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MATEER AND PETERSON

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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By George G. Mateer and Victor L. Peterson

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SUMMARY

Equilibrium and frozen nozzle-flow properties for carbon dioxide are presented in the form of charts. In the calculations for the frozen flows the flow was assumed to be in equilibrium to specified points in the nozzle where the chemistry was assumed to freeze instantly. Then, the flows were further expanded with the energy in molecular vibrations either frozen or in equilibrium with translational temperatures. Results are presented for total pressures ranging to 1000 atmospheres and total enthalpies ranging to 55 kilojoules per gram. The properties of temperature, pressure, density, velocity, dynamic pressure, Mach number, Reynolds number, molecular weight ratio, and species concentrations are presented in charts. Temperature, pressure ratio, and density ratio across normal shock waves in a nozzle are also included. author

INTRODUCTION

All the suggested model atmospheres for Mars and Venus contain varying amounts of carbon dioxide. In the absence of definitive estimates of gas composition, it is appropriate to investigate flight in carbon dioxide as one limit of possible atmospheres. To do this, it is necessary to document its thermodynamic and flow properties. These properties for carbon dioxide in molecular form, given analytically in reference 1, correspond to low flight speeds. For total enthalpy levels in carbon dioxide corresponding to higher flight speeds, the equilibrium thermodynamic and one-dimensional flow properties have been presented in graphical form in references 2 and 3, respectively. In addition, the properties of flows across plane shock waves in carbon dioxide for speeds to 16 km/s have been presented in reference 4 for assumed equilibrium flows and for flows with frozen chemistry and molecular vibrations either not excited or fully excited.

Not all nozzle flows, particularly those of high enthalpy, remain in thermodynamic and chemical equilibrium throughout. The purpose of this report is to extend the body of charts for carbon-dioxide flow to include those which can be used to estimate possible nonequilibrium effects in hypervelocity nozzles. It is difficult to obtain exact solutions of the nonequilibrium nozzle flow, and often the treatment of the attendant complexities is not justified in light of the results desired. In this study, estimates of nonequilibrium effects are based on the assumption of an instant freeze. This technique is described in more detail in reference 5. In this method it is assumed that the flow leaves the reservoir and travels in equilibrium to a certain point in the nozzle, beyond which the chemical and thermodynamic rate processes can no longer maintain equilibrium. At this nozzle position, termed the freeze point, it is assumed that the species concentrations remain constant (frozen) for the remainder of the expansion. The flow properties are then calculated with the molecular vibrational energy either remaining constant (frozen) at the value corresponding to the freeze point or continuing in equilibrium with translational and rotational temperatures. The properties of flows in equilibrium are presented for comparison. Results of a similar study for air are charted in reference 6.

Results are presented for specified stagnation pressures of 1 to 1, 000 atm, stagnation enthalpies of 2. 5 to 55 kJ/g (1, 075 to 23,650 Btu/lbm), and assumed freeze points corresponding to Mach numbers of 1 through 6. The quantities presented are temperature, pressure, density, velocity, dynamic pressure, Mach number, Reynolds number, molecular weight ratio, and species concentrations. Temperature, pressure ratio, and density ratio across normal shock waves in a nozzle are also included.

SYMBOLS

a	sound speed
A	area
c_p	specific heat at constant pressure
c_v	specific heat at constant volume
h	enthalpy
l	characteristic length
m	molecular weight of mixture
m_o	molecular weight of undissociated carbon dioxide
M	Mach number
p	pressure
q	dynamic pressure
R	universal gas constant
Re	Reynolds number
T	temperature
u	velocity
x	mole fraction, moles of species per mole of gas
y	mole fraction, moles of species per mole of undissociated gas at STP

Z	molecular weight ratio, $\frac{m_o}{m}$
γ	isentropic exponent, $\left(\frac{\partial\, ln\, p}{\partial\, ln\, \rho}\right)_s$
ρ	density
ρ_o	reference density, 1.979 kg/m^3
μ	coefficient of viscosity
$(\ )_s$	differentiation at constant entropy
$(\ )^*$	sonic point

Subscripts

f	frozen condition
o	reference condition
t	total condition
1	condition in front of a normal shock wave
2	condition behind a normal shock wave

COMPUTATION PROCEDURE

Nozzle-flow properties were calculated for three types of flow. In one type, the flow was assumed to be in chemical and thermodynamic equilibrium throughout. In the other two types, the flow was in equilibrium from the reservoir to points in the nozzle at which various assumed Mach numbers occurred. The chemical species concentrations were evaluated at these points, and it was assumed that they remained frozen in these proportions for the remaining length of the nozzle. The two types of flow involving frozen chemistry differed in the manner in which the flow was expanded beyond the freeze point. In one case, the energy in molecular vibrations was held constant at the value consistent with the equilibrium conditions at the freeze point, and in the other, the vibrations were assumed to be in equilibrium with translational and rotational temperatures.

The computational techniques are similar to those used in references 3 and 6, but the key steps are repeated here for completeness. All calculations were made with an electronic digital computer.

Equilibrium Flow

A convenient method for calculating equilibrium flow quantities is to use the static pressure as the independent variable. It is desirable from the physical standpoint, however, to present results as functions of area ratio. The equilibrium thermodynamic properties of reference 2 were used to determine the flow properties in the following manner.

The equation of state,

$$\rho = \frac{pm_o}{ZRT} \tag{1}$$

and the energy equation,

$$u = \sqrt{2(h_t - h)} \tag{2}$$

form the basis for the computation. The thermodynamic properties of temperature, molecular weight ratio, and enthalpy were obtained from the results of reference 2. It was first assumed that there was an isentropic expansion from the reservoir pressure to a number of assumed values of static pressures, p. The product ρu was then calculated for each value of the static pressure, and the maximum of this quantity was taken to be the mass flow per unit area at the throat. This value was then used in the continuity equation to calculate the area ratio, A/A^*:

$$\frac{A}{A^*} = \frac{\rho^* u^*}{\rho u} \tag{3}$$

Mach number was obtained from

$$M = \frac{u}{a} = \frac{u}{\sqrt{\gamma ZRT/m_o}} \tag{4}$$

where

$$a = \text{speed of sound}$$

$$\equiv \sqrt{\left(\frac{\partial p}{\partial \rho}\right)_s} \tag{5}$$

$$\gamma = \text{isentropic exponent}$$

$$= \left(\frac{\partial \ln p}{\partial \ln \rho}\right)_s \tag{6}$$

The following equation was used to calculate the Reynolds number per unit pressure and unit length

$$\frac{Re}{l p_t} = \frac{u\rho}{\mu p_t} \tag{7}$$

Values for the viscosity, μ, of carbon dioxide were not available for most of the ranges of temperature and pressure considered. Therefore the viscosity was assumed to be the same as for air. Furthermore, the effects of dissociation and ionization on the viscosity were disregarded, so that viscosity could be calculated from Sutherland's formula for air (ref. 7)

$$\mu = 1.09\times10^{-6}T^{1/2}\left(1+\frac{112}{T}\right)^{-1}, \quad \frac{\text{N-s}}{\text{m}^2} \tag{8}$$

where T is in $^{\circ}$K. Because of these approximations, emphasis should not be placed on quantitative results for Reynolds number but rather on the qualitative manner in which it varies with nozzle area ratio.

The properties presented for the normal shock wave correspond to those that would occur if a normal shock wave existed at various values of area ratio. They were calculated in the following manner, with equilibrium flow assumed through the shock:

1. The density ratio, ρ_2/ρ_1, was assumed, and the pressure behind the shock was calculated from the combination of the momentum and continuity equations:

$$p_2 = p_1 + \rho_1 u_1^2 \left[1 - \left(\frac{\rho_1}{\rho_2}\right)\right] \tag{9}$$

2. The static enthalpy, h_2, was calculated from the energy equation in the following form,

$$h_2 = h_1 + \frac{u_1^2}{2}\left[1 - \left(\frac{\rho_1}{\rho_2}\right)^2\right] \tag{10}$$

3. Molecular weight ratio, Z_2, and static temperature, T_2, were then found from the results of reference 2 for the state properties p_2 and h_2.

4. Density, ρ_2, was calculated from equation (1) and a new density ratio formed.

5. The iteration was continued until two successive values of density ratio differed by a small amount (10^{-4}).

The stagnation conditions behind the shock were calculated with the assumptions of an adiabatic process through the shock and an isentropic compression from the static to stagnation conditions.

The species concentrations existing in the flow at various stations in the nozzle were obtained from reference 2 and were included so that frozen flows could be calculated, as explained in the following section.

Frozen Flow

The flow was assumed to expand in equilibrium from the reservoir to a specified location in the nozzle at which the chemical species concentrations were assumed to freeze instantaneously. This location, called the freeze point, was specified for a given equilibrium value of Mach number, denoted M_f, at that point. The subscript f identifies the equilibrium properties at the freeze point. The expansion beyond the freeze point was then assumed to occur with the energy in molecular vibrations either held constant at the value corresponding to the freeze point or continuing in equilibrium with translational temperatures. The two types of frozen flow are discussed in more detail in the following sections.

Frozen chemistry and frozen molecular vibrations. - These calculations were made by first determining the specific heats, c_p and c_v, and their ratio, γ, at the chosen freeze point.

$$c_p = \sum_i y_i c_{p_i} \tag{11}$$

$$c_v = \sum_i y_i c_{v_i} \tag{12}$$

$$\gamma = c_p/c_v \tag{13}$$

The quantity, y_i, denotes the concentration of the ith species in moles per mole of undissociated carbon-dioxide gas at STP (1 atm, 273° K). The species concentrations were determined from reference 2 for the equilibrium thermodynamic properties at the freeze point. The value for γ in equation (13) is not the same as that for equilibrium flow; consequently, the value of Mach number is discontinuous at the freeze point.

With static pressure again the independent variable, the following equations were used.

$$\frac{T}{T_f} = \left(\frac{p}{p_t}\right)^{(\gamma-1)/\gamma} \left(\frac{p_f}{p_t}\right)^{(1-\gamma)/\gamma} \tag{14}$$

$$\frac{\rho}{\rho_o} = \left(\frac{\rho_f}{\rho_o}\right) \left(\frac{p_f}{p_t}\right)^{-1/\gamma} \left(\frac{p}{p_t}\right)^{1/\gamma} \tag{15}$$

$$h = h_f + c_p(T - T_f) \tag{16}$$

$$u = \sqrt{2\left[(h_t - h_f) - c_p(T - T_f)\right]} \tag{17}$$

$$\frac{A}{A^*} = \frac{\rho^* u^*}{\rho u} \tag{3}$$

$$M = \frac{u}{a} = \frac{u}{\sqrt{\gamma ZRT/m_o}} \tag{4}$$

$$\frac{p_{t_2}}{p} = \left[\frac{(\gamma + 1)M^2}{2}\right]^{\gamma/(\gamma-1)} \left[\frac{\gamma + 1}{2\gamma M^2 - (\gamma - 1)}\right]^{1/(\gamma-1)} \tag{18}$$

Equation (18) was used to determine the total pressure behind a normal shock wave with the assumption that the flow was frozen through the shock; whereas, in the equilibrium section this total pressure was found with the assumption of equilibrium flow through the shock.

Frozen chemical reactions and equilibrium molecular vibrations. - The equations of reference 1 are applicable to flows expanded from specified reservoir conditions with frozen chemistry and vibrational equilibrium. In the present study the flow with frozen chemistry and vibrational equilibrium is expanded from some specified freeze point ($M_f \geqq 1$) downstream of the specified equilibrium reservoir condition. However, the equations of reference 1 may be used if appropriate frozen reservoir conditions can be found, such that the temperature and pressure at the freeze point are equal to the corresponding values for equilibrium flow. Since the chemistry is frozen, those quantities that depend on γ will be discontinuous at the freeze point.

The procedure for determining the appropriate stagnation conditions to use with the equations of reference 1 is as follows:

1. At the freeze point, equilibrium values of temperature, species concentrations, and velocity were used with the equations of reference 1 to calculate γ, speed of sound, and Mach number.

2. To calculate the variation of stagnation temperature with static temperature the equations of reference 1 were used with the species concentrations and Mach number determined in step (1).

3. The appropriate stagnation temperature was determined from the results obtained in step (2) and the static temperature given in step (1).

4. An expansion starting with the stagnation temperature of step (3) was calculated by the method of reference 1; however, only that portion beyond the freeze point was used.

Note that the values of A^* and total pressure associated with this frozen flow are different from those of the equilibrium flow upstream of the freeze point. The values of flow area and static pressure for the flow downstream of the freeze point were normalized with respective values of A^* and p_t for the equilibrium flow upstream of the freeze point.

RESULTS

All of the results are presented in graphical form in charts 1 through 18. An index to the charts is given in table I. Results are given for reservoir pressures of 1, 100, and 1000 atm and reservoir enthalpies ranging from 2.5 to 55 kJ/g. Results obtained for flows with both chemistry and molecular vibrations frozen are presented for assumed freeze-point Mach numbers of 1, 2, 4, and 6. A limited number of calculations were made for flows with frozen chemistry and equilibrium vibrations, and results are presented for the quantities of Mach number, velocity, temperature, and pressure for a reservoir pressure of 100 atm and for reservoir enthalpies of 2.5, 20, and 55 kJ/g. Unit conversion factors are presented in table II to aid in converting results to other units.

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TABLE I. - INDEX TO CHARTS

Chart	Ordinate		Type of flow	Page
1	Temperature	T	Equilibrium	11
2		T	Equilibrium and frozen	12
3		T_{t_2}	Equilibrium	21
4	Pressure	p/p_t	Equilibrium	24
5		p/p_t	Equilibrium and frozen	25
6		p_{t_2}/p_{t_1}	Equilibrium and frozen	31
7	Density	$(\rho/\rho_0)/p_t$	Equilibrium	37
8		ρ/ρ_0	Equilibrium and frozen	38
9		ρ_2/ρ_1	Equilibrium	44
10	Velocity	u	Equilibrium	47
11		u	Equilibrium and frozen	48
12	Dynamic pressure	q/p_t	Equilibrium	54
13		q/p_t	Equilibrium and frozen	55
14	Mach number	M	Equilibrium	57
15		M	Equilibrium and frozen	58
16	Reynolds number	$Re/p_t l$	Equilibrium	64
17	Molecular weight fraction	Z	Equilibrium	67
18	Mole fraction	x	Equilibrium	70

TABLE II. - CONVERSION FACTORS

Quantity	Multiply	By	To obtain
Temperature	^{o}K	1.800	^{o}R
Pressure	N/m^2	1.450×10^{-4}	$lbf/in.^2$
	N/m^2	9.871×10^{-6}	atm
Density	kg/m^3	1.940×10^{-3}	$slugs/ft^3$
Velocity	m/s	3.281	ft/s
Enthalpy	kJ/g	4.300×10^{2}	Btu/lbm

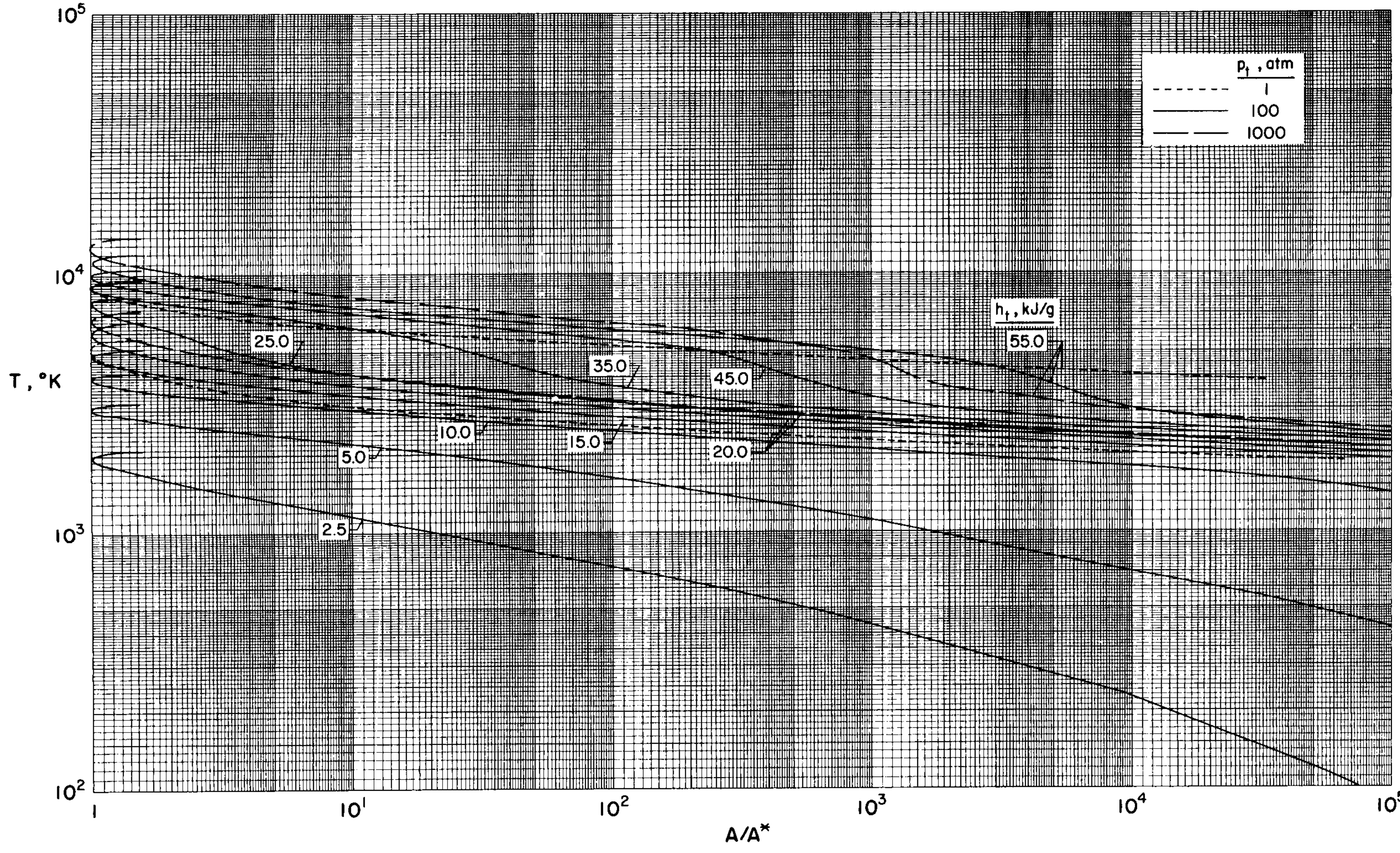
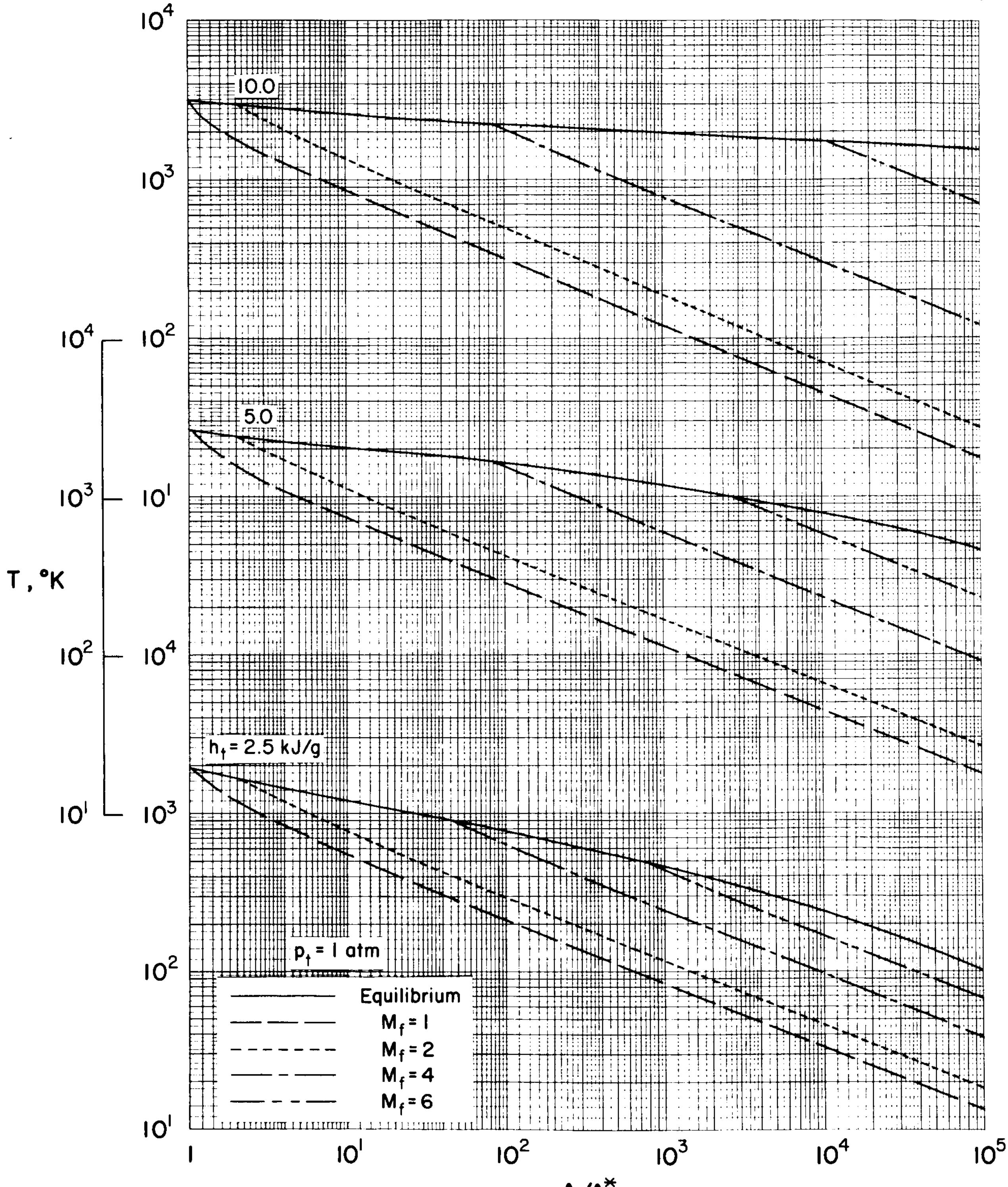
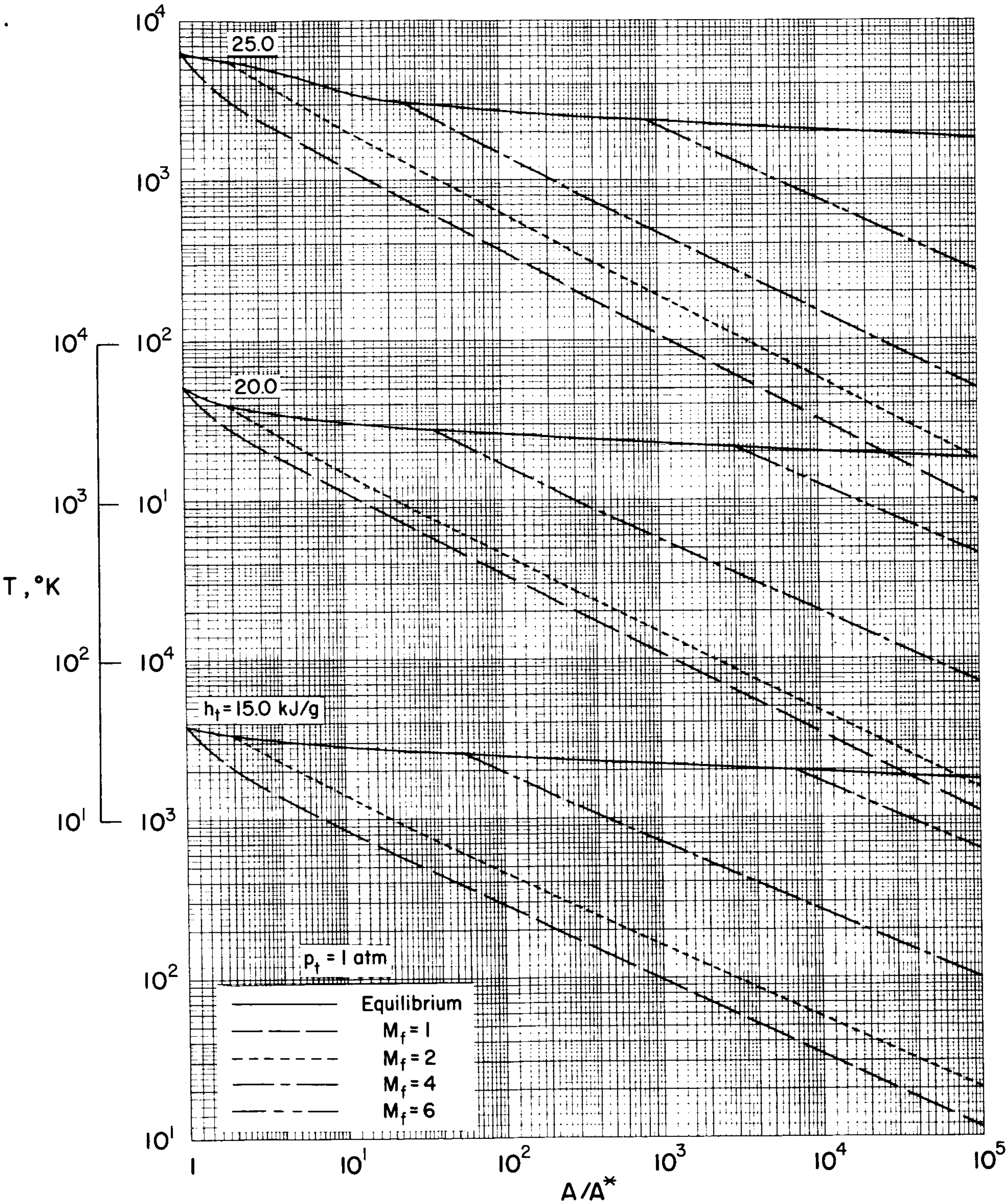


Chart 1. - Variation of temperature with area ratio; equilibrium flow.



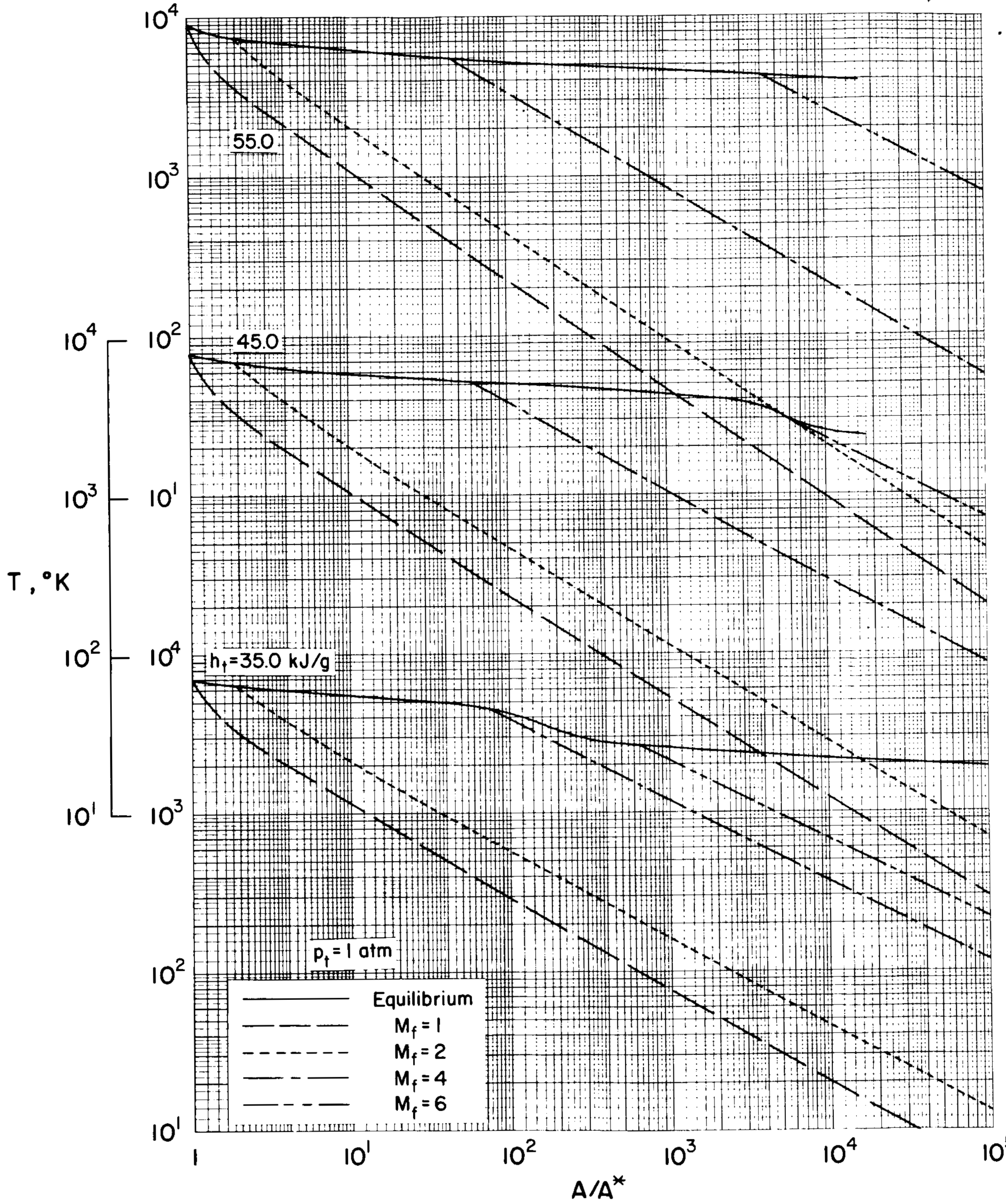
(a) p_t = 1 atm; h_t = 2.5, 5.0, 10.0 kJ/g

Chart 2. - Variation of temperature with area ratio; equilibrium and frozen flows.



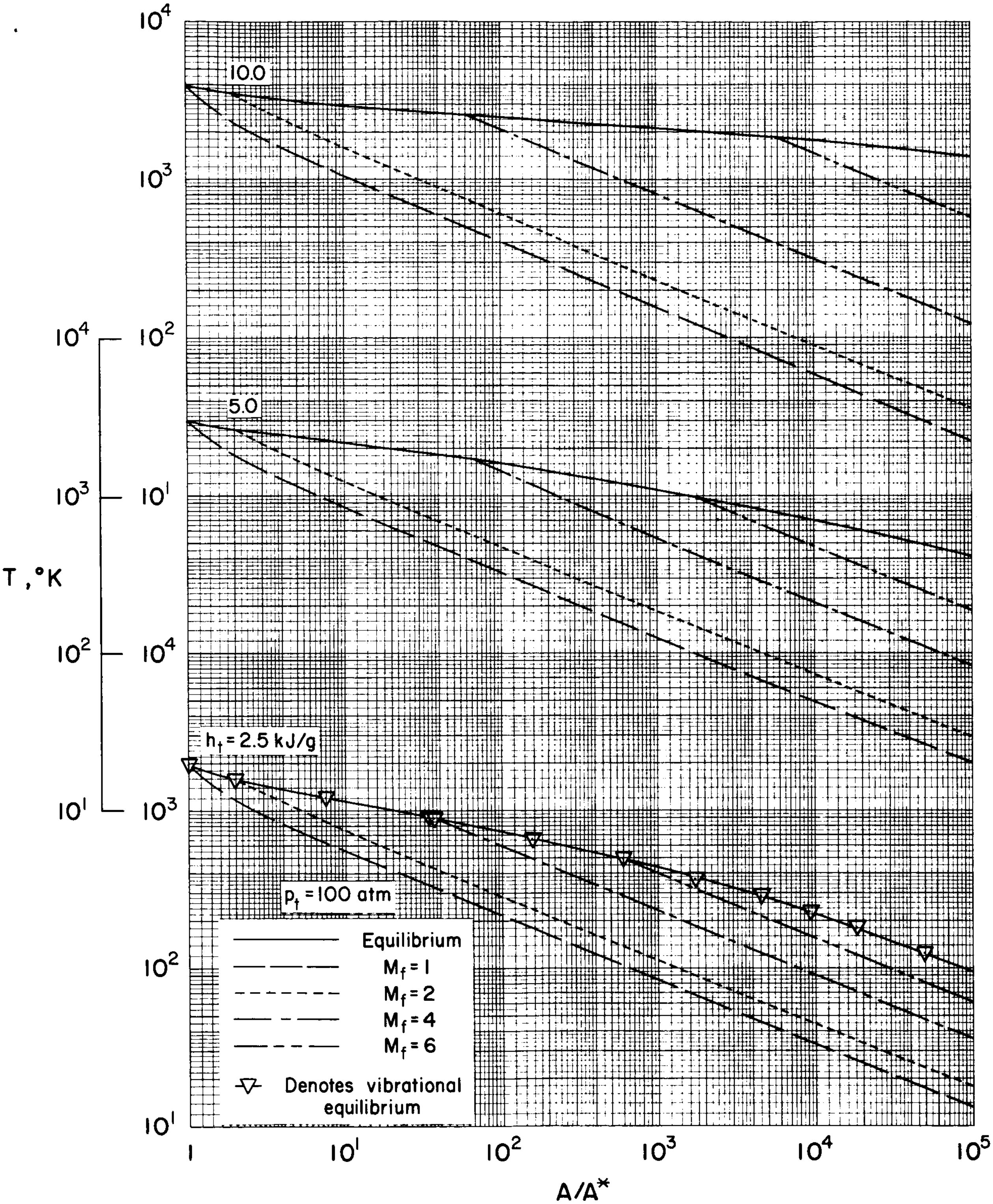
(b) p_t = 1 atm; h_t = 15.0, 20.0, 25.0 kJ/g

Chart 2. - Continued.



