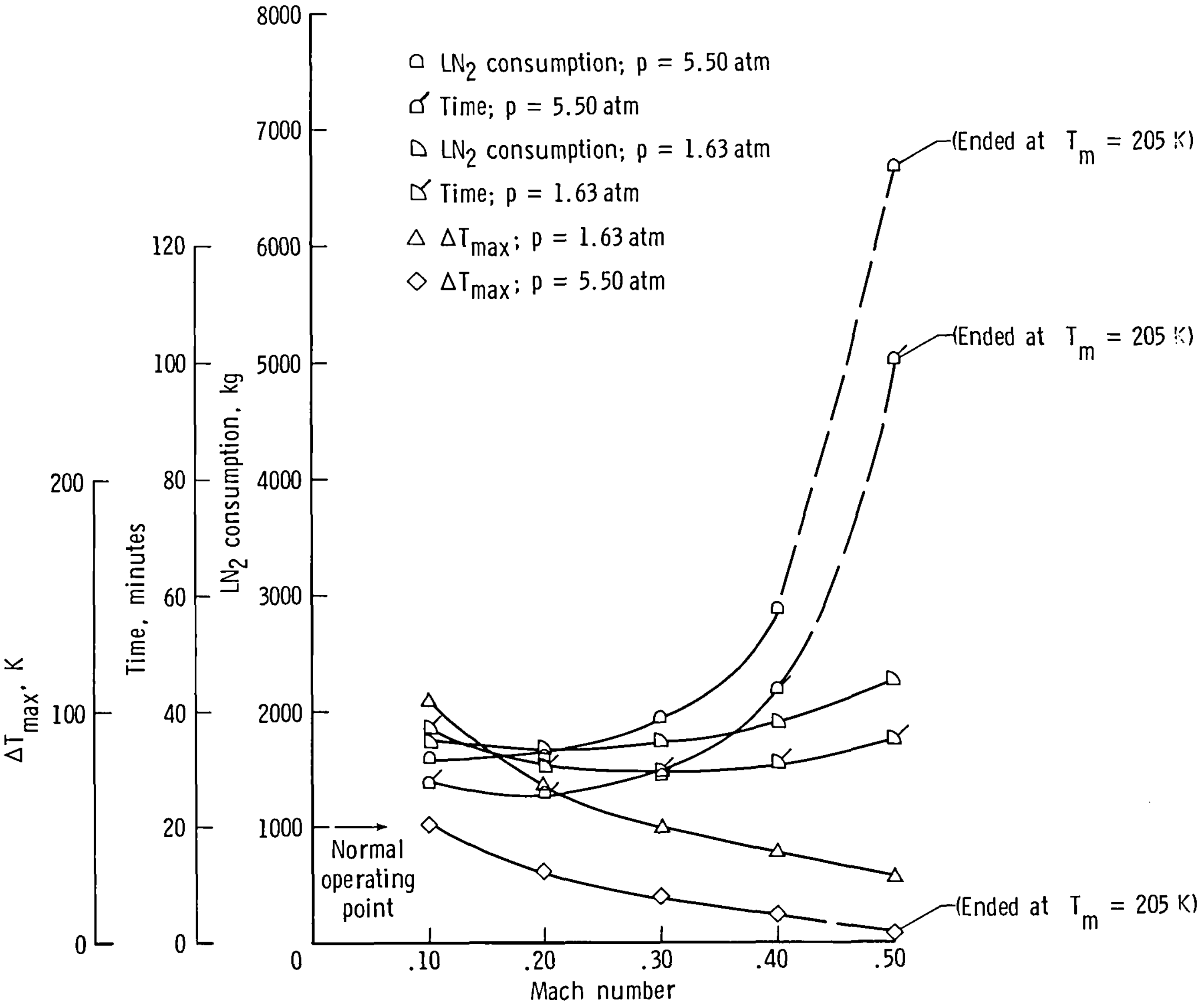


Figure 7.- Cool-down optimization on the 0.3-m TCT simulator using 1.11 kg/sec $LN_2$ injection rate.

