

***Critical Review of
"Life Cycle Assessment of Selected
Technologies for CO₂ Transport and
Sequestration"***
***Diploma Thesis No. 2007MS05 by
C. Wildbolz***

Commissioner

PAUL SCHERRER INSTITUT



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Introduction

The Diploma Thesis No. 2007MS05 by Caroline Wildbolz on "Life Cycle Assessment of Selected Technologies for CO₂ Transport and Sequestration" dated July 12, 2007 is reviewed, which comprises:

- verification of the calculations
- verification of the assumptions for average conditions in Europe
- verification of the key parameters
- editorial remarks to the text

Abridged review comments

The final report of the diploma thesis (MSWord) and calculations sheets (MSExcel) were provided for the review. This allowed for a thorough checking of the figures. The found mistakes are in part a result of a transparent documentation, and CW should be commended for that.

More review comments are included in the MSWord-File of the diploma thesis.

DS means 'dataset'. CW indicates Caroline Wildbolz; GD is Gabor Doka.

LCI Calculations

LCI exchanges of the following datasets were corrected:

Transport, pipeline, supercritical CO₂, w/o recompression

For an operation time of 30 years, with 7.9 Mt CO₂/yr and a distance of 200 km a lifetime transport service of 47'400 Million tkm results. Thus for a pipeline of 200 km a pipeline infrastructure of 200km/47'000 Million tkm = **4.21941E-09 km per functional unit of 1 tkm** is necessary. CW calculates $200 \text{ km} / (30\text{yr} * 7.9\text{E}6 \text{ tons} * 200 \text{ km}) * 1.5 = 6.34\text{E-}09 \text{ km}$. CW introduces a factor of 1.5. to account for a lifetime of 45, not 30 years (based on CW comment in calculation sheet). Lifetime according to the text is 30 years. Data was changed to correspond to 30 years, as written in the text.

Transport, pipeline, supercritical CO₂, w compression

I think this dataset should be based on a system with one recompression 80->110bar and a subsequent transport over 200km (not 400 km). The calculation procedures and usage of this dataset reveal that the latter was intended. The issue is not very clearly presented in the report. Functional unit is (correct) per tkm.

As above, also here a pipeline infrastructure of **4.21941E-09 km per tkm** (not 6.34E-09) should be inventoried.

Gas turbine infrastructure is calculated by CW in calculation sheets from a formula (I added units here) = $7.03 \text{ Jahre} / (6.4 \text{ Jahre} * 7884000 \text{ t CO}_2/\text{yr} * 200 \text{ km}) = 6.97\text{E-}10$ units per tkm. I cannot understand this formula. With a transport service of $7.9\text{E}6 \text{ t/yr} * 200 \text{ km} = 1'580$ Million tkm per year, this would mean that the compressors would have to be replaced every eleven months ($0.9 \text{ yr/unit} = 1 / (1.58\text{e}9 \text{ tkm/yr} * 6.97\text{E-}10 \text{ units/tkm})$)! This seems highly unlikely. Lifetime of gas turbines in (ecoinvent 2003) is 15 years. With such a lifetime we get $1 / (15 \text{ years} * 1'580 \text{ Million tkm/yr}) = \mathbf{4.22 \text{ E-}11 \text{ units per tkm}}$ pipeline transport (assuming 1 turbine per pipeline), i.e. a factor 15 smaller than what CW suggests.

Power for compression P is calculated by CW over a formula by Dialer

$$P = \Delta p \cdot \dot{V} \cdot \frac{1}{\eta} \quad \eta = \frac{P_{ideal}}{P_{real}}$$

CW uses the pressure increase (30 bar = 3MPa), a volume flux 0.56 m³/sec (based on an average density of 446 kg/s) and an pump efficiency of 85%. Unfortunately the formula is rather doubtful. The volume flux is not constant, but changes during compression. So the formula should probably be integrated over small Δp . The formula is also not specific to CO₂ compression, but seems generic for any gas. Finally the efficiency of (electrical power -> mechanical power -> volumetric power) of 85 % seems high.

