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Classification of Solid Fossil Fuels and Their Processing Products Depending on Trace Elements Contained in Them

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Abstract—It was shown that products or wastes (the primary concentrates of potentially valuable elements (PVEs)) suitable as source materials for the manufacture of commercial PVE compounds or their industrial concentrates can be obtained upon the processing of coal, oil shale, or peat as fuel for combustion or a source material for coking. It was proposed to classify solid fossil fuels containing PVEs with the following two groups: the first group, those suitable for the priority use in the production of primary PVE concentrates and the second group, those promising for the production of primary PVE concentrates after performing appropriate technical and economic calculations. The type of the initial solid fossil fuel or its processing product; the PVE content of the initial solid fossil fuel; the characteristics of PVE distributions in the products of its enrichment, coking, combustion, gasification, and hydrogenation; and the chemical species of ash and slag residues upon combustion (gasification) were chosen as classification parameters, which were designated using numerical or alphanumeric codes.

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As a rule, the elements whose concentrations in coals and other solid fossil fuels are $\leqslant 0.1$ wt % are referred to as trace or impurity elements or the microcomponents of the mineral matter of solid fossil fuels. Almost all of the elements of the Mendeleev periodic table were detected in coals and other solid fossil fuels. The trace elements of the greatest scientific and, especially, practical interest (whose production as commercial compounds is economically sound) are referred to as industrially potentially valuable elements (PVEs), and the trace elements that can pass into the environment in the form of compounds dangerous for the biosphere in the course of the production or processing of solid fossil fuels are referred to as potentially toxic elements (PTEs) [1–7]:

PVEs: Ag, Au, Ce, Co, Cd, Cr, Cu, Ga, Ge, total rare-earth elements (TREs), Li, Mo, Nb, Pt and platinum group metals, Sc, Se, V, Y, Zr, W, U, and Th;

PTEs: As, Be, Ba, Cd, Co, Cr, Cu, Hg, Mn, Mo, Ni, Pb, Se, Sr, Tl, V, Zn, and natural radionuclides (Th, U, ^{40}K, Rn, etc.).

It is necessary to note that many of the trace elements enter into both of the PVE and PTE groups. Consequently, the industrial production of commercial PVE compounds simultaneously solves the problem of the prevention of a dangerous environmental impact of corresponding PTEs.

Obviously, this grouping is tentative, especially, as applied to the PVEs. Thus, the classification of a particular trace element to PVEs depends on a number of variable factors: the PVE content of the initial solid fossil fuel, the state of technologies for PVE extraction from the products of solid fossil fuel conversion, a demand for the compounds in Russia and on the world market and hence the prices for the PVE compounds, promising methods for the use of particular solid fossil fuels, etc.

Based on the really detected PVE concentrations in industrially produced solid fossil fuels, it is possible to make a preliminary conclusion that a promising and economically effective process for the production of PVEs should be based on the rigorous use of the power or chemical energy potential of corresponding solid fossil fuels with the utilization of low-value wastes or by-products. Furthermore, expenditures for the accumulation of PVEs in these products and the trapping and collection of these products should be relatively small, and they should cause no substantial changes in the technical and economic indices of the main process with the use of the source solid fossil fuels. The products enriched in one or more PVEs are referred to as primary PVE concentrates if their further processing makes it possible to economically profitably produce commercial PVE compounds or commercial PVE concentrates for their current use on an industrial scale for the manufacture of commercial compounds from them.

Coking and combustion are currently the largest scale processes that use coals in Russia and many other countries.

Upon the coking, the main amounts of organic and mineral substances, including Ge, Cr, Ni, and Zr and, probably, rare-earth elements, Mo, Nb, V, and W are concentrated in coke as the major product. By-products (ammonia-tar and pyroligenous liquors, tars, and sludge) usually contain less than 10–12% PVEs (on a total weight basis in the initial coal). The exception is provided by mercury, which, apparently, can form gaseous products in significant quantities in the high-temperature zones of coke ovens; after the cooling of coke oven gas, these products are partially condensed in the form of liquid mercury metal. The collected liquid mercury metal is an almost finished commodity product. However, up to now, studies that make it possible to quantitatively estimate the yield of mercury metal upon the coking of coal charges with different mercury contents and mineral matter compositions were not carried out.

