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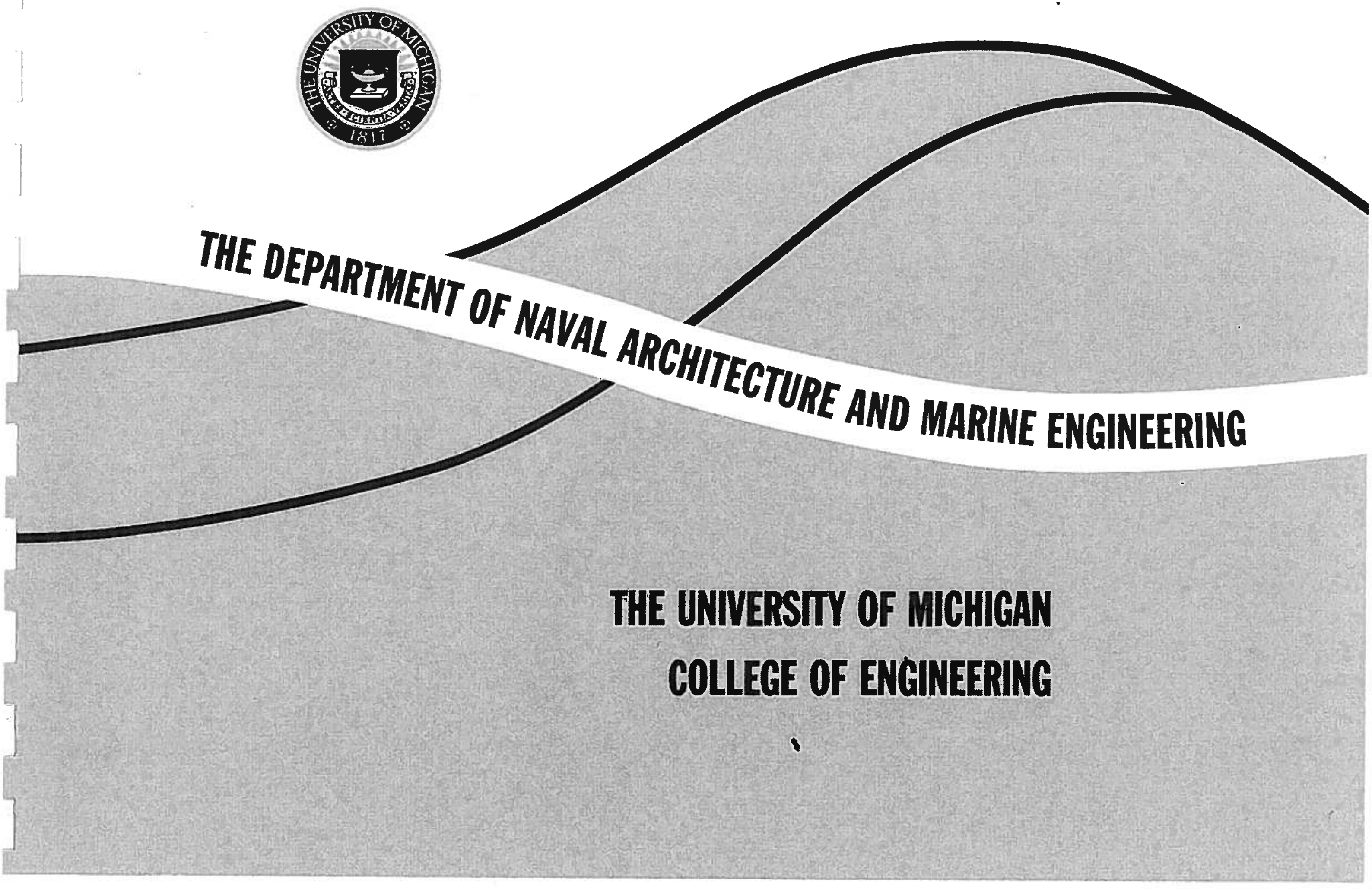

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THE UNIVERSITY OF MICHIGAN
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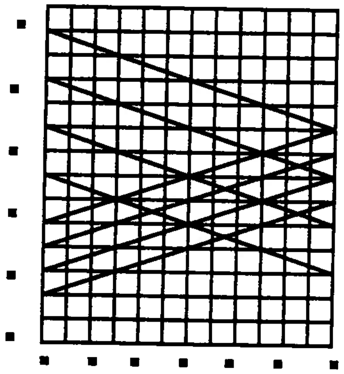

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Introduction

Steam or liquid water is injected into the air (or air plus combustion products) that constitutes the working fluid of a gas turbine or of the Brayton cycle that is the theoretical foundation of such an engine. Presumably the air is at the temperature produced by combustion, with the injection being performed to cool the air to a temperature acceptable to the turbine.

We assume that the mixing constituents are initially at the same pressure, and that this pressure is also the pressure of the mixture. Each constituent assumes a partial pressure in the mixture proportional to the number of its moles present, this in accord with Dalton's law. (Although Dalton's law assumes perfect gas behavior, its application to the fluids treated here produces only negligible error.)

The first law of thermodynamics expresses itself as

$$m_{mix}h_{mix} = m_1h_1 + m_2h_2$$

where m is mass and h is enthalpy. The same formula applies to other properties as well. However, in the case of entropy, it is applicable only in finding that property from the constituent properties of an *existing* mixture. Mixing of dissimilar fluids produces an increase in entropy. If that increase is to be found, the equation becomes an inequality; one subtracts the sum of the two right-hand terms from the left hand term.

Properties of air and air-plus-products are taken from Joseph Keenan, Jing Chao, and Joseph Kaye, *Gas Tables,* International Version, Krieger Publishing, Malabar, Florida, 1992. Properties of steam are taken from Joseph Keenan, Frederick Keyes, Philip Hill, and Joan Moore, *Steam Tables,* Wiley-Interscience, New York, 1978.

Only SI units are used in this report.

Steam in all cases is taken to be dry, saturated, at the same pressure as the air. Fuel in all cases is taken to be of the $(CH_2)_n$ family.

Figures 1 – 4

These figures give mean values of k (ratio of specific heats) and c_P (constant pressure specific heat) for isentropic exansions of steam-plus-air (Figs.1, 2) and steam-plus-air-plus-products (Figs. 3, 4) from pressures in the range 1.0 to 4.0 MPa to atmospheric pressure (0.1 MPa). The word "mean" implies a value to give the same end temperature by means of the equation

$$T_2 = T_1 r^{\gamma} \qquad \text{(r is pressure ratio; } \gamma \text{ is } (k-1)/k)$$

as found by use of the tables. Error introduced by using these mean values instead of the tables should be less than 0.5%. "Error" here is defined as the difference between an enthalpy change found by these curves, and the change found using the tables.

Figures 5 – 6

These figures show the same information as Figs. 1 – 4, but cover a range of air/fuel ratios. The initial pressure is 3.0 MPa. However, if an error of no more than 1.0% is tolerable, the curves can be used for initial pressures over the 1.0 to 4.0 MPa range of Figs. 1 – 4.

Figures 7 – 12

Mixing of steam with air or with air-plus-products generates an increase in entropy. Figs. 7 and 9 show the change of air temperature to be expected from the mixing with steam, and with liquid water, respectively.

