EUR 5103 e

COMMISSION OF THE EUROPEAN COMMUNITIES

HYDROGEN, OXYGEN AND NATURAL GAS BY PIPELINES: COMPARATIVE TRANSPORT COSTS

by

G. BEGHI, J. DEJACE (Euratom)
B. CIBORRA (Istituto di Macchine - Politecnico di Milano)
C. MASSARO (SNAM Progetti - Milano)

1974

Joint Nuclear Research Centre
Ispra Establishment - Italy

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ABSTRACT

A technical-economical comparison was made between the transport by pipeline of natural gas, hydrogen and oxygen. Comparative costs were calculated for distances up to 2000 Km, and flows up to 4000 Gcal/sec; the influence of transport pressure and intermediate compression stations was also taken into account.

KEYWORDS

INDEX

1. INTRODUCTION

Hydrogen is mentioned with increasing frequency in energy market forecasts for its potential in various fields 1), 2), 3), 4).

Since one of the most important elements in the development of a fuel is ease of transport, it is important to have some information on this subject.

The technical fesibility of hydrogen pipelines has already been demonstrated; we can mention, amongst others, the several hundreds of kilometers of ducts which link petrochemical centres and chemical industries in Western Germany 5).

This study makes a preliminary attempt, within the limits set by assumptions, to make technico – economical comparisons between hydrogen and an already existing conventional energy source, such as the widely employed natural gas. For the purposes of this comparison we have taken into consideration only transport over long distances with or without intermediate compressor stations.

The transport cost for oxygen has also been calculated, due to the fact that a chemical plant for hydrogen production by water decomposition gives oxygen as a byproduct; this gas may have interesting applications.

2. GENERAL DATA AND BASIC HYPOTHESES

2.1 Characteristics of Gas

We are considering the transport of 100% pure hydrogen and oxygen, and natural gas composed of 100% methane. The principal characteristics are as follows:

	Hydrogen	Methane	Oxygen
– Chemical formula	H_2	CH_4	O_2
– Specific gravity at 0°C and 700 mm Hg	.08987	.7168	1.42904
– Molecular weight	2.016	16.032	32.
– $R = \frac{848}{M}$ m/°	420.6	52.9	26.5
– C_p (Cal/°Kg)	3.408	.531	.218
– C_v (Cal/°Kg)	2.420	.406	.156
– $K = C_p/C_v$	1.407	1.31	1.401
– $\psi = \frac{K-1}{K}$	.289	.237	.285
– P_{ci} = Heat of combustion (net) KCal/m³ (0°C, 760mm Hg)	2600	8600	–––
– Zm, average compressibility coefficient in transport conditions	1.02	.94	.975 (40 Kg/cm²)
	1.03	.90	.96 (65 Kg/cm²)
	1.042	.86	.95 (90 Kg/cm²)

2.2 Average Temperature for Transport

We have assumed for transport in the ducts an average temperature equal to 10°C = 283°K.

2.3 Utilization Factor

For these preliminary calculations we will consider the case of regular operation, without peak period, equal to 8000 hours/per year, with a resulting utilization factor of approximately 91%.

2.4 Pressure in the Pipeline

We have assumed three values for the pressure in the pipeline: 90 Kg/cm²; 65 Kg/cm²; 40 Kg/cm²

65 Kg/cm^2 is a value which is normally utilized for methane. For the other gases it will be possible to have information on the best values for the pressure.

2.5 Materials

We consider to use API 5LX-X60 steel or an equivalent (yield point 42 Kg/mm^2).

Calculations of the wall thickness of the pipes were carried out according to DIN 2413 norms.

During this preliminary phase no special attention was paid to any particular safety measures relating, for instance, to the materials of the duct itself, which might be required for hydrogen transport.

2.6 Terminal Station

We assumed two cases:

- production pressure equal to transport pressure. In this case we do not have to calculate the cost of constructing and operating a special terminal station for compressing the gases.
- a production pressure equal to 10 Kg/cm^2 (for hydrogen and oxygen only).
  In this case, a terminal station is necessary between production plant and the duct.

2.7 Gas Flow

In order to have a term for comparison purposes, for methane and hydrogen, the flow has been expressed in heat quantity, the calculations have been made on the basis of an equal number of KCal transported in a unit of time, combustion efficiency being assumed equal. In the case of oxygen, only volume units have been considered.

3. TECHNICAL ECONOMIC EVALUATION

3.1 Calcutation of Pipe Diameter

For a determination of the pressure drop the general formula of gases has been taken into consideration, together with the expression of the friction coefficient as proposed by Weymouth.

We have referred to this formula of Weymouth, both because of its simplicity and because of the lack of semiempirical formulae for hydrogen and oxygen gas as accurate and as experimentally tested as those at present available for natural gas.

This equation becomes:

$$Q = 130 \sqrt{\frac{(P^2_1 - P^2_2)\, D^5}{\gamma_o\, \ell\, \lambda\, T Z_m}} \qquad (1)$$

where:

Q gas flow, Nm^3/sec (0°C 760 mm Hg)

P_1 P_2 pressures at the beginning and at the end of the section of gas-duct under consideration, Kg/cm^2

D diameter of the pipe, m,

γ_o specific gravity of the gas, Kg/Nm^3 (0°C e 760 mm Hg)

ℓ length of the section of gas-duct under consideration, Km

λ friction coefficient according to Weymouth = 0,00941 $D^{-1/3}$ (D in m)

T average transport temperature, °K

Zm compressibility factor of the gas

Substituting the value of λ using the compression ratio $\rho = (P_1/P_2)$ and setting γ_o T Zm = a (constant depending only of gas and temperature) we find:

$$D = \left[5.56 \cdot 10^{-7} \frac{Q^2\, a\, \ell}{P^2_1 \left(1 - \frac{1}{\rho^2}\right)} \right]^{3/16} \qquad (2)$$

D diameter of pipeline as function of the flow Q, of the length of the pipeline's section, of pressure P_1 of transport and of compression ratio ρ.

3.2 The Cost of the Pipe

The cost per unit of length of the pipe has been calculated as a function of the diameter D, taking into consideration the thicknesses and the materials mentioned in § 2.5, the cost of the steel, the costs of the protective coatings, the assembly, the transport, and also the various indirect costs which must be added.

In these estimates we have considered average european costs (for year 1970) and have left out eventual special safety devices arising out of the transport of hydrogen. Part of the cost (essentially the price of steel) is taken as proportional to the thickness (i.e. proportional to the pressure) through the following formula:

$$C_{Tu} = (0.985 \cdot 10^3\, P_1 + 127 \cdot 10^3)\, D^{1.6}$$

where:

C_{Tu} is the cost of the pipe (Lit/m), P_1 the transport pressure (Kg/cm^2) and D the diameter of the pipe (m). For the particular case of $P_1 = 65$ Kg/cm^2 we obtain a formula for methane which is in good agreement with experience.

$$C_{Tu} = 191 \cdot 10^3 \cdot D^{1.6}$$

By substituting the value of D from formula (2) and setting $\ell = (L/t)$, where L is the total length of the pipe (in Km) and t the number of sections, we have:

$$C_T = (1.308 \cdot 10^4 P_1 + 1.688 \cdot 10^6) \left(\frac{a Q^2 L}{t P_1^2 (1 - \frac{1}{\rho^2})}\right)^{0.3} \cdot L \qquad (3)$$

3.3 The Cost of Compression Stations

The power absorbed by each station is given by

$$N = \frac{\gamma_0 Q H}{\eta}$$

where

η is the compression efficiency (assumed equal to .8)

H is the adiabatic work given by

$$H = Z_m \frac{RT}{\psi} (\rho^{\psi} - 1)$$

If we express N in HP, substitute the value of R and let $(\gamma_0 Z_m T)/(m \psi) = b$ (constant depending only on gas and temperature) we obtain:

$$N = 14.13 \; b Q \; (\rho^{\psi} - 1) \qquad (4)$$

Allowing for an increase of 25% for obtaining the installed power, we obtain for the cost of one compression station

$$CS = 1{,}25 \cdot N \cdot P_{cv} \qquad (5)$$

where P_{cv} is the price of the installed HP

3.4 Economical Evaluation

The price of transport was calculated under the following assumptions:

Devaluation allowance (15 years at 8%)

for pipeline	.12 CT/year
for stations	.12 CS/year

Maintenance costs

for pipeline	.005 CT/year
for stations	.035 CS/year

Energy costs per year for one station

$$CE = .736 \cdot N \cdot P_{kw} \cdot n_h \qquad (6)$$

where

P_{kw} is the price of Kwh

n_h is the number of operating hours per year.

Personnel costs

C_{pers} per year for one station

As the flow Q is given in m^3/sec the price of transport of one cubic meter is given by

$$C = \frac{1}{Q \cdot Sec.} [\,.125\, CT + .155\, CS \cdot (t-1) + CE \cdot (t-1) + C_{pers} \cdot (t-1)] + Ci$$

where

Sec = $3600 \cdot n_h$ is the operating time per year expressed in seconds

Ci takes in account the cost of eventual initial compression

Substituting the values of CT, CS, CE from formulae (3), (5), (6) and grouping into coefficients all quantities not dependent on ρ, we find

$$C = \alpha (1 - \rho^{-2})^{-0.3} + \beta \rho^{\psi} + \gamma$$

where

$$\alpha = (.163 \cdot 10^4 \cdot P_1 + .2115 \cdot 10^6) \left(\frac{a Q^2 L}{P_1^2 t}\right)^{0.3} \frac{L}{Q \cdot sec}$$

$$\beta = \left(\frac{2.741}{Sec} P_{cv} + 2.88 \cdot 10^{-3} P_{kw}\right) b \; (t-1)$$

$$\gamma = \frac{C_{pers} (t-1)}{Q \cdot Sec} + Ci$$

It is now possible to calculate the value of the compression ratio ρ which minimizes the price C.

For this value of ρ, the first derivative $(dc)/(d\rho)$ will vanish

$$\frac{dc}{d\rho} = -0.6 \alpha (1 - \rho^{-2})^{-1.3} \rho^{-3} + \beta \psi \rho^{\psi - 1} = 0$$

After some calculation and setting

$$\mu = \frac{0.6 - \psi}{-1.3}$$

and

$$B = \left(\frac{\beta \psi}{0.6 \alpha}\right)^{-\frac{1}{1.3}}$$

we obtain an equation in ρ easily solved by the Newton method

$$\rho^{\mu} (\rho^2 - 1) = B \qquad (7)$$

It should be noted that, in the case of t = 1, which means a duct without intermediate compression station, β vanishes and equation (7) no longer makes sense. In this case we have assumed for the compression ratio a value of $\rho = 1.5$ (average value encountered in the majority of cases).