In (Hendriks et al. 2004) a more realistic formula is given, which is based on mass flow, is for compression of supercritical CO₂, and is based on energy demand of real pumps (by Sulzer for the year 1999). Hendriks confirms by mail that the formula is still appropriate for current CO₂ compression (cf. appendix).

$$E = 87.85 \text{ kJ/kg} \cdot \ln\left(\frac{P_{out}}{P_{in}}\right) \cdot F$$

where

E electricity demand [kJe/s]

P_{out} output pressure [Pa]

P_{in} input pressure [Pa]

F CO₂ flow [kg/s]

For a pressure increase from 80 bar to 110 bar, 250 kg CO₂/s (7.9 Mt/yr), an energy demand of 7 MW (=MJ/sec) is necessary. That is 0.028 MJe per kg CO₂ and (for one recompression over 200km) **0.0389 kWh/tkm**. This is a factor 3.5 larger than what CW calculates. This is a very relevant contribution for transport.

btw. the Dialer formula would have yielded approximately realistic results, if η were chosen to be 24%.

well double, aquifer, 2030

In the text CW writes that land use transformation is 'from unknown'; the inventory lists 'from pasture and meadow'. Correction to the choice declared in the report has only very minor consequences in EI99HA.

well double, depleted gas field

Side note: The name of DS should include year to be consistent with 'well double, aquifer, 2030'.

Drilling, deep borehole for HDR, 2030

Imported from other work, not checked

Storage, CO₂, aquifer, 200 km pipeline

As in pipeline transport, CW uses the debatable Dialer formula. Additionally, CW calculates a MJ per t CO₂ figure and then mistakenly doubles it, because she has two wells (which is irrelevant, when a per mass figure is attained).

With the Sulzer formula by (Hendriks et al. 2004) again larger energy demands for injection result. For a pipeline pressure of 80 bar and injection pressure of 108.4 bar (for saline aquifer) an electricity demand of **0.0371 kWh/kg CO₂** results. This is a factor 5.5 larger than what CW calculates. This is a very relevant contribution for storage. This figure also applies to 'Storage, CO₂, aquifer, 400 km pipeline'.

All four 'storage...' DS need compression. The *infrastructure* for compression is approximated with a gas turbine. CW calculates = $(45/6.4 \text{ Jahre}) / 7884000 \text{ tCO}_2/\text{a} / 1000 = 8.92\text{E-}10$ units/kg. Again, I do not understand that formula. With 7884 million kilograms CO₂ per year and site, this would mean that the compressors would have to be replaced every two months ($0.14 \text{ yr/unit} = 1 / (7.884\text{E}9 \text{ kg/yr} * 8.92\text{E-}10 \text{ units/kg})$)! Again simply assuming 15 years lifetime for compressors we get $1/(15 \text{ years} * 7.884\text{E}9 \text{ kg/yr}) = \mathbf{8.44\text{E-}12 \text{ units per kg CO}_2 \text{ storage}}$; i.e. a factor 100 smaller than what CW suggests. This figure applies to all 'storage...' DS. With the correct figure compression infrastructure returns to the common realms of negligibility, while in CW's results it attained an unusually prominent ranking of up to 15% LCIA contribution.

Also, all four 'storage...' DS refer to the datasets 'well double,...' (unit) which actually contain the drilling of the wells (2 wells per site plus one monitoring well) and the drilling site infrastructure. The well's lifetime in CW report is 15 years.

CW calculates

$$= 3 / (250 \text{ kg CO}_2/\text{s} * 3600\text{s/h} * 24 \text{ h/day} * 365 \text{ days/yr} * 15 \text{ yr})$$

which includes a factor 3 apparently in order to assess 6 wells, instead of 2. In the text however 2 wells per site are specified and justified (*"Under the constraint of data availability the number of wells is only assumed over the selected injection rate of 125 kg CO₂ per second and well"* cf. 'Number of Wells' in Section 4.3.3), although imho a rather large injection rate of 125 kg CO₂ per second and well was chosen, which seems rather large compared to the values of table 17. This is a minor issue for the final result, but it would be good if it were resolved clearly (why 2 wells, not e.g. 4? Or why 125 kg/s per well, not 63?).