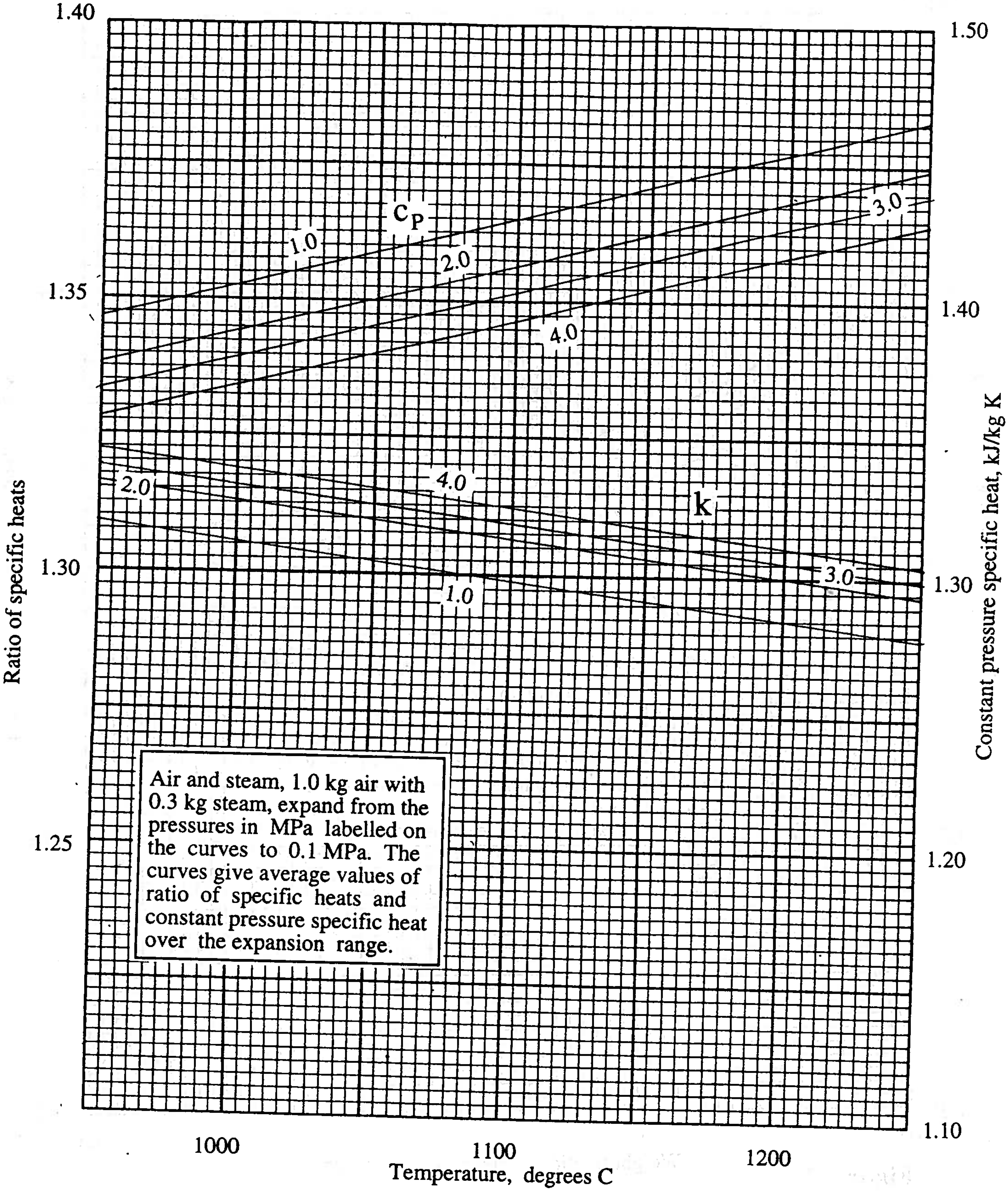
Figs. 8 and 10 show the increase in entropy per kg air to be expected from the mixing with steam, and with liquid water, respectively.

Figs. 11 and 12 show the air temperature and the increase in entropy for mixing of steam and air with stoichiometric products of combustion. The curves are virtually identical to those for air without combustion products, and hence are presented here only to demonstrate that circumstance. Water and air-plus-products curves are likewise virtually identical to water and air curves, and are not given here.

No pressure labelling is shown on these curves because the mixing entropy curves are virtually independent of pressure over the range 1.0 to 4.0 MPa.

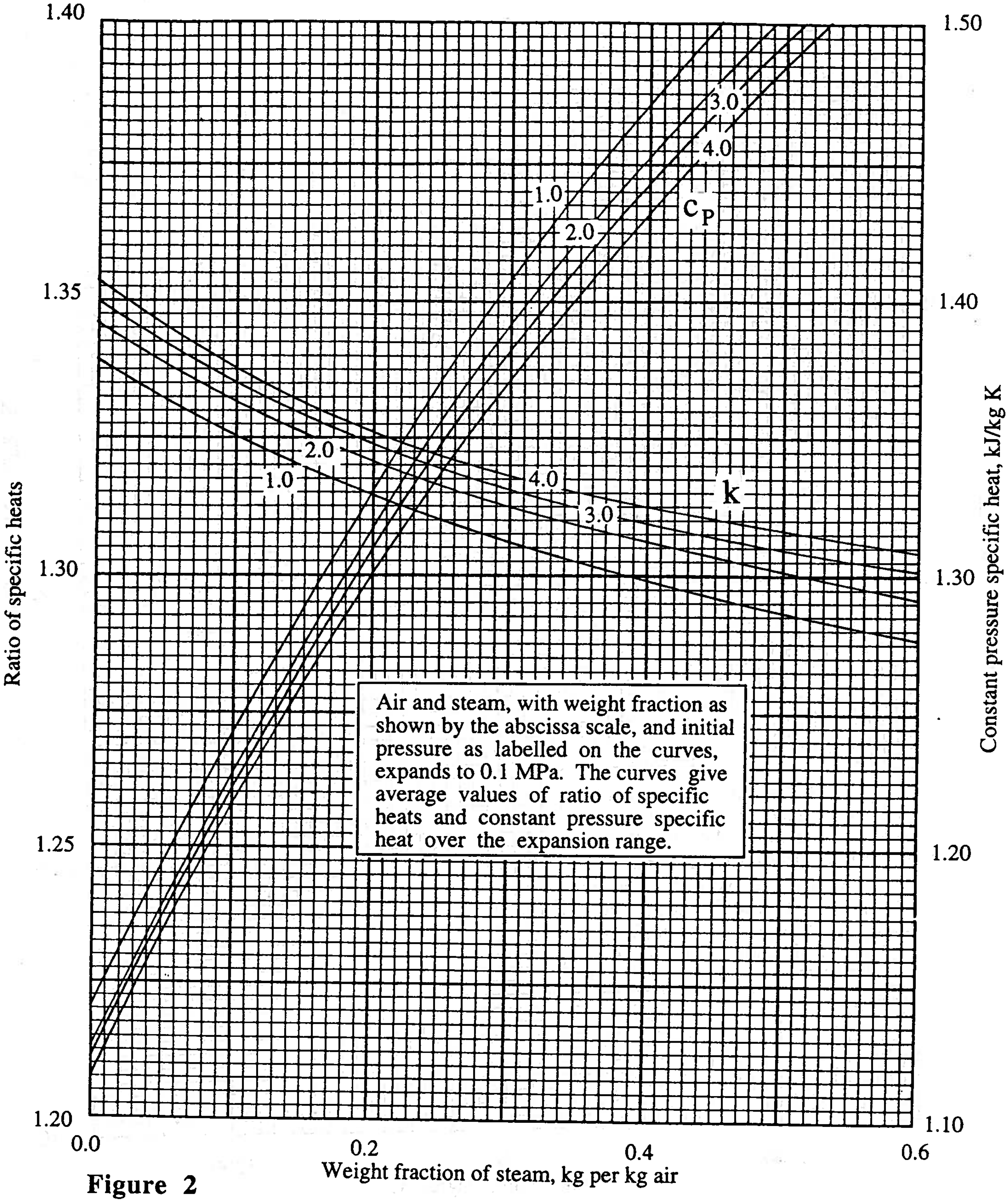
Figure 13

Working fluid for a gas turbine is diluted below the stoichiometric fuel/air ratio to produce an acceptable turbine inlet temperature. The curves of Fig. 13 show the increase in entropy per kg of air (i.e. not air + products) caused by this dilution.



