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ARCHIVES

BREAKAGE OF OIL SHALE BY MINING*

An important problem in oil shale longwall mining by shearer is the identification of rational methods and conditions for breakage of oil shale by cutting tools. The summary of the monograph dedicated to the theory, experimentation of several years and practical oil shale mining experience concerning this problem is given below in the present paper.

1. Specific Features of Oil Shale Longwall Mining

1.1. Characteristic Data on Baltic Oil Shale Basin

The oil shale deposit occurring in the Baltic basin is characterized by its composite structure of oil shale layers. The oil shale layers contain up to 30 vol.% of hard limestone concretions and are at the same time interbedded with limestone interlayers. The quality of different oil shale layers and that of the full oil shale bed is best characterized by heating value (Fig. 1.1).

The heating value of oil shale seams or that of the total mine-run shale is calculated by

$$Q_{br}^{d} = \sum Q_{bi}^{d} p_i \,/\, \sum p_i \qquad (1)$$

where: Q_{bi}^{d} - heating value (dry basis);
p_i - mass productivity of seam.

Coarse oil shale particles (exceeding 20-30 mm) are subjected to upgrading the oil shale fines being marketed as mine-run shale. Therefore, it is feasible to use mining methods that provide for breaking interlayers and concretions into predominantly fairly large particles, thus leading to production of shale fines of higher heating value, along with large oil shale particles suitable for further upgrading.

Methods of face working have been proposed for selective exposure of interlayers with subsequent breaking of oil shale as a rock of lower

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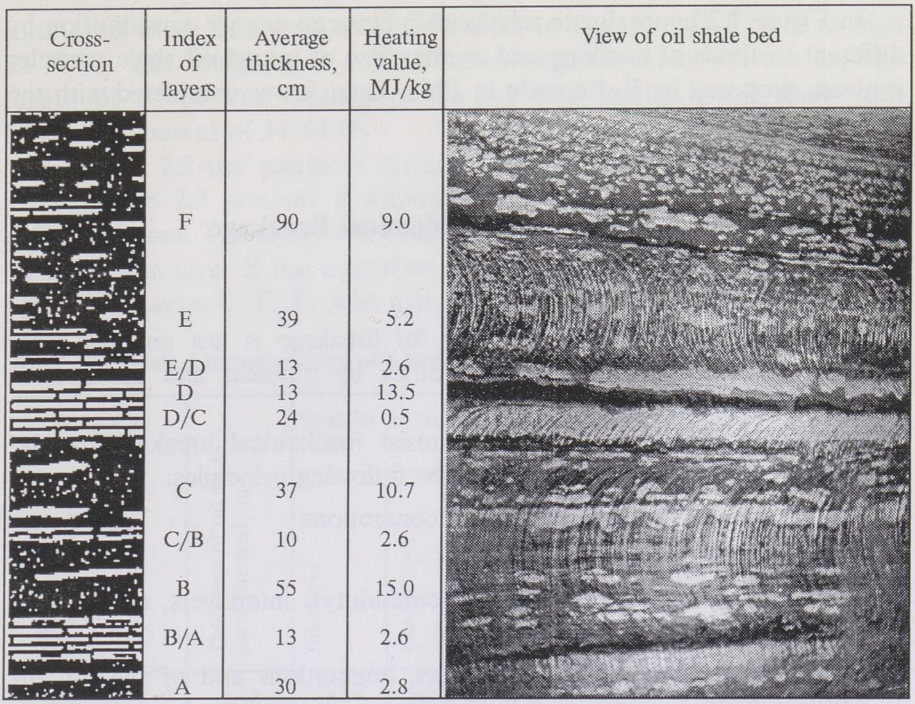
[*] Revised summary of the monograph by V. Pozin, A. Adamson and V. Andreyev (former Estonian Branch of A. A. Skotchinsky Institute of Mining Engineering, Kohtla-Järve), Moskva, Nauka, 1984, 142 p. (in Russian).

The summary was revised and completed by A. Adamson, Tallinn Technical University, Department of Mining.



Cross-section	Index of layers	Average thickness, cm	Heating value, MJ/kg	View of oil shale bed
	F	90	9.0	
	E	39	5.2	
	E/D	13	2.6	
	D	13	13.5	
	D/C	24	0.5	
	C	37	10.7	
	C/B	10	2.6	
	B	55	15.0	
	B/A	13	2.6	
	A	30	2.8	

Fig. 1.1. Structural cross-section of the Estonian oil shale deposit

cuttability by advancing drum (diameter less than the thickness of B-C, i.e. 1.0 m) which leads to reduced specific energy consumption for the breaking operation and to increased shearer loader performance and a higher oil shale quality.

Sizing of the winned oil shale which determines the upgradability and grade of the trade oil shale is closely connected with energy consumption by the selected oil shale breaking method.

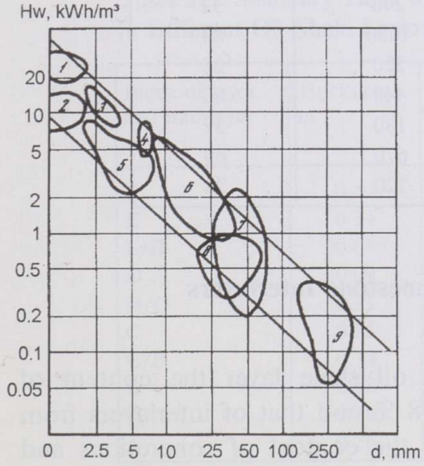


Fig. 1.2. Effect of method of breakage on specific energy consumption and the resulting average oil shale sizing. Legend:

1 - drilling in limestone;
2 - drilling in oil shale;
3 - cutting machine in limestone;
4 - cutting machine in oil shale;
5 - cutting of layer B by shearer loader UKR-1;
6 - cutting by shearer;
7 - cutting by DKS (measuring instrument of cuttability) in limestone;
8 - cutting by DKS in oil shale;
9 - breaking by ripper (surface mining)

In Figure 1.2 approximate relationship between energy consumption by different methods of breaking and average size of mined oil shale particles is given, proposed by E. Reinsalu in 1968. Later it was completed with the data from the present investigation.