Coke is a relatively expensive product, and all of the studies on the extraction of trace elements, primarily germanium, from it did not lead to the development of a technology acceptable in terms of technical and economic indices. For the same reasons, works dedicated to an increase in the recovery of germanium into gaseous, liquid, or solid coke by-products were unsuccessful. For germanium and gallium, it was experimentally established that no more than 10–12% of these PVEs (on a total weight basis in the initial coal) usually passed into the by-products (ammonia-tar and pyroligenous liquors, tars, and sludge). Technologies for the production of commercial Ge and Ga concentrates from aqueous solutions are not associated with high expenditures, and the production of the industrial concentrates of germanium from ammonia-tar liquor and coal coking tar has been performed for many years [1]. For its economically feasible implementation, there are limitations on the amount of germanium in these products, which is proportional to the germanium content of the initial charge for coking.

Laboratory and pilot studies performed in Russia and Hungary [1] showed that, in principle, the production of cokes (semicokes) with the increased concentrations of some PVEs (rare-earth elements, V, Ni, Co, Mo, W, etc.) for use in the manufacture of special steels characterized by increased concentrations of some of the above trace elements is promising.

As compared with coking, processes for obtaining by-products enriched in PVEs can be implemented on much larger scales in industrial combustion and, to a lesser degree, in the gasification of coals. The results of studies on the behavior of PVEs on combustion and, in a smaller volume, on the gasification of coals performed by thermodynamic calculation and experimental methods both on laboratory and bench testing units and under semiindustrial and industrial conditions were published [7, 8].

The generalization of this information makes it possible to develop principles for the classification of solid fossil fuels or their processing products as potential raw materials for the production of PVEs or special steels. Based on this classification, it is possible to prepare preliminary recommendations for a particular solid fossil fuel of interest with respect to the advisability of the simultaneous manufacture of primary PVE concentrates after the combustion of solid fossil fuels[1] or cokes (semicokes) for obtaining special steels[2].

The selection of the parameters of this classification is based on the following considerations:

– their values can be obtained either from known information, which describes coal or other forms of solid fossil fuels, or as a result of the analysis of their representative samples by the standard methods of coal chemistry;

– there are published data on the influence of a selected parameter on the distribution of PVE compounds between the conversion products of coal or another form of solid fossil fuels in question.

For the characterization of a distribution of trace elements between conversion products, the reduced concentrations Y_i or Y_i^A calculated on a source material basis (for the test solid fossil fuel) or on an ash basis, respectively, and the yield U_{ig} in the conversion product were accepted:

$$Y_{ig} = C_i/C_0, \quad (1)$$

$$Y_{ig}^A = C_i^A/C_0^A, \quad (2)$$

$$C_0^A = 100C_0/A_0, \quad (3)$$

$$U_{ig} = Y_{ig}\gamma_g, \quad (4)$$

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[1] Commercial compounds cannot be obtained immediately after the combustion of solid fossil fuels; as noted above, the by-products of combustion enriched in PVEs are referred to as their primary concentrates. Their commercial compounds or industrial concentrates are produced by the processing of the primary concentrates if related expenditures are redeemed by the market values of their commercial compounds or industrial concentrates.

[2] The distributions of trace elements upon the gasification of solid fossil fuels were studied to a much smaller degree than those upon the combustion; because of this, an appropriate classification of solid fossil fuels cannot be proposed.