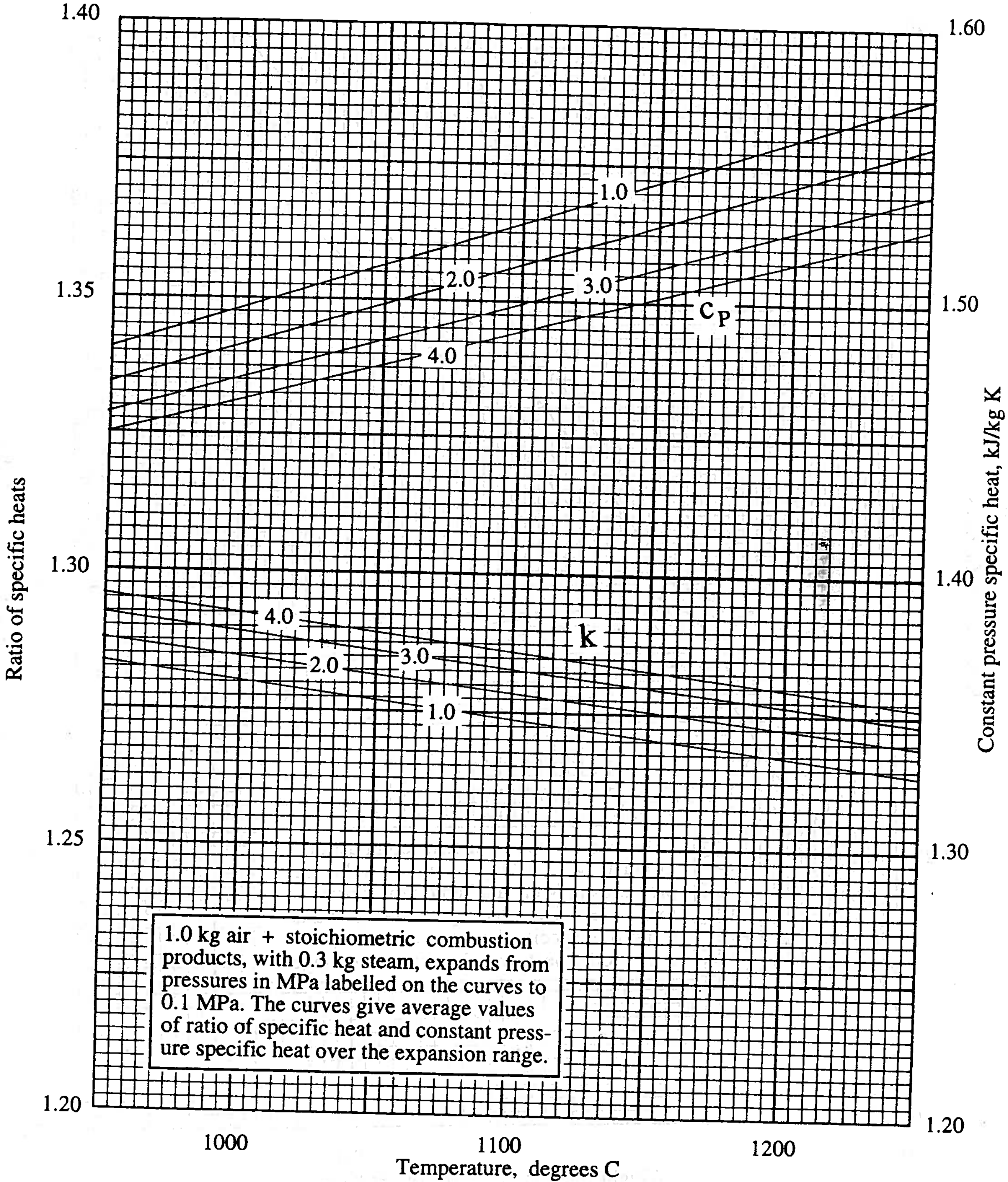
Air and steam, 1.0 kg air with 0.3 kg steam, expand from the pressures in MPa labelled on the curves to 0.1 MPa. The curves give average values of ratio of specific heats and constant pressure specific heat over the expansion range.

Figure 1



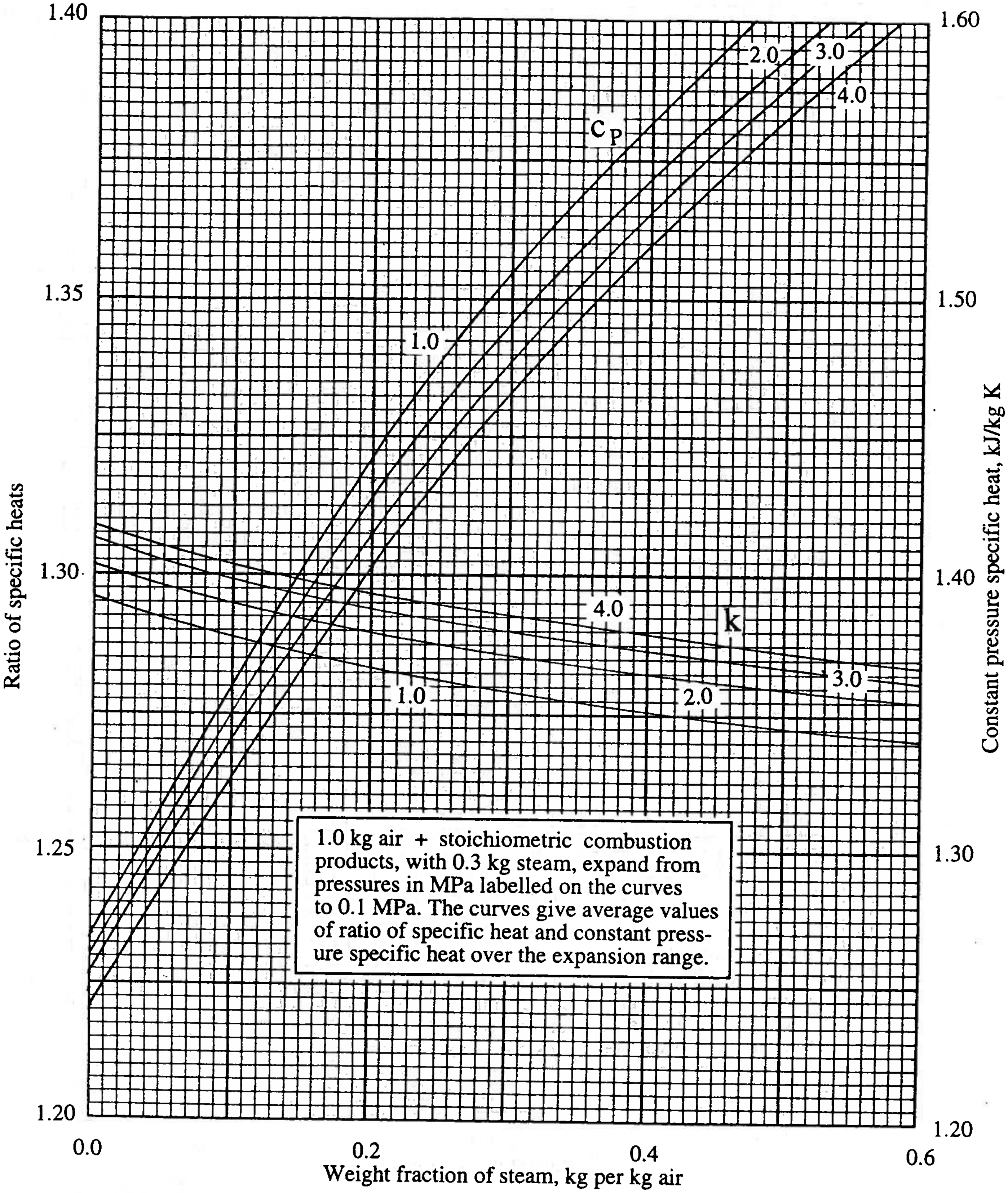
Air and steam, with weight fraction as shown by the abscissa scale, and initial pressure as labelled on the curves, expands to 0.1 MPa. The curves give average values of ratio of specific heats and constant pressure specific heat over the expansion range.

