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Technical and Economic Operation Parameters of a High-Temperature Plasma Plant for Production and Consumption Waste Conversion (Calculation Results and Their Analysis)

A. V. Artemov, V. A. Bul'ba, S. A. Voshchinin, Yu. A. Krutyakov, A. A. Kudrinskii, I. I. Ostryi, and A. V. Pereslavtsev

KORTEZ OOO, ul. Kuusinena 21A, Moscow, 125252 Russia
e-mail: artemov.a@kortez.org

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Abstract—Principal technical and economic operation parameters of the high-temperature plasma waste conversion plant (production of electricity, heat, and basaltiform slag, amount of waste disposed, profitability, payback period, etc.) are presented. The combination of plasma waste conversion and electricity generation with the help of the self-produced pyrolysis gas provides a high profitability index and an acceptable payback period.

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INTRODUCTION

High-temperature plasma processes hold great promise for the development of environmentally friendly and economically efficient technologies for production and consumption waste treatment [1–9]. Such technologies can be implemented in a high-temperature plasma converter (its design and operation principle have been described in [10]).

The KORTEZ company is performing active research into the practical use of plasma technologies for production and consumption waste treatment. In the present paper we present the results of estimation of technical and economic operation parameters of a plant which implements the high-temperature plasma technology for solid waste utilization. Analysis relates to the simplest variant of the technology, which involves production as commercial products of electric power, heat energy (steam and hot water), and basaltiform slag and involves no Fischer−Tropsch hydrocarbon synthesis [11−13]).

The advantage this technology offers over the usual waste incineration technology is that it allows an almost complete isolation of CO_2 from из pyrogas and its repeated use as a plasma-forming gas. Moreover, the temperature regime and design features of the plasma plant exclude formation of such toxic compounds as dibenzodioxins and dibenzofurans.

The high-temperature plasma complex allows the following types of productiona and consumption wastes (and their mixtures) to be treated:

− solid municipal wastes (paper, plastics, wood, textile, metals, glass, etc.);

− heavy oil fractions;

− waste oil products mixed with coke-chemical and other industrial wastes;

− chlorine-free polymer wastes;

− waste car tyres;

− sludges accumulated at car-wash stations;

− wastewater sludges;

− medical (sanitary) wastes, etc.

The yield and composition of pyrgas and, conesquently, its calorific capacity and energy operation parameters of the whole complex are largely controlled by two factors: the composition of wastes and the composition of the plasma-forming gas.

In the present work we studied dependence of the technical and economic operation parameters of the high-temperature plasma plant on the composition of the raw material, i.e. production and consumption wastes to be treated.

By the developed algorithm we calculated the following technical and economic parameters: calorific power of wastes; revenues from waste treatment; amount and cost of products (basaltiform slag, electric power, and heat carrier); pure reduced production cost; internal revenue rate; discounted payback period; and degree of natural gas replacement with pyrogas.

The technical and economic operation parameters of the plant were calculated under the following assumptions: constant annual productivity of the plant 25000 thsd. tons (3500 kg h^{-1}) of wastes, plasma-forming gas (CO_2) consumption 560 kg h^{-1}, minimum oxygen feed rate to the reaction zone 100 kg h^{-1}.

Separate Treatment of Different-Type Wastes

The calculation of technical and economic parameters of single-type wastes (the variant when a mixture of wastes was treated was not analyzed) gave positive results in the cases of solid municipal wastes, medical wastes, waste oil products mixed with coke-chemical and industrial wastes, and sludges from car-wash stations.

With other types of wastes, much more oxygen should be fed to the pyrolysis zone, primarily because of their high calorific power (high carbon content). Therefore, such wastes are better treated in a mixture with less calorific wastes. The minimum oxygen feed rate to the pyrolysis zone depends on waste type as follows, kg h^{-1}:

wastewater sludge	387
polymer waste	870
heavy oil residues	1765
car tyres	3120

Burning characteristics of wastes (calorific power) determine one of the principal environmental characteristics of the process, specifically degree of replacement of natural gas by pyrogas. As the calorific power of wastes increases, the degree of replacement of natural gas by pyrogas increases (the dependence is nearly linear, Table 1).

The production of heat carriers (steam, hot water) is almost independent of wastes; the average amount of heat energy generated by the high-temperature plasma technology is 25.59 Gcal h^{-1}.