2. Oil Shale as a Medium for Mechanical Breakage

2.1. Introductory Information

Evaluation of oil shale as a medium for breakage is not an easy task, because its composite parts sharply differ by physical and mechanical properties (Table 2.1).

The ability of oil shale seams to resist mechanical breakage can be evaluated by integral consideration of the following principles:

- Shape, size and volume content of concretions
- Volume content of interlayers
- Resistance to cutting of oil shale (cuttability), interlayers, concretions and of the full oil shale bed
- Abrasiveness of oil shale, interlayers, concretions and of the full oil shale bed
- Degree of brittleness of oil shale
- Breakablility of oil shale

Table 2.1. **Physical and Mechanical Properties of Oil Shale**

Index of layer and interlayer	Rock type	Percussive strength, N/mm^2	Compressive strength, MPa
F_1	Oil shale	190	37
E	Oil shale	150	35
E/D	Limestone	400	75
D	Oil shale	240	32
D/C	Limestone	1030	84
C	Oil shale	220	28
C/B	Limestone	440	80
B	Oil shale	180	37
B/A	Limestone	670	69
A	Oil shale	120	28

2.2. Content of Hard Concretions and Limestone Interlayers in Oil Shale Bed

Depending on the method of working oil shale layer the content of limestone concretions varies from 6 to 18 % and that of interlayers from 12 to 30 %. By working the seam A-C the content of concretions and interlayers totals from 18.5 to 22.5 % while in the seam D-F_1 it is as high as 30 %. The thickness of concretions averages 3-4 cm with an average length of 9.5-12 cm. Mining of the full bed results in oil shale with limestone content of 34-43 %.

In Table 2.2 the results of statistical analysis of experimental data are given. Table 2.3 presents a summary of the content of concretions in different layers. The layers A and D are represented practically entirely by oil shale, the layer B has a content of concretions as low as 6-9 % while that of the layers C, E, F_1 is as high as 17-23 %.

Table 2.2. **Basic Characteristics of Limestone Concretions in Oil Shale**

Mine, oil shale seams worked	Thickness of oil shale seams worked, m	Specific content, m^2/m^2		Number of concertions per 100 m of face, 10^3	Size of concretions		Surface of concretions, cm^2
		Interlayer	Concretions		Length, cm	Thickness, cm	
Sompa, A-C	1.48	0.14	0.065	2.4	1.3-54 11	1-11.3 3.3	1-450 38.5
Kohtla, A–C	1.45	0.165	0.06	2.1	1.5-59 10.9	1-12.5 3.6	1-425 45.3
Ahtme, A-C	1.4	0.145	0.065	2	1-66 11.7	1-12.5 3.9	1-455 47.8
Tammiku, A-C	1.5	0.13	0.055	1.9	1.5-59 11.8.	1-12.2 2.7	1-400 30.5
Ahtme, D-F_1	1.1	0.12	0.18	8	3-46 10	1-7 2.7	3-359 24
Leningrad following dirt-III	1.9	0.305	0.13	5	2-69 13	1-14.4 4.5	1-350 54.5

Note: The lowest and highest figures are given in the numerator, the average values in the denominator.

Table 2.3. **Summary Table of the Content of Concretions in Different Oil Shale Layers**

Index of layer and interlayer	Thickness, m	Concretions	
		Average thickness, cm	Content, %
F_1	0.59	2-4	17-21
E	0.34	2-4	18-22
E/D	0.08	0.08	100
D	0.09	—	0
D/C	0.21	0.21	100
C	0.35	3-5	18-23
C/B	0.13	0.13	100
B	0.58	2-3.5	6-9
B/A	0.16	0.16	100
A	0.26	—	0

2.3. Cuttability of Oil Shale

For determining the cuttability of oil shale, and its interlayers and concretions, the SDM-1 dynamometric drill was used combined with ASR instrumentation developed by A. A. Skotchinsky Institute of Mining Engineering and Donetsk Coal Mining Institute for testing composite bed rocks.

Table 2.4. **Cuttability of Different Oil Shale Layers**

Layer and interlayer	Cuttability, N/mm, *Kohtla, Sompa, Ahtme* and *Tammiku* mines
F_1 (I)	
Oil shale	185-195
Limestone	430-440
E (I)	
Oil shale	180-195
Limestone	400-425
E/D (“Sputnik”)	
Limestone	410-450
(“Mergel”)	
Oil shale	180-200
D/C (“Plita”)	
Limestone	510-530
C (II)	
Oil shale	180-205
Limestone	430-480
C/B (“Kulak”)	
Limestone	425-460
B (III)	
Oil shale	185-195
B/A (“Sinukha”)	
Limestone	400-440
A (IV)	
Oil shale	170-190

Note: Designation of layers and interlayers in Gdov (Leningrad) deposit is given in brackets.

