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EVALUATION OF THE EFFICIENCY OF IMPACT MECHANISMS ON THE EXAMPLE OF HYDRAULIC ROTARY HAMMER DRILLS

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Abstract:
The efficiency of energy transfer in impact mechanisms, often referred to as impact engines, is of key importance for users of these devices, including hydraulic rotary hammer drills. The choice of a method that allows for accurate and repeatable determination of the impact frequency and impact energy as a function of supply parameters (supply flow rate, supply pressure,) is an important issue, ultimately enabling the assessment of the efficiency of these devices. For this purpose, an analysis was carried out of the available analytical, analytical-empirical, and empirical methods, along with their associated measurement systems. In conclusion to this analysis, a proprietary method was proposed, which involved empirically determining the impact frequency fum and impact energy Eum as a function of the feed rate qzum and the feed pressure pzum. Simultaneously, for hydraulic rotary-percussive drills, the rod rotational speed nwou, the feed rate qzo, and the feed pressure pzo were empirically determined. For this method, a mobile measurement station was constructed, allowing for the performance of the tests at the drilling machines' worksite. Appropriate tests were then conducted using this station. Based on the measurement results, the mechanical, hydraulic, and overall efficiency of the tested rotary percussion drills were determined. This allows for an assessment of the performance of the tested drills and for making informed decisions about their future use. This is important for the proper organization of the hydraulic rotary hammer drills' operation, their servicing, repairs, and overhauls.

Key words: hydraulic rotary rotary-percussion drills, determination of impact energy, force sensor

INTRODUCTION

Impact mechanisms, often referred to as impact engines, exemplified by impact hammers, are used to generate and transmit impact energy of a predetermined value and frequency. The reciprocating motion of the piston, also called the striker, is driven by compressed air or by a stream of hydraulic fluid. The collision of the striker with the tool results in the transfer of impact energy, which is utilized for the destruction of artificial or natural materials (disintegration of cohesion). In such cases, the device is referred to as a pneumatically or hydraulically driven impact hammer.

Users are interested in functional parameters, which for impact are the impact frequency f_u and impact energy E_u, as well as power supply parameters, namely the supply flow rate q_{zu} and pressure p_{zu} of the medium (compressed air, hydraulic oil). For rotary percussion drills, the rod speed (n_{wou}), the flow rate (q_{zo}), and the rotational supply pressure (p_{zo}) are also important parameters.

The above-mentioned parameters should be provided by the manufacturer, but with an indication of the method of their determination. This applies particularly to the determination of impact energy, as this parameter can be determined analytically, empirically, or empirically-analytically. Other parameters, such as pressure, flow rate, and rotational speed, can be determined empirically using appropriate transducers (sensors). Therefore, in this case, the most important thing is to clearly and accurately determine the energy E_u and the impact frequency f_u as a function of the supply parameters (medium supply intensity q_{zu} and supply pressure p_{zu}). This allows for the assessment of the technical performance of hydraulic rotary-percussion drills, both new and used.

METHODS FOR DETERMINING IMPACT ENERGY AND IMPACT FREQUENCY

As mentioned earlier, the impact energy Eu and impact frequency fu can be determined using various methods, namely analytical, empirical, and analytical-empirical methods [1, 2, 3, 4]. The least accurate results are obtained using analytical methods to determine impact energy. More accurate results can be obtained using analytical-empirical methods, where the force driving the piston (ram) in the equations of motion is determined by measuring the pressure values at the feed and return. The most commonly used method is measurement with strain gauges attached to the rod, tip, or intermediate element. When properly applied and calibrated, strain gauge measurements enable accurate and repeatable results. Accurate and detailed information on this topic is provided in the cited literature [4, 5, 6, 7,8, 9, 10, 11, 12, 13].

In the case of rotary-percussive drills, an empirical method was chosen to assess their technical condition, using measurement of impact energy and frequency using a strain gauge transducer. This required the development of a concept, design, and documentation for a mobile measurement station that would allow for the performance of these tests at the drilling site [14].

EVALUATION OF THE TECHNICAL EFFICIENCY OF ROTARY PERCUSSION DRILLS

Determining the technical efficiency of rotary percussion drills is necessary to establish their actual parameters and the degree of wear. Therefore, determining the impact energy and frequency, as well as the feed parameters (pressure and flow rate), is required.

