EIR-Bericht Nr. 252

EIR-Bericht Nr. 252

Eidg. Institut für Reaktorforschung Würenlingen
Schweiz

Thorium, Uranium, other Metals and Materials from Earth's Crust Rocks

M. Taube

Würenlingen, April 1974

Abstract

The general use of the rocks of the earth's crust as a source of nuclear energy (from thorium-uranium extracted with 30% efficiency), and a source of metals (aluminium, iron etc.), a source of ceramics (cement, glass, quartz) and other materials is discussed. The proposal is to use their source to meet the needs of a future stable civilization requiring a unit power production of some 20 kw per capita and source material supply of 1 tonne per capita per year (additional to recycling). The impact of this on the philosophy a reactor development is also discussed.

I. General remarks

The aim of this paper is to outline and discuss the possible future sources and flows of energy in the next 50 to 200 years, in the world as a whole, and more especially in Switzerland. It is a continuation of the well known idea of A. Weinberg of 'rocks burning'.

It can be debated that any numerical or quantitative evaluations on these topics have little value at the present time, but the author is of the firm opinion that such an evaluation could have an impact on the philosophy of reactor development especially in the qualitative choice of reactor type.

Since it seems to take some 20 years from paper studies to full reactor operations (of a new type) and a further 30-40 years of life, then the minimum time scale we should consider is of the order of 50 years.

II. World energy development, and the case of Switzerland

It is well known that the number of prognoses for the future development of our civilization is equal to the number of papers on the subject. Here the following assumptions have been made.

1. The world population increases continuously to 9-10 x 10^9 people after 200 years and then reduces to a stable level of 8 x 10^9 people (for Switzerland - today 6 x 10^6 people, in the next 50 years 8 x 10^6 and then stabilization).

2. The abundance of available energy sources is the most important factor in the development of any civilization.

3. The regeneration of the natural environment is one of the most important factors in considering the transformation of matter into energy.

4. Our civilization achieves a steady state level in approx 200-250 years and this level will have the following characteristics

   - production of fresh materials (from ores etc.) would be a factor 2-3 times lower than at present.
   - recycling will, therefore, be greatly increased.
   - the spectrum of material use will be drastically altered.
   - the free energy available for these needs will be increased per capita mean by approx 10 times.

<u>The size of the fissile material requirement</u>

The calcualtions are made on the following basis:

1 MWd(t) $\cong$ 1.1 g fissile nuclide (F.N.)
1 MWyear (e) $\cong$ 1.0 kg fissile nuclide (F.N.)

and therefore

1 TW(t) year $\cong$ 400 ton FN
1 GW(t) year $\cong$ 0.4 ton FN

for the far distant future, for the steady state case:

World:
8 Giga people x 20 kw per capita gives
160 TW(t) $\cong$ 64'000 ton FN/year

Fig. 1 Energy Growth: World and Switzerland

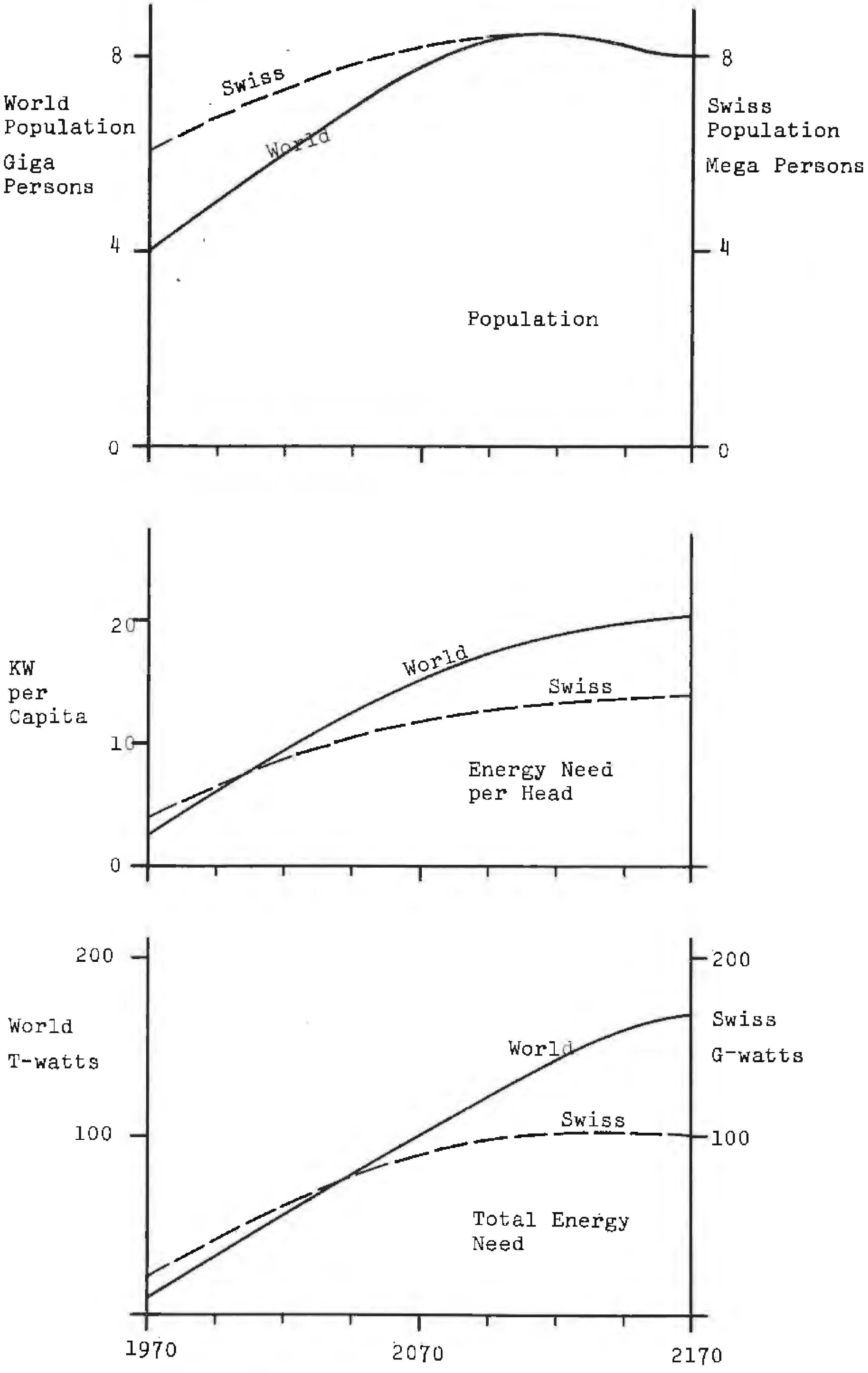
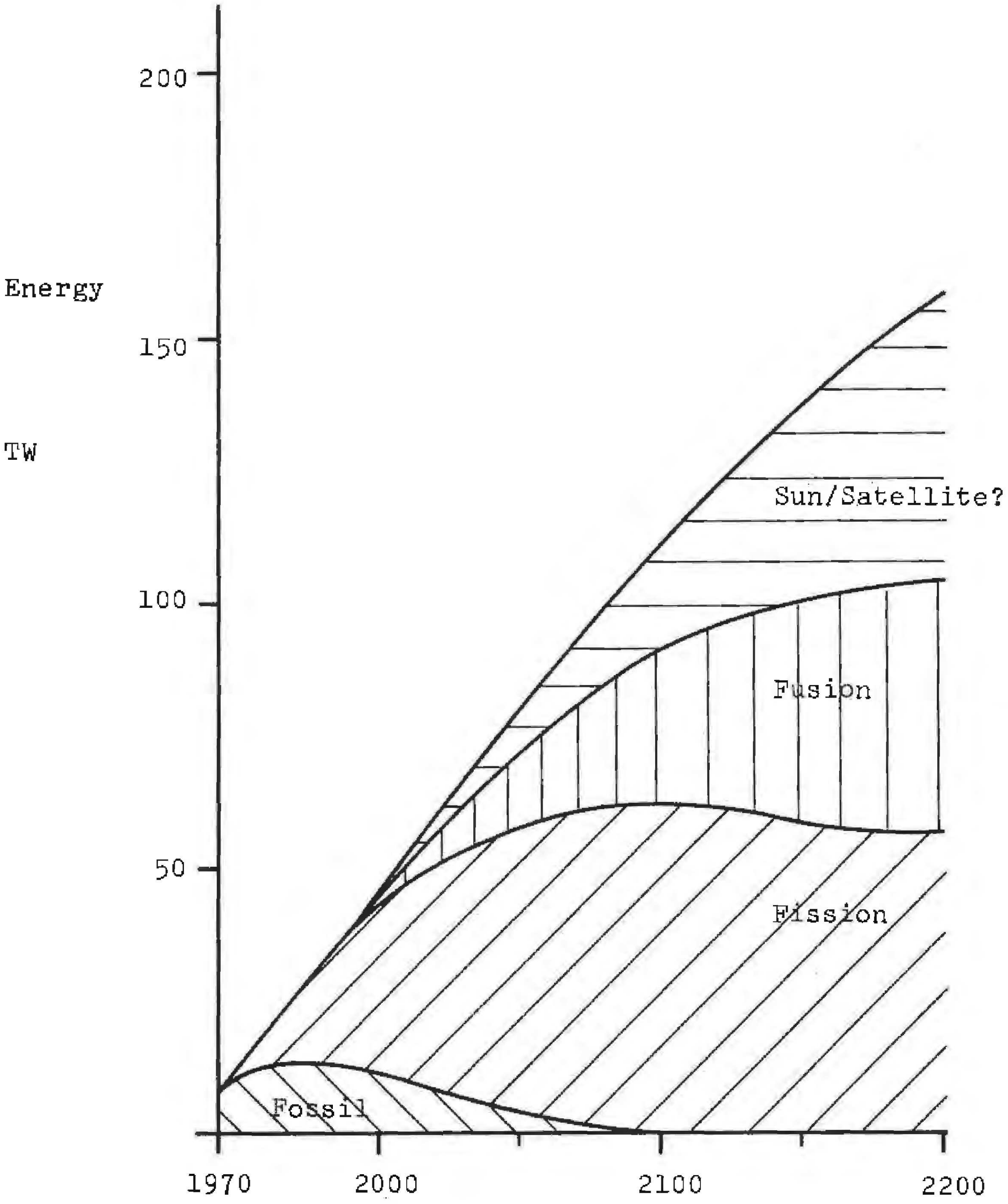


