NASA Technical Memorandum 81802

Estimation of Fan Pressure Ratio Requirements and Operating Performance for the National Transonic Facility

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and Space Administration

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SUMMARY

The National Transonic Facility (NTF), a fan-driven, transonic, pressurized, cryogenic wind tunnel, will operate over the Mach number range of 0.10 to 1.20 with stagnation pressures varying from 1.00 to about 8.8 atm (1 atm = 101.3 kPa = 1.01 bar) and stagnation temperatures varying from 77 to 340 K. The design Reynolds number capability of this wind tunnel is 120×10^6, based on a reference length of 0.25, at a Mach number of 1.00. The NTF is cooled to cryogenic temperatures by the injection of liquid nitrogen into the tunnel stream with gaseous nitrogen as the test gas. The NTF can also operate at ambient temperatures using a conventional chilled-water heat exchanger with air or nitrogen as the test gas. This report describes the methods used in estimating the fan pressure ratio requirements and presents the estimated NTF operating envelopes at Mach numbers from 0.10 to 1.20.

INTRODUCTION

The National Transonic Facility (NTF), a fan-driven, transonic, pressurized, cryogenic wind tunnel, will bridge the gap between the Reynolds numbers attained in conventional wind tunnels and those of actual flight. This facility will operate at Mach numbers up to 1.20, stagnation pressures from 1.00 to about 8.8 atm (1 atm = 101.3 kPa = 1.01 bar), and stagnation temperatures from 77 to 340 K. The design Reynolds number capability of this wind tunnel is 120×10^6 based on a reference length of 0.25 m (the NTF has a square, 2.5 m by 2.5 m, test section with filleted corners) at a Mach number of 1.00. The test medium in the NTF is gaseous nitrogen or air. In the cryogenic mode, the tunnel and test medium (gaseous nitrogen) are cooled to cryogenic temperatures with liquid nitrogen injected into the tunnel stream, and in the ambient temperature mode the tunnel and air are held at a constant temperature by the use of a water-cooled heat exchanger installed in the settling chamber. For further details concerning the NTF see references 1 to 5.

Several factors complicate the performance estimation of the NTF. The range of extrapolation from the low Reynolds number, fan pressure ratio requirements (obtained experimentally) to the full-scale Reynolds number conditions, associated with the NTF, is considerably greater than that usually encountered. In addition, since the tunnel operates primarily with cryogenic gaseous nitrogen as the test medium, real gas effects must be accounted for in making the estimates of NTF drive power requirements (see ref. 6). Also, the fan compression ratio (test-section Mach number) may be changed for the NTF by either changing the fan rotational speed or changing the inlet guide vane angle. Since the NTF drive system is rather complicated and the tunnel stagnation pressure and temperature are both variable, the NTF performance maps are rather complex.

The purpose of this paper is to summarize the methods used in estimating the fan pressure ratio requirements and to illustrate their application to the generation of the NTF performance maps. Although, since the time this work was carried out, additional data and information have been made available that would alter somewhat the approaches taken, no effort has been made to update this work. This report simply documents the methods used at the time the NTF design studies were made. However, the sources of the more recent information are referenced in this document.

SYMBOLS

A/A^*	isentropic area ratio, $\frac{1}{M}\left[\left(\frac{2}{\gamma + 1}\right)\left(1 + \frac{\gamma - 1}{2} M^2\right)\right]^{\frac{\gamma+1}{2(\gamma-1)}}$
A_T	test-section cross sectional area, 6.25 m^2
$\bar{c}$	wing reference chord, $\bar{c} = 0.1\sqrt{A_T}$
c_p	specific heat at constant pressure for nitrogen
g	gravity constant, (kg-meter)/(newton-sec^2)
GVA	fan inlet guide vane angle, deg
K	real gas correction factor, $1.0 - \frac{Power_{real}}{Power_{ideal}}$
$\dot{m}$	mass flow rate, kg/sec
M	free-stream Mach number in test section
M_L	local Mach number over model surface
P	test-section static pressure
P_T	free-stream stagnation pressure in test section, atm
$P_{T,2}$	free-stream stagnation pressure downstream of fan, atm
ΔP	total pressure loss in tunnel circuit, atm
R	gas constant for nitrogen, 296.7905 m^2/sec^2-K
$R_{\bar{c}}$	Reynolds number based on $\bar{c}$, $\frac{\rho V \bar{c}}{\mu}$
rpm	revolutions per minute

T test-section static temperature

ΔT $= \frac{\Delta T'}{\eta}$

$\Delta T'$ $= T_{T,2} - T_{T,1}$

T_T free-stream stagnation temperature in test section, K

$T_{T,1}$ free-stream stagnation temperature upstream of fan, K

$T_{T,2}$ free-stream stagnation temperature downstream of fan, K

U_T velocity of fan tip, m/sec

$U_T/\sqrt{\theta}$ corrected tip speed, m/sec

V free-stream velocity, m/sec

γ ratio of specific heats (1.4 for ideal diatomic gas)

η fan efficiency factor

θ temperature ratio, $T_T/288$

λ fan pressure ratio (total pressure ratio across fan)

μ absolute viscosity, $N\text{-sec/m}^2$

ρ density of fluid in tunnel, kg/m^3

Subscripts:

ideal power obtained using ideal gas dynamics

Re Reynolds number

real actual power including real gas effects

DISCUSSION

Circuit Loss Estimation

A 0.186-scale model of the NTF contraction, test section, and high speed diffuser, described in reference 7, was utilized to obtain the estimated pressure loss through these NTF tunnel sections. Table I shows the stagnation pressure losses measured in this 0.186-scale model of the NTF. The remaining circuit losses were estimated and reported in reference 8. Figure 1 shows a plot of the estimated NTF fan pressure ratios λ which were based on scale-model test data (table I) and the estimates shown in reference 8. Since the

NTF pressure ratio estimates shown in figure 1 are for low unit Reynolds number conditions, these estimates must be corrected for the high unit Reynolds number conditions of the NTF. The data in figure 2 show the Reynolds number effect on λ for the Langley 0.3-Meter Transonic Cryogenic Tunnel. In figure 2, the total pressure ratio across the fan was assumed to be equal to the measured static pressure ratio. Reference 9 converts these measured data to total pressure ratios. However, the incremental change with Reynolds number is not appreciably affected. The data in figure 2 show a linear relationship between λ and $\log R_{\bar{c}}$, thus allowing the extrapolation of these data from their upper limit ($R_{\bar{c}} \approx 40 \times 10^6$, $\bar{c} = 0.31$ m) to the upper limit of the NTF ($R_{\bar{c}} \approx 183 \times 10^6$, $\bar{c} = 0.31$ m) at a Mach number of 1.00. Using the data in figure 2, it was found that a linear (or at least nearly linear) relationship existed between the ratio $\Delta P/\Delta P_{low\ Re}$ (where $\Delta P_{low\ Re}$ is the pressure rise across the fan for a stagnation pressure of 1.2 atm and a stagnation temperature of 300 K) and the test-section Mach number. This allowed the data to be extrapolated from the maximum Mach number of these data (M = 0.85) to the maximum NTF Mach number (M = 1.20). Although the data in figures 2 and 3 are derived from 0.3-Meter Transonic Cryogenic Tunnel test results, it must be assumed that these corrections hold for the NTF, since these are the only available data. These Reynolds number correction ratios, $\Delta P/\Delta P_{low\ Re}$, are then used in conjunction with the low Reynolds number pressure ratio data in figure 1 $\left(\left(\frac{\Delta P}{P_{T,2}}\right)_{low\ Re} = \frac{\lambda - 1}{\lambda}\right)$ to obtain the corrected pressure loss for the NTF.

Drive System

The fan is powered by two variable-speed wound rotor induction motors and a synchronous motor, with 10-minute maximum power ratings of 48.4 megawatts and 45.0 megawatts, respectively. As shown in figure 4, the induction motors are coupled to the fan drive shaft through a two-speed gear box with gear ratios (fan to motor speed) of 360/835 in low gear and 600/835 in high gear. The purpose of the two-speed gear box is to provide a better match of the available motor torque to the required fan torque at different operating temperatures. It should be noted that the primary use for high gear operation will be for the ambient temperature test conditions (T_T = 340 K). The synchronous motor is in line with the fan drive shaft and rotates at fan speed at all times.

The maximum shaft power (10-min rating) available from the combination of drive motors, as a function of fan rotational speed is shown in figure 5 for both the high and low gear ratios. The synchronous motor is operated at the fan shaft speed, corresponding to the maximum speed of the induction motors in the low gear ratio, and is brought up to synchronous speed by the induction motors. The rotational speed of the induction motors is controllable within 1/4 percent over the entire range using a modified Kramer drive control system.

Under high power conditions, when the power of both the induction and synchronous motors is required, the fan is rotated at the synchronous motor speed of 360 rpm and the tunnel speed is controlled by varying the inlet guide vane angle. At lower power conditions where only the induction motor power is required, tunnel speed can be varied either by inlet guide vane angle variation or by motor rotational speed variation.

Performance Calculations

The NTF power requirements, in megawatts, were estimated using equation (1), where the stagnation pressure P_T and the stagnation temperature T_T have units of atmospheres and kelvins, respectively:

$$\text{Fan shaft power} = 26.165 \frac{P_T\sqrt{T_T}}{A/A^*\eta}\left(\lambda^{0.286} - 1\right)\left(1 - K \frac{P_T}{8.8}\right) \quad (1)$$

The appendix has a detailed derivation of equation (1). Equation (2) relates the fan rpm to the fan corrected tip speed $U_T/\sqrt{\theta}$ and stagnation temperature T_T:

$$\text{rpm} = 0.1874 \frac{U_T}{\sqrt{\theta}} \sqrt{T_T} \quad (2)$$

See the appendix for the derivation of equation (2). The fan design data of table II provides the corrected tip speed parameter $\left(0.1874U_T/\sqrt{\theta}\right)$ as a function of Mach number, fan pressure ratio, inlet guide vane angle, and fan efficiency factor η. Presented in table III are values for the real gas correction factor K (see eq. (1)); these values of K were obtained by comparing real gas and ideal gas isentropic compressions for nitrogen in a manner similar to that outlined in reference 6. Since K is only a weak function of Mach number, values of K at Mach numbers not included in table III can be obtained by linear interpolation; or if the desired Mach number is outside the range of data shown in table III, the correction factor at the Mach number nearest the desired Mach number can be used with little loss of accuracy.

Operating Envelopes

With the Reynolds number correction applied to those tunnel pressure ratios shown in figure 1, the tunnel operating envelopes (performance maps) have been calculated for the Mach number range 0.1 to 1.2 (see figs. 6 to 17). The envelopes are in the form of stagnation pressure versus Reynolds number with lines of constant stagnation temperature superimposed. The estimated power required to obtain these conditions is indicated by the constant power lines on the maps. The maximum operating envelope is shown by the cross-hatched line. The boundaries on the figures are formed on the left by the maximum operating temperature, induction motor limit (high gear), or inlet guide vane limits for the synchronous motor. It should be noted here that for the synchronous motor (constant rpm motor), lines of constant temperature are lines of constant guide vane angle (see eq. (2) and table II). The boundaries across the tops of the maps are formed by the total available drive power or tunnel shell pressure limits, and on the right by the minimum stagnation temperature.

