Oil Shale, Vol. 15, No. 2 SPECIAL
pp. 111-133

ISSN 0208-189X

https://doi.org/10.3176/oil.1998.2S.03

CRITERIA AND SIZE OF ESTONIAN OIL SHALE RESERVES

E. REINSALU[*]

Tallinn Technical University,
Department of Mining
82 Kopli St., Tallinn
EE0004 Estonia

There are several criteria for determining mineable oil shale reserves and resources. Three characteristics: thickness, average calorific value, and depth of the mineable bed were used in the era of planned economies, based on available mining technology capabilities. The reserve cut-off values had been estimated mostly for the needs of the large power industry. A research project to find new characteristics for the determination of oil shale reserves which are compatible with today's economy was performed in 1996/1997.

According to this study, a given oil shale bed is defined as a reserve, provided that the costs of its mining and delivery to the consumer are lower than the consumer's expenditure of coal procurement. This study also defines an oil shale bed with an energy rating above 25 GJ/m^2 as a resource. Using these criteria, Estonia's oil shale resources are over 6 billion tonnes, or over 47 EJ (EJ - 10^{18} J) of energy, including active reserves exceeding 2 billion tonnes, with over 17 EJ of energy.

Criteria Established Formerly

Until 1998, the size of Estonian oil shale reserves was determined on the basis of three characteristics: thickness, average calorific value, and depth of the mineable bed. The regulation concerning the geological exploration of mineral resources and the establishment of mineral reserves [1] provided the following:

oil shale shall be regarded as a mineral resource if:

- *the calorific value of the bed is not below 6.1 MJ/kg (1450 kcal/kg)*
- *bed thickness is not less than 0.5 m at the overburden thickness of up to 10 m*

  or bed thickness is not less than 1.4 m at the overburden thickness of over 10 m.

---

[*] *e-mail*: ere@cc.ttu.ee

Table 1. **Calculation Table of the Reserve Block (Block: Kohtla-Vanaküla; mineable oil shale layers - A-F)**

Rock	Layer and interlayer	Natural thickness, m	Mineable thickness, m	Calorific value, kcal/kg	Calorific value, GJ/t	Density, t/m^3	Productivity of mass, t/m^2	Energy rating of the layer, GJ/m^2
Soil		0.30	0.00	0	0.00	0.00	0.00	0.000
Moraine		1.49	0.00	0	0.00	0.00	0.00	0.000
Rock		2.44	0.00	0	0.00	2.38	0.00	0.000
Upper seam:								
	H	0.18	0.00	2657	11.12	1.55	0.00	0.000
	H/G	0.19	0.00	0	0.00	2.53	0.00	0.000
	G	0.22	0.00	2657	11.12	1.55	0.00	0.000
	G/F	1.03	0.00	630	2.64	2.12	0.00	0.000
Bed (productivity seam):								
	F_2	0.19	0.00	910	3.81	1.99	0.00	0.000
	F_1	0.40	0.40	2080	8.71	1.66	0.67	5.832
	E	0.49	0.49	2970	12.43	1.48	0.73	9.064
	E/D	0.10	0.00	680	2.85	2.11	0.00	0.000
	D	0.11	0.11	2740	11.47	1.49	0.16	1.858
	D/C	0.22	0.00	0	0.00	2.53	0.00	0.000
	C	0.38	0.38	2720	11.39	1.52	0.58	6.611
	C/B	0.08	0.00	680	2.85	2.11	0.00	0.000
	B	0.55	0.55	3910	16.37	1.33	0.72	11.863
	B/A	0.14	0.00	380	1.59	2.22	0.00	0.000
	A’	0.09	0.09	2050	8.58	1.40	0.12	1.026
	A’/A	0.02	0.00	670	2.80	2.11	0.00	0.000
	A	0.18	0.18	3610	15.11	1.36	0.24	3.615
	Sum/Avg.	9.82	2.19	2953	12.36	1.47	3.23	39.87

In fact, except for overburden thickness, these criteria, established in 1965 by the *Giproshaht*, a former Soviet design institute, were applied at the Oudova (Leningrad) deposit. Later, the same criteria were introduced in Estonia. Estonia's and Oudova's oil shale constituted basic mineral fuel resources for the USSR northwestern region, which required massive reserves. Thus, low criteria were established for the determination of oil shale reserves. Soviet criteria proved unsuitable under new economic conditions. Furthermore, the characteristics applied in the eastern and central Baltic resource area proved inadequate in the western deposit area.

As a result, in 1996, the Estonian Ministry of Environment and the Ministry of Economic Affairs launched a research project to find new characteristics, compatible with today's economy, for the determination of oil shale reserves. The marginal values of the characteristics or criteria had to be found to specify both active and passive reserves and their sizes. It should be noted that according to Estonian terminology, an active reserve is defined as a reserve worth mining, and a passive reserve is specified as the one that can become worth mining in line with economic and technological developments.

Initial Data

This study is based on the mean data obtained from the exploration blocks of Estonian oil shale resources and from those being mined. The exploration blocks amounted to 88 and those being mined included 23. The data used were collected at the Estonian Geological Survey, prepared by the geologists V. Kattai and U. Lokk.

The data were entered into the calculation tables (Table 1) block-wise, thus allowing for the determination of average thickness *m* of any combination of layers and interlayers in each block, calorific value (kcal/kg), density (t/m^3), bed productivity of mass (t/m^2) and energy rating (GJ/m^2). Here, the productivity of mass equals the sum of the products of layer thicknesses, forming the bed or mineable seams and densities. Energy rating implies the sum of the products of the same parameters and calorific values. Thus, the productivity of mass is directly related to the layer thickness, forming the bed or to that extracted at mining, whereas density is an intensifying factor. The density of limestone is higher than that of oil shale. Because of high bed density, this criterion was regarded essential when in the 1970's the *Kuremäe* field was chosen as a new mining site. The energy rating of the bed combines the two characteristics used for the estimation of oil shale reserves: bed thickness and calorific value. In addition, it describes directly the main consumption value of oil shale.

In Table 1 and in the text below, we use the term 'calorific value' and its unit kcal/kg. The latter is used because over the years geological information has been recorded in these units. As an example, Table 1 shows the parameters of oil shale rather than those of the bed.

