A R C H I V E S O F M E T A L L U R G Y A N D M A T E R I A L S
Volume 54 2009 Issue 1

J. NORWISZ[**], B. BORYCZKO[*], A. HOŁDA[**], Z. KOLENDA[**]

THERMO – ECOLOGICAL COST ANALYSIS OF SHAFT AND FLASH SMELTING PROCESSES OF COPPER PRODUCTION – GENERAL APPROACH

ANALIZA PORÓWNAWCZA PROCESÓW SZYBOWEGO I ZAWIESINOWEGO PRODUKCJI MIEDZI METODĄ KOSZTU TERMOEKOLOGICZNEGO

Thermo-ecological cost method, formulated by Szargut, has been proposed to be applied for comparison of two different and most frequently used technologies of copper production.

The method, based on minimization of depletion of nonrenewable natural resources takes also under consideration the problem of the deleterious ecological impact of highly aggressive waste products. The further is especially important as the copper technologies belong to the group of highly hazardous from ecological point of view, nonferrous metals industry.

Two technologies – shaft furnace and flash smelting Outokumpu technologies have been analyzed considering all step from copper mine to final product (copper cathodes).

The method of calculation is based on the set of balance equations determining the value of specific thermo-ecological cost.

To recommend copper technology a minimum value of the thermo-ecological cost is proposed to be criterion.

Keywords: Thermo – ecological cost.

W artykule przedstawiono wyniki analizy porównawczej dwóch pełnych technologii otrzymywania miedzi katodowej, opartej na pojęciu kosztu termoekologicznego. Rozważania dotyczą procesów szybowego i zawiesinowego. W proponowanej metodzie podstawę stanowią skumulowane zużycia egzergii prowadzące do minimalizacji wyczerpywania nieodnawialnych zasobów bogactw naturalnych z uwzględnieniem szkodliwego wpływu emisji szkodliwych produktów do otoczenia. Analiza obejmuje rudy miedzi w kopalni do wyprodukowania miedzi katodowej. Obliczenia przeprowadzone przez rozwiązanie układów równań bilansowych strumieni egzergii typu input – output. Wykorzystano wyniki bezpośrednich pomiarów w hutach miedzi po uzgodnieniu bilansów substancji i energii.

Zaproponowano kryterium wyboru technologii o najmniejszej wartości kosztu termoekologicznego przez co uwzględniono problemy degradacji energii wynikające z II zasady termodynamiki.

NOMENCLATURE

a_i	coefficient of the consumption or by-production of i-th product per unit major product,
p_{jk}	amount of k-th aggressive component of waste product rejected to the environment per unit of j-th product,
X_i	fraction of i-th product,

Greek letters

ρ_i	specific thermo-ecological cost of the i-th product,
ξ	thermo-ecological cost of waste product,

Subscripts

conc	concentrate
conv.	converter
Cu	copper
gasPP	combustion gases from power plant
g.ff	gases from flash furnace
n.g.	natural gas
s.a.	sulfuric acid
w.v.	water vapour

[*] AGH – UNIVERSITY OF SCIENCE AND TECHNOLOGY, DEPARTMENT OF METAL WORKING AND PHYSICAL METALLURGY OF NON-FERROUS METALS, 30-059 KRAKÓW, 30 MICKIEWICZA AV., POLAND
[**] AGH – UNIVERSITY OF SCIENCE AND TECHNOLOGY, DEPARTMENT OF PROCESS ENGINEERING, 30-059 KRAKÓW, 30 MICKIEWICZA AV., POLAND

1. Introduction

Since the early 70's, the availability of nonrenewable natural resources over the long term – a period spanning the coming centuries – has intrigued our society. Without adequate supplies of oil, natural gas and coal, modern civilization as we know it is difficult to imagine. Many consider resource availability one of the major challenges facing humanity, along with nuclear war, population growth and *environmental preservation* [6].

As Szargut states [1] – *The inevitable depletion of nonrenewable natural resources is very dangerous for the future existence of mankind* and he has proposed *the cumulative exergy consumption of nonrenewable natural resources, termed ecological cost*, as a measure of their depletion. The balance equations of CexC (*Cumulative Exergy Consumption*) [1] is a basis for calculation of the thermo-ecological cost.