The minimum stagnation temperature is determined by the condensation of nitrogen gas in sufficient quantities to appreciably affect test results. This limit is probably a function of the model configuration in the test section since the maximum local Mach number in the flow field and the extent of the high Mach number flow field play a major role in setting the condensation boundaries for a particular flow field. The condensing of the free stream (near free-stream saturation) is a well established lower bound. The other saturation line, shown on the maps, is specified at a local Mach number and is an estimate for the upper boundary. For further discussion on the condensation of nitrogen gas, the reader is referred to reference 10.

For the case where the synchronous motor is not utilized, there are an infinite number of combinations of fan rpm and guide vane setting for a given test-section condition; thus, since fan efficiency changes somewhat with inlet guide vane setting, there are an infinite number of lines (although there will be little difference between them) that would satisfy a given fan shaft power level. Thus, the lines of constant power for power levels less than the variable speed motor limits are not unique. Any discontinuities noted in the lines of constant power are due to changes in fan efficiency caused by changes in gear ratio or guide vane setting.

As indicated earlier, the NTF will be capable of operating in an ambient temperature mode using either air or nitrogen as the test gas with cooling accomplished by a conventional chilled-water heat exchanger. The cooling capacity of the heat exchanger corresponds to a power input of about 35 megawatts. However, ambient temperature testing, using nitrogen as the test gas may be accomplished with the injection of liquid nitrogen to cool the test gas. Then the power limit for ambient testing becomes 93.37 megawatts.

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APPENDIX

DERIVATION OF POWER AND RPM EQUATIONS

The derivation of the power equation shown in equation (1) of the text is as follows. An expression for the power required assuming isentropic compression is shown in equation (A1)

$$\text{Power} = \dot{m} c_p \, \Delta T' \tag{A1}$$

However, the mass flow rates $\dot{m}$ may be written as

$$\dot{m} = \rho A_T V = \frac{P}{RT} A_T \sqrt{\gamma RT} \tag{A2}$$

Upon further substitution equation (A2) becomes

$$\dot{m} = \frac{P}{P_T} P_T A_T M \sqrt{\frac{\gamma}{R}} \frac{1}{\sqrt{(T/T_T)\, T_T}} = g \sqrt{\frac{\gamma}{R}} \frac{P_T A_T}{\sqrt{T_T}} \frac{M}{\left(1 + \frac{\gamma - 1}{2} M^2\right)^3} \tag{A3}$$

Finally, the expression for mass flow rate becomes

$$\dot{m} = g \sqrt{\frac{\gamma}{R}} \left(\frac{2}{\gamma + 1}\right)^3 A_T \frac{P_T}{\sqrt{T_T}} \frac{1}{A/A^*} \tag{A4}$$

A temperature difference based on isentropic compression can be written as

$$\Delta T' = T_{T,1}\left(\frac{T_{T,2}}{T_{T,1}} - 1\right) = T_{T,1}\left(\lambda^{\frac{\gamma-1}{\gamma}} - 1\right) \tag{A5}$$

However, fans do not achieve isentropic compression and the actual temperature rise is given by

$$\Delta T = \frac{\Delta T'}{\eta} = \frac{T_{T,1}}{\eta}\left(\lambda^{\frac{\gamma-1}{\gamma}} - 1\right) \qquad \text{(A6)}$$

Assuming that $T_T = T_{T,1}$, equation (A6) then becomes

$$\Delta T = \frac{T_T}{\eta}\left(\lambda^{\frac{\gamma-1}{\gamma}} - 1\right) \qquad \text{(A7)}$$

Substituting equations (A4) and (A7) into equation (A1), and making proper allowances for the dimensions of the quantities involved, results in equation (A8)

$$\text{Power (in megawatts)} = 26.165\,\frac{P_T\sqrt{T_T}}{A/A^*\eta}\left(\lambda^{0.286} - 1\right) \qquad \text{(A8)}$$

Finally, the real gas correction for power is applied to equation (A8)

$$\text{Power (in megawatts)} = 26.165\,\frac{P_T\sqrt{T_T}}{A/A^*\eta}\left(\lambda^{0.286} - 1\right)\left(1 - K\,\frac{P_T}{8.8}\right) \qquad \text{(A9)}$$

The derivation of the rpm equation shown in equation (2) of the text is as follows. Equation (A10) defines rpm as

$$\text{rpm} = \frac{60U_T}{\pi \times \text{Fan diameter}} \qquad \text{(A10)}$$

Using a fan diameter of 6.00 m, equation (A10), when multiplied by T_T and divided by 288 K (reference temperature) becomes

$$\text{rpm} = \frac{60}{6.00\pi\sqrt{288}}\,\frac{U_T}{\sqrt{\theta}}\,T_T \qquad \text{(A11)}$$

Finally equation (A11) reduces to

$$rpm = 0.1874 \frac{U_T}{\sqrt{\theta}} \sqrt{T_T} \tag{A12}$$

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TABLE I.- MEASURED PRESSURE LOSSES

[0.186-scale model of the NTF contraction, test section, and high speed diffuser]

Mach number, M	*$R_{\bar{c}}$	**$\Delta P/P_T$
1.20	3.1×10^6	0.1335
1.10	3	.1015
1.00	3.05	.0782
.90	2.95	.0568
.80	2.9	.0438
.60	2.4	.0230
.40	1.8	.0120

*$\bar{c}$ = 0.25 m.

**All measurements made at a stagnation pressure of 1 atm (1 atm = 101.3 kPa).

TABLE II.- NTF FAN DESIGN DATA

GVA, deg	$0.1874U_T/\sqrt{\theta}$, m/sec	η	$0.1874U_T/\sqrt{\theta}$, m/sec	η	$0.1874U_T/\sqrt{\theta}$, m/sec	η	$0.1874U_T/\sqrt{\theta}$, m/sec	η
	M = 1.20 λ = 1.2330		M = 1.10 λ = 1.160		M = 1.00 λ = 1.160		M = 0.90 λ = 1.1280	
30	No solution		45.61	0.761	41.73	0.785	38.50	0.788
25	46.86	0.780	42.64	.816	39.22	.820	36.22	.815
20	44.10	.828	40.37	.840	37.20	.837	34.39	.822
10	40.13	.865	36.81	.855	33.90	.844	31.22	.830
0	37.05	.870	33.83	.857	31.06	.847	28.46	.833
-10	34.28	.869	31.09	.855	28.46	.845	26.02	.824
-20	31.58	.864	28.49	.846	26.12	.824	24.04	.781
-25	30.21	.859	27.29	.831	25.11	.801	23.17	.751
-30	28.85	.850	26.16	.809	24.14	.773	22.34	.716
	M = 0.80 λ = 1.100		M = 0.70 λ = 1.0775		M = 0.60 λ = 1.055		M = 0.50 λ = 1.0405	
30	35.51	0.785	31.69	0.780	29.07	0.774	24.55	0.781
25	33.50	.801	29.69	.791	27.44	.787	23.13	.792
20	32.33	.809	28.27	.800	25.99	.795	21.98	.799
10	28.75	.818	25.58	.808	23.51	.804	19.41	.808
0	26.14	.821	23.53	.812	21.41	.807	17.99	.810
-10	23.95	.799	21.53	.779	19.76	.770	16.56	.777
-20	22.24	.743	19.99	.718	18.46	.704	15.53	.719
-25	21.49	.708	19.41	.680	17.87	.667	15.02	.672
-30	20.77	.671	18.84	.641	17.30	.629	14.56	.636
	M = 0.40 λ = 1.0260		M = 0.30 λ = 1.0175		M = 0.20 λ = 1.0120		M = 0.10 λ = 1.0075	
30	21.49	0.787	18.21	0.787	11.99	0.787	5.82	0.787
25	20.35	.800	17.24	.800	11.42	.800	5.54	.800
20	19.37	.806	16.33	.806	10.85	.806	5.14	.806
10	17.30	.813	14.67	.813	9.65	.813	4.57	.813
0	16.04	.815	13.59	.815	8.91	.815	4.28	.815
-10	14.73	.795	12.56	.795	8.28	.795	4.00	.795
-20	13.80	.739	11.53	.739	7.71	.739	3.71	.739
-25	13.35	.704	11.25	.704	7.34	.704	3.54	.704
-30	12.93	.668	10.85	.668	7.14	.668	3.43	.668

TABLE III.- REAL GAS CORRECTION FACTOR K

M = 1.20		M = 1.10		M = 1.00		M = 0.90		M = 0.80	
T_T, kelvins	K	T_T, kelvins	K	T_T, kelvins	K	T_T, kelvins	K	T_T, kelvins	K
353	0	353	0	353	0	353	0	353	0
285	0	285	0	311	0	253	.002	267	0
266	.001	266	.001	256	.001	234	.003	233	.003
247	.002	247	.002	211	.006	214	.006	200	.008
228	.004	228	.004	200	.008	195	.010	178	.013
209	.006	209	.006	189	.011	175	.015	167	.018
190	.010	190	.010	167	.017	156	.024	156	.023
171	.015	171	.015	156	.023	136	.039	144	.031
152	.023	152	.023	144	.030	117	.068	133	.040
133	.038	133	.038	133	.040	113	.076	122	.055
112	.068	112	.068	111	.073	109	.087	111	.078
89	.140	89	.140	100	.011	89	.140	89	.140
				89	.140				

TABLE III.- Concluded

M = 0.70		M = 0.60		M = 0.50		M = 0.40	
T_T, kelvins	K	T_T, kelvins	K	T_T, kelvins	K	T_T, kelvins	K
353	0	353	0	353	0	353	0
255	.002	244	.001	257	.001	244	.001
236	.003	211	.006	237	.003	211	.006
216	.006	189	.011	217	.005	189	.011
196	.009	167	.018	197	.008	167	.019
177	.015	156	.024	178	.014	156	.025
157	.024	144	.032	158	.023	144	.033
137	.039	133	.044	138	.039	133	.045
118	.069	122	.060	118	.070	122	.063
114	.078	111	.084	111	.091	111	.090
106	.103	108	.095	105	.113	110	.138
89	.140	89	.160	89	.150	89	.180