After some discussion with the supervisor Roberto Dones 2 wells per site were maintained, but the lifetime of wells was reduced from 15 years to 12 years. For the corrected request of 'well double,...' (which contain 2 wells) I thus calculate $1/(12 \text{ years} * 7.884\text{E}9 \text{ kg/yr}) = 1.057\text{E}-11$ **units per kg CO₂ storage**, i.e. for 2 wells per injection site and 125 kg CO₂ per second and well according to the current text. This figure applies to all 'storage...' DS. Reducing the lifetime of wells also affects the land occupation exchanges in the "wells,..." datasets above from 900 + 8100 m²a to 720 + 6480 m²a industrial area resp. industrial area, vegetation.

Storage, CO₂, aquifer, 400 km pipeline

Corrected electricity demand for injection, see above.

Corrected infrastructure for compression, see above.

Corrected well infrastructure, see above.

Storage, CO₂, depleted gas field, 200 km pipeline

With the Sulzer formula by (Hendriks et al. 2004) larger energy demands for injection result. For a pipeline pressure of 80 bar and injection pressure of 201.5 bar (for depleted gas field) an electricity demand of **0.1127 kWh/kg CO₂** results. This is a factor 4 larger than what CW calculates. This is a very relevant contribution for storage. This figure also applies to 'Storage, CO₂, depleted gas field, 400 km pipeline'.

Corrected infrastructure for compression, see above.

Corrected well infrastructure, see above.

Storage, CO₂, depleted gas field, 400 km pipeline

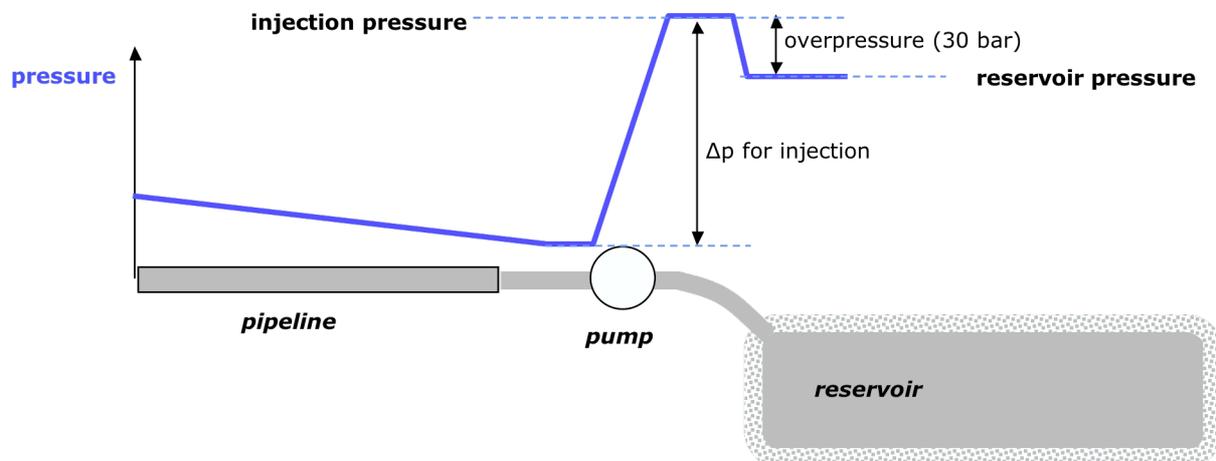
Corrected electricity demand for injection, see above.

Corrected infrastructure for compression, see above.

Corrected well infrastructure, see above.

Reservoir pressure and overpressure for storage

A diagram like this would help to understand the various pressures:



CO₂ density and pressure drop

Density of CO₂ is an important issue as it has consequences for the transport speed in the pipeline, for transport friction, for pressure drop and ultimately for the energy needed for recompression, which is the dominant variable for pipeline transport.