2. Thermoecological cost calculation

Calculation method of thermoecological cost is based on the solution of the system of linear input – output equations describing cumulative consumption of exergy. General elements of the balance equation for any *j-th* industrial process is shown in Fig.1.[1]

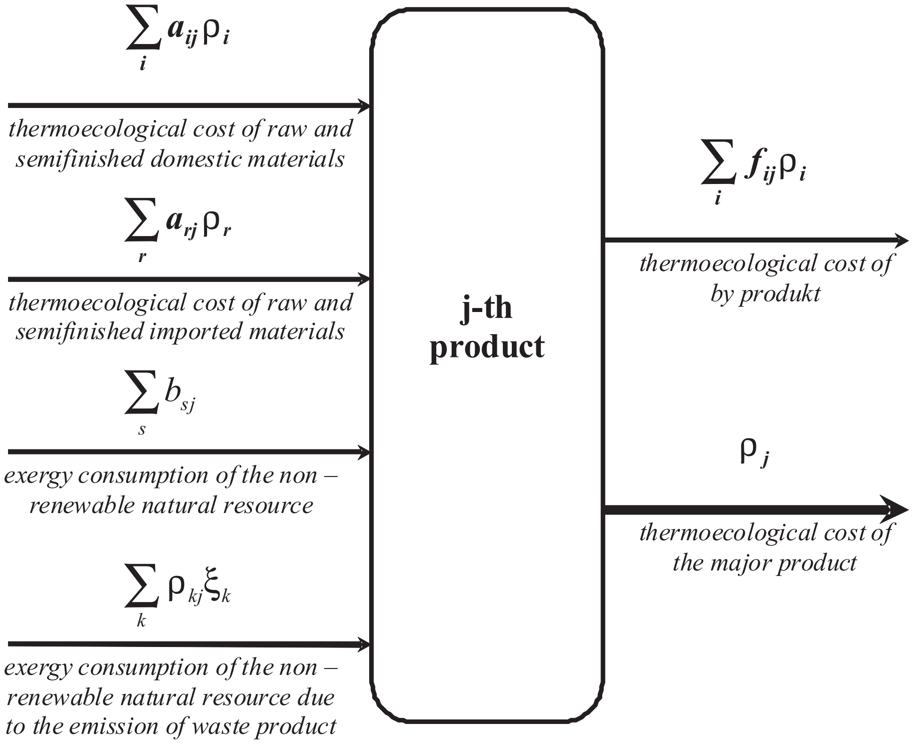

Fig. 1. Components of thermecological cost balance equation[1]

Mathematical form of the balance equation is[1]

$$\rho_j + \sum_i \left(f_{ij} - a_{ij}\right)\rho_i = \sum_s b_{sj} + \sum_k p_{kj}\xi_k + \sum_r a_{rj}\rho_r \quad (1)$$

where:

- *rho*$_j$, ρ_i – specific thermoecological cost of the major product of the *j-th* and *i-th* process,
- b_{sj} – exergy consumption of the *s-th* non-renewable natural resource, per unit of the *j-th* product,
- p_{kj} – emission of the *k-th* waste product per unit of the *j-th* product,
- ρ_r – specific thermoecological cost of the imported *r-th* semifinished product,
- f_{ij}, a_{ij} – consumption coefficient of the *i-th* material and *i-th* by-product per unit of the *j-th* major product.

The additional exergy consumption of non-renewable natural resource due to the emission of waste product (for example in kJ/kg) is given by equation.[1]

$$\xi_k = \frac{B \cdot \delta_k}{DCP + \sum P_k \delta_k}$$

where:

ξ_k – annual consumption of the nonrenewable exergy from own sources,

δ_k – monetary index of harmfulness of the *k-th* waste product,

DCP – domestic consumption product,

P_k – annual emission of the *k-th* waste product in the country.