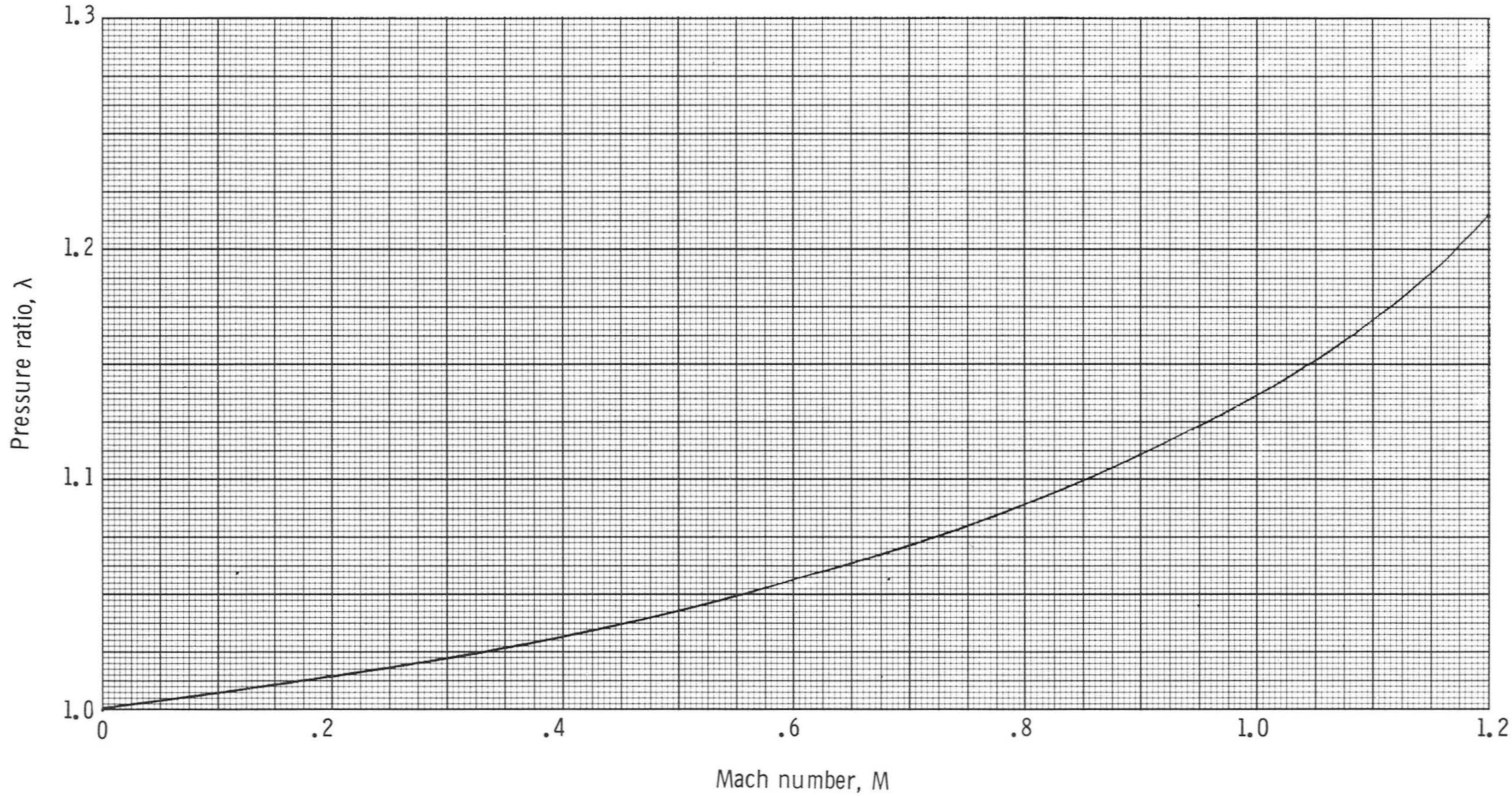

Figure 1.- Estimated NTF fan pressure ratio. Low Reynolds number; P_T = 1 atm; T_T = 340 K.

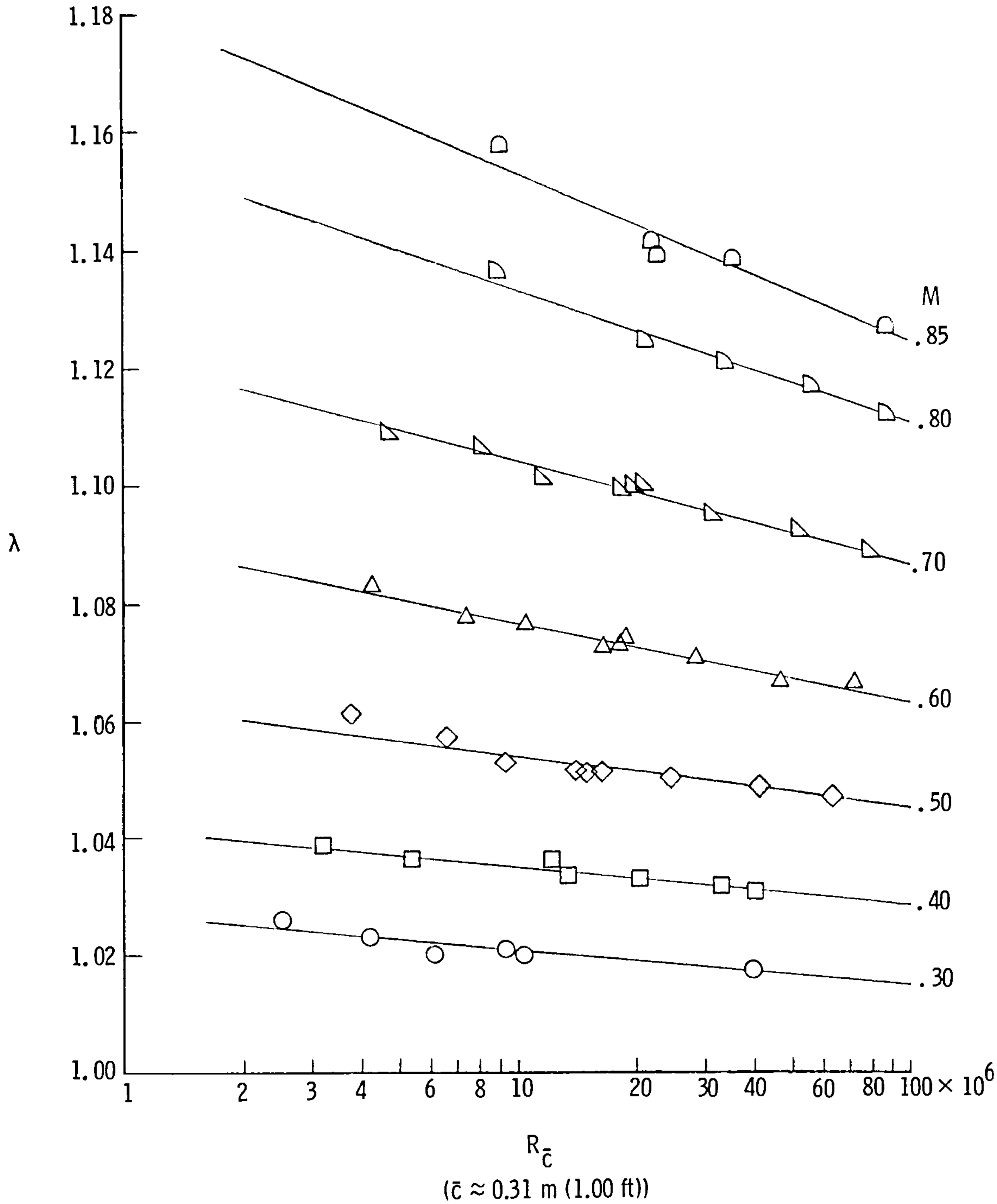

Figure 2.- Effect of Reynolds number on tunnel pressure ratio for the 0.3-Meter Transonic Cryogenic Tunnel.

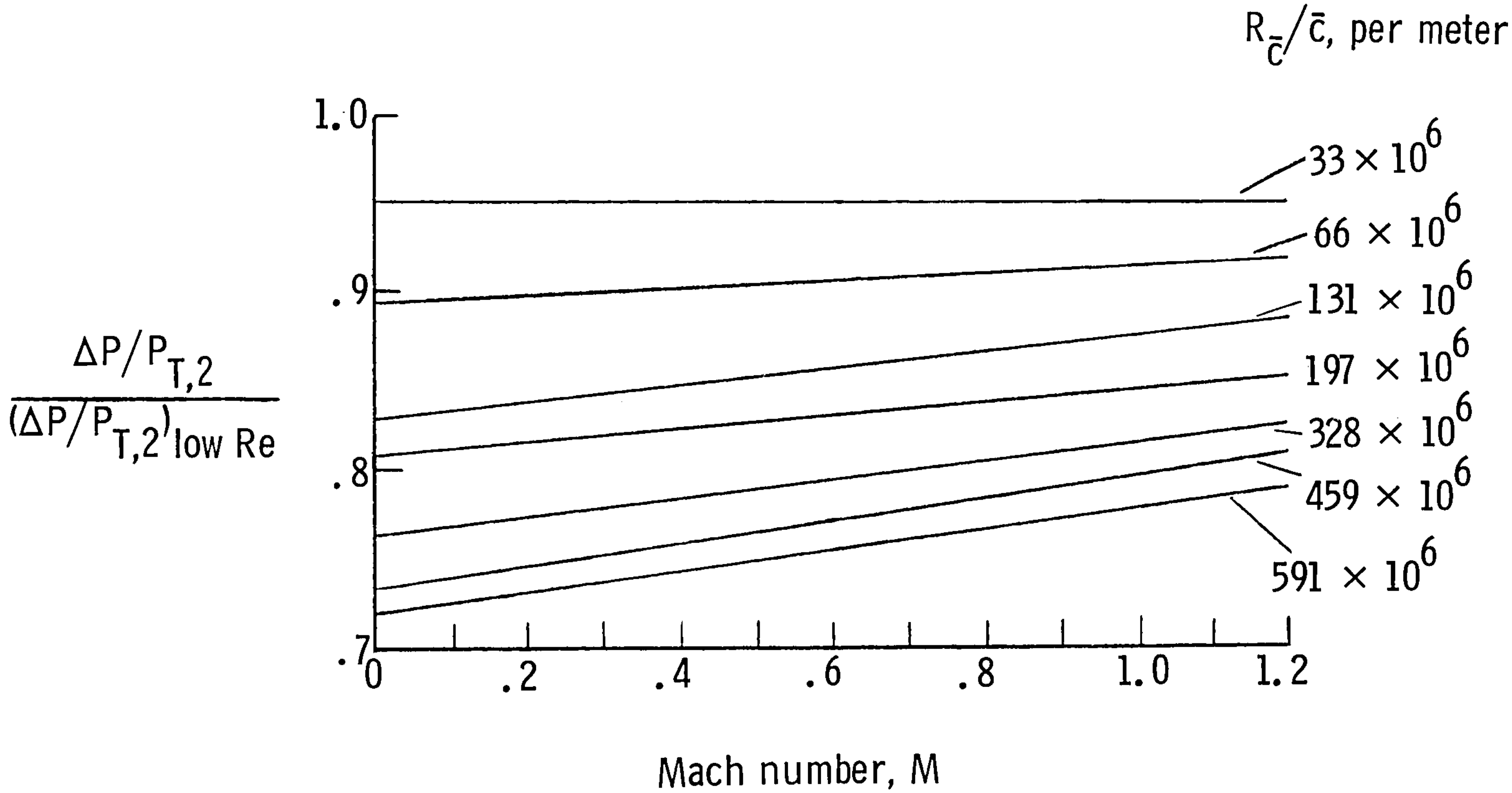

Figure 3.- Effect of Reynolds number on tunnel pressure loss, based on 0.3-Meter Transonic Cryogenic Tunnel data.