3.5 Initial Compression

The initial compression ratio is calculated by:

$$\rho_i = \frac{P_1}{P_P}$$

where

P_1 is the pressure in the duct

P_P is the production pressure

The energy of compression was calculated with the formula (4) used in § 3.3. With some simplified assumptions the cost of initial compression was evaluated in the various cases. Exemples of the obtained results are given in the diagrams of Fig. 4.

3.6 Numerical Calculations

A computer program has been written in Fortran IV language.
The input consists of:

- **gas data**: specific gravity, molecular weight, ψ, heat of combustion, compressibility coefficient.
- **transport parameters**: temperature, production pressure, maximum transport pressure, P_1, cost of installed horse-power, P_{cv}, cost of kwh, P_{kw}, cost of personnel C_{pers}, number of hours of exercise per year, n_h.
- quantity of gas with an option for the units (volume or energy)
- total length of the duct and minimum and maximum number of sections.

The following prices valid for year 1970 [1] were assumed

Price of Kilowat-hour P_{kw} = 10 Lit (Italian lire) [2]
Price of installed horse-power P_{cv} = 180 000 Lit
Cost of personnel per station and year $C_{pers} = 100 \cdot 10^6$ Lit.

The flow for methane and hydrogen was made to vary between 500 and 4000 MCal/sec; which correspond to flow between 200 000 and 1 600 000 Nm^3/h for methane and between 700 000 and 5 600 000 Nm^3/h for hydrogen.

For oxygen, flow varying between 500 m^3/sec (1 800 000 Nm^3/h) and 1500 m^3/sec (5,400,000 Nm^3/h) were considered.

The total length of the pipe varies between 500 and 2000 Km. Three transport pressures, as previously mentioned, were used: 40, 65 and 90 Kg/cm^2.

For each pair of Q and L and for different values of t, the value of compression ratio ρ, which minimizes the cost, was calculated. Other quantities which may be interesting were also calculated; an example of output is given in Table II for methane at 65 Kg/cm^2.

4. RESULTS

4.1 General Considerations

A synthesis of results is given in Figs. 1, 2, 3 which for a different flows (.5, 1,2,3, 4 GCal/sec), different distances (500, 1000, 1500, 200 Km) and different transport pressures (40, 65, 90 Kg/cm^2) give the optimized cost of transportation.

Table I a) gives the detailed results for pressure of 90 Kg/cm^2 (which gives the minimum cost); only the line corresponding to the number of sections t which minimizes the cost has been printed.

In Table I b) the results are reported for 65 Kg/cm^2, which is the pressure currently utilized for natural gas.

The influence of eventual initial compression is illustrated in Figure 4. It is clear that this initial compression becomes, specially over short distances, an important factor in the total cost. This may influence the choice of pressure in the pipe; in a practical calculation, the utilization pressure needed at the end of the pipeline should also be considered.

Influence of pressure P_1 is illustrated in Table III; for the three gases (without taking account of initial compression) the optimized price is decreasing with pressure in the duct.

We must underline that all the evaluations are based on simplified assumptions.

4.2 Comparisons of Costs for Methane and Hydrogen

The widely diverse physical characteristics of the two gases, methane and hydrogen, give rise to different consequences.

First of all, the lower heating value in the case of hydrogen gives the result that, according to the thermal energy transported, much higher volumes of gas are needed.

But other factors, such as the much lower specific gravity, are involved, and as a consequence, we have a nearly compensating increase of the flow capacity. One less favourable aspect is the pumping energy for transmission, in view of the greater volumes to be handled.

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[1] **All the utilized prices are 1970 prices: this does not influence the main objective of the work, which is a comparative ratio of costs.**

[2] **The influence of the price of the KWh has been verified: an increase or a reduction of this price by a factor 2 will influence the total transport cost by less than 5%.**

Indicative data for comparison of transport costs are given in Table IV referring to a pressure P_1 in the pipe of 90 Kg/cm^2.

We may consider for hydrogen calorie an increase of costs of transport varying from 30% to 50% when compared to natural gas. The ratio of costs increases with distance and diminishes (slowly) with flow.

It appears also from Table IV that the optimum distance between intermediate compression stations is higher for hydrogen than for methane.

Similar results were also obtained for other working pressures. Nevertheless it should be emphasized that the total costs vary very slowly with the number of sections. For instance one can see from Table II that for methane (2 GCal/sec and 2000 Km) varying t from 9 to 15 (minimum) (distance from 220 Km to 133 Km) changes the price by only .6%.

The ratio of investment costs in costructing a gas pipeline is also about 45% to 60% higher for hydrogen, due to the larger diameter of the pipe used.

4.3 Oxygen

It might be interesting to see if it is worthwile to transport oxygen from the production plant to a utilization plant. One of the uses could be to substitute air for the combustion of hydrogen, thus increasing the efficiency because the gross heat of combustion (3100 KCal/m^3) can be considered.

So starting with a production price of hydrogen of 12 mills/m^3 and assuming an increased efficiency for combustion in pure oxygen of 20%, a first estimation shows that for transporting 4.10^6 Nm^3/hr of hydrogen the breakeven distance is about 1000 Km. This distance will of course be longer if hydrogen prices increase.

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CAPTION TO TABLES I AND II

Column			
1	Flow in m^3/sec		
2	Flow in GCal/sec		
3	Total length in Km		
4	Number of section		
5	Compression ratio		
6	Diameter of tube in m		
7	Absorbed power for transport (thousand of HP)		
8	Absorbed power for initial compression (thousand of HP)		
9	Cost of installation	tubes	in 10^9 Lit
10		stations	
11		total	
12	Partial costs in % of total costs for	– depreciation of tubes	
13		– transport compression: degreciation of stations + energy (column 15 is included)	
14		– initial compression	
15		– energy for intermediate compression stations	
16		– energy for initial compression	
17	Total costs	in 10^{-3} Lit/m^3	mLIT
18		in 10^{-6} Lit/KCal	μLIT

METHANE

QUANTITY C.M.	GCAL	DIST. KM	NR SC	RO	DIAM M	ABS. TRSP	POWER(KHP) IN.C.	COST (IN BILLIONS) TUBES	STAT.	T.+S.	PARTIAL COSTS (IN PER CENTS) T.	T.C.	I.C.	T.F.	I.F.	TOT. COST MLIT /C.M.	MULIT /KCAL
58.	0.50	500.	2	1.829	0.452	6.	0.	30.	1.	32.	85.	15.	0.	8.	0.	2641.	307.
58.	0.50	1000.	5	1.495	0.453	15.	0.	61.	3.	64.	81.	19.	0.	9.	0.	5618.	653.
58.	0.50	1500.	8	1.438	0.453	24.	0.	91.	5.	97.	80.	20.	0.	10.	0.	8555.	995.
58.	0.50	2000.	12	1.381	0.450	33.	0.	120.	7.	128.	78.	22.	0.	10.	0.	11494.	1335.
116.	1.00	500.	2	1.689	0.595	10.	0.	47.	2.	49.	85.	15.	0.	9.	0.	2059.	239.
116.	1.00	1000.	5	1.407	0.600	25.	0.	95.	6.	101.	81.	19.	0.	10.	0.	4393.	510.
116.	1.00	1500.	9	1.319	0.596	41.	0.	141.	9.	151.	79.	21.	0.	11.	0.	6664.	775.
116.	1.00	2000.	13	1.288	0.595	56.	0.	188.	13.	200.	78.	22.	0.	11.	0.	8938.	1039.
233.	2.00	500.	2	1.570	0.786	17.	0.	73.	4.	77.	84.	16.	0.	9.	0.	1615.	188.
233.	2.00	1000.	6	1.274	0.789	45.	0.	147.	10.	157.	80.	20.	0.	11.	0.	3449.	401.
233.	2.00	1500.	10	1.234	0.789	69.	0.	221.	16.	237.	79.	21.	0.	12.	0.	5229.	609.
233.	2.00	2000.	15	1.204	0.787	95.	0.	294.	21.	315.	78.	22.	0.	12.	0.	7023.	817.
349.	3.00	500.	2	1.510	0.922	23.	0.	95.	5.	100.	84.	16.	0.	10.	0.	1405.	163.
349.	3.00	1000.	5	1.298	0.940	58.	0.	195.	13.	208.	81.	19.	0.	11.	0.	3006.	350.
349.	3.00	1500.	11	1.188	0.931	95.	0.	288.	21.	309.	79.	21.	0.	12.	0.	4557.	531.
349.	3.00	2000.	16	1.169	0.930	128.	0.	384.	29.	413.	78.	22.	0.	12.	0.	6121.	712.
465.	4.00	500.	2	1.471	1.036	29.	0.	114.	6.	120.	84.	16.	0.	10.	0.	1273.	148.
465.	4.00	1000.	5	1.274	1.058	71.	0.	236.	16.	252.	81.	19.	0.	11.	0.	2730.	317.
465.	4.00	1500.	11	1.173	1.050	116.	0.	349.	26.	375.	79.	21.	0.	12.	0.	4149.	482.
465.	4.00	2000.	16	1.156	1.049	158.	0.	465.	35.	501.	78.	22.	0.	12.	0.	5559.	646.

HYDROGEN

QUANTITY C.M.	GCAL	DIST. KM	NR SC	RO	DIAM M	ABS. TRSP	POWER(KHP) IN.C.	COST (IN BILLIONS) TUBES	STAT.	T.+S.	PARTIAL COSTS (IN PER CENTS) T.	T.C.	I.C.	T.F.	I.F.	TOT. COST MLIT /C.M.	MULIT /KCAL
192.	0.50	500.	1	1.500	0.591	0.	0.	46.	0.	46.	100.	0.	0.	0.	0.	1049.	403.
192.	0.50	1000.	2	1.652	0.577	19.	0.	89.	4.	94.	85.	15.	0.	9.	0.	2352.	905.
192.	0.50	1500.	4	1.382	0.577	36.	0.	134.	8.	142.	82.	18.	0.	10.	0.	3692.	1420.
192.	0.50	2000.	8	1.235	0.568	54.	0.	174.	12.	187.	79.	21.	0.	12.	0.	4982.	1915.
385.	1.00	500.	1	1.500	0.767	0.	0.	70.	0.	70.	100.	0.	0.	0.	0.	795.	306.
385.	1.00	1000.	2	1.541	0.761	33.	0.	139.	7.	147.	85.	15.	0.	9.	0.	1858.	715.
385.	1.00	1500.	2	1.770	0.796	44.	0.	225.	10.	235.	87.	13.	0.	8.	0.	2919.	1123.
385.	1.00	2000.	8	1.192	0.758	90.	0.	276.	20.	297.	79.	21.	0.	12.	0.	3945.	1517.
769.	2.00	500.	1	1.500	0.994	0.	0.	107.	0.	107.	100.	0.	0.	0.	0.	607.	233.
769.	2.00	1000.	2	1.447	1.006	56.	0.	219.	11.	230.	84.	16.	0.	10.	0.	1468.	565.
769.	2.00	1500.	2	1.640	1.048	75.	0.	349.	17.	366.	86.	14.	0.	9.	0.	2294.	882.
769.	2.00	2000.	7	1.180	1.017	146.	0.	442.	33.	475.	79.	21.	0.	12.	0.	3140.	1208.
1154.	3.00	500.	1	1.500	1.158	0.	0.	136.	0.	136.	100.	0.	0.	0.	0.	512.	197.
1154.	3.00	1000.	1	1.500	1.318	0.	0.	335.	0.	335.	100.	0.	0.	0.	0.	1261.	485.
1154.	3.00	1500.	2	1.574	1.233	104.	0.	452.	23.	475.	85.	15.	0.	9.	0.	1965.	757.
1154.	3.00	2000.	2	1.737	1.273	128.	0.	634.	29.	663.	87.	13.	0.	8.	0.	2752.	1058.
1538.	4.00	500.	1	1.500	1.290	0.	0.	167.	0.	167.	100.	0.	0.	0.	0.	457.	176.
1538.	4.00	1000.	1	1.500	1.469	0.	0.	398.	0.	398.	100.	0.	0.	0.	0.	1124.	432.
1538.	4.00	1500.	2	1.531	1.383	130.	0.	543.	29.	572.	85.	15.	0.	10.	0.	1809.	696.
1538.	4.00	2000.	2	1.683	1.427	161.	0.	761.	36.	798.	86.	14.	0.	9.	0.	2490.	958.