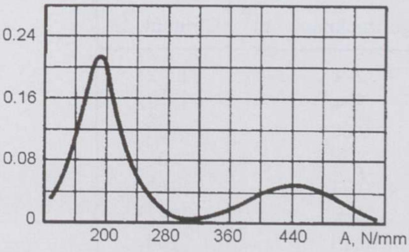


Fig. 2.1. Distribution of values of cuttability of oil shale

In Table 2.4, it is shown that the cuttability of concretions and interlayers is 2-2.5 times higher than that of oil shale. The distribution of values of cuttability of oil shale and concretions may be described with accuracy sufficient for engineering calculations by normal distribution.

Distribution of cuttability values for different seams, as well as for the full oil shale bed has a two-peak character being a summation of distribution of cuttability of oil shale and limestone (Fig. 2.1).

2.4. Abrasiveness of Oil Shale Rock

Abrasiveness is generally defined as intensity of wear of cutting tools. For its determination a method has been used proposed by L. I. Baron and A. V. Kuznetsov. It has been experimentally shown that all oil shale layers and interlayers may be rated to low abrasive rocks (not exceeding 5 mg).

2.5. Breakability and the Degree of Brittleness of Oil Shale

Evaluation of breakability was performed by a method developed by A. A. Skotchinsky Mining Institute. For this purpose over 100 samples were analyzed produced by cutting of oil shale and limestone, and also taken in mines by mechanical cutting of oil shale. Samples taken in mines were divided into size classes of 1-6, 6-13, 13-25, 25-50, 50-75, 75-100, 100-125, 125-150 and above 150 mm and respectively the laboratory samples into classes of 0-3, 3-5, 5-10, 10-13, 13-16, 16-20, 20-25, 25-50 and above 50 mm. The screen analysis showed that the sizing of oil shale broken by cutting is described by Weibull distribution, as is also the case at breaking coal by cutting. The characteristic sizings presented in Fig. 2.2 indicate that all the straight lines shown in figure run practically in parallel. This evidences that the factor of breakability has a constant value both for different seams and for their ingredients. The average value of the breakability factor $m = 0.76$.

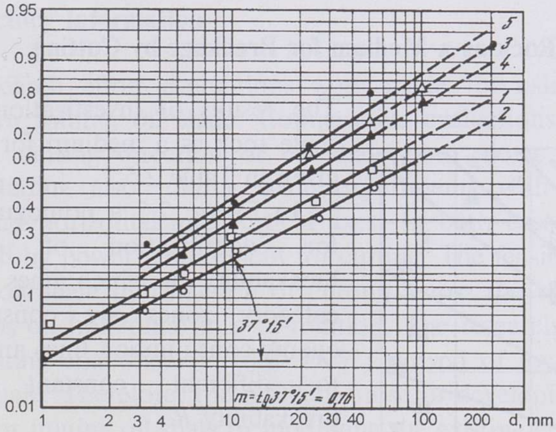


Fig. 2.2. Screening results on functional sizing set: *1* - oil shale; *2* - limestone; *3* - seam D-F$_1$; *4* - seam A-C; *5* – following dirt-III

According to the calculation method used for determining of loads and energy consumption for cutting, the brittleness degree for coal is evaluated by the break-out angle of the cutting ridge produced by DKS testing machine under standard operating conditions. At the A. A. Skotchinsky Mining Institute, a method has been developed for evaluation of the degree of coal brittleness, according to which the side slope tangent is expressed by the equation:

$$\mathrm{tg}\varphi = Bh^{-0.5} \tag{2}$$

where B - factor of the degree of coal brittleness, invariant to breaking process, and equal to the tangent of break-out angle at a depth of cut of $h = 1$ cm.

The analysis of experimental results indicated that the brittleness degree for oil shale of markedly stratified structure, and which is assessed by the break-out angle

$$\mathrm{tg}\varphi = ch^{-0.7} \tag{3}$$

depends also on the direction of cutting (along or across the bedding)

$$c = BK_{sl} \tag{4}$$

where $B = 1.48$ - factor of the degree of oil shale brittleness;

K_{sl} - factor allowing for cutting direction. For cutting along the bedding $K_{sl} \cong 0.8$, across the bedding $K_{sl} \cong 1.2$.

Thus, considering the values of m and B, the oil shale layers, according to their breakability by cutting may be rated to tough rocks. For the calculation of the break-out angle the following equation is to be used:

$$\mathrm{tg}\varphi = K_{sl}[\exp(2.3m)/m^2 - 8.4]h^{-0.7} \tag{5}$$

2.6. Oil Shale Rock as a Medium for Breakage by Cutting

The results of investigations of the oil shale rock as a medium for breaking are given in Table 2.5.

In Figure 2.3 a nomograph is shown for identification of category of breakability in which lines between the category zones are constant specific energy consumption lines and correspond to different constant values of breakability R.

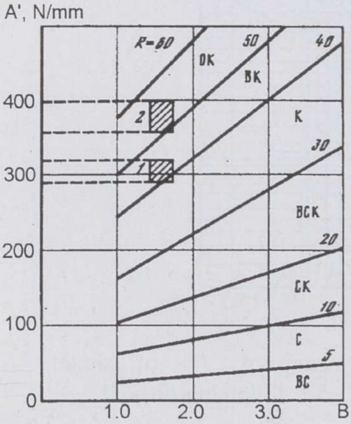


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Fig. 2.3. Category of oil shale layers according to breakability

For identification of the breakability category of oil shale in comparison to coal corresponding values of A and B are to be inserted in the nomograph. Thus, it was determined that by mining the A-C and D-F_1 seams the factor of breakability equals to R = 40-45 kWh cm/m^3 classifying the breakability category as BK (rather hard). From the point of view of standard conditions for using mining equipment, the oil shale seams are rated to the most complicated group III.