Table 1. Parameters of the classification of trace elements as a potential raw material source for the production of valuable trace elements

Classification group and subgroup parameters	Alphanumeric code	Numerical code	
		Position in the numerical code	symbol
1. Type of the initial raw material			
1.1. Coal	–	1	–
(*a*) power-generating coal	1.1*a*	1	1
(*b*) coking coal	1.1*b*	1	2
1.2. Shale	–	1	–
(*a*) oil shale	1.2*a*	1	3
(*b*) black shale	1.2*b*	1	4
1.3. Cleaning rejects	–	1	–
(*a*) gravitation rock	1.3*a*	1	5
(*b*) flotation tailings	1.3*b*	1	6
1.4. Enrichment concentrate	–	1	–
(*a*) power-generating coal	1.4*a*	1	7
(*b*) coking coal	1.4*b*	1	8
(*c*) oil shale	1.4*c*	1	9
1.5. Combustion product	–	1	–
(*a*) fly ash	1.5*a*	1	10
(*b*) slag	1.5*b*	1	11
1.6. Dump waste product (from waste bank or pond)	1.6	1	12
1.7. Ash pond product	1.7	1	13
1.8. Overburden	1.8	1	14
2. Concentration in raw material, g/t			
2*a*. $\geqslant$ 0.2–1	2*a*	2	1
2*b*. 1–5	2*b*	2	2
2*c*. 5–50	2*c*	2	3
2*d*. 50–150	2*d*	2	4
2*e*. 150–250	2*e*	2	5
2*f*. > 250	2*f*	2	6
3. Distribution between the concentrates of solid fossil fuels			
3*a*. An increased concentration in a concentrate ($Y_{ic} \geqslant 1$) with a density of < 1.6 g/cm^3	3*a*	3	1
3*b*. An increased concentration in a fraction of > 1.6 g/cm^3 ($Y_{i\,w} \geqslant 1$	3*b*	3	2
3*c*. Approximately equal concentrations in light and heavy fractions ($Y_{ic} \approx Y_{iw}$ to within ± 15 rel %)	3*c*	3	3
4. Behavior in thermal treatment processes			
4.1. Combustion	–	4	–
(*a*) condensed at $\geqslant$ 100°C;	4.1*a*	4	1
(*b*) noncondensed at $\geqslant$ 100°C;	4.1*b*	4	2
(*c*) predominant transfer to a gas phase in the high-temperature zone with the subsequent quantitative condensation at $\geqslant$ 100°C,	4.1*c*	4	3
(*d*) predominant transfer to condensed phases in the high-temperature zone	4.1*d*	4	4
(*e*) distribution between phases in the high-temperature zone practically depends on only the yields of slag and fly ash ($Y_{is} \approx Y_{if}$)	4.1*e*	4	5

Table 1. (Contd.)

Classification group and subgroup parameters	Alphanumeric code	Numerical code	
		Position in the numerical code	symbol
4.2. Gasification	–	4	–
(*a*) condensed at $\geqslant$ 100°C	4.2*a*	4	6
(*b*) noncondensed at $\geqslant$ 100°C	4.2*b*	4	7
(*c*) predominant transfer to condensed phases in the high-temperature zone	4.2*c*	4	8
(*d*) distribution between phases depends on the conditions of gasification	4.2*d*	4	9
(*e*) predominant transfer to a gas phase in the high-temperature zone	4.2*e*	4	10
4.3. Coking	–	4	–
(*a*) condensed at $\geqslant$ 100°C,	4.3*a*	4	11
(*b*) noncondensed at $\geqslant$ 100°C	4.3*b*	4	12
(*c*) predominant transfer to condensed phases,	4.3*c*	4	13
(*d*) almost uniform distribution between phases	4.3*d*	4	14
4.4. Hydrogenation	–	4	–
(*a*) gaseous products ,	4.4*a*	4	15
(*b*) products with T_b < 500°C	4.4*b*		16
(*c*) products with T_b < 500°C	4.4*c*	4	17
5. Chemical species in ash and slag products			
5.1. Predominant formation of gaseous $GeCl_4$ after the action of concentrated hydrochloric acid on fly ash ($T \geqslant$ 100°C)	5.1	5	1
5.2. Passage into solution (80–90%) after treatment ($T \geqslant$ 90°C) with 10–15% aqueous solutions of sulfuric, nitric, or hydrochloric acid.	5.2	5	2

where C_i and C_0 are the concentrations of the *i*th trace element in the conversion product obtained and the source material, respectively; C_i^A, C_0^A are the concentrations of the *i*th trace element on an ash basis for the conversion product or source material, respectively; γ_g is the yield of the *g* fraction of a solid fossil fuel or conversion product (arb. units or wt %); and A_0 is the ash content of solid fossil fuel or a concentrate after its enrichment directed for combustion.