OXYGEN

QUANTITY C.M.	GCAL	DIST. KM	NR SC	RO	DIAM M	ABS. TRSP	POWER(KHP) IN.C.	COST (IN BILLIONS) TUBES	STAT.	T.+S.	PARTIAL COSTS (IN PER CENTS) T.	T.C.	I.C.	T.F.	I.F.	TOT. COST MLIT /C.M.	MULIT /KCAL
500.	0.0	500.	2	1.501	1.226	37.	0.	149.	8.	158.	84.	16.	0.	10.	0.	1541.	0.
500.	0.0	1000.	7	1.704	1.232	97.	0.	301.	22.	323.	80.	20.	0.	12.	0.	3295.	0.
500.	0.0	1500.	14	1.146	1.227	153.	0.	448.	34.	483.	78.	22.	0.	13.	0.	4976.	0.
500.	0.0	2000.	20	1.134	1.226	205.	0.	597.	46.	644.	78.	22.	0.	13.	0.	6552.	0.
1000.	0.0	500.	1	1.500	1.811	0.	0.	279.	0.	279.	100.	0.	0.	0.	0.	1210.	0.
1000.	0.0	1000.	5	1.741	1.663	151.	0.	486.	34.	520.	81.	19.	0.	12.	0.	2516.	0.
1000.	0.0	1500.	14	1.119	1.643	251.	0.	715.	56.	771.	78.	22.	0.	13.	0.	3946.	0.
1000.	0.0	2000.	22	1.099	1.639	341.	0.	951.	77.	1027.	78.	22.	0.	13.	0.	5308.	0.
1500.	0.0	500.	1	1.500	2.109	0.	0.	356.	0.	356.	100.	0.	0.	0.	0.	1029.	0.
1500.	0.0	1000.	2	1.685	2.049	143.	0.	679.	32.	711.	86.	14.	0.	9.	0.	2278.	0.
1500.	0.0	1500.	14	1.105	1.950	335.	0.	941.	75.	1016.	78.	22.	0.	13.	0.	3479.	0.
1500.	0.0	2000.	23	1.084	1.946	455.	0.	1250.	102.	1352.	78.	22.	0.	13.	0.	4556.	0.

TABLE Ia

METHANE

QUANTITY		DIST.	NR	RO	DIAM	ABS.	POWER(KHP)	COST (IN BILLIONS)			PARTIAL COSTS (IN PER CENTS)					TOT. COST	
C.M.	GCAL	KM	SC		M	TRSP	IN.C.	TUBES	STAT.	T.+S.	T.	T.C.	I.C.	T.F.	I.F.	MILIT /C.M.	MILIT /KCAL
58.	0.50	500.	2	1.852	0.514	6.	0.	33.	1.	34.	86.	14.	0.	8.	0.	2863.	333.
58.	0.50	1000.	5	1.510	0.515	15.	0.	66.	4.	70.	81.	19.	0.	9.	0.	6072.	706.
58.	0.50	1500.	9	1.401	0.510	26.	0.	98.	6.	103.	79.	21.	0.	10.	0.	9234.	1074.
58.	0.50	2000.	12	1.392	0.512	35.	0.	131.	8.	139.	79.	21.	0.	10.	0.	12392.	1441.
116.	1.00	500.	2	1.709	0.676	11.	0.	51.	2.	53.	85.	15.	0.	8.	0.	2233.	260.
116.	1.00	1000.	6	1.345	0.673	29.	0.	101.	6.	108.	80.	20.	0.	11.	0.	4738.	551.
116.	1.00	1500.	10	1.295	0.673	45.	0.	152.	10.	162.	79.	21.	0.	11.	0.	7197.	837.
116.	1.00	2000.	14	1.276	0.673	61.	0.	202.	14.	216.	78.	22.	0.	11.	0.	9650.	1122.
233.	2.00	500.	2	1.587	0.891	18.	0.	79.	4.	83.	85.	15.	0.	9.	0.	1751.	204.
233.	2.00	1000.	6	1.282	0.895	48.	0.	160.	11.	171.	80.	20.	0.	11.	0.	3729.	434.
233.	2.00	1500.	11	1.219	0.892	76.	0.	238.	17.	255.	79.	21.	0.	12.	0.	5661.	658.
233.	2.00	2000.	16	1.197	0.890	103.	0.	317.	23.	340.	78.	22.	0.	12.	0.	7586.	882.
349.	3.00	500.	2	1.525	1.048	25.	0.	103.	6.	108.	84.	16.	0.	10.	0.	1523.	177.
349.	3.00	1000.	6	1.251	1.058	65.	0.	209.	15.	224.	80.	20.	0.	12.	0.	3252.	378.
349.	3.00	1500.	12	1.178	1.052	103.	0.	311.	23.	334.	78.	22.	0.	12.	0.	4936.	574.
349.	3.00	2000.	17	1.164	1.052	139.	0.	414.	31.	446.	78.	22.	0.	12.	0.	6613.	769.
465.	4.00	500.	2	1.485	1.177	31.	0.	124.	7.	131.	84.	16.	0.	10.	0.	1390.	160.
465.	4.00	1000.	6	1.231	1.192	80.	0.	253.	18.	271.	80.	20.	0.	12.	0.	2955.	344.
465.	4.00	1500.	12	1.163	1.187	127.	0.	377.	29.	405.	78.	22.	0.	12.	0.	4494.	521.
465.	4.00	2000.	17	1.151	1.187	171.	0.	503.	39.	541.	78.	22.	0.	13.	0.	6007.	699.

HYDROGEN

QUANTITY		DIST.	NR	RO	DIAM	ABS.	POWER(KHP)	COST (IN BILLIONS)			PARTIAL COSTS (IN PER CENTS)					TOT. COST	
C.M.	GCAL	KM	SC		M	TRSP	IN.C.	TUBES	STAT.	T.+S.	T.	T.C.	I.C.	T.F.	I.F.	MILIT /C.M.	MILIT /KCAL
192.	0.50	500.	1	1.500	0.667	0.	0.	50.	0.	50.	100.	0.	0.	0.	0.	1126.	433.
192.	0.50	1000.	2	1.689	0.647	20.	0.	95.	4.	100.	86.	14.	0.	8.	0.	2505.	963.
192.	0.50	1500.	5	1.315	0.638	40.	0.	139.	9.	148.	81.	19.	0.	11.	0.	3901.	1500.
192.	0.50	2000.	8	1.249	0.635	57.	0.	185.	13.	197.	79.	21.	0.	11.	0.	5257.	2022.
385.	1.00	500.	1	1.500	0.864	0.	0.	76.	0.	76.	100.	0.	0.	0.	0.	853.	328.
385.	1.00	1000.	2	1.572	0.853	34.	0.	148.	8.	156.	85.	15.	0.	9.	0.	1959.	757.
385.	1.00	1500.	4	1.333	0.857	63.	0.	224.	14.	238.	82.	18.	0.	11.	0.	3087.	1187.
385.	1.00	2000.	8	1.204	0.847	94.	0.	293.	21.	314.	79.	21.	0.	12.	0.	4163.	1601.
769.	2.00	500.	1	1.500	1.121	0.	0.	115.	0.	115.	100.	0.	0.	0.	0.	647.	249.
769.	2.00	1000.	2	1.473	1.127	58.	0.	231.	13.	244.	84.	16.	0.	10.	0.	1554.	598.
769.	2.00	1500.	2	1.677	1.176	79.	0.	371.	18.	389.	86.	14.	0.	9.	0.	2433.	936.
769.	2.00	2000.	8	1.166	1.131	155.	0.	465.	35.	500.	79.	21.	0.	12.	0.	3313.	1274.
1154.	3.00	500.	1	1.500	1.305	0.	0.	146.	0.	146.	100.	0.	0.	0.	0.	550.	211.
1154.	3.00	1000.	1	1.500	1.486	0.	0.	360.	0.	360.	100.	0.	0.	0.	0.	1354.	521.
1154.	3.00	1500.	2	1.607	1.383	108.	0.	481.	24.	505.	85.	15.	0.	9.	0.	2116.	814.
1154.	3.00	2000.	7	1.170	1.346	204.	0.	614.	46.	660.	80.	20.	0.	12.	0.	2904.	1117.
1538.	4.00	500.	1	1.500	1.454	0.	0.	174.	0.	174.	100.	0.	0.	0.	0.	490.	189.
1538.	4.00	1000.	1	1.500	1.656	0.	0.	428.	0.	428.	100.	0.	0.	0.	0.	1206.	464.
1538.	4.00	1500.	2	1.561	1.551	134.	0.	578.	30.	608.	85.	15.	0.	9.	0.	1917.	737.
1538.	4.00	2000.	2	1.721	1.602	166.	0.	811.	37.	849.	87.	13.	0.	8.	0.	2643.	1016.

