AESB3342 Extractive Metallurgy and Physical Processing

July 1, 2016

Time: 9:00 – 12:00
Location: CTBM- IZ B and C

This examination contains questions with total of 50 points for extractive metallurgy of the course (including the phase diagrams question). The 50 points are sub-dived into two parts: 40 points from this written exam and the rest of 10 points is accounted for by the excursion to and guest lectures at Tata Steel in IJmuiden.

Put your name and student number on EVERY sheet of paper you hand in!!

Please write down your answers clearly to assist the reading and evaluation.
N.B.: Illegible answers are considered to be wrong answers!!

Exam Questions for Extractive metallurgy

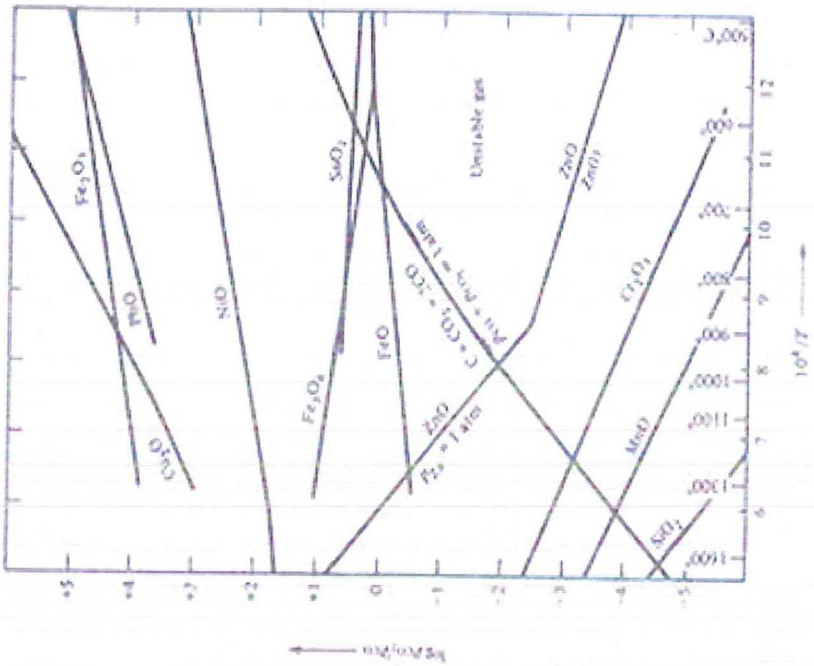
Questions Y. Yang – please answer on (a) separate sheet(s)