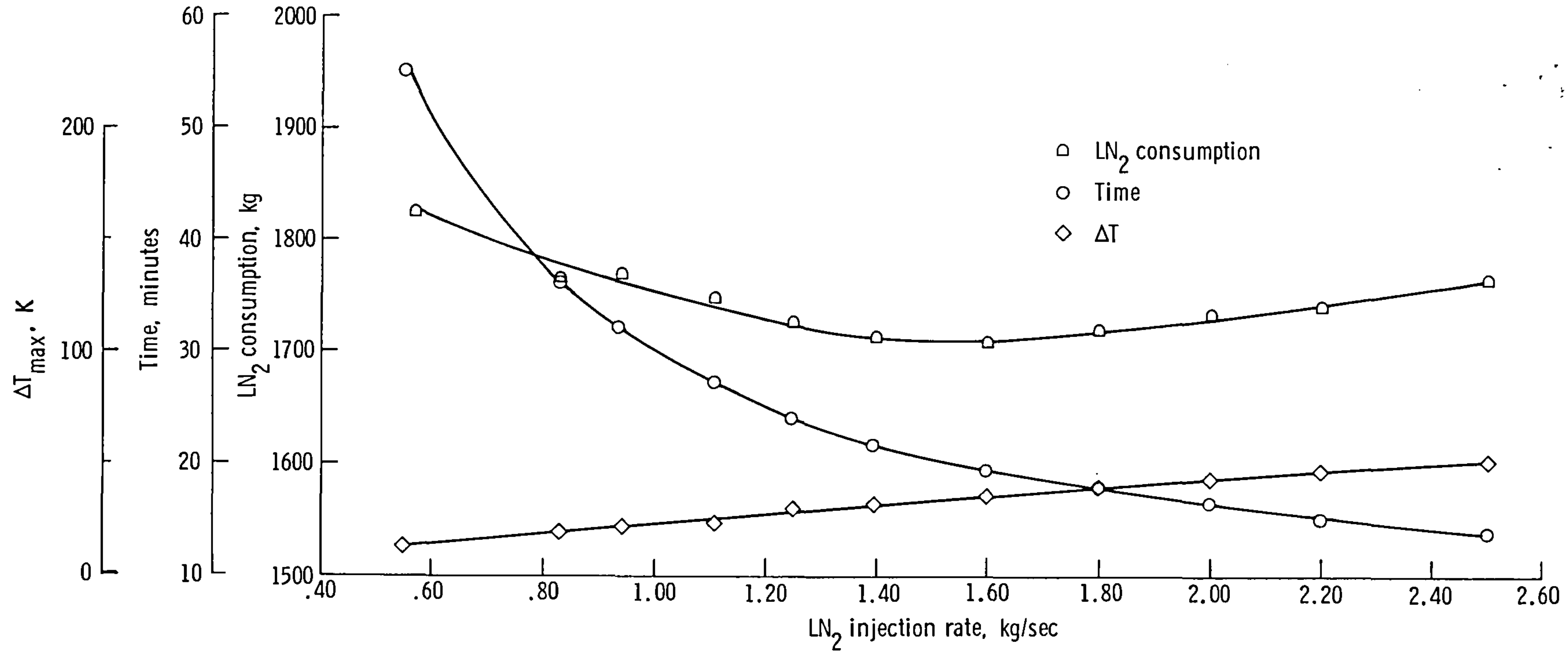