Figure 2



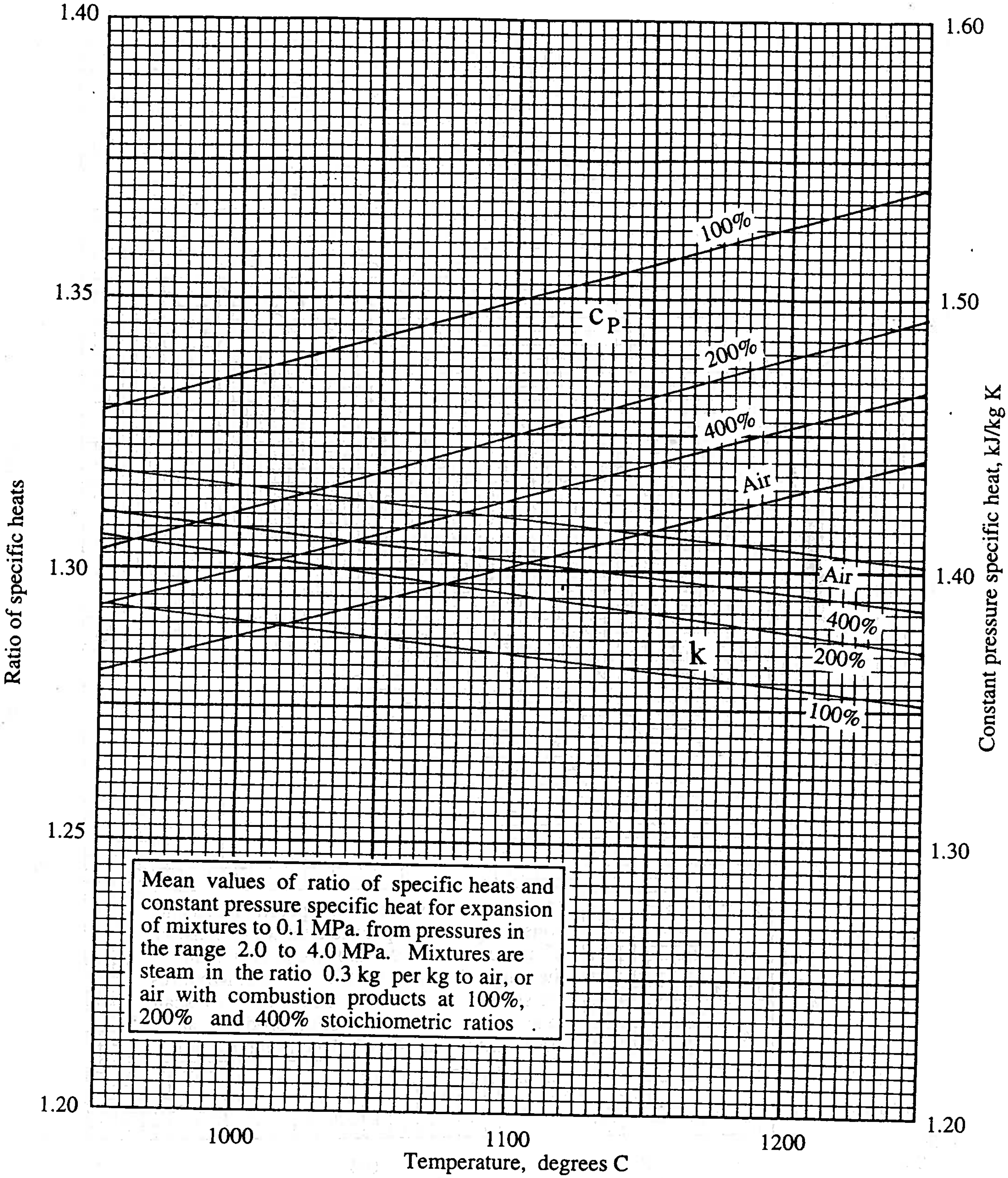
1.0 kg air + stoichiometric combustion products, with 0.3 kg steam, expands from pressures in MPa labelled on the curves to 0.1 MPa. The curves give average values of ratio of specific heat and constant pressure specific heat over the expansion range.

Figure 3



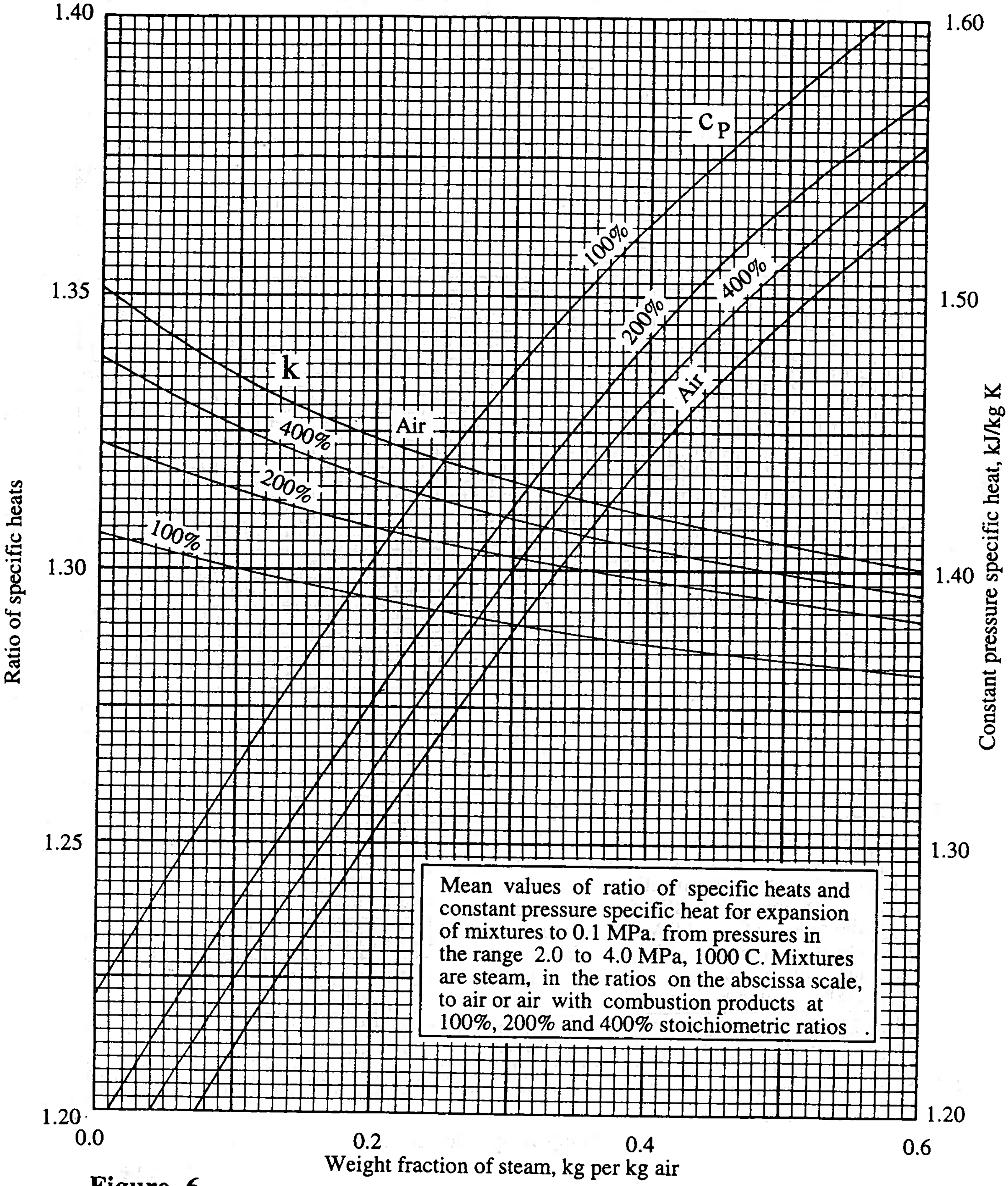
1.0 kg air + stoichiometric combustion products, with 0.3 kg steam, expand from pressures in MPa labelled on the curves to 0.1 MPa. The curves give average values of ratio of specific heat and constant pressure specific heat over the expansion range.