Fig. 2 Development of new World Energy Sources in the Future



Switzerland:

8 Mega people x 12 kW per capita gives

0.1 TW(t) ≅ 40 ton FN/year

For a period of let us say 1000 years steady civilization

World requirements: 64×10^6 ton FN

Swiss requirements: 40×10^3 ton FN

Of course the development of other energy sources will change and may dramatically after the assumptions given above, but fig. 2 makes the arbitrary assumptions clear.

Here the assumption of fission energy covers approx 1/3 of all energy needs and thus the data given above are too big only by a factor 3 in the worst case.

III. Uranium-Thorium sources in ores, granites and the earth's crust

The most important assumption made here is that the fission energy is the main source of free energy not only in the next century but also in later periods. At present uranium is recovered from the following ores.

USA ores	1800 ppM
Canada ores	1100 ppM
South Africa ores	250 ppM
Other West Hemisphere ores	1940 ppM
Mean for West Hemisphere	820 ppM

It must be stressed that at the present time the "uranium ores" have a commercial value of approx. 20$ per kg of U_3O_8 even if the uranium contents equals only 250 ppM!

But as is well known the mean distribution of uranium and thorium in the earths crust is approximatly 12 ppM for both elements. The proportion of these fissionable elements is higher in the granites (typical continental rocks) and reaches 50 ppM. In the basalts (typical oceanic rocks) it is lower at about 1 ppM (see fig. 3).

Of course in the continental rocks there are some significant accumulations of uranium and to save extent thorium. The probable amounts of high and low grade ores are given in fig. 4 (rough estimates).

IV. Resources of other elements

An underlying feature of the arguments developed in this paper is that the extraction of the fissionable nuclides U and Th from the rocks of the earth's crust must be coupled with the extraction of all the utilizable elements from these cources, which must decrease the cost of the recovery of all appropriate elements.