Other technical characteristics, namely, the amounts of basaltiform slag and electric power generated in the plasma complex do not linearly correlate with the calorific power of wastes.

Table 1. Degree of replacement of natural gas depending on the calorific power of waste

Consumption and production wastes	Calorific power, kcal kg^{-1}	Degree of replacement of natural gas by pyrogas, %
Sludge from car wash stations	1610	7.4
Solid municipal wastes	2916	26.2
Medical wastes	3044	27.9
Waste oil products mixed with coke-chemical and industrial wastes	3588	32.8
Waste polymer materials	5931	51.1
Wastewater sludges	5803	53.5
Heavy oil residues	7294	57.7
Waste car tyres	9763	71.6

The principal economic operation parameter of the high-temperature plasma waste conversion plant is, from our viewpoint, the discounted payback period. It is this parameter that allows to judge about the expediency of realization of the high-temperature plasma waste conversion plant in the framework of the accepted economic model.

According to the calculations, the payback period of the plasma plant is quite reasonable: 4–6 years with all the above wastes, except for solid municipal wastes and wastewater sludge. With the latter two types of wastes the payback period is much longer than 6 years. The best payback characteristics were obtained with medical wastes and waste car tyres (Table 2).

As the payback period increases, the pure reduced production cost and internal revenue rate decrease. The same dependence is observed between the payback period and total annual revenues from sales of products of the high-temperature plasma plant: Increasing payback period decreases total annual sales revenues.

Thus, the principal economic parameter of the process: pure reduced production cost, internal revenue rate, and total annual sales revenues of products are closely related to the discounted payback period of the plasma plant. Therefore, to a first approximation, the problem of optimization of the plant performance is limited to the optimization of its payback period.

Payback period strongly depends on product sales revenues. At a high waste treatment cost (in the case of

Table 2. Principal economic operation parameters of the high-temperature plasma plant depending on waste type

Consumption and production wastes	Total annual revenues from product sales, mln RUR	Pure reduced production costs, mln RUR	Internal revenue rate, %	Discounted payback period, years
Solid municipal wastes	681	642	22.5	8.12
Medical wastes	1204	2961	51.3	3.46
Waste oil products mixed with coke-chemical and industrial wastes	869	1464	32.1	5.34
Waste polymer materials	957	1864	37.3	4.58
Wastewater sludges	636	444	20.1	9.42
Heavy oil residues	870	1474	32.5	5.29
Waste car tyres	832	1298	30.2	5.72
Solid municipal wastes	1040	2207	40.7	4.20

medical wastes, waste oil products, and polymer wastes), the payback period is no longer than 6 years and linearly related to product sales revenues. If the waste treatment cost is not higher than 10% of the product sales revenues, this parameter has almost no effect on the payback period which varies from 4 to 10 years in the case of other types of wastes.

Treatment of Mixtures of Heavy Oil Residues and Solid Municipal Wastes

Special attention to treatment of a mixture of solid municipal wastes with oil residues in the technical and economic operation analysis of the high-temperature plasma plant is explained by the urgency of the problem of utilization of oil-containing wastes.

The calculations show that the treatment of solid municipal wastes in a mixture with highly calorific heavy oil residues (average calorific power 7294 kcal kg^{-1}) at a large fraction of the latter not always gives positive results when the oxygen feed rate to the pyrolysis zone is 100 kg h^{-1}. Satisfactory results can only be obtained if the fraction of heavy oil residues is no more than 34%. At a larger fraction, the oxygen feed rate should be increased:

Fraction of oil residues in the mixture, wt %	Oxygen feed rate to the pyrolysis zone, kg h^{-1}
50	555
75	1175
88	1495
100	1765

It was established that the linear dependence between the calorific power of wastes and the oxygen feed rate is characteristic of all the types of wastes and their mixtures. The maximum oxygen feed rate to the pyrolysis zone in the case of a mixture of solid municipal wastes and oil residues is ~1800 kg h^{-1}. This value should be taken into account in designing the air separation unit in the high-temperature plasma plant or, vice versa, the fraction of oil residues should be limited because of their high calorific power.

The calorific power of wastes and degree of natural gas replacement with pyrogas increase, as the fraction of oil residues in their mixture with solid municipal wastes increases. Therewith, the production of heat energy (steam, hot water) is almost independent of the content of oil residues (on average, 25.15 Gcal h^{-1}). The electric power generation rate depends on the oil residues/solid municipal waste ratio.