Upon enrichment, trace elements are distributed between the fractions of different density: concentrate, intermediate product, and high-ash fraction with densities of <1.6, 1.6–1.8, and >1.8 g/cm^3, respectively. Because both the concentrate and the intermediate product are used for combustion, it is tentatively considered that the fraction with a density of >1.8 g/cm^3 is the solid waste of enrichment.

In the processes of combustion and gasification, slag, which is formed directly in the furnace volume, and fly ash removed from the furnace with the gaseous products are considered as solid products. They are characterized by the reduced concentrations Y_{is} and Y_{ig}^A for slag or Y_{if} and Y_{if}^A for fly ash, respectively, that is, those calculated for the initial fuel on a total weight basis or an ash basis from Eqs. (1) and (2), respectively. If liquid products are obtained after heat treatment, the reduced concentrations can also be calculated for them from Eqs. (1) and (2). A conversion product is referred to as a concentrator of trace elements if its $Y_{ig} \geqslant 1$ or as a carrier of trace elements at $U_{ig} \geqslant 50\%$ (or 0.5, depending on the dimensionality of Y_{ig}). For many solid fossil fuels, a particular conversion product is not always simultaneously both a concentrator and a carrier of trace elements [1].

Because the values of C_i, C_0, C_i^A, C_0^A are determined experimentally, they mainly depend on the accuracy of the analytical determination of trace elements, which is usually no smaller than ±15 rel %. Therefore, for example, the assertion that $Y_i = 1$ actually indicates that $Y_i = 1 \pm 0.15$.

Taking into account the above considerations, we accepted the following parameters of the proposed classification of combustible solid materials used as fuels or coal for coking:

– the form of solid fossil fuel or solid waste material (a by-product of their processing);

– the concentration of trace elements in the material;

– the parameters of a trace element distribution (Y_{ig} and U_{ig}) between the products of solid fossil fuel conversion and between solid (liquid) and gas phases under the action of different reagents on a solid conversion product.

Table 1 summarizes the chosen parameters of the classification of solid fossil fuels as potential raw materials for the production of PVEs. The test coal or other forms of solid fossil fuels are designated by an alphanumeric code (Table 1, column 2) or a numerical code (Table 1, columns 3 and 4). In a numerical code, each parameter is characterized by a place (ordinal number), and its value, by a number in this place, as shown in Table 1. Each group of parameters is separated from the subsequent group of parameters by a semicolon, and the parameters in a group are separated by commas. The parameters of the same group separated from each other by commas are designated as the parameters of the same subgroup. If the parameters of a particular group (subgroup) are unknown for a trace element, the corresponding group (subgroup) is not included in the alphanumeric code, but 0 is placed at the corresponding place in the numerical code.

For example, we consider power-generating coal with a Ge content of 120 g/t. According to reliable experimental data [1], upon the enrichment of coal, germanium is concentrated in concentrate fractions with a density of <1.6 g/cm^3 or in a mixture of concentrate and intermediate product with a density of <1.8 g/cm^3. Upon combustion, the main amounts of germanium and some other PVEs described by the parameters 4.1*c* and 4.1*a* form gaseous compounds in a high-temperature zone; these compounds condensed on the surface of fly ash at $T < 600–700°C$. Germanium and other PVEs from the above subgroups can be trapped together with fly ash on the removal of solid particles from the gaseous products of the combustion of solid fossil fuels. However, the degree of their trapping together with fly ash (U'_f) is usually lower than the degree of trapping of the latter [1]. The distribution of germanium between gasification products depends on the conditions of gasification; after coking, the main amounts of germanium are concentrated in the coke, whereas, after hydrogenation, they are concentrated in high-boiling fractions and solid residues, which are usually combusted together with the solid residue of unreacted organic matter and the hydrogenation products of the mineral components of the initial coal and the catalyst added.