OXYGEN

QUANTITY		DIST.	NR	RO	DIAM	ABS.	POWER(KHP)	COST (IN BILLIONS)			PARTIAL COSTS (IN PER CENTS)					TOT. COST	
C.M.	GCAL	KM	SC		M	TRSP	IN.C.	TUBES	STAT.	T.+S.	T.	T.C.	I.C.	T.F.	I.F.	MILIT /C.M.	MILIT /KCAL
500.	0.0	500.	2	1.525	1.382	38.	0.	160.	9.	169.	84.	16.	0.	10.	0.	1647.	0.
500.	0.0	1000.	8	1.185	1.379	105.	0.	319.	24.	343.	79.	21.	0.	12.	0.	3500.	0.
500.	0.0	1500.	15	1.143	1.375	163.	0.	477.	37.	513.	78.	22.	0.	13.	0.	5297.	0.
500.	0.0	2000.	22	1.128	1.374	221.	0.	634.	50.	684.	78.	22.	0.	13.	0.	7089.	0.
1000.	0.0	500.	2	1.433	1.828	65.	0.	250.	15.	265.	83.	17.	0.	10.	0.	1302.	0.
1000.	0.0	1000.	7	1.174	1.850	169.	0.	511.	38.	549.	79.	21.	0.	12.	0.	2789.	0.
1000.	0.0	1500.	16	1.109	1.839	269.	0.	759.	61.	819.	78.	22.	0.	13.	0.	4222.	0.
1000.	0.0	2000.	23	1.099	1.839	362.	0.	1012.	82.	1093.	78.	22.	0.	13.	0.	5649.	0.
1500.	0.0	500.	1	1.500	2.387	0.	0.	384.	0.	384.	100.	0.	0.	0.	0.	1111.	0.
1500.	0.0	1000.	2	1.716	2.311	150.	0.	729.	34.	763.	87.	13.	0.	8.	0.	2439.	0.
1500.	0.0	1500.	16	1.096	2.183	359.	0.	999.	81.	1079.	78.	22.	0.	13.	0.	3704.	0.
1500.	0.0	2000.	25	1.081	2.181	486.	0.	1329.	109.	1438.	78.	22.	0.	13.	0.	4955.	0.

TABLE Ib

QUANTITY		DIST.	NR	RO	DIAM	ABS.	POWER(KHP)	COST (IN BILLIONS)			PARTIAL COSTS (IN PER CENTS)					TOT. COST	
C.M.	GCAL	KM	SC		M	TRSP	IN.C.	TUBES	STAT.	T.+S.	T.	T.C.	I.C.	T.F.	I.F.	MLIT /C.M.	MULIT /KCAL
116.	1.00	1500.	12	1.245	0.666	46.	0.	149.	10.	160.	77.	23.	0.	11.	0.	7206.	838.
116.	1.00	1500.	13	1.226	0.663	47.	0.	148.	11.	159.	77.	23.	0.	11.	0.	7216.	839.
116.	1.00	1500.	14	1.210	0.661	47.	0.	148.	11.	158.	76.	24.	0.	12.	0.	7228.	841.
116.	1.00	2000.	9	1.429	0.693	56.	0.	212.	13.	225.	81.	19.	0.	10.	0.	9730.	1131.
116.	1.00	2000.	10	1.386	0.688	57.	0.	210.	13.	223.	81.	19.	0.	10.	0.	9697.	1128.
116.	1.00	2000.	11	1.351	0.683	58.	0.	207.	13.	221.	80.	20.	0.	11.	0.	9675.	1125.
116.	1.00	2000.	12	1.322	0.679	59.	0.	205.	13.	219.	79.	21.	0.	11.	0.	9661.	1123.
116.	1.00	2000.	13	1.297	0.676	60.	0.	204.	14.	217.	79.	21.	0.	11.	0.	9653.	1122.
116.	1.00	2000.	14	1.276	0.673	61.	0.	202.	14.	216.	78.	22.	0.	11.	0.	9650.	1122.
116.	1.00	2000.	15	1.258	0.670	62.	0.	201.	14.	215.	78.	22.	0.	11.	0.	9652.	1122.
116.	1.00	2000.	16	1.241	0.668	62.	0.	200.	14.	214.	77.	23.	0.	11.	0.	9657.	1123.
116.	1.00	2000.	17	1.227	0.665	63.	0.	199.	14.	213.	77.	23.	0.	11.	0.	9664.	1124.
116.	1.00	2000.	18	1.215	0.664	63.	0.	198.	14.	212.	76.	24.	0.	12.	0.	9674.	1125.
116.	1.00	2000.	19	1.203	0.662	64.	0.	197.	14.	212.	76.	24.	0.	12.	0.	9686.	1126.
233.	2.00	500.	1	1.500	1.030	0.	0.	100.	0.	100.	100.	0.	0.	0.	0.	1868.	217.
233.	2.00	500.	2	1.587	0.891	18.	0.	79.	4.	83.	85.	15.	0.	9.	0.	1751.	204.
233.	2.00	500.	3	1.331	0.877	22.	0.	77.	5.	82.	81.	19.	0.	11.	0.	1785.	208.
233.	2.00	500.	4	1.232	0.870	24.	0.	76.	5.	82.	79.	21.	0.	12.	0.	1808.	210.
233.	2.00	1000.	2	2.067	0.970	30.	0.	182.	7.	188.	89.	11.	0.	7.	0.	3823.	445.
233.	2.00	1000.	3	1.623	0.935	38.	0.	171.	9.	180.	85.	15.	0.	9.	0.	3768.	438.
233.	2.00	1000.	4	1.443	0.916	43.	0.	166.	10.	176.	83.	17.	0.	10.	0.	3743.	435.
233.	2.00	1000.	5	1.345	0.904	46.	0.	162.	10.	173.	81.	19.	0.	11.	0.	3732.	434.
233.	2.00	1000.	6	1.282	0.895	48.	0.	160.	11.	171.	80.	20.	0.	11.	0.	3729.	434.
233.	2.00	1000.	7	1.239	0.889	49.	0.	158.	11.	169.	79.	21.	0.	12.	0.	3731.	434.
233.	2.00	1000.	8	1.207	0.884	50.	0.	157.	11.	168.	78.	22.	0.	12.	0.	3736.	434.
233.	2.00	1500.	5	1.500	0.936	64.	0.	258.	14.	272.	83.	17.	0.	10.	0.	5759.	670.
233.	2.00	1500.	6	1.412	0.923	67.	0.	252.	15.	267.	82.	18.	0.	10.	0.	5719.	665.
233.	2.00	1500.	7	1.350	0.914	70.	0.	248.	16.	264.	81.	19.	0.	11.	0.	5693.	662.
233.	2.00	1500.	8	1.304	0.906	72.	0.	245.	16.	261.	80.	20.	0.	11.	0.	5677.	660.
233.	2.00	1500.	9	1.269	0.901	73.	0.	242.	17.	259.	80.	20.	0.	11.	0.	5667.	659.
233.	2.00	1500.	10	1.242	0.896	75.	0.	240.	17.	257.	79.	21.	0.	12.	0.	5662.	658.
233.	2.00	1500.	11	1.219	0.892	76.	0.	238.	17.	255.	79.	21.	0.	12.	0.	5661.	658.
233.	2.00	1500.	12	1.200	0.888	77.	0.	237.	17.	254.	78.	22.	0.	12.	0.	5662.	658.
233.	2.00	1500.	13	1.185	0.885	78.	0.	236.	17.	253.	78.	22.	0.	12.	0.	5665.	659.
233.	2.00	1500.	14	1.171	0.883	78.	0.	235.	18.	252.	77.	23.	0.	12.	0.	5669.	659.
233.	2.00	2000.	9	1.353	0.919	94.	0.	334.	21.	355.	81.	19.	0.	11.	0.	7658.	891.
233.	2.00	2000.	10	1.317	0.913	96.	0.	330.	22.	352.	81.	19.	0.	11.	0.	7634.	888.
233.	2.00	2000.	11	1.288	0.908	97.	0.	327.	22.	349.	80.	20.	0.	11.	0.	7616.	886.
233.	2.00	2000.	12	1.263	0.903	99.	0.	324.	22.	347.	80.	20.	0.	11.	0.	7604.	884.
233.	2.00	2000.	13	1.243	0.899	100.	0.	322.	23.	345.	79.	21.	0.	12.	0.	7595.	883.
233.	2.00	2000.	14	1.225	0.896	101.	0.	320.	23.	343.	79.	21.	0.	12.	0.	7590.	883.
233.	2.00	2000.	15	1.210	0.893	102.	0.	319.	23.	342.	78.	22.	0.	12.	0.	7587.	882.
233.	2.00	2000.	16	1.197	0.890	103.	0.	317.	23.	340.	78.	22.	0.	12.	0.	7586.	882.
233.	2.00	2000.	17	1.185	0.888	104.	0.	316.	23.	339.	78.	22.	0.	12.	0.	7587.	882.
233.	2.00	2000.	18	1.175	0.886	105.	0.	315.	24.	338.	77.	23.	0.	12.	0.	7590.	883.
233.	2.00	2000.	19	1.166	0.884	105.	0.	314.	24.	337.	77.	23.	0.	12.	0.	7594.	883.
349.	3.00	500.	1	1.500	1.199	0.	0.	128.	0.	128.	100.	0.	0.	0.	0.	1588.	185.
349.	3.00	500.	2	1.525	1.048	25.	0.	103.	6.	108.	84.	16.	0.	10.	0.	1523.	177.
349.	3.00	500.	3	1.295	1.036	30.	0.	101.	7.	108.	81.	19.	0.	11.	0.	1556.	181.
349.	3.00	500.	4	1.206	1.030	32.	0.	100.	7.	107.	79.	21.	0.	12.	0.	1576.	183.

TABLE II

TABLE III Exemple of influence of pressure of transport

Flow (GCal/sec)	Length (km)	Pressure (kg/cm^2)	Gas	Cost (Lit/MCal)	Number of sections
2	1000	40	H_2	.678	2
2	1000	65	H_2	.598	2
2	1000	90	H_2	.565	2
2	1000	40	CH_4	.499	7
2	1000	65	CH_4	.434	6
2	1000	90	CH_4	.401	6
(C.M./sec)				(Lit/C.M.)	
1000	1000	40	O_2	3.171	9
1000	1000	65	O_2	2.789	7
1000	1000	90	O_2	2.616	5

TABLE IV Comparison of costs for hydrogen and methane.