CW uses values from VDI for three different stages of the pipeline transport:

Case	Temperature	Pressure	Density
Unit	°C	bar	kg/m ³
Inlet condition	50	110	447.5
mean condition	45	95	446
outlet condition	40	80	277.9

The development of the temperature decrease is determined by the insulation and the degree of variation can effectively be chosen more or less freely. The pressure and density are mutually dependent over the formulas presented in CW's Equation 3. Density depends on prevailing temperature and pressure; pressure drop over the pipeline varies with the density and the velocity (all other parameters are assumed to be constant).

$$\Delta p = \lambda \frac{L}{D_i} \cdot \rho \cdot \frac{v^2}{2}$$

CW calculates the pressure drop using the *inlet* density ($\rho = 447.5 \text{ kg/m}^3$) but uses a velocity (2.1 m/s) which is based on the *average* density of 445.925, which seems conceptually inconsistent¹ (but numerically uncritical). Using only *average* values for equation 3 however would presume that velocity, density and pressure develop in a linear fashion over pipeline length, but this is not so.

Furthermore the density values used by CW are faulty. The initial value of 447.5 kg/m^3 for $50^\circ/110 \text{ bar}$ is a linear interpolation from VDI's values of 384.4 at 100 bar and 699.8 at 150 bar for the 50° isothermal line. Unfortunately the isothermal line is far from linear in the range 100-150 bar. More detailed data is available in Mollier diagrams (Enthalpy-pressure diagrams). For example from http://www.chemicallogic.com/download/co2_mollier_chart_met.pdf (also reproduced in IPCC 2005:388) and http://www.hs-karlsruhe.de/servlet/PB/show/1017452_11/fbm_R744.jpg (for CO_2 as a coolant = R744). Both diagrams are reproduced in the appendix. Please note the logarithmic scale for pressure (y-axis).

It is not clear from the text which roughness number λ CW finally uses for Equation 3. The calculation sheets make clear that she calculated the pressure drops like in table 9 for *various* steel roughness numbers and determined from that, that 30 bars pressure drop is an appropriate value. It should be stated clearly that the roughness number is initially unknown, and that a mean average pressure drop of 30 bars is derived from table 9. 30 bars is then consistent with a roughness number of 0.008158.

The Mollier diagrams suggest densities at $50^\circ/110 \text{ bar}$ of 585 kg/m^3 , not 447.5. At that density (and inner diameter $D_i = 0.573 \text{ m}$ and $M = 7.9\text{E}9 \text{ kgCO}_2/\text{yr}$) initial transport velocity is 1.66 m/s. The specific pressure drop *per meter* according to Equation 3 (with roughness number λ of 0.008158) is then 11.50 Pa/m (1.15 bar over 10 km). In a simple numerical integration the development of density, velocity and pressure is determined:

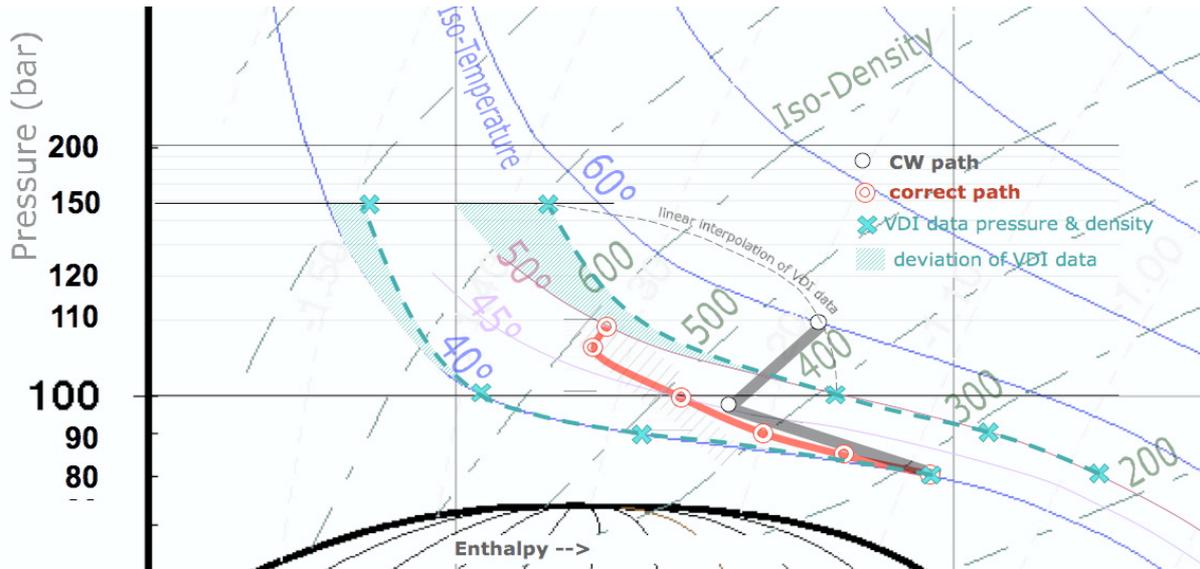
¹ In table 18 for injection compression the outlet density (228 kg/m^3) is used.