Fig. 3 Composition of Earth's Crust

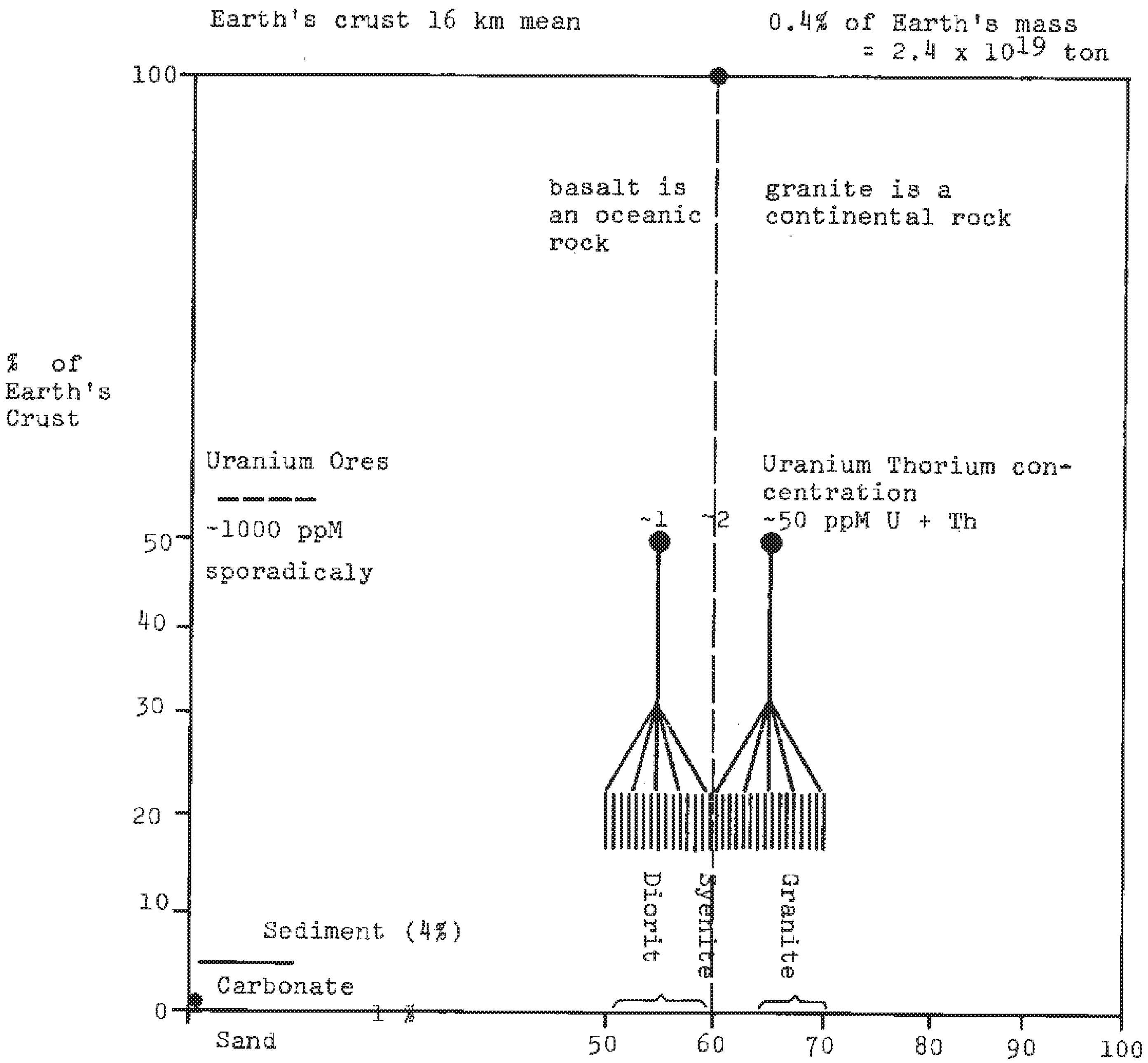
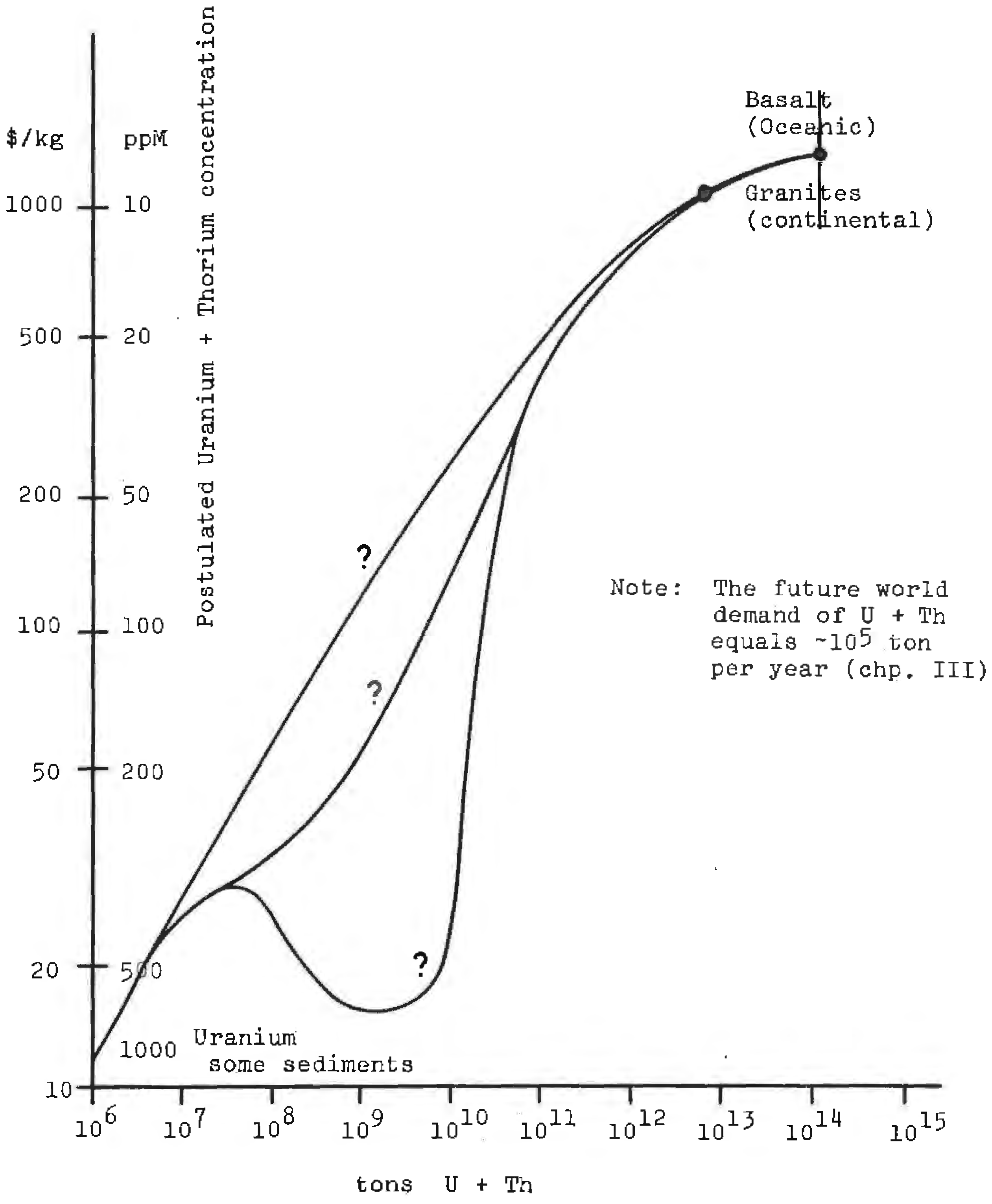


Fig. 4 U + Th World Reserves



In table 1 are given the abundance of chemical elements in the earth's crust. Of course there is some disagreement about this data in different references but for our purposes the influence of these uncertainties is not great.

Fig. 5 shows the distribution of the most abundant elements (in the earth's crust) versus the electronegativity according to Pauling and periodic table. This gives the first indication concerning the thermodynamic stability of the possible chemical compounds such as silicates, alumosilicates and so on.

We attempt here to discuss the technical and energetical features of the industrial extractions of these components of the rocks in the future.

We can make a very simplified calculation based on the following:

Take first 1 ton of each of the today's commercially important ores (arbitrarily chosen) providing the following eleven metals

Fe, Al, Cr, Mn, Ni, Cu, Zn, Sn, Ag, Au, Pb

totalling 11 tons of ores.

Commercial ores today contain approx the following amounts of metal

Fe 20%; Al 30%; Cr 30 %; Mn 20%; Ni 1%; Cu 0.5%; Zn 4%; Sn 0.2%; Pb 2%; Ag 0.05%; Au 0.005%.