Figure 4



Mean values of ratio of specific heats and constant pressure specific heat for expansion of mixtures to 0.1 MPa. from pressures in the range 2.0 to 4.0 MPa. Mixtures are steam in the ratio 0.3 kg per kg to air, or air with combustion products at 100%, 200% and 400% stoichiometric ratios .

Figure 5



Mean values of ratio of specific heats and constant pressure specific heat for expansion of mixtures to 0.1 MPa. from pressures in the range 2.0 to 4.0 MPa, 1000 C. Mixtures are steam, in the ratios on the abscissa scale, to air or air with combustion products at 100%, 200% and 400% stoichiometric ratios .

Figure 6

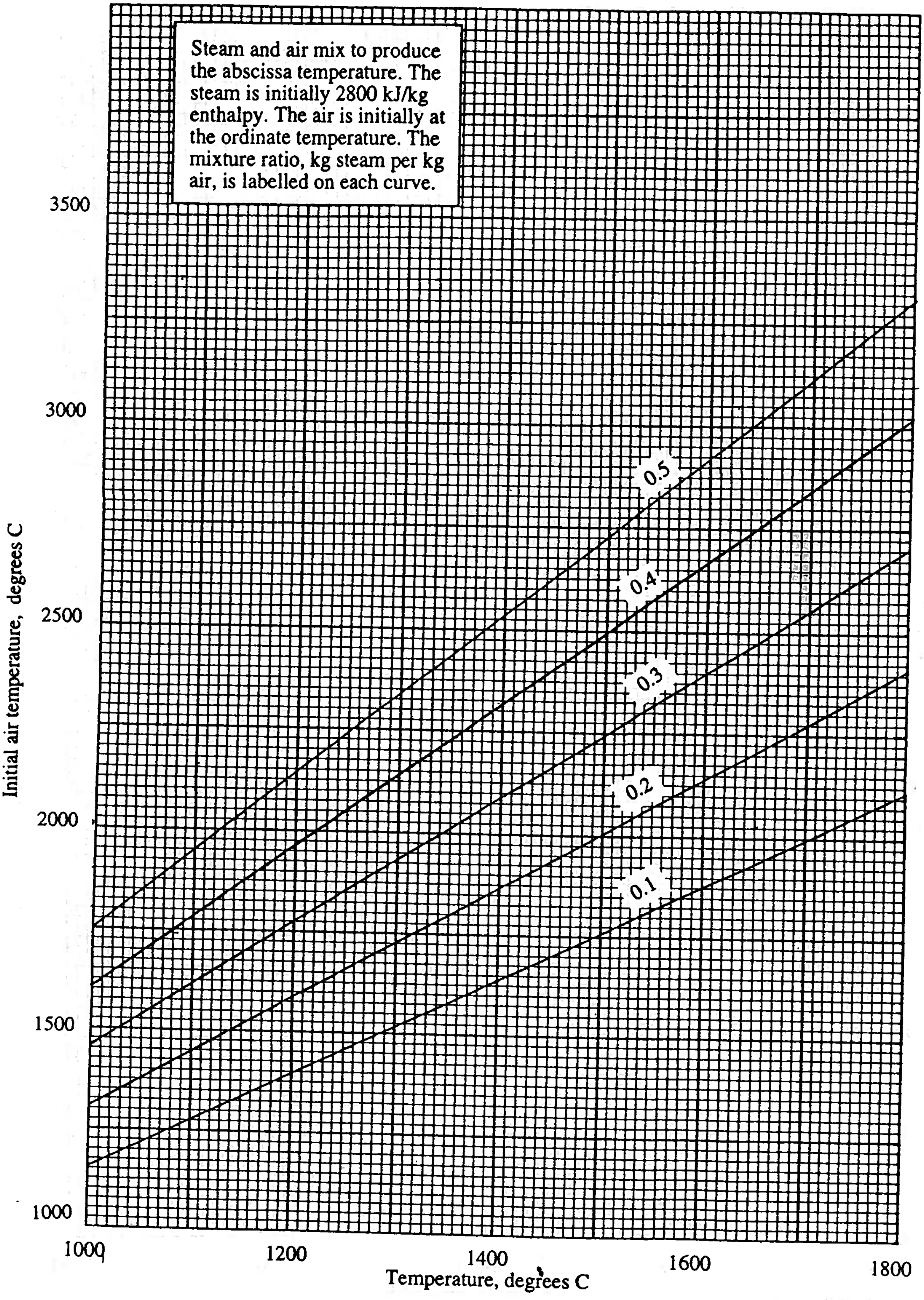
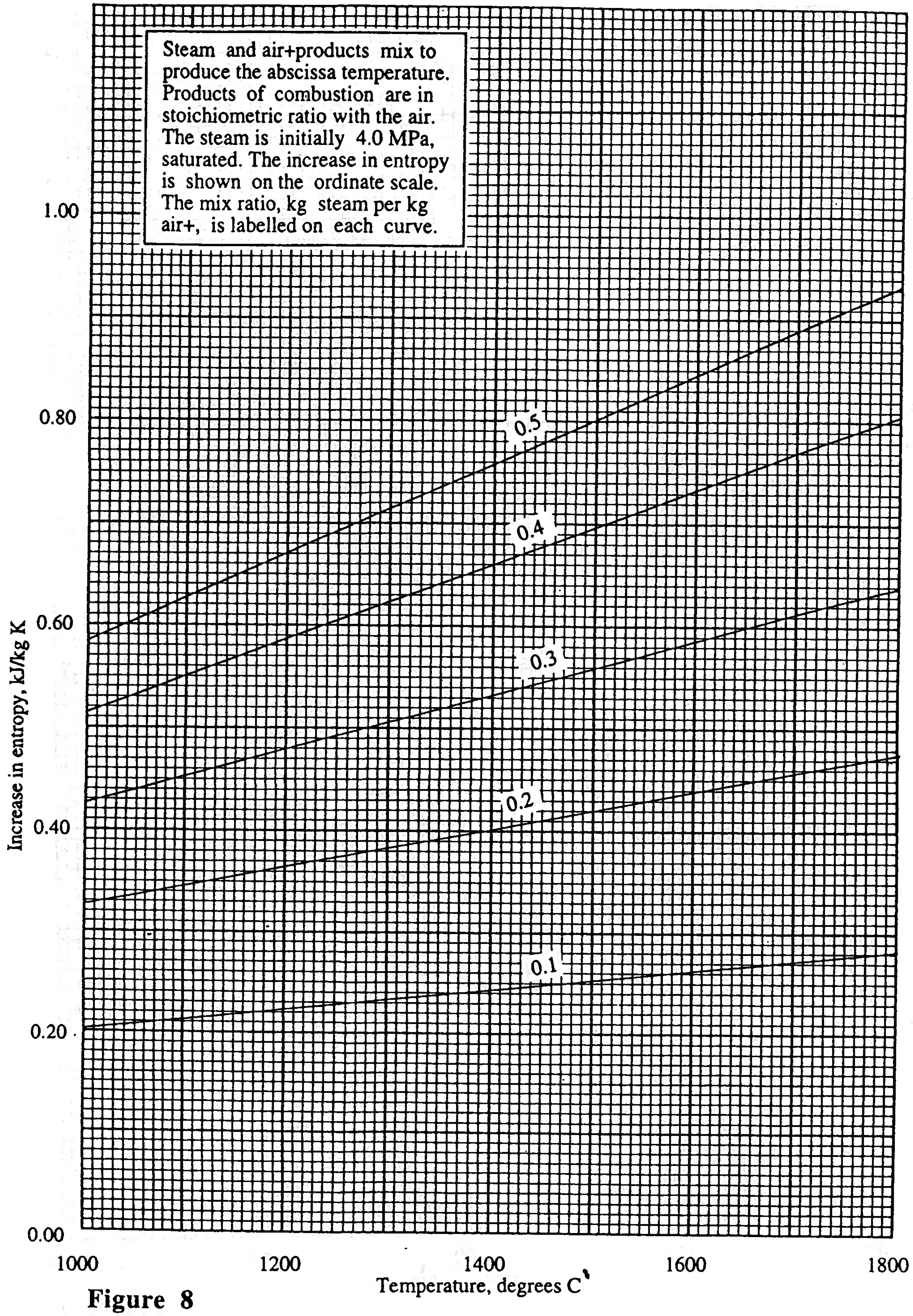