Table 2.5. **Basic Properties of Oil Shale as a Medium for Breaking**

Winning	Mining by seams	Mining of full bed
Cuttability, N/mm	280-330	340-400
Share of limestone, %	18-32	34-40
Abrasiveness, mg/km	15-20	15-20
Breakability factor	0.7-0.8	0.7-0.8
Factor of brittleness degree	1.45-1.7	1.45-1.7
Factor of breakability, kWh cm/m^3	40-45	50-55
Class of cuttability	V-VI	VII
Category of breakability	BK	OK
Group of standard conditions of using shearers	IIIa	IIIb

As a result of the above research it was concluded that oil shale may be rated as a breakable medium by cutting tools. Initial data were identified for calculation of loads on cutting tools and for rating the capacity of shearers.

3. Loads on Cutting Drums and Tools

3.1. Introductory Information

In early research effort evaluations were made for using coal mining equipment for mining oil shale. Comparative evaluations were made by experimental cutting direction of oil shale both along and across the bedding including also mining scale experiments with cutting drums rotating round horizontal and vertical axes. In both cases the efficiency was estimated by power requirement for cutting. The feasibility was shown of breaking oil shale by direction of cutting across the bedding by using cutting drums on horizontal axis of rotation. The research also evidenced that the existing coal shearers (e.g. 2K52) proved of low endurance for mining oil shale. Therefore, the problem arose of developing special types of shearers for mining oil shale or modifying the existing coal shearers.

At the initial research stage attempts were made to calculate the parameters for oil shale shearers according to the methods developed for corresponding coal shearers. The results, however, showed that calculated energy consumption figures were by 30-40 % lower than those determined experimentally by mining the A-C seam with shearers 2K52 and 1GSh68. Therefore, special laboratory experiments were performed of cutting oil shale and limestone with the use of single cutting tools accompanied by corresponding experiments in the mines. In Table 3.1 the results are presented of determining the cuttability and strength properties of oil shale blocks tested.

The parameters of the cutting process and the characteristics of the cutting tools used in the experiments were calculated according to methods used for coal shearers and the rated figures compared with experimental results. The determination of cutting force components (*X*, *Y*, Z) during cutting of oil shale was effected with three-component tensiometric dynamometer. Based on the results of experiments decisions were made of using the methods and developing their modifications for oil shale mining technology.

Table 3.1. **Cuttability and Strength Properties of Oil Shale and Limestone Blocks Tested**

Rock type	Cuttability A, N/mm	Resistance, N/cm^2		Percussive strength, N/mm^2
		to compression	to tension	
Limestone	$\frac{485}{6}$	$\frac{8090}{11}$	$\frac{700}{15}$	$\frac{950}{9}$
Oil shale (layer B)	$\frac{180}{13}$	$\frac{2150}{11}$	$\frac{360}{15}$	$\frac{120}{14}$
Oil shale with concretions (seams E-F$_1$)	$\frac{250}{12}$	$\frac{3040}{9}$	$\frac{460}{15}$	$\frac{190}{18}$

Note: Average data are given in the numerator, the variation factors in the denominator.

For determining the force characteristics and specific energy for cutting of oil shale along and across the bedding in mines the ASR instrumentation was used. Forces on the cutting tools were measured by using special tensor cutting tools.

3.2. Research on Breaking Oil Shale Along and Across the Bedding

The initial experimental studies on breaking oil shale along and across the bedding were performed using the USR-1 unit. The results confirmed that breaking oil shale across the bedding leads to considerably lower load requirements and lower specific energy consumption than cutting along the bedding.

Analogous conclusions may be made on the results of the use of the MK-67 shearer equipped with a vertical cutting drum for breaking the seams along the bedding, and the 2K52 shearer equipped with cutting drums on the horizontal axis of rotation for breaking across the bedding. The above results predetermined the use of shearers designed for cutting oil shale across the bedding.

For studying the physical nature of the results obtained the research was continued by experimenting with single cutter. In this case differences were observed in the values of the break-out angles. The break-out angle is by 1.5 times smaller by cutting along the bedding than by cutting across it.

Table 3.2. **Parameters of Cutting Oil Shale Along and Across the Bedding (Evened Surface Basis)**

Cutting direction	Depth of cut h, cm	Cross-section of cut S, cm^2	Average cutting force Z_0, N	Specific energy H_w, kWh/m^3
Laboratory experiments				
Along	1	3.2	1830	1.56
	2	6.7	3340	1.36
Across	1	3.8	1680	1.2
	2	8.6	3200	1.01
Mine-scale experiments				
Along	1	3.1	1900	1.67
	2	6.8	3560	1.42
Across	1	3.8	1750	1.25
	2	8.4	3380	1.09

The analysis of data presented in Table 3.2 led to the following conclusions:

1. Cutting across the bedding, with other conditions being equal, results in an increased cross section cut by 25 % on an average. The corresponding break-out angles are 32-36° by cutting along the bedding, and 40-50° across the bedding.
2. Specific energy for cutting across the bedding is 1.3-1.35 times lower which practically corresponds to the change of the factor of stratification K_{sl}.

3.3. Forces on Tools at Breaking Oil Shale

Since oil shale is of a non-uniform structure, cutting forces on a single tool were determined separately for breaking oil shale, oil shale with concretions and interlayers. Under laboratory conditions tool loads were measured by cutting with DKS, T100 and 1T100 tools. In Table 3.3 relative levels are given (forces on tools by cutting oil shale free of concretions was taken as unit).