As a precondition, the calculation of the bed and oil shale rock parameters requires knowledge of the density of the bed forming oil shale and limestone. Earlier, density was determined under laboratory conditions. Later, based primarily on the studies of H. Sits [2] and V. Kattai [3], density was calculated on the basis of calorific value. The method established, developed primarily by V. Kattai [1], presents in tabular form the calculations obtained through the corresponding formula. The tradition is that mining engineers use Sits's formulas and geologists make use of Kattai's tables. However, commonly, the densities determined by different methods are not in very good agreement. These discrepancies led us to the analysis of the issue.

Sits's calculation methods of density are based on the assumption that the components of an oil shale bed consist of a burning agent made up primarily of kerogen and a non-burning agent comprising carbonate and clay minerals. The burning agent has a lower thickness than that of the non-burning agent. The amount of the burning agent in the sample rock is proportional to its calorific value. Thus, if a rock contained only a burning agent, its density would equal that of the latter. If a rock consists only of a non-burning agent, its density will be equal to that of the latter. If a rock comprises a mixture, its density will be determined by the ratio of the burning agent to the non-burning agent. This ratio can be determined through calorific value, because the approximate calorific value is known and the calorific value of the non-burning agent is zero. A problem arises because the density of the non-burning agent depends on its mineral ingredients. However, in different layers and interlayers, the density of carbonate and clay minerals and their ratio vary. In addition, this ratio varies in different parts of the deposit. Therefore, Sits's method does not allow the use of the same formula to determine the density of the samples taken from different layers and from different deposit parts.

As a result, Sits has presented the so-called formula of partial relations

$$d = d_m/((d_m/d_p - 1)Q/Q_p + 1) \tag{1}$$

in the transformed form

$$d = d_m/(cQ + 1)\ (\mathrm{kg/dm^3},\ \mathrm{t/m^3}) \tag{2}$$

where d_m - density of the non-burning agent, kg/dm^3, t/m^3;

d_p - density of the burning agent, kg/dm^3, t/m^3;

Q - calorific value of the rock tested, Mcal/kg;

Q_p - calorific value of the burning agent, Mcal/kg;

$$c = (d_m / d_p - 1)/Q_p \text{ (kg/Mcal)}. \qquad (3)$$

The formula (2) can easily be linearized, allowing for the use of the well-known regression analysis to determine factors c and d_m.

In his studies concerning the relationship of the density, the calorific value of oil shale layers and limestone interlayers and the changes within the resource area, Sits determined probable values of all types of rock c and d_m in the productive bed (Table 2).

Table 2. **Factors Determined Using Equation (2) by Sits**

Notation of layer and interlayer	Composite factor c, kg/Mcal	Density of non-burning agent d_m, t/m^3
F_2	0.304	2.55
F_1	0.223	2.43
E	0.209	2.41
E/D	0.191	2.38
D	0.163	2.16
D/C	0.211	2.53
C	0.219	2.42
C/B	0.191	2.38
B	0.206	2.40
B/A	0.191	2.38
A′	0.105	1.70
A′/A	0.191	2.38
A	0.163	2.16
Bed A-F_1 average		2.33

To analyse Sits's methods, we transformed Eq. (3):

$$c = d_m / Q\, d_p - 1/Q$$

and using the values of c and d_m, presented in Table 2, found $1/Q\, d_p$ and $1/Q$ values by the regression analysis. These values show that the factors in Table 2 are satisfied by:

- the density of the burning agent $d_p = 1.19$ kg/dm^3 and
- the calorific value of the burning agent $Q_p = 4860$ kcal/kg.

These considerations do not comply with the contemporary knowledge of kerogene as burning agent.

Kattai's methodology of calculating density is also based on the logic of partial relations. However, these neglect the different ratio of the non-burning agent in minerals. To check this, we used the data from the density table presented in the official methodology [1] and approximated these to Eq. (1).

As a result, we obtained:

- the density of the non-burning agent $d_m = 2.27$ kg/dm^3, t/m^3 and
- the density of the burning agent $d_p = 0.98$ kg/dm^3, t/m^3

if the calorific value of the burning agent $Q_p = 8900$ kcal/kg, which is in agreement with the available mean values of these parameters. However, the regressive analysis of the tabular data presented in this methodology [1] shows that the following relation suits better for describing the relation than the partial relations formula (1):

$$d = 1.3831 exp(-0.0003Q) + 0.98 \text{ (kg/dm}^3\text{, t/m}^3\text{)} \quad (4)$$

where the unit of Q is kcal/kg.

The parameters calculated from Eq. (4):

- the density of the non-burning agent ($Q = 0$) $d_m = 2.36$ kg/dm^3, t/m^3 and
- the density of the burning agent ($Q = \infty$) $d_p = 0.98$ kg/dm^3, t/m^3

are also in good agreement with the data available.

In summary, despite the fact that Sits's methodology is based on good logic, we had to abandon it. Instead, we entered the tabular data of the official methodology [1] in our calculation programs in the form of Eq. (4).

Main Parameters of the Investigated Blocks

The distribution of the main parameters of the bed and the bedding conditions is shown in Fig. 1.

As can be seen, the relation between energetic parameters is good in the central part of the deposit, both for mining and for the explored blocks. At the same calorific value, energy rating is up to 10 GJ/m^2 lower in the western blocks than elsewhere. In the blocks currently mined, the average calorific value is 2170 kcal/kg and energy rating amounts to 42.21 GJ/m^2, while the lowest calorific value, below 2000 kcal/kg and the energy rating of 36.6 to 38.4 GJ/m^2, were observed at the *Aidu* and *Estonia* mining fields (Fig. 1*a*).

In the western-most part of the deposit, at the same energy capacity, the bed is 30-40 cm thicker than in the south-east. In the blocks mined currently, the mean thickness is 2.72 m, while the thickest bed, less than 2.7 m, is found in the *Narva* and *Estonia* fields. The thickness of 2.8 m, prevailing in the statistical reports, is greater than that found by geological exploration. However, this is based on the fact that the boundary between the layers F_1 and F_2 is not interpreted in a single way (Fig. 1*b*).