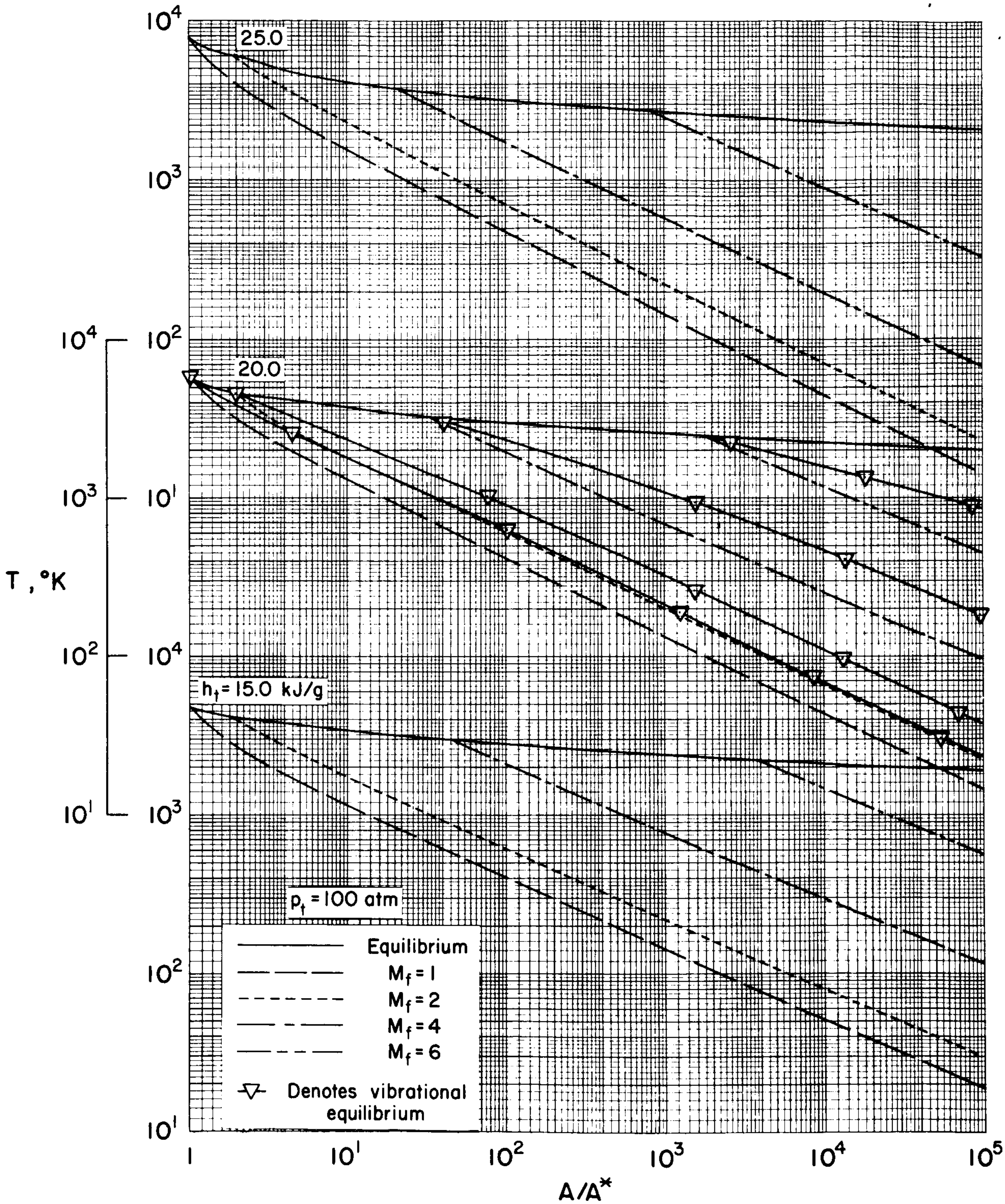
(c) p_t = 1 atm; h_t = 35.0, 45.0, 55.0 kJ/g

Chart 2. - Continued.



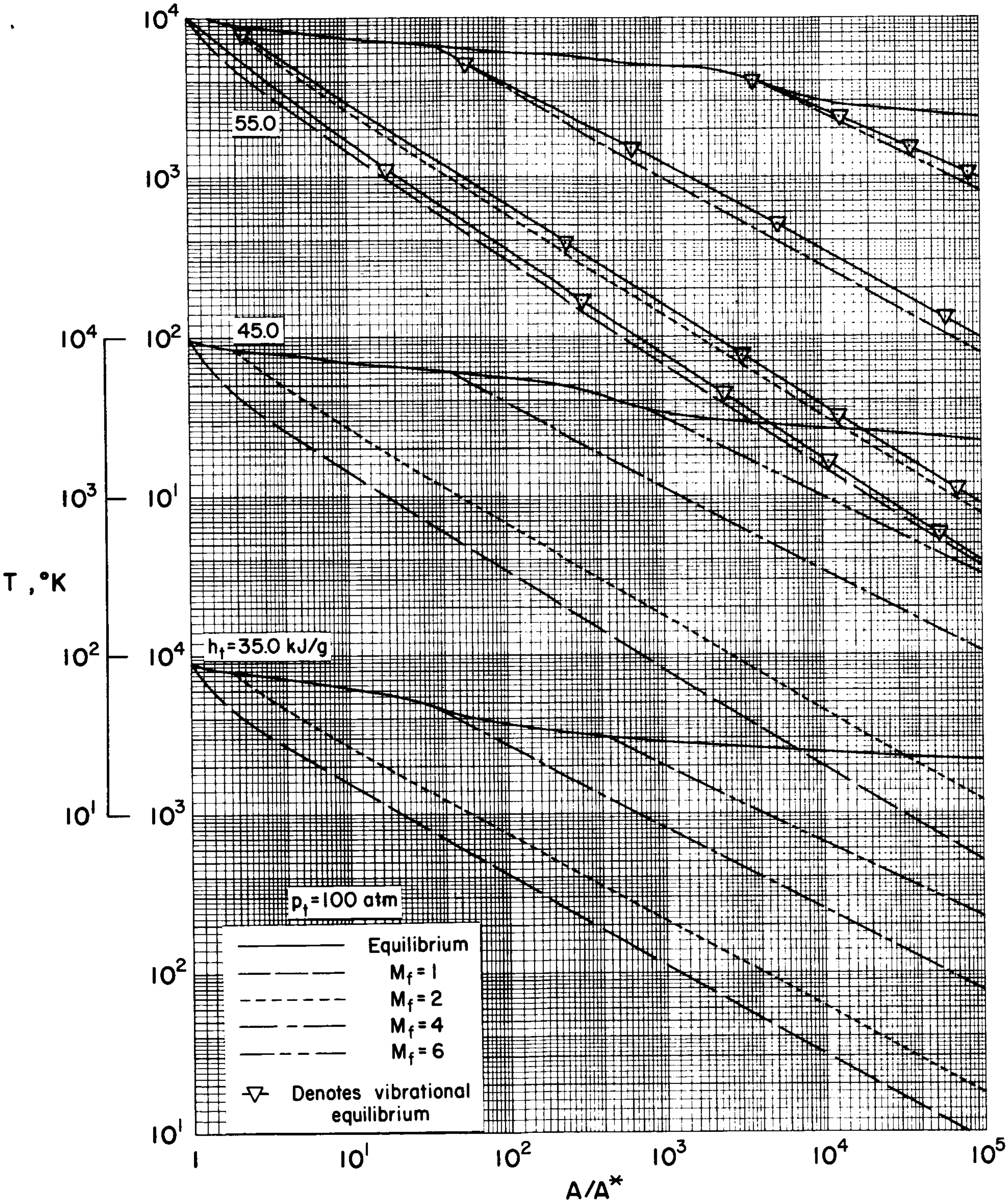
(d) p_t = 100 atm; h_t = 2.5, 5.0, 10.0 kJ/g

Chart 2. - Continued.



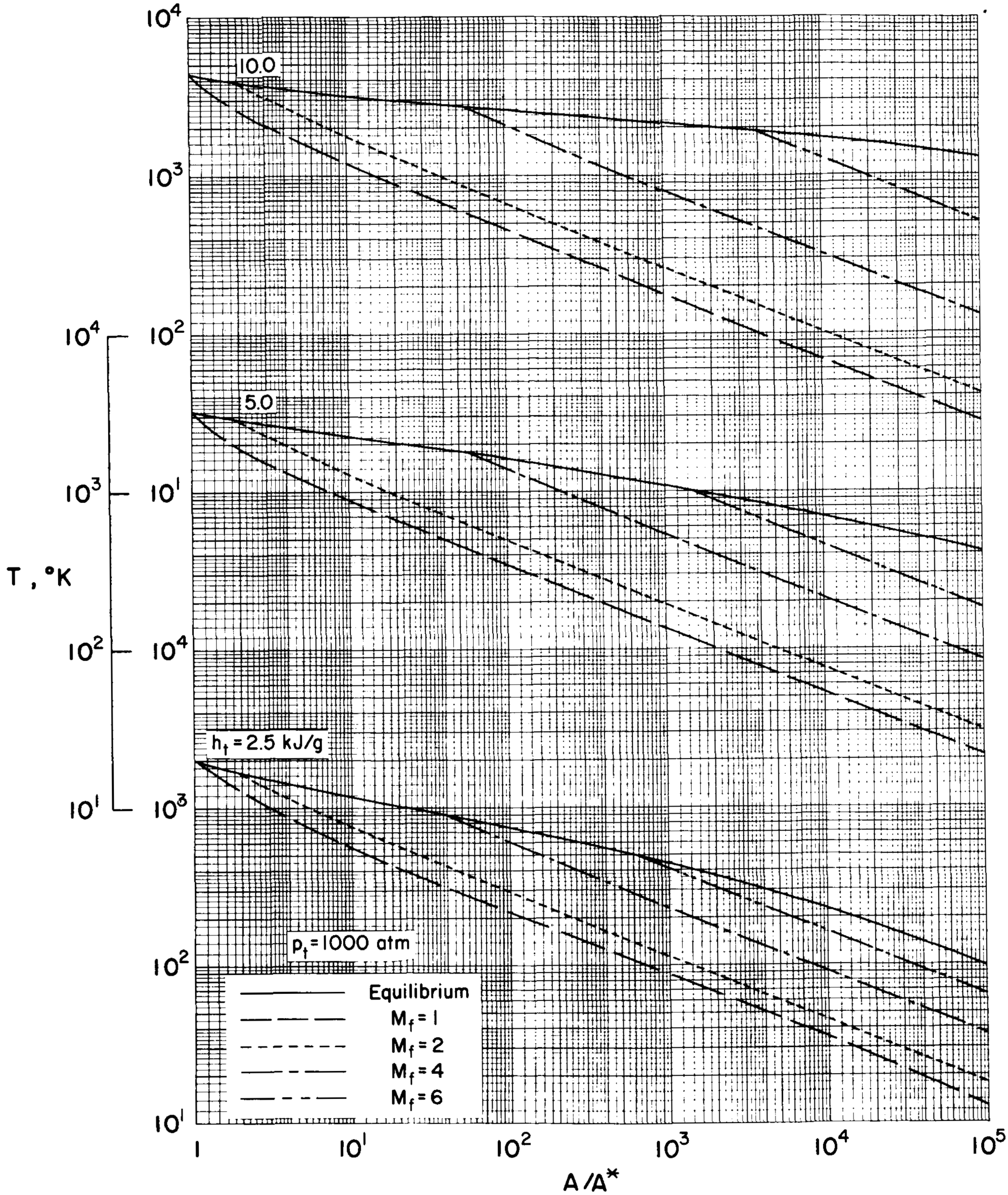
(e) p_t = 100 atm; h_t = 15.0, 20.0, 25.0 kJ/g

Chart 2. - Continued.



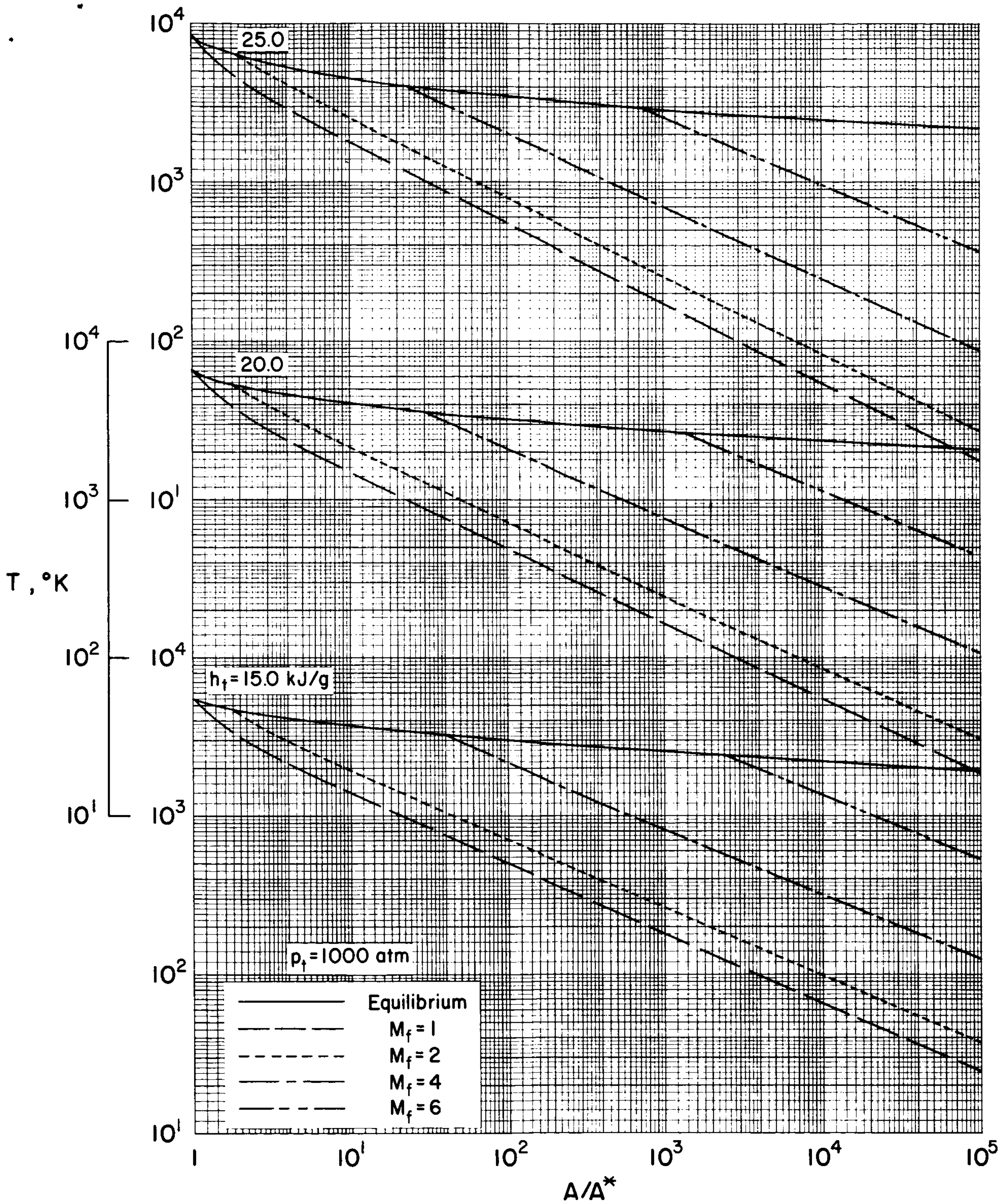
(f) p_t = 100 atm; h_t = 35.0, 45.0, 55.0 kJ/g

Chart 2. - Continued.



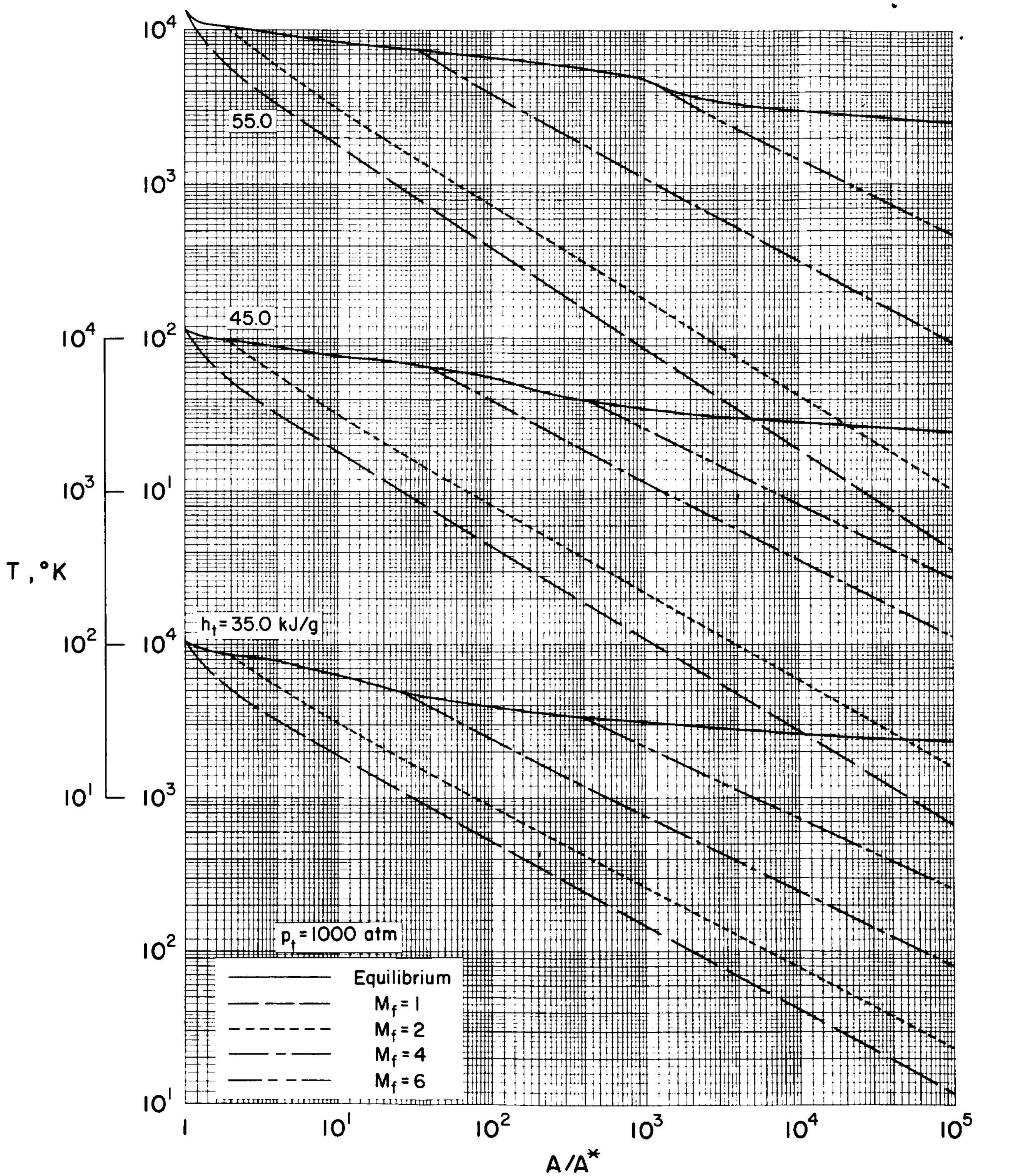
(g) p_t = 1000 atm; h_t = 2.5, 5.0, 10.0 kJ/g

Chart 2. - Continued.



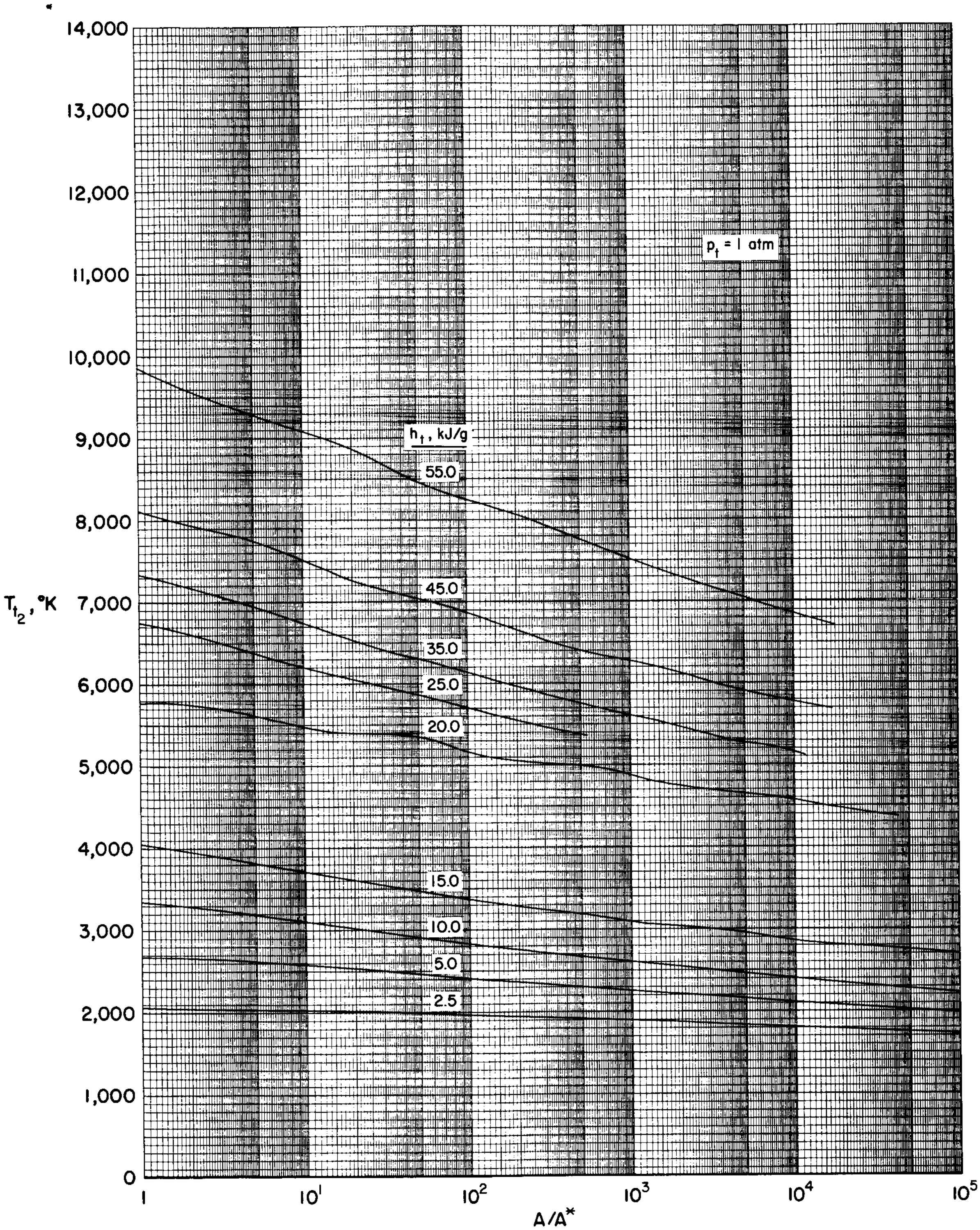
(h) p_t = 1000 atm; h_t = 15.0, 20,0, 25.0 kJ/g

Chart 2. - Continued.



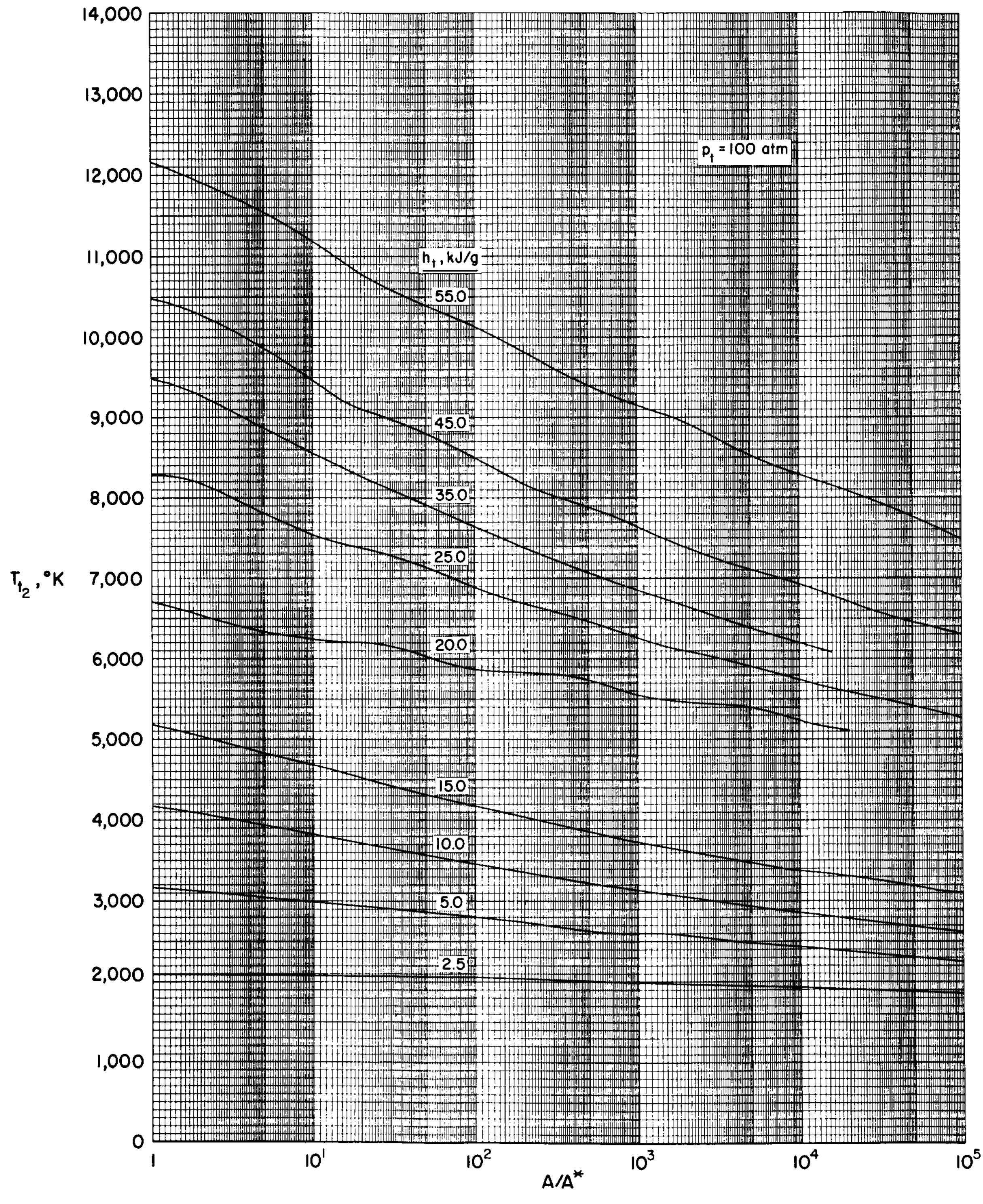
(i) p_t = 1000 atm; h_t = 35. 0, 45. 0, 55. 0 kJ/g

Chart 2. - Concluded.



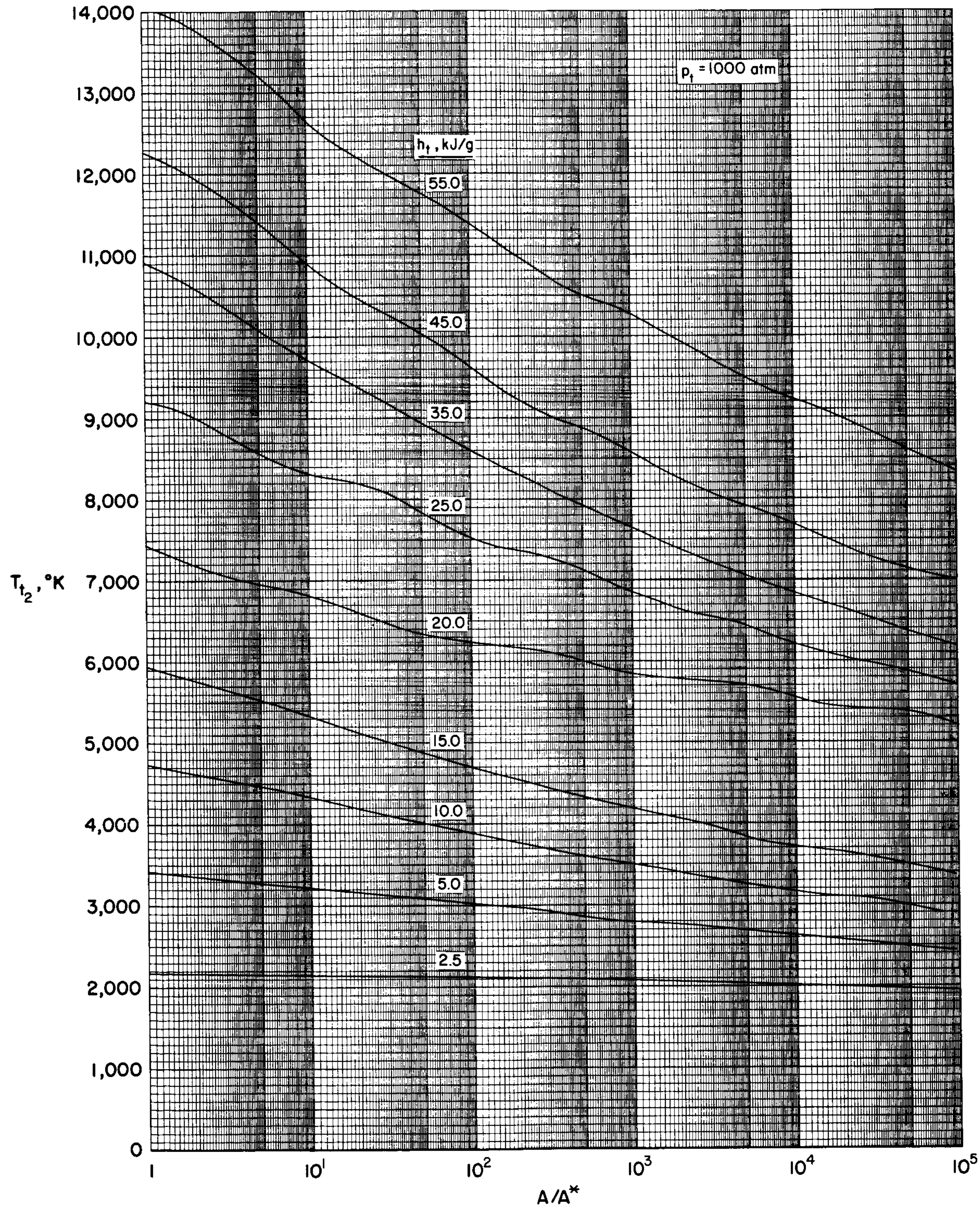
(a) $p_t = 1$ atm

Chart 3. - Variation of total temperature behind a normal shock wave with area ratio; equilibrium flow.



(b) p_t = 100 atm

Chart 3. - Continued.



(c) p_t = 1000 atm

Chart 3. - Concluded.