Based on the above published information, the test sample of coal is described by the following alphanumeric code: 1.1a; 2d; 3a; 4.1a, 4.1s, 4.2a, 4.3s, 4.4s. The numerical code of this test sample is 1; 3; 1; 3, 6, 8, 13, 17. It should be noted that, in the evaluation of coals or other solid fossil fuels with respect to the extraction of germanium from them, their codes will differ from the above alphanumeric and numerical codes only in the parameters that characterize the type of solid fossil fuels and the concentrations of germanium in them.

The primary PVE concentrates obtained as a result of the combustion of solid fossil fuels are fly ash or the mixtures of fly ash and slag, which are collected upon the combustion of coals or other solid fossil fuels. Consequently, for the calculation of the reduced concentrations and the recoveries of PVEs, their degrees of extraction into these collected products should be taken into consideration [1, 5, 6].

The selection of optimum technologies for the processing of primary PVE concentrates, for example, fly ash or ash and slag, depends on many factors (the possible site of ash and slag removal, the local infrastructure, the prices of world market, the need for the resulting commercial PVE compounds, etc.) in addition to the concentrations of PVEs and the physicochemical properties of their compounds in fly ash or ash and slag. Therefore, is necessary to perform technical and economic calculations for the solution of this problem. However, promising methods for the production of primary PVE concentrates can be preliminary selected based on the proposed classification of solid fossil fuels (Tables 1, 2).

Because either fly ash or ash and slag can be a primary concentrate for the manufacture of commercial PVE compounds in actual practice, Table 2 shows the possible solutions of the problem of selecting a method for the combustion of solid fossil fuels or their processing products as an example. This makes it possible to reach a maximum degree of enrichment (Y_f) in these products, as compared with the concentration in the burnt raw material (coal, shale, or peat).

The values of the parameters Y_f and U'_f in Table 2 were calculated from the relationships proposed by Shpirt and Rashevskii [1] for fly ash or ash and slag, which do not contain unburned carbon:

$$Y_f = 100(1 - Y_s K_s)/A^d(1 - K_s), \quad (5)$$

$$U'_f = a_i U_f, \quad (6)$$

where K_s is the slag trapping coefficient, which is 0.05 for pulverized-coal furnaces with dry slag removal or 0.75 for fuel-bed or torch furnaces; Y_s is the reduced PVE concentration in the slag calculated in accordance with experimental data from Eq. (2); for coal or oil shale, the average ash contents $A^d = 20$ or 60% were taken; and a_i is the degree of PVE trapping in collected fly ashes ($a_i \leqslant 1$).

In accordance with published data [1], the values of Y_s for pulverized-coal furnaces ($K_s = 0.05$) were taken the same for coals, oil shales, and concentrates after their enrichment and equal to 0.1 as applied to Au, Ag, Ge, W, and Mo and 0.8 for Co, Cr, Ni, ∑TRE, and V; after the combustion of coals or concentrates after the enrichment of coals or oil shales in fuel-bed and torch furnaces ($K_s = 0.75$), they were 0.20 for Au, Ag, Ge, W, and Mo and 0.85 for Co, Cr, Ni, ∑TRE, and V.