L	T	p	ρ	v	Δp
transport distance km	temperature T °C <i>linear decrease</i>	pressure p at the start of the 10km segment bar $p_{n+1} = p_n - \Delta p_n$	average density in 10km segment kg/m ³ <i>from Mollier Diagram = f(T,p)</i>	speed in 10km segment m/s $v_n = \frac{M}{\rho_n \cdot (D_i/2)^2 \cdot \pi}$	Pressure drop over last 10km segment bar $\Delta p_n = \lambda \frac{\partial L_n}{D_i} \cdot \rho_n \cdot \frac{v_n^2}{2}$
0	50	110	585.0	1.659	-
10	49.5	108.85	583.6	1.663	1.15
20	49	107.70	582.2	1.667	1.15
30	48.5	106.54	580.8	1.671	1.16
40	48	105.39	579.4	1.676	1.16
50	47.5	104.22	578.0	1.680	1.16
60	47	103.04	565.3	1.717	1.19
70	46.5	101.82	552.7	1.757	1.21
80	46	100.58	540.0	1.798	1.24
90	45.5	99.27	512.5	1.894	1.31
100	45	97.89	485.0	2.002	1.38
110	44.5	96.47	473.0	2.052	1.42
120	44	95.02	461.0	2.106	1.46
130	43.5	93.52	449.0	2.162	1.49
140	43	91.99	437.0	2.221	1.54
150	42.5	90.41	425.0	2.284	1.58
160	42	88.71	395.0	2.458	1.70
170	41.5	86.87	365.0	2.660	1.84
180	41	84.87	335.0	2.898	2.00
190	40.5	82.67	305.0	3.183	2.20
200	40	80.23	275.0	3.530	2.44
Total					29.77 over 200 km

Towards the end of the pipeline velocity and pressure drop per meter increase progressively and non-linearly, while density decreases. Over 200 km a total pressure drop of 30 bars (29.77) results. So the values derived by CW are correct, but for the wrong reasons, especially data for density needs to be corrected in the text.

The correct path in the Mollier diagram is depicted below in red. The path suggested by CW (initial, middle, outlet) defined from (pressure, density)-pairs is shown in grey. VDI data points are shown as turquoise crosses (lines are manual interpolations) and it is apparent that for higher pressures >100 bar there is some deviation between the VDI data and the Mollier diagrams. Starting out with a smaller initial density, as suggested by VDI data, e.g. 550 kg/m³ changes the overall pressure drop to 30.70 bar over 200 km, so this deviation is not very significant.