Table 3.3. **Relative Levels of Forces**

Material for cutting	Cutting force Z_0	Normal force Y_0	Sideways force X_0	Ratio $Kp = Y_0/Z_0$	Factor of force variations	Specific energy at $h = 2$ cm
Oil shale	1	1	1	1	1	1
Oil shale with concretions	1.2-1.5	1.3-1.4	1.1-1.5	0.98	1.2	1.5
Limestone	2.5-3	3.2-3.5	1.6-1.8	1.07	1.1	2.6

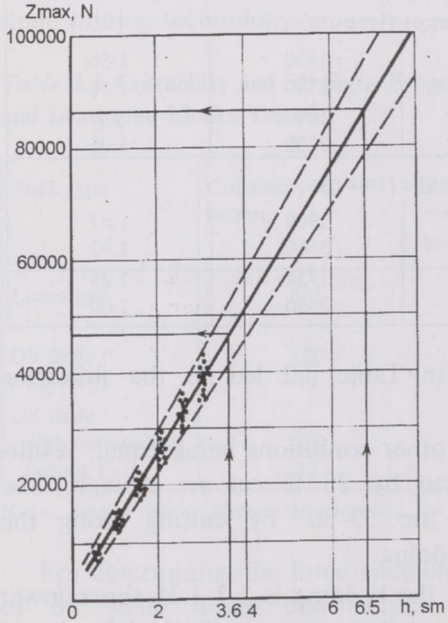

Fig. 3.1. Relationship between the peak cutting force on single tool and the depth of cut

In comparison to cutting oil shale the average cutting forces for oil shale with concretions are 1.2-1.5 times higher while those for cutting limestone interlayers exceed 2.5-3 times the forces required for oil shale. The corresponding figures for normal forces were 1.3-1.4 and 3.2-3.5 and those for sideways forces 1.1-1.5 and 1.6-1.8. Since the peak forces level is required for cutting interlayers with a thick-ness exceeding 2-3 times that of the largest concretions, the maximum force calculations are to be performed for that part of the oil shale layers.

In Figure 3.1 the peak cutting forces are shown determined by using the T100 tool with a spacing of t = 5-7 cm for cutting the hardest interlayers.

The average relationship is practically linear.

$$Z_{peak} = [5800(1 + 2.45h)t]/(t + 2) \qquad (6)$$

3.4. Determination of Rational Parameters for Breaking Oil Shale by Cutting Tools

For determining rational parameters for breaking oil shale and limestone according to existing procedures the T100 and IT125 cutting tools were used. The tools have fairly good cutting characteristics, have good wear resistance, and the sizing of the resulting oil shale particles is acceptable. Besides this, for determining the optimum parameters for breaking oil shale by DKS tools in the mines the ASR instrumentation was used. This approach was considered admissible since the DKS and T100 cutting tools have practically similar width and shape of the cutting edge. The research was aimed at attaining two goals:

1. Identification of rational depth of cut for which the parameters of the cutting process are determined
2. Determination of rational parameters of cutting schemes for oil shale bed

To attain the solution for the first goal, the cutting results were analyzed of operations with T100 and DKS cutting tools on the layer B ($A = 185$ N/mm) and with T100 cutting tool on interlayers D/C ($A = 485$ N/mm).

The results of analysis indicate that the specific energy consumption by cutting oil shale and limestone (evened surface basis) becomes practically stable at the depth of cut h = 2.5-3 cm. Further increase in the depth of cut does not lead to significant reduction of specific energy consumption. On the basis of the data obtained, and taking into consideration the need for a higher haulage speed (for increased productivity), it may be assumed that the average rational depth of cuts for breaking oil shale layers is as high as h = 3-3.5 cm. As the character of the relationship between specific energy for cutting and the depth of cuts are identical for both oil shale and limestone, the above conclusion may be regarded as correct also for cutting of the full bed of oil shale.

For the solution of the second goal a series of experiments was carried out by cutting both oil shale and limestone at a depth of cuts of h = 0.5-2.5 cm and a spacing of t = 3-7 cm.

Further analysis of the experimental results by cutting oil shale by DKS tool and limestone by T100 tool confirmed the conclusion that for each depth of cut value, the dependence of specific energy on the ratio of t/h has optimum values corresponding to optimum $(t/h)_{opt}$ values.

For determination of $(t/h)_{opt}$ in the range of changes in the depth of cuts up to 3.5 cm with an accuracy sufficient for engineering calculations, the following equation may be used:

$$(t/h)_{opt} = 1.4 + 2.2/h \qquad (7)$$

The comparison of Eq. (7) with calculated expression of optimum ratio of t/h for tough coals shows that both curves are practically similar, but in the case of oil shale the values of t/h are somewhat higher in the range of higher depth of cuts. The relationship (7) is correct for cutting tools with a width of the cutting edge of b_p = 2 cm. In case of tools with a width of the cutting edge other than 2 cm, for determination of the optimum spacing relationships developed for the tough coal group may be used.

The analysis of experimental results indicates that for cutting oil shale the zones of rational specific energy values lay in a sufficiently broad range of variation of the spacing, i.e. it is possible to operate at a larger spacing with only a slight determination in specific energy values. For example, if changing from a spacing of $t = 4$ cm which is the optimum for a depth of cuts of $h = 1.5$ cm, to a cutting of $t = 6$ cm, the specific energy shows an increase of only 7 %. If changing from a spacing of $t = 5$ cm which is the optimum for a depth of cuts of $h = 2$ cm, to a spacing of $t = 6$ cm, the corresponding increase in the specific energy is as low as 3 %.