Steam and air mix to produce the abscissa temperature. The steam is initially 2800 kJ/kg enthalpy. The air is initially at the ordinate temperature. The mixture ratio, kg steam per kg air, is labelled on each curve.
Initial air temperature, degrees C
3500
3000
2500
2000
1500
1000
1000
1200
1400
1600
1800
Temperature, degrees C
0.5
0.4
0.3
0.2
0.1

Figure 7



Steam and air+products mix to produce the abscissa temperature. Products of combustion are in stoichiometric ratio with the air. The steam is initially 4.0 MPa, saturated. The increase in entropy is shown on the ordinate scale. The mix ratio, kg steam per kg air+, is labelled on each curve.

Figure 8

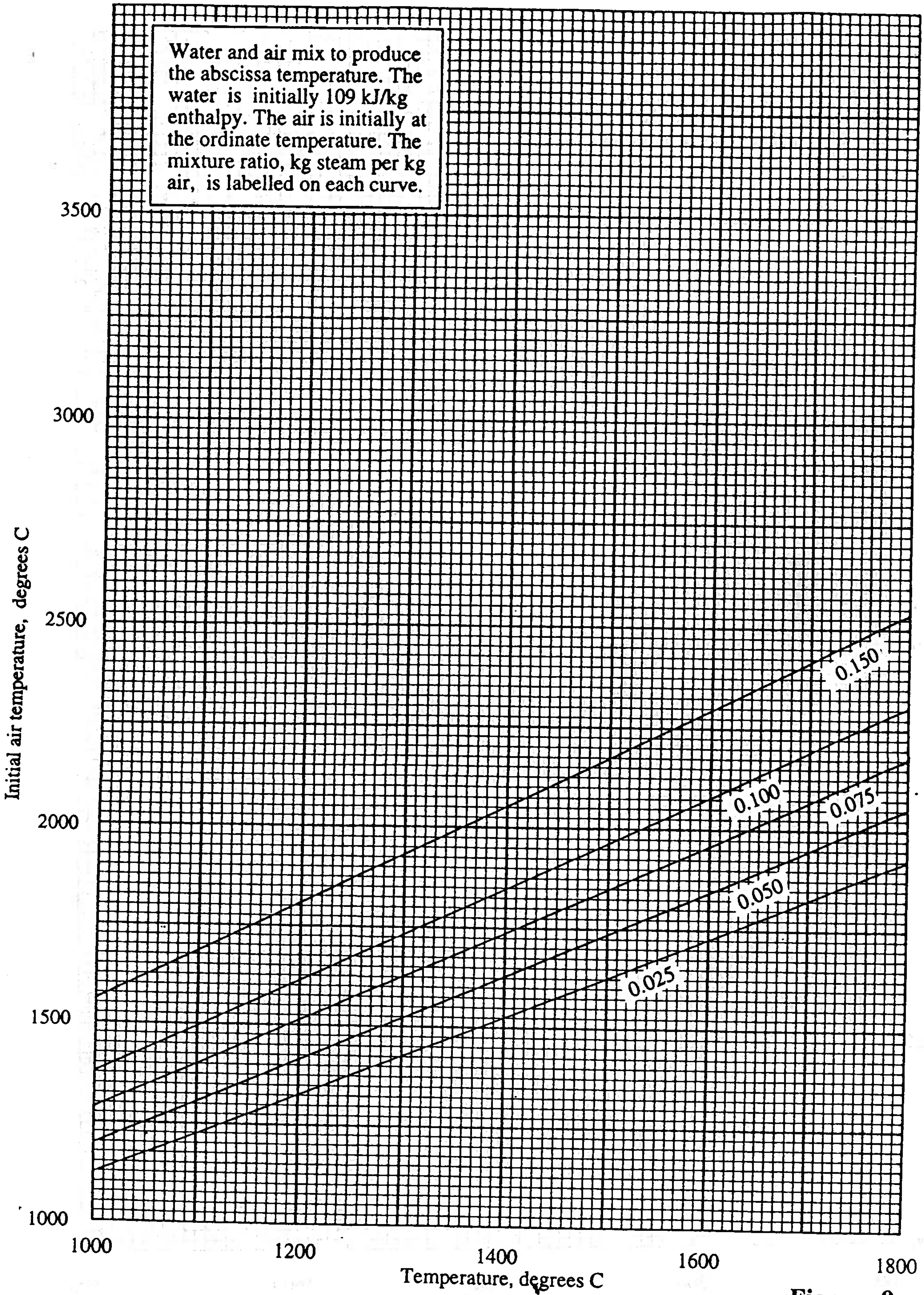

Water and air mix to produce the abscissa temperature. The water is initially 109 kJ/kg enthalpy. The air is initially at the ordinate temperature. The mixture ratio, kg steam per kg air, is labelled on each curve.
Initial air temperature, degrees C
3500
3000
2500
2000
1500
1000
0.150
0.100
0.075
0.050
0.025
1000
1200
1400
1600
1800
Temperature, degrees C