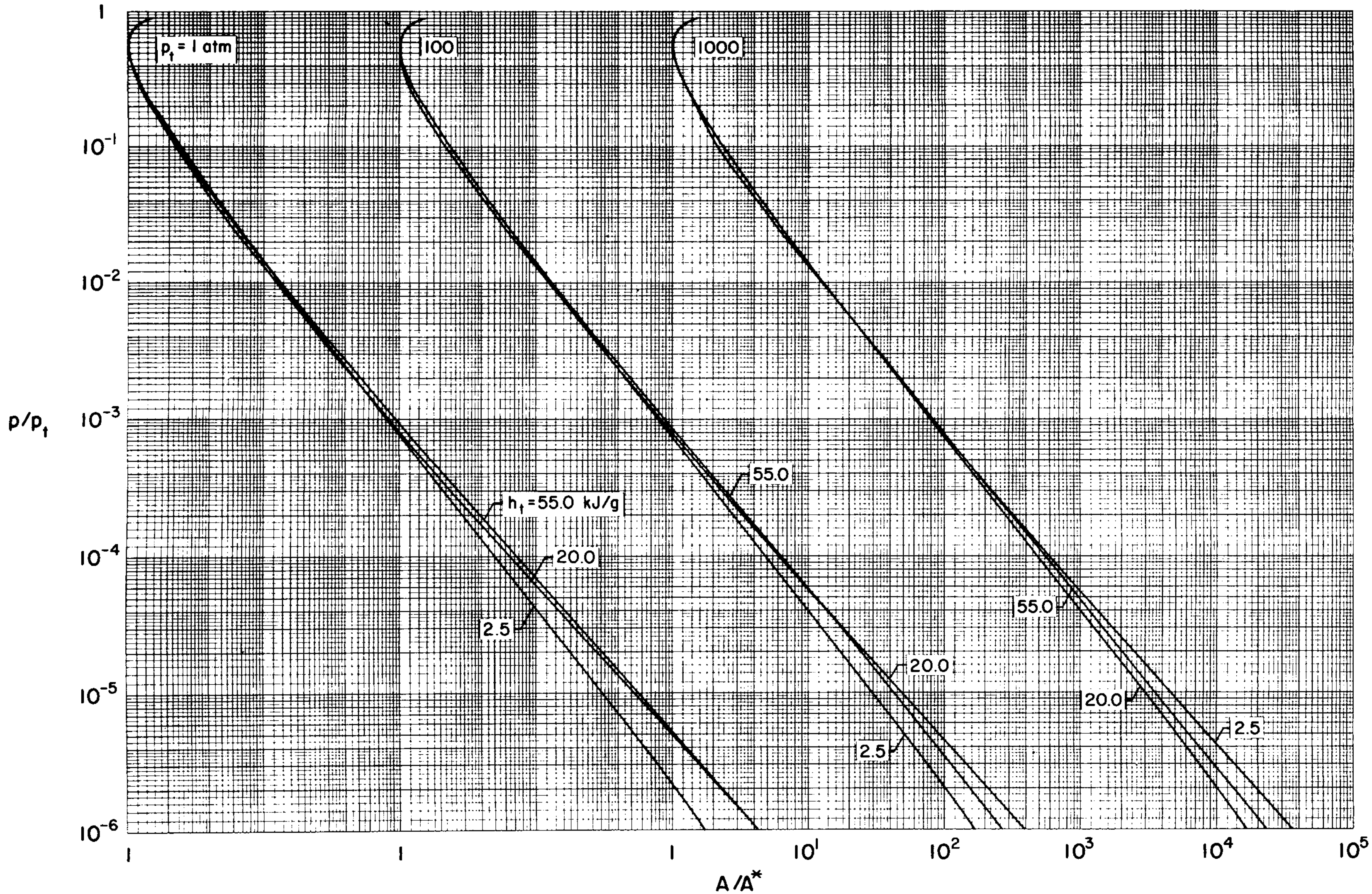
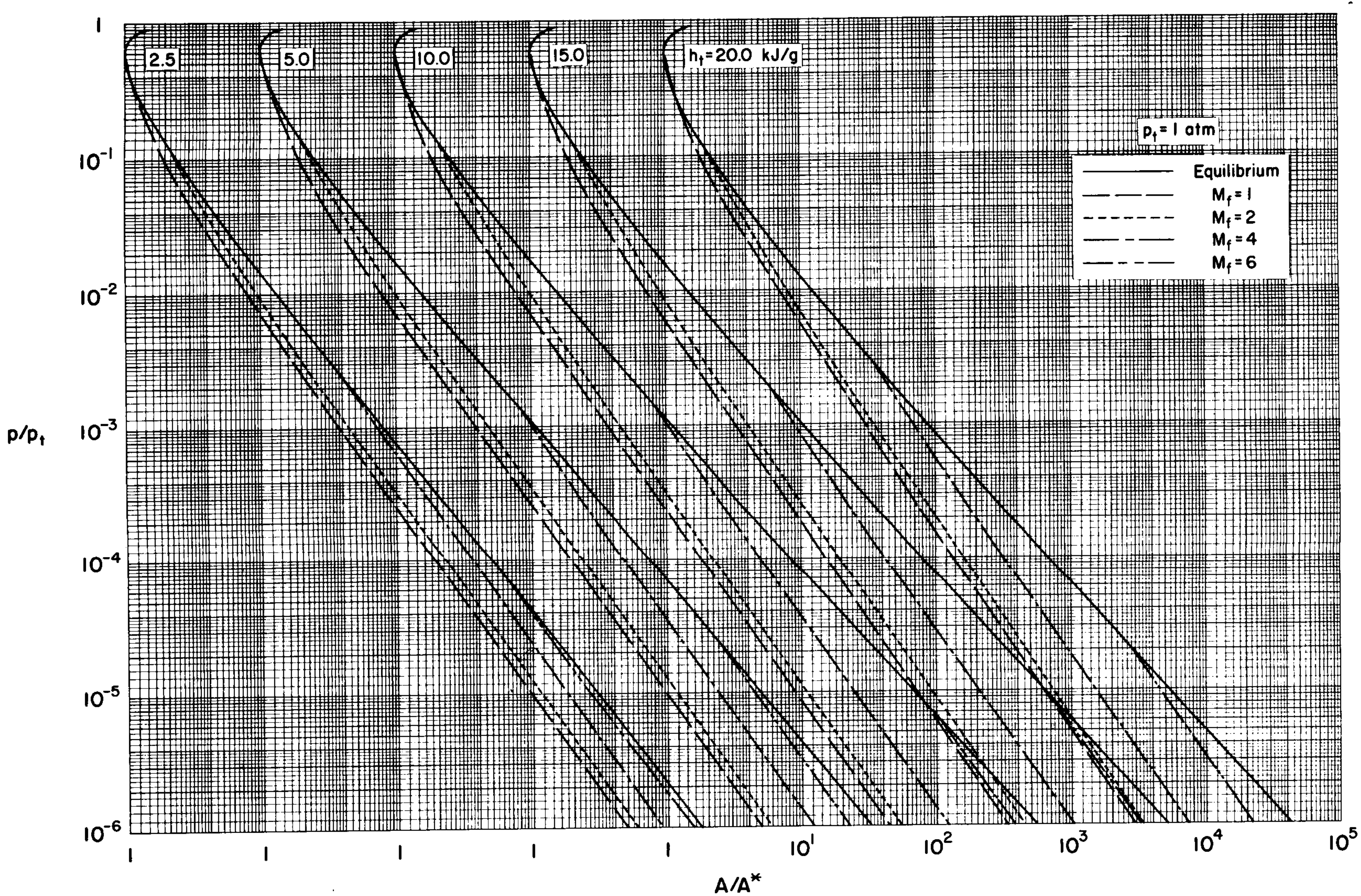
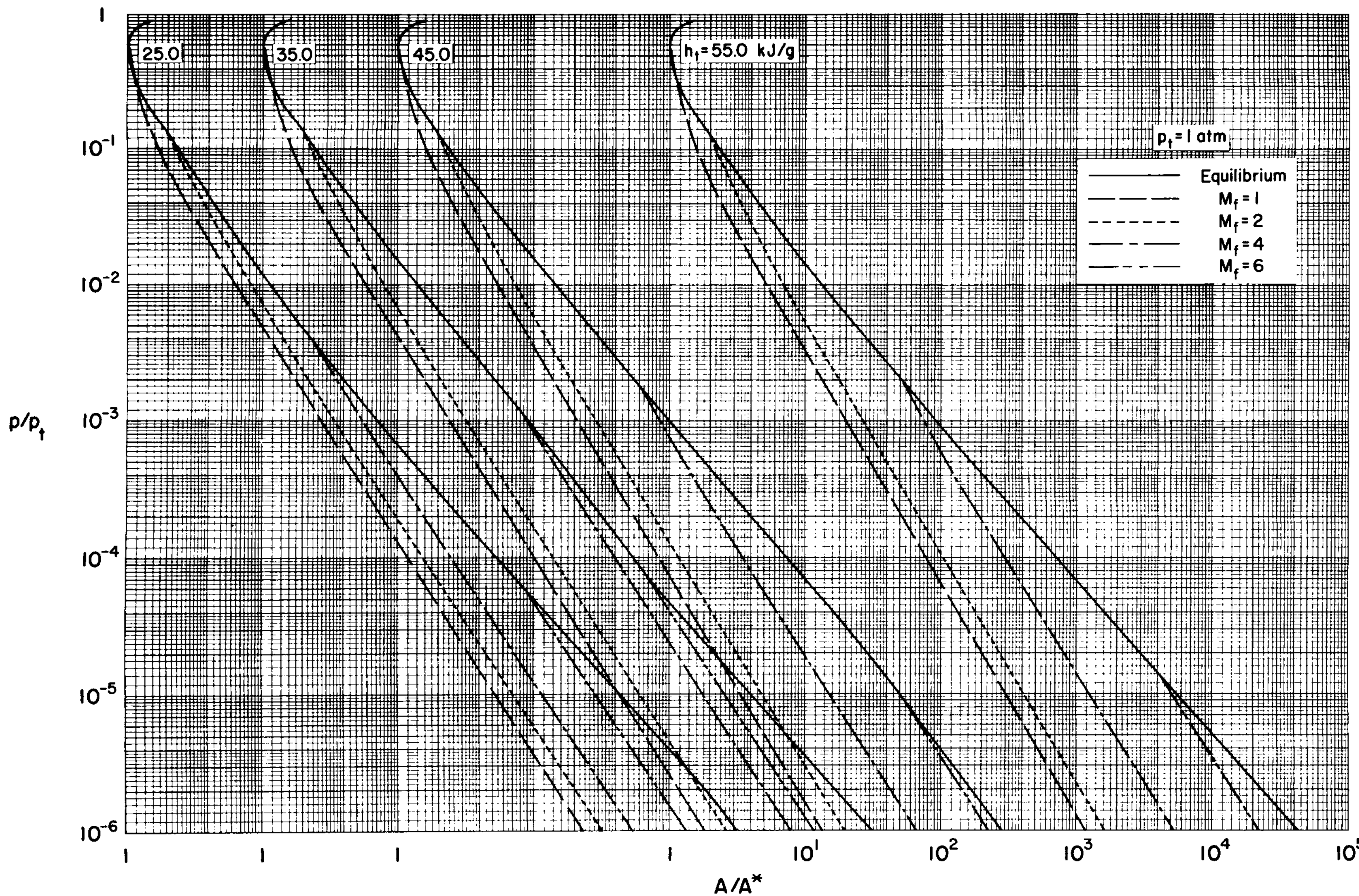


Chart 4. - Variation of pressure ratio with area ratio; equilibrium flows.



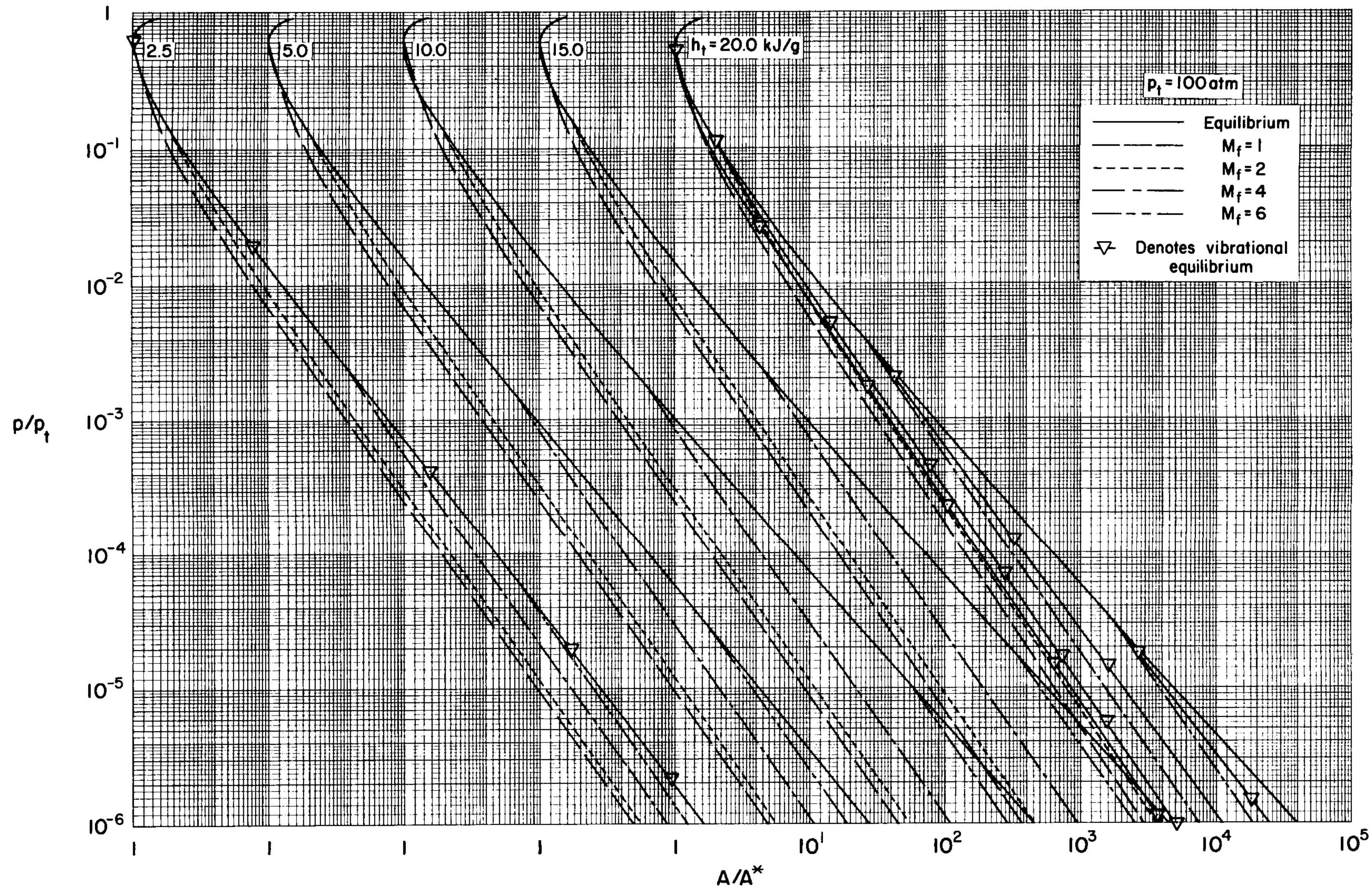
(a) p_t = 1 atm; h_t = 2.5, 5.0, 10.0, 15.0, 20.0 kJ/g

Chart 5. - Variation of pressure ratio with area ratio; equilibrium and frozen flows.



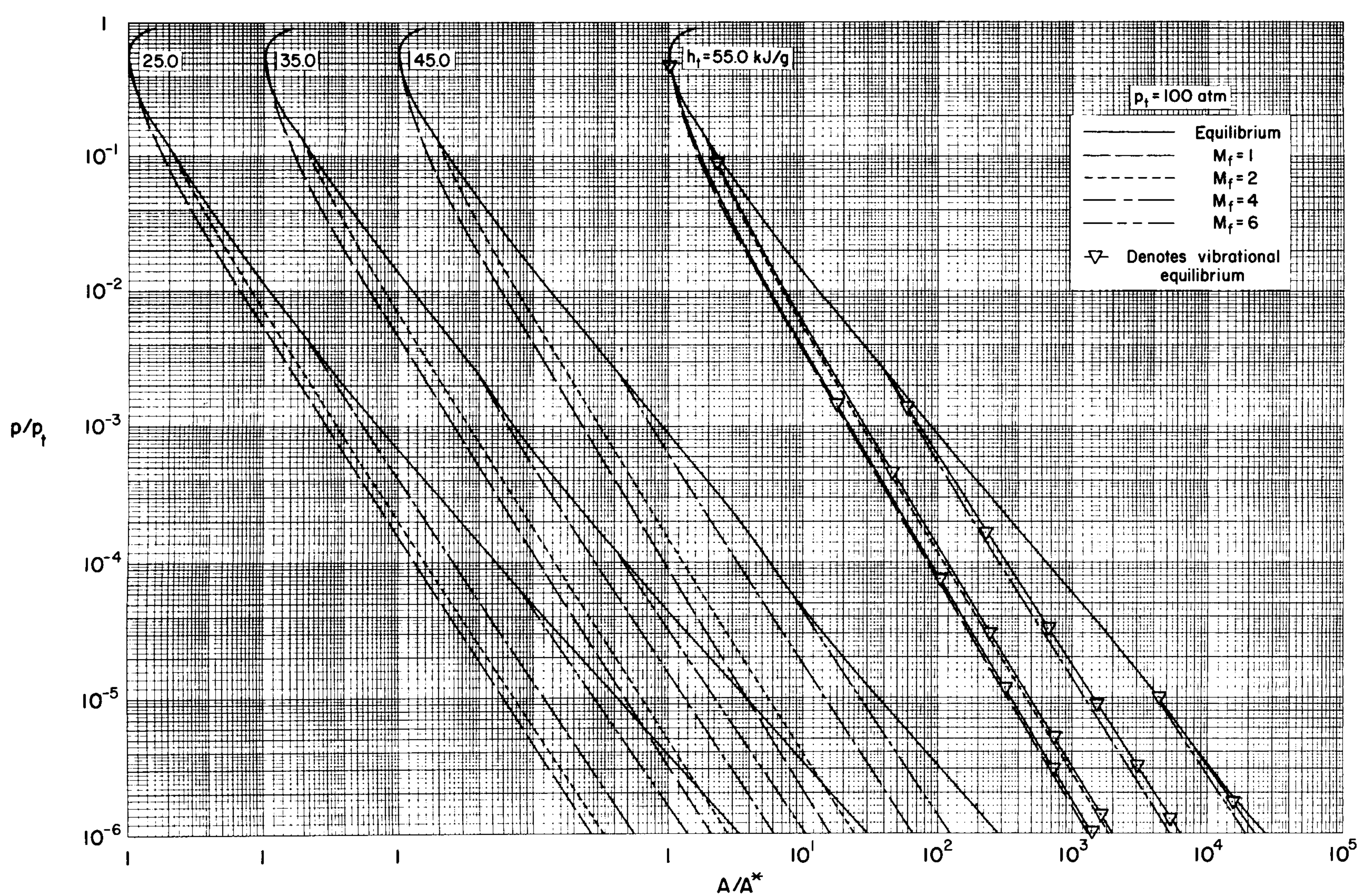
(b) p_t = 1 atm; h_t = 25.0, 35.0, 45.0, 55.0 kJ/g

Chart 5. - Continued.



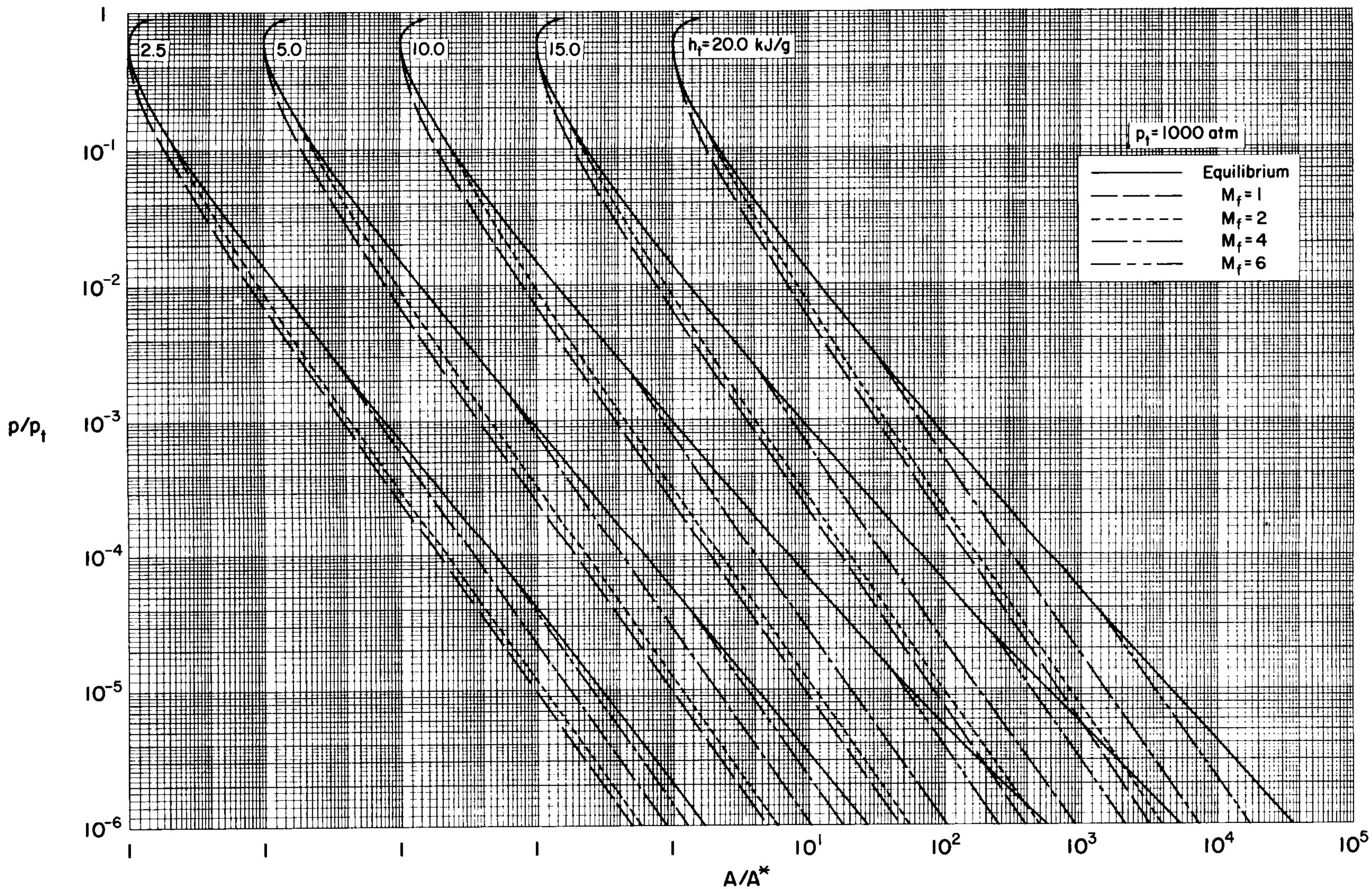
(c) p_t = 100 atm; h_t = 2.5, 5.0, 10.0, 15.0, 20.0 kJ/g

Chart 5. - Continued.



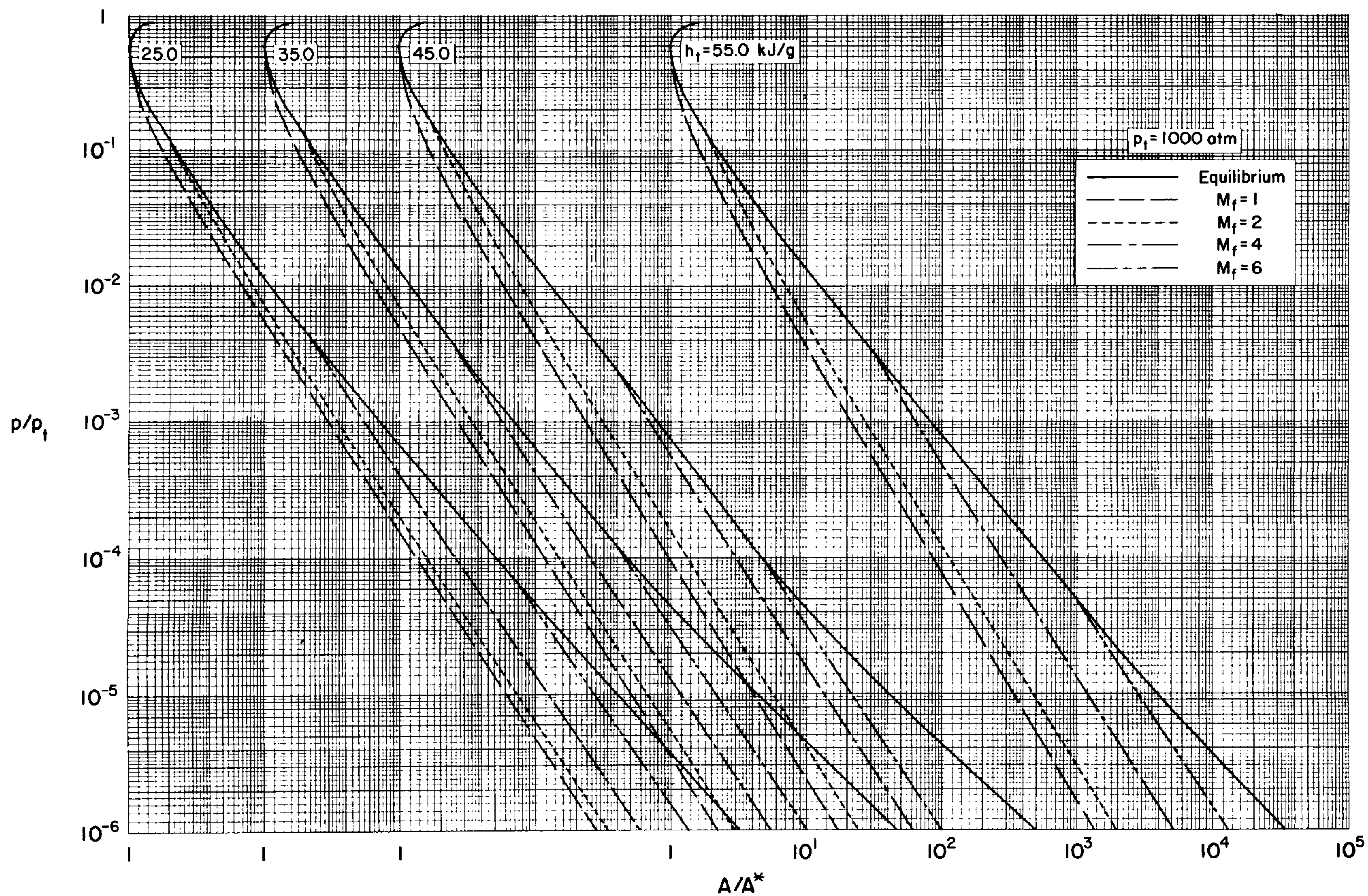
(d) $p_t = 100$ atm; $h_t = 25.0,\ 35.0,\ 45.0,\ 55.0$ kJ/g

Chart 5. - Continued.



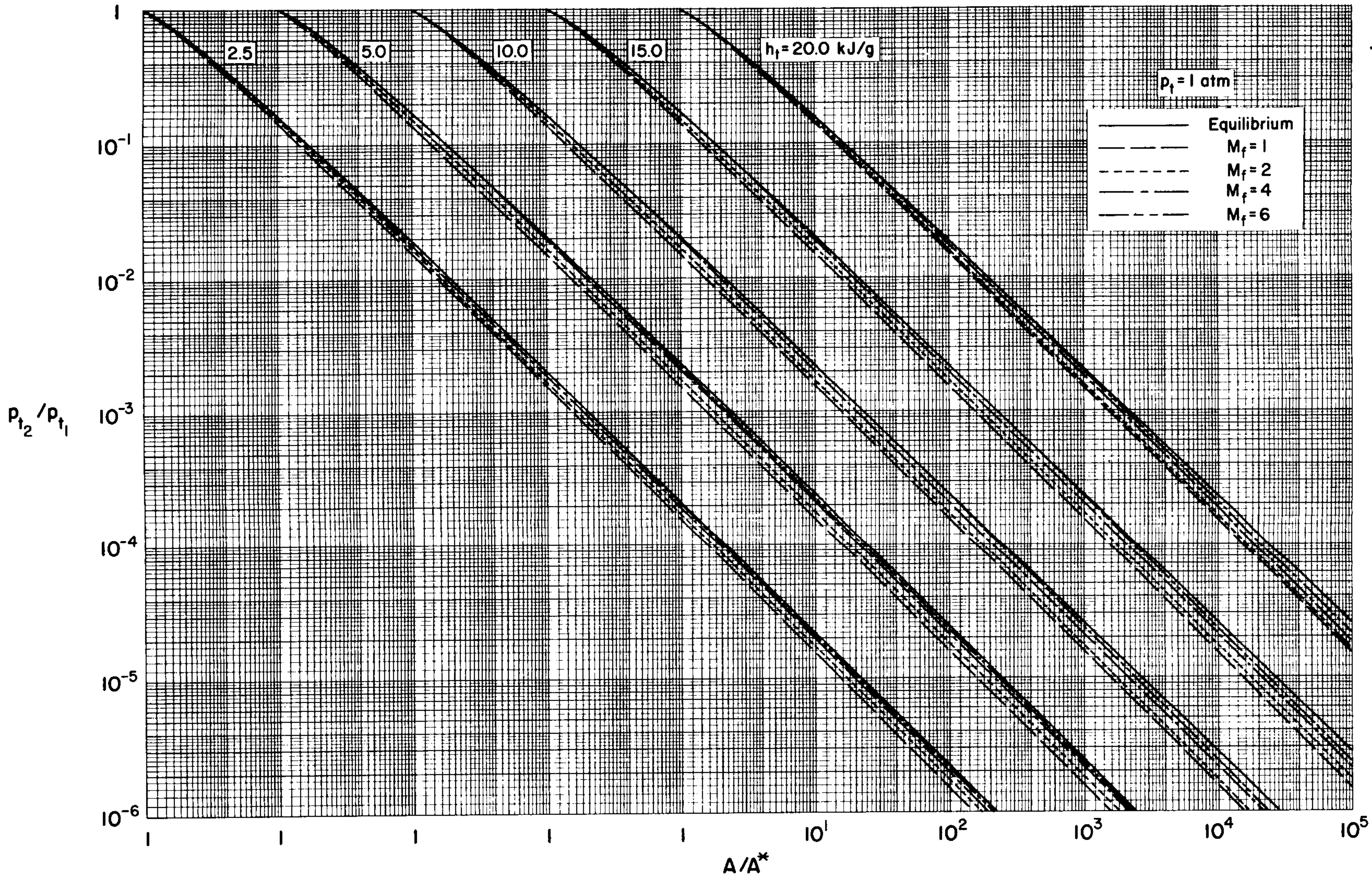
(e) p_t = 1000 atm; h_t = 2.5, 5.0, 10.0, 15.0, 20.0 kJ/g

Chart 5. - Continued.



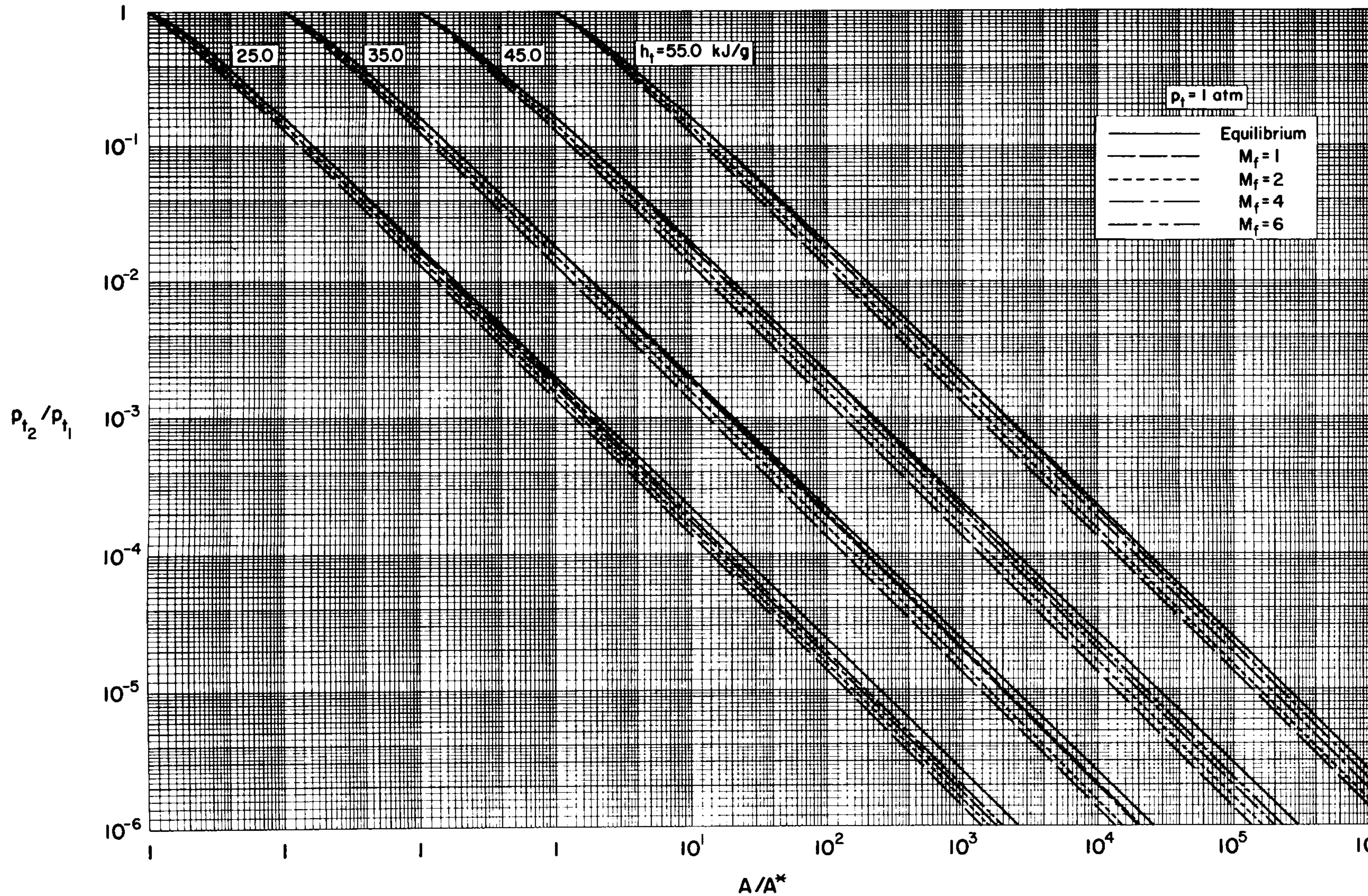
(f) p_t = 1000 atm; h_t = 25.0, 35.0, 45.0, 55.0 kJ/g

Chart 5. - Concluded.



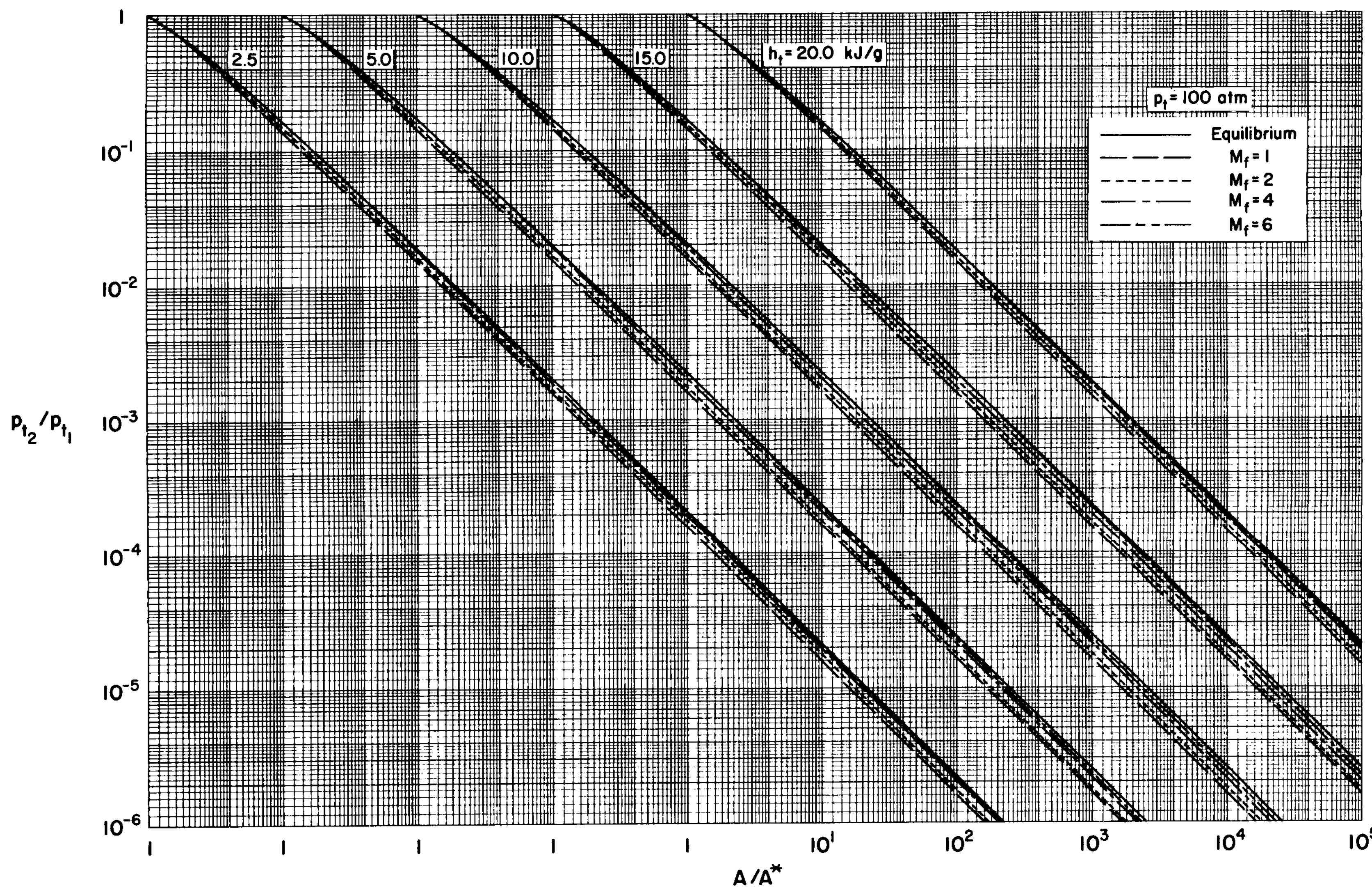
(a) $p_t = 1$ atm; $h_t = 2.5,\ 5.0,\ 10.0,\ 15.0,\ 20.0$ kJ/g

Chart 6. - Variation of total pressure ratio across a normal shock wave with area ratio; equilibrium and frozen flows.