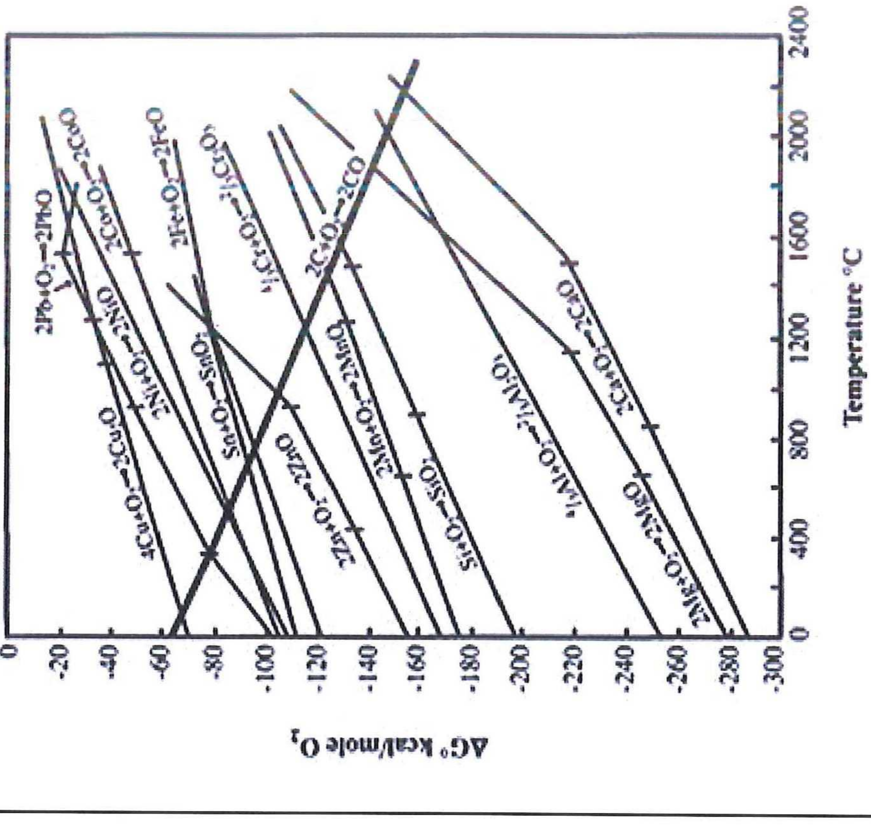
EM1: General questions *(10 points)*

(5 points for each sub-question)

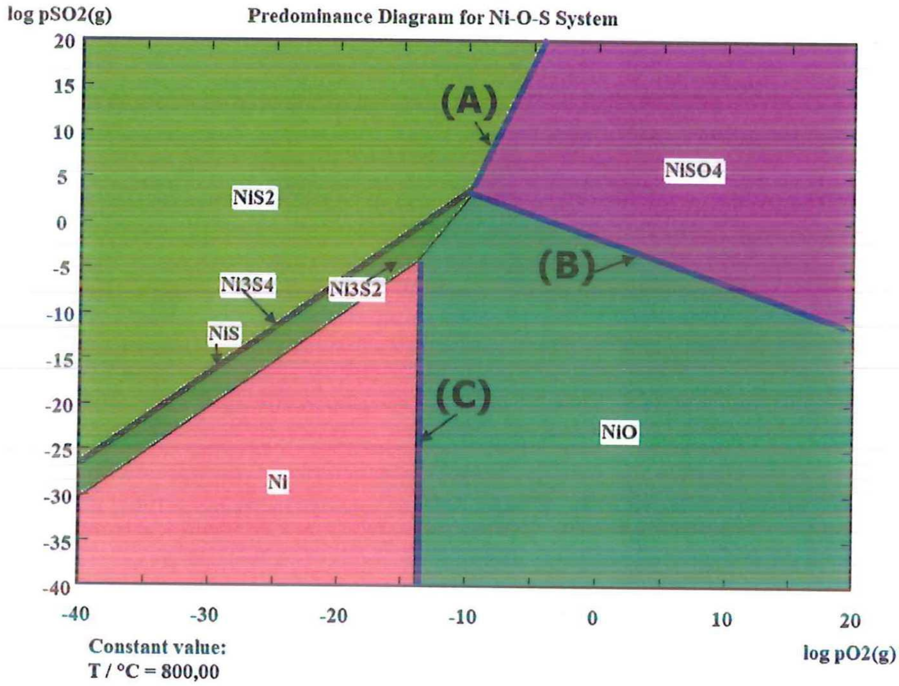
(1-1) Please write down the reduction reactions of metal oxides SnO_2 and Cr_2O_3 by using **carbon**. What is the **Boudouard** reaction, and what role it plays in the carbothermic reduction of these metal oxides?

Use the Ellingham diagrams (see next page) to determine the minimum reduction temperature of SnO_2 and Cr_2O_3 by using carbon (left graph) and the approximate equilibrium partial pressure ratio of log(pCO_2/pCO) (right graph).




ΔG° kcal/mole O2
Temperature °C

(1-2) What is the Kellogg diagram? Where and how it is used in the evaluation of metallurgical processes. Please write down the chemical reactions along the border lines (A), (B), and (C) shown below:



Kellogg diagram of Ni-S-O system at 800°C
(calculated with HSC Chemistry 6.0)

EM2: Metal production processes *(20 points)*

(2-1) Blast furnace ironmaking (5 points)

Please describe the working principles of ironmaking blast furnaces. Please include at least the following aspects:

- Raw materials and their preparations (including pelletizing, sintering and coke making)
- Main chemical reactions (all possible reactions) at different zones
- Products of the process and their compositions (major and minor elements or compounds)
- The roles of metallurgical coke, and how coke is made