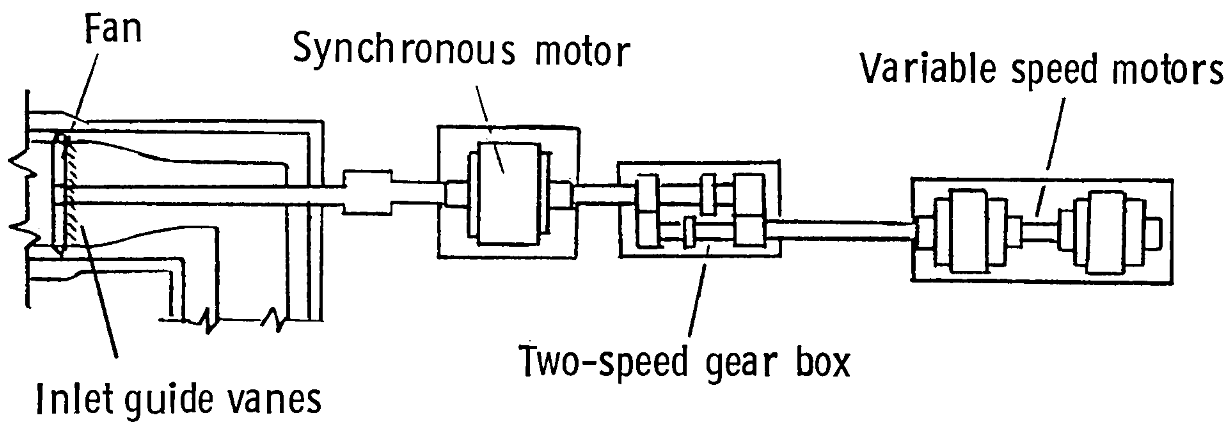

Figure 4.- Schematic of the NTF drive system.

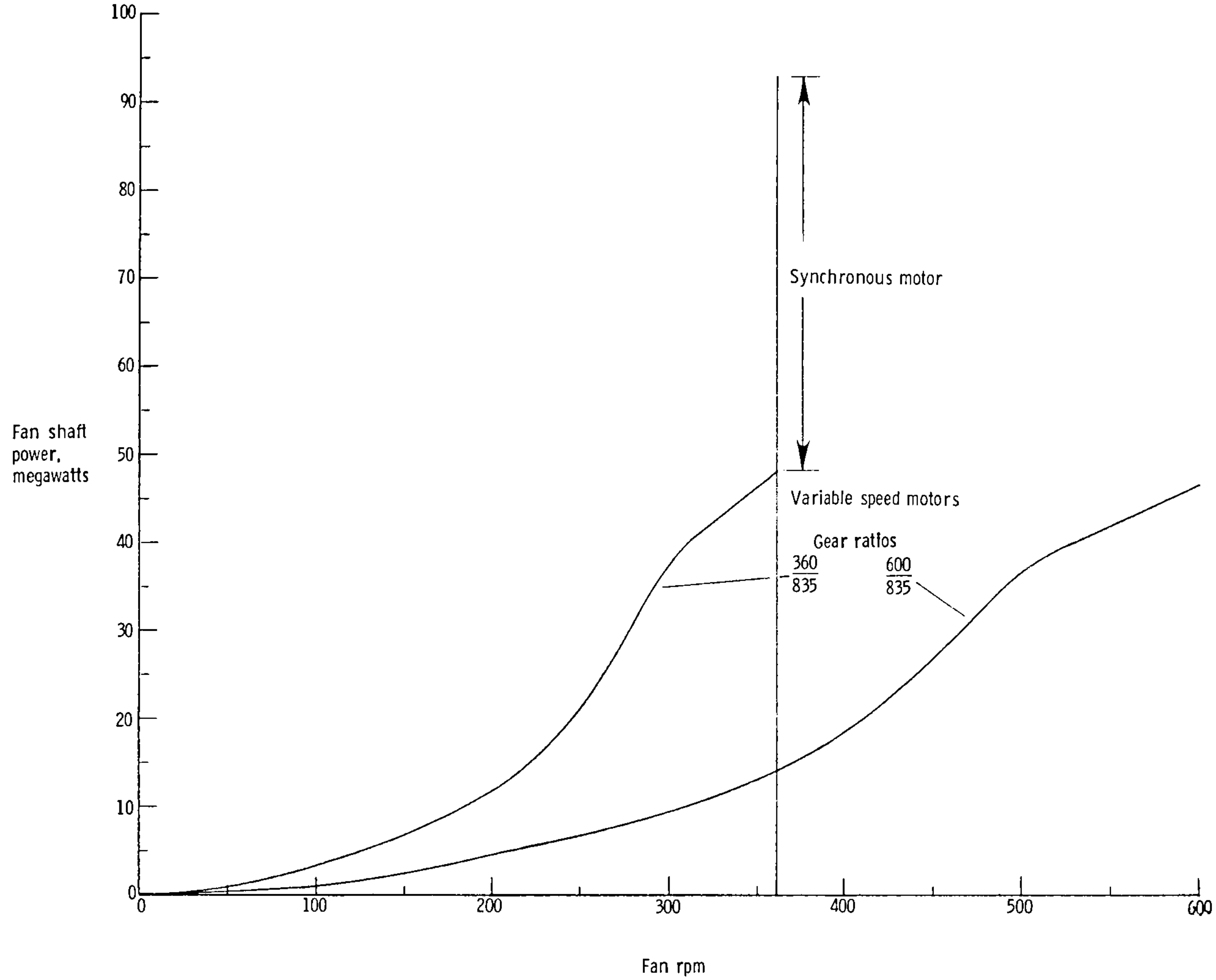

Figure 5.- Estimated NTF 10-min fan shaft power rating.

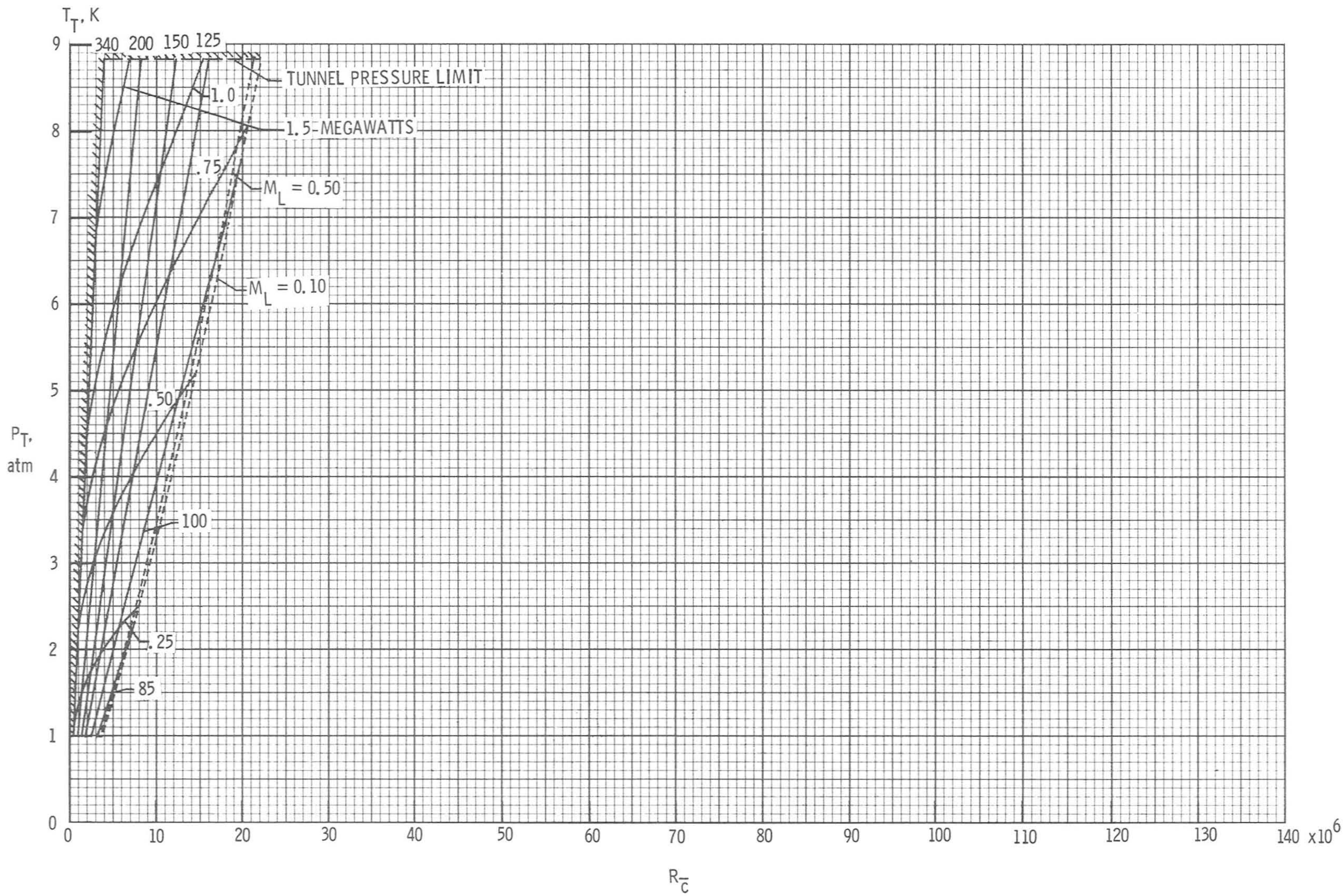

Figure 6.- Estimated NTF performance map for free-stream Mach number of 0.10.