In the western part of the deposit, the bed has a prevalently low energy rating. In the operating mining fields, the mean overburden thickness is 31 m. The deepest (at 60 m) is the *Estonia* mining field. In the majority of westernmost exploration blocks, the beds of low energy rating are bedded deeper than in the operating part of the deposit (Fig. 1*c*).

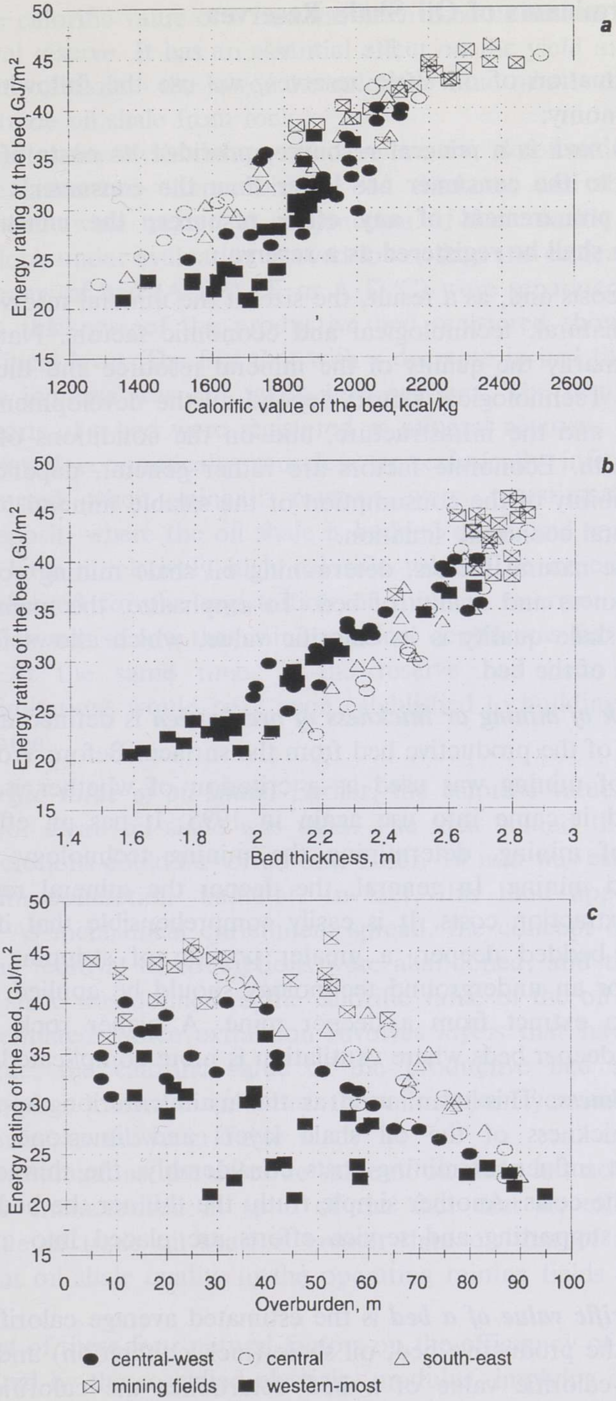

Fig. 1. Distribution of oil shale blocks according (*a*) to the calorific value and the energy rating of the bed, (*b*) to bed thickness and energy rating, (*c*) to energy rating of bed and overburden rock thickness

Size Determinants of Oil Shale Reserves

In our estimation of oil shale reserves, we use the following axiom of mining economy:

A. **A useful rock is a mineral resource, provided its costs of mining and delivery to the consumer are lower than the consumer's expenditure on the procurement of any other resource; the mineable mineral resource shall be registered as a reserve.**

Mining costs and, as a result, the size of the mineral reserve are determined by natural, technological and economic factors. Natural factors include primarily the quality of the mineral resource and the conditions of bedding. Technological factors depend on the development of mining engineering and the infrastructure, and on the conditions of the use of natural wealth. Economic factors are rather general, depending mainly on the feasibility of the consumption of the salable mineral resource and on the general economic situation.

The basic natural factors, determining oil shale mining costs, are the depth, thickness and quality of bed. To emphasize, the main characteristic of oil shale quality is its calorific value, which allows for different descriptions of the bed.

The depth of mining or thickness of overburden is defined as the depth of the head of the productive bed from the surface. Before World War II, the depth of mining was used as a criterion of whether it was worth mining, and it came into use again in 1995. It has an effect on the efficiency of mining, determining the mining technology: surface or underground mining. In general, the deeper the mineral resource, the higher its extraction costs. It is easily comprehensible that if a mineral resource is bedded deeper, a greater portion of stripping should be eliminated or an underground technology should be applied. It is more expensive to extract from a deeper mine. A higher rock pressure is observed in deeper beds where ventilation is more complicated.

Bed thickness. This term, used as the main criterion, applies to the summary thickness of the oil shale layers and limestone interlayers. Moreover, it influences mining costs considerably; the thinner the bed, the higher the costs. Another simple truth: the thinner the bed, the more developing, supporting and service efforts are placed into extracting a unit of rock.

The calorific value of a bed is the estimated average calorific value of all parts of the productive bed, oil shale (incl. concretion) and limestone layers. The calorific value of a bed determines the calorific value of mined rock (broken oil shale bed). If the whole bed is extracted, the calorific value of rock will equal the calorific value of the bed. With selective winning, the calorific value of mined rock is higher than that of the bed. However, then part of the energy of the mineral reserve will not be used. The calorific value of a bed has been used as the main criterion of the mineral reserve. It has an essential effect on the yield and calorific value of trade oil shale - the lower the calorific value of a bed, the lower the yield of trade oil shale from rock.