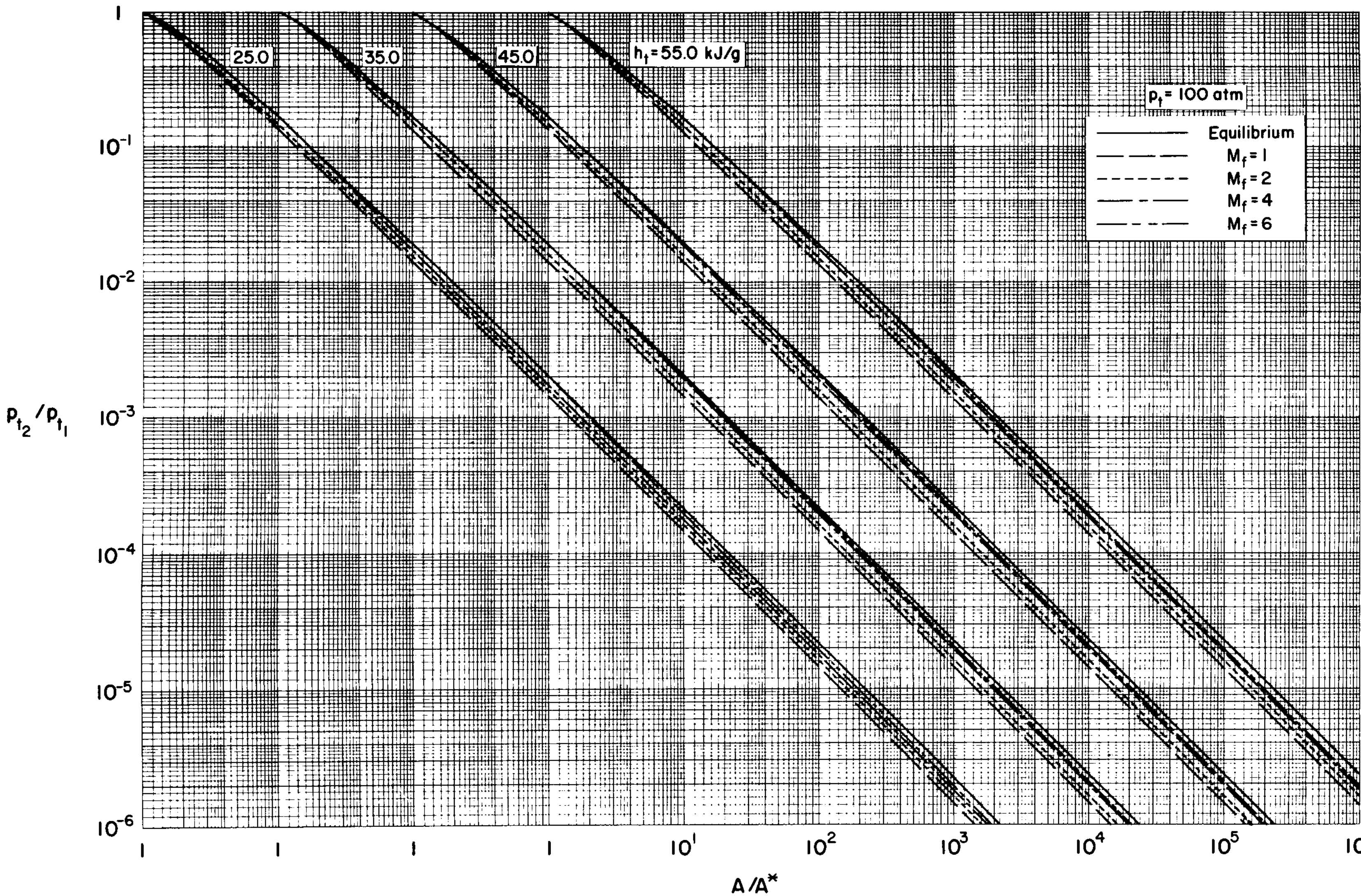
(b) p_t = 1 atm; h_t = 25.0, 35.0, 45.0, 55.0 kJ/g

Chart 6. - Continued.



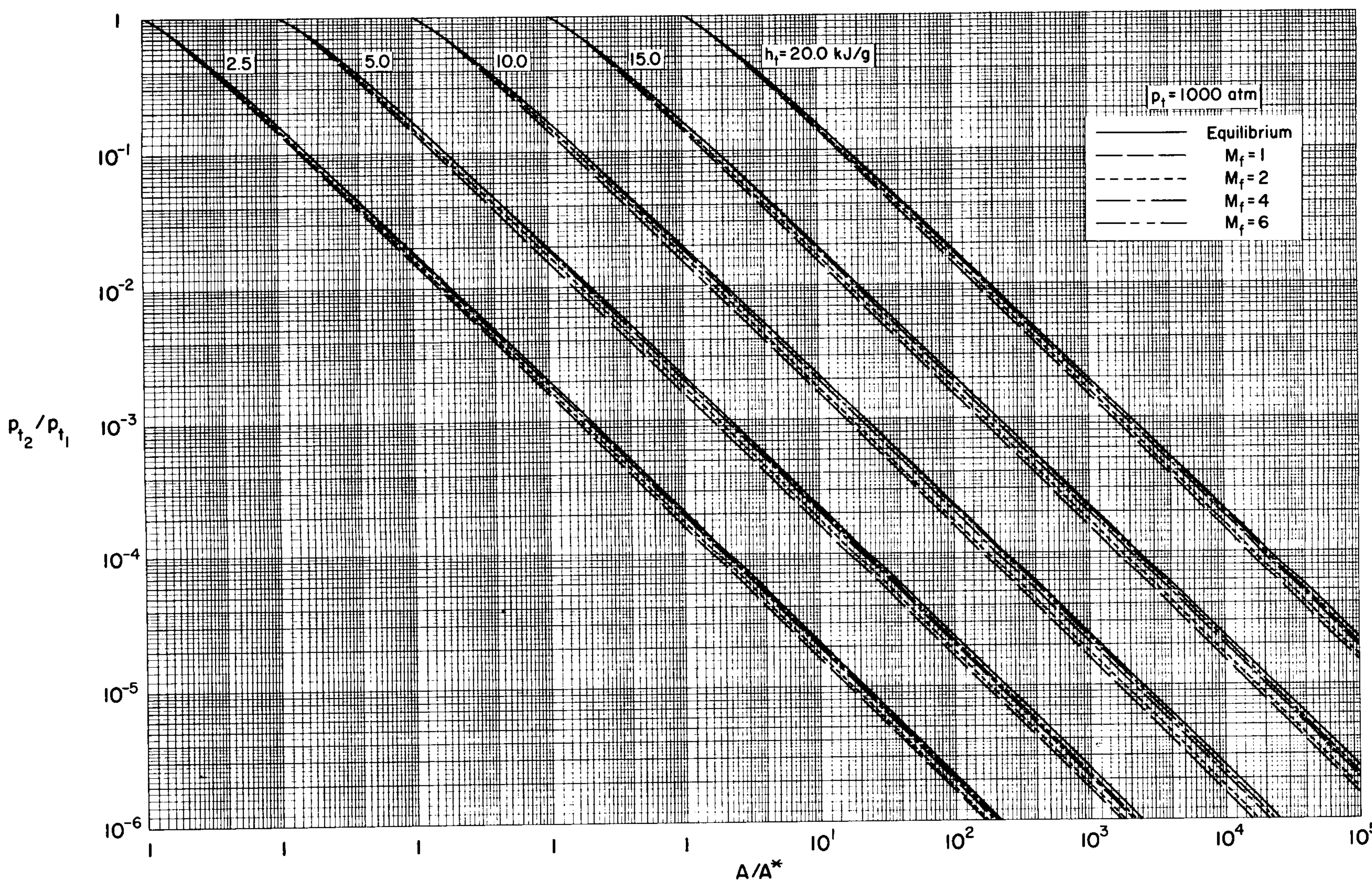
(c) p_t = 100 atm; h_t = 2.5, 5.0, 10.0, 15.0, 20.0 kJ/g

Chart 6. - Continued.



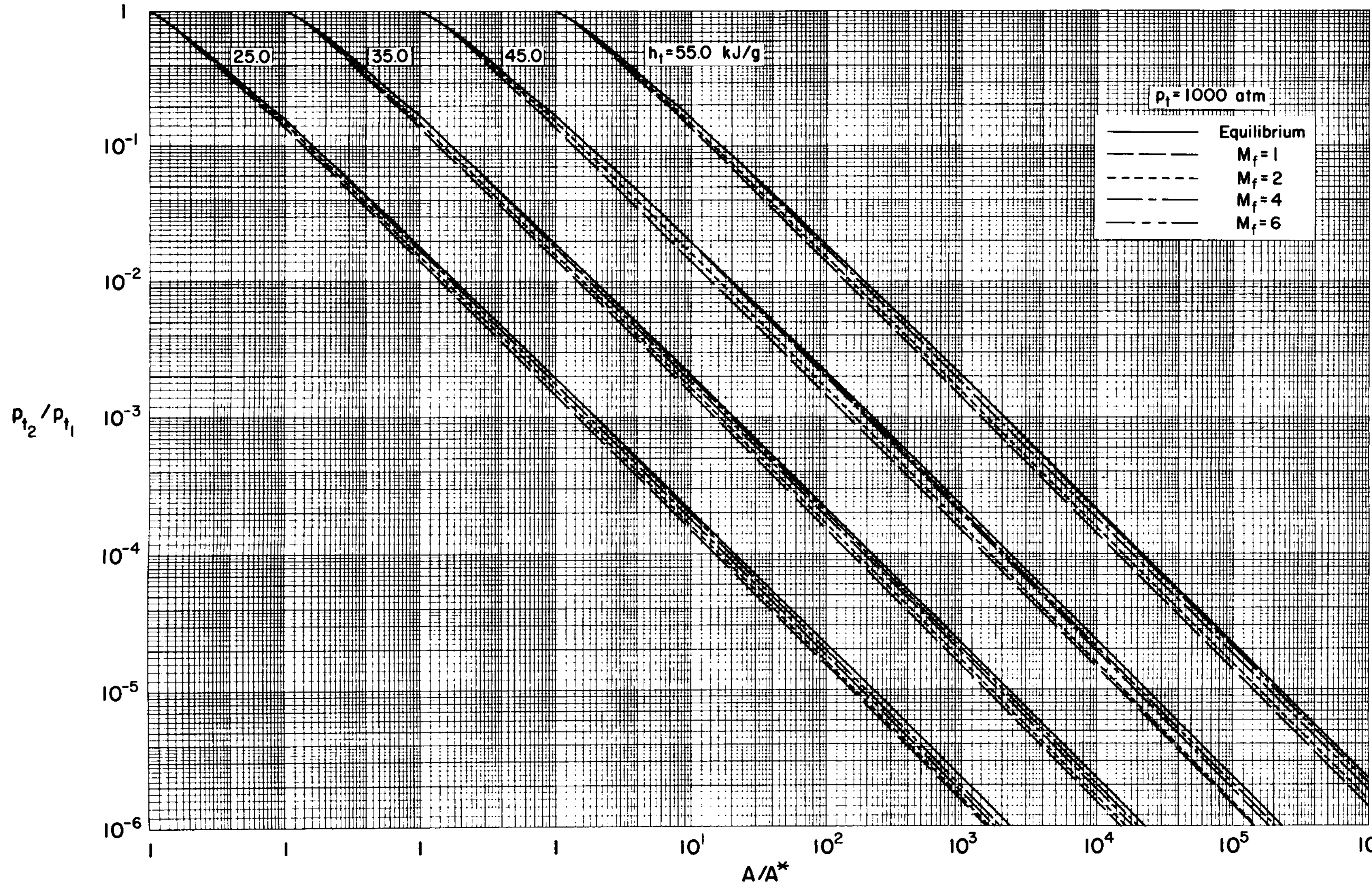
(d) p_t = 100 atm; h_t = 25.0, 35.0, 45.0, 55.0 kJ/g

Chart 6. - Continued.



(e) p_t = 1000 atm; h_t = 2.5, 5.0, 10.0, 15.0, 20.0 kJ/g

Chart 6. - Continued.



(f) p_t = 1000 atm; h_t = 25.0, 35.0, 45.0, 55.0 kJ/g

Chart 6. - Concluded.

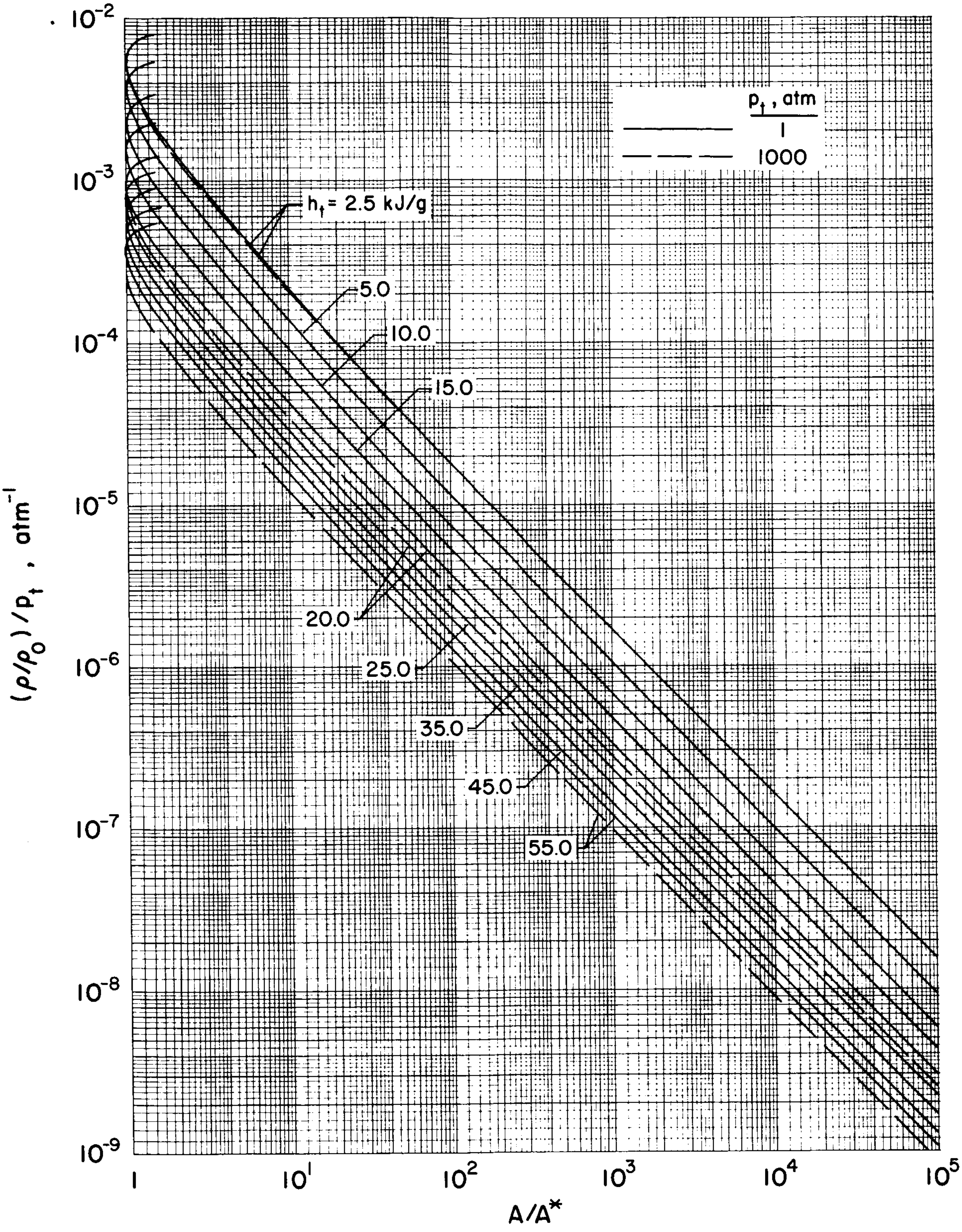
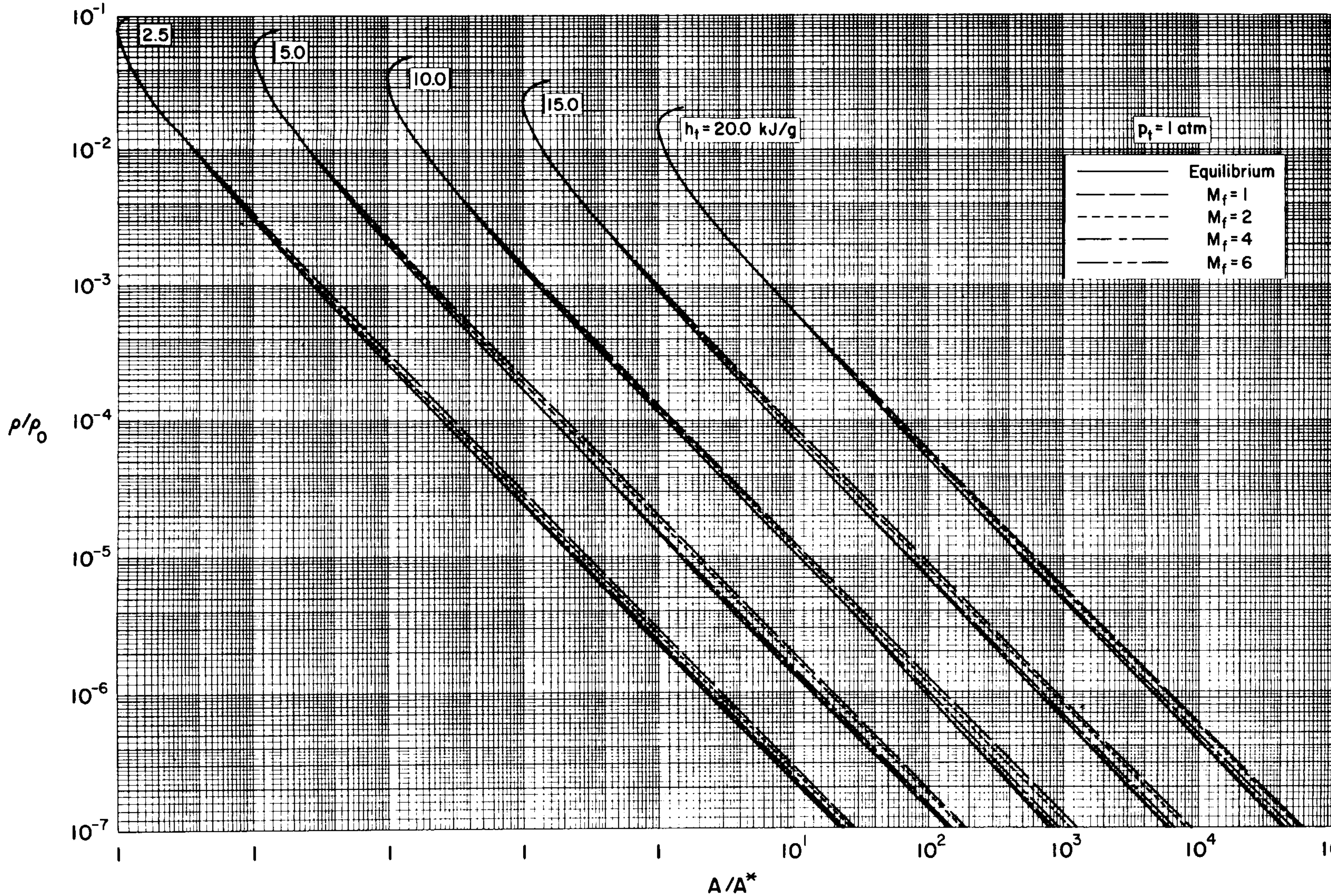
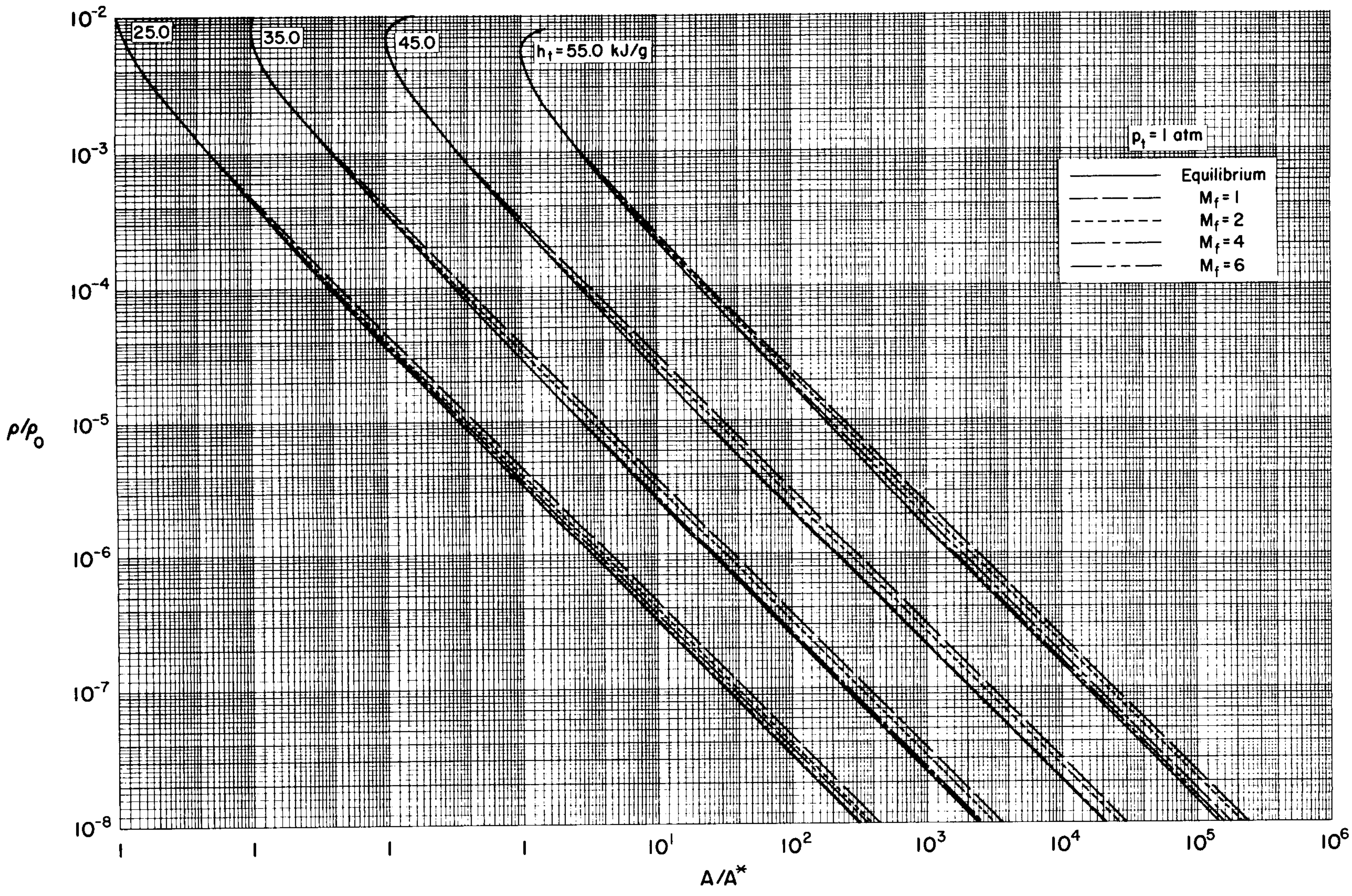


Chart 7. - Variation of density with area ratio; equilibrium flow.



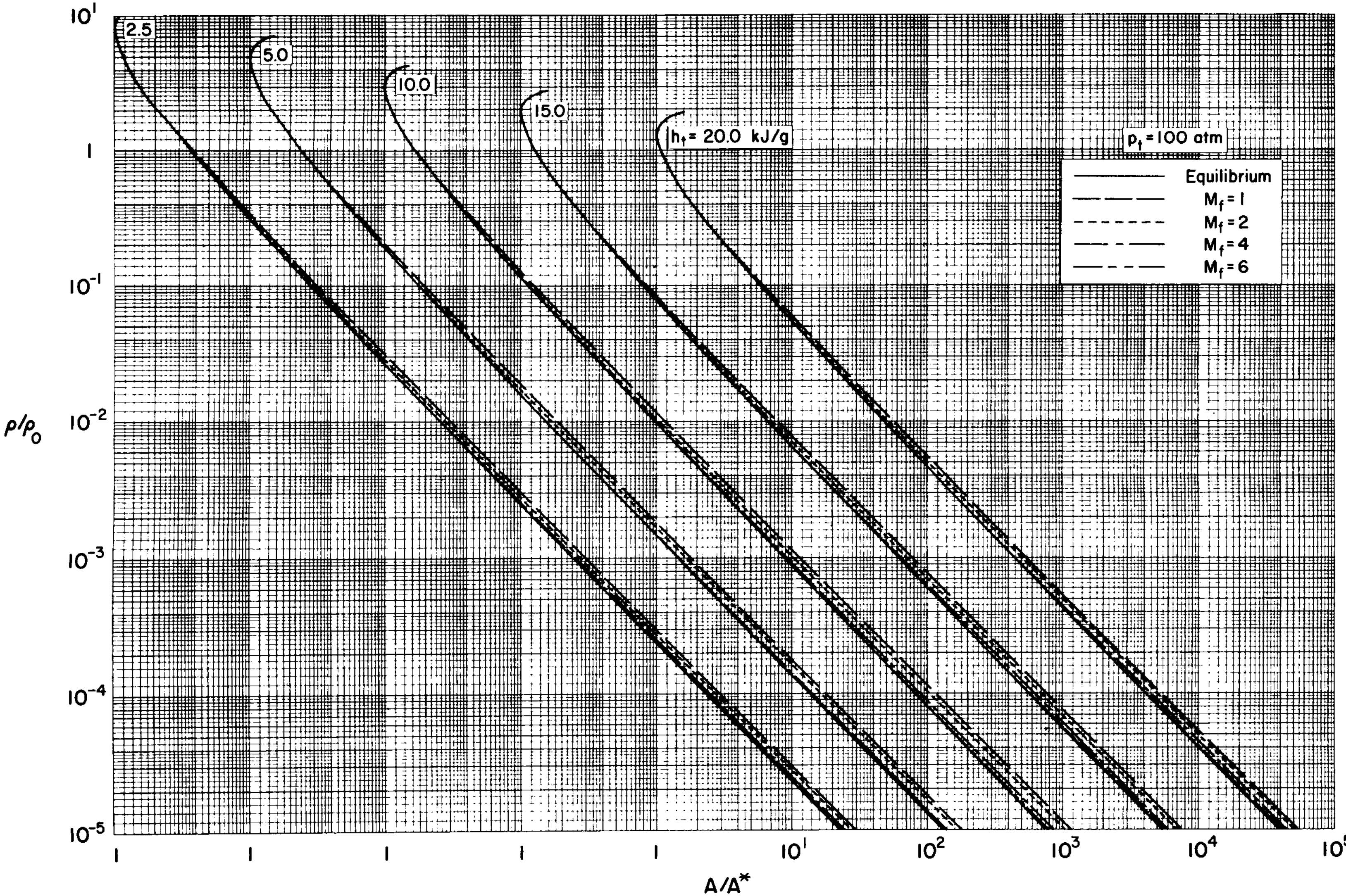
(a) p_t = 1 atm; h_t = 2.5, 5.0, 10.0, 15.0, 20.0 kJ/g

Chart 8. - Variation of density with area ratio; equilibrium and frozen flows.



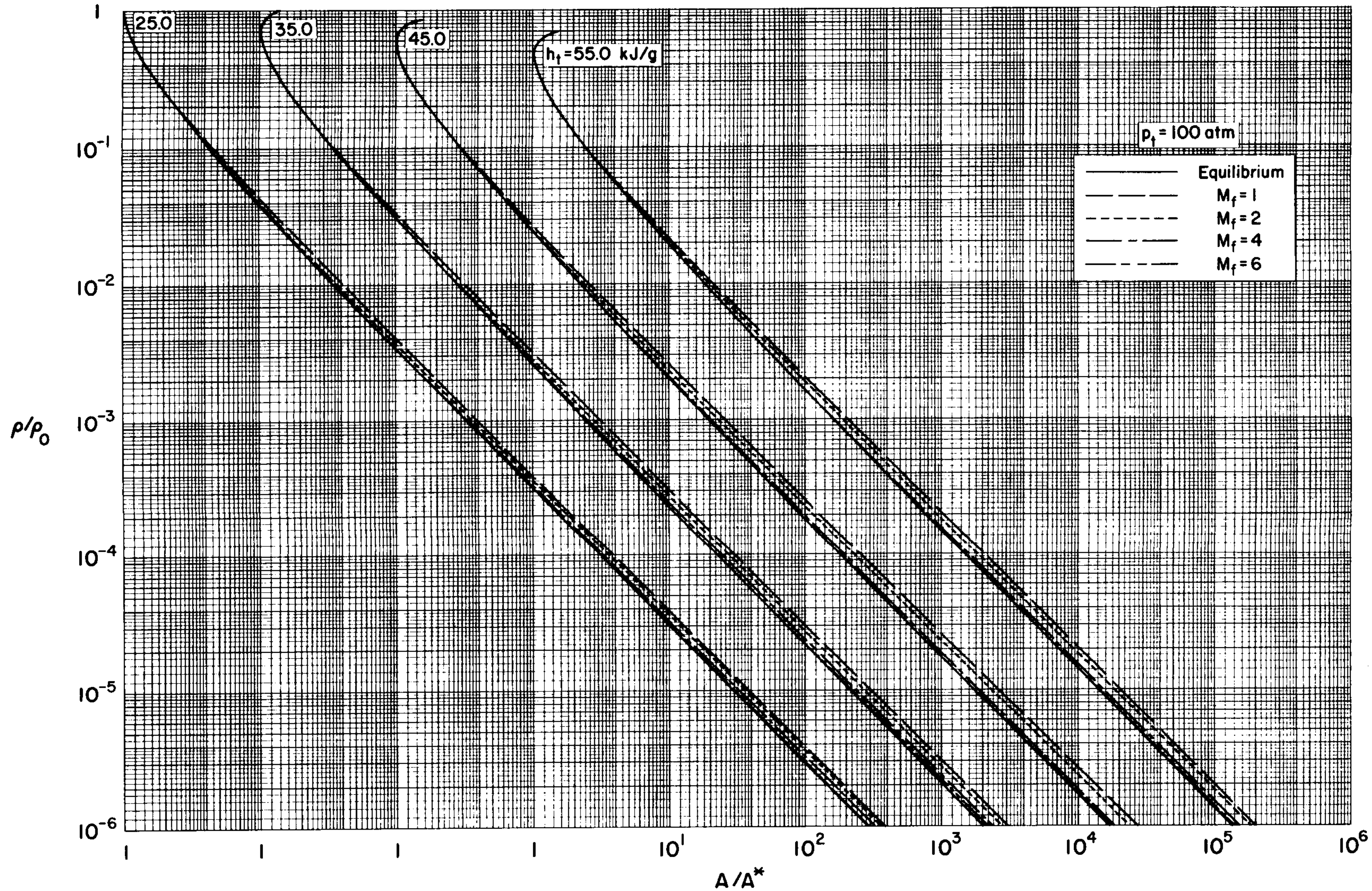
(b) $p_t = 1$ atm; $h_t = 25.0,\ 35.0,\ 45.0,\ 55.0$ kJ/g

Chart 8. - Continued.



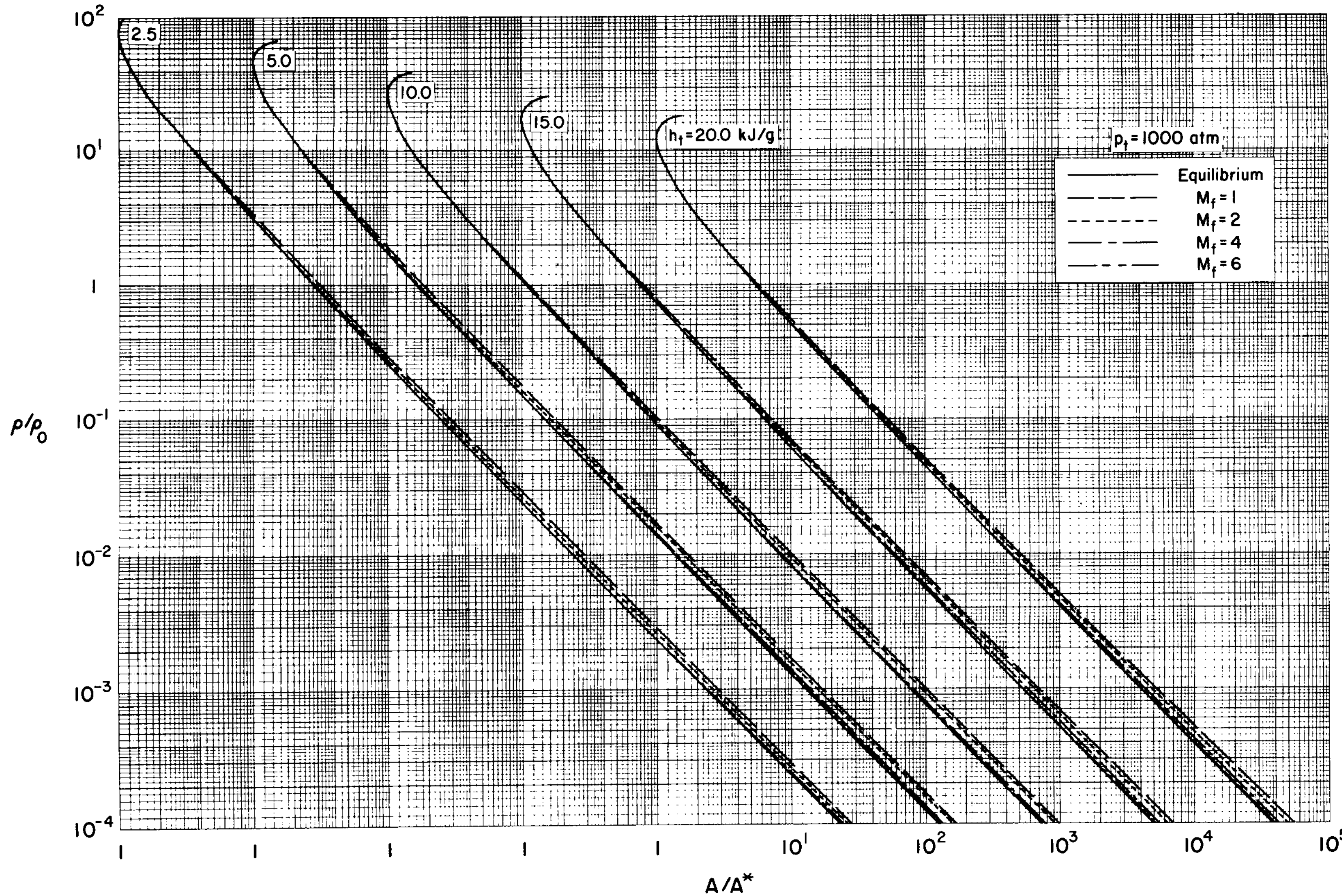
(c) p_t = 100 atm; h_t = 2.5, 5.0, 10.0, 15.0, 20.0 kJ/g

Chart 8. - Continued.