Table 1 Element abundance in Earth's Crust

1 ton (ρ = 2.8 kg/dm^3) ~ 357 dm^3

Number	Z	Element		Number	Z	Element	
1	8	O	466 kg	21	37	Rb	90 g
2	16	Si	277 kg	22	28	Ni	75 g *
3	13	Al	81 kg*	23	30	Zn	70 g*
4	26	Fe	50 kg*	24	58	Ce	60 g
5	20	Ca	36 kg	25	23	Cu	55 g
6	11	Na	28.3 kg	26	39	Y	33 g
7	19	K	25.9 kg	27	57	La	30 g
8	12	Mg	20.9 kg**	28	60	Nd	28 g
9	22	Ti	4.4 kg*	29	27	Co	25 g
10	1	H	1.4 kg	30	21	Sc	22 g
11	15	P	1.1 kg	31	7	N	20 g
12	25	Mn	950 g	32	41	Nb	20 g
13	9	F	625 g	33	3	Li	20 g ←
14	56	Ba	425 g	34	31	Ga	15 g
15	38	Sr	375 g	35	82	Pb	13 g*
16	16	S	260 g	36	5	B	10 g
17	6	C	200 g	37	90	Th	10 g ←
18	40	Zr	165 g*	38	50	Sn	3 g
19	23	V	135 g*	39	92	U	2.4 g ←
20	24	Cr	100 g*				
					80	Hg	0.08 g
					78	Pt	0.01 g

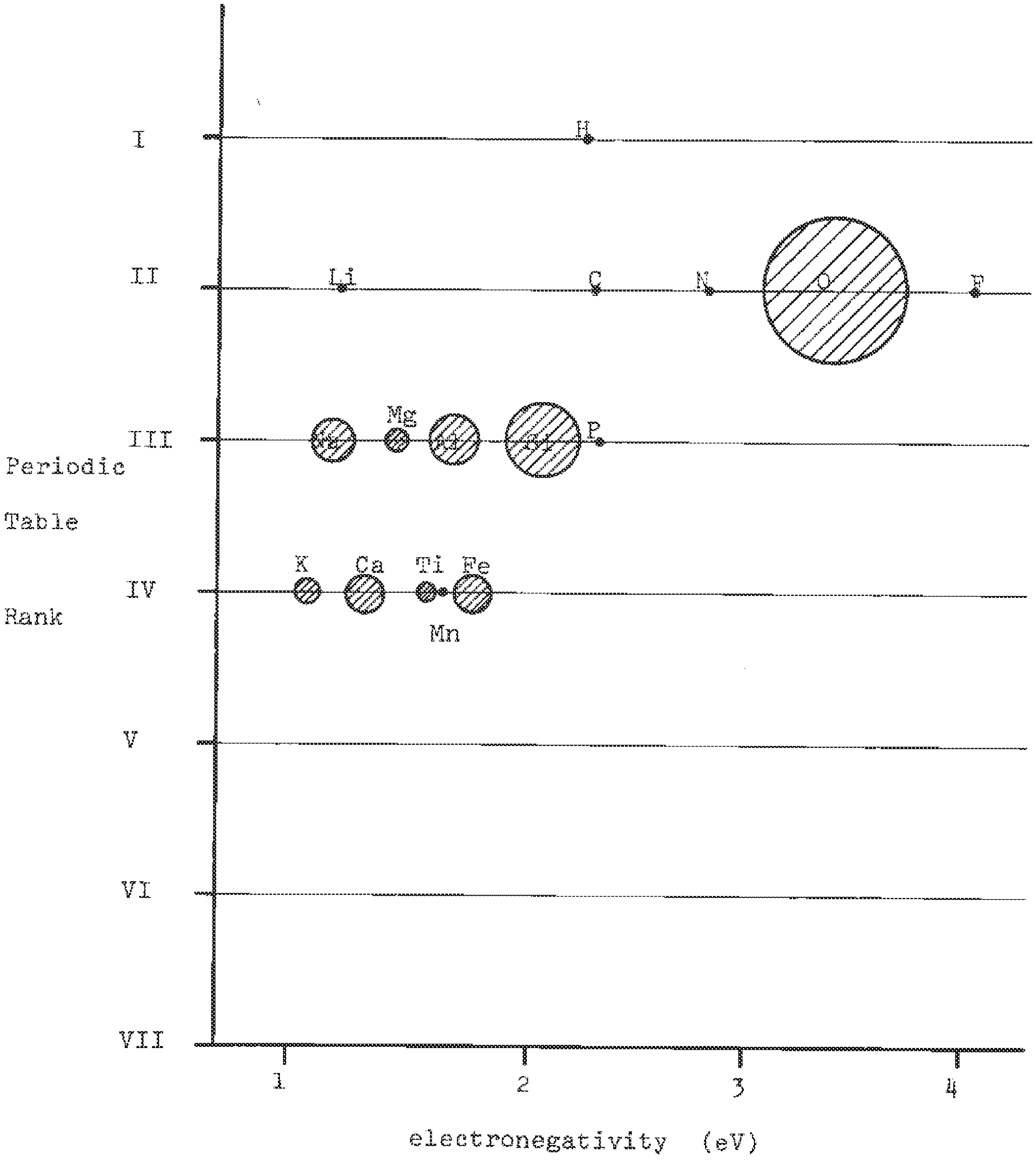
Z = atomic number

* Approx all metals for metallurgy

** Only partially for metallurgy
Other metals for ceramics etc.

Energy carriers ←

<u>Fig. 5</u> The 16 most important components of rocks



The total amount of metals produced from the 11 tons of ores is approx 1078 kg. The mean value of the commercial ores is therefore

$$\frac{1073 \text{ kg metal}}{11000 \text{ kg ores}} \cong 10\ \% \text{ by weight}$$

The earth's crust contains the elements listed in table 2 among others. The total amount of metal there is 130 kg in 1000 kg or 13 weight %. Thus the earth's crust taken as a whole has the same approximately total content of metals as a mean mixture of commercial ores, if the ratios of metals could be changed in an appropriate way.

From fig. 6 it can be seen that the ratio of metal concentration in commercial ores varies from less than 10 (e.g. Fe, Al) to more than 1000 (Pb, Mo, Ta, Sn, Ag, Au, Hg, Sb) but only $\frac{280}{50} \cong 6$ for Uranium + Thorium in granites and only $\frac{280}{12} \cong 20$ for Uranium + Thorium in the earth's crust. (Note: based on the very low, but still commercial uranium ores from South Africa).

A rather important conclusion can be drawn from fig. 7. We have arbitrarily assumed that the most metal - iron is extracted from the earth in a "resonable" way - that is protioned to its abundance in the earth crust by assuming the ratio

$$\text{for Fe} \qquad \frac{\text{annual world production at 1960}}{\text{abundance in the earth's crust}} = 1$$

Table 2 Contents of some metals in ores and in earth crust

	Present commercial ores (weight %)	in present commercial ores	in earth crust
Fe	20	200	50
Zn	4	40	0.07
Cu	0.5	5	0.055
Pb	2	20	0.013
Al	30	300	81
Cr	30	300	0.2
Sn	0.2	2	0.003
Ni	1	10	0.08
Au	0.005	0.050	0.000005
Ag	0.05	0.5	0.00001
Mn	20	200	1
Metals		1077 kg	130 kg
Total			
Ores	11 tonne		1 tonne
Mean weight %		$\frac{1077\ \text{kg}}{11\ \text{tonne}} = 10\%$	$\frac{130\ \text{kg}}{1\ \text{tonne}} = 13\%$

Note: This table does not give a good picture because the amounts of metal actually used are probably in another ratio to the simplest one used here 1:1:1...