According to the methodology used so far for determining mineral reserves, the latter two characteristics: bed thickness and the calorific value of the bed, were treated in conjunction. If the calorific value of a bed in the block under evaluation proved lower than the critical level, the peripheral seams of bed (A-B/A, F or A-D/C) were separated to ensure that the rest thickness of the productive bed registered should not fall below the critical level. The fact that with a decrease in bed thickness the mining costs increase was not taken into account. The result was that such small parts of a bed were registered as mineral reserves, the mining of which proved economically senseless or technically infeasible. This danger occurred when mineral reserves were re-estimated in the southwest deposit, where the oil shale is bedded deep, and some thin oil shale layers have a relatively high calorific value. The criteria effective until 1998 allowed for the registration of mineral reserves, the energy rating of which was so low that mining at low depths was far from being reasonable. At the same time, if the reserve had been registered, substantial limitations would have been established to building activity in the deposit area.

The calorific value of oil shale. Earlier, the calorific value of the so-called pure or clean oil shale was used. The idea behind this was that sizeable concretions could be sorted out. Later, 10 mm was established as the maximum concretion diameter. In fact, this limit appeared only conditional. As mechanical enrichment spread, the concept of clean oil shale and the removal of concretions were abandoned, and the calorific value of oil shale was defined as the calorific value of the oil shale layer to be differentiated. Since extraction involves layers that have different calorific value, the calorific value of the productive bed implies the estimated average calorific value of the oil shale layers registered as mineral reserves, as shown in Table 1.

In recent evaluations, the calorific value of oil shale has not been used as a reserve characteristic in spite of the fact that its effect on the calorific value of trade oil shale is greater than on that of a bed. The reason is that oil shale quality in the operating mining fields is relatively stable.

The effect of these four natural factors on the efficiency of mining has been evaluated by the so-called elasticity modulus, implying a change in the percentage of mining costs caused by one per cent change in the factor. Examples concerning the elasticity modulus are illustrated in Table 3.

Table 3. **Some Values of Elasticity Modulus Showing the Effect of Mining Conditions [6]**

Function, economic indicator	Factor characteristic of mining conditions	Elasticity modulus
Rock mining:		
Mining costs	Depth of mining	0.1
Owner costs	Depth of mining	0.31
Mining costs	Bed thickness	−0.68
Owner costs	Bed thickness,	−0.37
Yield of saleable oil shale from rock	Calorific value of bed	0.81
	Calorific value of oil shale	0
Calorific value of saleable oil shale	Calorific value of bed	0.17
	Calorific value of oil shale	0.39

Table 4. **Estimation of the Minimum Calorific Value of Oil Shale by Using Selective Winning**

Dry calorific value of mineable oil shale, GJ/t	Heat value of trade oil shale, GJ/t, at moisture content		Efficiency of conversion	Relation of energetic oil shale at coal, t/t	Maximum permissible price of oil shale, EEK/t, at coal price 600 EEK/t
	8 %, technological oil shale	12 %, energetic oil shale			
6	4.82	0.26	0.29	8.87	67.64
7	5.69	0.27	0.35	7.17	83.62
8	6.55	0.28	0.40	6.02	99.61
9	7.42	0.28	0.43	5.19	115.60
10	8.28	0.29	0.46	4.56	131.59
11	9.15	0.29	0.48	4.07	147.58
12	10.02	0.30	0.50	3.67	163.57
13	10.88	0.30	0.52	3.34	179.55
14	11.75	0.30	0.53	3.07	195.54

The positive elasticity modulus shows that with an increase in the factor value, the economic indicator grows. For instance, with an increase in the depth of mining, both mining and capital costs increase. In contrast, the negative modulus means that with an increase in the factor (such as bed thickness), costs decrease. As can be seen, bed thickness and the calorific value of the bed have the strongest effect. Hence, so far the determination of mineral reserves has been confined to the above. According to the strength of the effect, next come the calorific value of oil shale and the depth of mining (in particular, concerning the capital costs). It should be noted that the latter has been reentered, whereas the calorific value of oil shale has not yet.

Table 3 shows the values of elasticity modulus established at drilling and blasting. Though different at longwall mining, they remain analogous. With drilling and blasting technology, the effect of the calorific value on the yield of trade oil shale is not substantial (elasticity modulus - 0). At continuous mining, it is different. For that reason, with the prevailing drilling and blasting technology, the calorific value of oil shale has not been used as a criterion for determining mineral reserves.

The evaluation of mining efficiency should not be confined to the mining costs. The rock mined must be enriched, which involves additional expenses. The sum of mining and enrichment costs is added to that of the enriched material, the salable amount of oil shale, determined by the yield. The yield is defined by the ratio of the mass of trade oil shale to the broken rock mass, which is below one. Therefore, the smaller the yield, the more expensive the trade oil shale will be. As can be seen in Table 3, the yield depends strongly on the calorific value of the bed.

Studies of operating oil shale mining economy have shown that other natural conditions have less effect on the mining costs. With regard to the establishment of new mines, they are still essential.

For instance, ***the structure of overburden*** is not used as a criterion in the mineral reserve estimations, although mining technology depends on it. Surface mining is aggravated in the case of clay and peat overburden at small slope angle. Room-and-pillar mining is aggravated if the overlying rocks contain primarily brittle Devonian marl or is impossible if it is composed mainly of Quaternary sediments.

The carst, with its areas excluded from mineral resources, is taken into account in the determination of mineral reserves.

In global practice, such natural characteristics as the oil yield of oil shale or sands, moisture and sulphur content, are used. Since the oil yield of kukersite is in strong correlation with its calorific value, and moisture and sulphur content are low and practically constant, we need not take these criteria into account.

Natural factors should also include ***the location of the mineral reserve in relation to the consumer***. So far this factor has not been considered. At the same time, such examples exist as registering Cambrian blue clay of the Kunda deposit as cement clay, because it is located close to the cement plant, whereas in the Aseri deposit, located close to the brick plant, the same clay is registered as ceramic clay.

Location of oil shale in an area unsuitable for mining. According to the Estonian Law on the Protection of Natural Objects, mining of the mineral resource in natural reserves is excluded. This act provides that the oil shale reserves located in the natural reserve can be registered as passive reserves. Since natural conditions in some natural reserves allow for underground mining, the criterion is directly related to the depth of the bed. In addition to natural reserves, a provision is made to exclude mining of oil shale bedded under essentially important structures and buildings.

Lack of suitable oil shale mining technology. This criterion is not completely categorical because there is always a mining technology available. More importantly, it is the problem of cost. Unfortunately, based on this criterion, many areas, which could be exploited under current economic conditions, have been excluded.