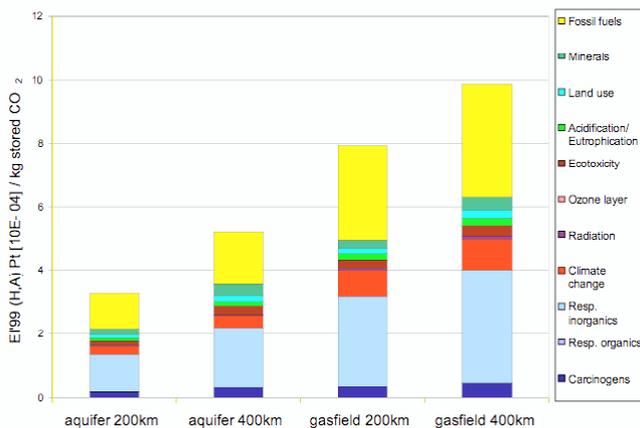
A pressure drop of 30 bar can be confirmed to be appropriate for the chosen values of mass flux, inner diameter, temperature and steel pipe roughness.



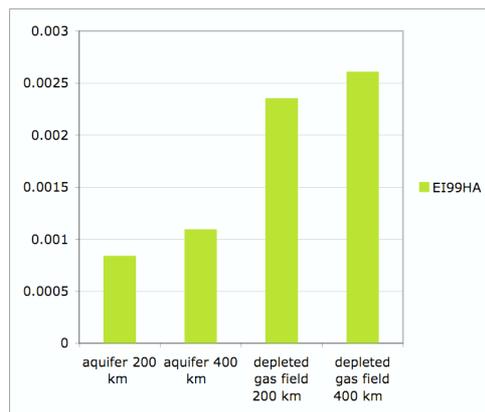
Results

These changes affect the results substantially. For EI99 the results are a factor 2 to 3 higher than originally devised. Also there is a clearer distinction between aquifer storage and depleted gas field storage. Overall burden for all four options is dominated by electricity use. Thus the result figures look very similar for GWP100a and UBP'97.

Results in Wildbolz:



Corrected results:



Appendix

E mail by Chris Hendriks, ECOFYS, Netherlands, July 31, 2007

Subject: **RE: Reference to compressor energy requirement**
Date: Tue, 31 Jul 2007 09:25:03 +0200
From: "Chris Hendriks" C.Hendriks@ecofys.nl

Dear Gabor,

Compression energy is approximately linear to the ln of the pressure quotient. This is more or less confirmed by the data given by Sulzer (only in the high pressure range there is some small deviation. As a good approximation the formula (1) can be used therefore. I believe, that the values (constants) are still quite a good approximation.

You are right that the reference to Sulzer is missing. This were calculation which they have specifically done for us (thus private communication). The results are summarized in table 7.

It should be noted that also other compression strategies can be applied. E.g first liquefaction and then pumping. In the case of CO₂, this does not make much differences in terms of energy use.

Best wishes,
Chris

Chris Hendriks
Ecofys bv
T: +31 (0)30 280 83 93

-----Original Message-----

From: Gabor Doka [mailto:gabor@doka.ch]
Sent: maandag, juli 30, 2007 18:40
To: Chris Hendriks
Subject: Reference to compressor energy requirement

Good day Chris Hendriks,

In your 2004 publication "GLOBAL CARBON DIOXIDE STORAGE POTENTIAL AND COSTS "
<http://www.ecofys.com/com/publications/documents/GlobalCarbonDioxideStorage.pdf>
you calculate the electricity use for compressors in CO₂ transport.

Formula (1) on page 10.

A reference for the formula is not indicated, but I assume it is (Sulzer 1999) as in Table 10.

However, Sulzer 1999 is not listed in the references.

I tried to locate a reference, but did not succeed.