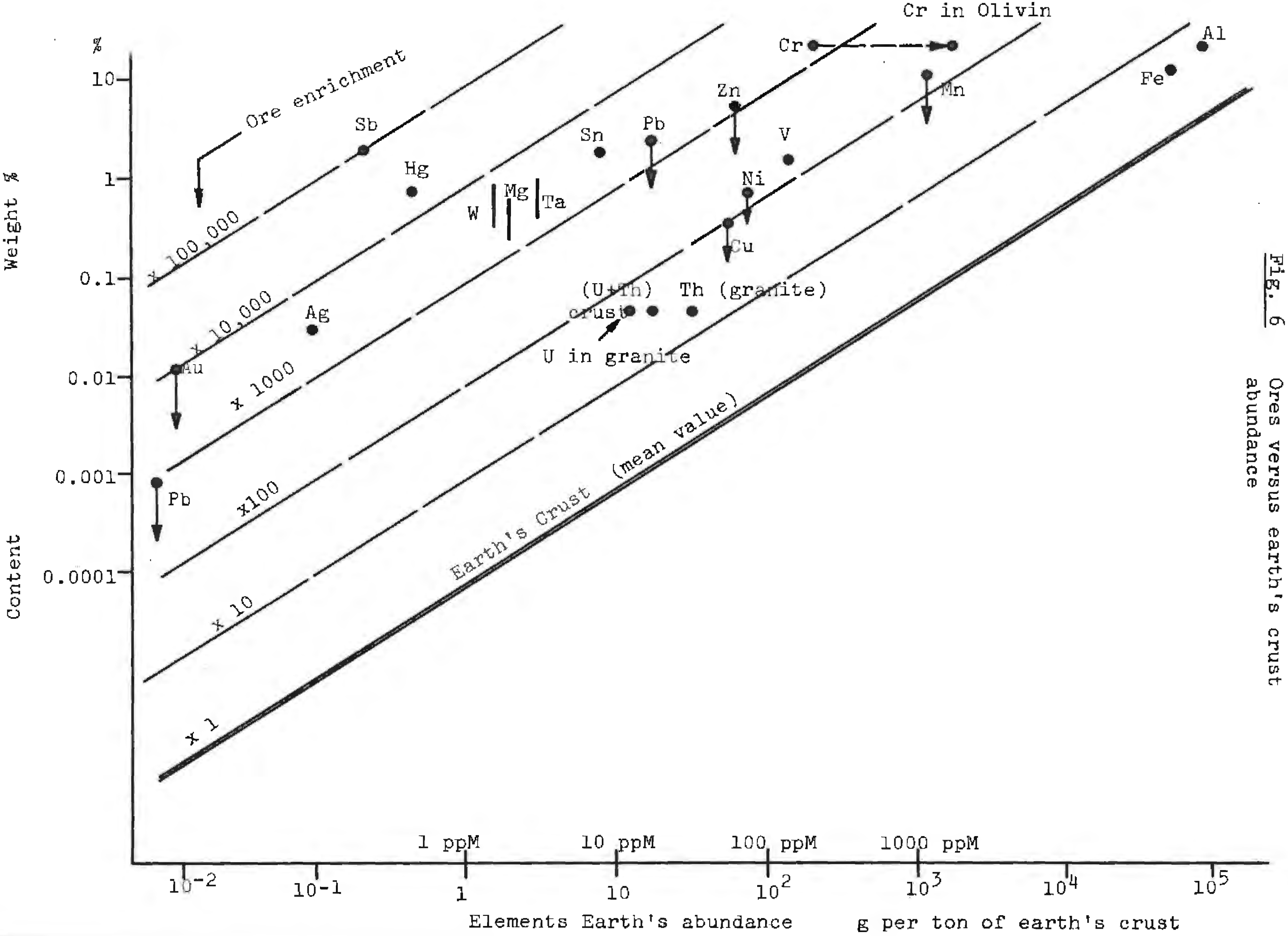
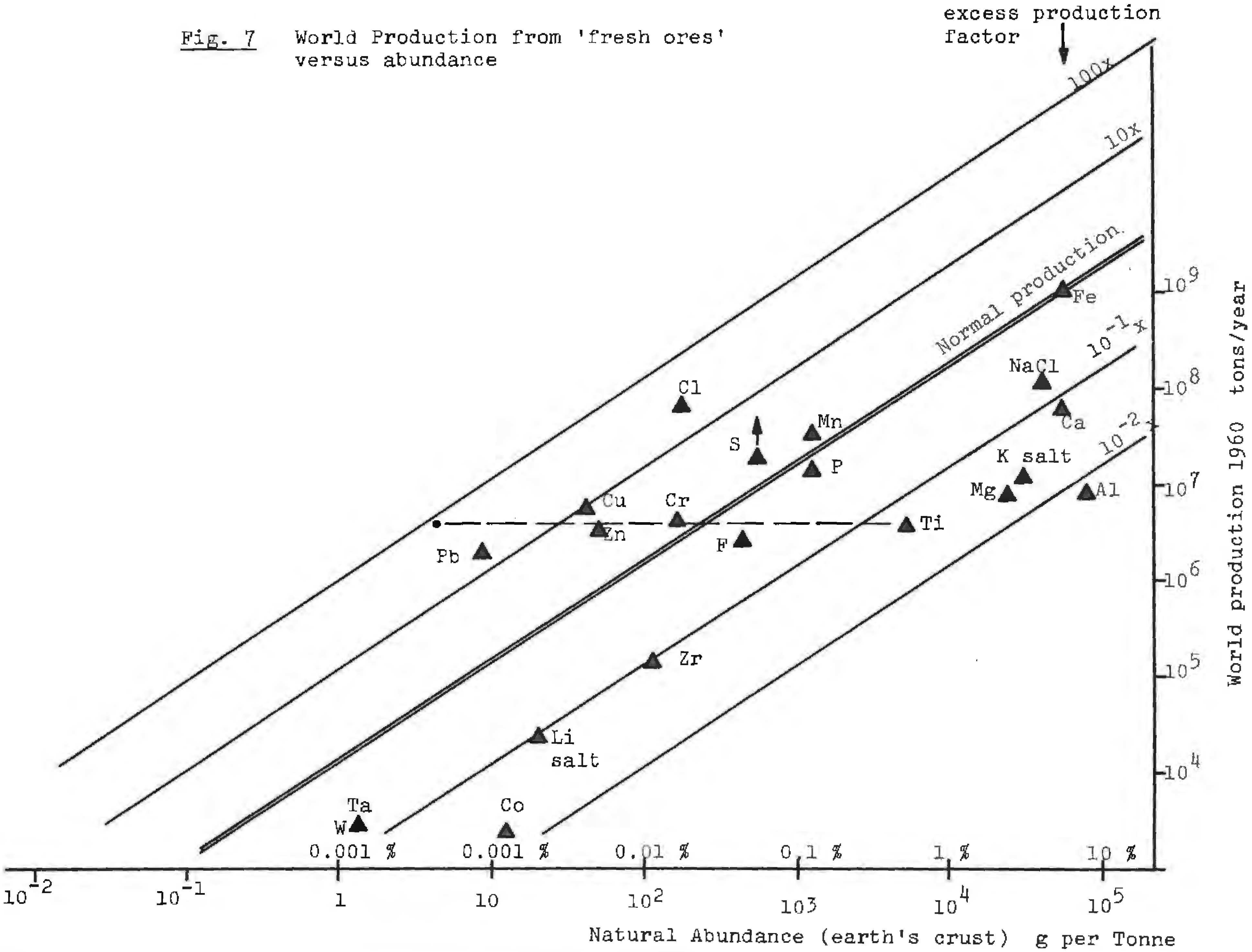


Fig. 6 Ores versus earth's crust abundance

Fig. 7 World Production from 'fresh ores' versus abundance



Then we classify the other metals in the following classes:

- metals being extracted more or much more than the 'natural ratio' e.g. Pb, Sn, Ag, Au, Cd, Hg, W, Zn
- metals being extracted in the right proportion
  Fe (reference) Mn, Cr and U (when taken together with Thorium)
- metals being extracted at a too low rate
  Al (the most important!)
  Mg, Ti, Zr, Mg, Co.