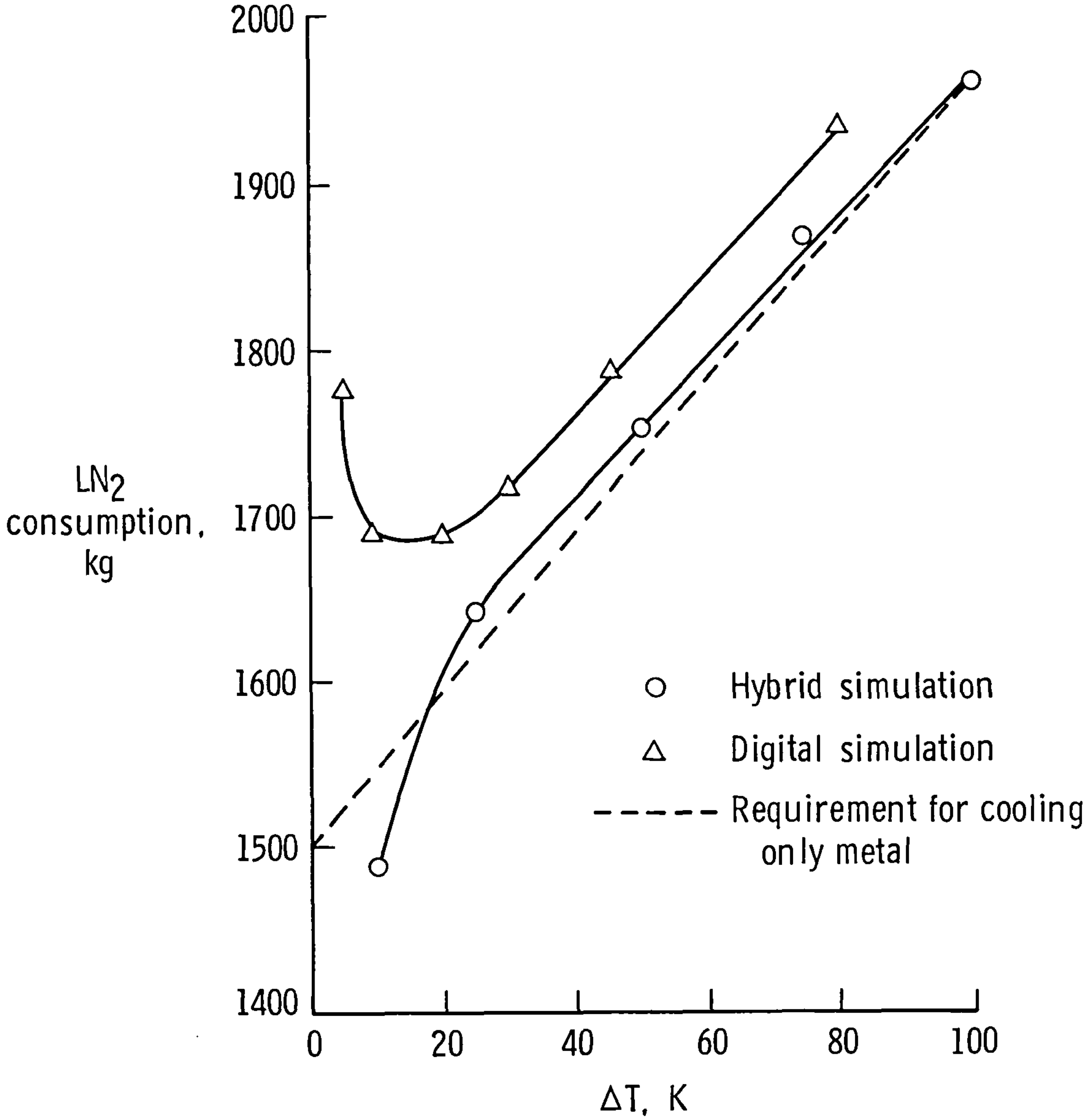