Table 2. Degrees of enrichment of ash and slag products in PVEs at different methods of the combustion of solid fossil fuels or their preliminary processing products

PVE	Numerical code	Degree of enrichment* of fly ash (as compared with the concentration in the initial fuel), Y_f						Notes
		slag trapping coefficient of the furnace, K_s		fly ash trapping method		ash and slag directed to processing		
		$K_s = 0.05$	$K_s = 0.75$	dry**	wet	fly ash	fly ash and slag	
Ag	1; 2; 3; 1, 3, 6	5.2	15.6	$\frac{15.3}{5.0}$	–	15.3	–	Minimum concentrations, which are responsible for the potential of extraction, should be evaluated
Au	1; 1; 3; 1, 3; 6	5.2	15.6	$\frac{15.3}{5.0}$	–	15.3	–	Parameters 3*a*–3*c* (Table 1) should be refined for each particular coal
Co	1; 4; 0; 1, 4	5.05	7.2	$\frac{7.06}{4.9}$	–	–	4.9	Minimum concentrations, which are responsible for the potential of extraction, should be evaluated
Cr	1; 5; 2; 1, 4	5.05	7.2	$\frac{7.06}{4.9}$	–	–	4.95	The same
Ge	1; 3; 1; 1, 3, 6, 9, 17	5.2	15.6	$\frac{15.3}{5.0}$	–	15.3	–	”
Ge	7; 4; 0; 1, 3, 6, 9	N/A	3.8	$\frac{3.6\text{****}}{8.2}$	–	$\frac{3.56\text{****}}{8.12}$	–	”
Σ*TRE****	1; 5: 1: 1; 5	5.05	7.2	$\frac{7.06}{4.9}$	–	7.13	4.95	$T_{\text{combustion}} \leqslant 850°\text{C}$
Mo	1; 3; 1; 1, 3	5.2	15.5	$\frac{15.3}{5.0}$	–	15.3	–	Minimum concentrations, which are responsible for the potential of extraction, should be evaluated
Ni	1; 5; 1; 5	5.05	7.2	$\frac{7.06}{4.9}$	–	–	4.95	The same
W	1; 3; 1; 1, 3	5.05	$\frac{15.3}{5.0}$	15.6	–	15.3	+	”
V	1; 5; 1; 5	5.05	7.2	$\frac{7.06}{4.9}$	–	–	4.95	”

* The signs + and – indicate whether or not it is reasonable to use a PVE trapping method and fly ash or a mixture of fly ash and slag for the production of PVEs, respectively.

** Dry methods include bag filters or electrostatic precipitators at the degree of ash trapping of ⩾99% in the numerator at $K_s = 0.75$ and 0.05, respectively.

*** ∑TRE is the total concentration of lanthanides, yttrium, and scandium.

**** At a 10% yield of slag ($K_s = 0.1$).

For the trapping of fly ashes, which are considered as primary PVE concentrates that form gaseous compounds in the high-temperature zones of a furnace volume to be removed from it together with the gaseous products of combustion and condensed on the surfaces of fly ash particles, equipment that makes it possible to reach the degrees of ash trapping (b_i) of no less than 0.96 is commonly used; however, the degrees of PVE trapping are lower than the degree of trapping of fly ash particles. Quantitatively, the functions $a_i = f(b_i)$ are not identical, and they were not determined for different furnace plants and different PVEs. The

Table 3. Classification of solid fossil fuels as raw materials for the production of the primary concentrates of potentially valuable trace elements