This phenomenon may be explained in some degree by peculiarities of breaking oil shale rock. The analysis of the character of oil shale cleavage in the process of breaking at different ratios of t/h indicates that break-out of oil shale particles from the seam mass results in producing particles of irregular form (depending on the cutting direction), elongated in the direction of the preceding cut (repeated cutting procedure). This is probably the reason for a rather low effect of changing the spacing on the change of the specific energy.

The factor of working face exposure K_{ex} can be determined:
For limestone

$$K_{ex} = 0.44 + 0.2/h \tag{8}$$

For oil shale with concretions

$$K_{ex} = 0.42 + 0.2/h \tag{9}$$

Along with the analysis of load and energy data of the cutting process at different parameters, the analysis was also performed of the results of screening the products of breaking. The analysis shows that the value of reduced breaking degree factor K_m depends on the cross-section of the cut. If the latter is increased, K_m decreases and becomes stable at $S = 15$-20 cm^2 that corresponds to operating at optimum ratios of t/h. It is pertinent to note that 1GSh68S shearers operate at an average cross-section of 5 cm^2 of the cuttings (one I90MB tool on the cutting line, $t = 3$ cm, $v_n = 1.5$-1.7 m/min) to which the value of $K_m = 0.046$ and yield of 65-70 % of 0-25 mm oil shale fines correspond. If the T100 (1T100, IT125) tools are used, efficient cutting can be performed at $h = 2.5$-3 cm and $t = 6$ cm which at $S = 15$-20 cm^2 leads to a value of $K_m = 0.025$-0.027 and to a reduction of the yield of 0-25 mm oil shale fines to 45-50 %.

The average optimum depth of cuts at the existing conditions of oil shale bed and a minimum of specific energy consumption and a minimum yield of shale fines is $h = 2.5$-3.5 cm and the ratio $t/h = 2$-2.5.

The average optimum cross-section of cuttings is in a range of $S = 15$-20 cm^2, and the corresponding optimum spacing $t = 6$-7 cm.

3.5. Method of Determining Average Forces on Cutting Tools and Cutting Drums

In spite of the fact, that shearer loaders (2K52, 1GSh68, 1GSh68S) have been operated in the oil shale basis since 1971, no methods of calculating the loads on cutting tools for breaking oil shale and recommendations for the selection of cutting tools and parameters for cutting drums had been developed by the time when the writing of the monograph commenced. The analysis indicated that the calculation methods for loads and the recommendations developed for the selection of cutting parameters and procedures for breaking of coal seams of composite structure, may serve as a theoretical basis for research on oil shale breaking.

Adequate representative data on cutting oil shale and limestone obtained by laboratory and mine-scale experiments enabled to develop methodical recommendations for the calculation of loads acting on cutting tools in the process of breaking oil shale. As a basis the load calculation methods were taken developed for coal shearers.

In order to check the applicability of the methods used in the calculation of average loads on tools for breaking oil shale, experiments were performed for the same parameters as during the experiments of cutting oil shale, limestone and the seam D-F$_1$. It was found that in case of all types of oil shale seams and cutting processes a systematic one-way deviation exists between calculated and experimental data with an insignificant dispersion of results (K_{var} = 13 %). The standard calculation method gives lower cutting force values in comparison to experimental data ($Z_{calc} \sim 0.57 Z_{exp}$).

Since the deviation is systematic and depends on neither the properties of the working medium nor the parameters of the process, one may assume that the method developed for cutting force calculations in coal mining may also be used for oil shale cutting processes if due consideration is taken to the causes of systematic deviation:

A. **Differences between the brittleness degree of oil shale and the average friability degree of tough coals**. Reduced values of the break-out angle by cutting oil shale (by 28 % on an average) compared to the break-out angle accepted for tough coals is a cause for increased average forces noted above.

B. **Differences in the character of changes of cuttability in the zone of operation of the cutting drum**. The research results have shown that under the present conditions of breaking oil shale no squeezing action takes place, therefore in calculation $K_{sq} = 1$.

C. **Optimum spacing**. Besides the above causes, that are considered the most important, the experimentally established effect of dependence of the optimum spacing t_{opt} on the depth of cut h (see Eq. (7)), and also of the average value of the optimum face exposure factor K_{ex} on the depth of cuts make the method of calculation more precise.

D. For the determination of full average cutting forces and of the average normal force on the tool, the experimental data obtained about the single-axle compressive strength σ_{comp} (MPa): for oil shale - 21.5, for oil shale with concretions - 30, for limestone - 80 are also to be taken into account.

E. The ratio of the normal force to the cutting force on a sharp tool at $h = 1\text{-}3$ cm, is to be taken, according to experimental data, equal to $K_p = 0.62$.

Thus, for the calculation of average loads on cutting oil shale a method may be recommended for use taking into account the above consideration. The average cutting force on a sharp tool is determined according to the following modified equation:

$$Z_0 = A[(0.35b_p + 0.3)/(b_p + Bh^{0.3})]htK_{ex}K_c \qquad (10)$$

where h and t - depth of cut and spacing, cm;

A - average cuttability, N/mm;

B - average degree of brittleness, $B = 1.48$;

b_p - calculated width of tool, mm;

K_c – cutting tool and drum design factor.

The proposed modification of the calculation method enables to obtain data corresponding to experimental results (deviation from experimental data is in a range of ±10 %).