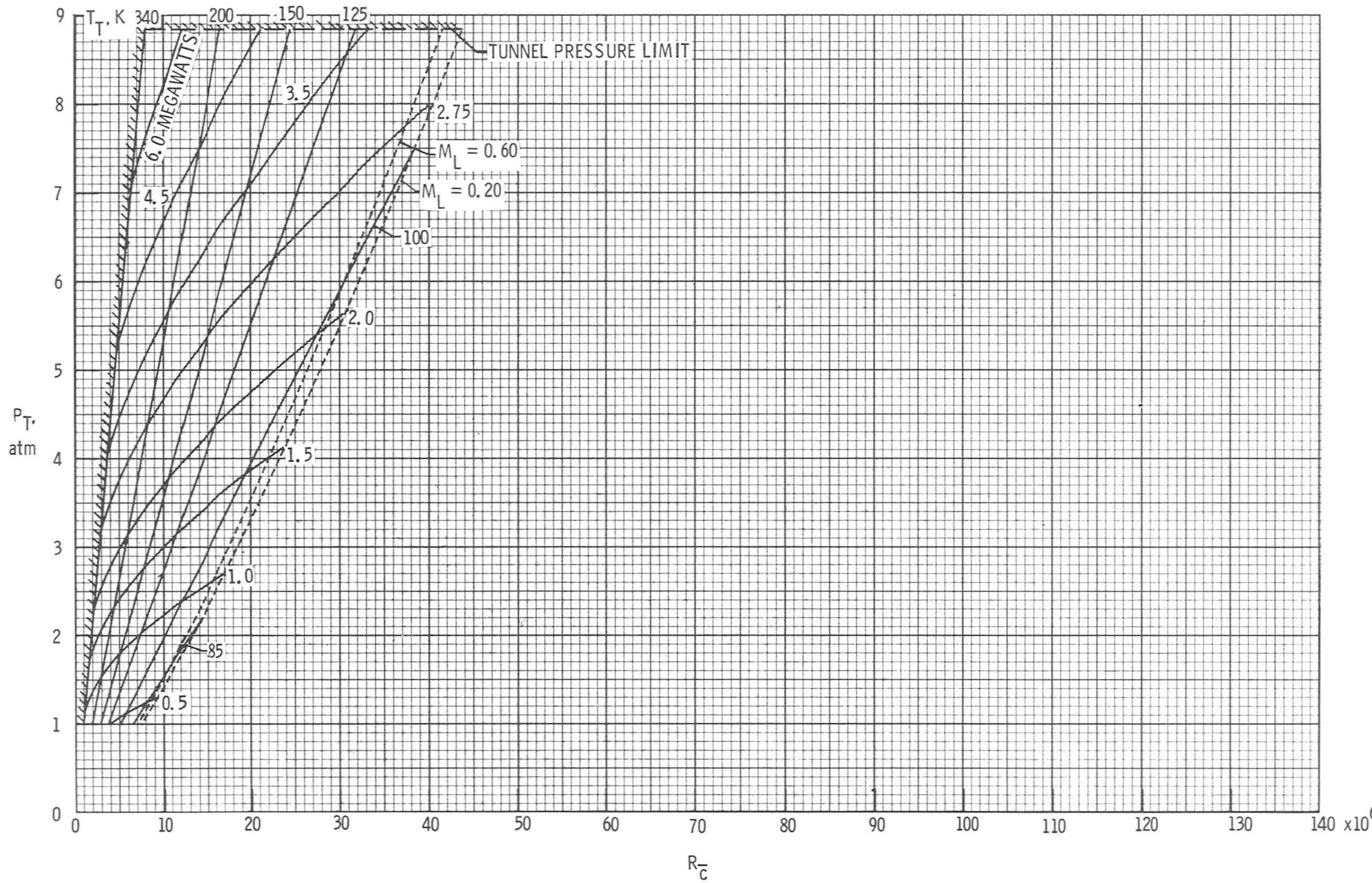

Figure 7.- Estimated NTF performance map for free-stream Mach number of 0.20.

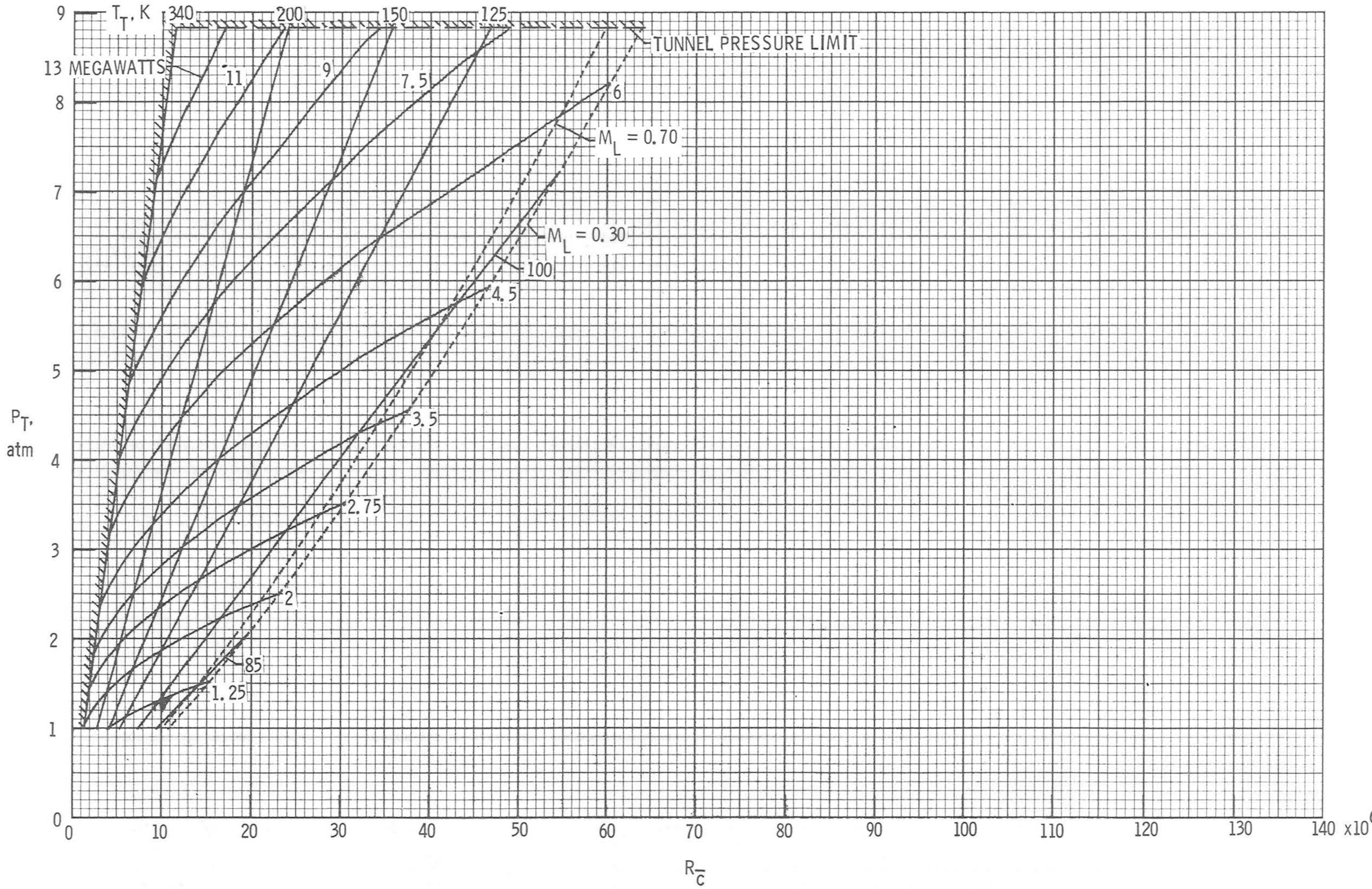

Figure 8.- Estimated NTF performance map for free-stream Mach number of 0.30.

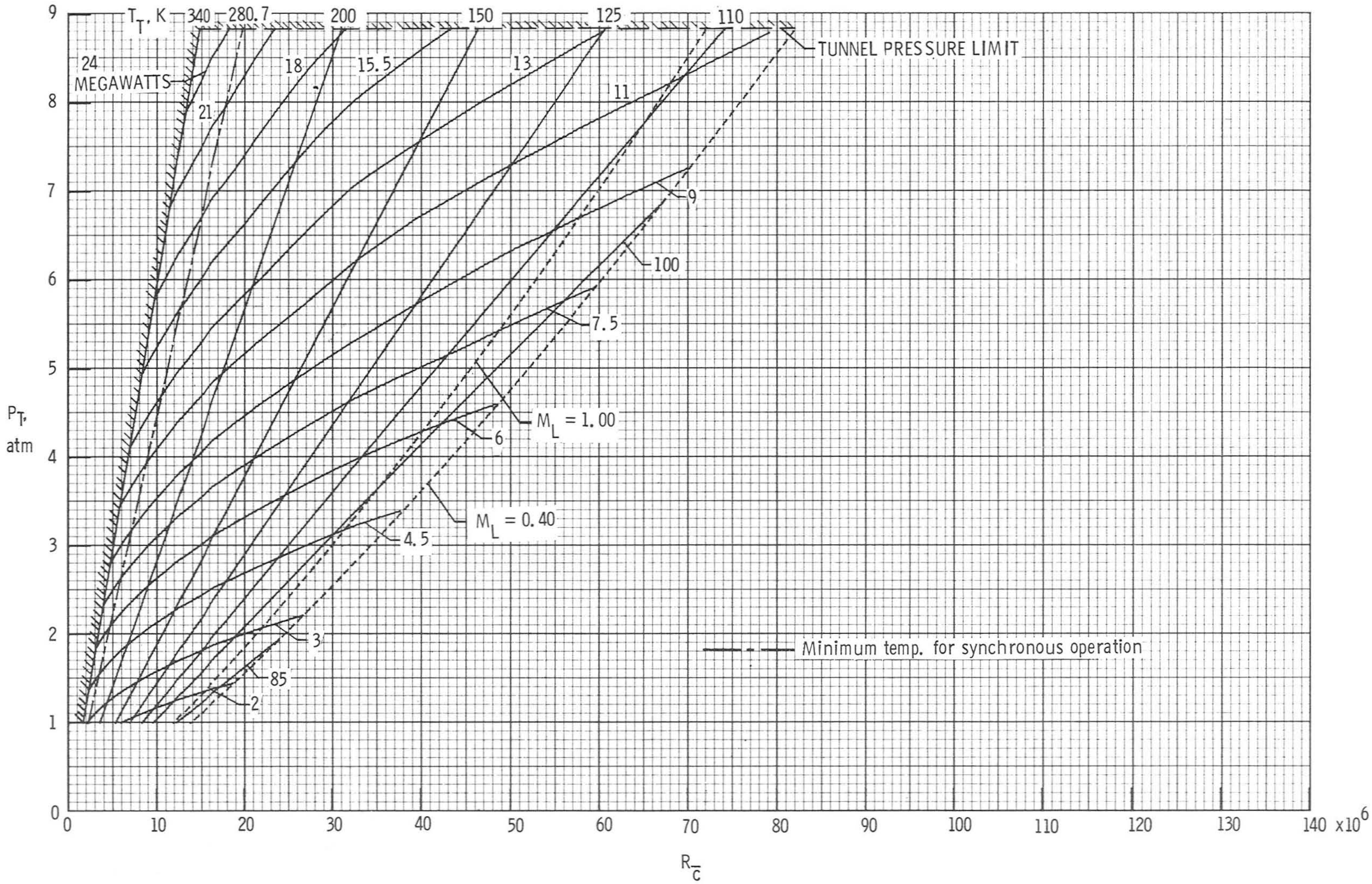

Figure 9.- Estimated NTF performance map for free-stream Mach number of 0.40.