Flow of energy (Gcal/sec)	Total length (km)	Number of sections		Optimal distance between stations		Minimum costs (Lit/Mcal)		H_2/CH_4 transport costs	H_2/CH_4 capital costs	Compression ratio	
		H_2	CH_4	H_2	CH_4	H_2	CH_4			H_2	CH_4
1	1000	2	5	500	200	.715	.510	1.40	1.46	1.541	1.407
2	1000	2	6	500	167	.565	.401	1.41	1.46	1.447	1.274
3	1000	1	5	1000	200	.485	.350	1.38	1.61	1.500	1.298
4	1000	1	5	1000	200	.432	.317	1.36	1.58	1.500	1.274
1	2000	8	13	250	154	1.517	1.039	1.46	1.48	1.192	1.288
2	2000	7	15	285	133	1.208	.817	1.48	1.51	1.180	1.204
3	2000	2	16	1000	125	1.058	.712	1.48	1.59	1.737	1.169
4	2000	2	16	1000	125	.958	.646	1.48	1.59	1.683	1.156
.5	500	1	2	500	250	.403	.307	1.31	1.43	1.500	1.829

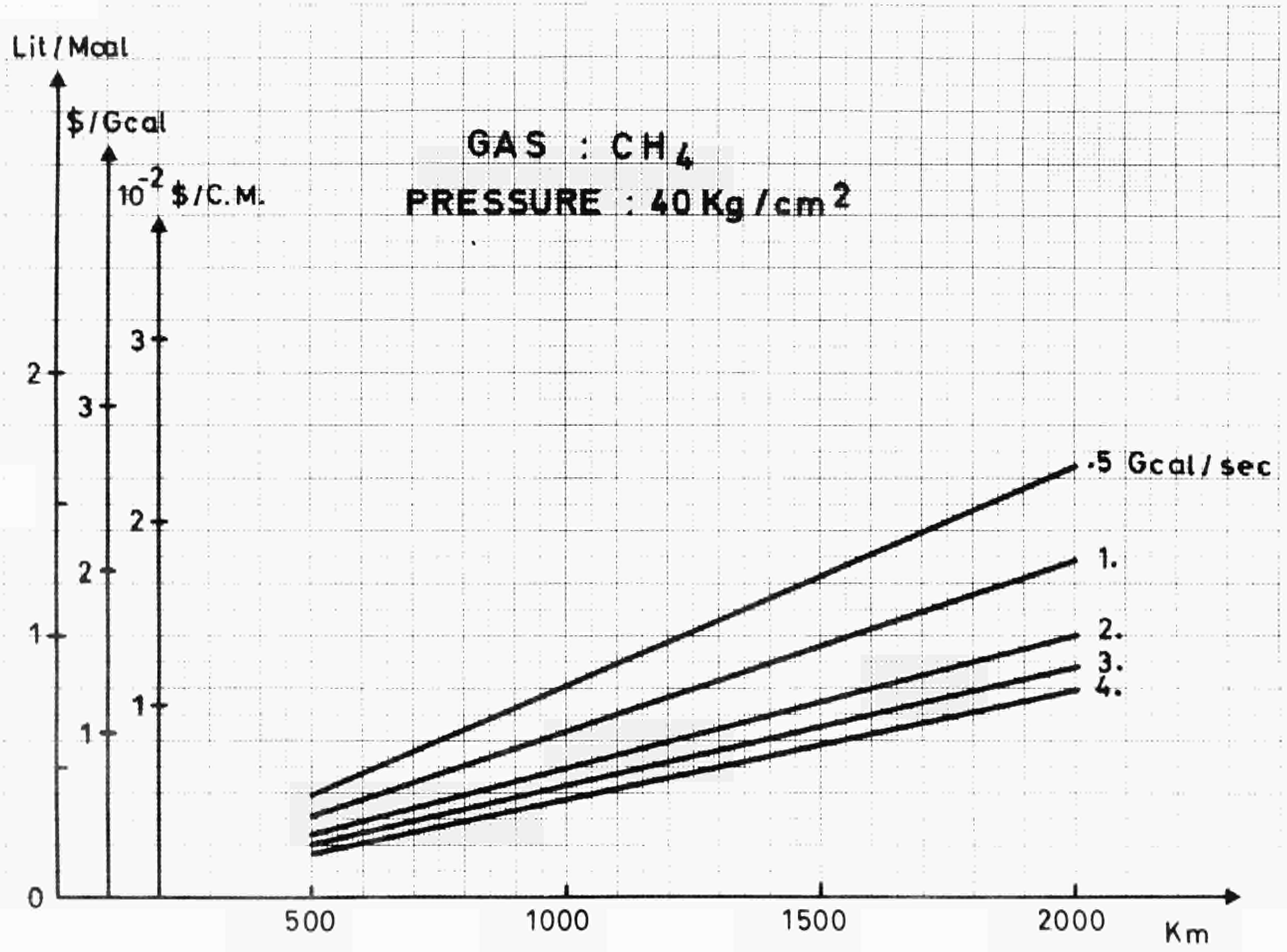

Fig. 1 a : Cost of CH_4 transport for different flows and distances, at three different pressures (1970 costs)

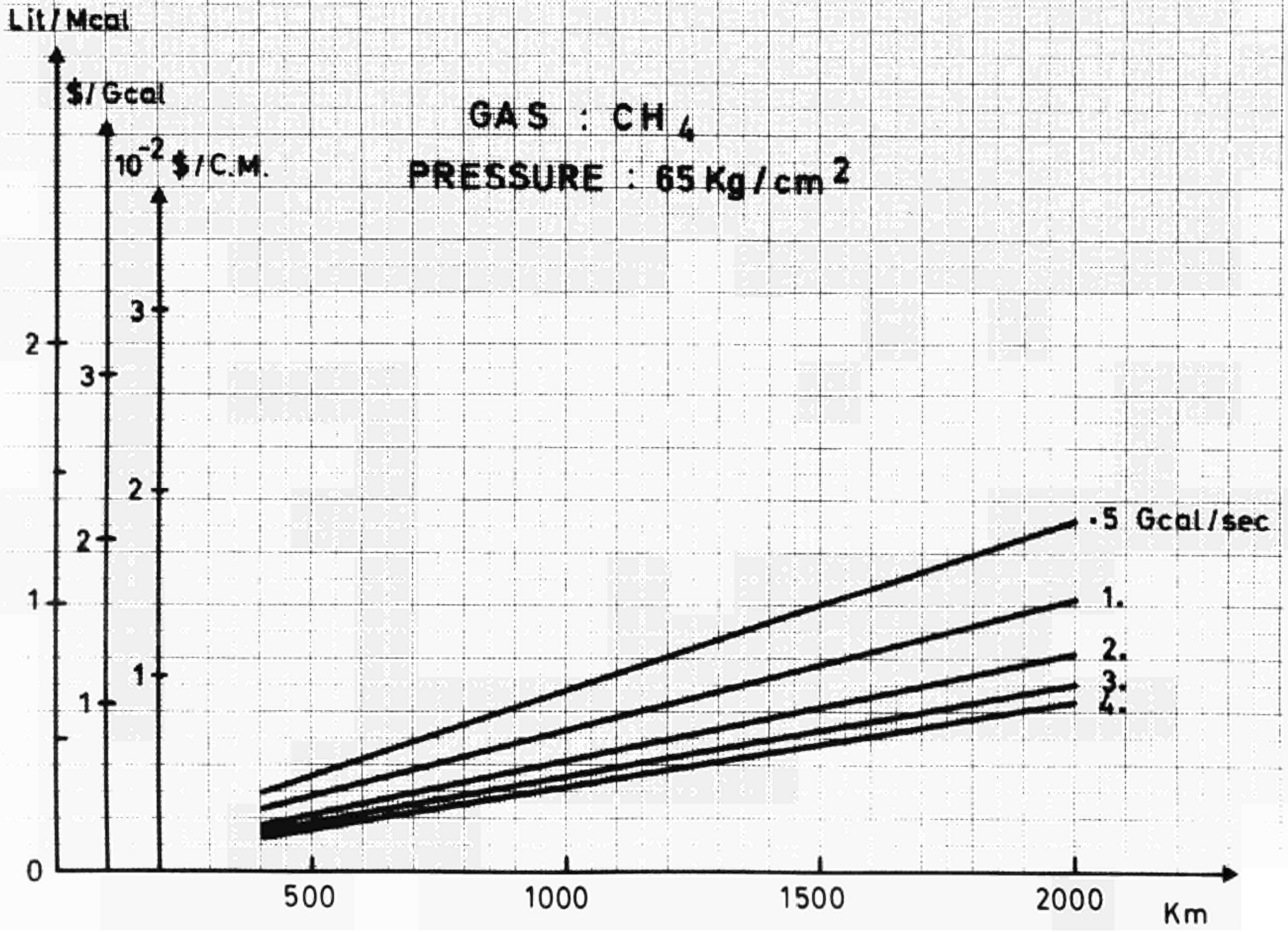

Fig. 1 b : Cost of CH_4 transport for different flows and distances, at three different pressures (1970 costs)

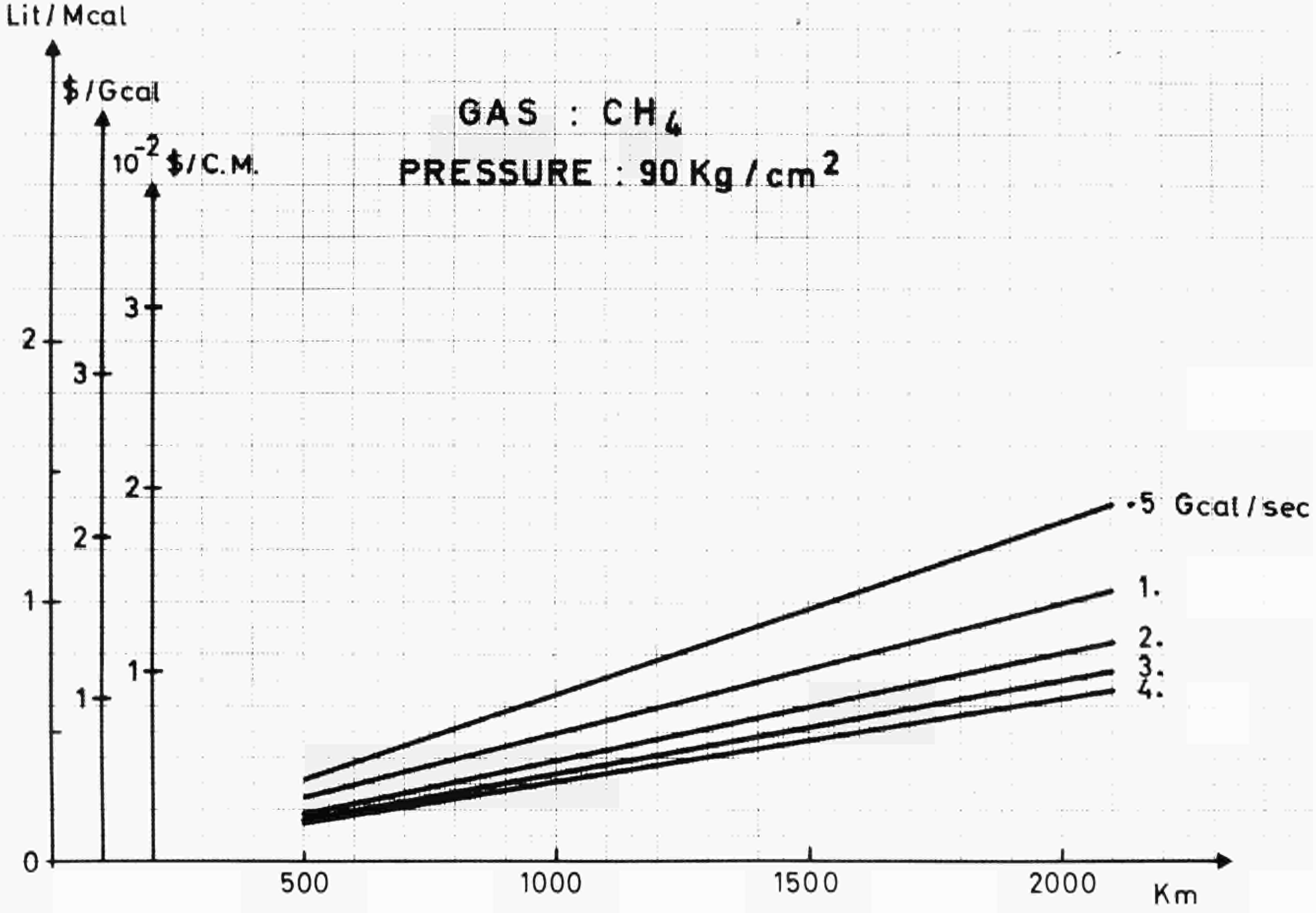

Fig. 1 c : Cost of CH$_4$ transport for different flows and distances, at three different pressures (1970 costs)