3.6. Determination of Maximum Loads for Breaking Interlayers and Concretions

For the selection of drive mechanisms and calculation of the strength and durability of their elements, it is essential to know not only the average cutting forces, but also the maximum cutting forces and their appearance frequency. In the process of breaking oil shale seams of composite structure by shearers, the appearance of maximum loads on the cutting drums is caused by simultaneous contacts of a number of cutting tools also with interlayers and concretions scattered across the entire working face.

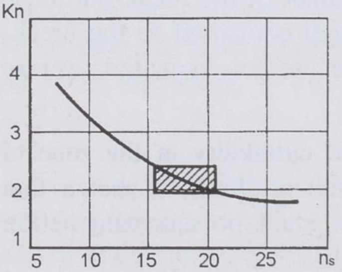

Fig. 3.2. Effect of the number of simultaneously operating cutting tools on the load irregularity factor

It has been shown that for the evaluation of the effect of cutting load irregularities on the implement mechanism, a load irregularity factor K_n is to be used depending on the number of cutting tools simultaneously involved. Under the usual cutting tools arrangement schemes K_n lies in the range of 2-2.5 (the shaded zone in Fig. 3.2).

According to the adopted method, in case of monotonous stalling of the drive the maximum torque $M_{\max}$ in transmission reduced to the driving shaft is determined by the level of the average torque M_{av} and the overload appearing at the contact of several cutting tools with concretions:

$$M_{\max} = K_t M_{av} \tag{11}$$

The overload factor K_t, in the absence of shock-absorbing devices (dampers), equals to K_n that leads to the following equation for calculation of the maximum torque:

$$M_{\max} = K_n M_{av} \tag{12}$$

The maximum torque (Nm) in the transmission during regular operation of a shearer loader may also be determined by the level of the average dynamic torque M_d appearing at cutting of a hard obstacle by a single cutting tool of the drum:

$$M_{\max} = M_{av} + M_d \tag{13}$$

The dynamic torque in the transmission M_d reduced to the shaft of the drive is determined by the resistance torque on the drum at cutting of a hard obstacle and by its intensification factor in the transmission:

$$M_d = K_{int} M_{res} \tag{14}$$

The resistance torque (Nm) on the drum reduced to the shaft of the drive with no dampers involved is determined by the following equation:

$$M_{res} = (Z_{peak} D_d)/2i_{gr} \tag{15}$$

where D_d - drum diameter, m;
i_{gr} - gear ratio;
Z_{peak} - max. peak cutting force.

For evaluation of the applicability of the method for calculating maximum loads appearing during cutting of interlayers and concretions, the calculated parameters were compared with corresponding experimental data obtained by cutting with T100 cutting tool under laboratory conditions.

The above comparison led to the following `conclusions:

- Calculation of average peak cutting forces Z_{peak} results in satisfactory convergence with the experimental data;
- The calculated peak cutting forces significantly exceed (by 1.5-2 times) the experimental figures that can be explained by physical peculiarities of cutting oil shale leading to rather low differences between peak

cutting forces and the average peak cutting forces in contradistinction to cutting of coal.

The maximum peak cutting force Z_{peak} is determined

$$Z_{peak} = Z'_{peak}\ (1 + 3v_{Z'_{peak}}) \tag{16}$$

$$Z'_{peak} = 1300 + 520d_{in} + 1300h \tag{17}$$

It may be assumed that the difference in peak cutting forces for oil shale and coal is explained by differences in variation factors $v_{Z'_{peak}}$. For the oil shale layer it is to be determined by the equation:

$$v_{Z'_{peak}} = 0.08 + 1250/Z'_{peak} \tag{18}$$

The results of comparison indicate that the calculated values of the peak cutting forces variation factors are on an average 3 times higher than those determined by actual cutting of oil shale. Because of the above difference, lower levels of peak forces in comparison to average peak cutting forces characterize the cutting of oil shale. Thus, for calculation of the maximum forces for cutting oil shale the following method may be suggested:

1. Determination of average peak cutting forces is performed applying the following equation:

$$Z'_{peak} = (6500(1 + 2h_{max})t)K_b/(t + 2.5) \tag{19}$$

where h_{max} - maximum depth of cut, cm;
K_b - factor of cuttings.

2. The maximum peak cutting force is determined by equation (16), where $v_{Z'_{peak}}$ is calculated by (18).

In case of using T100 (IT125) cutting tools the maximum force may be calculated by the equation (6).

3.7. Determination of the Load Spectrum on Cutting Drums

Determination of the load spectrum on the cutting drums of shearers is performed by a method based on the identification of the overall load variation factor taking into consideration the following:

- Type and design features of the cutting drums characterized by the variation factor v_1
- Specific properties of the oil shale layer subjected to breaking characterized by the variation factor v_2
- Variability in cuttability of oil shale across and deep into the layer characterized by the variation factor v_3

- Variability in cuttability of oil shale along the working face characterized by the variation factor ν_4
- Unevenness of the hauling motion of the shearer characterized by the variation factor ν_5

The overall load variation factor ν_{tr} in the transmission to the cutting drums is determined by the equation:

$$\nu_{tr} = (\nu_1^2 + K_{int}(\nu_2^2 \nu_3^2) + \nu_4^2 + \nu_5^2) \tag{20}$$

where K_{int} - factor of load intensification in the transmission to the cutting drum compared to load on the cutting drum; K_{int} equals to 1.23.