In the estimation of mineral reserves, considerations of economic conditions are the requirement.

The so-called world price of substitute fuel or raw material (competitive fuel or raw material) is crucial, which is the commonly accepted price of a unit of an analogous fuel or raw material in a place agreed upon, generally expressed in US dollars. The substitute price of oil shale used in power stations is the price of the coal equivalent (7000 kcal/kg) on board a ship. According to the classical approach, crude oil in Rotterdam should be regarded as the competitive material of shale oil. According to the current practice in Estonia, the price of crude oil is regarded as an important factor in evaluating the competitiveness of shale oil.

The transportation costs of substitute fuel. These include the expenditure of the consumer who can choose between oil shale or some other fuel for transporting the substitute fuel to its place of consumption. For instance, the consideration that transportation of a small coal quantity to the Kunda Port is easier than delivering a large quantity to Narva, leads to differences in the evaluation of the same quality oil shale in Estonia's western and eastern oil shale deposit.

The mining costs of oil shale are defined as the sum of the winning, enrichment and other required expenditures transformed to a unit comparable to the substitute fuel in the location of mining. As shown above, this is directly related to natural factors. However, the level of mining costs is determined by the mining technology and economic situation by and large.

The transportation costs of oil shale imply the same as those of substitute fuel.

The estimation of the economic factor is complicated because of the fact that mineral reserves are intended for future use. Consequently, prices and expenditure must be calculated in view of future. It is a well known fact that the mining costs of oil shale are increasing because of changing economic conditions. To some extent, the mining costs of oil shale are characterized by its cost, which has remained at the level of mining costs under the official political pressure. An increase in oil shale price is illustrated in Fig. 2.

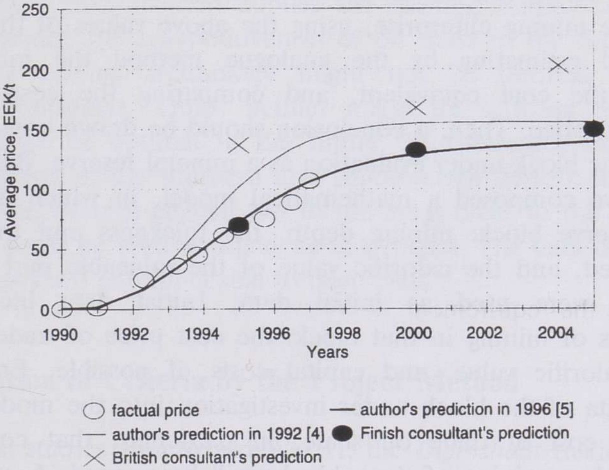

Fig. 2. Increase in oil shale price and its prediction

The price prediction demonstrated in Fig. 2 are based on the assumption that in the market economy, oil shale price inevitably rises to a marginal value, the price ceiling, determined by the substitute fuel.

To reach a comparative analysis of the mining costs and the prices of competitive fuels, the latter must be reduced to the same quantity of fuel or energy. If one compares oil shale with coal, then, on the one hand, the mining costs of oil shale must be expressed in the coal equivalent. On the other hand, it should be noted that with coal burning, the efficiency of a boiler aggregate is 1/3 times higher than with the current quality oil shale, because the efficiency of burning (as well retorting) is reduced when the calorific value of fuel decreases.

The issue of oil shale as a raw material of oil is more complex. Although retorting can be regarded as beneficiation, and the dependence of the yield of shale oil on the calorific value of the raw material is known, processing costs are difficult to calculate, because oil is not the single product of oil shale processing. For this reason, shale oil and crude oil are not in one-to-one correspondence.

Determination of Reserve Criteria by the Analogue Method

In addition to the above mining economy axiom A, we will proceed now, applying another axiom.

B. Provided the mining costs in some mining conditions and the fact how the costs change as the conditions alter are known, the costs can be evaluated in other conditions.

According to the above, this approach should be based on the mining costs of some mining enterprise, using the above values of the elasticity modulus and estimating by the analogue method the mining costs reduced to the coal equivalent, and comparing the costs with the substitute fuel price. Then, a conclusion should be drawn concerning the oil shale of the block under evaluation as a mineral reserve. Based on this procedure, we composed a mathematical model, in which data of the mineable reserve block: mining depth, the thickness and the calorific value of a bed, and the calorific value of the mineable part of the oil shale layers were used as initial data. Initial data included the characteristics of mining in that block: the cost price of trade oil shale, yield and calorific value, and capital costs, if possible. Entering the geological data of the block under investigation into the model, we can evaluate the cost of trade oil shale, in particular, that cost of coal equivalent, when mining of these blocks will be opened. A comparative analysis of the calculation results block-wise and the price of the substitute fuel helps to reach the decisions if the mineral reserves of a block are worth mining.

Using the mathematical model in the central and southeastern deposit, we applied the *Estonia* mine as an analogue. This mine utilizes full-face mining of the bed and rock enrichment. For the price level of the substitute fuel of 50 USD/tce, we obtained the following results:

- If the mining costs do not exceed 80 EEK/t (Estonian kroons/tonne), then oil shale mining of the whole eastern Estonian oil shale deposit is economically reasonable; in fact, today, the mining costs in the *Estonia* mine exceed 120 EEK/t.
- If the mining costs are up to 120 EEK/t, then the southeastern reserves of the deposit are not worth mining.
- If the mining costs are up to 160 EEK/t, even the reserve blocks neighboring the *Estonia* mining field will be excluded from the reserves worth mining.

The analogue method allows for drawing the conclusion that with optimal mining technology, if the mining costs reach the level of 150-160 EEK/t, then in economic terms, mining in deeper blocks, with thinner beds and lower calorific value than in the *Estonia* mine, is senseless. These calculation results were used as a basis for the hypothesis, in which 35 GJ/m^2 was used as a marginal energy rating of the bed for the oil shale active reserve. The part of the deposit where the energy rating of the bed exceeded 35 GJ/m^2 is the area of operating mines and open casts. The area could also have accommodated for most of the mining fields planned in the 1970's at Kuremäe, Uus-Kiviõli, and Permisküla. The Oudova deposit, owned by Russia, has the energy rating lower than 35 GJ/m^2.