With the other product, i.e. basaltiform slag, the following result was obtained: As the fraction of heavy oil residues in the mixture increases, the production of basaltiform slag decreases.

The principal economic operation parameters of the high-temperature plasma plant for treatment of a mixture of solid municipal wastes with heavy oil residues are presented in Table 3. As seen from these data, the dependences of the payback period and pure reduced production cost on the fraction of heavy oil residues in the mixture are evidently extreme, implying that there is an optimum waste composition favoring the best economic operation parameters of the plant. Similar extreme dependences are observed with the internal revenue rate and total annual revenues from sales of products.

Treatment of a Mixture of Solid Municipal Wastes, Medical Wastes, and Waste Car Tyres

The necessity in technical and economic analysis of the process of treatment of the title mixture in the high-

Table 3. Principal economic operation parameters of the high-temperature plasma plant on utilization of mixtures of solid municipal wastes and heavy oil residues

Parameter	Fraction of heavy oil residues in the mixture, wt %						
	0	12	25	50	75	88	100
Total annual revenues from product sales, mln RUR	681	656	629	674	755	797	832
Pure reduced production costs, mln RUR	642	532	414	613	965	1146	1298
Internal revenue rate, %	22.5	21.2	19.8	22.2	26.3	28.4	30.2
Discounted payback period, years	8.12	8.79	9.66	8.29	6.70	6.12	5.72

Table 4. Principal economic operation parameters of the high-temperature plasma plant on utilization of mixtures of solid municipal wastes and medical wastes

Parameter	Fraction of medical wastes in the mixture, wt %						
	0	12	25	50	75	88	100
Total annual revenues from product sales, mln RUR	681	744	812	943	1074	1142	1204
Pure reduced production costs, mln RUR	642	951	1223	1803	2382	2683	2961
Internal revenue rate, %	22.5	25.9	29.5	36.6	43.8	47.7	51.3
Discounted payback period, years	8.12	6.84	5.87	4.64	3.92	3.67	3.46

temperature plasma converter is associated with the fact that utilization of solid municipal wastes is the primary concern of municipal services. In selecting conditions for efficient utilization of this type of wastes we took into account the following circumstances.

According to the calculations, the shortest discounted payback period of the plant is with wastes whose treatment brings high revenues. Such wastes primarily include medical wastes and waste car tyres. The mean utilization costs of these wastes are 15000 and 2000 RUR/ton. Therewith, medical wastes and waste car tyres guarantee continuous operation of the plasma plant. Other types of wastes, in particular, wastes of polymer materials and waste oil products mixed with coke-chemical and industrial wastes, while having a high utilization cost (4500 and 8000 RUR/ton, respectively). However, according to expert's estimates, such wastes will not be delivered on an even basis and cannot ensure continuous operation of the plant.

Therefore, the most appropriate waste composition which, on the one hand, would allow treatment of the required amount of solid municipal wastes in the region and, on the other, would ensure continuous and cost-efficient operation of the high-temperature plasma plant, presumably is the ternary mixture: solid municipal wastes + medical wastes + waste car tyres.

The fact that medical wastes and waste car tyres positively affect the utililization of solid municipal wastes is evidenced by the results of technical and economic analysis of binary mixtures of these wastes.

Mixture of Solid Municipal Wastes and Medical Wastes

The calorific power of solid municipal wastes and medical wastes is generally not too high (2916 and 3044 kcal kg^{-1}, respectively), and, therefore, their mixture may well be treated at an oxygen feed rate of 100 kg h^{-1}. By the same reason, the degree of replacement of natural gas by the pyrogas generated from this waste mixture varies in a fairly narrow range (26.2−27.9%).

The production of heat carriers (steam and hot water) in the plasma plant is almost independent of the fraction of solid municipal wastes in their mixture with medical wastes.

The amount of basaltiform slag, produced by treatment of this mixture, linearly increase with increasing fraction of medical wastes, and the production of electric power decreases.

The principal economic operation parameters of the high-temperature plasma plant on utilization of a mixture of solid municipal wastes and medical wastes are listed in Table 4.

As the fraction of medical wastes in the mixture increases, the discounted payback period period decreases considerably (two times) and the internal revenue rate increases to the same extent; the production cost also increases. Thus, medical wastes favor economically more efficient treatment of solid municipal wastes.