Vales of thermoecological cost of selected energy carriers is listed in Table 1.[1]

TABLE 1

Energy carriers thermoecological cost [1]

Energy carrier	Lower heating value	Chemical exergy	Thermoecological cost
	MJ/u.m.	MJ/u.m.	MJ/u.m.
Coal (special) *	27.8	30.2	31.2
Coal for electric plant *	24.0	26.2	27.1
Coke *	29.2	31.8	46.1
Natural gas (domestic) **	790.0	821.6	713.1
Natural gas (imported) **	790.0	821.6	835.7
Coke-oven gas (domestic) **	380.0	380.0	356.5
Coke-oven gas (replacement of natural gas) **	380.0	380.0	312.1
Electric energy (MJ/MJ)			3.4
Oil (imported) *	42.6	45.6	31.6
Gasoline *	47.3	50.6	52.2

u.m. – unit mass

* – kg

** – kmol

3. Technological processes

General schemes of two different technologies of copper production are shown in Fig. 2 and Fig.3. The main difference between two technologies of copper production is that in the case of shaft furnace necessary energy for the process is the chemical exergy of coke and for the flush smelting process, chemical exergy of the copper concentrate and electric energy used by the electric furnace. Because of those two different exergy sources, the CexC values can differ significantly.

3.1. Shaft furnace

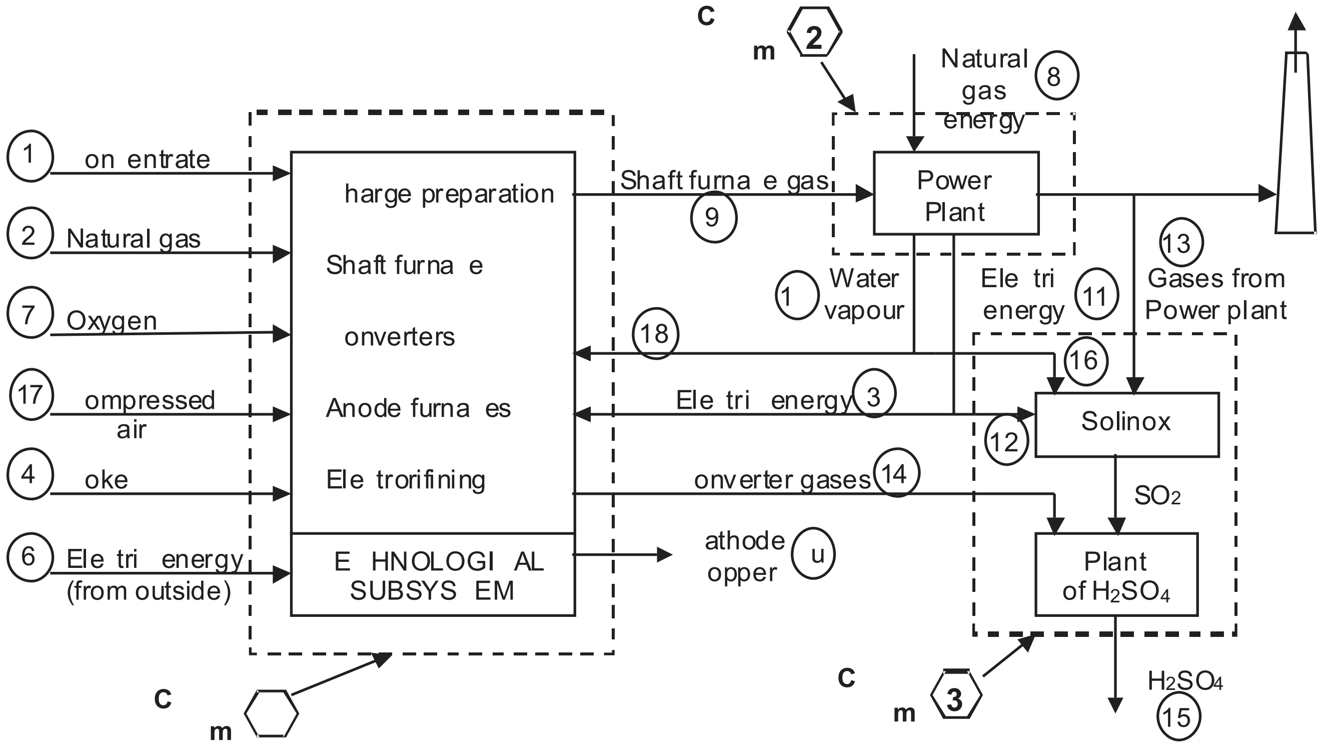

Fig. 2. Subsystems of shaft furnace technology

Balance equations for the calculation of the thermo-ecological cost of cathode copper are[1]:
– *Technological subsystem*

$$\rho_{Cu} + a_9\rho_9 + a_{14,1}\rho_{14} = a_1\rho_1 + a_2\rho_2 + X_3a_3\rho_3 + a_4\rho_4 + a_6\rho_6 + a_7\rho_7 + a_{17}\rho_{17} + X_4a_{18}\rho_{10} + \sum_k p_{1k}\xi_k \quad (2)$$