(2-2) Steelmaking (5 points): Please describe how crude (carbon) steel is produced with BOF steelmaking process. Please include at least the following aspects:

- The main objectives of steelmaking processes

- Raw materials and their roles/function, and the main products
- Chemical reactions for removal of the major impurities (carbon, silicon, sulphur and phosphorus)

(2-3) **Aluminium production (5 points):** How many steps are needed to produce Al metal from bauxite ore? Please explain the technologies used currently in industry (Bayer process and Hall-Héroult-process with key chemical reactions)? Please explain why we DO NOT use carbothermic reduction to produce Al metal from bauxite ore (like in blast furnace ironmaking)?

(2-4) **Zinc production (5 points):** Please describe the complete flowsheet of hydrometallurgical zinc production from zinc sulphide concentrates to pure zinc metal. Please explain the metallurgical principles and the main chemical reactions for each main steps (roasting, leaching, solution purification, eelctrowinning)?

EM 3: Metallurgical thermodynamics *(10 points)*

(3-1) **Thermodynamic evaluation of copper converting process (5 points)**

- What are the objectives of copper converting, why it is divided into 2-stage process, and what two stages are they? *(2 point)*
- Copper converting is carried out at about 1200°C in two steps: slag-making and copper-making. Oxidations of FeS and Cu_2S are two major competing reactions (see below). The standard Gibbs energy change for reactions (1) and (2) are given below.

$$\tfrac{2}{3} Cu_2S_{(l)} + O_2 = \tfrac{2}{3} Cu_2O_{(l)} + \tfrac{2}{3} SO_2 \qquad (1)$$

$$\Delta G^o_{(1)} = -256898 + 81.17T \qquad (J/mole\ O_2)$$

$$\tfrac{2}{3} FeS_{(l)} + O_2 = \tfrac{2}{3} FeO_{(l)} + \tfrac{2}{3} SO_2 \qquad (2)$$

$$\Delta G^o_{(2)} = -303340 + 52.68T \qquad (J/mole\ O_2)$$

a. Please calculate the equilibrium constants for both reactions at 1200°C. *(2 points)*

b. Please use the values from the calculated standard Gibbs energy change to explain the oxidation order of the 2 sulphide compounds (Cu_2S and FeS) in the matte: which sulphide is oxidized first, and WHY? *(1 points)*