Mixture of Solid Municipal Wastes and Car Tyres

Since one of the components of the mixture is waste car tyres has a high calorific power (on average, 9763 kcal kg^{-1}), treatment of solid municipal wastes in a mixture of waste car tyres, especially when the fraction of the latter is high (more than 21%), additional oxygen should be fed to the pyrolysis zone:

Fraction of car tyres in the mixture, wt %	Oxygen feed rate to the pyrolysis zone, kg h^{-1}
25	267
50	1217
75	2167
88	2660
100	3120

The maximum oxygen feed rate to the pyrolysis zone is 3120 kg h^{-1}. It was found that the degree of replacement of natural gas by pyrogas and feeding additional oxygen to the pyrolysis zone of the plasma converter are linearly related to each other whatever the type of wastes and depends exclusively on the calorific power of pyrogas.

The production of heat carries (steam, hot water) is almost independent of the fraction of car tyres in the waste mixture; the average production of heat energy is 25.30 Gcal h^{-1}. The calorific power of wastes and the degree of replacement of natural gas by pyrogas increase as the fraction of car tyres increases. The dependence between electricity production and content of waste car tyres is extreme: there is some mixture composition at which the electric power production is a minimum. As to basaltiform slag, its yield decreases with increasing fraction of car tyres in the mixture.

The principal economic operation parameters of the high-temperature plasma plant on utilization of a mixture of solid municipal wastes and waste car tyres are listed in Table 5.

The dependences of payback period and pure reduced production costs on the fraction of car tyres in the mixture is evidently extreme in nature, implying that these is an optimum waste composition favoring the best economic parameters of the plant. Extreme dependences are also observed with internal revenue rate and total annual revenues from product sales.

Mixture of Medical Wastes and Waste Car Tyres

The material of car tyres has a high calorific power (9763 kcal kg^{-1}), and, therefore, for treating them in a mixture with medical wastes, especially when the fraction of car tyres is high (more than 16.5%), the oxygen feed rate to the pyrolysis zone should be increased:

Table 5. Principal economic operation parameters of the high-temperature plasma plant on utilization of mixtures of solid municipal wastes and waste car tyres

Parameter	Fraction of waste car tyres in the mixture, wt %						
	0	12	25	50	75	88	100
Total annual revenues from product sales, mln RUR	681	646	645	776	908	976	1040
Pure reduced production costs, mln RUR	642	491	484	1058	1632	1929	2207
Internal revenue rate, %	22.5	20.7	20.6	27.5	34.1	37.5	40.7
Discounted payback period, years	8.12	9.07	9.11	6.38	5.01	4.55	4.20

Table 6. Principal economic operation parameters of the high-temperature plasma plant on utilization of mixtures of medical wastes and waste car tyres

Parameter	Fraction of waste car tyres in the mixture, wt %						
	0	12	25	50	75	88	100
Total annual revenues from product sales, mln RUR	1204	1107	1073	1062	1050	1045	1040
Pure reduced production costs, mln RUR	2961	2533	2382	2323	2263	2232	2207
Internal revenue rate, %	51.3	45.9	43.8	42.7	41.7	41.1	40.7
Discounted payback period, years	3.46	3.78	3.92	4.00	4.10	4.16	4.20

Fraction of car tyres in the mixture, wt %	Oxygen feed rate to the pyrolysis zone, kg h^{-1}
25	435
40	1329
75	2222
88	2687
100	3120

The maximum oxygen feed rate to the pyrolysis zone is 3120 kg h^{-1}. The calorific power of the waste mixture in question and the degree of replacement of natural gas by pyrogas increase with increasing fraction of car tyres in the mixture. The production of heat carriers is almost independent on the fraction of waste car tyres in the mixture; the average production of heat energy is 25.27 Gcal h^{-1}. The dependence between electric power production and the fraction of car tyres is extreme, and, therewith, there is such mixture composition at which the production of electric power is a minimum. The yield of basaltiform slag decreases as the fraction of car tyres increases.