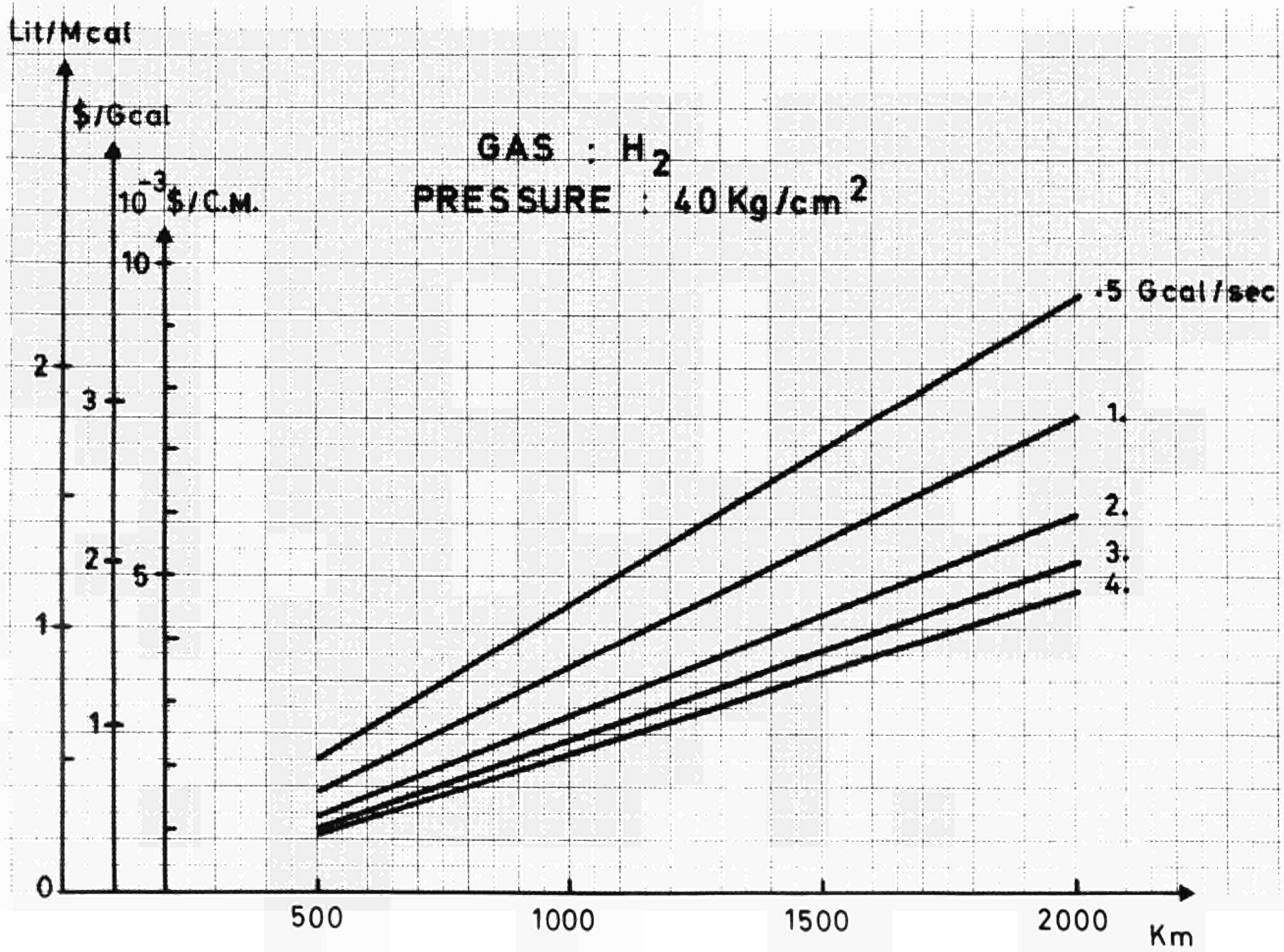

Fig. 2 a : Cost of H_2 transport for different flows and distances at three different pressures (1970 costs)

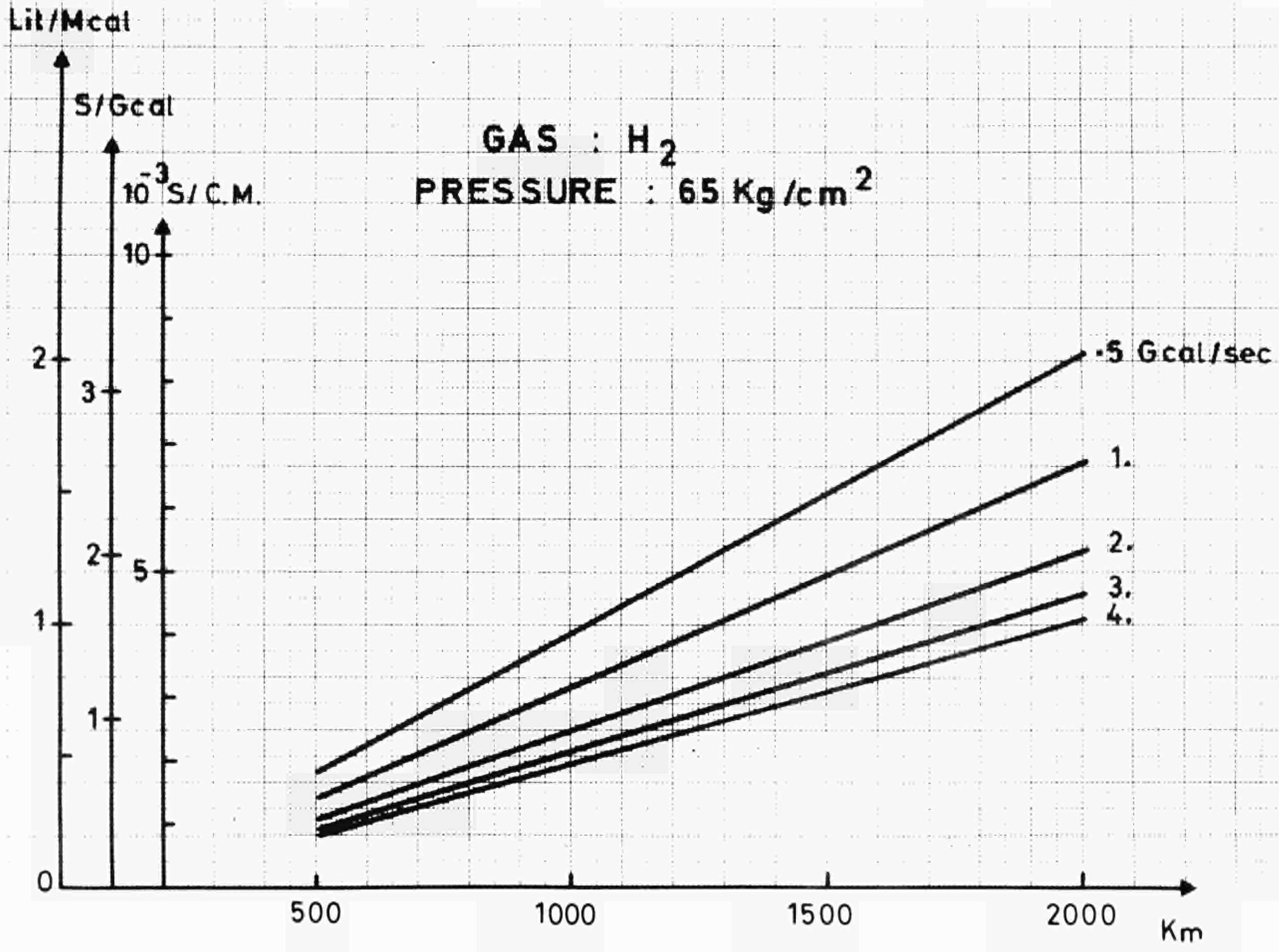

Fig. 2 b : Cost of H_2 transport for different flows and distances at three different pressures (1970 costs)