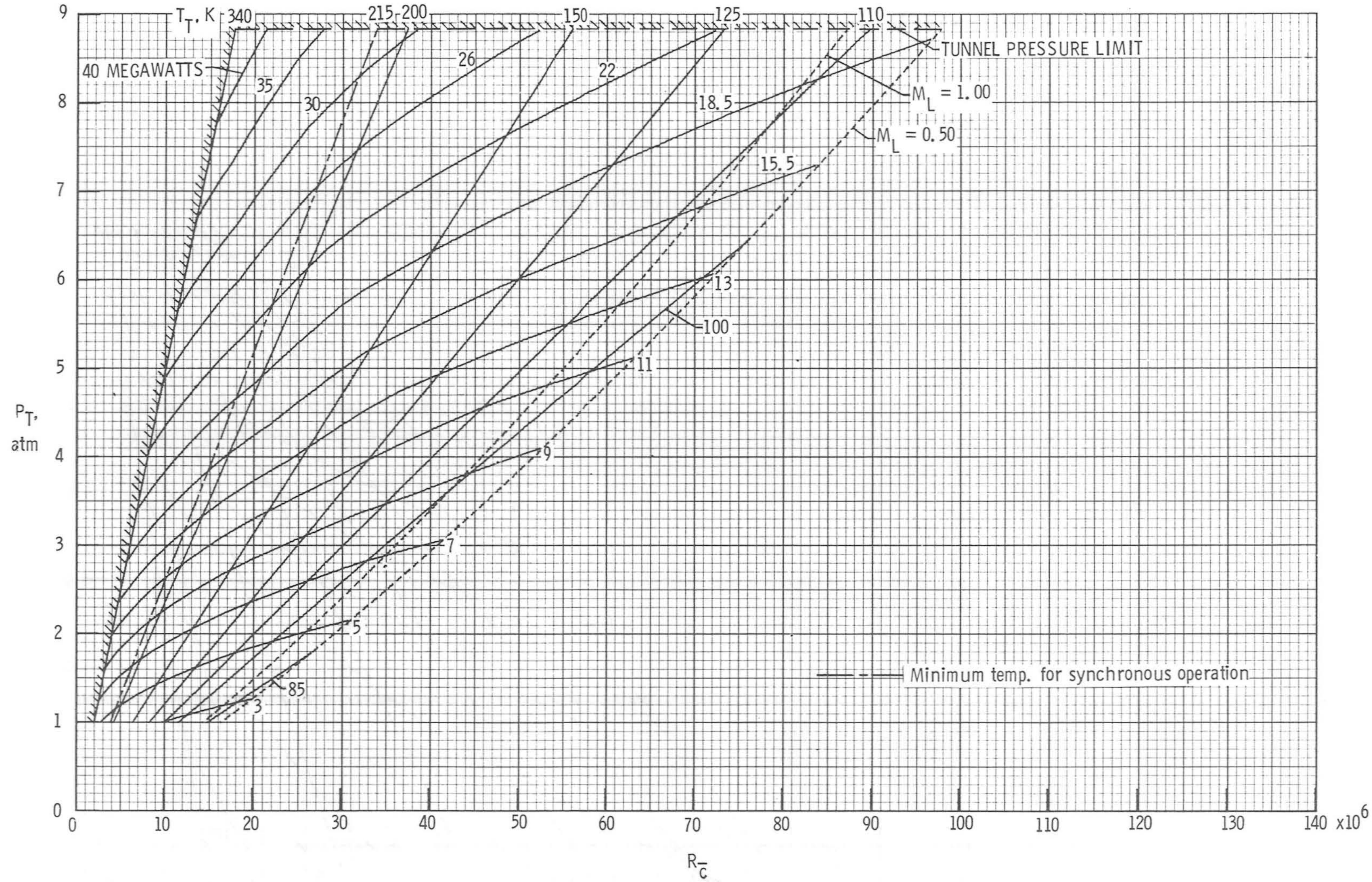

Figure 10.- Estimated NTF performance map for free-stream Mach number of 0.50.

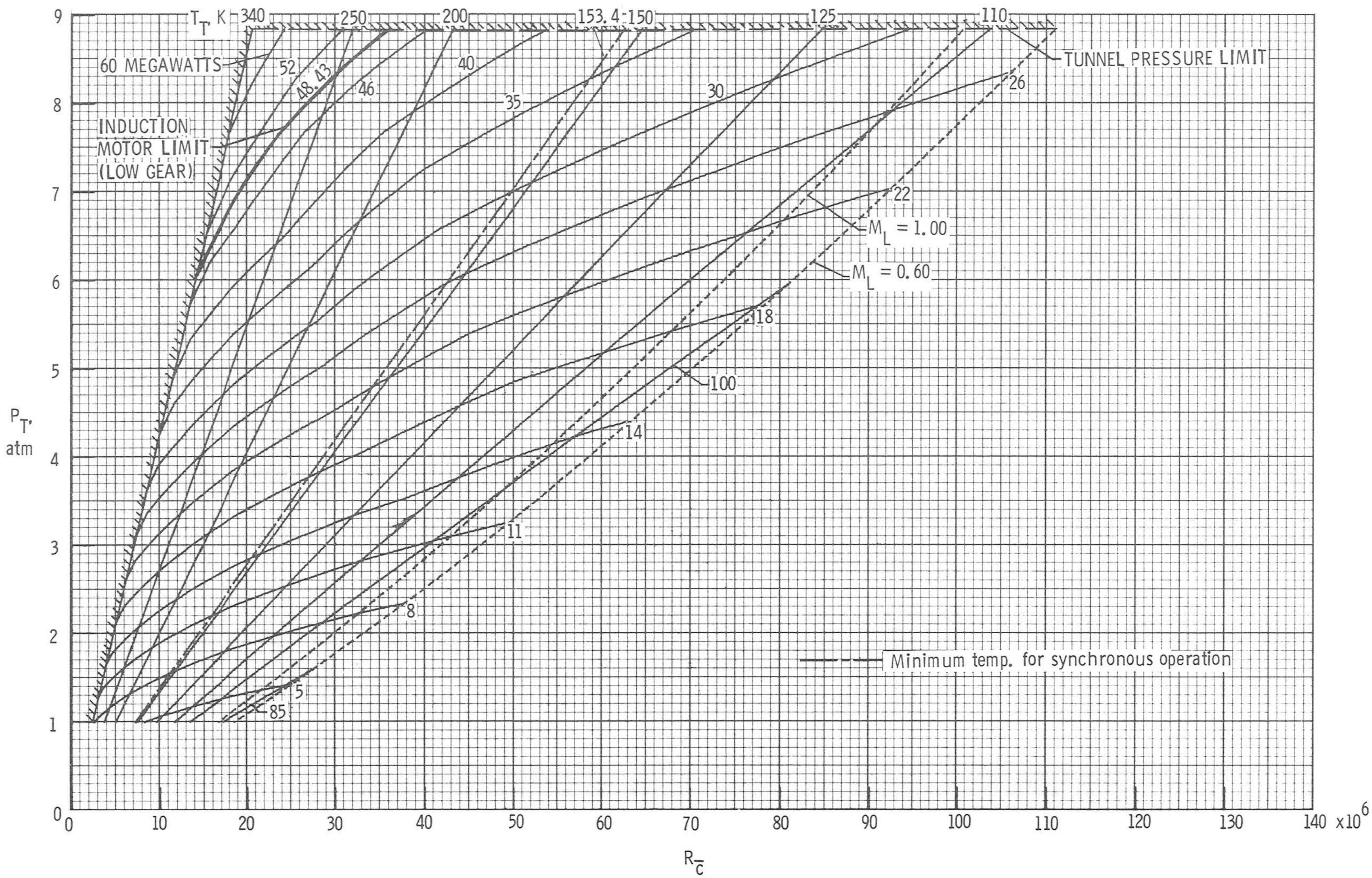

Figure 11.- Estimated NTF performance map for free-stream Mach number of 0.60.

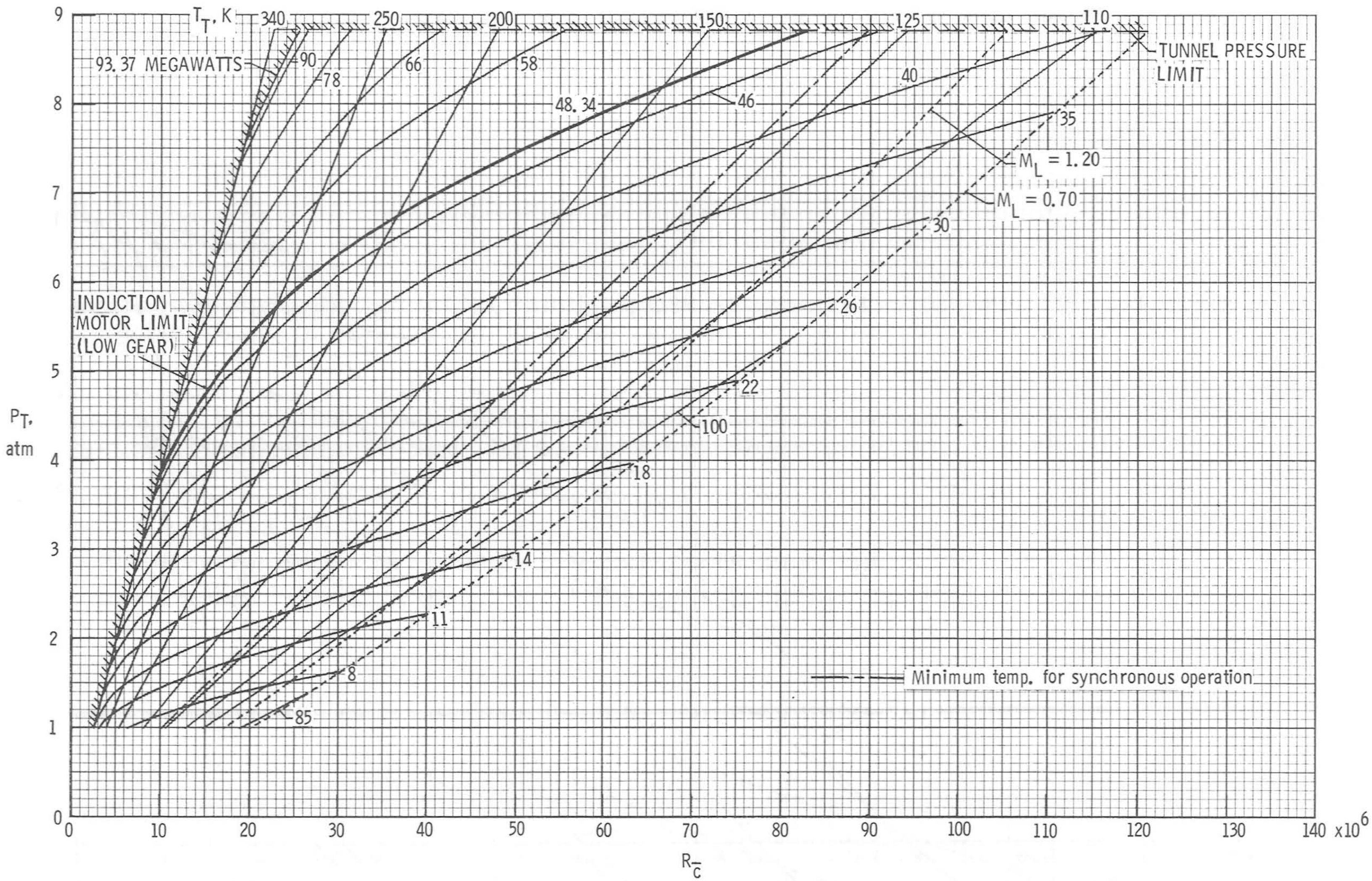

Figure 12.- Estimated NTF performance map for free-stream Mach number of 0.70.