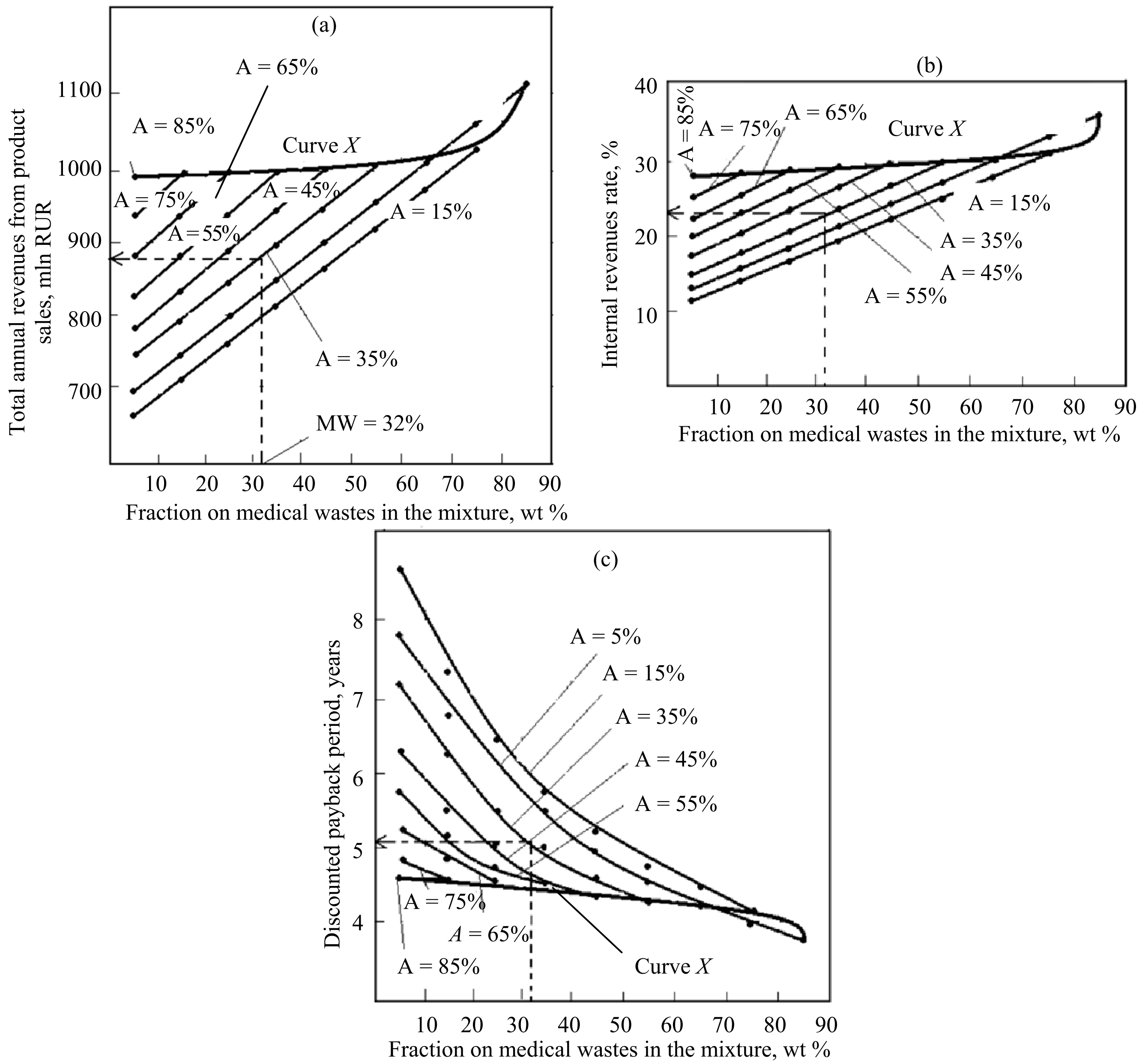

Fig. 1. Dependence of the (a) total annual revenues, (b) internal revenues rate, and (c) discounted payback period on the quantitative composition of the mixture solid municipal wastes + waste car tyres + medical wastes. (A) Waste car tyres and (MW) medical wastes.