Unfortunately, the results of the analogue method are not sufficiently accurate. First, this method applies the existing mining costs, but we need to evaluate the competitiveness of oil shale in the future. Second, the existing mining technology might not be optimal in the new economic conditions. Third, neither might the existing technology of using oil shale be optimal in the future. Furthermore, the calculation results obtained in the southern and southeastern deposit are applicable neither to the western deposit nor to the areas close to the fields, where open casts could be used as analogue enterprises. The data obtained from the open casts are not applicable to deep beds.

Determination of Criteria by the Project Method

In their first studies after World War II, the *Giproshaht* Institute used the project method. This involved designing a project of a mine or an open cast for the mining conditions of a prospective exploration field. The procedure comprised an evaluation of the congruent price (cost value plus part of special capital costs), a comparison of the result with the directive marginal costs - maximum permissible congruent price of coal equivalent in the Baltic region. If the mining costs of oil shale proved smaller than the marginal costs, the corresponding mining conditions (bed thickness and the calorific value of the bed) were regarded as complying with the conditions. The same calculations were repeated for other mining conditions such that by the test and trial method, data for generalizations were obtained. Later, in view of lack of time and labour and based on adequate experience, the *Giproshaht* introduced the Oudova deposit criteria for the peripheral areas of Estonia deposit.

This method was sufficiently reliable for the stable planned economy. Some of the results, taking into account the energy situation in the Baltic region by and large, are still regarded as applicable. For instance, the evaluation conducted by the Leningrad Department of the

Energosetprojekt Design Institute [6], according to which the oil shale in new Estonian mine fields is not competitive in power generation, is true in the current economic situation. However, the evaluation above was neglected by the decision-making persons in the oil shale industry.

There is not enough time and labour at our disposal to develop optimal technological projects of mines and open casts to estimate the criteria for reserves in each exploration field. Therefore we confine ourselves to discussing the most important fields and technologies in the current situation. In the peripheral area of the oil shale deposit, with energy rating approximating 35 GJ/m^2 and below, exploration fields exist where thin layers of oil shale of relatively high calorific value are bedded. As a result, ideas and proposals concerning possible selective winning and sales without enrichment of these layers have emerged. From the point of view of oil processing and cement plants owners, the most valuable fields are located in the western deposit, next to the railway track, where oil shale lies close to the surface. If the selectively mined and non-enriched oil shale found in the low energy rating fields is consumed, the mineral reserves of these fields will be active.

Highly selective winning is feasible without blasting. This would need sufficiently powerful mining machinery, available due to the developments in mechanical engineering. Underground mining would need a shearer, which could selectively extract both limestone and oil shale. Under surface mining, rippers have been used to test selective winning in oil shale open casts. For surface cutting, surface miners have been tested and used in any limestone quarries. Stripping and oil shale selective winning would be performed by the help of the same machine.

Underground technological schemes of selective winning have been devised and recommended both for room-and-pillar and longwall mining. Ordered by the *Eesti Põlevkivi* Ltd., feasibility studies have been conducted in the southern part of the *Narva* open cast and in the active reserve area of the western *Sompa* mine. All the calculations have shown that selective underground mining is not cheaper than the room-and-pillar mining with enrichment used so far. Consequently, the possible selective underground mining of oil shale does not change our earlier hypothesis based on full-face mining, implying that an oil shale bed is not worth mining if its energy rating is below 35 GJ/m^2.

Selective winning is suitable when the calorific value of non-enriched broken oil shale is acceptable to the consumer. Calculations in Table 4 provide an answer to the question of the minimum calorific value of trade oil shale. It is an important condition that trade oil shale should be cheaper than 600 EEK/t for coal use. The dependence of the efficiency of the main users of technological processes on the calorific value of raw material and fuel was taken into account.

Table 5. **Economic Indicators of Selective Winning in Small Open Casts**

Open cast	Annual output, mill. tonnes	Cost of winning		Yield of oil shale per rock	Overburden thickness, m	Thickness of bed, m	Calorific value of oil shale, kcal/kg
		Mass, EEK/t	Energy, EEK/GJ				
Tammiku	0.79	42.92	4.72	0.86	11.00	2.11	3020
Kohtla-Vanaküla	1.32	25.56	2.87	0.87	5.20	2.24	2900
Sonda (I*)	0.98	34.62	4.07	0.88	7.00	1.68	2570
Sonda (II*)	0.88	38.44	4.37	0.81	7.00	1.57	2610
Pada (I*)	0.94	36.17	4.17	1.13	9.00	1.71	2520
Pada (II*)	0.81	41.71	4.69	0.96	9.00	1.30	2620
Kohala (I*)	0.72	46.71	5.58	1.12	15.60	2.37	2440
Kohala (II*)	0.53	63.40	7.11	0.85	15.60	1.66	2630
Haljala	0.39	85.98	9.34	1.02	21.40	1.78	2719
Kõnnu	0.34	99.14	11.78	1.15	28.60	1.41	2495

* Variant.

Table 6. **Distribution of Costs in Oil Shale Open Casts, % [7]**

Open cast	Winning	Stripping	Drilling and blasting at winning	Drilling and blasting at stripping	Total
Sirgala	9.8	17.9	5.2	21.7	54.6
Viivikonna	12.1	20.8	6.6	16.4	55.9
Narva	8.2	30.7	2.7	20.1	61.7
Aidu	7.4	23.8	2.3	16.8	50.3
Average	9.38	23.30	4.20	18.75	55.63

There are seven small open casts where selective winning is possible (Table 5).