PVE	Promising applications	
	top priority use of solid fossil fuels	use after performing the refined technical and economic assessment of solid fossil fuels
	classification parameter	classification parameter
Ge	1.1*a*, 1.4*a*; 2*c*-2*f*; 3*a*; 4.1*a*, 4.1*c*, 4.2*a*, 4.2*e*; 5.1, 5.2	1.5*a*; 2*d*
Ge*	1.1*b*, 1.4*b*; 2*b*-2*f*	1.1*a*, 1.4*a*; 2*b*
РЗЭ	1.1*a*, 1.4*a*; 2*e*, 2*f*	1.1*a*, 1.4*a*; 2*d*
РЗЭ*	1.1*b*, 1.4*b*; 2*e*, 2*f*	1.1*b*, 1.4*b*; 2*d*
Ag	1.1*a*, 1.4*a*; 2*b*-2*f*, 3*a*, 3*c*	1.2*a*, 1.2 *b*, 1.4*c*, 1.5*a*; 2*b*-2*f*; 4.1*a*, 4.1*c*
	1.5*a*, 1.5*b*, 1.6, 1.7, 1.8; 2*c*-2*f*	
Au	1.1*a*, 1.4*a*; 2*a*-2*f*; 3*a*, 3*c*; 4.1*a*, 4.1*c*, 4.4*c*	1.2*a*, 1.2*b*, 1.4*c*, 1.5*a*; 2*a*-2*f*; 4.1*a*, 4.1*c*
Co	N/A	1.1*a*, 1.4*a*; 2*d*-2*f*; 3*b*, 3*c*; 4.1*a*, 4.1*e*
		1.5*a*,1.5*b*; 2*d*-2*f*
Co*	The same	1.1*b*, 1.4*b*; 2*d*, 2*f*; 4.3*c*
Cr	“	1.1*a*, 1.4*a*; 2*e*, 2*f*; 3*b*, 3*c*; 4.1*a*, 4.1*e*
Cr*	“	1.1*b*, 1.4*b*; 2*e*, 2*f*; 4.3*c*
Ga	“	1.1*a*, 1.4*a*; 2*d*-2*f*; 3*c*; 4.1*a*, 4.1*c*
Mo	1.1*a*, 1.4*a*; 2*d*–2*f*; 3*a*, 3*c*; 4.1*a*, 4.1*c*, 4.4*c*; 5.2	1.1*a*, 1.4*a*; 2*d*-2*f*; 3*a*, 3*c*; 4.1*a*, 4.1*c*, 4.1*e*, 4.4*c*; 5.2
Mo*	N/A	1.1*b*, 1.4*b*; 2*c*-2*f*; 4.3*a*, 4.3*c*
Ni	The same	1.1*a*, 1.4*a*; 2*c*-2*f*; 3*b*, 3*c*; 4.1*a*, 4.1*e*
		1.5*a*,1.5*b*; 2*d*-2*f*
Ni*	“	1.1*b*, 1.4*b*; 2*d*-2*f*; 4.3*a*, 4.3*c*
Nb	“	1.1*a*, 1.4*a*; 2*d*-2*f*; 3*b*, 3*c*; 4.1*a*, 4.1*e*
		1.5*a*, 1.5*b*; 2*d*-2*f*
Nb*	“	1.1*b*, 1.4*b*; 2*d*-2*f*; 4.1*a*, 4.3*c*
Se	“	1.1*a*, 1.4*a*; 2*d*-2*f*; 3*b*, 3*c*; 4.1*a*, 4.1*c*
Sr	“	1.1*a*, 1.4*a*; 2*d*-2*f*; 3*a*, 3*c*; 4.1*a*, 4.1*e*
Sc	1.1*a*, 1.4*a*; 2*e*–2*f*; 3*a*, 3*c*; 4.1*a*, 4.1*e*	1.1*a*, 1.4*a*; 2*d*-2*f*; 3*b*, 3*c*; 4.1*a*, 4.1*e*
Ta	N/A	1.1*a*, 1.4*a*; 2*d*-2*f*; 3*b*, 3*c*; 4.1*a*, 4.1*e*
		1.5*a*, 1.5*b*; 2*d*-2*f*
Ta*	The same	1.1*b*, 1.4*b*; 2*d*-2*f*; 4.3*c*
V	“	1.1*a*, 1.4*a*; 2*d*-2*f*; 3*a*, 3*c*; 4.1*a*, 4.1*e*
		1.5*a*, 1.5*b*; 2*d*-2*f*
V*	“	1.1*b*, 1.4*b*; 2*d*-2*f*; 4.3*a*, 4.3*c*
Zn	“	1.1*a*, 1.4*a*; 2*e*, 2*f*; 3*b*, 3*c*; 4.1*a*, 4.1*c*
Zr	“	1.1*a*, 1.4*a*; 2*d*-2*f*; 3*b*, 3*c*; 4.1*a*, 4.1*e*
		1.5*a*, 1.5*b*; 2*d*-2*f*
Zr*	“	1.1*b*, 1.4*b*; 2*d*-2*f*; 4.3*c*
W	“	1*a*, 1.4*a*; 2*d*-2*f*; 3*a*; 4.1*a*, 4.1*c*, 4.4*c*
W*	“	1.1*b*, 1.4*b*; 2*d*-2*f*; 4.3*a*, 4.3*c*