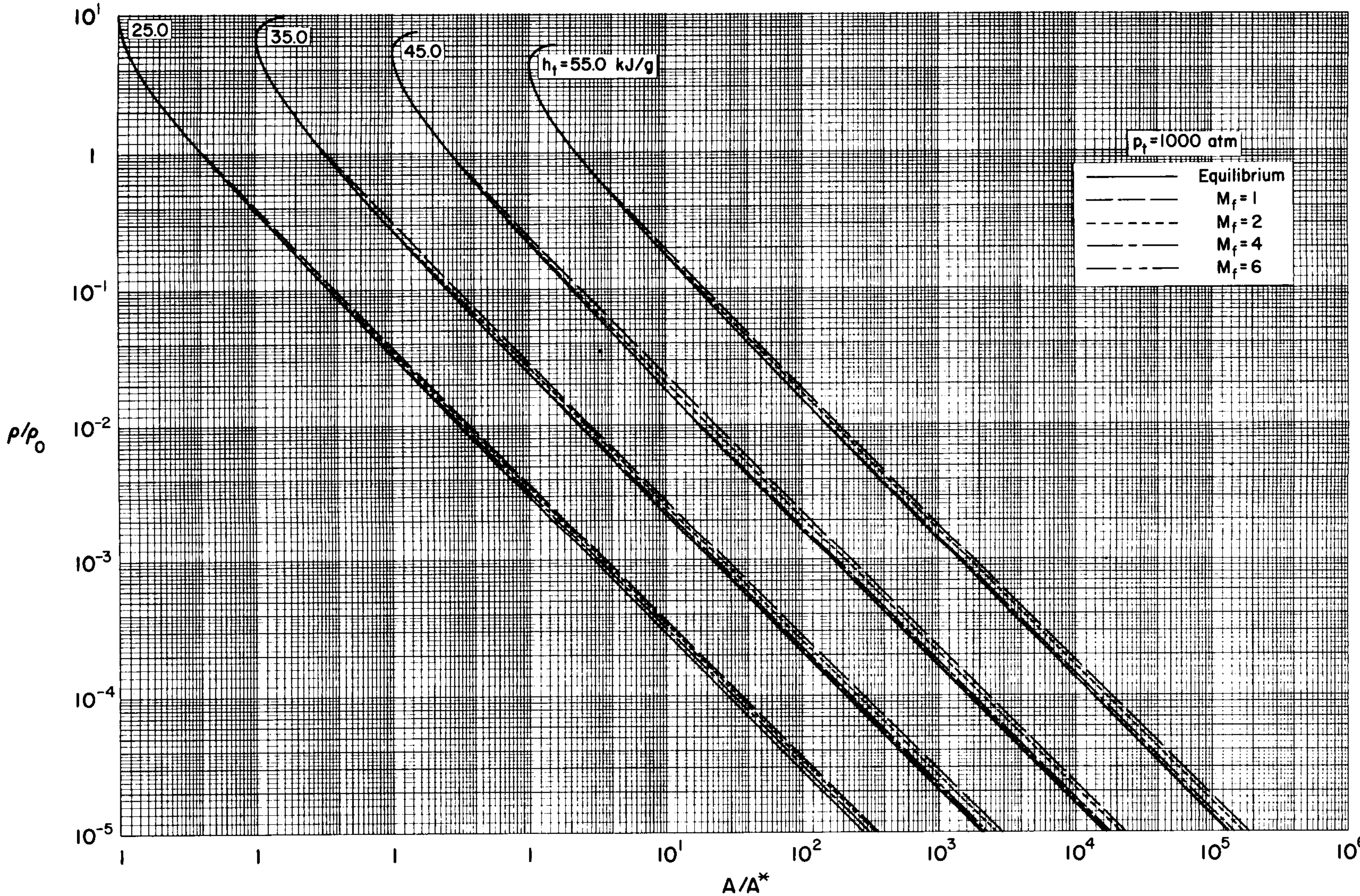
(d) p_t = 100 atm; h_t = 25.0, 35.0, 45.0, 55.0 kJ/g

Chart 8. - Continued.



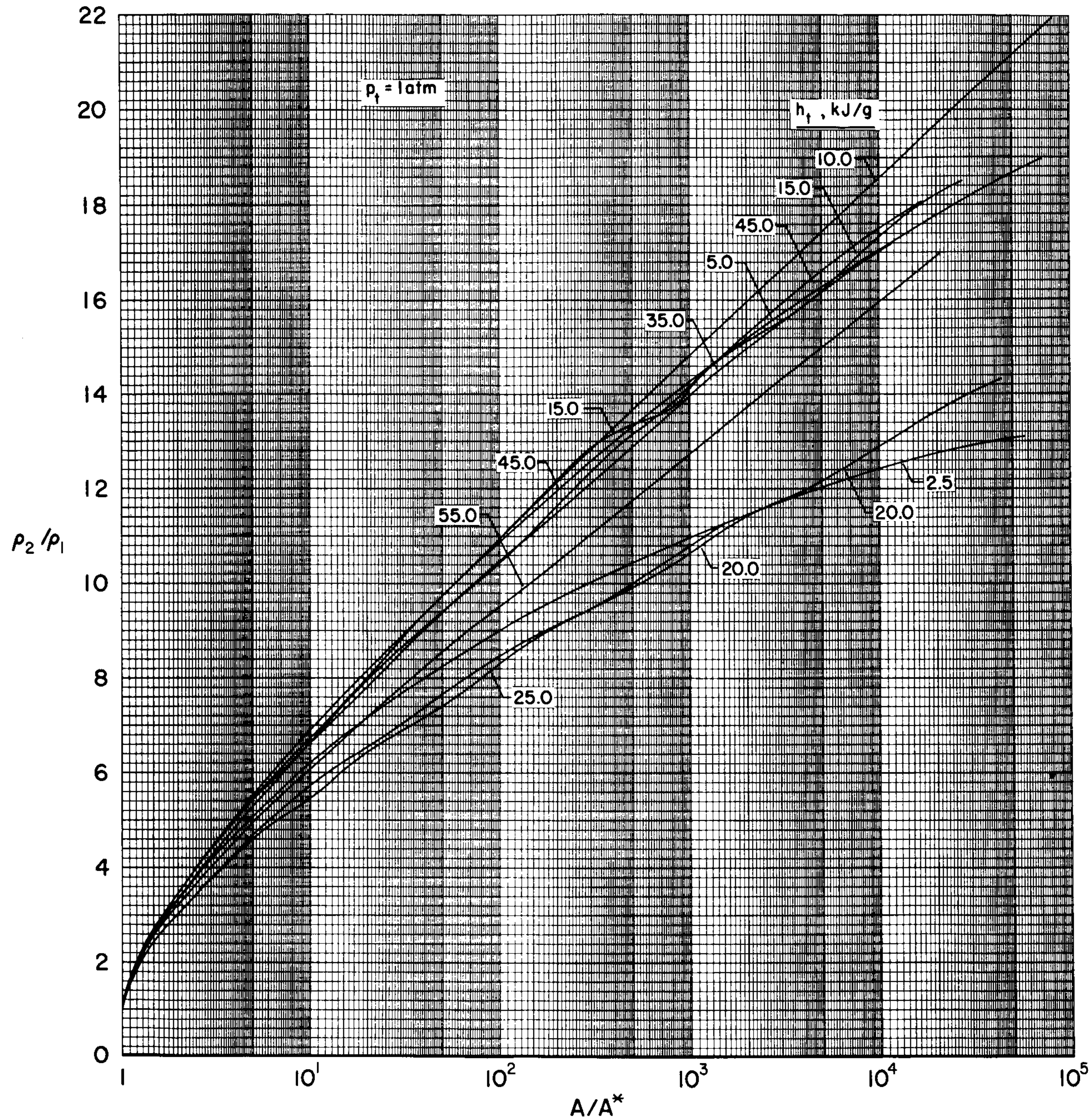
(e) p_t = 1000 atm; h_t = 2.5, 5.0, 10.0, 15.0, 20.0 kJ/g

Chart 8. - Continued.



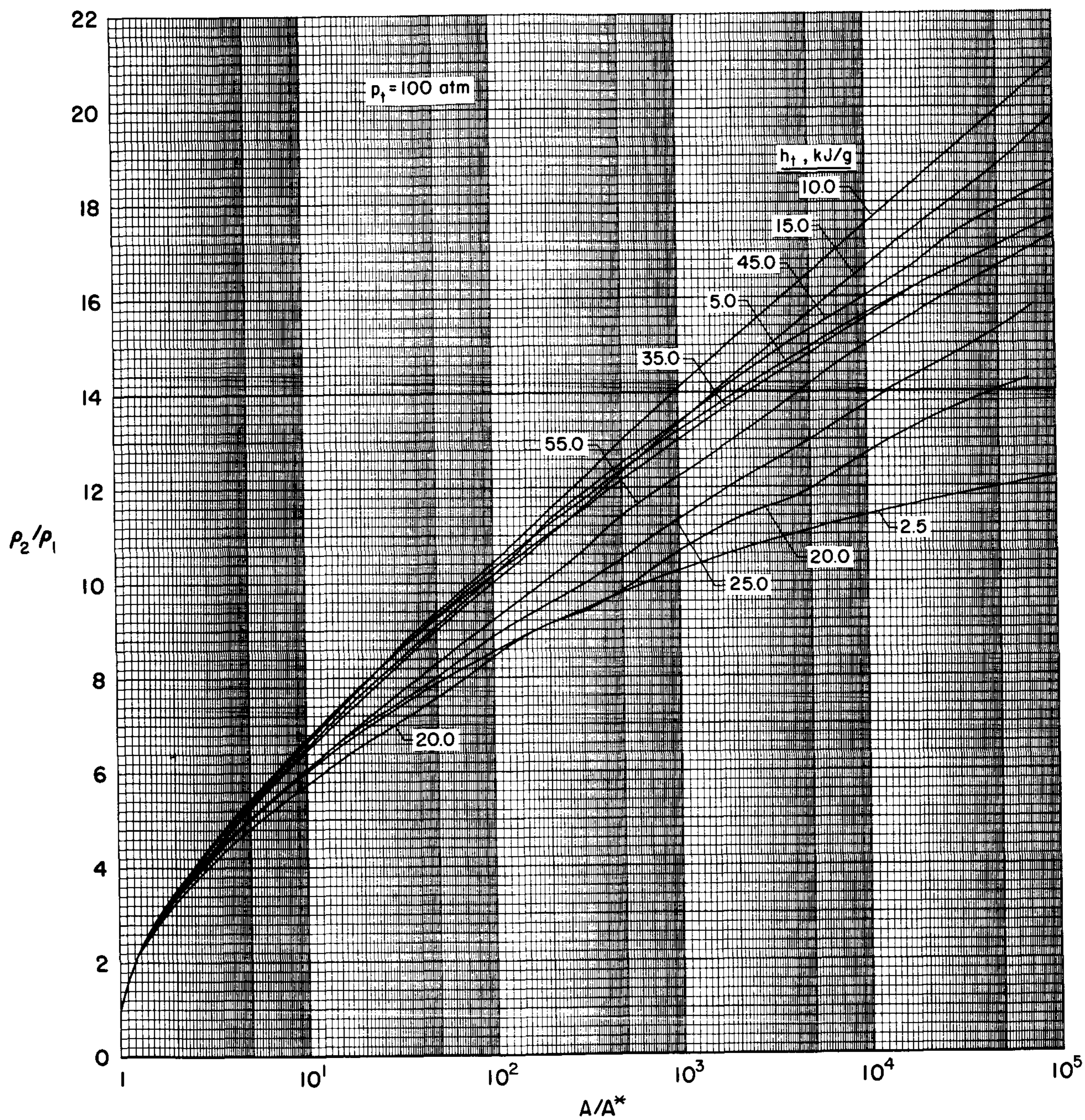
(f) p_t = 1000 atm; h_t = 25.0, 35.0, 45.0, 55.0 kJ/g

Chart 8. - Concluded.



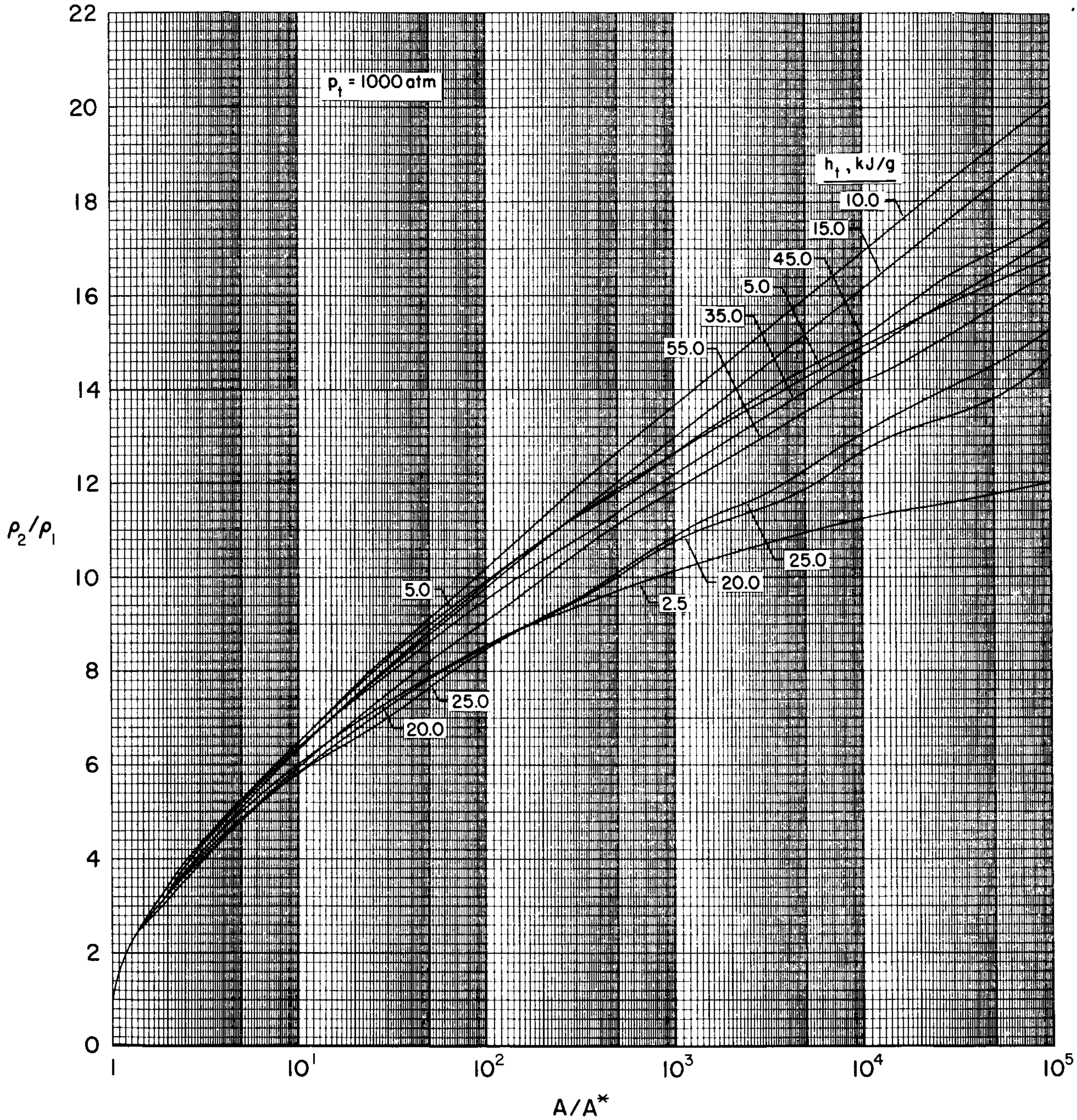
(a) p_t = 1 atm

Chart 9. - Variation of density ratio across a normal shock wave with area ratio; equilibrium flow.



(b) p_t = 100 atm

Chart 9. - Continued.



(c) $p_t = 1000$ atm

Chart 9. - Concluded.

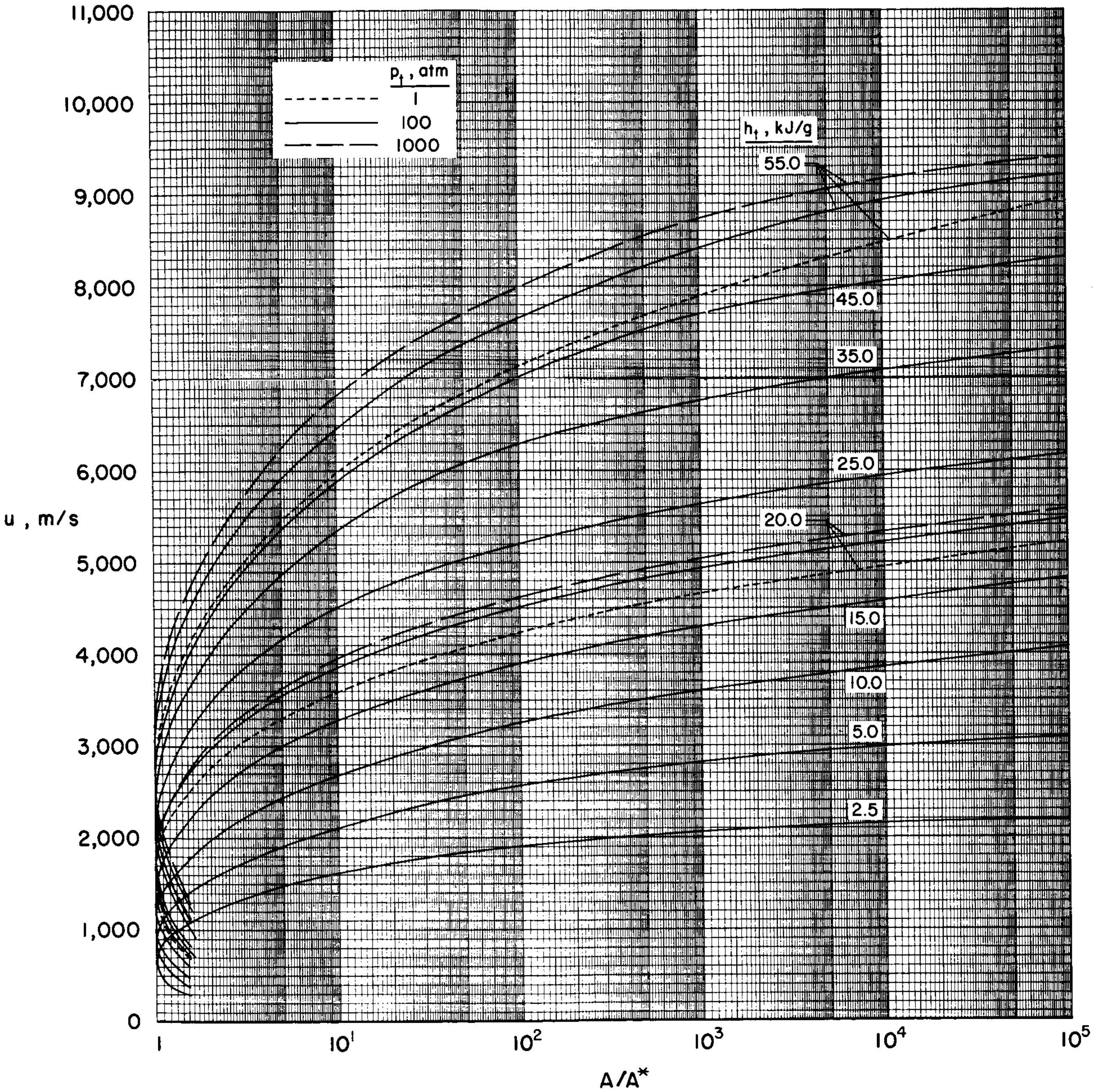
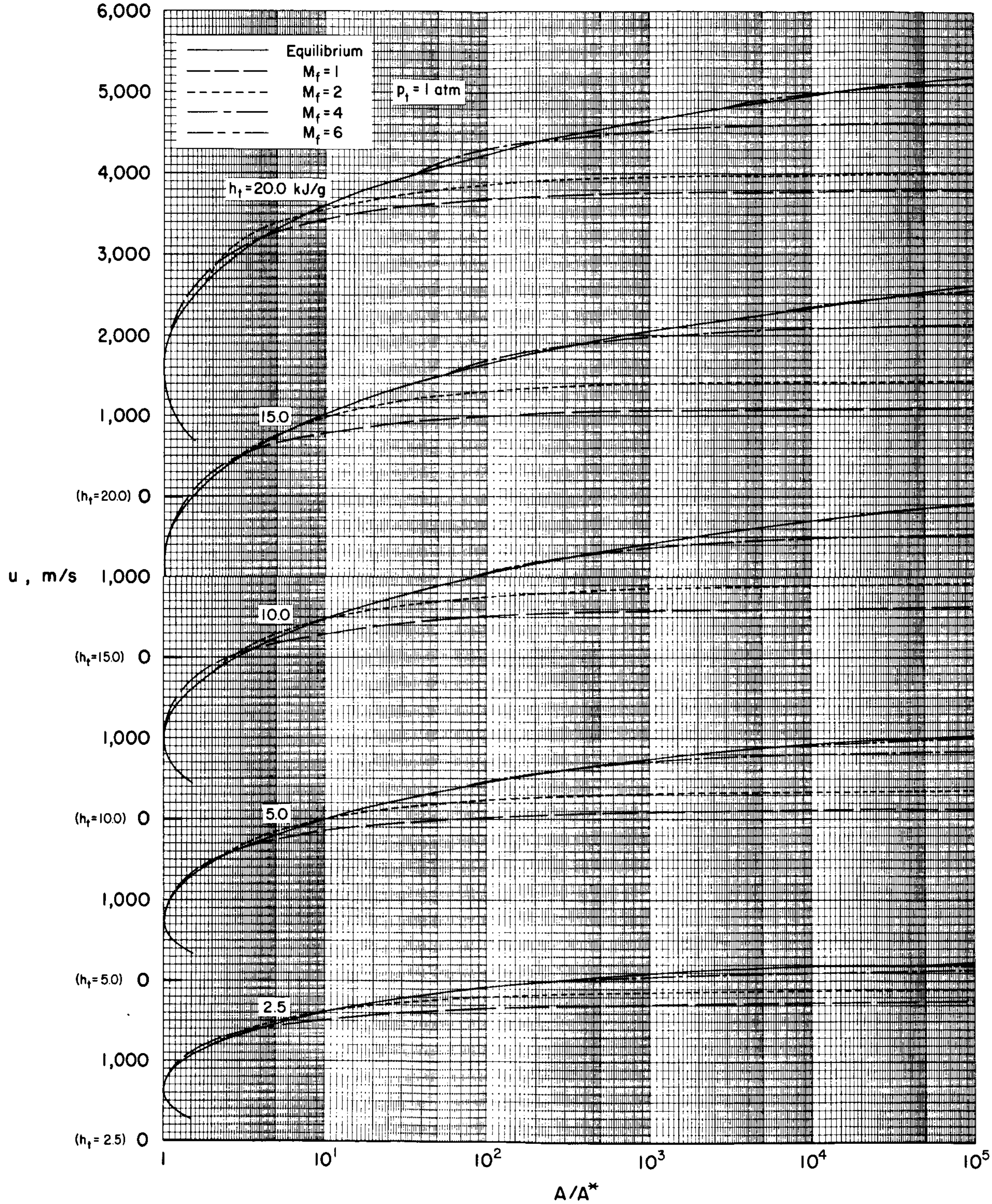
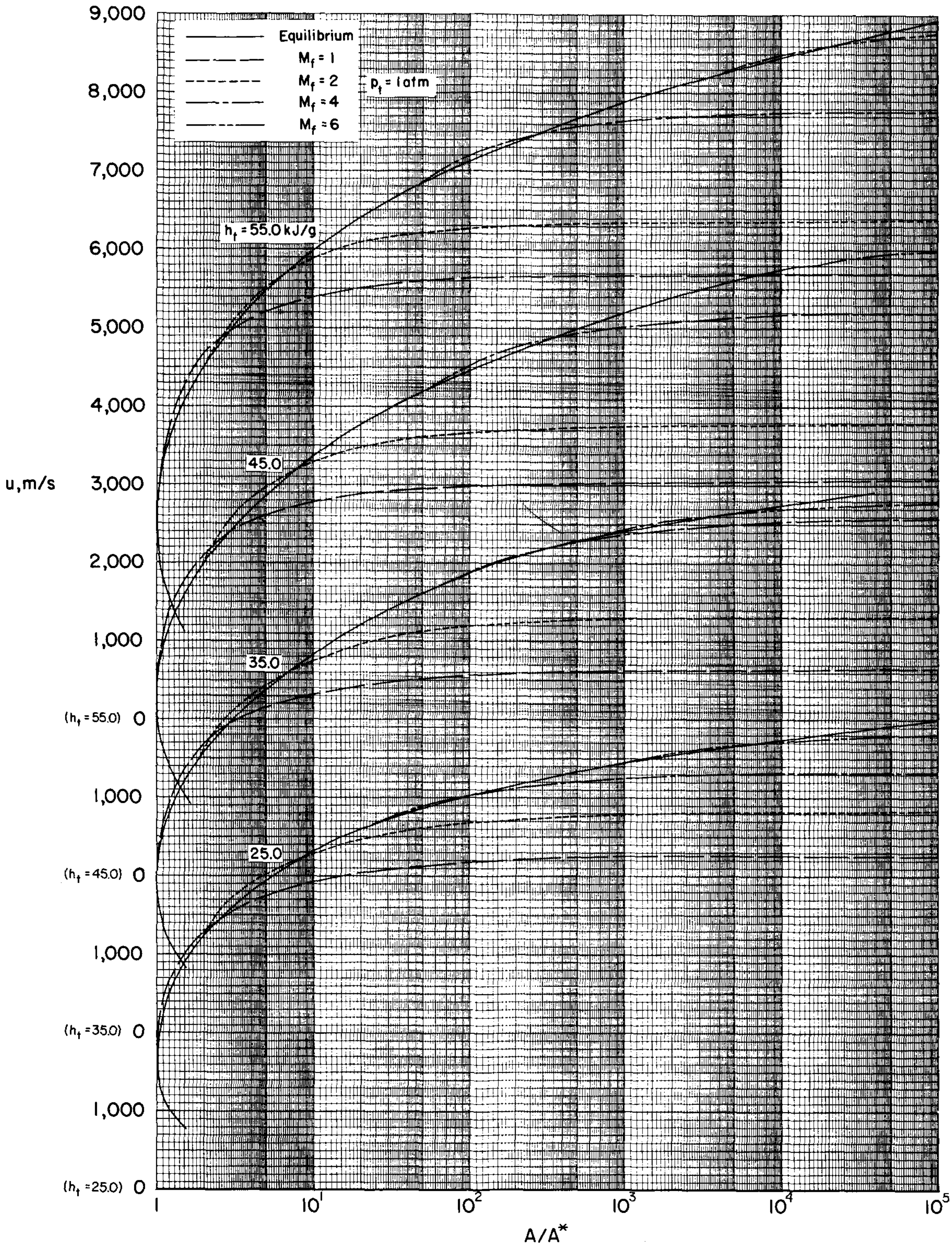


Chart 10. - Variation of velocity with area ratio; equilibrium flow.



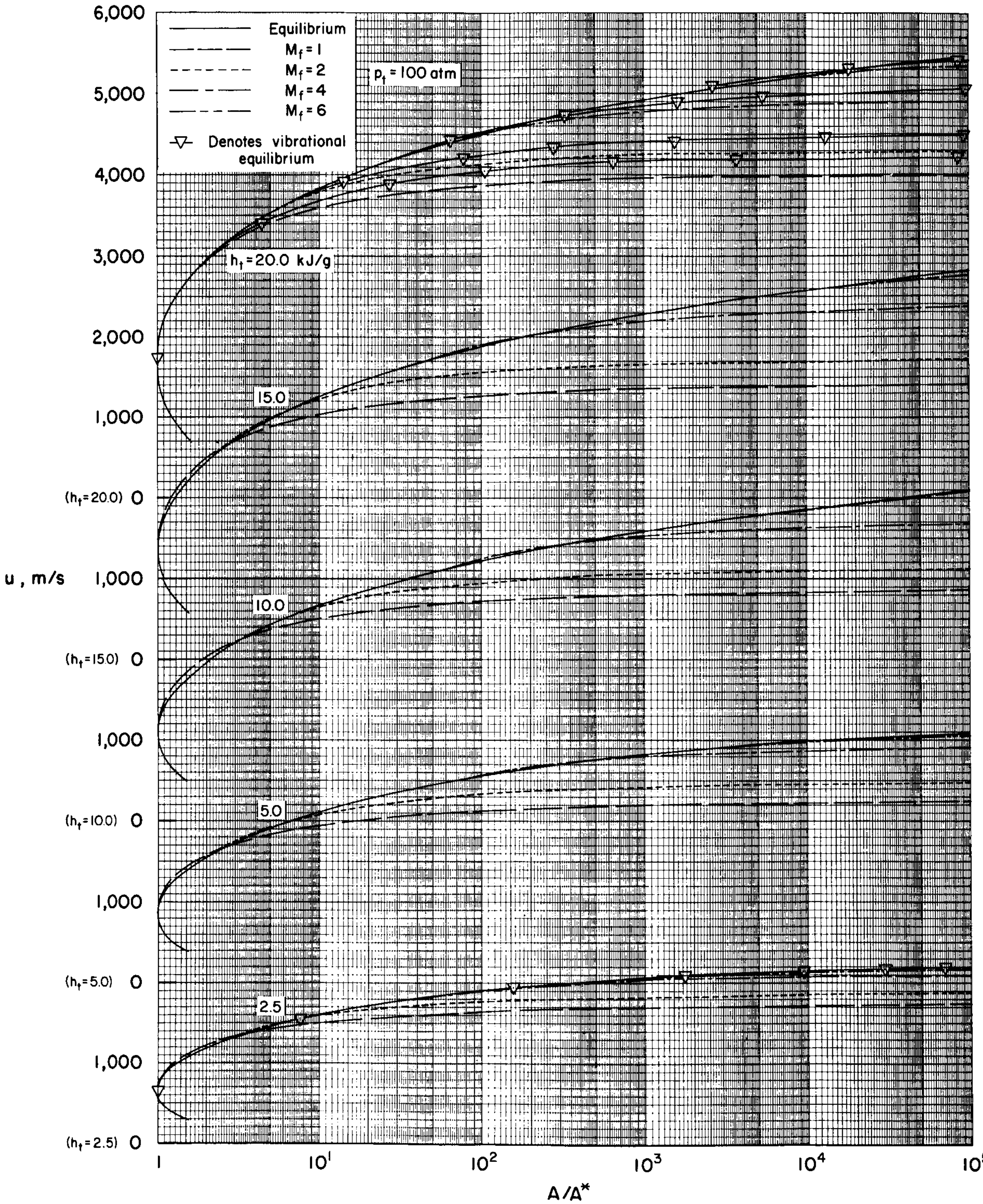
(a) $p_t = 1$ atm; $h_t = 2.5,\ 5.0,\ 10.0,\ 15.0,\ 20.0$ kJ/g

Chart 11. - Variation of velocity with area ratio; equilibrium and frozen flows.



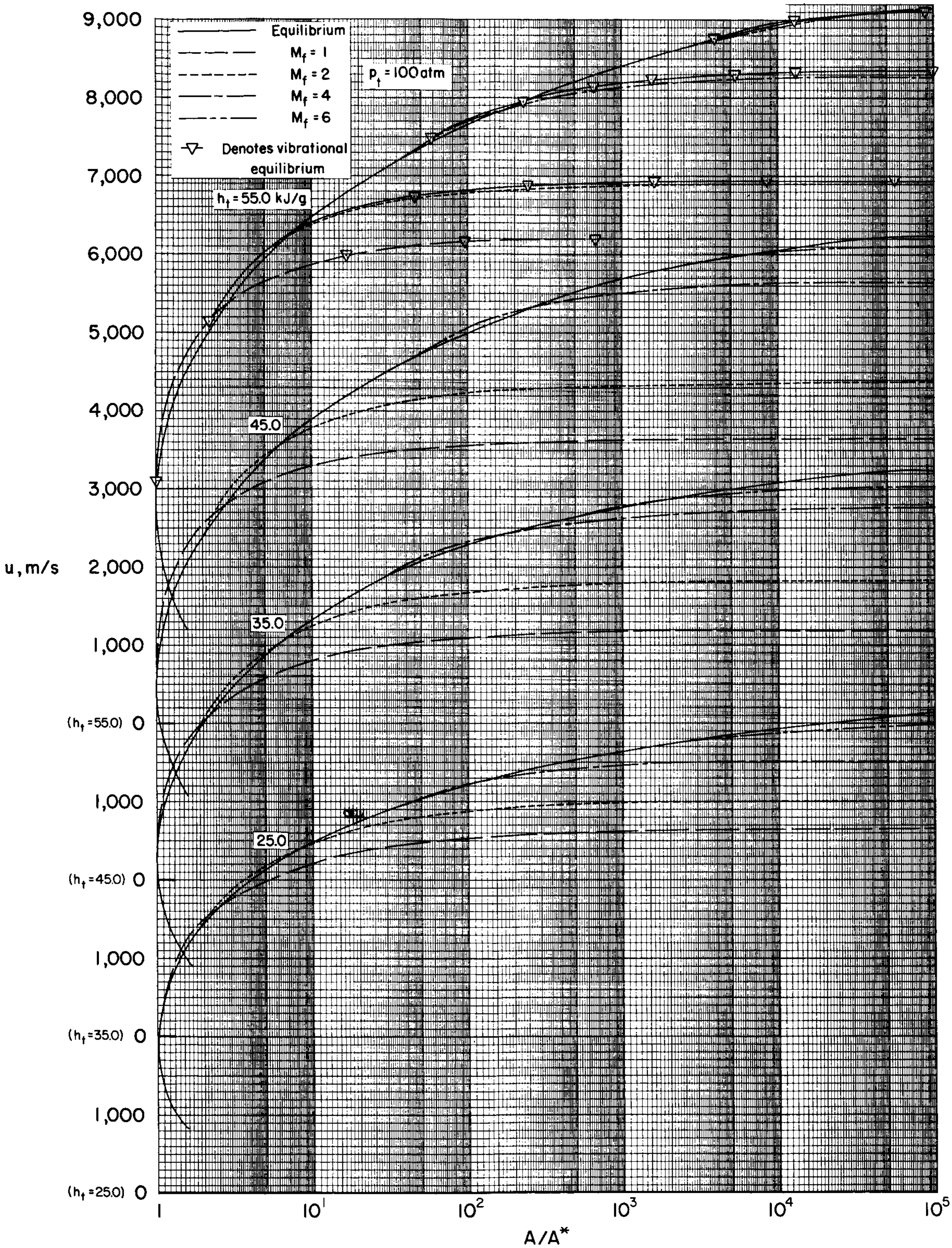
(b) p_t = 1 atm; h_t = 25.0, 35.0, 45.0, 55.0 kJ/g

Chart 11. - Continued.