In Table 5, the first lines show the open casts where selective winning of A-F bed is used. Among these, undoubtedly, the *Tammiku* and *Kohtla-Vanaküla* open casts provide good economic basis for mining. A feasibility study conducted for the *Sonda* open cast, planned in the *Põhja-Kiviõli* exploration field, has provided positive results. Mining of the whole A-H seam has been intended in the *Pada* and *Kohala* open casts. It should be noted that the calorific values of G and H layers are based on the analogy and need not be sufficiently precise. In terms of mining engineering, only selective winning of the D-H seam is reasonable in view of mining engineering in the *Haljala* and *Kõnnu* open casts. Marks 'I' and 'II' behind the mine names denote the variants. Variant I implies that all the oil shale layers, the mining of which is reasonable in terms of mining engineering, will be winned. Commonly, it implies that layers A′ and D will not be extracted because of their very low calorific value. Variant II means that only those layers will be selectively mined the calorific value of which exceeds 2600 kcal/kg. At selective winning, frequently, the upper part of low calorific value of layer F will not be extracted. The calorific value of the trade oil shale can be calculated, implying that dilution is not taken into account, as a result, the calorific value of trade oil shale can appear lower than the calculated one. The basic economic evaluation contains the winning cost of a tonne of oil shale and stripping of rock overburden and elimination of intermediate layers by means of the same machine. Thus, the cost of winning in Table 5 does not contain the costs of stripping, removed interbed or transportation of the mined oil shale. In addition, the expenditures of structures, recultivation, sorting, dewatering and organization of open cast operation are excluded. Furthermore, royalty as well pollution and water taxes are not included. Thus, winning costs are only part of the mining costs. The question arises - what the overall mining costs of oil shale are. The fact is that with the same technology used in the *Sonda* mine, the total expenses of the surface miner 3700SM will be 45 % of the cost price of production. Using surface mining technology in oil shale open casts today, stripping and winning costs account for 56 % of the total costs on average (see Table 6).

The cost of stripping shown in Table 6 contains both the costs of removal of alluvial and rock overburden. Consequently, considering only rock overburden, the cost of stripping and winning would be smaller, apparently at about 50 %.

On the basis of these data, approximately evaluated, oil shale mining costs can be expressed as the double winning cost shown in Table 5. Provided the future price of oil shale is 150 EEK/t (Fig. 2), the reserve close to the surface, located in the northern *Haljala* and *Kõnnu* exploration fields, where the extraction costs range from 85 to

100 EEK/t, is not worth of mining. Then, the deeper reserve, located in the southern exploration fields, is clearly not worth mining. In the other areas, suitable for surface mining (Table 5), oil shale mining is obviously reasonable.

The comparison of variants I and II of selective winning shows, however, that partial extraction of the bed allows for higher calorific value of rock, but increases its cost, because the thinner the mineable layer, the more overburden and barren rock should be removed per tonne of trade oil shale. The question arises - what the reasonable depth of selective winning is and how this process depends on the quality of a bed.

Suitable Depth Limit of Surface Mining

Technological depth limit of surface mining is covered by I. Valgma [8] in this issue of the journal. If in the eastern open casts (*Sirgala* and *Narva*), the depth limit is 27 m, then, accordingly, the marginal stripping ratio is up to 9 m^3/t. However, when we estimate reserves, we need the economic rather than the technological marginal stripping ratio. The economic marginal stripping ratio shows how many cubic meters of the overburden are reasonable to be removed in order to achieve that surface mining would be cheaper than underground mining.

By the conventional method, comparing the expenses of underground and surface mining and those for the removal of the overburden, the main economic marginal stripping ratio is 6-8 m^3/t. It should be noted that in the *Aidu* open cast, the marginal stripping ratio is 5-6 m^3/t, in the eastern open casts, 9-12 m^3/t. The difference is accounted for by the fact that in the eastern open casts, because of old excavators used for

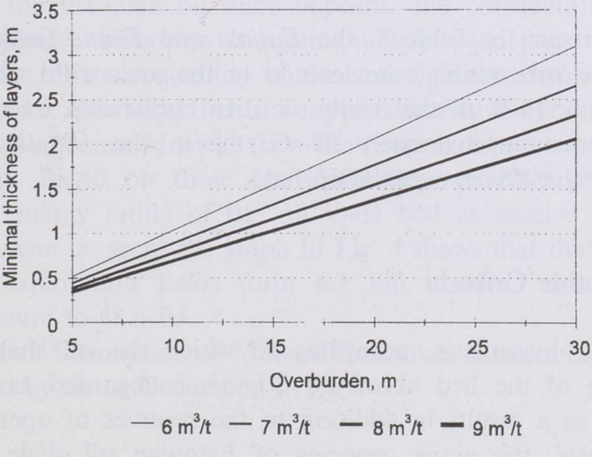

Fig. 3. Minimum thickness of selective winning oil shale layers, depending on overburden thickness at different marginal stripping ratios

stripping, it is nearly twice cheaper than at *Aidu*. Until no accurate project evaluations exist for possible stripping costs, based on new machinery, precise calculations of the marginal stripping ratio are unlikely to be achieved. We take 6 m^3/t as the first approximation.

The minimum total thickness of oil shale layers mined by selective technology, at which mining is useful, is in direct relationship with layer thickness and the economic minimal stripping ratio. This relation is described in Fig. 3.

Based on this analysis, an additional criterion of the active reserve, to be more exact, a pair of criteria, was developed to be used in the areas where oil shale is bedded close to the surface, but where energy rating is under 35 GJ/m^2. We recommend to register as worth-mining oil shale the oil shale with selective mineable layers whose total thickness is higher than 10 % of the overburden thickness (see Table 4). The mean calorific value of these layers should be above 11 GJ/t (2600 kcal/kg). In other words, in the area, where the energy rating of A-F bed is below 35 GJ/t, oil shale layers with the mean calorific value above 2600 kcal/kg (dry) and with the summary thickness above 10 % of overburden thickness, will be registered as active oil shale reserves.

In fact, 10 % is a coincidence, because the minimum thickness $h_{\min}$ is expressed by

$$h_{\min} = H/k_{\max}d \approx H/6 \times 1.67 = H/10 = 0.1H \text{ (m)}$$

where H - overburden thickness, m;

$h_{\max}$ - the economic marginal stripping ratio, 6 m^3/t;

d - rock density, 1.6-1.7 t/m.

In the case of different values of the marginal stripping ratios, the ratio of the thickness of the mineable layer to the overburden is different (see Fig. 5).

As can be seen in Table 5, the *Haljala* and *Kõnnu* fields, where oil shale is not worth mining, are located in the area with mineable layer thickness below 10 % of the overburden. In both fields, energy rating of the bed is low: approximately 30 GJ/m^2 in the *Haljala* and below 25 GJ/m^2, in the *Kõnnu* exploration field.