It is assumed that the total (energy) efficiency η_{co} of an impact engine is expressed by the general relationship [2]:

$$\eta_c = \eta_h \cdot \eta_m, \quad (1)$$

where:

η_h – efficiency of the internal hydraulic system of the hammer (hydraulic efficiency),

η_m – efficiency of the ram-tool-rock system (mechanical efficiency).

$$\eta_h = \frac{E_u \cdot f_u}{p_{zm} \cdot q_{zm}}, \quad (2)$$

where:

E_u – impact energy [J],

f_u – impact frequency [Hz],

p_{zm} – fluid pressure at supply [MPa],

q_{zm} – fluid flow rate at supply [dm^3/min].

In the case of bench tests, the hydraulic efficiency η_h is of interest and is expressed by the relationship:

$$\eta_h = k_p \cdot k_\Theta, \quad (3)$$

where:

k_p – proportionality coefficient of the impact energy and the power supply pressure [kJ/MPa]

k_Θ – proportionality coefficient of the frequency and the flow rate of the fluid at the supply [1/dm^3]

then:

$$E_u \approx k_p \cdot p_{zm}, \quad (4)$$

$$f_u = k_\Theta \cdot q_{zm}. \quad (5)$$

Determining the overall efficiency η_c applies to reciprocating motors (impact hammers, drills) and the transfer of impact energy at a specific frequency. However, if the impact motor system simultaneously rotates continuously (rotary-impact drill), then the hydraulic efficiency of the rotation mechanism η_{co} (6) must also be determined.

$$\eta_o = \frac{n_o}{q_{zo}} \left[\frac{obr}{dm^3}\right], \quad (6)$$

where:

p_{zo} – supply pressure to the rotation mechanism, [MPa],

q_{zo} – flow rate of the rotation mechanism, [dm^3/min].

Determining the efficiency of the impact and rotational motors of a rotary-percussion drill allows for the assessment of its technical efficiency at the time of selection and later during operation [6, 7, 9, 10]. As can be easily seen, it is necessary to determine the impact energy and frequency, rotational speed, and power supply parameters.

MEASURING THE IMPACT ENERGY OF HYDRAULIC ROTARY HAMMER DRILL

To measure the impact energy and frequency of rotary percussion drills, an indirect method was chosen, consisting of measuring stresses with a strain gauge transducer placed under the drill rod. Using a separate strain gauge transducer eliminates the aforementioned inconveniences and drawbacks of previous solutions (Fig. 1).

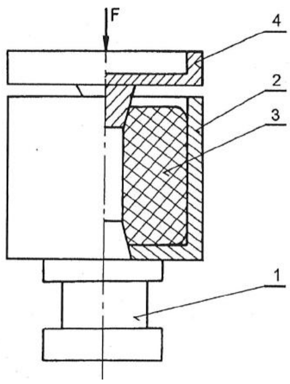

Fig. 1 Design diagram of the energy (force) transducer: 1 – measuring shaft, 2 – cylinder spring 3 – element, 4 – cover

The principle of kinetic (measured) and potential (calibration) energy equivalence was used to calibrate the transducer. Calibration is performed on a stand designed to allow a reference mass m_w to be freely lowered from a specified height h_w onto a strain gauge transducer with mass m_c [8, 9]. Then, using relationship (7), the measured impact energy and frequency can be determined.

$$E'_m = \frac{4 \cdot m_g \cdot m_w{}^2}{m_b \cdot (m_g + m_w)^2 \cdot A_w{}^2} \cdot \left(A_m{}^2 - A_n{}^2\right) \cdot E_w, \quad (7)$$

where:

A_w, A_m, A_n – signal values [mV] corresponding to forces P_w, P_m, P_n,

k_w, k_m, k_n – calibration constants for forces P_w, P_m, P_n, if the transducer does not have a linear relationship, otherwise $k_w = k_m = k_n = k$.

MOBILE MEASURING STATION FOR HYDRAULIC ROTARY-PERCUSSIVE DRILLS IMPACT HAMMERS

Rotary-percussive drills, and formerly percussive drills, are widely employed in drilling machines known as self-propelled drilling rigs, which are capable of relocating for operation (drilling). The substantial mass of these drills precludes their manual handling and particularly their transport. Consequently, an objective rather than subjective assessment of their technical condition is facilitated by the deployment of a mobile test rig enabling the determination of impact energy (E_{um}) and impact frequency (f_{um}), drill rod rotation speed (n_{wou}), and the pressure and flow rate supplying the impact motor (p_{zum}, q_{zum}) and rotation motor (p_{zo}, q_{zo}).