Figure 9

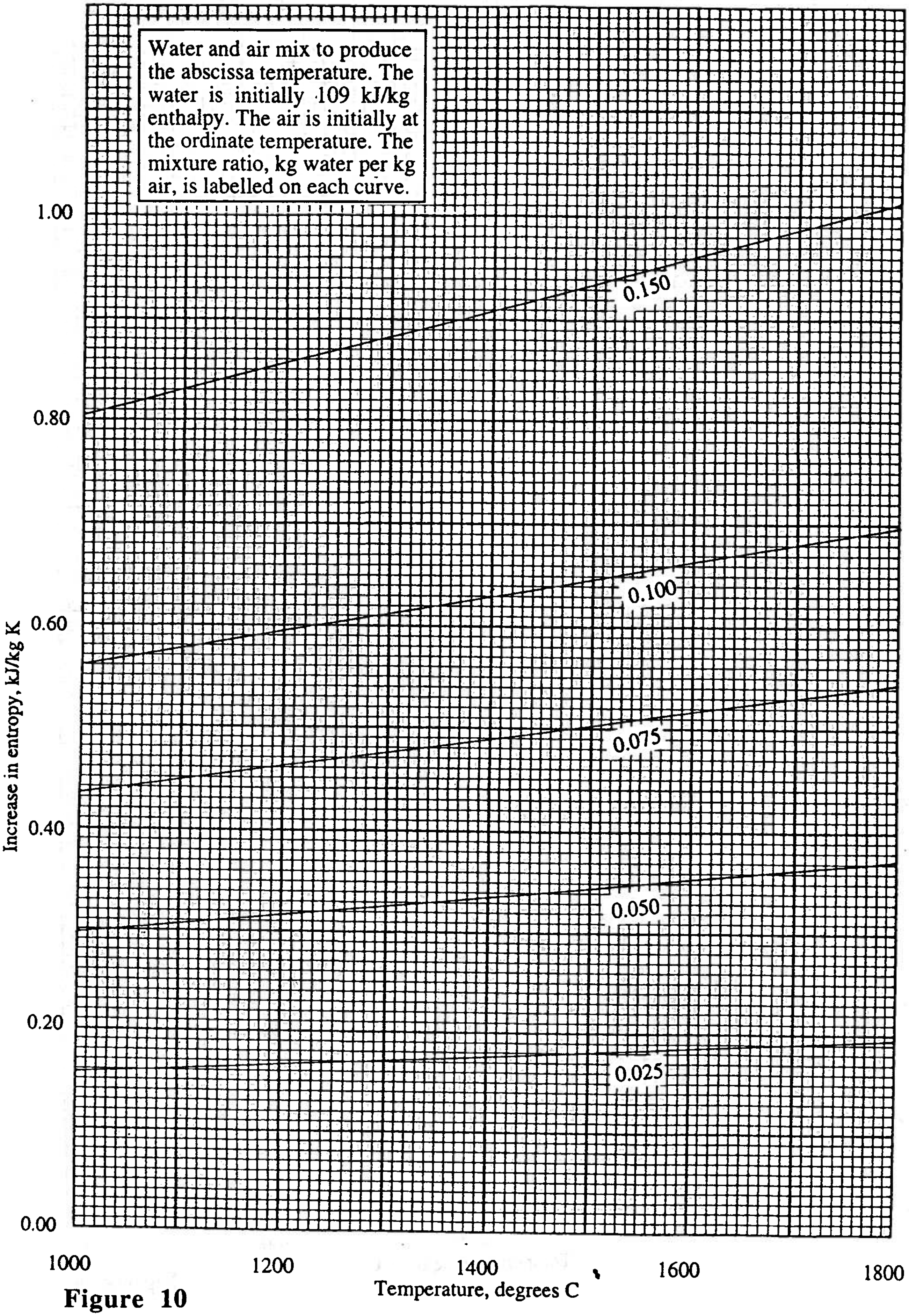
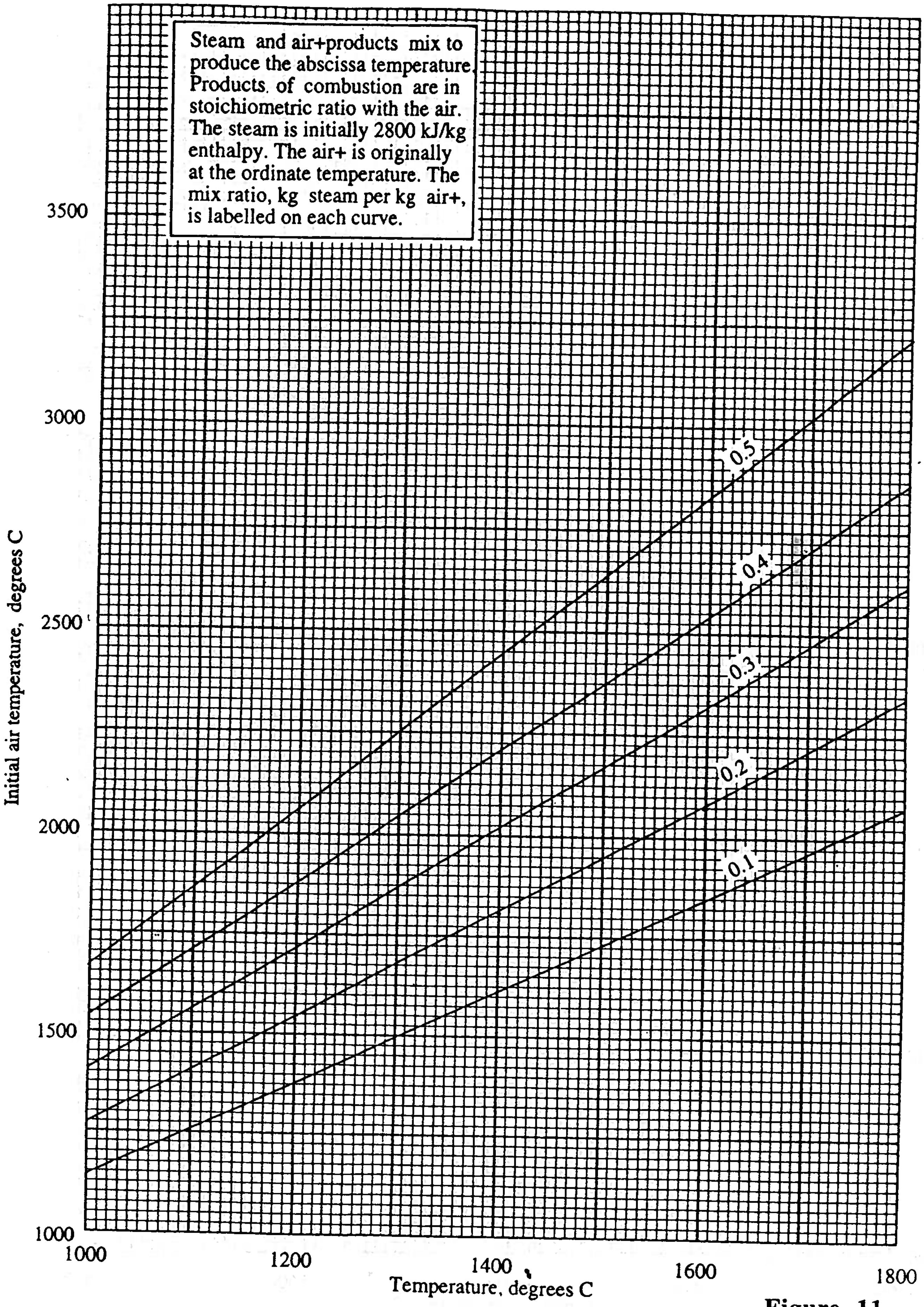

Water and air mix to produce the abscissa temperature. The water is initially 109 kJ/kg enthalpy. The air is initially at the ordinate temperature. The mixture ratio, kg water per kg air, is labelled on each curve.
Increase in entropy, kJ/kg K
1.00
0.80
0.60
0.40
0.20
0.00
0.150
0.100
0.075
0.050
0.025
1000
1200
1400
1600
1800
Temperature, degrees C

Figure 10



Steam and air+products mix to produce the abscissa temperature. Products of combustion are in stoichiometric ratio with the air. The steam is initially 2800 kJ/kg enthalpy. The air+ is originally at the ordinate temperature. The mix ratio, kg steam per kg air+, is labelled on each curve.