Could you please

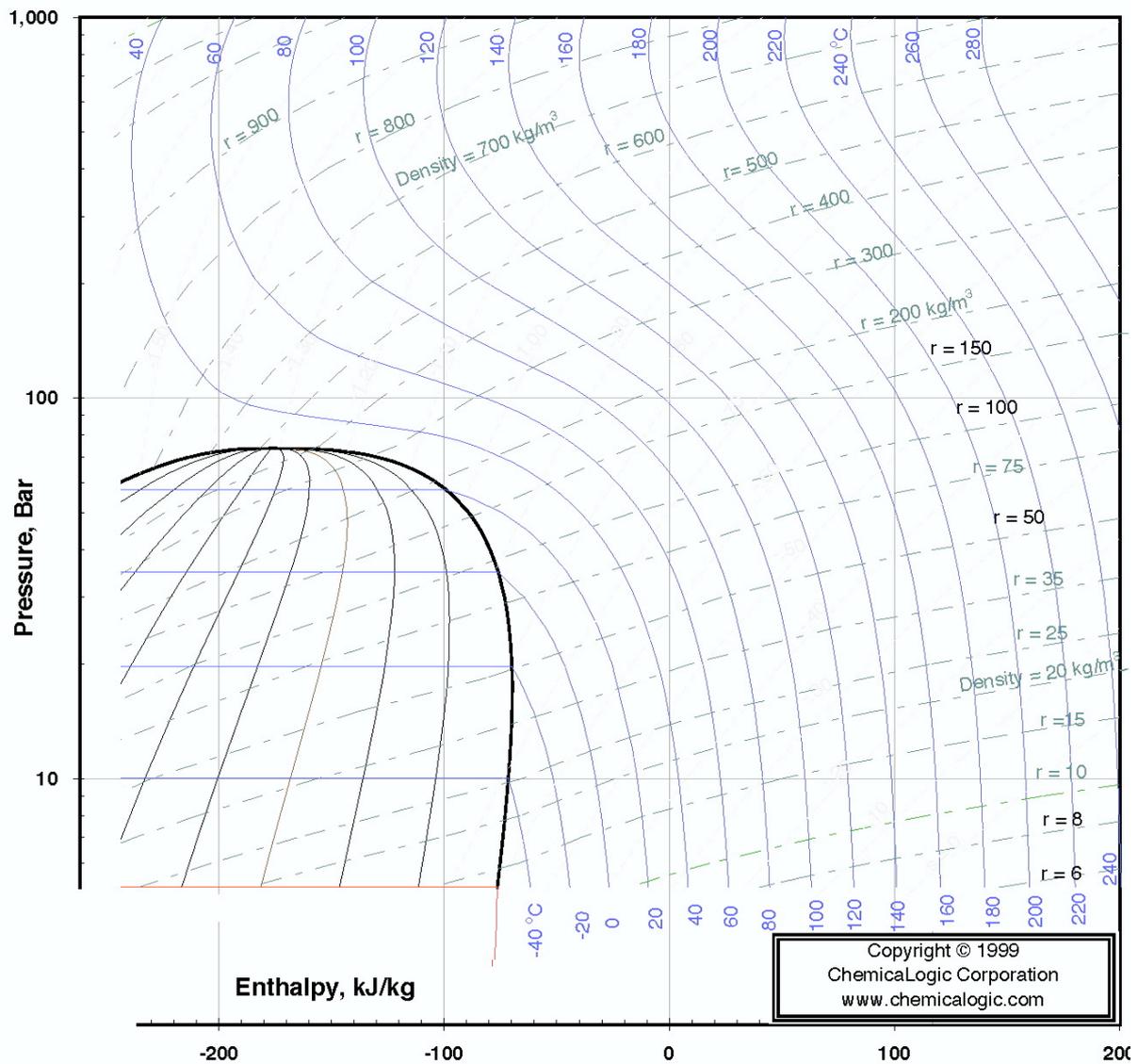
- indicate the source for the formula (1)?
 - maybe comment on the formula (is it still appropriate/ a good average?)
- Are there other sources for similar formulas?)

Thank you for any reactions on this,

Gabor Doka

Mollier diagrams for CO₂

from http://www.chemicallogic.com/download/co2_mollier_chart_met.pdf



from http://www.hs-karlsruhe.de/servlet/PB/show/1017452_l1/fbm_R744.jpg



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- Hendriks et al. 2004 Hendriks C., Graus W., van Bergen F. (2004) Global Carbon Dioxide Storage Potential And Costs. ECOFYS and TNO, Netherlands. Download of July 26, 2007 from <http://www.ecofys.com/com/publications/documents/GlobalCarbonDioxideStorage.pdf>