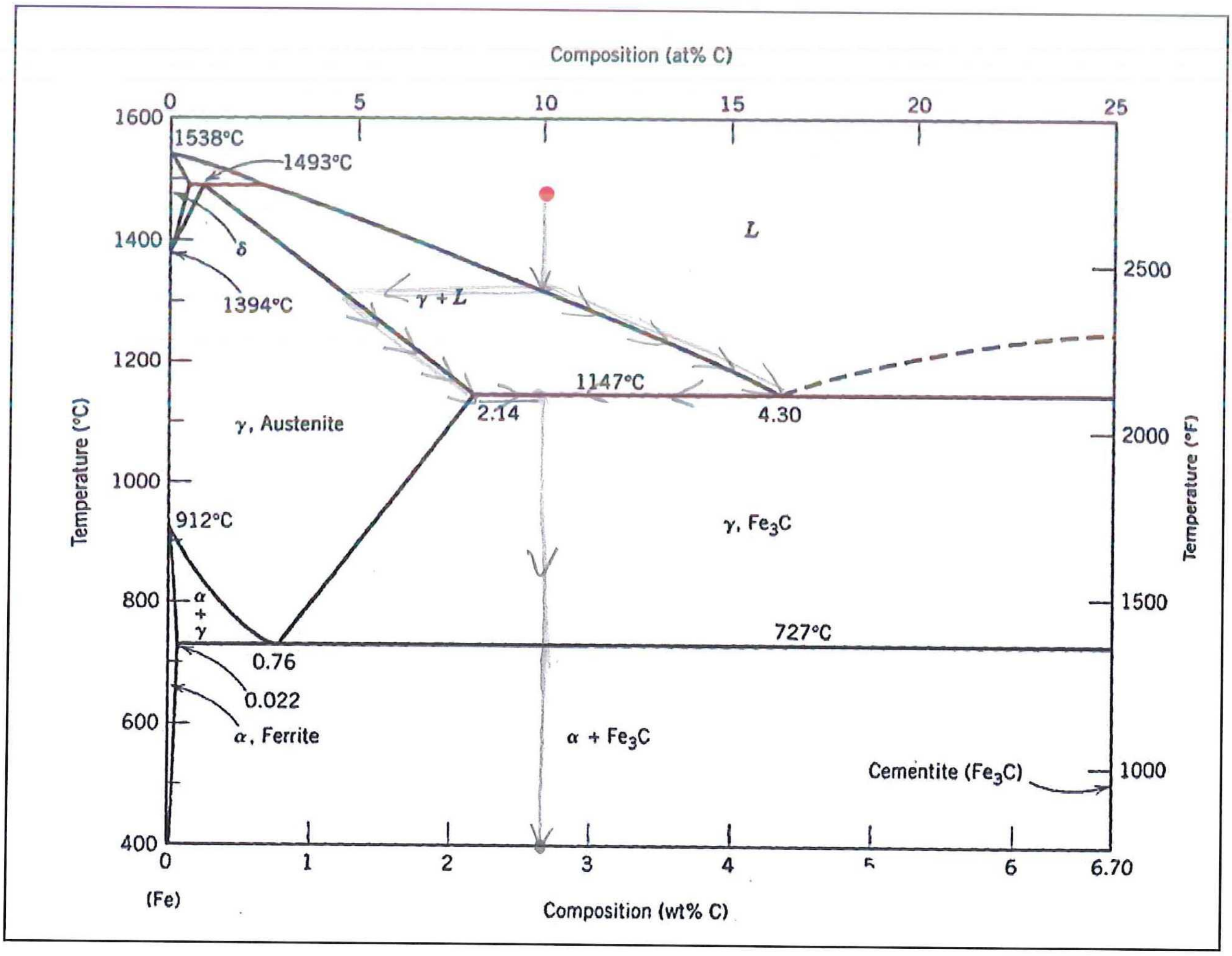
(EM 3-2) Question Phase Diagrams

Please answer this question on a separate sheet for Dr. J.Vonckenl!

Below you see the phase diagram of the binary system Fe – Fe_3C.
A liquid with the composition indicated by the *red dot* is cooling down.

a. Draw on the separate answer sheet (provided) the crystallisation path **(4 points).**

b. Indicate what the final crystallized composition will be. **(1 point).**



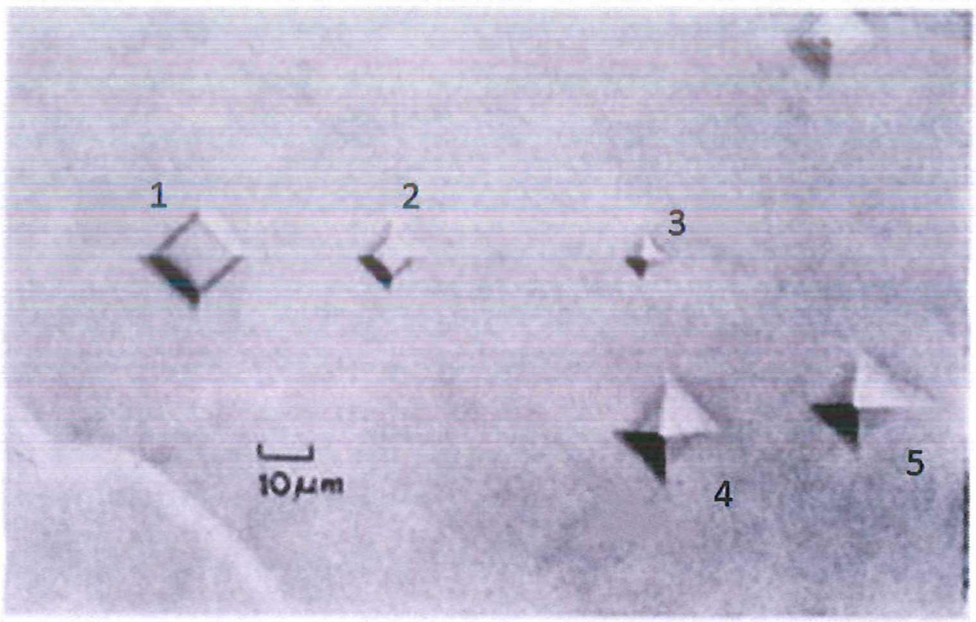
Part II: Physical Processing

Please answer this part of the exam on separate sheets

Questions J. Voncken – please answer on (a) separate sheet(s)