* With the use of black coal for coking.

rough values of the function for PVEs, which are characterized by the parameters 4.1a and 4.1c (Table 1), are as follows:

$$b_i: 0.96; 0.97; 0.98; 0.99;$$

$$a_i: 0.94; 0.945; 0.95; 0.955.$$

The degrees of PVE trapping with fly ash together with its particles from gaseous products before their ejection into the atmosphere are usually somewhat smaller than those in the trapping of fly ash with the use of electrostatic filters or bag-type filters for this purpose even for PVEs that do not form gaseous compounds in the furnace volume (parameters 4.1d, 4.1e in Table 1) because the concentrations of PVEs in the untrapped most highly dispersed particles are usually higher than those calculated from Eq. (5) on a total fly ash weight basis, and the higher the degree of ash trapping (b), the greater a difference from the degree of PVE trapping (a_i), whose approximate values are as follows:

$$b_i: 0.95; 0.96; 0.97; 0.98; 0.99;$$

$$a_i: 0.945; 0.9555; 0.965; 0.975; 0.98.$$

With a dry method used for the purification of the gaseous products of combustion (gasification) with a 99% degree of ash trapping, the degrees of trapping were taken equal to 96% for Au, Ag, Ge, W, and Mo and 98% for Co, Cr, Ni, TRE, and V.

On the combustion of concentrates with ash contents smaller than 20 or 60%, in accordance with Eq. (5), the degrees of enrichment can increase depending on the ash content of a concentrate and the extraction of a particular PVE in it. For the calculation of the values of Y_f, Table 2 tentatively gives the ash content of the concentrates obtained after the enrichment of coal or oil shale of 12 or 20%, respectively; the recovery of the PVEs Ge, W, Mo, and ∑TRE (U_c), 90% and the reduced concentration (Y_c) = 1.1; Au and Ag, 70%; Co, Cr, Ni, and V, $U_c = 60\%$; and $Y_c = 0.8$.

The real appropriateness of the extraction of PVEs from solid fossil fuels in many respects depends not only on their concentrations in the initial solid fuel, the selected conditions of its combustion, and the degree of trapping in fly ash or in a mixture of fly ash with slag but also, as noted above, on the economic situation of Russia on the world market. Taking into account these considerations, we propose to classify solid fossil fuels containing PVEs as follows (Table 3): the solid fossil fuels of the first category, which have, according to our information, at least preliminary technical and economic calculations of their usability as rare-metal raw materials, and the solid fossil fuels of the second category, for which the potential usability for this purpose was determined based on our especially tentative calculations.

The technical and economic calculations to refine the appropriateness of the use of solid fossil fuels as rare-metal raw materials should be carried out taking into account the possibility of obtaining the primary concentrates of several PVEs, which simultaneously occur in solid fossil fuels and are characterized by similar behaviors in the course of processing, that is, by the identical parameters of groups 3 and 4 and subgroup 5.2.

Thus, we demonstrated possible solutions as applied to several PVEs, for which information on the effects of their classification parameters on the selection of optimum combustion technologies to ensure the production of ash and slag most promising for the manufacture of commercial PVE compounds is available.

The above classification makes it possible to minimize preliminary studies in the selection of waste coal from particular enterprises, which should be reasonably directed to technological tests for obtaining complete information required for the preparation of initial data for the design of an industrial enterprise for waste coal processing.

It should also be noted that this classification is open; that is, it can be refined and supplemented with new characteristic parameters for the more accurate selection of the most promising trends of waste coal utilization in the course of further studies.

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