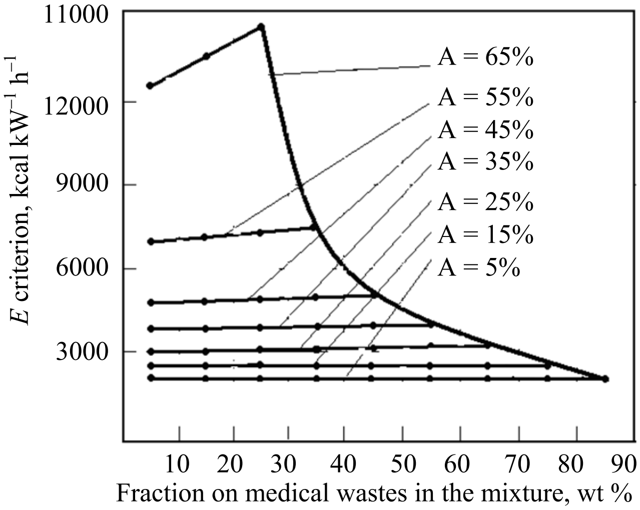

Fig. 2. Dependence of the energy efficiency of the plant (*E* criterion) on the quantitative composition of the mixture solid municipal wastes + waste car tyres + medical wastes.

The principal economic operation parameters of the high-temperature plasma plant on utilization of a mixture of medical wastes and waste car tyres are listed in Table 6.

As seen from the resulting data, the dependences of the payback period and pure reduced production costs on the composition of waste mixture are not extreme. As the fraction of car tyres in their mixture with medical wastes increases to above 30%, the payback period increases to 4. Vice versa, the pure reduced production costs smoothly decreases with increasing fraction of this waste. The dependences of the internal revenue rate and total annual revenues from product sales, too, are not extreme: these values smoothly decrease with increasing fraction of waste car tyres.

The results of the technical and economic parameters of binary waste mixtures are consistent with the above suggestion that ternary mixtures ensure the most efficient operation of the high-temperature plasma plant both interms of economics and in terms of stability. The calculated economic parameters of the plasma plant (total annual revenues from product sales, discounted payback period, and internal revenue rate) were correlated with the quantitative compositions of wastes and their mixtures (Fig. 1). From these dependences one can determine the optimal somposition of the mixture solid municipal wastes + car tyres + medical wastes, which allows the most efficient utilization of solid wastes.

Along with "purely" economic parameter, we also estimated the energy efficiency of the plant, which was measured by the ratio:

$$E = \frac{\text{Calorific power of pyrogas (kcal kg}^{-1}\text{)}}{\text{Electric power consumption for waste treatment (kW h}^{-1}\text{)}}.$$

These estimates (Fig. 2) show that the energy efficiency of the plant depends on the fraction of waste car tyres in waste mixture: the *E* value exponentially increase with increasing fraction of this type of wastes.

CONCLUSIONS

The data reported in this paper show that the technical and economic operation parameters of the high-temperature plasma plant are strongly dependent on the composition of the waste to be treated. Together with the composition of the raw material, there are other factors affecting the efficiency parameters: composition of the plasma-forming gas, engineering design features, number and arrangement of plasmatrons, etc. However, the introduction of high-temperature plasma processes into the practice of utilization of production and consumption wastes is undeniably able to solve the problem of environmental safety of waste treatment technologies. Moreover, combining plasma waste treatment and power generating plants with the use of the pyrogas generated by waste treatment provides a high cost-effectiveness of the enterprise with an acceptable payback period.

REFERENCES

1.*http://www.cpeo.org/techtree/ttdescript/plarctech.htm.*

2.*http://www.pyrogenesis.com.*

3.*http://www.enviroarc.com.*

4.*http://www.westinghouse-plasma.com*.

5.*http://www.europlasma.com*.

6.*http://iperas.nw.ru.*

7.Gnedenko, V.G., Dmitriev, S.A., Pereslavtsev, A.V., et al., *Proc. 18th Int. Symp. on Plasma Chemistry*, Kyoto, Japan, 2007, rep. 164.

8.Gnedenko, V.G., Ivanov, A.A., Komarov, N.S., et al., *Proc. V Int. Conf. Plasma Physics and Plasma Technology*, Minsk, 2006, p. 715.

9.Gnedenko, V.G., Ivanov, A.A., Pereslavtsev, A.V., et al., *Problems of Atomic Science and Technology, Ser. Plasma Electronics and New Acceleration Methods*, Kharkov, Ukraine, 2006, no. 5, p. 75.

10. RF Patent Appl. 2009105470/007340 of 18.02.2009 MPK C10J 3/14.

11.*http://www.hitgtl.ru/ru/.*

12.*http://www.streserves.ru/.*

13.*http://www.energosyntop.com.*