From this we might draw the following conclusion: if we are to operate a technology of metals use without waste or with the minimum of waste than the ratio of the extracted metals should be in accordance with the ratio existing in the earth's crust. Of course such an alteration in the relative and absolute amounts of extracted metals will have a vital impact on the technology.

V. Energy Balance for element extraction from the earth's crust

The jump from using the classical ores to the use of the earth's crust generally as a source of material clearly means an increase of free energy needed for element (or compound) extraction.

Questions to be answered

- are the potential energy sources large enough to meet this increased demand?
- is the increase in energy consumption a fair price to pay and a positive solution from the point of view of environmental policy?

The first of these questions is discussed here. The second is discussed elsewhere.

As can be seen from table 3, from 1 ton of rock with a mean elementary abundance for complete extraction and transformation of all components to free elements requires, if a electrolysis in molten salt media (e.g. chloride) is postulated.

- theoretically (100% efficiency) ≅ 11 Gigajoules (GJ)
- practically (20% efficiency) ≅ 55 GJ

(Remark: part of this energy in form of electrical energy, and part of heat)

For processing 1 ton of rock per capita per year the free energy requirement almost equals

$$\frac{55 \text{ GJ/year}}{3.15\text{x}10^7 \text{ s/year}} = 1700 \text{ watts/capita}$$

Table 3 Free energy for extraction from 1 tonne of rocks (simplified earth's crust chemical composition)

Element	In 1000 kg of rock		Oxide	Mol Oxygen	Free enthalpy KJ/ mol oxide (in 1000 kg rock)	Free enthalpy for dissociation (GJ) (theoretically)
	kg	mol				
Si	277	10.000	SiO_2	20.000	700	7.0
Al	81.3	3.000	Al_2O_5	4.500	670	2.01
Fe	50	900	$FeO_{1.2}$	1.200	200	0.18
Ca	36.3	880	CaO	880	530	0.47
Na	28.3	1.200	Na_2O	600	280	0.33
K	26.0	680	K_2O	340	220	0.23
Mg	21.0	860	MgO	860	540	0.46
				total		
O	466	29.000	---	28.380		3.68 without SiO_2 10.68 with SiO_2

Considering the contents of 1 ton of earth's crust from the point of view of the possible free energy carried (see table 1) we get

Th + U ~12 g

(the problem of lithium as a possible source of tritium for the $^{6}Li\ (n, {}^{4}He)\ {}^{3}T$ reaction or $^{7}Li\ (n,n\,{}^{4}He)\ {}^{3}T$ is not discussed here for the reasons given in chapter 1.)

We assume for the U + Th extraction efficiency a figure of 0.30 (but there no limitation for e.g. a two or three times higher efficiency) which gives:

(1 ton earth's crust rocks per year and capita)

$$\frac{12\ \text{g/ton} \times 0.30 \times 8.6 \times 10^{10}\ \text{J/g U,Th}}{3.15 \times 10^{7}\ \text{s/year}} \cong 10.9\ \text{kW/capita}$$

(1 ton granites per year and capita)

$$\frac{50\ \text{g/ton} \times 0.30 \times 8.6 \times 10^{10}\ \text{J/g U,Th}}{3.15 \times 10^{7}\ \text{s/year}} \cong 41\ \text{kW/capita}$$

With these assumptions we arrive at the following conclusions:

Processing of 1 ton per capita/per year of 'earth's crust rock' requires 1.7 kW (tot) even with only 30% extraction efficiency of thorium, uranium produces power of 11 kW or 6.5 times more.

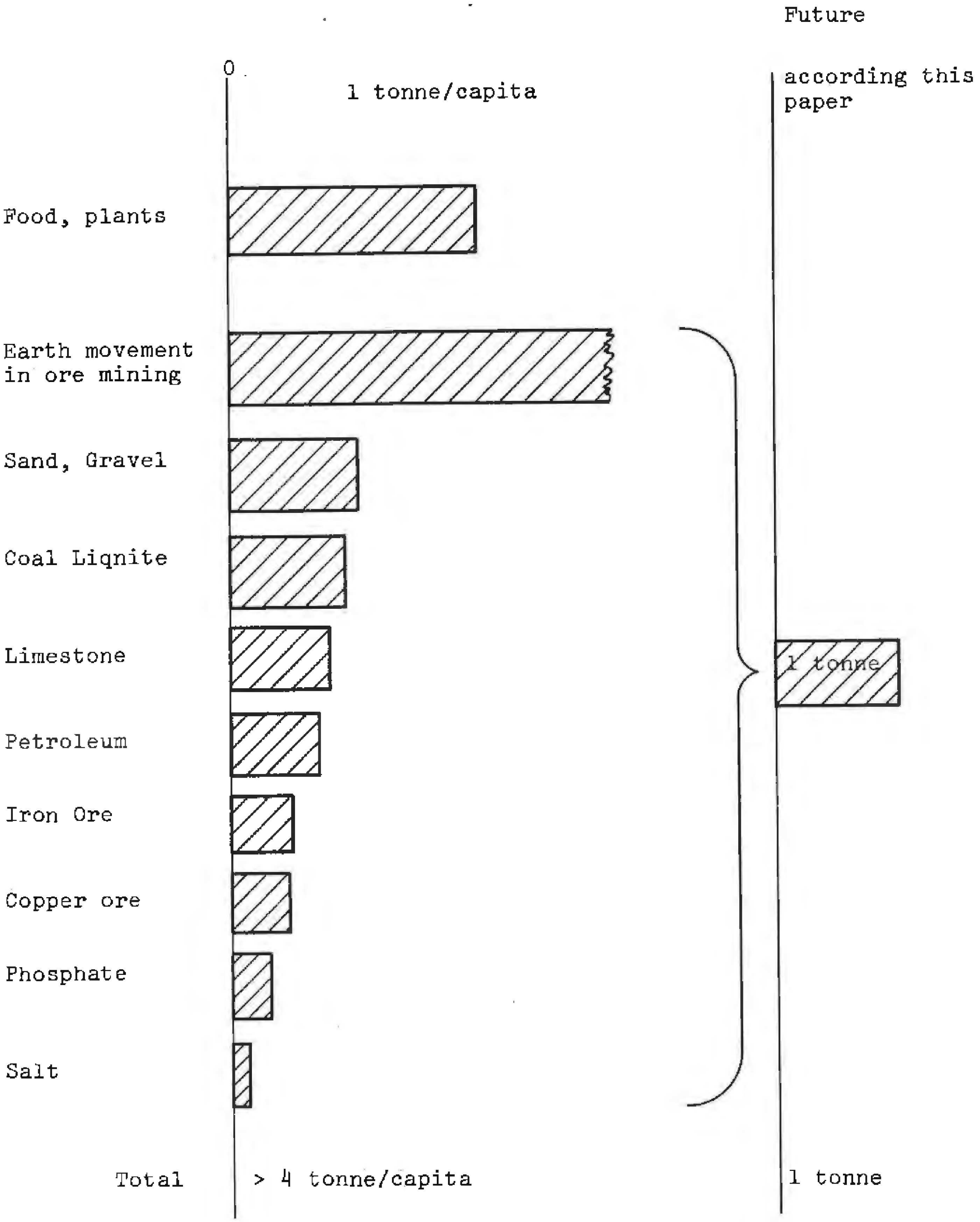
The same calculation for granites (1 ton per year per capita) gives an power of 41 kw per capita which is 24 times more than is needed for the extraction of the metals, or in other words about 4.1% of the energy available is used for mineral extraction. In the USA at the present time the raw material production requires 5.6% and electrolysis 1.1% making a total of 6.7% of the total energy consumption.