PP 1. Defects in materials, deformation, grinding and sintering (30 Points in total)

(PP 1 - 1) **Dislocation Theory (5 points)** Below you see a picture of etch pits on a polished surface. The etch pits are the result of dislocations ending at the surface of the material. The etching solution dissolves the material away there more easily, as the crystal structure around a dislocation is distorted.



This material was etched, then stressed in a mechanical device, and etched again. Looking at the same position as before, some dislocations appear to have moved from their original position, whereas others are have newly appeared in this section. Indicate for etch pit 1 – 5 whether they indicate a dislocation that moved away, or if they indicate a new dislocation at that position. Explain your answer.

(PP 1 - 2) Defects in Materials (2.5 points)

As a result of dislocation climb, an edge dislocation can leave its slip plane. However this process cannot takes place at very low temperature.
Explain this.

(PP 1- 3) Defects in Materials (7.5 points)

The energy for formation of a defect, for instance a dislocation, can be written as:

$\Delta G = \Delta H - T\Delta S$

When dislocations form spontaneously in a perfect crystal, $\Delta G < 0$. This means that

$\Delta H < T\Delta S$.

However, the spontaneous formation of dislocations stops at a certain moment. This is because at that moment $\Delta H = T\Delta S$, and thus $\Delta G = 0$.

Explain why this happens.

(PP 1 - 4) Grinding (5 points)

Below the Hall-Petch Equation is given.

$$\sigma = \sigma_0 + \frac{K_y}{\sqrt{d}}$$

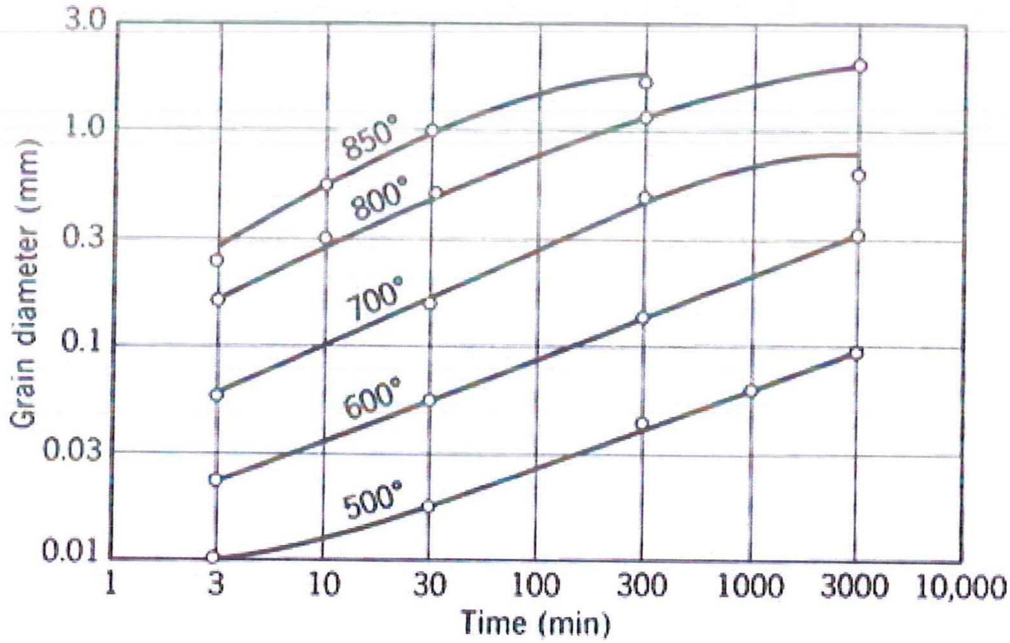
Here σ is the stress exerted on a grain, σ_0 = constant and K_y = constant, d = (average) grain diameter.