– *Power plant*

$$\rho_{11} + a_{10}\rho_{10} + a_{13,2}\rho_{13} = a_9\rho_9 + a_8\rho_8 + \sum_k P_{2k}\xi_k \quad (3)$$

– *Plant of H_2SO_4 production*

$$\rho_{15} = X_1a_{16}\rho_{10} + X_2a_{12}\rho_{11} + a_{13,3}\rho_{13} + \sum_k p_{3k}\xi_k$$
$$\rho_{H_2SO_4} = \rho_{15} + a_{14,3}\rho_{14} + a_{13,3}\rho_{13} \quad (4)$$

where: $\rho_{H_2SO_4}$ is thermo-ecological cost of typical sulfuric acid technology (9.1 $MJ/_{kgH_2SO_4}$ [2]).
Unknowns in Eqs (2)(3) and (4) are: ρ_{11}, ρ_{15} and ρ_{Cu}. Values of coefficients a_i and thermo-ecological costs ρ_i are listed in Table 2. They were calculated from direct measurement results, a_i [5] and from data in [2][3].

TABLE 2

Values of a_i and ρ_i (shaft furnace)

Notation	Unit	Value
Technological subsystem, [2][5]		
a_1	$\frac{kg_{conc}}{kg_{Cu}}$	4.2
ρ_1	$\frac{MJ}{kg_{conc}}$	20.6
a_2	$\frac{kmol_{n.g.}}{kg_{Cu}}$	0.0054
ρ_2	$\frac{MJ}{kmol_{n.g.}}$	835.7
a_3	$\frac{MJ}{MJ}$	1.0
$\rho_3 = \rho_{11}$	$\frac{MJ}{kg_{Cu}}$	calculated
a_4	$\frac{kg_{coke}}{kg_{Cu}}$	0.426
ρ_4	$\frac{MJ}{kg_{coke}}$	46.1
a_6	$\frac{MJ}{MJ}$	1.0
ρ_6	$\frac{MJ}{kg_{Cu}}$	19.5
a_7	$\frac{kmol_2}{kg_{Cu}}$	0.004
ρ_7	$\frac{MJ}{kmol_{O2}}$	153.0
a_9	$\frac{kmol_{n.g.}}{kg_{Cu}}$	0.0152
ρ_9	$\frac{MJ}{kmol_{n.g.}}$	835.7

cd. TABLE 2

Notation	Unit	Value
Technological subsystem, [2][5]		
a_{17}	$\frac{kmol_2}{kg_{Cu}}$	0.7121
ρ_{17}	$\frac{MJ}{kmol_{air}}$	29.7
a_{18}	$\frac{kg_{w.v.}}{kg_{Cu}}$	1.41
$\rho_{18} = \rho_{10}$	$\frac{MJ}{kg_{w.v.}}$	0.80
$a_{14,3}$	$\frac{kmol_{conv.}}{kg_{H_2SO_4}}$	0.91
ρ_{14}	$\frac{MJ}{kg_{conv.}}$	Calculated
Power plant		
a_8	$\frac{kmol_{n.g.}}{kg_{Cu}}$	0.023
ρ_8	$\frac{MJ}{kmol_{n.g.}}$	835.7
ρ_{11}	$\frac{MJ}{kg_{Cu}}$	Calculated
a_{10}	$\frac{kg_{w.v.}}{kg_{Cu}}$	1.41
ρ_{10}	$\frac{MJ}{kg_{w.v.}}$	0.8
$a_{13,2}$	$\frac{kmol_{gasPP}}{kg_{Cu}}$	0.843
ρ_{13}	$\frac{MJ}{kmol_{gasPP}}$	0.049
Plant of H2SO4 production		
$\rho_{12} = \rho_{11}$	$\frac{MJ}{kg_{Cu}}$	Calculated
a_{16}	$\frac{kg_{w.v.}}{kg_{Cu}}$	1.08
$\rho_{16} = \rho_{10}$	$\frac{MJ}{kg_{w.v.}}$	0.80
$a_{13,3}$	$\frac{kmol_{gasPP}}{kg_{H_2SO_4}}$	0.635
ρ_{13}	$\frac{MJ}{kmol_{gasPP}}$	0.049
X_1	–	0.41
X_2	–	0.18
X_3	–	0.82
X_4	–	0.59
$P_{1O_2,3}$	$\frac{kg_{SO_X}}{kg_{H_2SO_4}}$	0.0033
ξ_{SO_X}	$\frac{MJ}{kg_{SO_X}}$	49.3
$P_{SO_X,2}$	$\frac{kg_{SO_X}}{kg_{Cu}}$	0.0012
$P_{SO_X,1}$	$\frac{kg_{SO_X}}{kg_{Cu}}$	0.0003