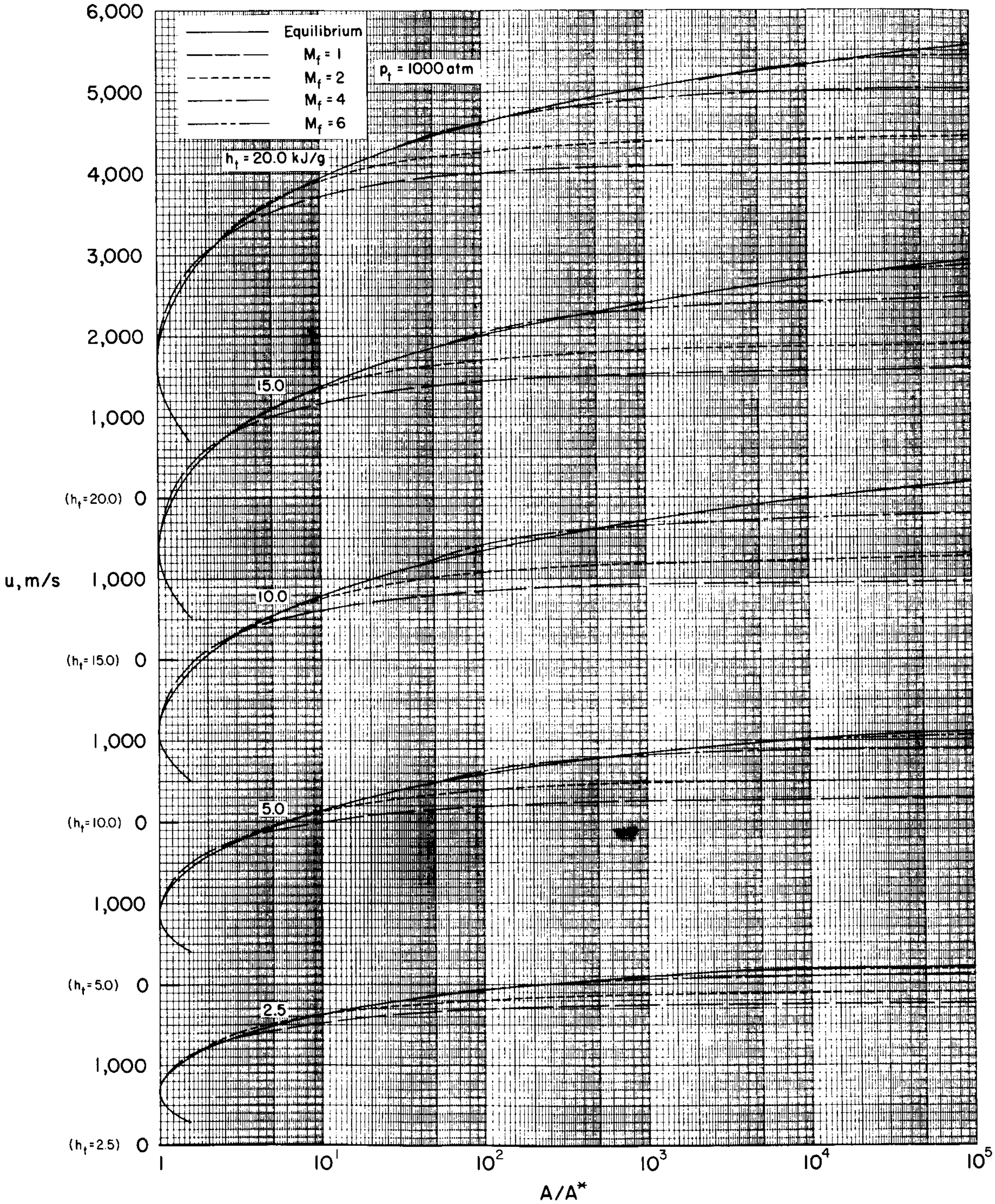
(c) $p_t = 100$ atm; $h_t = 2.5,\ 5.0,\ 10.0,\ 15.0,\ 20.0$ kJ/g

Chart 11. - Continued.



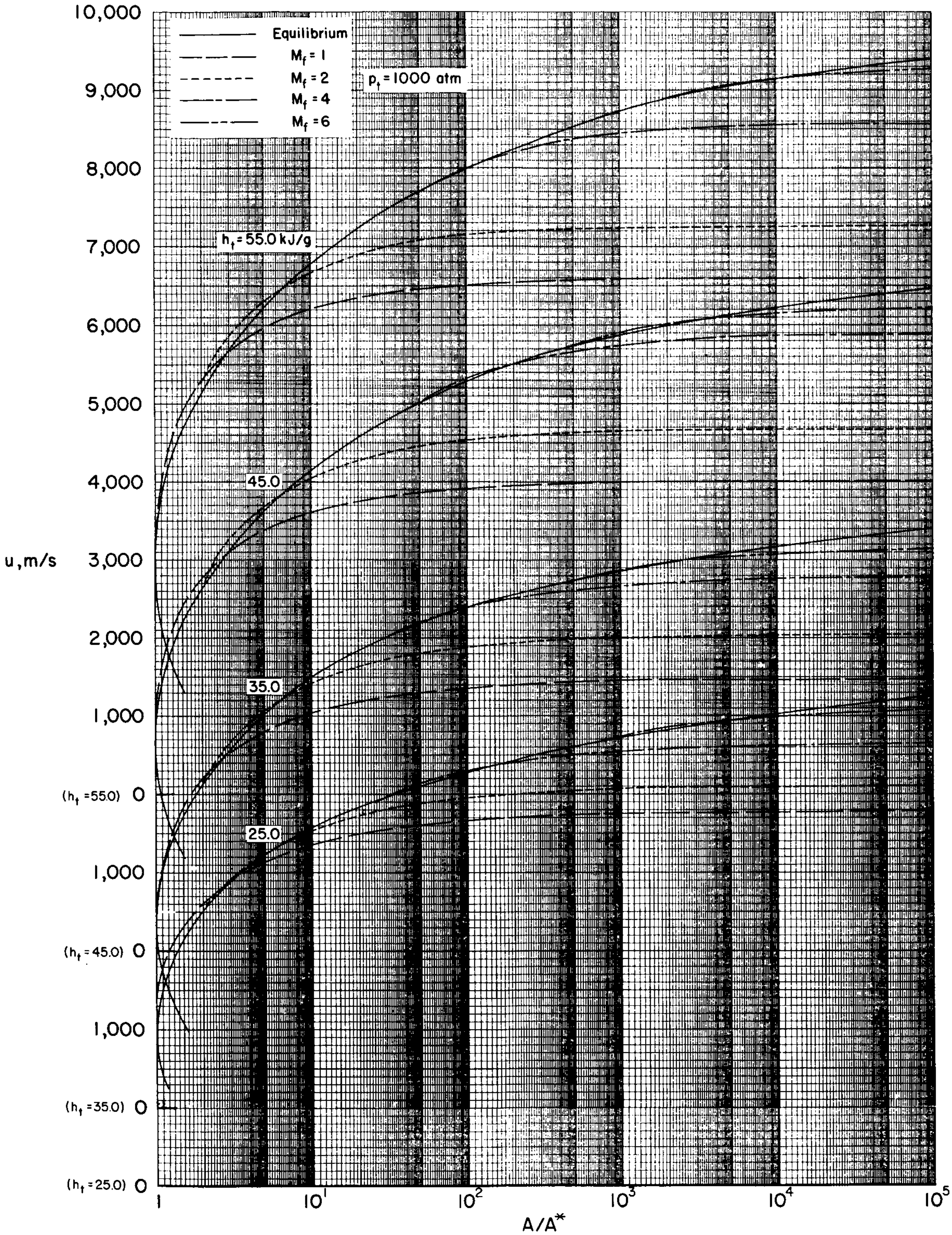
(d) p_t = 100 atm; h_t = 25. 0, 35. 0, 45. 0, 55. 0 kJ/g

Chart 11. - Continued.



(e) p_t = 1000 atm; h_t = 2.5, 5.0, 10.0, 15.0, 20.0 kJ/g

Chart 11. - Continued.



(f) p_t = 1000 atm; h_t = 25.0, 35.0, 45.0, 55.0 kJ/g

Chart 11. - Concluded.

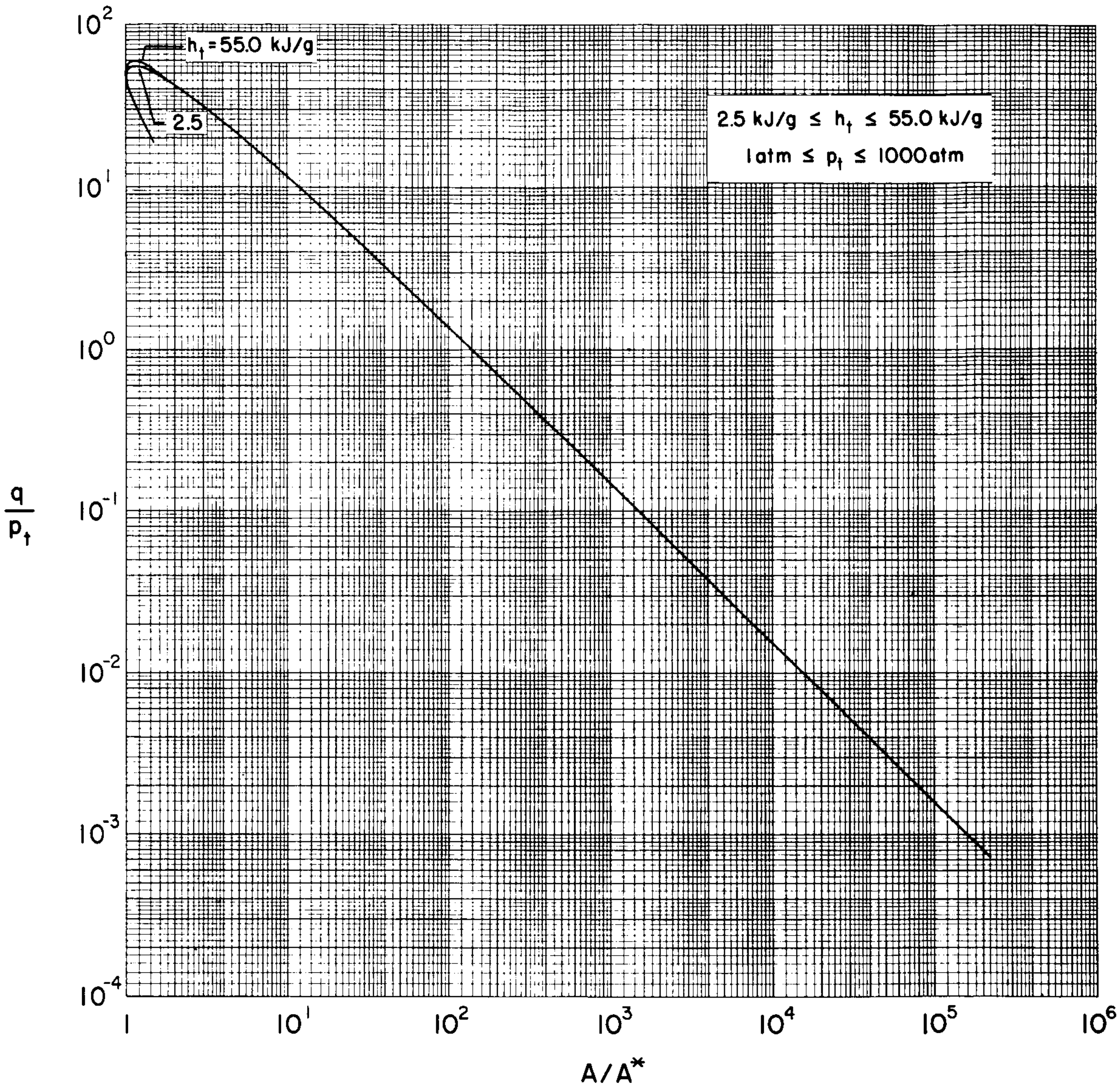
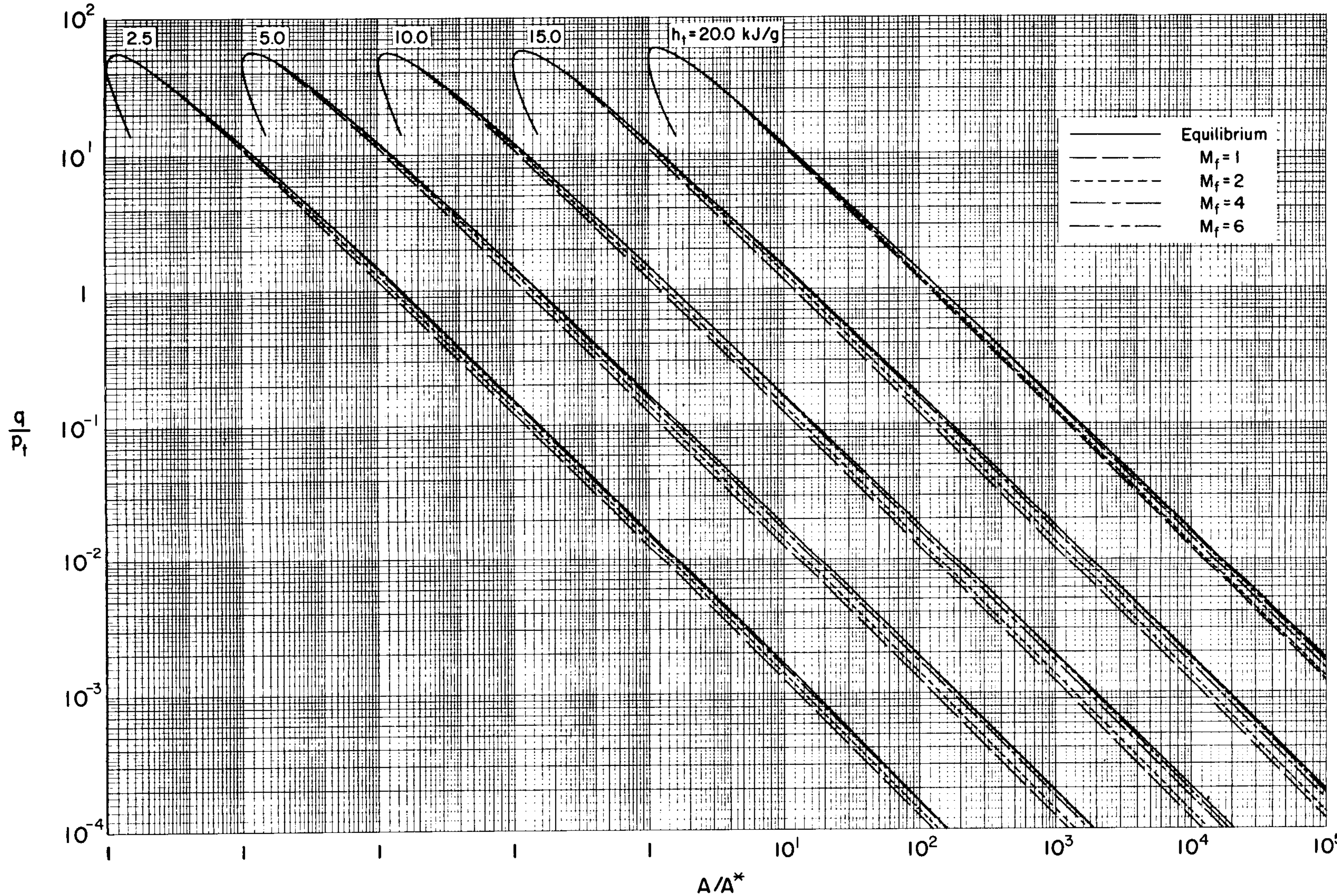
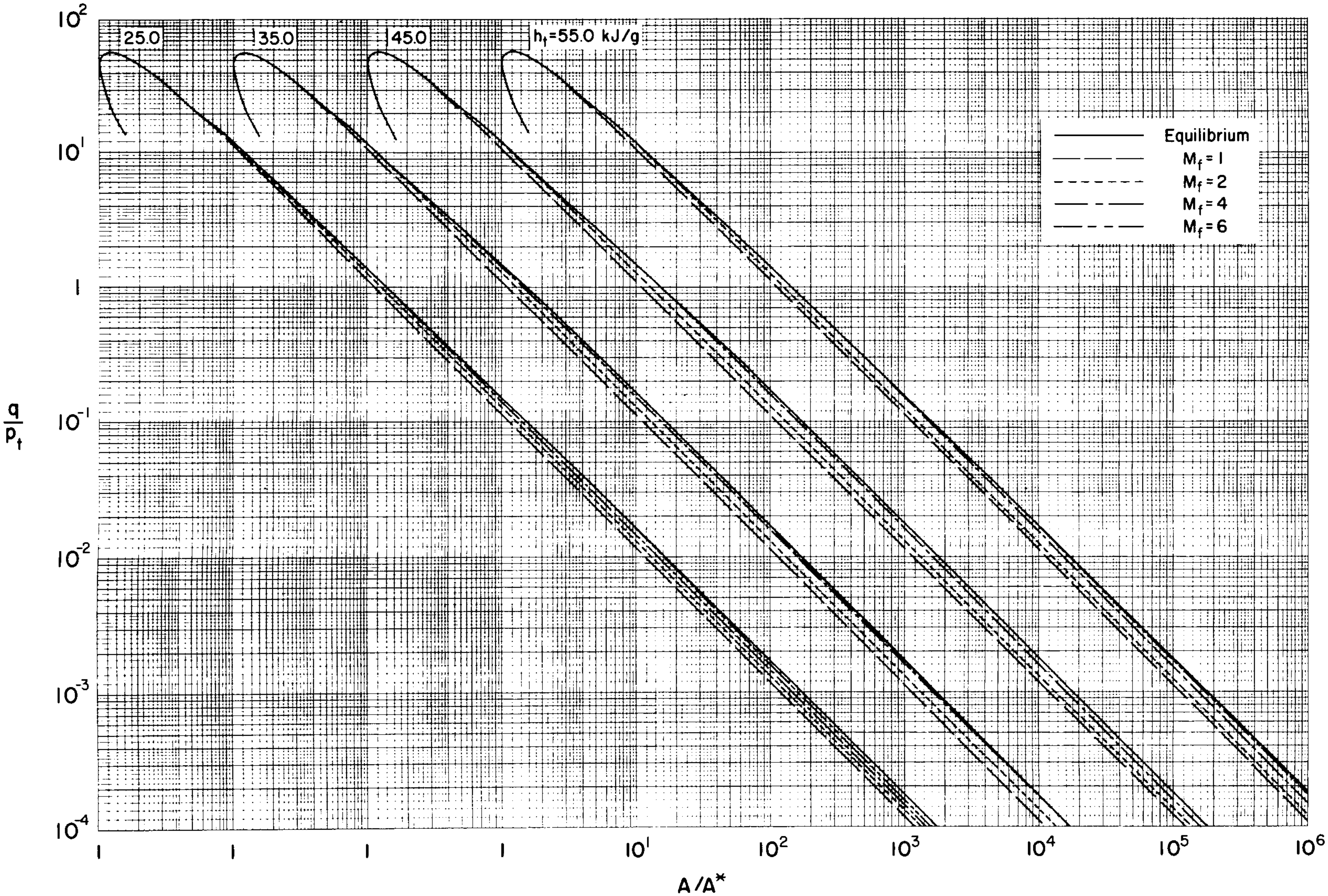


Chart 12. - Variation of dynamic pressure with area ratio; equilibrium flow.



(a) h_t = 2.5, 5.0, 10.0, 15.0, 20.0 kJ/g

Chart 13. - Variation of dynamic pressure with area ratio; equilibrium and frozen flows.



(b) h_t = 25.0, 35.0, 45.0, 55.0 kJ/g

Chart 13. - Concluded.

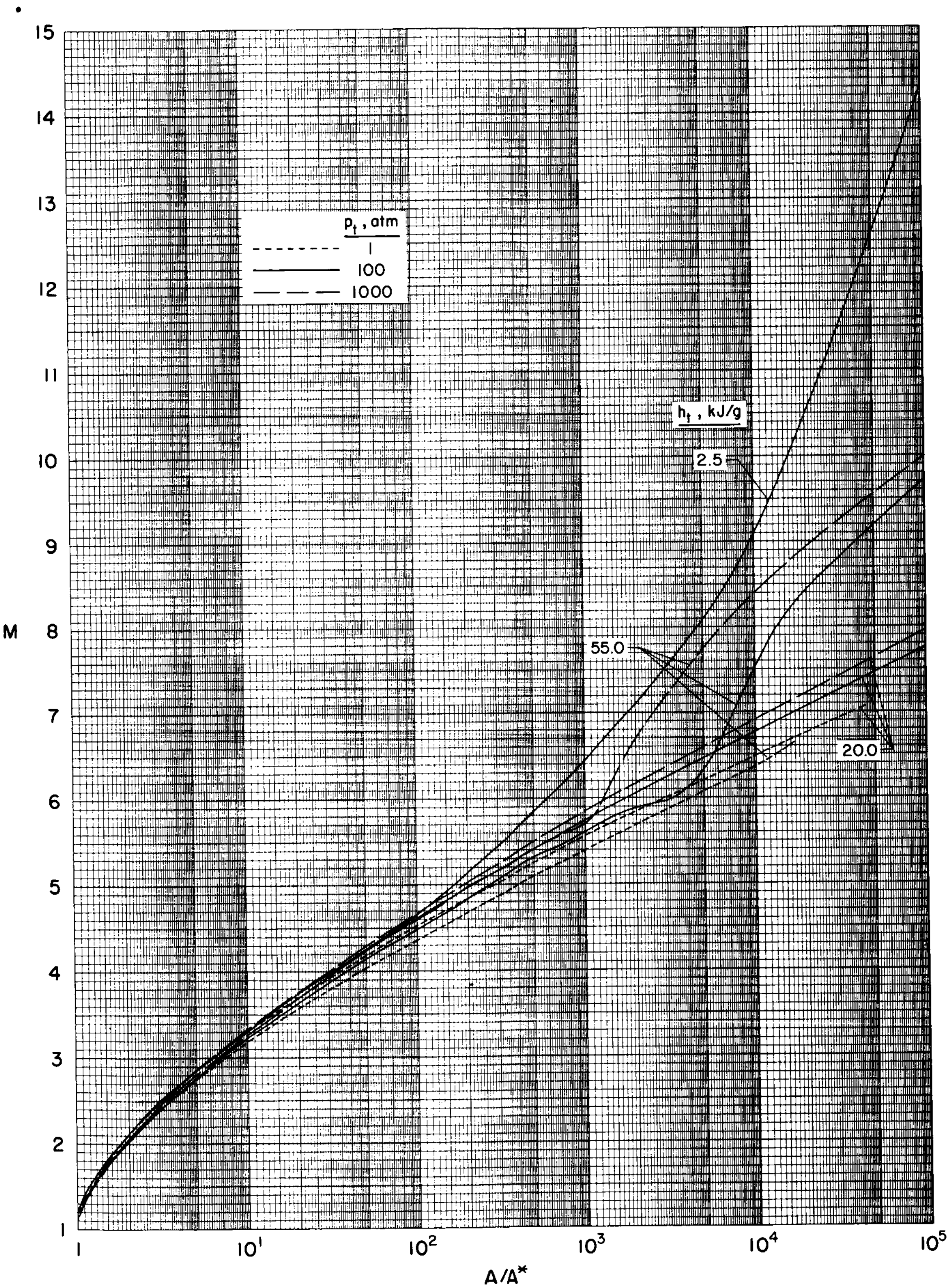
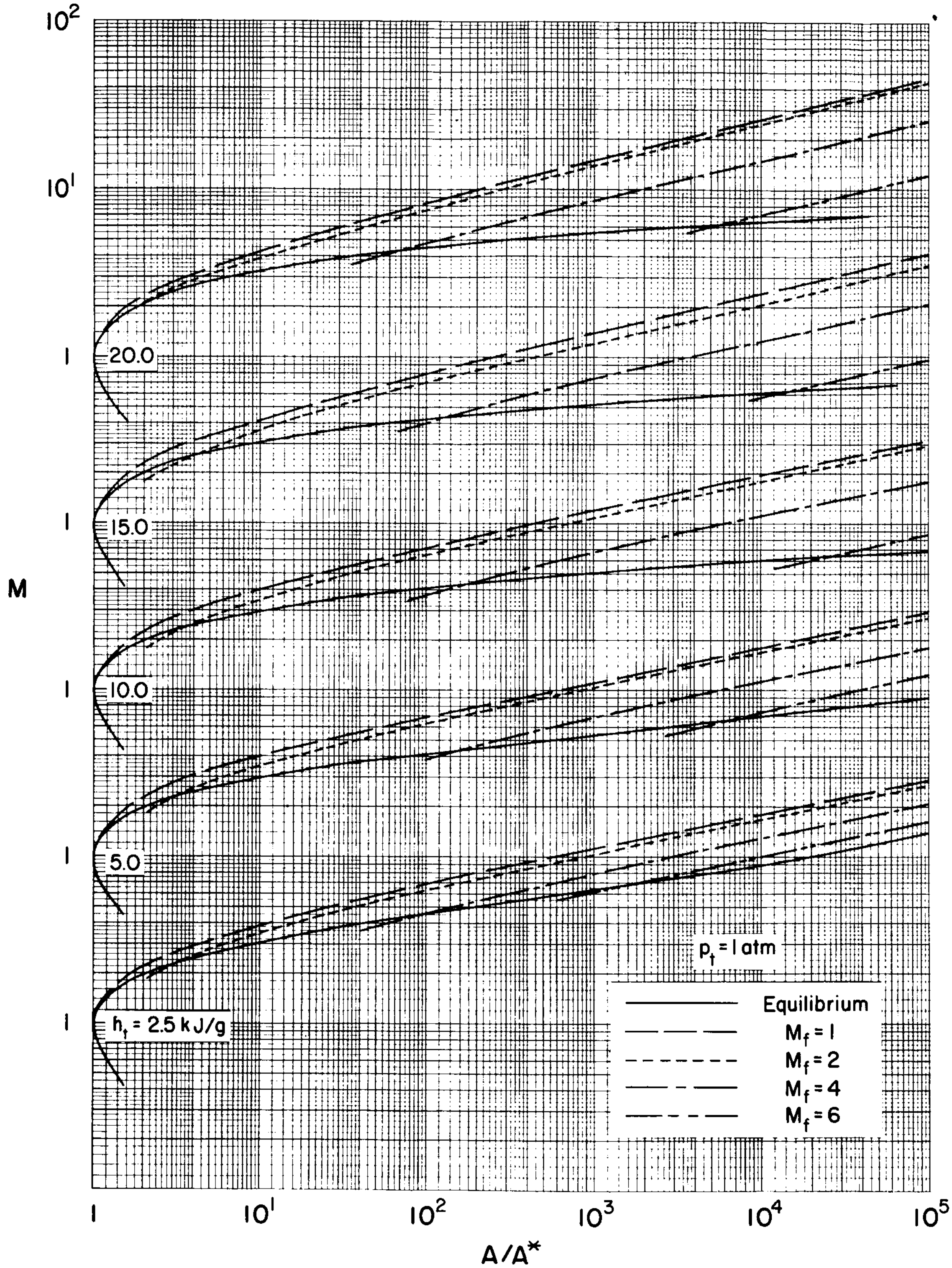
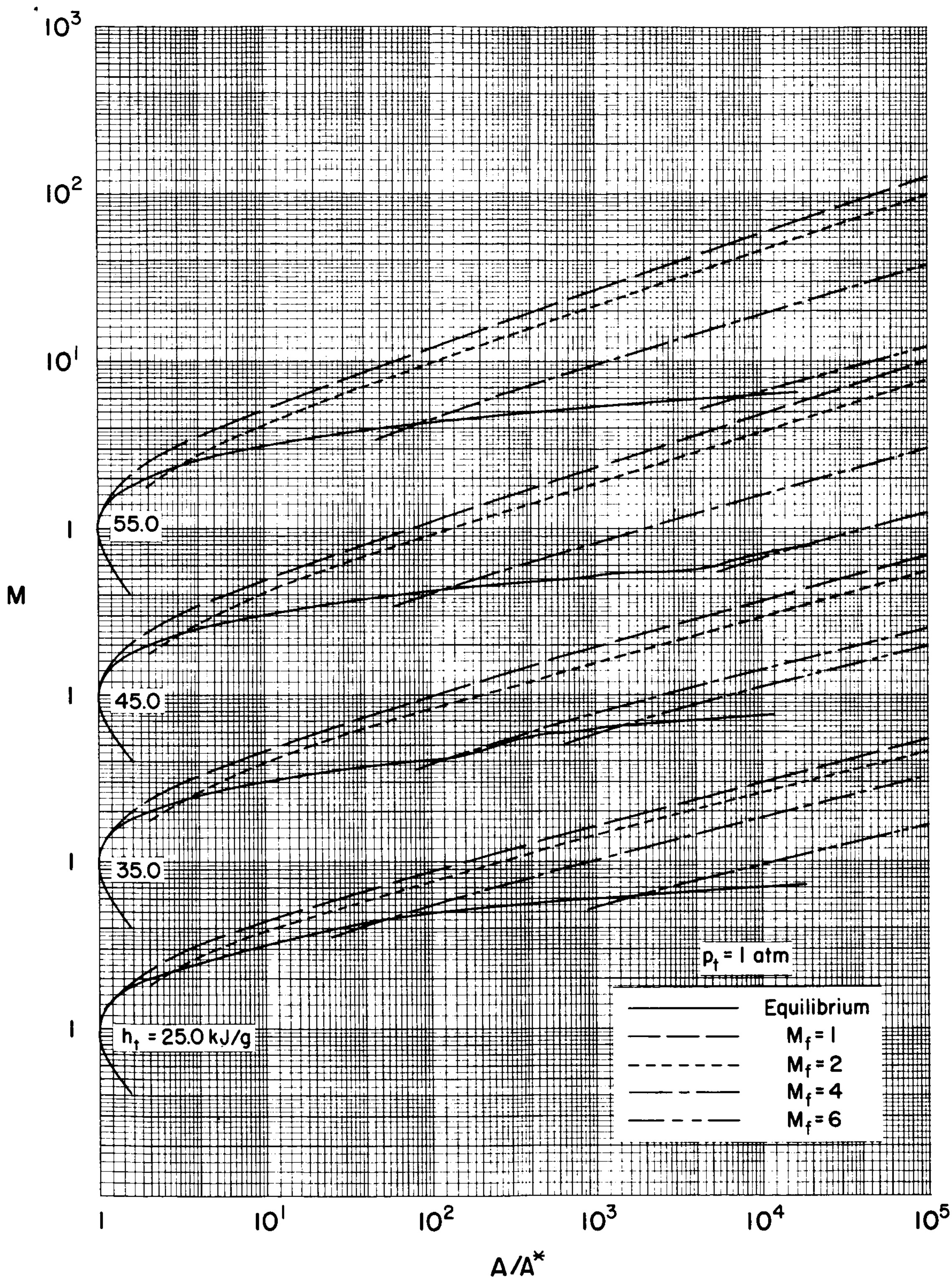


Chart 14. - Variation of Mach number with area ratio; equilibrium flow.



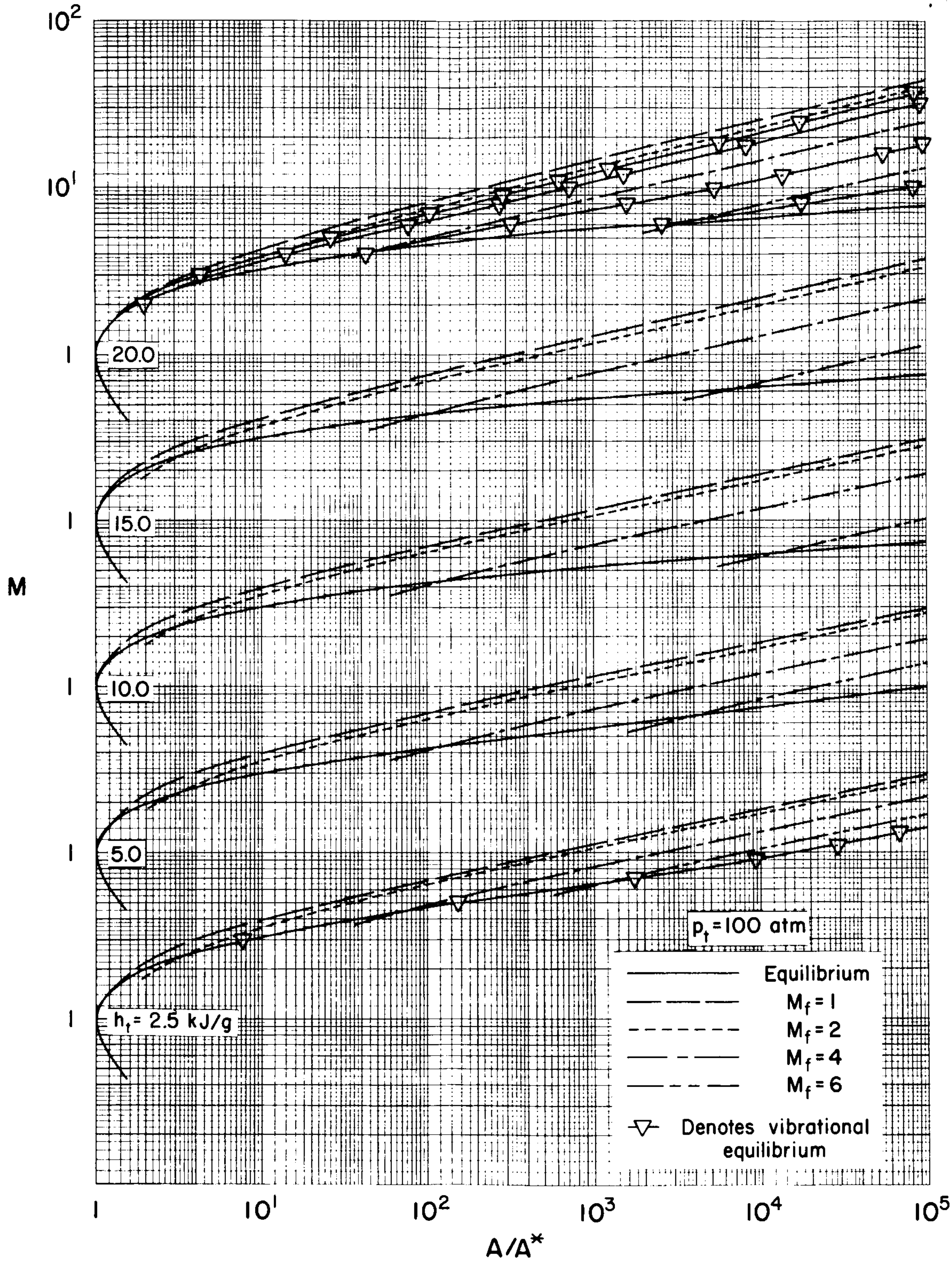
(a) p_t = 1 atm; h_t = 2.5, 5.0, 10.0, 15.0, 20.0 kJ/g

Chart 15. - Variation of Mach number with area ratio; equilibrium and frozen flows.