Recommendable Criteria

Based on our hypothesis, according to which the oil shale, with the energy rating of the bed above 35 GJ/m^2, is regarded as a mineable reserve, and as a result, in addition to the reserves of operating mines and open casts, the active reserves of Estonian oil shale amount to 2.03 bill. tonnes of rock or 17.06 EJ of potential energy (Fig. 4). If 33 % of the reserves account for loss and 60 % of rock forms the yield of oil

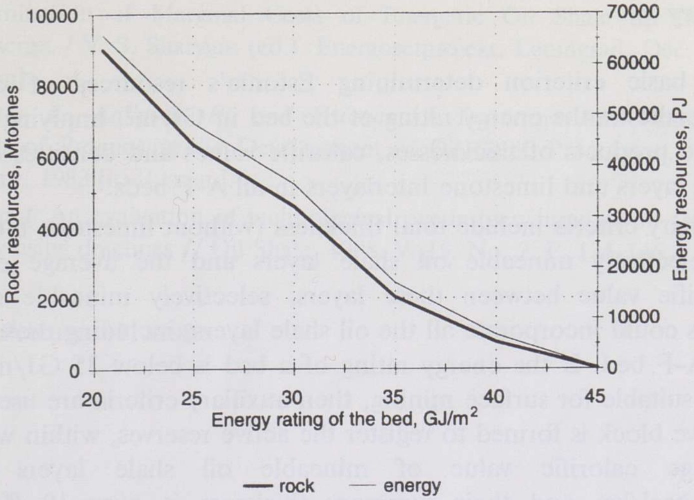

Fig. 4. Dependence of oil shale rock and energy resources of the Estonian deposit on the energy rating of the bed

shale, then it implies over 0.8 bill. tonnes of trade oil shale in addition to the established 0.6 bill. tonnes reserves of operating mine fields[*]. At the annual production of 1.3 bill. tonnes, at least 100 years of mining are ensured.

The resources of the deposit consist of mineable or active reserves and additional potential or passive resources. The size of passive resources also depends on the energy rating established as the minimum limit. However, no accurate regulations, such as mineability in terms of today's economy, exist to determine the minimum limit. As a condition, we selected the minimum limit of the energy rating determining passive resources of the Estonian oil shale deposits, the consideration that the quantity of passive resources is approximately equal to the mineable reserves. If the oil shale quantity of the active reserves of the operating enterprises and exploration fields is approximately 1.4 bill. tonnes oil shale or 3.2 bill. tonnes of rock, then the passive resources will form the same amount. Based on these considerations, we have presented the value of the energy rating of the oil shale bed as passive resources – 25 GJ/m^2. As can be seen, the graph in Fig. 4 shows that the resources of rock in all exploration fields form 6.3 bill. tonnes, and the energy resources amount to 48.6 EJ.

The Estonian Committee of Mineral Resources established the criteria recommended by us on December 4, 1997.

[* *] The reserves of the operating enterprises are based on the quantity of oil shale rather than on that of rock. 0.6 bill. tonnes of oil shale corresponds to 1.18 bill. tonnes of rock.

Summary

1. The basic criterion determining Estonia's resources of oil shale (kukersite) is the energy rating of the bed in GJ/m^2, implying the sum of the products of thicknesses, calorific values and densities of all oil shale layers and limestone interlayers in all A-F beds.
2. Auxiliary criteria include total thickness (without limestone interlayers) of selectively mineable oil shale layers and the average estimated calorific value between these layers; selectively mineable oil shale layers could incorporate all the oil shale layers, including those outside the A-F bed. If the energy rating of a bed is below 35 GJ/m^2 at the time suitable for surface mining, then auxiliary criteria are used, and a reserve block is formed to register the active reserves, within which the average calorific value of mineable oil shale layers exceeds 2600 kcal/kg, and their summary thickness is over 10 % of the overburden thickness.
3. The average energy rating of the bed in the oil shale exploration block registered as passive resource should be at least 25 GJ/m^2.
4. The reserves of the operating mines and open casts of Estonian oil shale deposits approximate 0.6 bill. tonnes plus the reserves of exploration fields. According to the criteria determined by us, the active reserves of exploration fields exceed 2 bill. tonnes of oil shale rock over 17 EJ of energy and passive resources account for over 4 bill. tonnes of oil shale rock or over 30 EJ of energy.

REFERENCES

1. Geological Exploration of Mineral Resources and Establishment of Mineral Reserves. Regulation of the Estonian Minister of Environment, 22 June 1995, 29 [in Estonian].
2. *Sits, H.* On variation of regularities concerning the calorific value, possible density and thickness of rock in kukersite oil shale beds // Issues of Mine Surveying and Geology in Oil Shale Resource Areas. Valgus, Tallinn, 1977. P. 52-57 [in Russian].
3. *Kattai, V.* Correlation method - a way of reducing the volume of oil shale laboratory research // Computer Use in Solving Problems of Mineral Resource Geology. Institute of Geology of the Estonian Academy of Sciences. Tallinn, 1991. P. 81-93 [in Russian].
4. *Reinsalu, E.* Economical aspects of oil shale mining and its use in power engineering. Estonian-Finnish Seminar, Tallinn, Sept. 23-24, 1993. P. 15-19.
5. *Reinsalu, E.* Oil shale trading and price // Energia Teataja (Energy News), Tallinn. 1996, 7/8 (11). P. 9-13 [in Estonian].

6. Determination of Marginal Costs of Energetic Oil Shale up to 2000 : manuscript / V. S. Sharygin (ed.). Energosetprojekt, Leningrad, Dec. 1983 [in Russian].
7. *Reinsalu, E., Kaljuvee, E., and Fraiman, J.* Economic and Mathematical Models of Prognosing the Development of Oil Shale Production. - Nauka, Moscow, 1983 [in Russian].
8. *Valgma I.* An evaluation of technological overburden limit of oil shale open cast by using draglines // Oil Shale. 1998. V. 15, No. 2. P. 134-146.

Received February 17, 1998