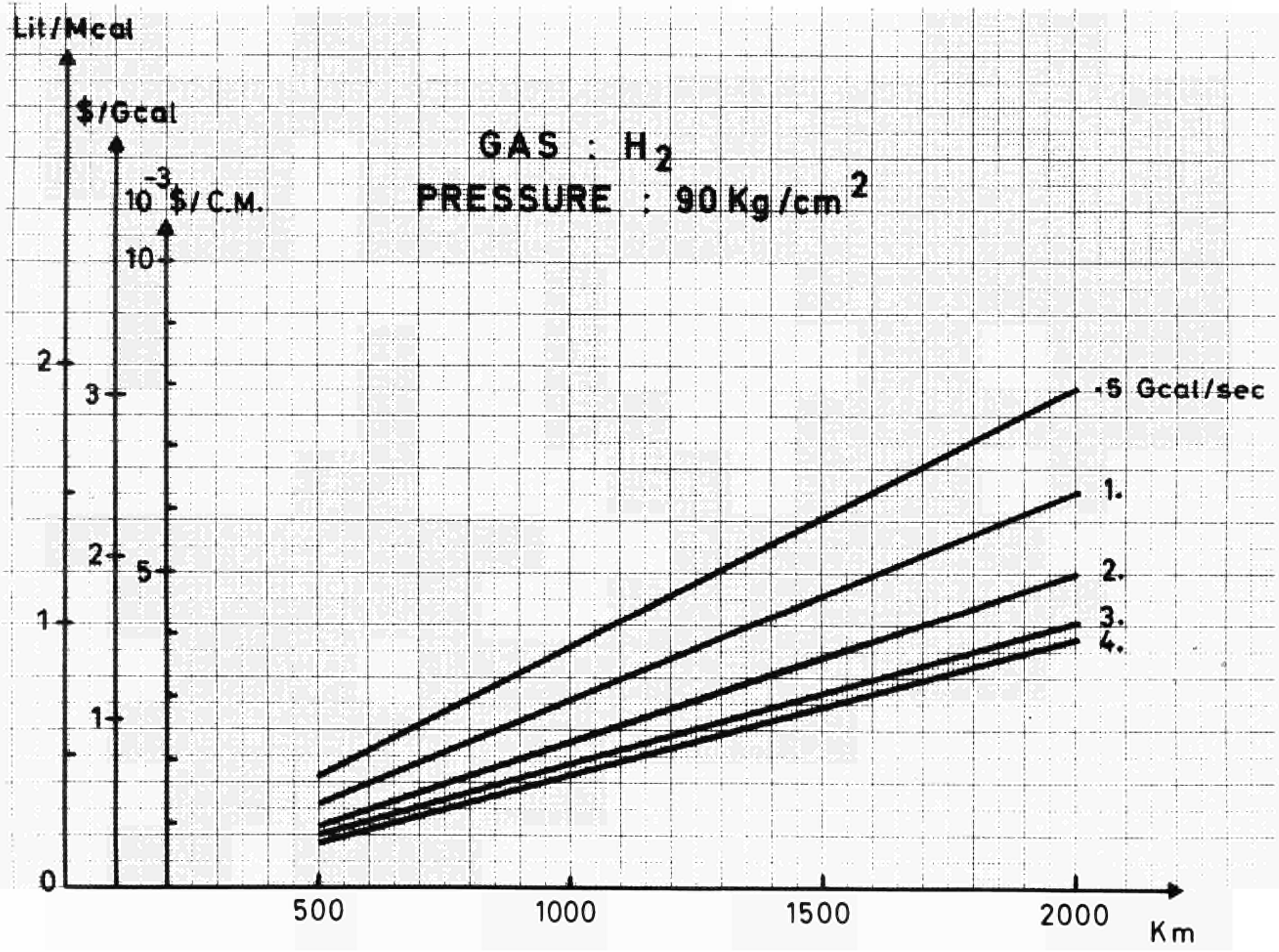

Fig. 2 c : Cost of H_2 transport for different flows and distances at three different pressures (1970 costs)

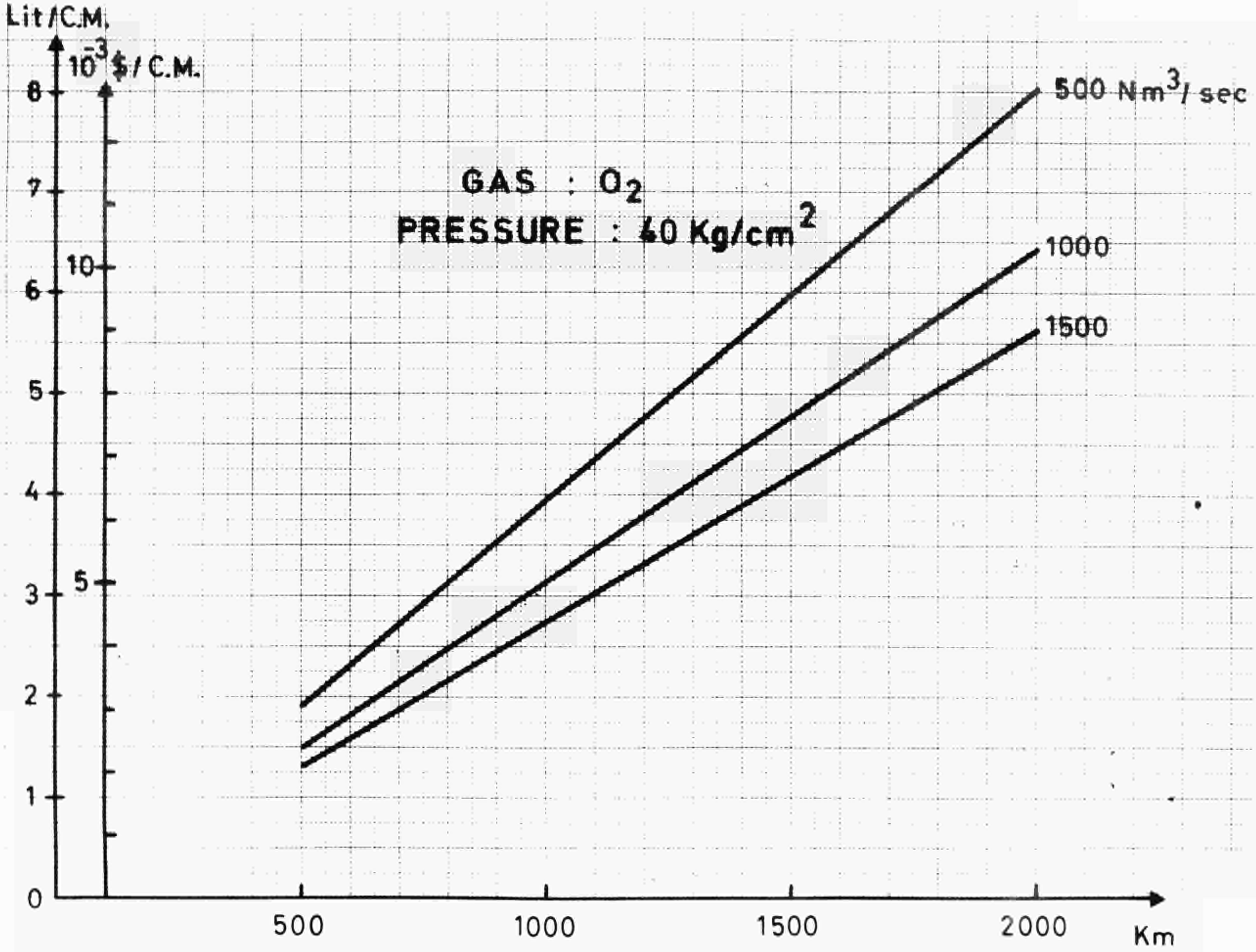

Fig. 3 a : Cost of O_2 transport for different flows and distances at three different pressures (1970 costs)

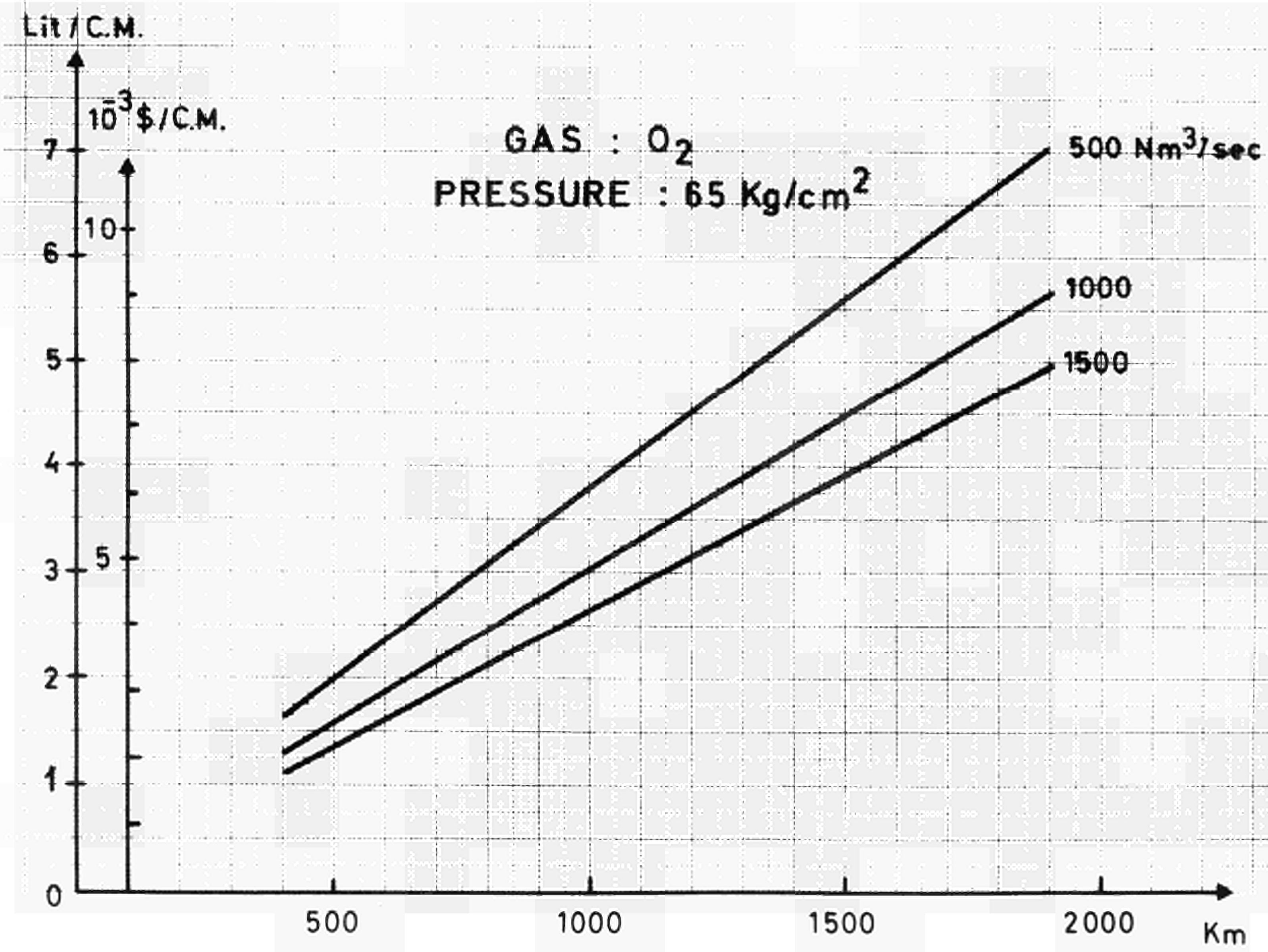

Fig. 3 b : Cost of O_2 transport for different flows and distances at three different pressures (1970 costs)