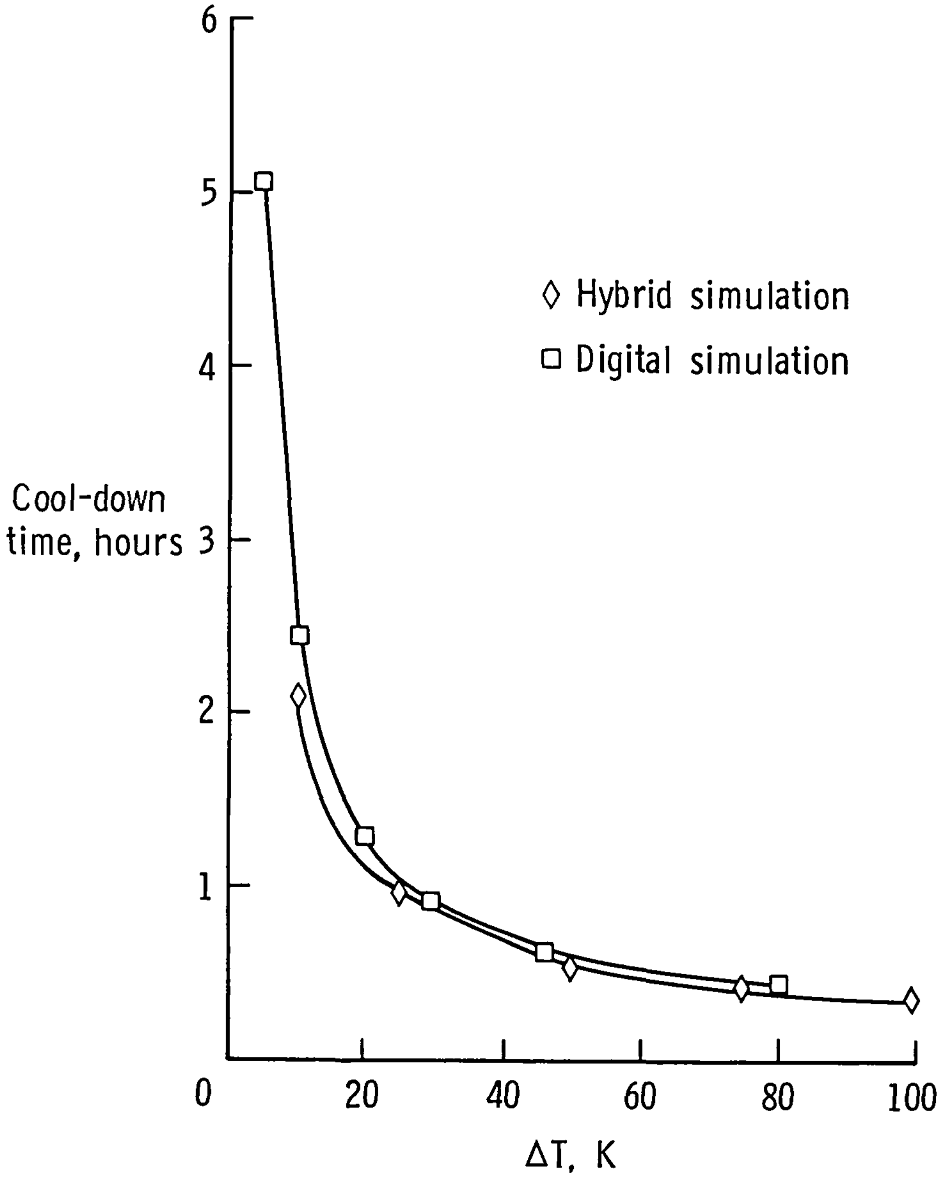