Figure 11

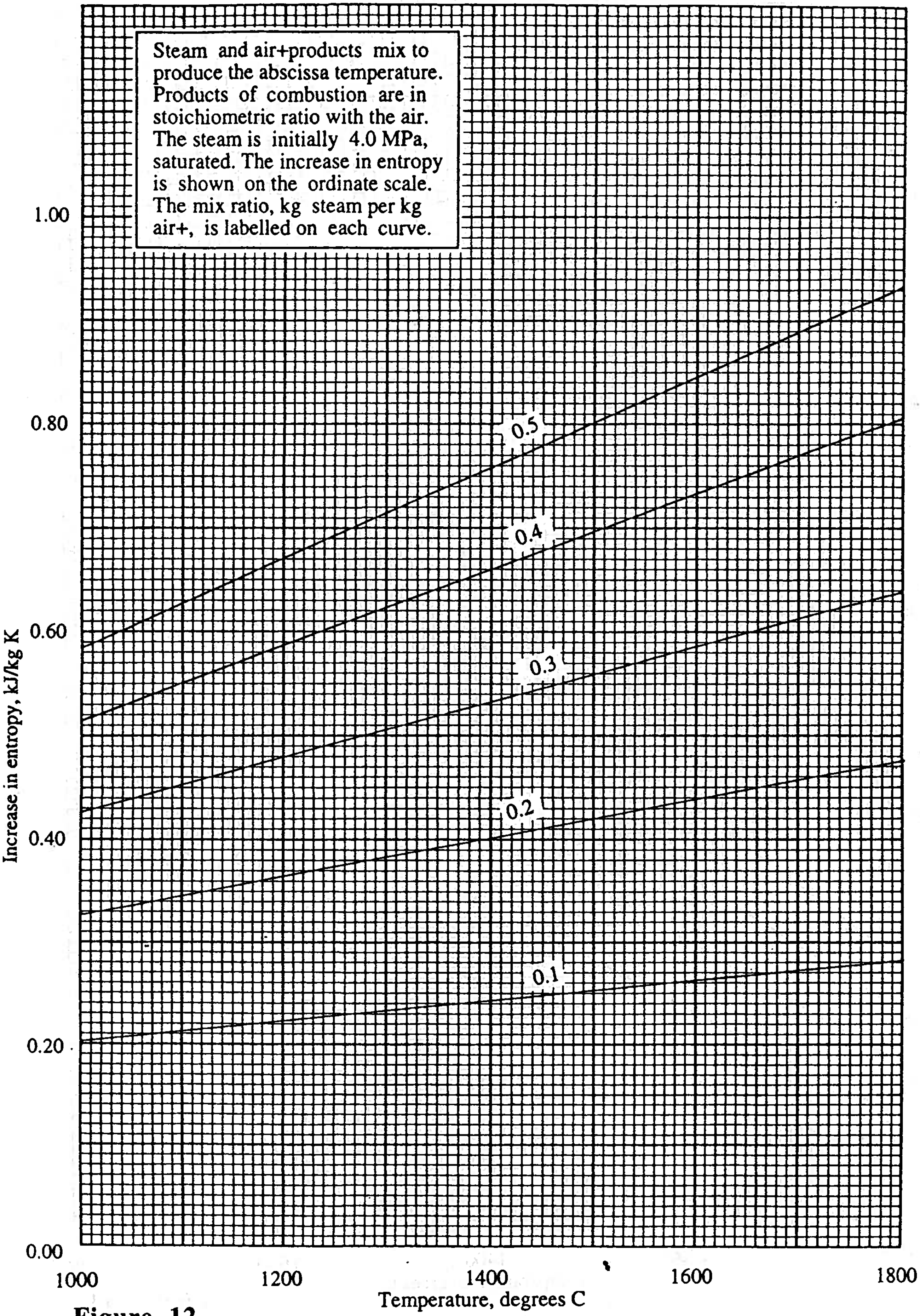
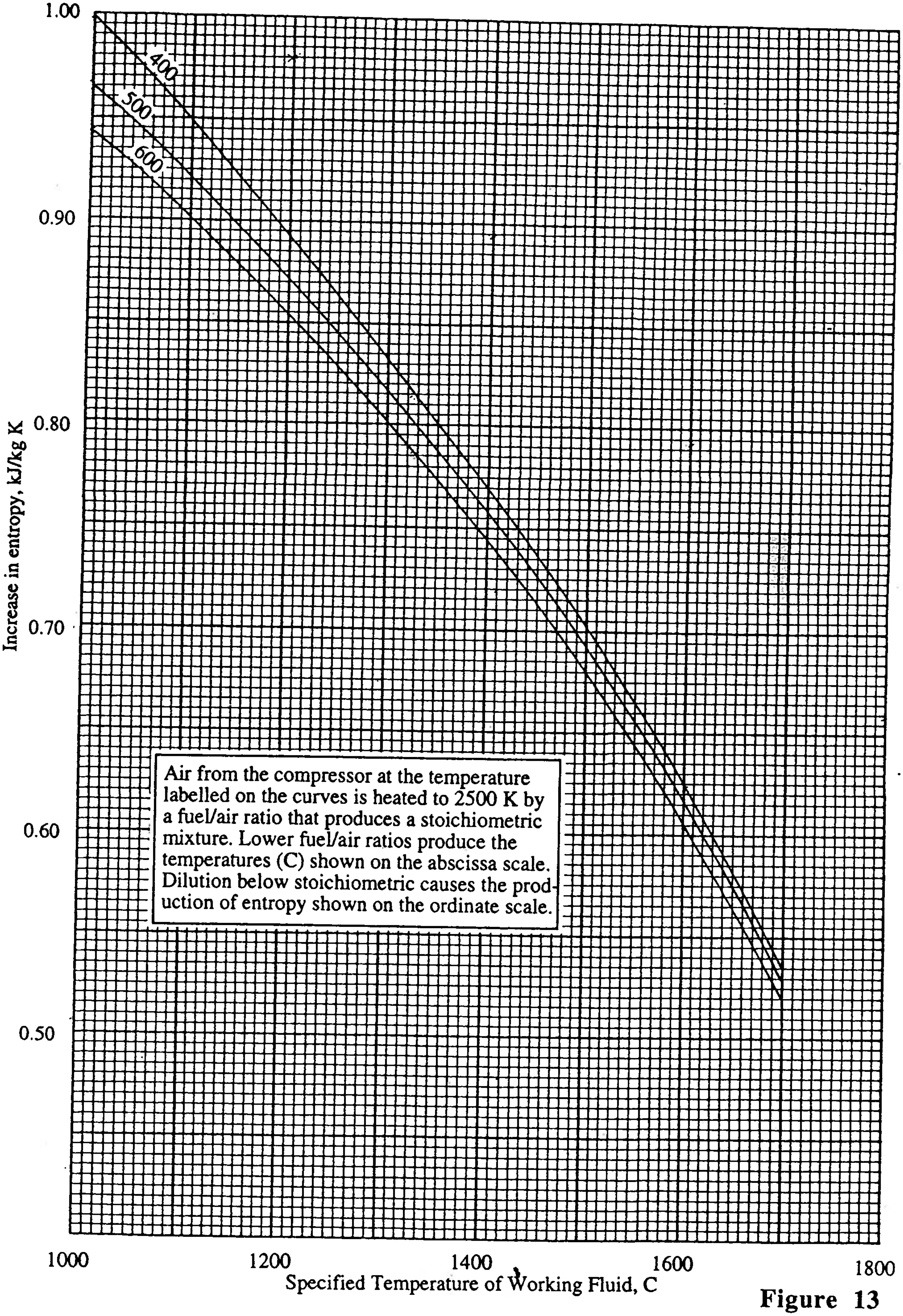

Steam and air+products mix to produce the abscissa temperature. Products of combustion are in stoichiometric ratio with the air. The steam is initially 4.0 MPa, saturated. The increase in entropy is shown on the ordinate scale. The mix ratio, kg steam per kg air+, is labelled on each curve.

Figure 12



Air from the compressor at the temperature labelled on the curves is heated to 2500 K by a fuel/air ratio that produces a stoichiometric mixture. Lower fuel/air ratios produce the temperatures (C) shown on the abscissa scale. Dilution below stoichiometric causes the production of entropy shown on the ordinate scale.

Figure 13