This equation predicts that when one is grinding a heterogeneous material (more than one mineral phase), every mineral phase will at the end of the grinding process have its own grain size distribution.

Explain this.

(PP 1 - 5) Sintering (10 points)

The figure below shows that during grain growth in a sintering process, at a certain moment and at a certain temperature the grain growth diminishes, and eventually becomes zero. This is caused by impurities or pores. Explain why the movement of a grain boundary can be impaired by pores or impurities, or even stopped by them.



Questions R. Chaigneau – please answer on (a) separate sheet(s)

Total 25 points.

PP (1-6)

A group students visited Tata Steel IJmuiden pellet plant which has as part of their processing a combined drying kiln followed by a dry grinding mill step, according to figure 1 in Appendix 1.

The flow sheet is designed to dry and grind 200 metric ton/hr of wet hematite ore. The ore has a moisture content of 10% (w/w). For the drying a natural gas fired burner is used. Assume for sake of argument that the ore exits the dryer section completely dry.

a. Design with above information and the info provided in Appendix 1, the heat and mass balance over the drying kiln section, with below questions as a guideline:
   1) Argue if this is a co-current or counter-current system **(2 points)**
   2) Argue what an appropriate exit temperature of the ore out of the drying kiln section is and perform your calculations with this temperature **(2 points)**
   3) Calculate the amount of energy that leaves the drying kiln for solids and gas, both in and out. Assume all this energy is generated by the burner. By combining these you can create a mass balance and associated heat balance. Use the data provided in Appendix 1 **(5 points)**
   4) Calculate the natural gas consumption in t/hr with the aid of Table 1 in Appendix 1 **(2 points)**
   5) With above data, calculations and answers, can you guarantee and argue to the manager of the operations that the ore comes out dry? **(1 point)**

b. The hematite ore is relative soft. The power drawn of the mill is 2.0 MW.
   1. Calculate the specific power (power per ton ore in kWh/t) of this mill **(1 point)**
   2. Figure 2 of Appendix 1 shows the particle size distribution of the dry **feed**. Draw in this graph the size distribution of the product, using the Bond Work Index equation from the Appendix and assuming the Bond work index of this hematite ore is W_i=10 kWh/t. **(3 points)**
      Do not forget to put your name/student number on the graph and attach it to your answers!

c. The operations manager is offered a dryer magnetite ore with 2% moisture and a Bond Work Index of W_i=20 kWh/t. Argue with operationally, technically and commercially reasons (4 items) why he should/should not consider this opportunity **(4 points)**

d. The supplier of the original hematite ore is not capable to provide 100% below the specified maximum size of 0.1". If 2% of the ore is larger than 5", why is this an issue**(1 point)** and which flowsheet before the dryer would you recommend to handle this supplied ore? Make a sketch with the required equipment, quote tonnage/hr for each stream and argue why you think this is the best solution **(4 points)**

END of question.
One Appendix to follow

Appendix 1

Relevant for question 3)

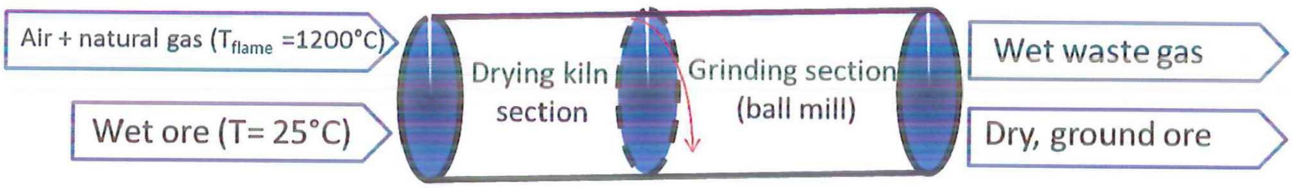


Fig 1: Drawing of combined drying kiln and ball mill (for grinding)