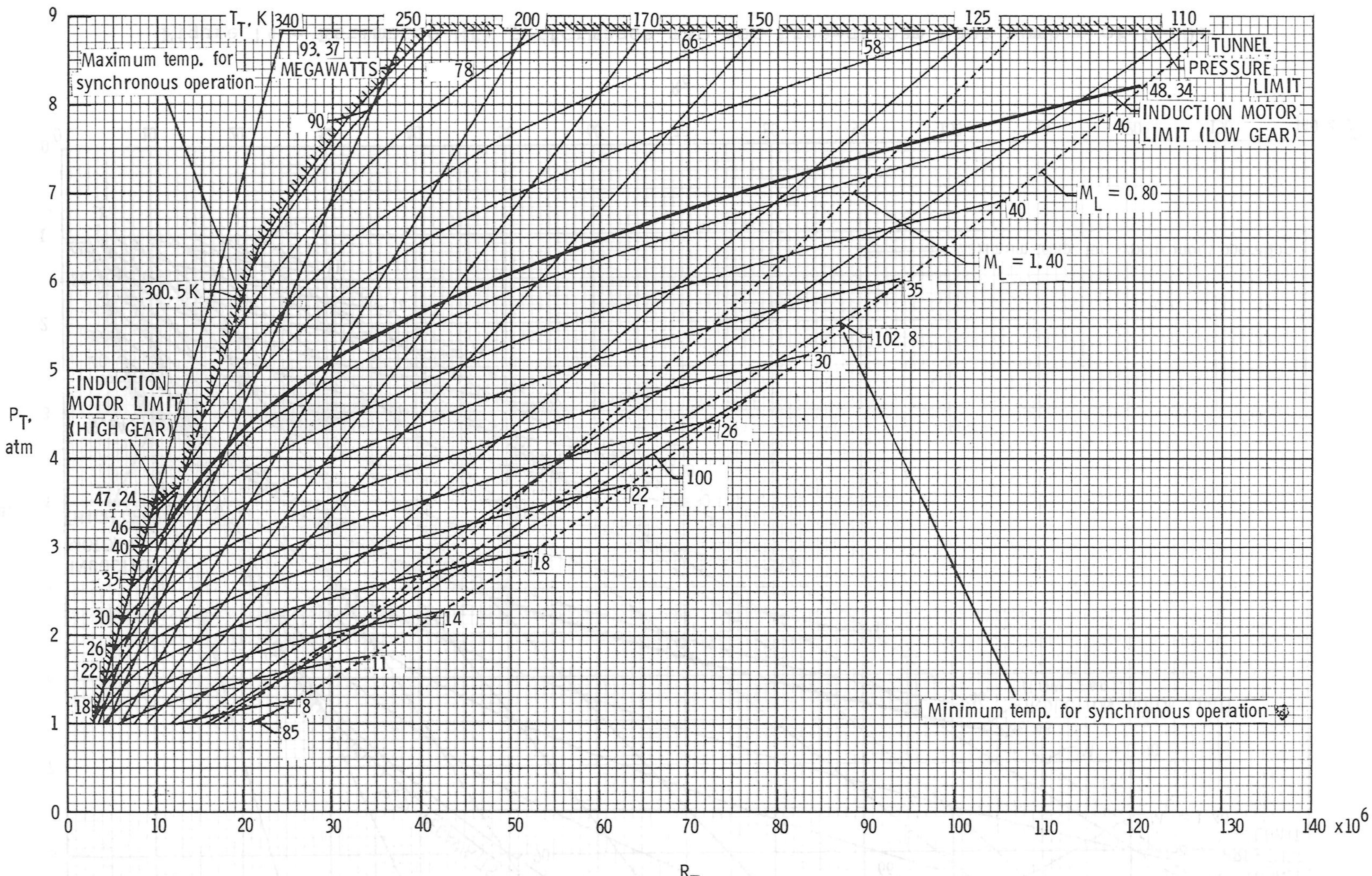

Figure 13.- Estimated NTF performance map for free-stream Mach number of 0.80.

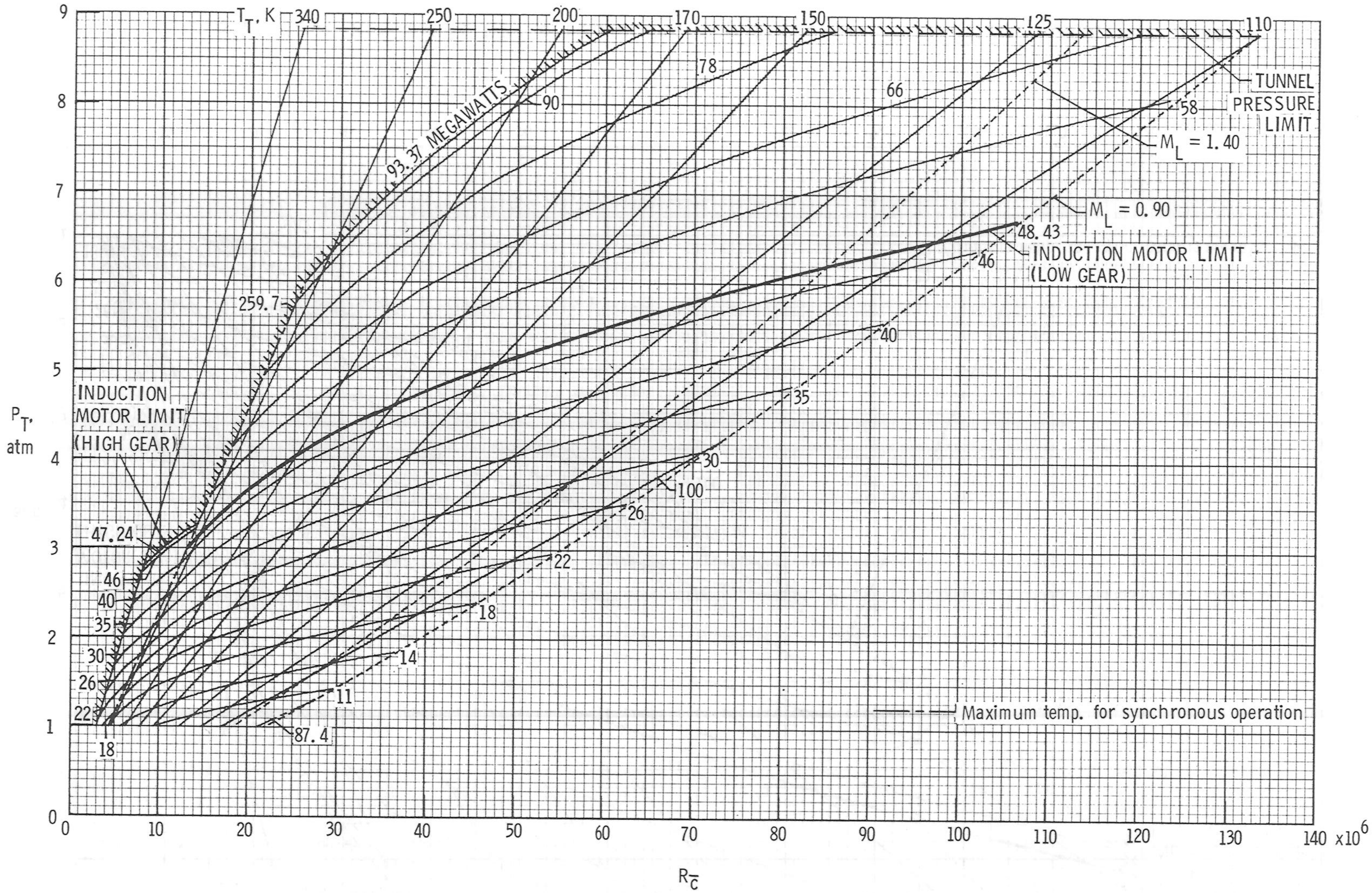

Figure 14.- Estimated NTF performance map for free-stream Mach number of 0.90.