Table 4 The efficiency (η) of metal extraction and metal recycling in terms of energy (in kW-hr/ton metal)

Metal	"Fresh" extraction			Recycling	
	free energy theoret.	free energy pract.	efficiency η %	Recycling: Technology practically	efficiency η %
Mg	1208	91000	1.3	1395	75
Al	4600	52000	9	1300	28
Fe (Fe ores)	941	4500	20	1240	60
Fe (Ti ores)	941	2500	45		
Cu	424	13500	2.5	630-1500	25-6
Ti	2885	140000	2	39000	28

Fig. 8 gives the present and possible future flows of material if the assumptions made here are correct.

Fig. 8 Material Flows Present



VI. Size of present and future material flows

One of the future aims of environmental protection among others will be without doubt the reduction in the amount of materials extracted from natural deposits per capita. We include here the waste together with the main products.

The present state of material flows seems to be far from the optimal (or rather far from a reasonable minimum). The material flow per capita per year is approx 4 tons without taking into account the large amounts of spoil (open cast mining etc.) moved, loss of agricultural land and disposal of wastes.

VII. Earth's crust rocks as an energy material source

To some extent the achievement of using rocks as a source of fissionable nuclides (or fissionable nuclides) depend on the ability to produce metal and ceramic materials as by-products of the process.

In table 5 is given a very simplified and approximate division of the earth's crust material for the production of some materials.

The results seem to indicate (for 1 ton rock/per capita)

Metals total		130 kg/year
Aluminium	70.0 kg	
Iron	45.0	
Magnesium	10.0	
Titanium	4.0	
Manganese	0.9	
Zirconium	0.15	
Vanadium	0.12	
Chromium	0.1	
Nickel	0.07	
Zinc	0.06	
Copper	0.05	

Cement	100 kg/year
Glass	200 kg/year
Quartz	100 kg/year
"Silicon"-plastics (C & H from other sources)	100 kg/year
Other (fillings)	250 kg
Free oxygen	150 kg

Table 5 Earth's crust rocks as potential source of material

Element	kg in 1 tonne	Pure metals	Cement	Glass	Quartz	"Silicons" (semiorganic plastics)	Other material (nondefined)	Non metallic elements
O	466	70	33	90	50	-	143	150 free
Si	277	-	12	70	50	50	95	-
Al	81	70	3	-	-	-	8	-
Fe	50	45	5	-	-	-	-	-
Ca	36	-	30	6	-	-	-	-
Na	28	-	-	20	-	-	8	-
K	26	-	-	10	-	-	16	-
Mg	21	10	10	1	-	-	-	-
Ti	4.4	4	-	-	-	-	-	-
H	1.4	-	-	-	-	-	-	-
P	1.1	-	-	-	-	-	1.1	-
Mn	0.9	0.9	-	-	-	-	-	-
F	0.6	-	-	-	-	-	0.6	-
Ba	0.4	-	-	-	-	-	-	-
S	0.25	-	-	-	-	-	-	0.25
C	0.20	-	-	-	-	30*		
Total		130	93	197	100	100	274	150

* From carbonate rocks

Table 6 Amounts of materials in use per capita

Material	Postulated production (kg/year)	Recycling (kg/year)	Time of life by users (years)	Amounts in continuous use (kg/capita)
Metals	130	12 times 1500	25	37,500
Cement	100	3 times 300	40	12,000
Glass	200	5 times 1000	10	15,000
Quartz	100			
"Silicons" plastics	100	5 times 500	5	2,500
Other	270	1 time 270	100	27,000

VIII Impact on the philosophy of reactor development

From all these developments we can suggest the following as that which might result in the development of reactor technology.

- the breeder reactors, both with Unat/Pu-239 and Th/U-233 fuel cycles could provide a total energy production of approximately 10,000,000 TW years.

that is a 160 TW civilization (8 Gigapeople with 20 kw/capita) for about one hundred thousand years even when one ten thoudandth part of the rocks will be burned.

- the breeder must in the future use both uranium and thorium and, therefore, probably both fast and thermal breeders are of interest (fig. 9, 10).
- the impact of the extraction of U + Th from the earth's crust rocks is small (see table 7).
- the use of the rocks for U + Th extraction must be coupled with the complex recovery of other materials, metals etc.
- the power production could be totally independant from the suppliers of 'energy carriers' (no monopoly of energy sources).
- the large amount of radioactive waste (fission) need not be stored but rather burned up in a high neutron flux reactor, or an accelerator.
- the cost of all these additional processes will be significant but not crucial.

If the so called 'environmental taxes' (or entropy taxes) proposed for the future come into effect then the penalty of these new processes will be small and even negative (a profit).

Fig. 9 Scheme of 'ideal' energy and material flux anually and per capita in future.