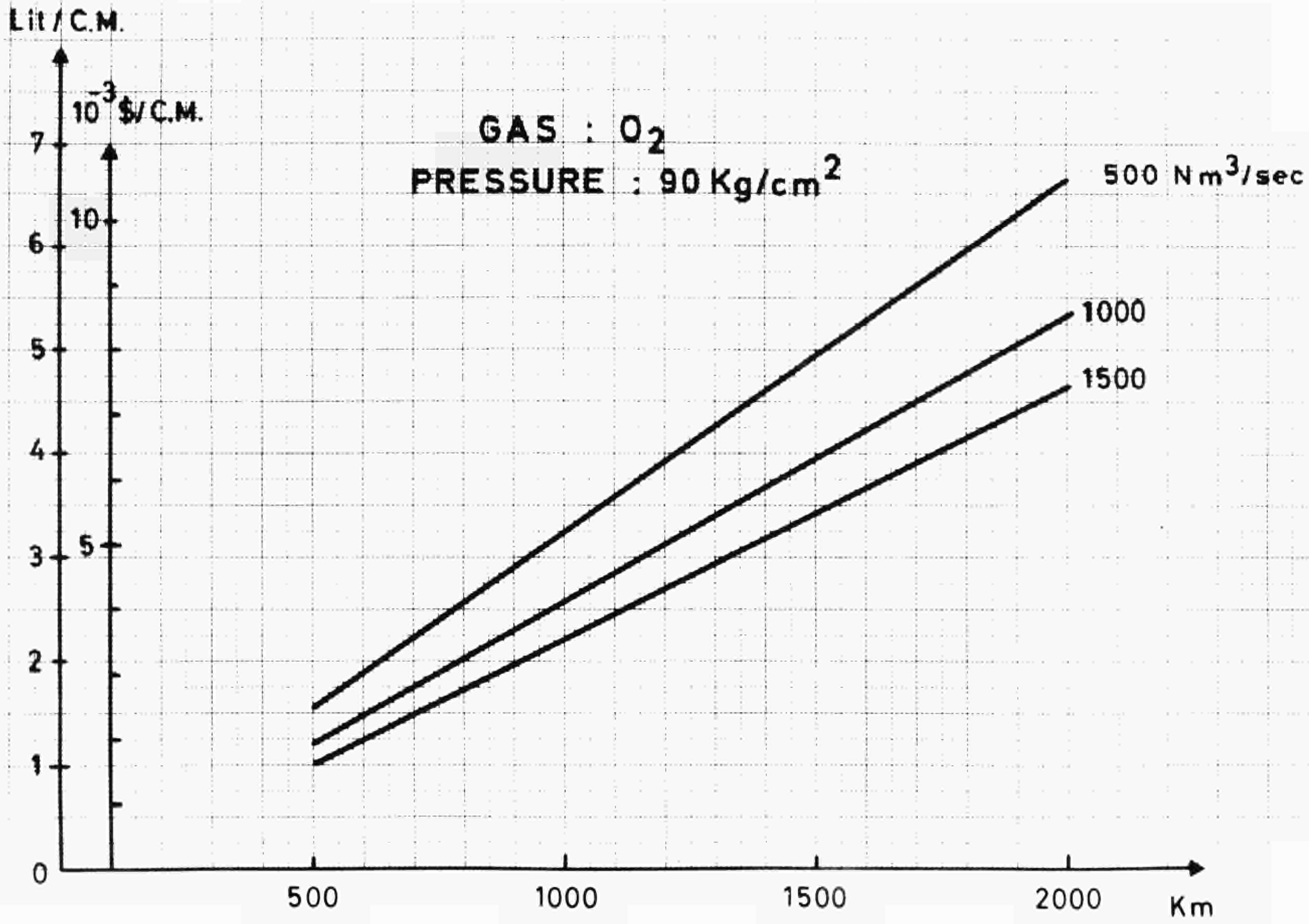

Fig. 3 c : Cost of O_2 transport for different flows and distances at three different pressures (1970 costs)

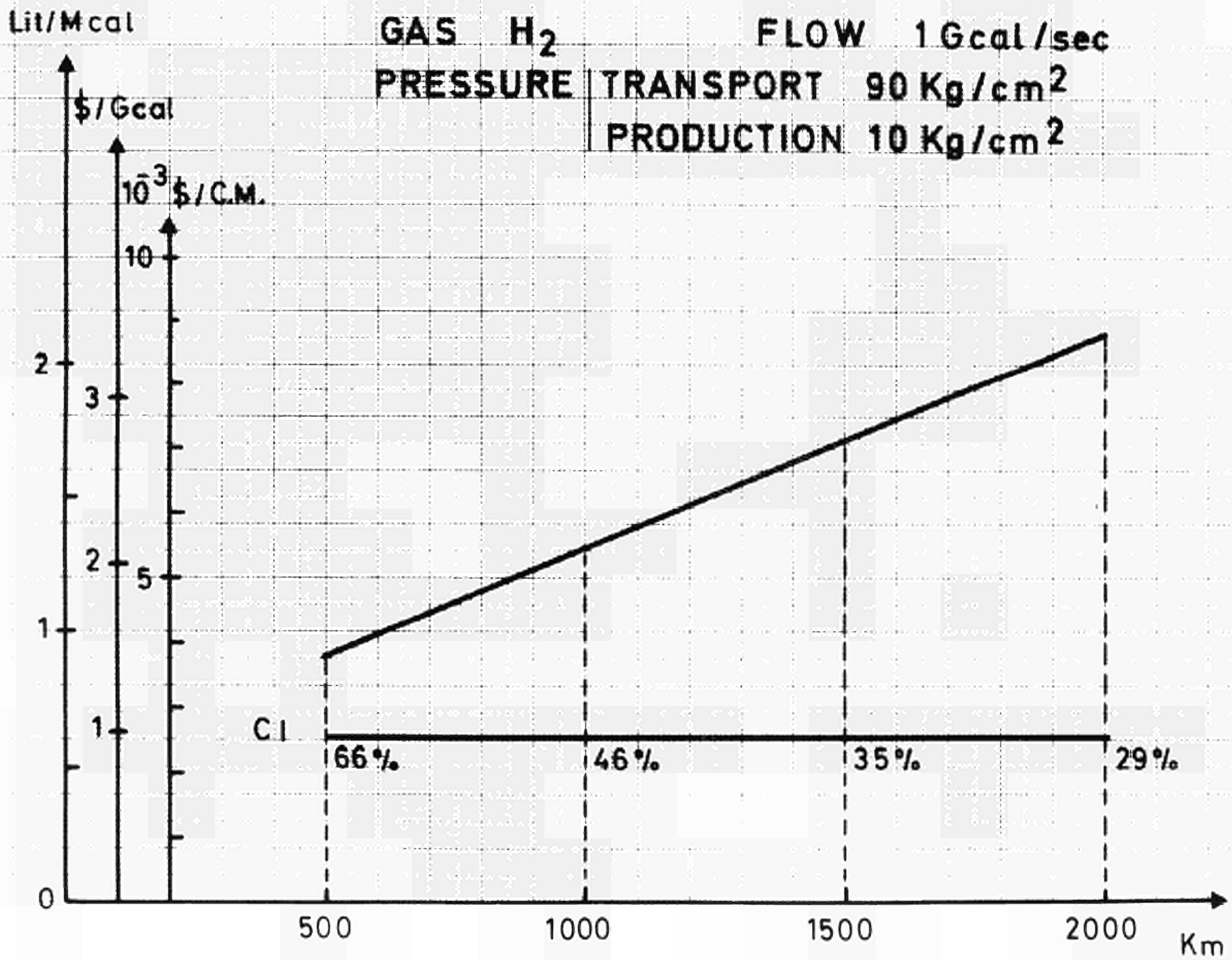

Fig. 4 a : Influence of an initial compression on transport cost (1970 costs)

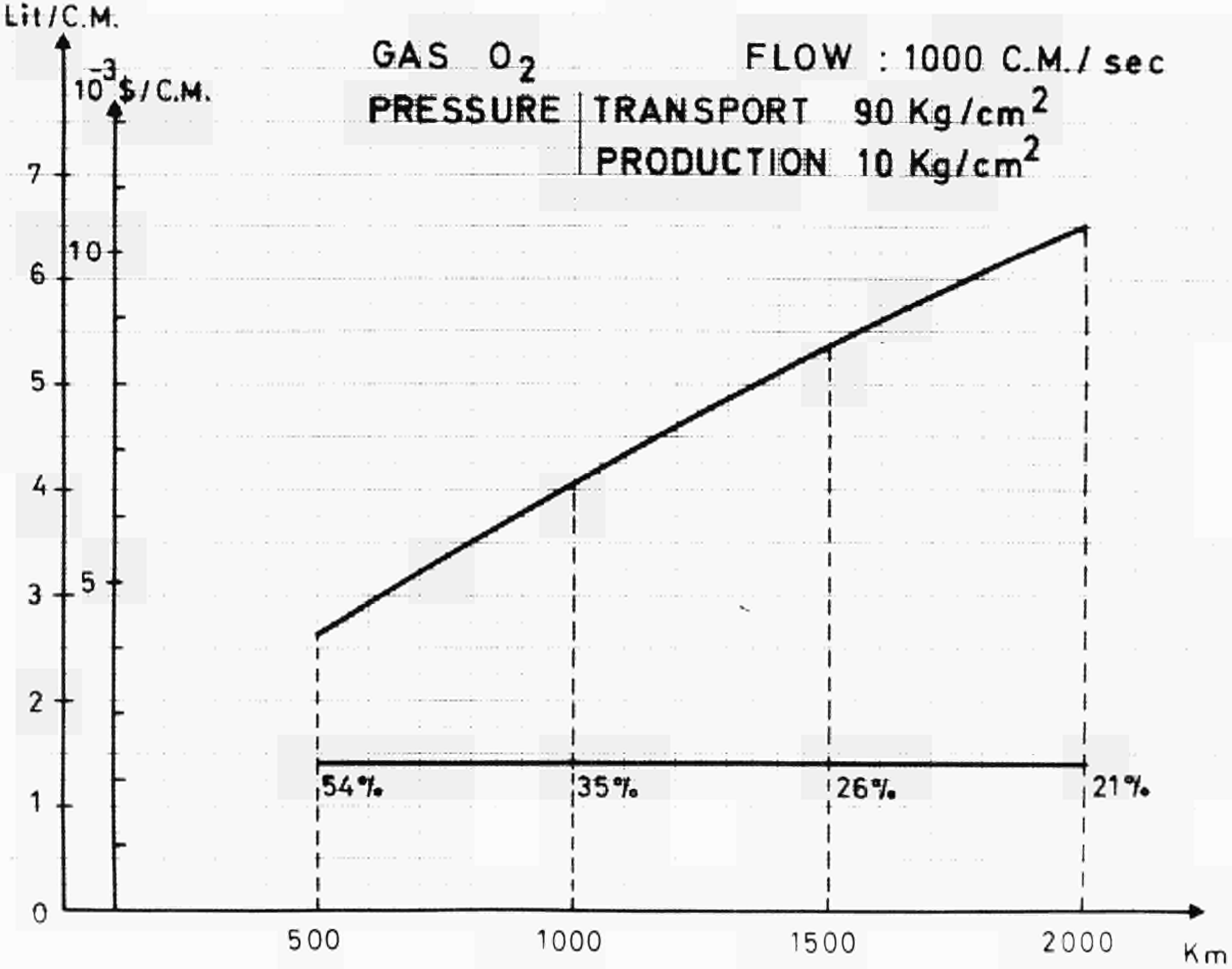

Fig. 4 b : Influence of an initial compression on transport cost (1970 costs)

To disseminate knowledge is to disseminate prosperity — I mean general prosperity and not individual riches — and with prosperity disappears the greater part of the evil which is our heritage from darker times.

Alfred Nobel

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