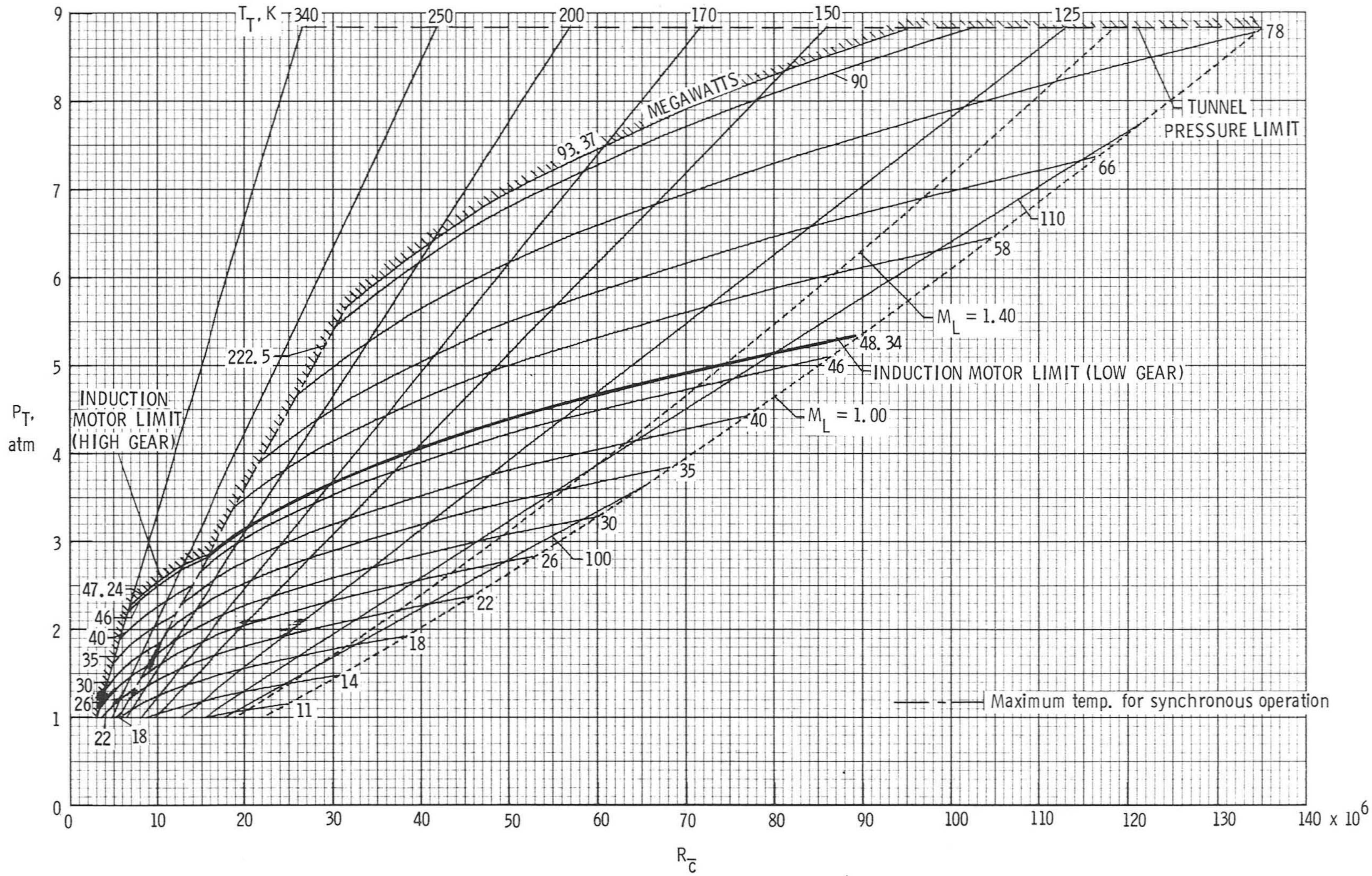

Figure 15.- Estimated NTF performance map for free-stream Mach number of 1.00.

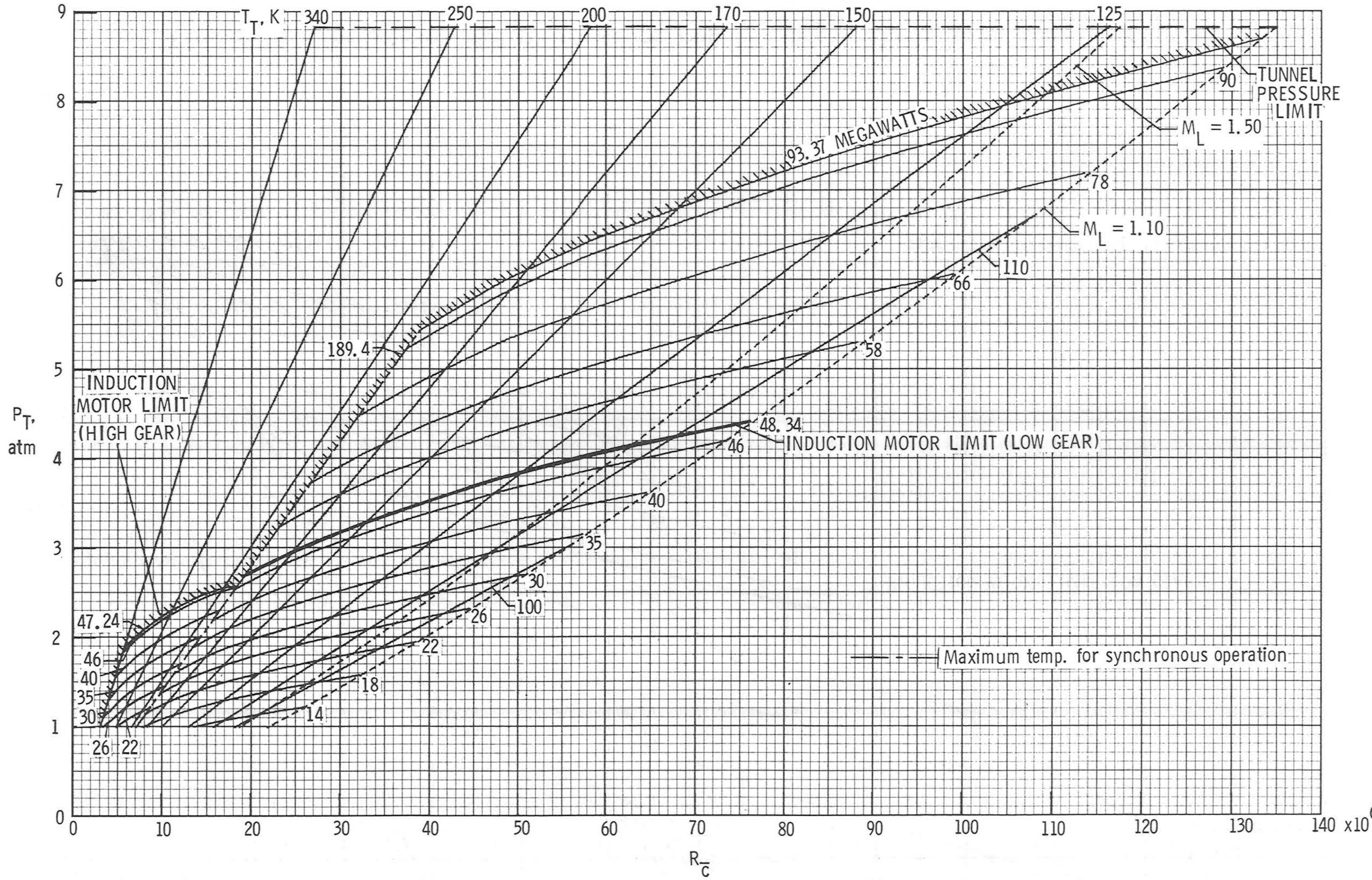

Figure 16.- Estimated NTF performance map for free-stream Mach number of 1.10.

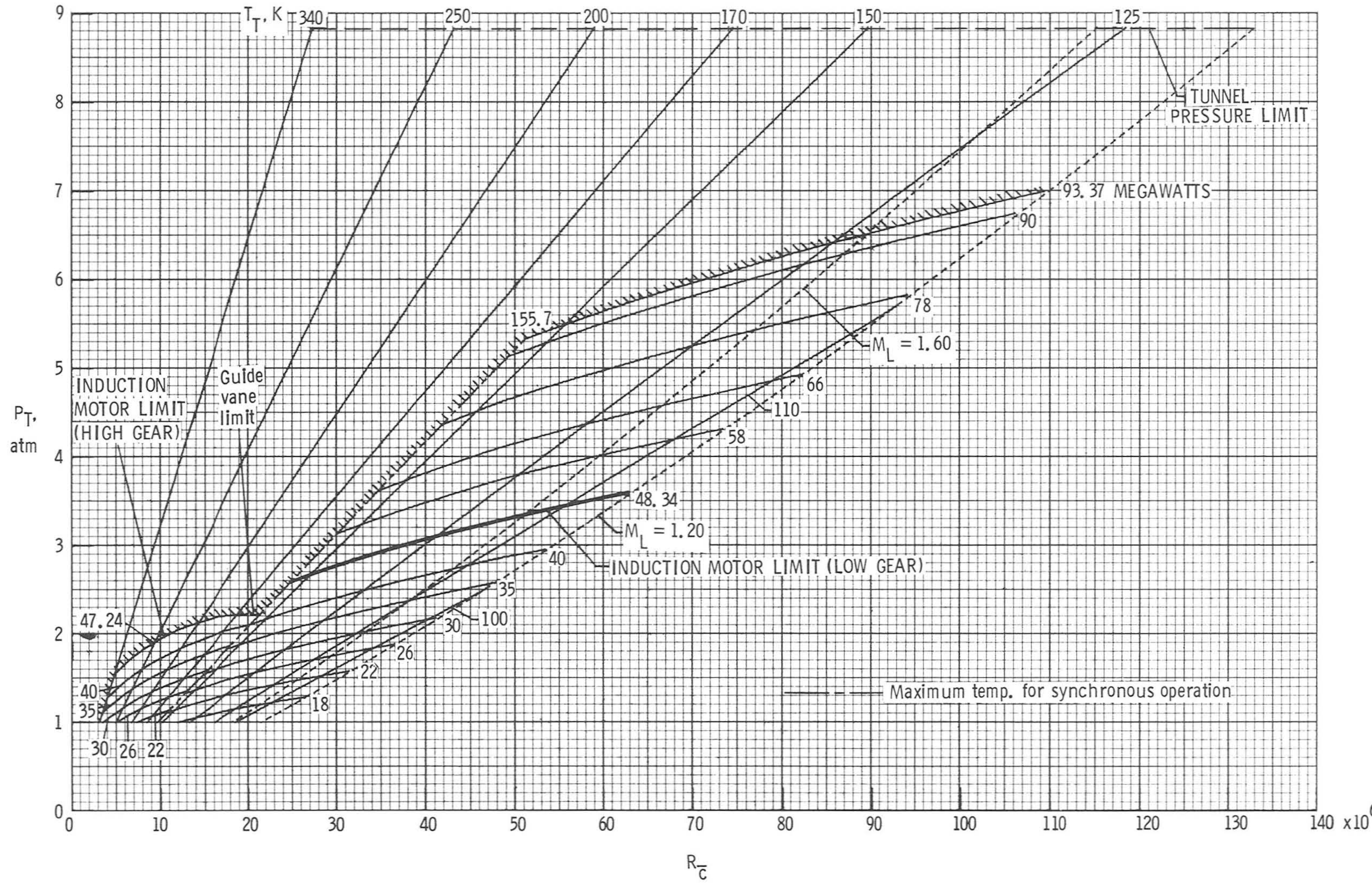

Figure 17.- Estimated NTF performance map for free-stream Mach number of 1.20.

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15. Supplementary Notes

16. Abstract

The National Transonic Facility (NTF), a fan-driven, transonic, pressurized, cryogenic wind tunnel, will operate over the Mach number range of 0.10 to 1.20 with stagnation pressures varying from 1.00 to about 8.8 atm (1 atm = 101.3 kPa = 1.01 bar) and stagnation temperatures varying from 77 to 340 K. The design Reynolds number capability of this wind tunnel is 120×10^6, based on a reference length of 0.25 m, at a Mach number of 1.00. The NTF is cooled to cryogenic temperatures by the injection of liquid nitrogen into the tunnel stream with gaseous nitrogen as the test gas. The NTF can also operate at ambient temperatures using a conventional chilled-water heat exchanger with air or nitrogen as the test gas. This report describes the methods used in estimating the fan pressure ratio requirements and presents the estimated NTF operating envelopes at Mach numbers from 0.10 to 1.20.

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