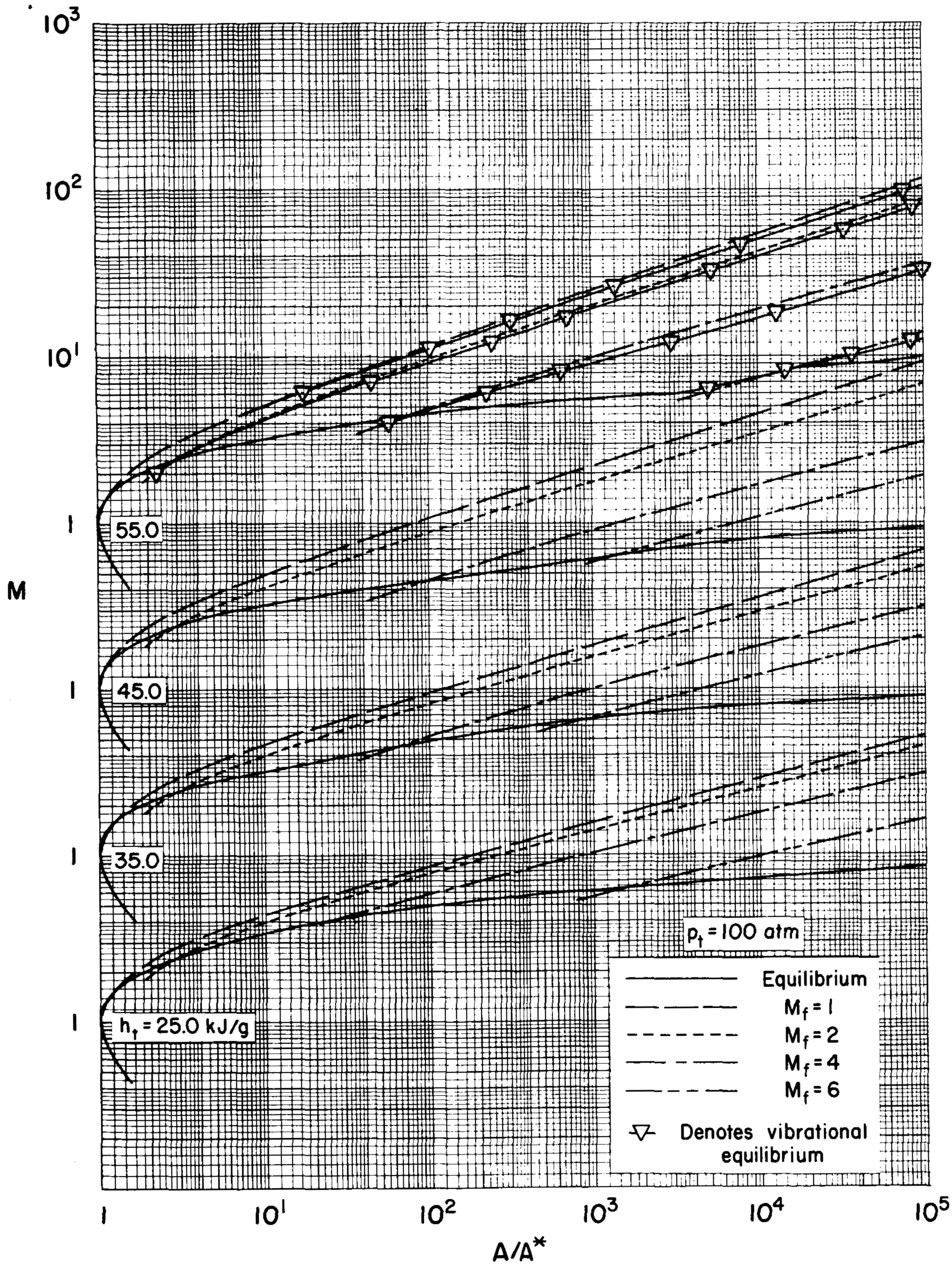
(b) p_t = 1 atm; h_t = 25. 0, 35. 0, 45. 0, 55. 0 kJ/g

Chart 15. - Continued.



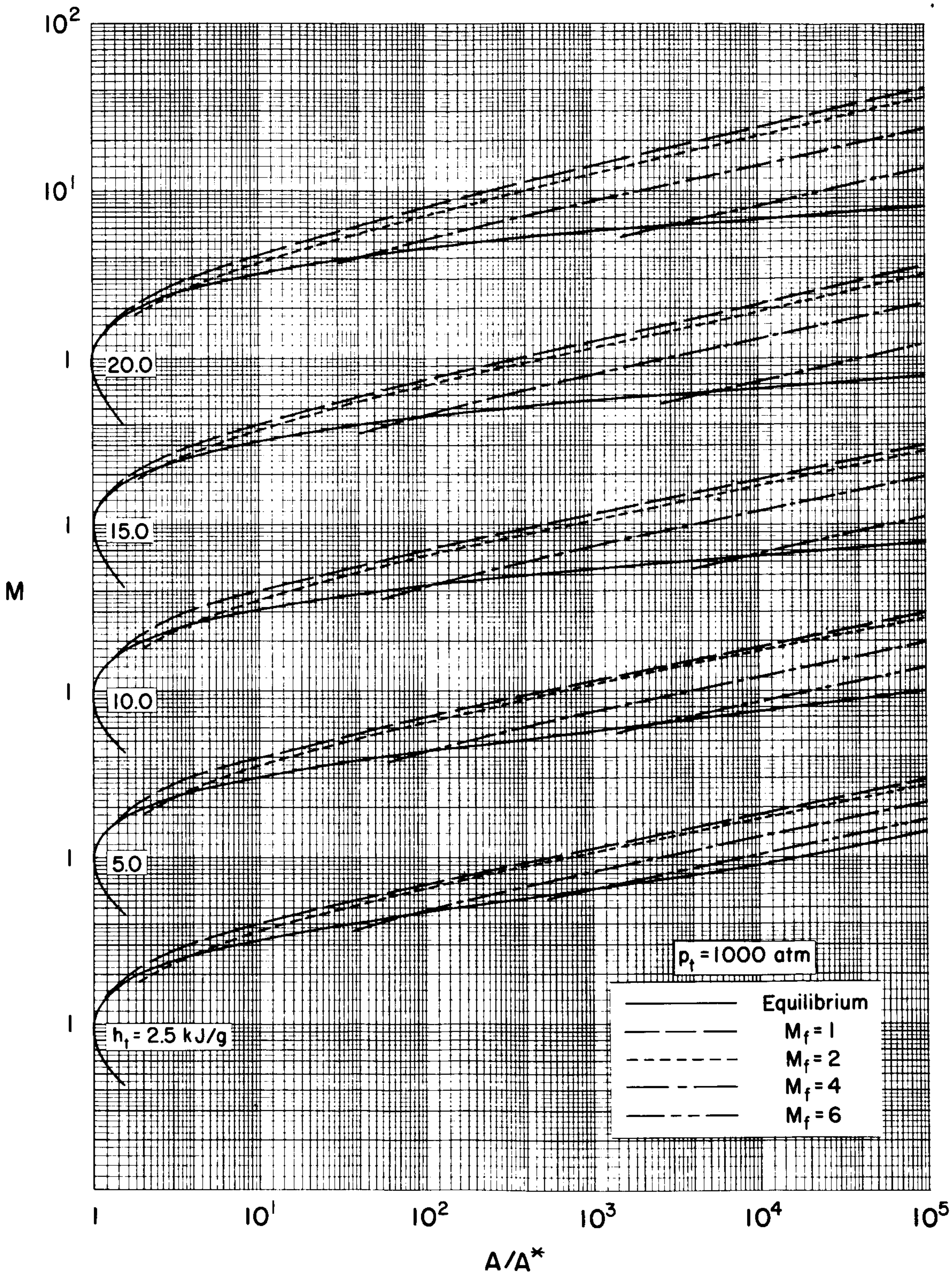
(c) p_t = 100 atm; h_t = 2.5, 5.0, 10.0, 15.0, 20.0 kJ/g

Chart 15. - Continued.



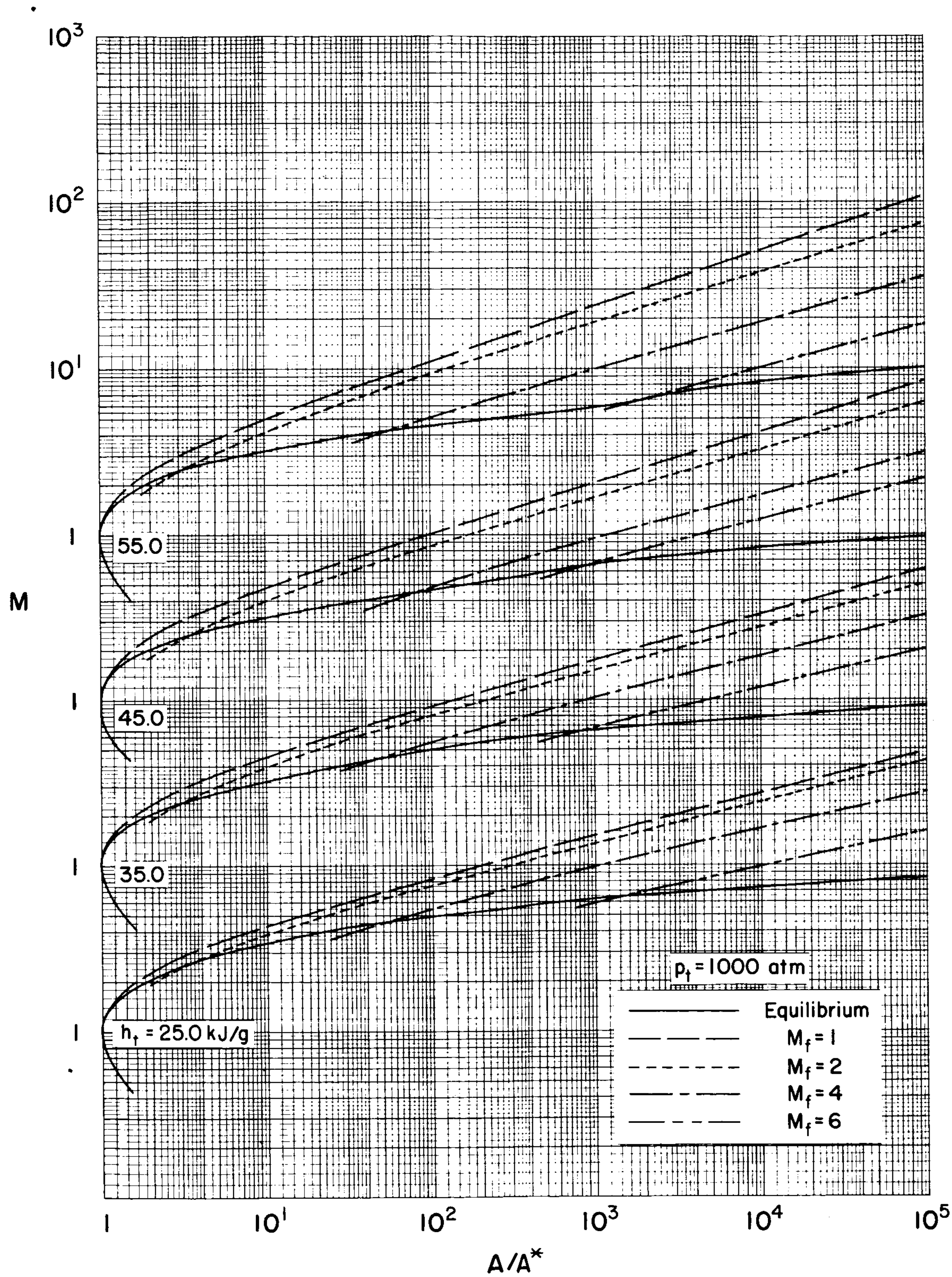
(d) p_t = 100 atm; h_t = 25.0, 35.0, 45.0, 55.0 kJ/g

Chart 15. - Continued.



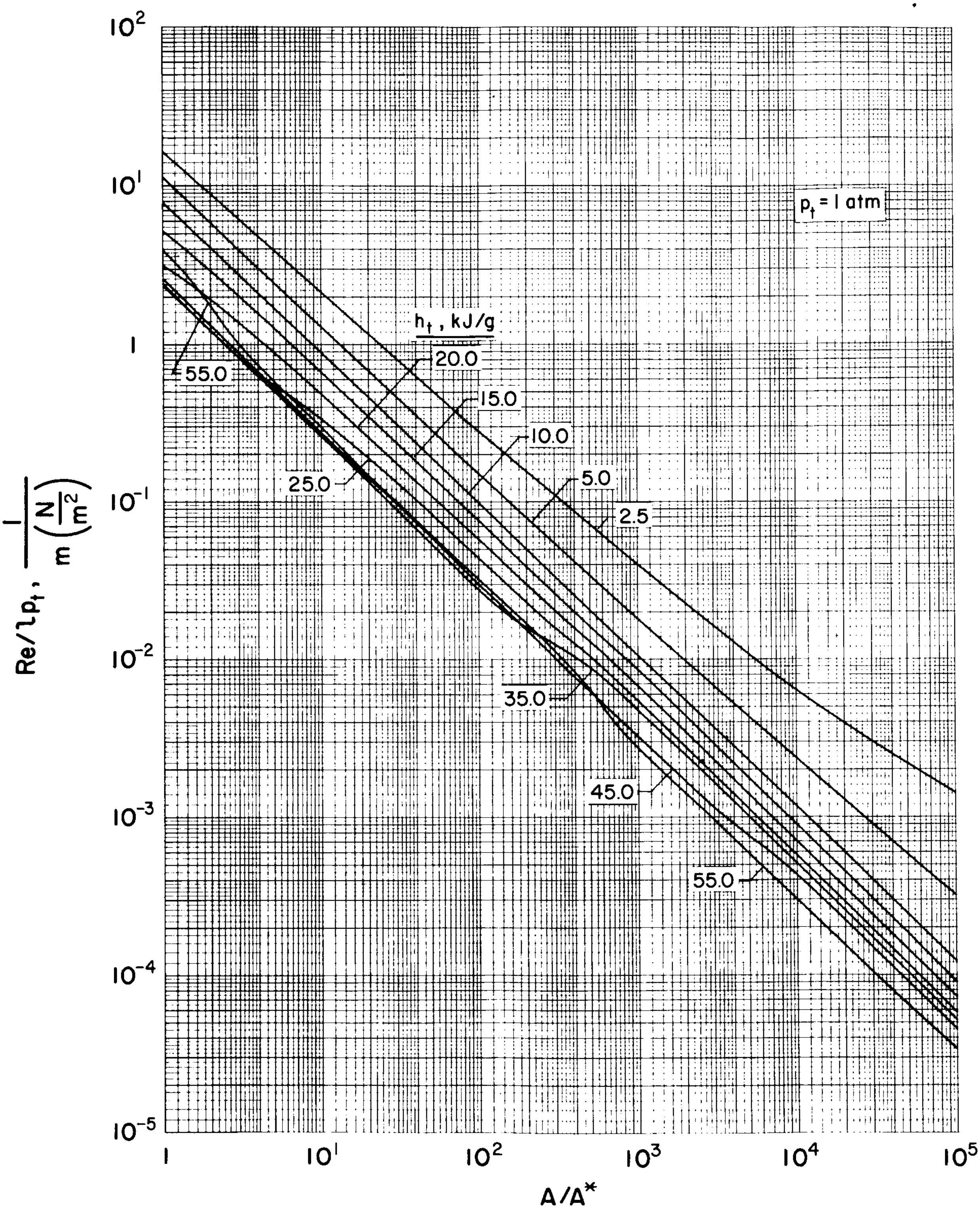
(e) p_t = 1000 atm; h_t = 2.5, 5.0, 10.0, 15.0, 20.0 kJ/g

Chart 15. - Continued.



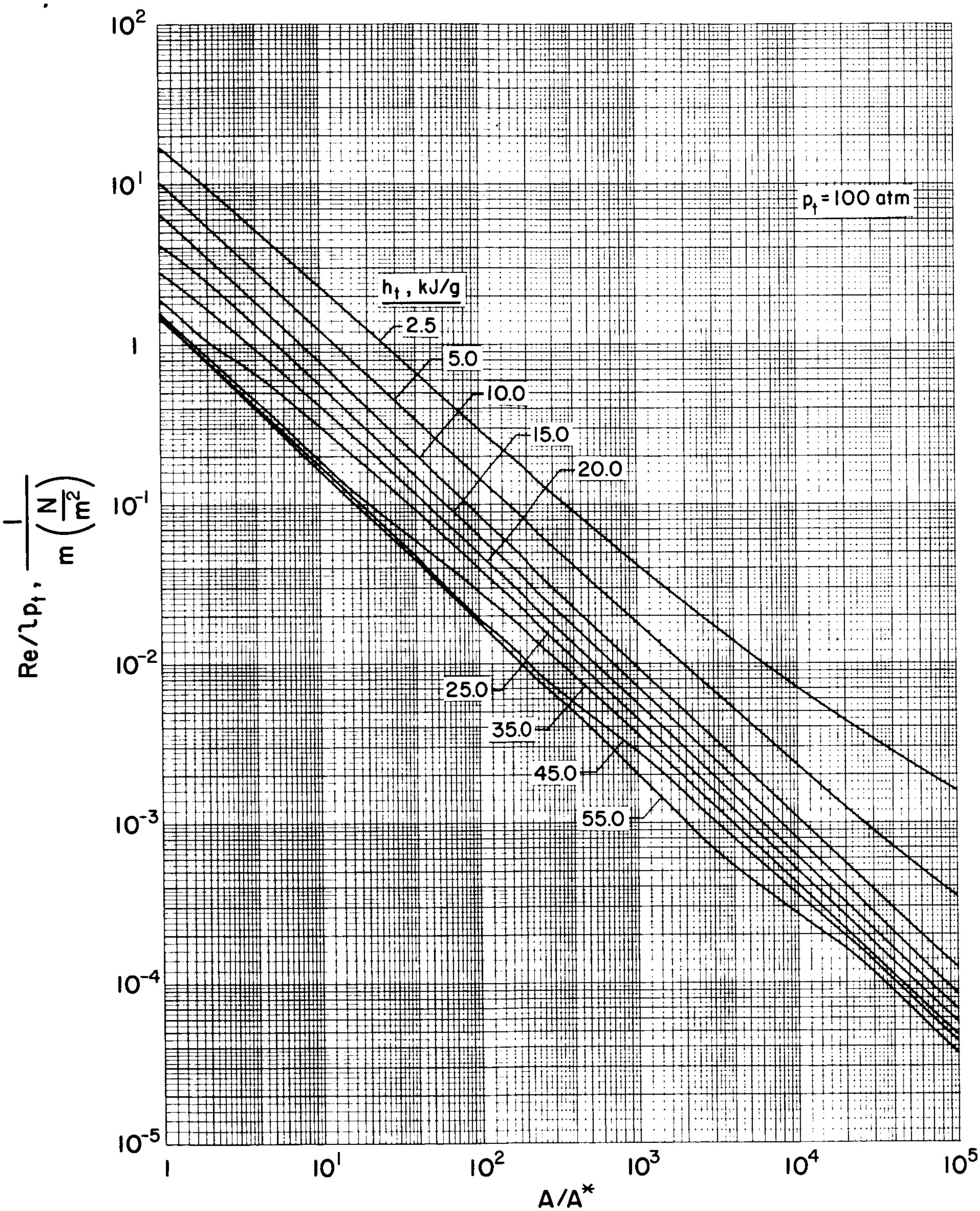
(f) p_t = 1000 atm; h_t = 25.0, 35.0, 45.0, 55.0 kJ/g

Chart 15. - Concluded.



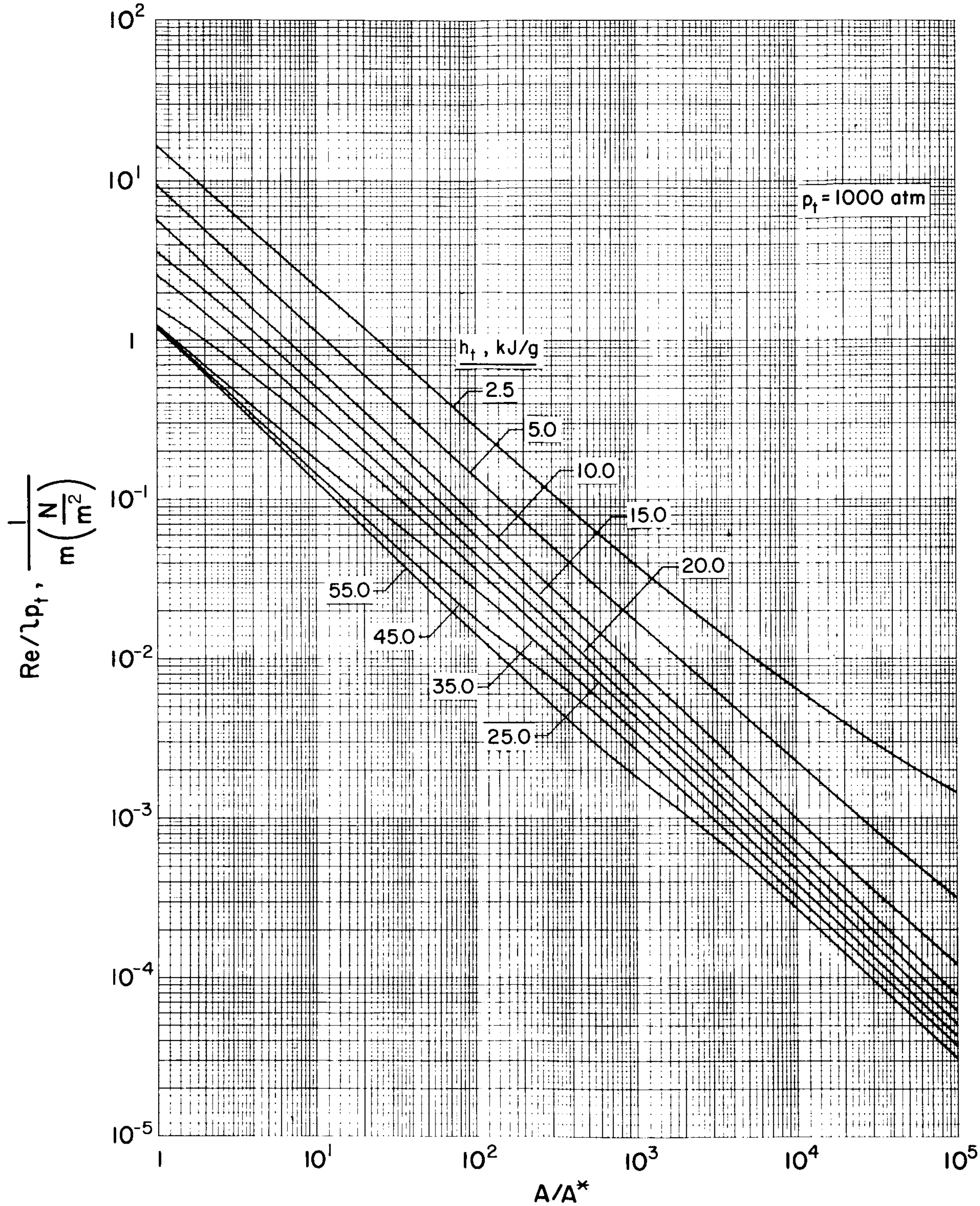
(a) $p_t = 1$ atm

Chart 16. - Variation of Reynolds number per unit length per unit total pressure with area ratio; equilibrium flow.



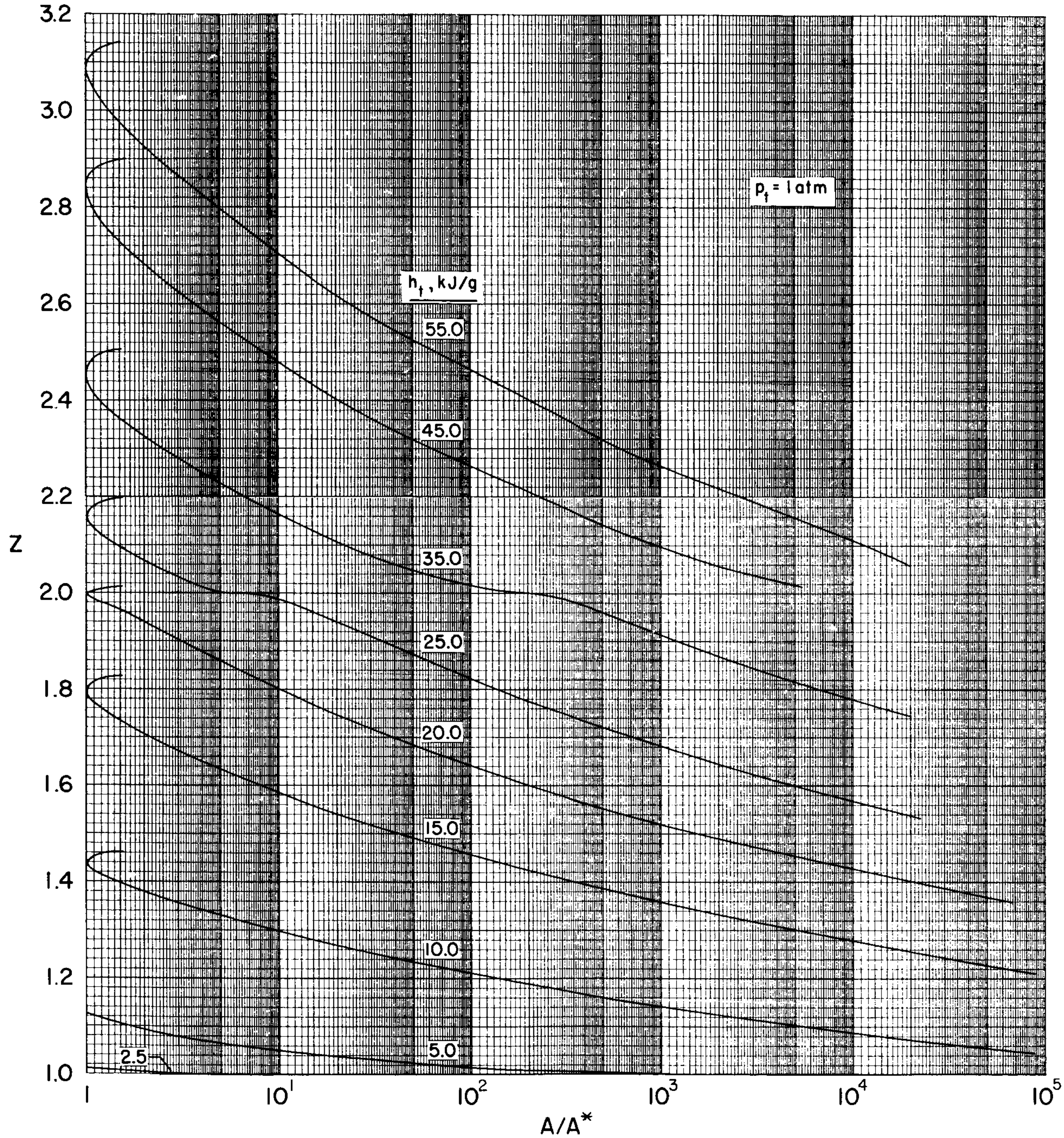
(b) p_t = 100 atm

Chart 16. - Continued.



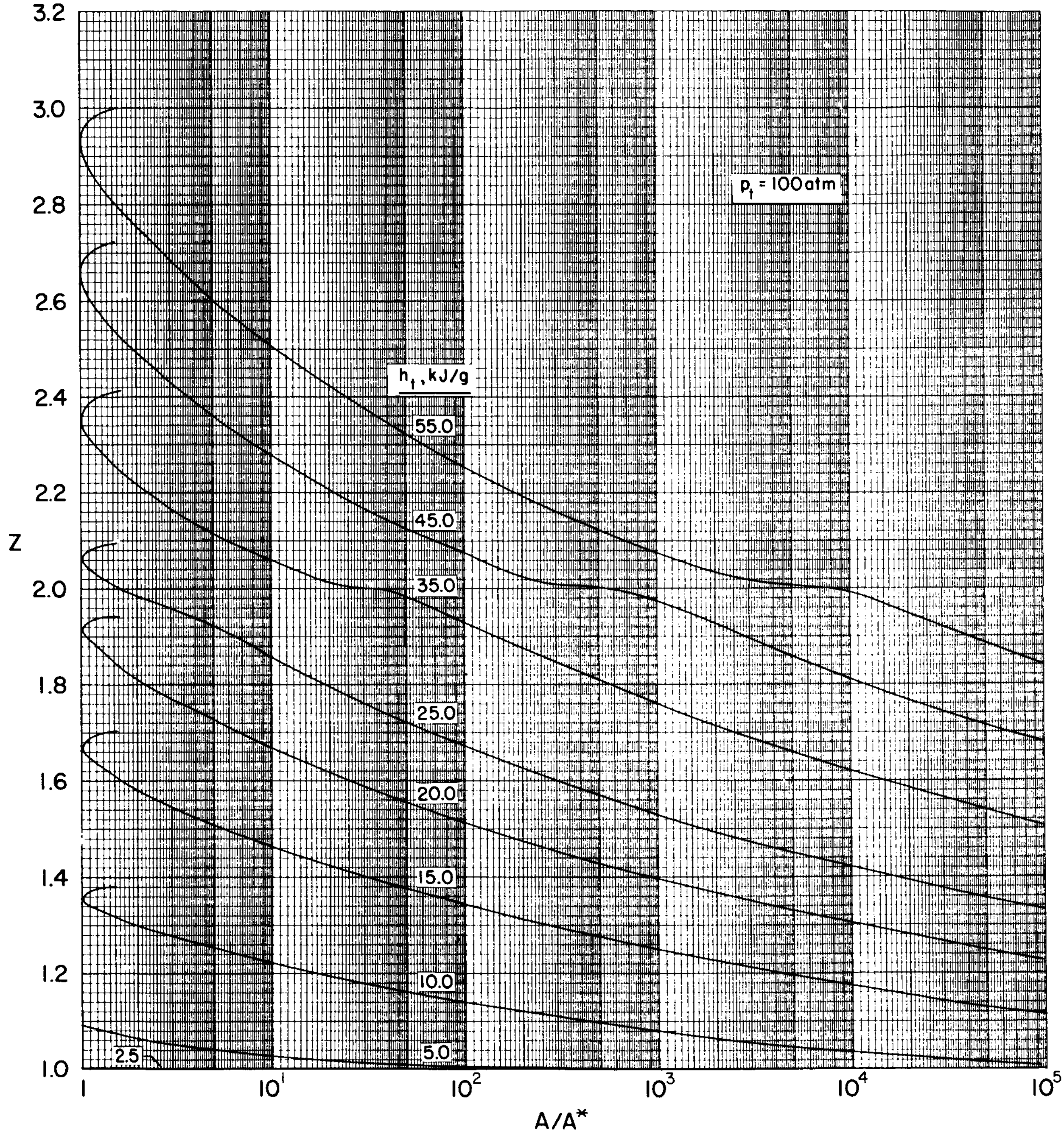
(c) p_t = 1000 atm

Chart 16. - Concluded.



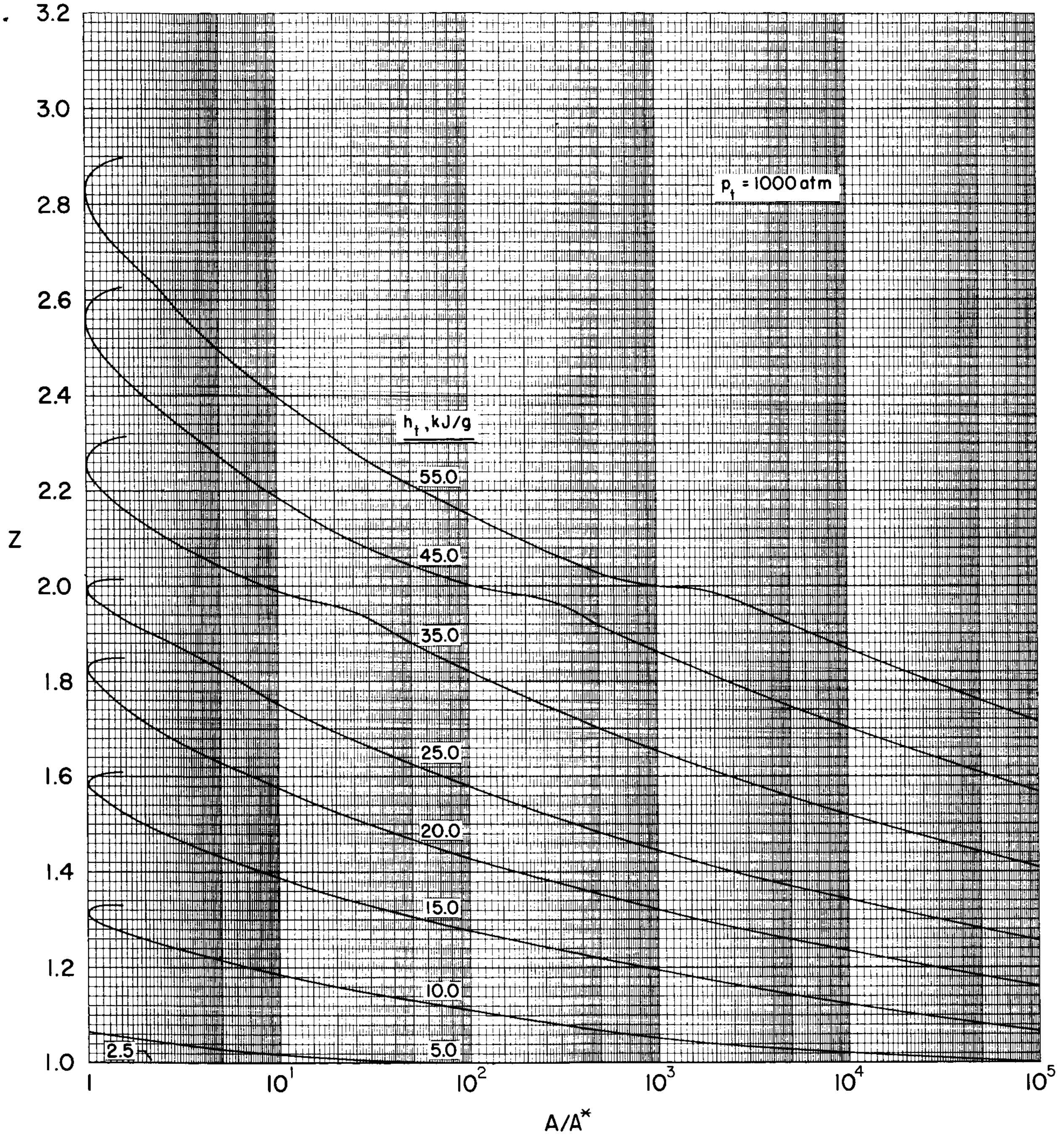
(a) p_t = 1 atm

Chart 17. - Variation of molecular weight fraction with area ratio; equilibrium flow.