Solution of Eqs. (2),(3) and (4) gives

$$\rho_{11} = 30.8\frac{MJ}{kg_{Cu}}$$

$$\rho_{15} = 4.74\frac{MJ}{kg_{H_2SO_4}}$$

Finally, thermoecological cost of cathode copper is

$$\rho_{Cu} = 176.0\frac{MJ}{kg_{Cu}}$$

3.2. Flash smelting

General scheme is shown in Fig.3.

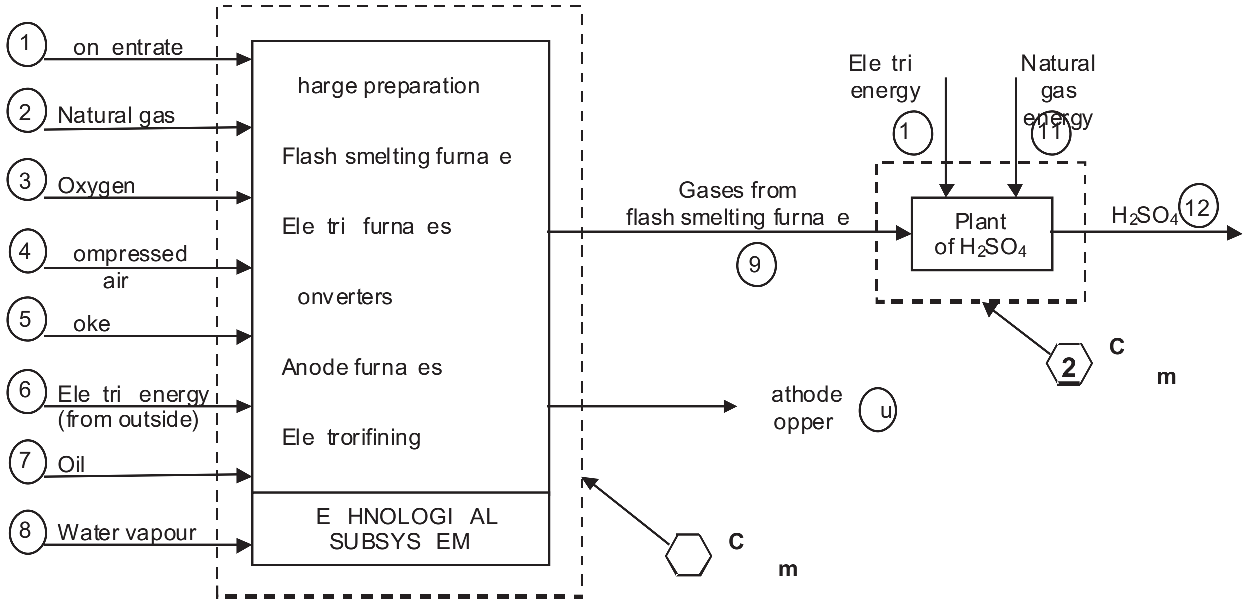

Fig. 3. Subsystems of flash smelting technology

Thermoecological cost balance equations are as follows:

– *technological subsystem*

$$\rho_{Cu} + a_9\rho_9 = a_1\rho_1 + a_2\rho_2 + a_3\rho_3 + a_4\rho_4 + $$
$$+ a_5\rho_5 + a_6\rho_6 + a_7\rho_7 + a_8\rho_8 + \sum_k p_{1k}\xi_k$$

– *plant of H_2SO_4*

$$\rho_{H_2SO_4} = \rho_{12} + a_{9,2}\rho_9 = a_{10}\rho_{10} + a_{11}\rho_{11} + a_{9,2}\rho_9$$

Unknowns are ρ_9 and ρ_{Cu}. Values of coefficients a_i and thermo-ecological costs ρ_i are listed in Table 3. They were calculated on the basis of direct measurement results a_i, [5] and from data [2].