The design variation factor ν_1 characterizing the unevenness of the circumferential force assumed for regular drums per revolution of cutting drum of the 1GSh68S shearers in the range of ν_1 = 0.046-0.053, and for the developed arrangement schemes of new types of tangential cutting tools (T100, IT125) ν_1 = 0.028-0.032, respectively.

The variation factor ν_2 characterizing specific structural properties of the oil shale layer, is determined by the equation:

$$\nu_2 = \nu_z / n_s^{1/2} \tag{21}$$

where ν_Z - load variation factor on single cutting tool;
n_s - number of cutting tools simultaneously in contact with the working face.

For the existing hauling speed (h < 2 cm) ν_Z is assumed in the range of 0.72-0.79 for selective mining by seams and 0.8-0.85 for full-face mining of full bed. For hauling speed ($h \geq 3$ cm) the values are ν_Z = 0.66-0.7 and ν_Z = 0.72-0.76, respectively.

The variation factor ν_3 characterizing the variability of load caused by non-uniformity of oil shale rock properties across the working face ranges from 0.3 to 0.38 and equals to 0.3 for D-F_1 seams, 0.33 for A-F_1 seams and 0.38 for A-C seam.

The variation factor ν_4 characterizing the variability of load caused by variability of resistance along the working face has been determined experimentally and for the oil shale bed equal to 0.12-0.15.

The variation factor ν_5 characterizing the unevenness in the depth of cuts at different hauling speed of shearers and different hauling chain lengths ranges from 0.15 to 0.4.

In conclusion it is pertinent to note that in the process of cutting oil shale high average loads have been observed at significant variations which lead to increased loading of the cutting drums and transmission of the shearers. As a result, the operating service life of shearers used for cutting oil shale is 1.5-2 times shorter than that of the shearers used in coal mines.

4. Calculation Method for Determination of Sizing and Heat Value of Oil Shale Mined by Cutting

By applying the statistical distribution according to Weibull the function of size distribution of oil shale particles may be assumed as follows:

$$W = 1 - \exp[-(d/d_0)^m] \qquad (22)$$

where $d_0 = \chi_{0.63}$ - diameter of screen opening to pass 63.2 % of broken oil shale;
m - breakability factor of oil shale - 0.76.

Hence, the share of oil shale to pass the 25 × 25 mm screen in the total mine-run shale equals to:

$$\delta_{-25} = 1 - \exp[-(25/\chi_{0.63})^{0.76}] \qquad (23)$$

(mining by seams) $\chi_{0.63} = 20 + 2.16S`$ and
(mining of full bed) $\chi_{0.63} = 17.41 + 1.22S`$
where S` - cross-section of cut, cm^2.

The above equation demonstrates the connection of the parameters of the law of distribution with the parameters of oil shale particles sizing.

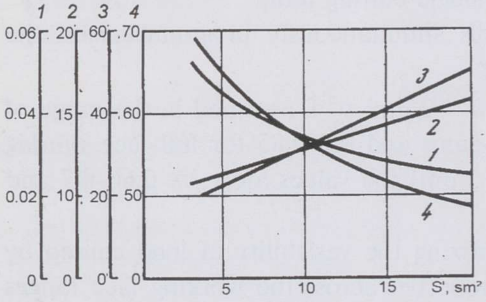

Fig 3.3. Calculated relationship between oil shale particle sizing and heat value and the average cross section of cuttings (A-C seam): *1* - K_m; *2* - Q^d_{bm} ; *3* - $\chi_{0.63}$; *4* - δ_{-25}

The heat value of the trade shale was calculated according to an algorithm developed by the former Estonian Branch of the A. A. Skotchinsky Institute of Mining Engineering. The results of calculations of the oil shale quality indices in relationship to the cross section of cut are shown in Fig. 3.3.

The relationship indicate that the yield of oil shale fines δ_{-25} and the breaking degree factor K_m decrease according to hyperbolic curves stabilizing at S values of 15-20 cm^2.

The average particle size $\chi_{0.63}$ and the heat value of shale fines Q^d_{bm} show a linear increase along with the increase of S. Deviation of calculated data from experimental does not exceed 8-12 %.

The calculation method developed enables to evaluate the shearers according to oil shale breakability factor under given mining conditions and to select the design and operational parameters of the cutting drums for pre-set yields of oil shale fines.

Conclusions

The research performed on breakage of oil shale by cutting and the recommendations developed enabled:

- To introduce longwall mining by shearers to Estonian oil shale deposit maintaining the optimum of performance between mining capacity and product grade
- To make recommendations for reinforcement of design elements of coal shearers
- To create a scientifically founded method for calculating the operative loads on cutting tools, cutting drums and transmissions of the shearers used for mining oil shale
- To develop reliable designs of cutting tools and drums for shearers capable of operating in tough rocks

There is no doubt that the identified relationships between the energy consumption in the process of breaking oil shale, the parameters of oil shale particle sizing and the distribution of heat value of the extracted product are of theoretical and practical importance.

At certain optimum levels of energy consumption for breaking oil shale the resulting product is represented mostly by large particle oil shale which, in its turn, determines the productivity of the shearers, the upgradability and the heat value of the extracted product. The optimum breakage of oil shale is performed under certain cutting processes, which determine the values of peak and average peak loads on the cutting drums and lead, in the long run, to fatigue phenomena of the elements of the shearers. Consequently, the energy consumption level and the parameters of the oil shale cutting process will be determined by the required productivity of the shearer, by the required grade of the product oil shale and by the need for leveling of loads on the mechanisms.

The above will contribute to further extension of the use of shearers for the extraction of oil shales and other similar types of rock.