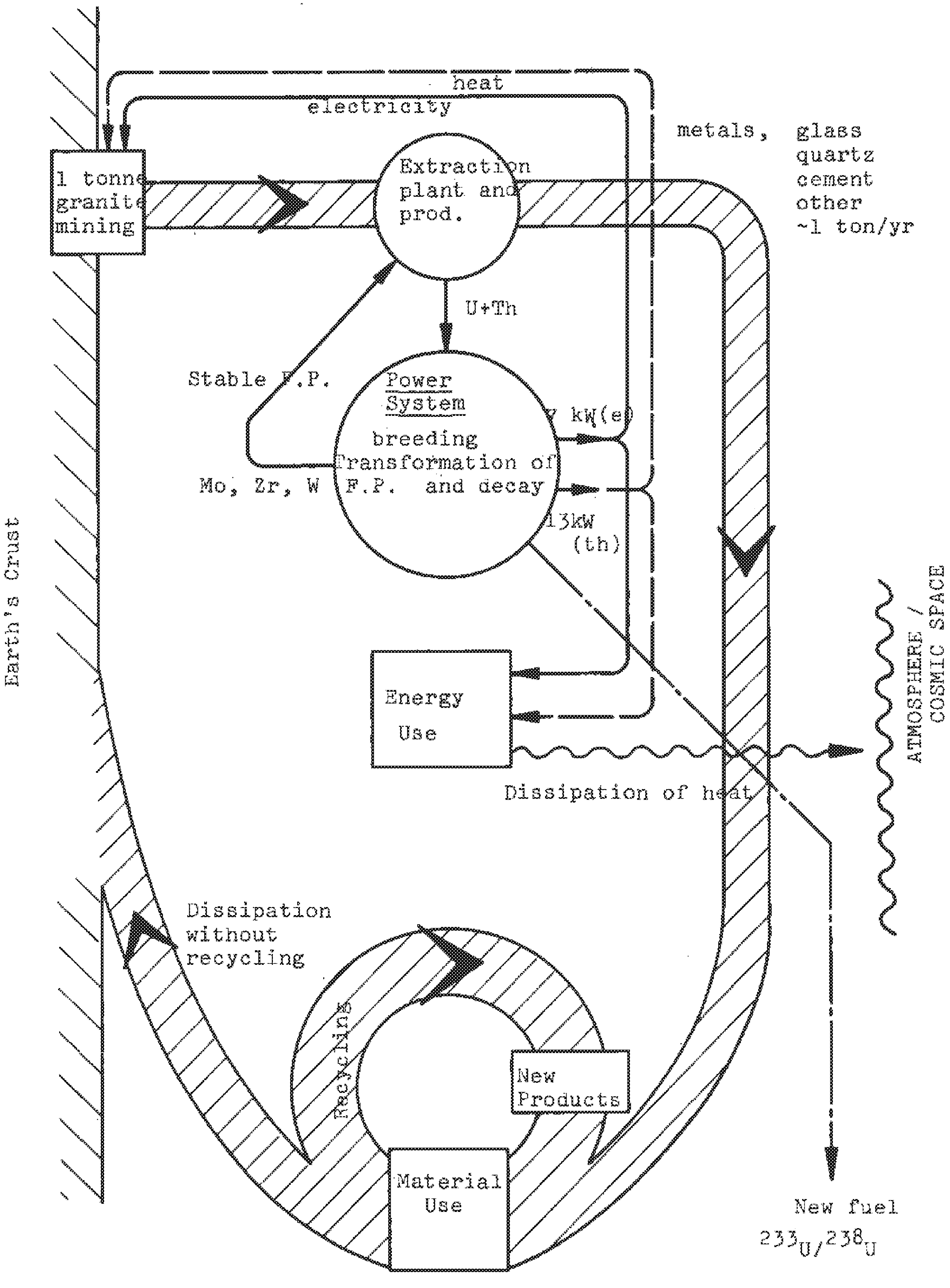


Fig. 10 Schematic Reactor Arrangement

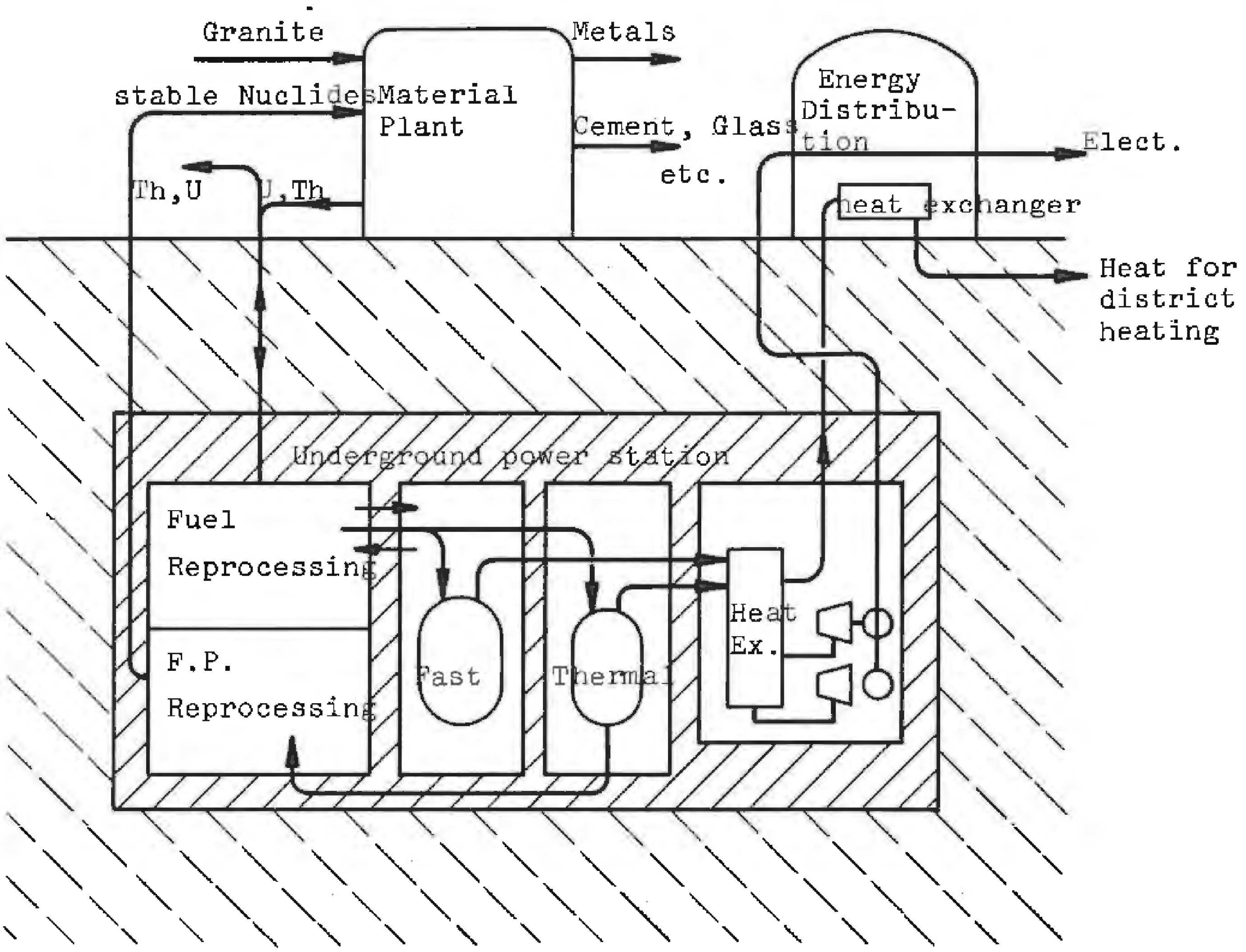


Table 7 Impact of the extraction U + Th from rocks

A) Price of plutonium = 10.000 \$/kg

$$1 \text{ kg Pu} = 10^3 \text{x} 10^6 \text{x} 8.6 \text{x} 10^4 \text{ J} = 8.6 \text{x} 10^{13} \text{ (tot)} = 3.4 \text{x} 10^{13} \text{J (el)}$$

$$= \frac{3.4 \text{ x } 10^{13} \text{ J (el)}}{3.6 \text{x} 10^6 \text{ J/KWhr (el)}} \cong 10^7 \text{ KWhr (el)}$$

$$\text{Pu cost in 1 KWhr (el)} = \frac{10^4 \text{\$/kgx} 10^3 \text{ mills/\$}}{10^7 \text{ KWhr(el)/kg Pu}} = \frac{1 \text{ mills/}}{1 \text{ KWhr (el)}}$$

B) The uranium cost for plutonium synthesis

1 kg U → ~1 kg Pu

If the cost of U production rises from 20\$ to 1000 \$/kg the contribution in the plutonium price will be approx 10%, because:

1) U price: 20\$/kg → 10.000 \$/kg Pu
2) U price: 1000 \$/kg → 11.000 \$/kg Pu

C) The element of plutonium cost in the electrical energy cost will change from 1 mills/KWhr to 1.1 mills/KWhr, so that in the total electrical KWh cost will change from 12 mills to 12,1 mills that is in the order of 0.8%.

Table 8 Preliminary costs of power generating

	Capital + operation $/KW(e)	Amort + Capital cost 12%/year	Mills KWh (e)	Classical fuel cycle
"Classical reactor"	500	60	8.5	
Reprocessing plant	100	12		out of power station
Nuclear transformation	100 400	12 48	6.8	waste storage
District heat	100	12		cooling tower pollution landscap safety tax
Unterground building	100	12		
Total	900	108	15.3	

Remark: because of rather preliminary and rough calculation of these problems, no references are given here explicity.