Drying

Assume radiation losses and other losses nil
Assume dry combustion air (79% N_2 and 21% O_2)
Assume thermal equilibrium between waste gas and dry solids (verbrandingsgas & droog erts)
Assume 100% dry solids out of drying kiln
Heat for water evaporation = 2449 kJ/kg
Specific heat of dried solids = 0.88 kJ/kg K
Specific heat of dry air/gas = 1.00 kJ/kg K
Specific heat of water vapor = 2.01 kJ/kg K
Specific heat of liquid water = 4.18 kJ/kg K
For 1 Nm^3 natural gas <u>stoichiometric</u> combustion requires 2 Nm^3 O_2 (equivalent to 9.6 Nm3 dry air). I can combust with more air (combustion ratio > 1), not with less air.
1 Nm^3 natural gas = 0.71 kg

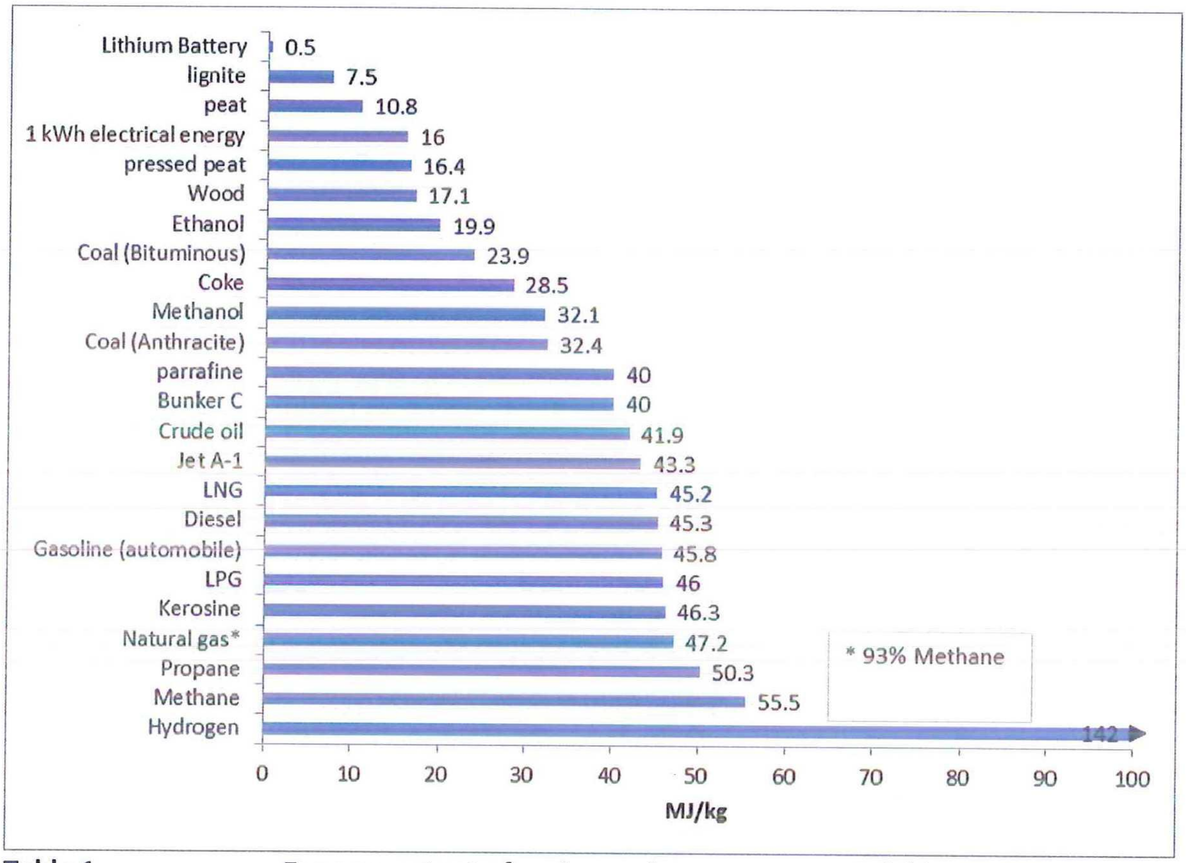


Table 1 **Energy content of various substances upon stoichiometric combustion with air**