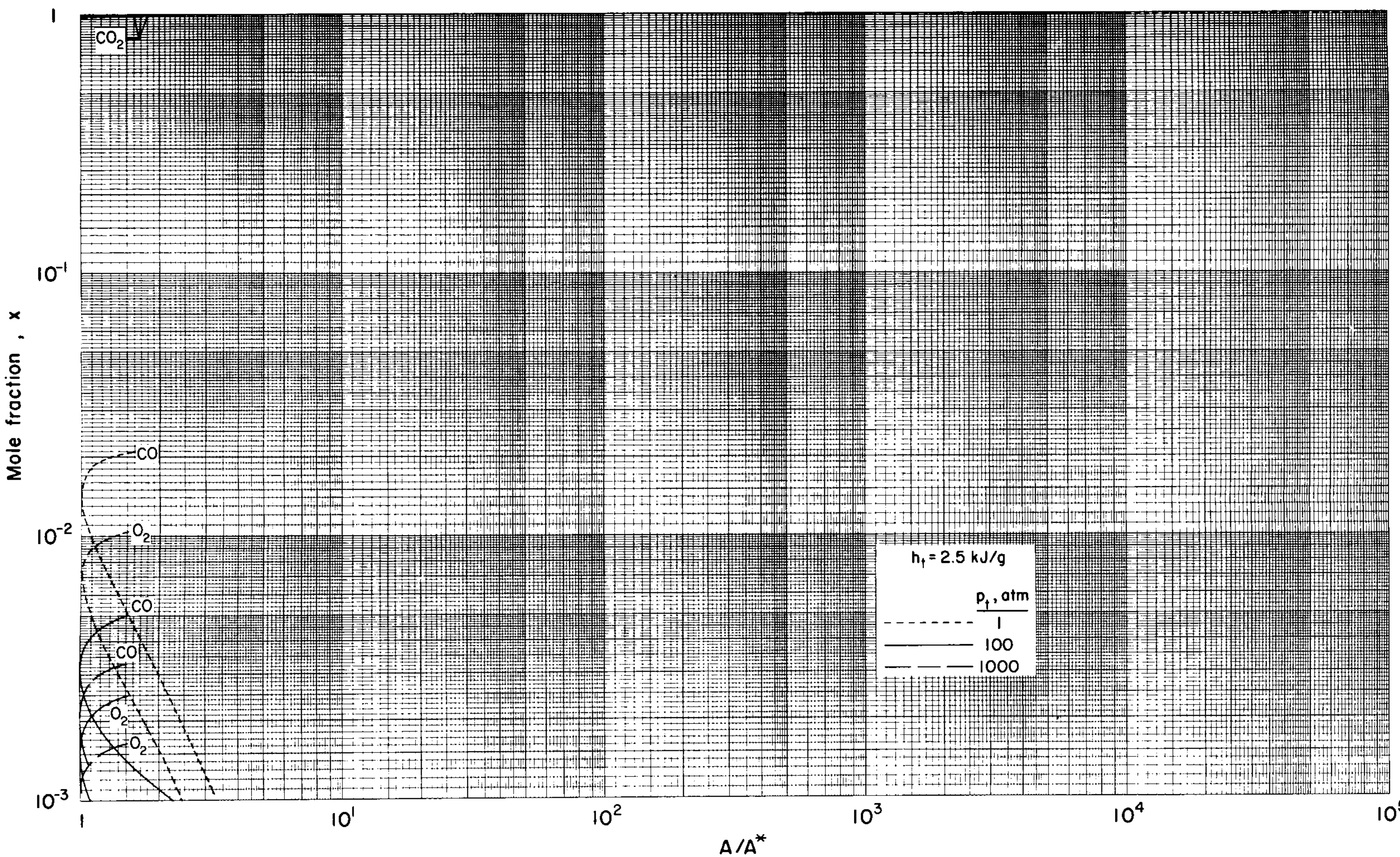
(b) p_t = 100 atm

Chart 17. - Continued.



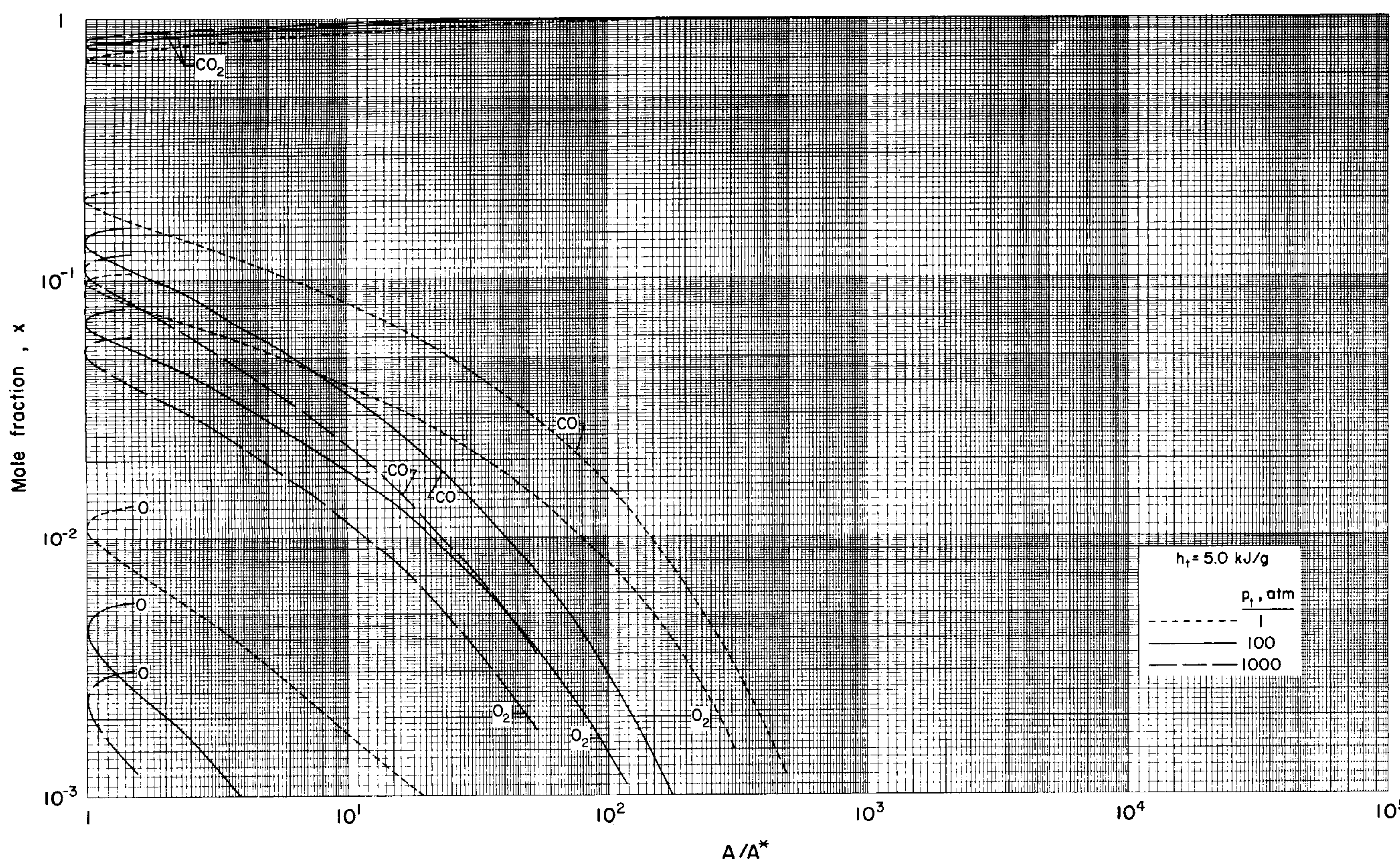
(c) $p_t = 1000$ atm

Chart 17. - Concluded.



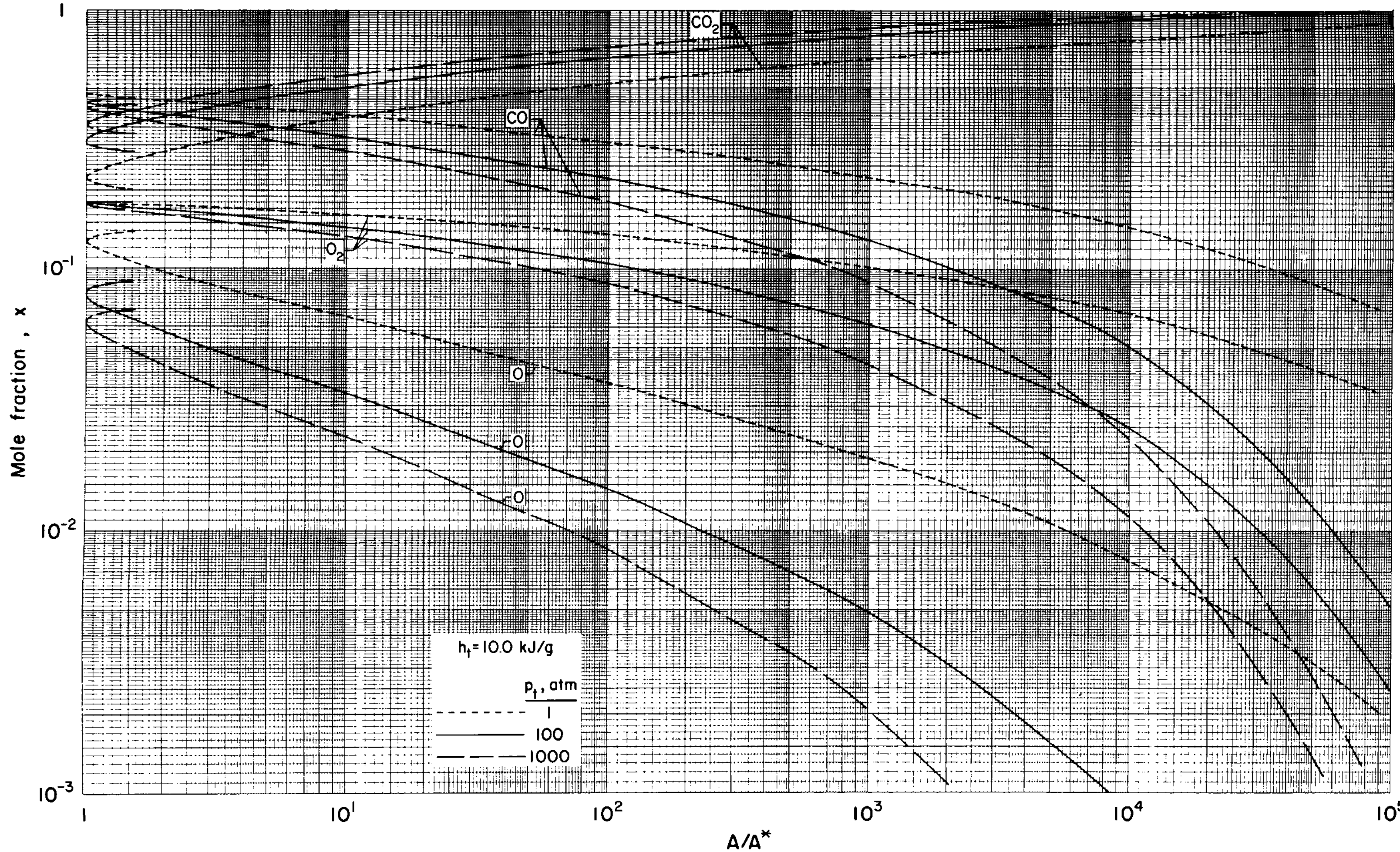
(a) 2.5 kJ/g

Chart 18. - Variation of species concentrations with area ratio; equilibrium flow.



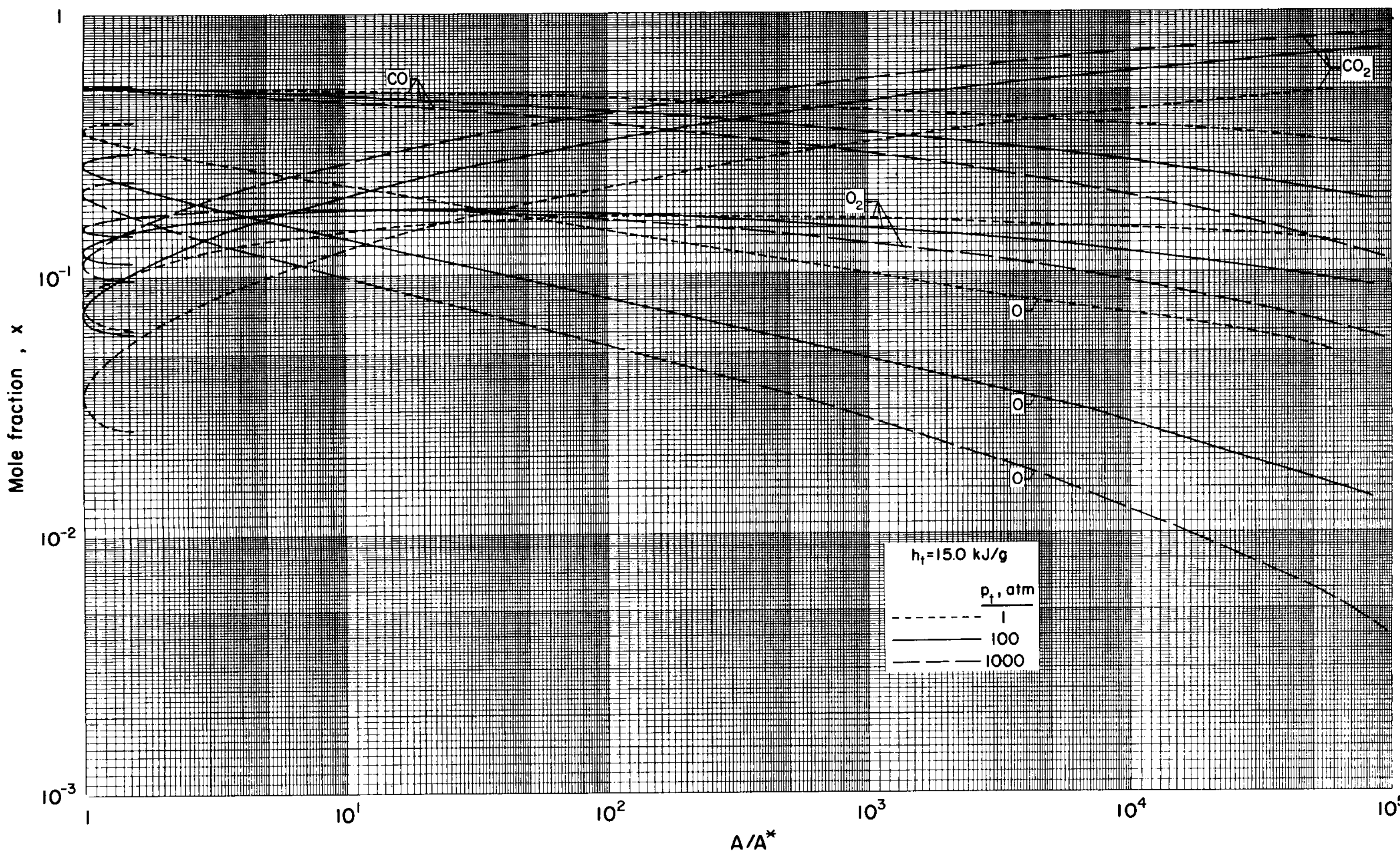
(b) 5.0 kJ/g

Chart 18. - Continued.



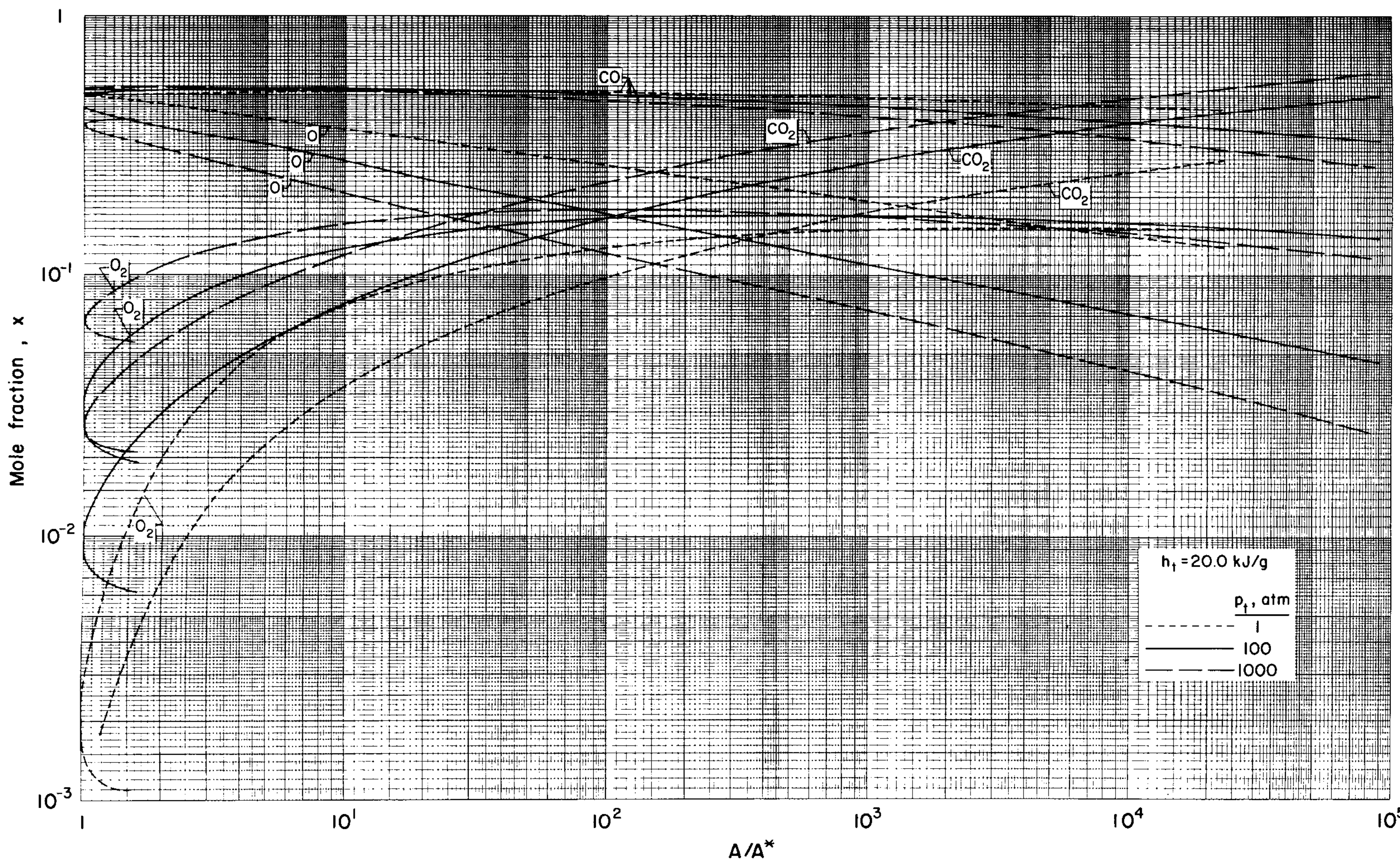
(c) 10. 0 kJ/g

Chart 18. - Continued.



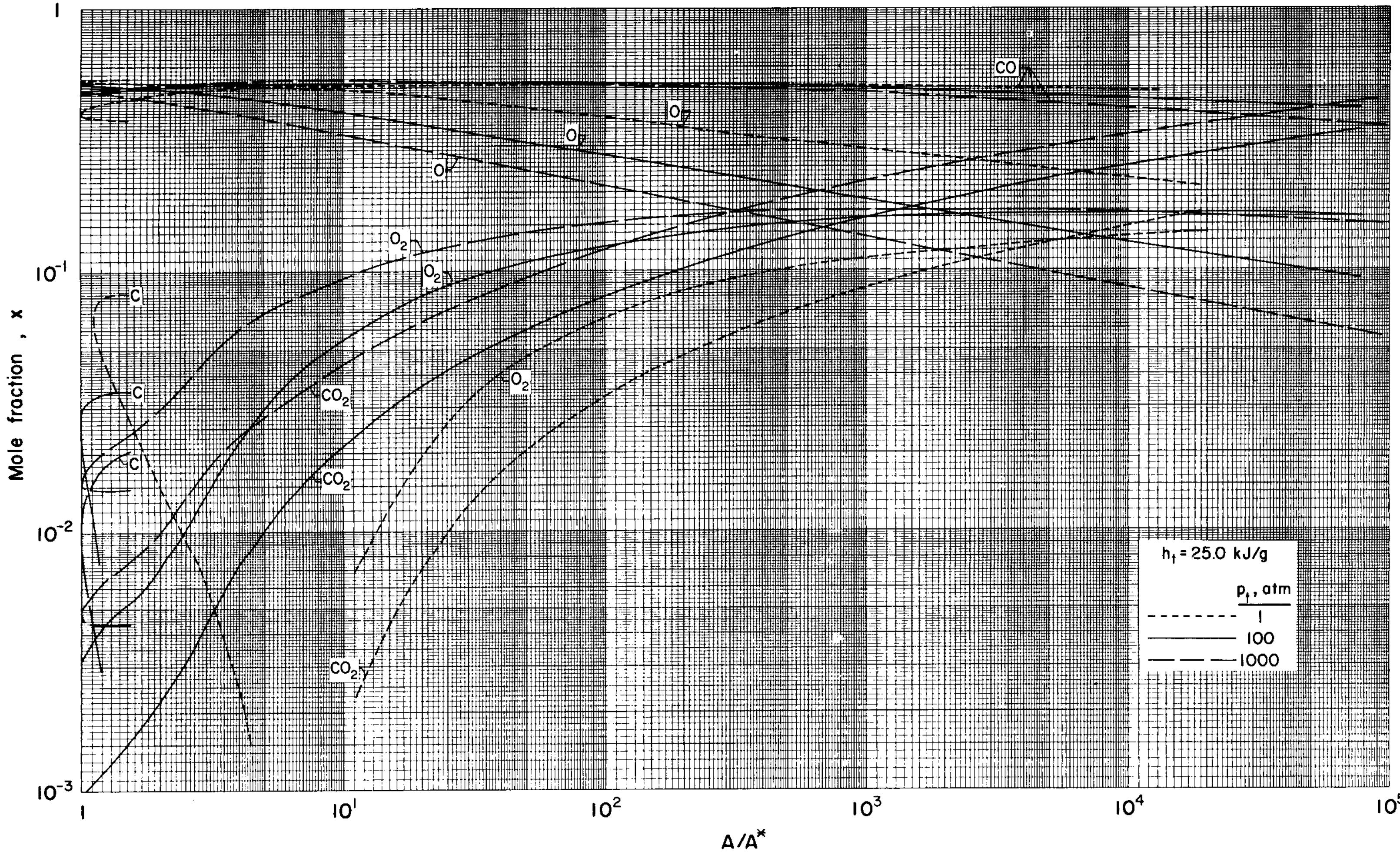
(d) 15.0 kJ/g

Chart 18. - Continued.



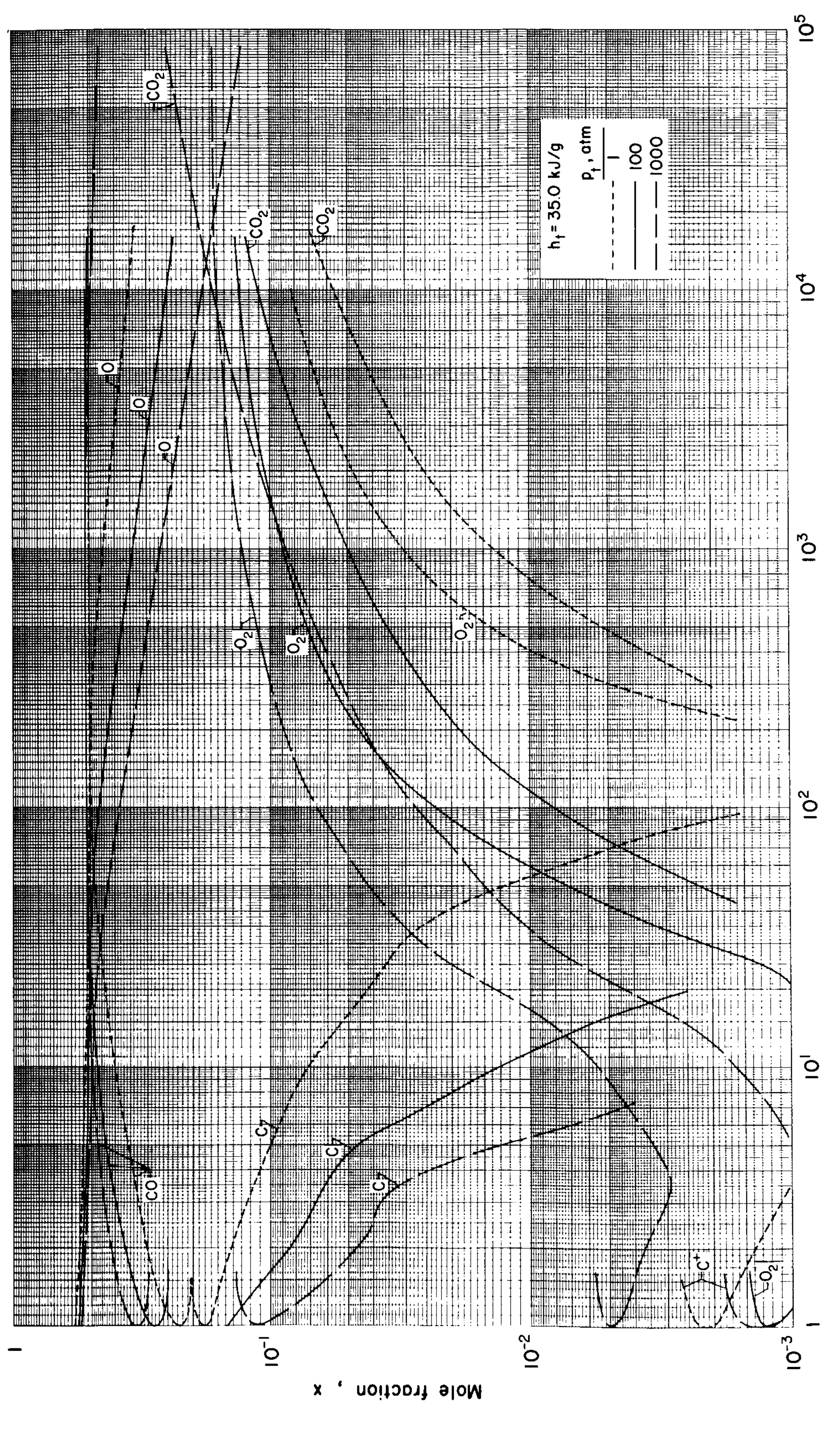
(e) 20.0 kJ/g

Chart 18. - Continued.



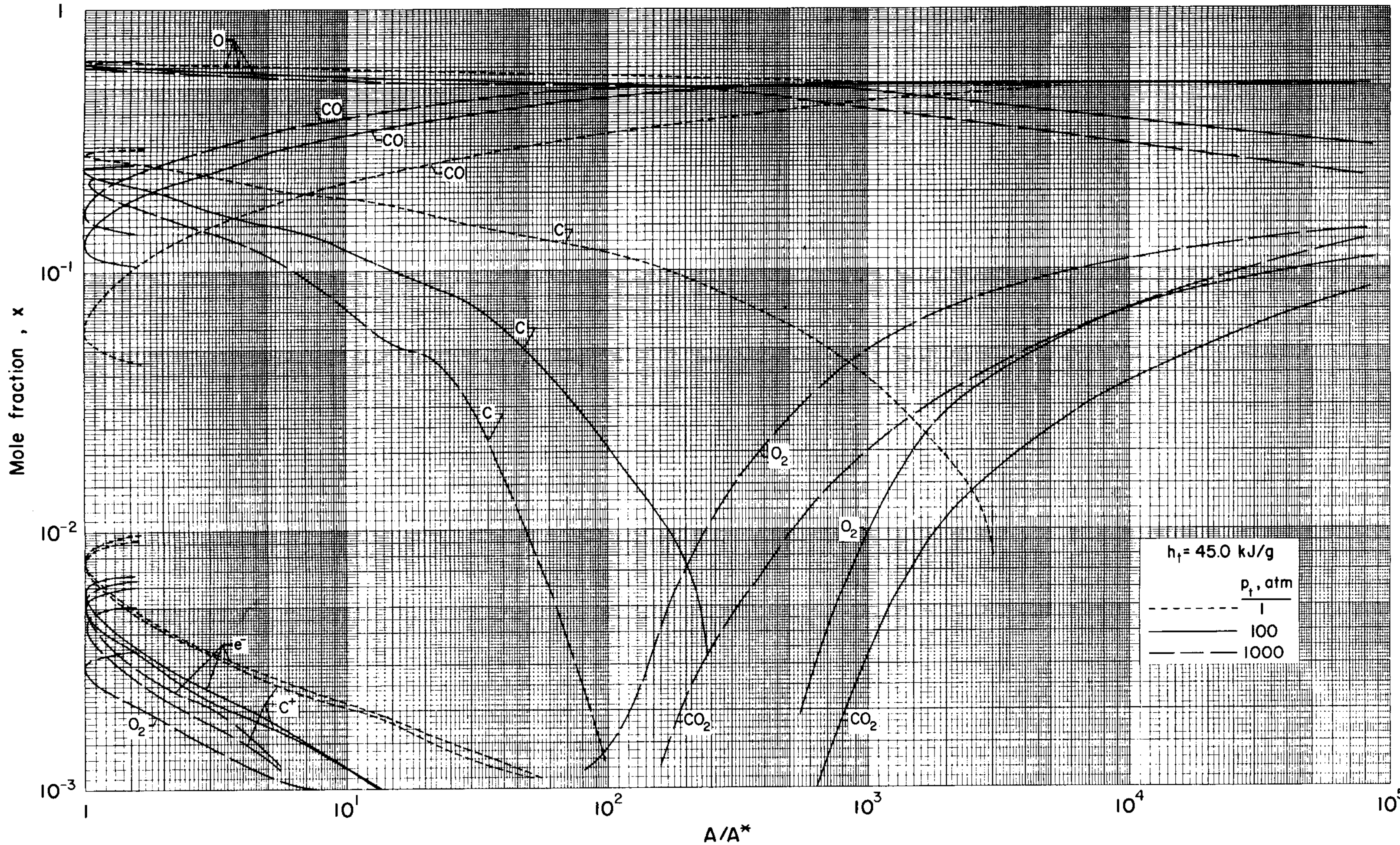
(f) 25. 0 kJ/g

Chart 18. - Continued.



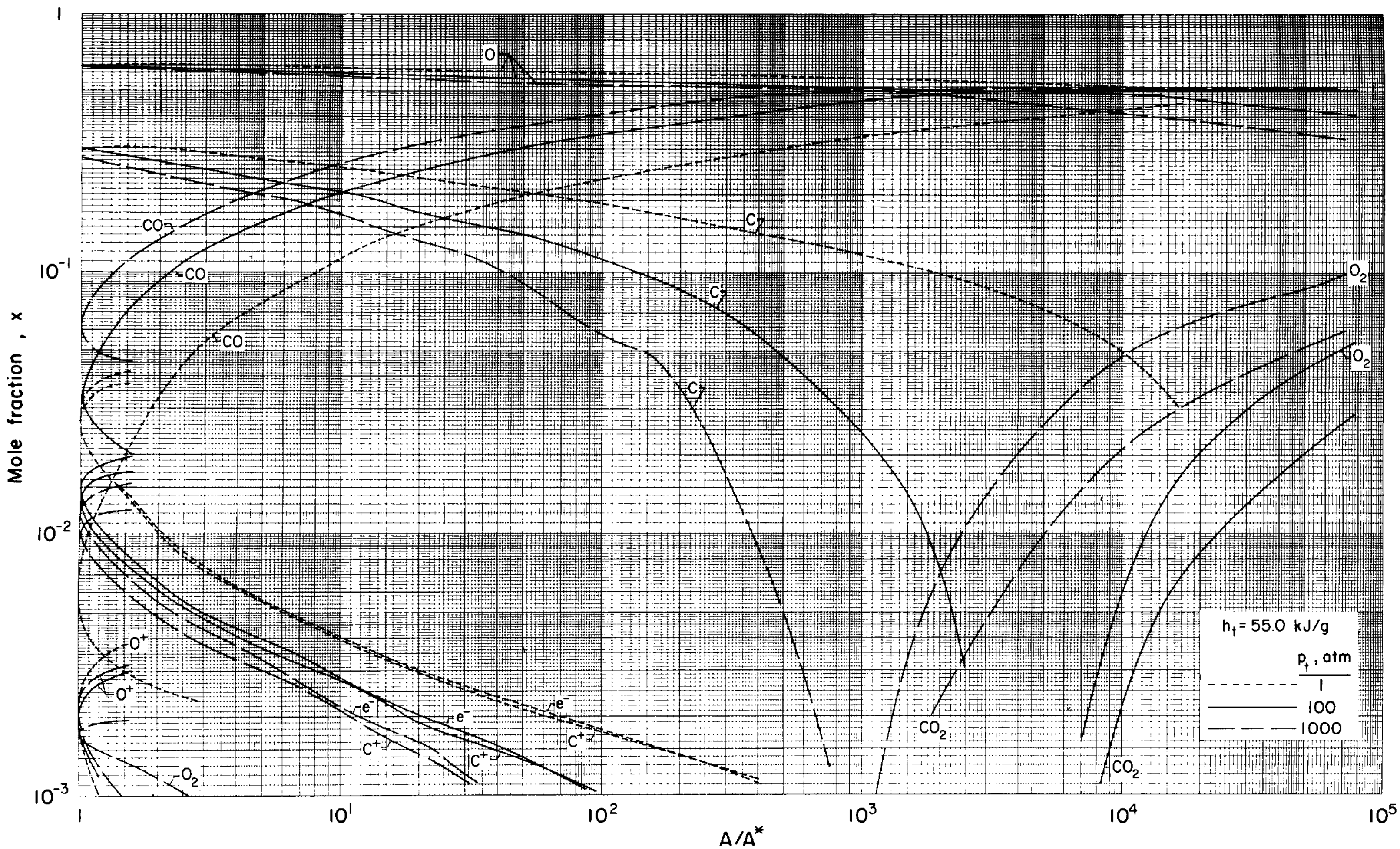
(g) 35.0 kJ/g

Chart 18. - Continued.



(h) 45.0 kJ/g

Chart 18. - Continued.



(i) 55.0 kJ/g

Chart 18. - Concluded

NASA-Langley, 1965