TABLE 3

Values of a_i and ρ_i (flash smelting)

Notation	Unit	Value
Technological subsystem		
a_1	$\frac{kg_{conc}}{kg_{Cu}}$	3.4
ρ_1	$\frac{MJ}{kg_{conc}}$	20.6
a_2	$\frac{kmol_{n.g.}}{kg_{Cu}}$	0.0077
ρ_2	$\frac{MJ}{kmol_{n.g.}}$	835.7
a_3	$\frac{kmol_{O_2}}{kg_{Cu}}$	0.070
ρ_3	$\frac{MJ}{kg_{O_2}}$	153.0
a_4	$\frac{kmol_{air}}{kg_{Cu}}$	0.0195
ρ_4	$\frac{MJ}{kmol_{air}}$	29.7
a_5	$\frac{kg_{coke}}{KG_{Cu}}$	0.12
ρ_5	$\frac{MJ}{kg_{coke}}$	46.1
a_6	$\frac{MJ}{kg_{Cu}}$	3.30
ρ_6	$\frac{MJ}{MJ}$	3.7
a_7	$\frac{kg_{oil}}{kg_{Cu}}$	0.090
ρ_7	$\frac{MJ}{kg_{oil}}$	31.6
a_8	$\frac{kg_{w.v.}}{kg_{Cu}}$	0.070
ρ_8	$\frac{MJ}{kg_{w.v.}}$	30.8
Plant of H_2SO_4		
a_{18}	$\frac{MJ}{kg_{s.a.}}$	0.478
ρ_{10}	$\frac{MJ}{MJ}$	3.4
a_{11}	$\frac{kmol_{n.g.}}{kg_{s.a.}}$	$4.9 \cdot 10^{-5}$
ρ_{11}	$\frac{MJ}{kmol_{n.g.}}$	835.7
a_9	$\frac{kmol_{g.ff}}{kg_{Cu}}$	0.067
ρ_9	$\frac{MJ}{kmol_{g.ff}}$	calculated
$a_{9.2}$	$\frac{kmol_{g.ff}}{kg_{s.a.}}$	0.0713

After calculation

$$\rho_9 = 30.4\frac{MJ}{kg_{Cu}}\left(36.1\frac{MJ}{kmol_{g.ff}}\right)$$

and thermoecological cost of cathode copper is

$$\rho_{Cu} = 116.5\frac{MJ}{kg_{Cu}}$$

4. Conclusion

The concept "*thermo-ecological cost*" (*cumulative consumption of nonrenewable natural exergy resources*) allows to choice technology of copper production characterized with the lowest cumulative exergy consumption of natural resources. Also, the method allowed to involve into analysis the problem of destruction of our natural environment.

Comparison of the values of the thermo-ecological cost of two technologies – shaft furnace and flash smelting shows, that the flash smelting Outokumpu technology is characterized by significantly lower thermo-ecological cost. In both cases thermo-ecological cost of copper concentrate plays most important rule.

Received: 15 June 2008.

Acknowledgements

The paper was partially supported by Polish Ministry of Education and Science, Grant No W 512 01 932 / 39 33.

REFERENCES

[1] J. S z a r g u t, Exergy Method – Technical and Ecological Applications. WIT Press, Southampton, Boston (2005).
[2] W. S t a n e k, Tables of Thermo-ecological Cost. private information.
[3] W. S t a n e k, A. Z i e b i k, An Example of Ecological Cost Calculation of Products Connected with the Blast-furnace Process. Proceedings of ECOS'99, Tokyo, s. 386-391, (1999).
[4] J. S z a r g u t, Application of Exergy for the Calculation of Ecological Cost. Bulletin of the Polish Academy of Sci. **34** (7-8), 475-480 (1986).
[5] A. H o l d a, An Analysis of Shaft Furnace and Flash Smelting Technologies on the Basis of Cumulative Energy and Exergy Consumption. PhD Thesis, University of Science and Technology, Cracow (1994).
[6] J. E. T i l d e n, On Borrowed Time? Assessing the Threat of Mineral Depletion, *Resources for the Future*, Washington (2003).