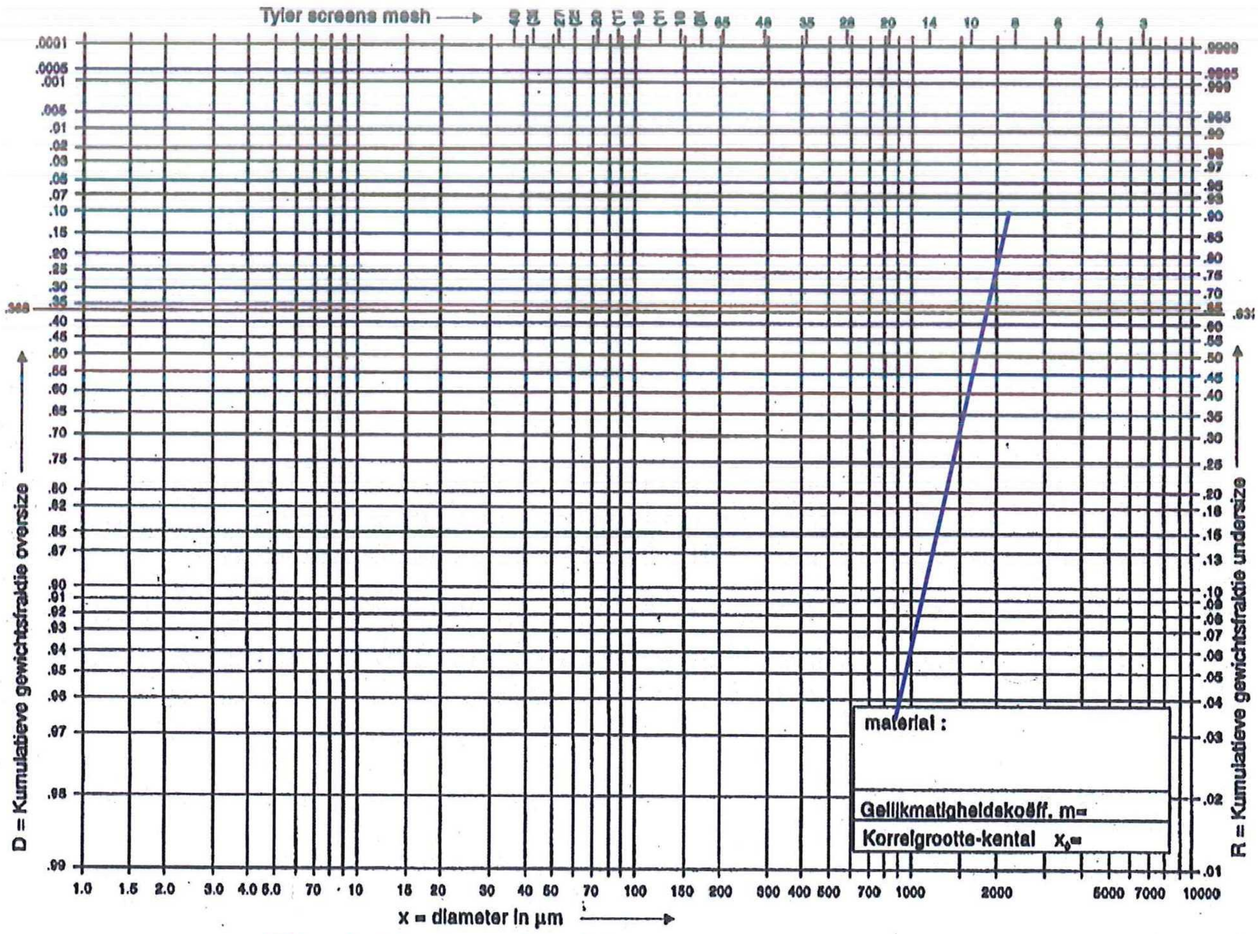
To be handed in together with your answers!

NAME ....
STUDY NUMBER ....

Grinding

1" equals 24.5 mm
Equation for specific mill power (kWh/t) as function of the Bond Work index W_i.
Product and Feed
P & F in µm!
P & F refer to the 80% passing size

$$W_{specificek} = 10\ W_i \left(\frac{1}{\sqrt{P}} - \frac{1}{\sqrt{F}}\right)$$



Hand this sheet in with your answer.