Figure 8.- Influence of LN$_2$ injection rate on cool-down. M = 0.25; p = 5.50 atm.



(a) $LN_2$ consumption.

Figure 9.- Cool-downs at constant metal-to-gas temperature differences. N = 1200 rpm; p = 1.63 atm.



(b) Cool-down time.

Figure 9.- Concluded.

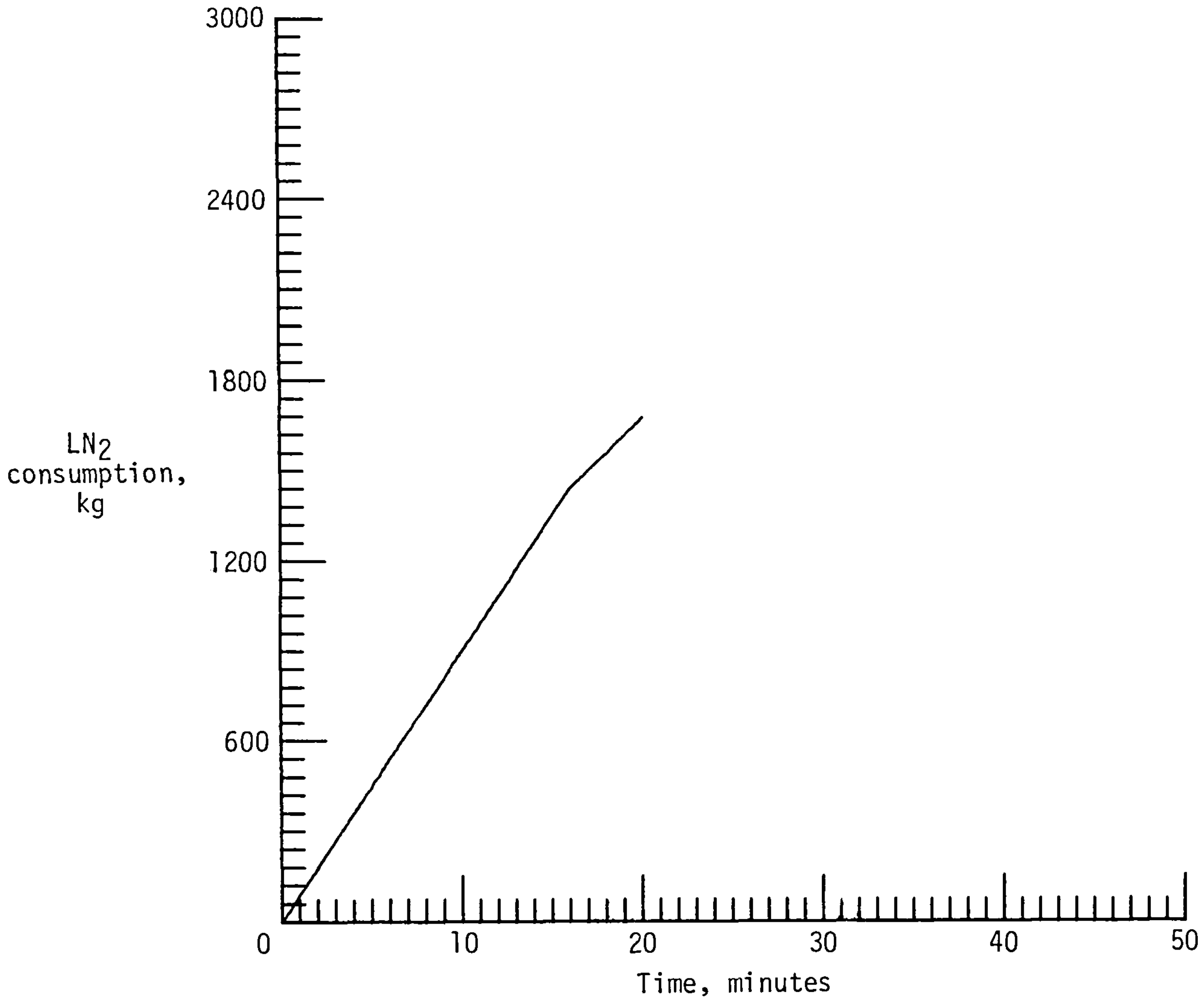


Figure 10.- Liquid-nitrogen consumption for optimum cool-down. $p = 5.50$ atm; $\dot{m}_L = 1.50$ kg/sec; $N = 1200$ rpm.

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15. Supplementary Notes

16. Abstract

This paper presents guidelines and suggestions substantiated by real-time simulation data to ensure optimum time and energy use of injected liquid nitrogen for cooling the Langley 0.3-Meter Transonic Cryogenic Tunnel (TCT). It is directed toward enabling operators and researchers to become cognizant of criteria for using the 0.3-m TCT in an energy- or time-efficient manner. The recommendations made herein, if followed, will result in minimum time and liquid-nitrogen usage during tunnel cool-down. These operational recommendations have been developed based on information collected from a validated simulator of the 0.3-m TCT and experimental data from the tunnel. Results and trends, however, can be extrapolated to other similarly constructed cryogenic wind tunnels.

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