Empirical determination of the functional parameters of rotary-percussive drills is achievable utilizing a test rig designed for real-time measurement and recording of the signals from the measured quantities. In the context of rotary-percussive drills, it is necessary to measure and record signals from the impact energy transducer (impact energy and frequency), rotational speed transducer, and pressure and flow rate transducers on the supply lines for both the impact and rotation motors. An additional requisite feature of such a test rig is its mobility, allowing for drill assessment at its operational site. Therefore, at the KMGPiT AGH (presently the Department of Mechanical Engineering and Transport), a methodology for conducting experiments, encompassing the measurement of energy, impact frequency, rotational speed, supply pressure, and flow rate, was developed, along with the requisite equipment for measuring these parameters (a mobile measurement station).

The measurement station comprises two primary subsystems. The first component is a mobile force sensor integrated with a calibration system (Fig. 2).

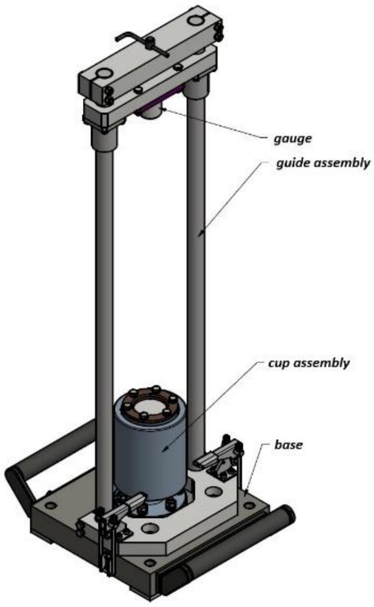

Fig. 2 Model of the impact energy measurement stand

A force sensor incorporating an elastomer insert is centrally mounted on a fixed base equipped with securing fixtures. Furthermore, a guide assembly supporting a reference mass is affixed to the base plate during the calibration procedure.

The second constituent of the station is a set of sensors installed on the drill's hydraulic supply lines. The signals generated by these sensor, as well as by the force sensor, are stored in the memory of a dedicated measurement computer.

For the purpose of energy measurement, a strain gauge force sensor, specifically engineered and fabricated for this application and featuring an elastomer insert, was utilized (Fig. 3).

Fig. 3 View of the force sensor housing equipped with an elastomer insert

To ascertain the rotational speed of the measurement drill rod, an optical system (FT 20 R-PSK4) was employed; this system is attached to the drill housing via a neodymium magnet, while a marker is affixed to the drill rod (Fig. 4).

Fig. 4 Optical system for measuring the rotational speed of the rod

Pressure measurement on the impact mechanism supply was performed using a pressure sensor (Danfoss MBF32), installed on the supply line in conjunction with a flow rate sensor (inductive turbine sensor type PMB-4000). An analogous setup involving a pressure sensor and a flow rate sensor (inductive turbine sensor type PMB-4000) is used for the rotation mechanism (Fig. 5).

Fig. 5 Pressure and power transducer of the impact mechanism and revolutions

The drill testing procedure should commence with the installation of the pressure and flow rate sensors, along with the rotational speed transducer. Subsequently, it is required to position the energy sensor and its associated calibration system at the designated energy measurement location (Fig. 6). Connecting all sensors to the measurement and recording station via cables enables verification of the measurement system's integrity.

Fig. 6 Station with a built-in measuring and recording system for calibrating the force sensor

Upon confirming its correct functionality, the force transducer calibration is performed in accordance with the previously outlined methodology.

Following the completion of the force sensor calibration and the determination of the calibration constants, measurement of impact energy and other parameters can commence, after prior removal of the guide assembly. The drilling feed frame should then be positioned and brought into contact with the force sensor such that the axes of the drill rod and the sensor are aligned (Fig. 7).

Fig. 7 Drilling feed frame positioned for testing

Applying the drill rod to the sensor with a specified preload force requires its registration at this stage. Subsequently, the drill can be activated to record the impact force signal and the signals of other measured quantities. Execution of the drill tests and the recording of the measured quantities' signals enable their processing using specialized software to determine the true values. This pertains to pressure, flow rate, and rotational speed, for which average values are computed, as well as the force signal and impact frequency. The impact energy, however, should be calculated from dependency (16), and the efficiencies from dependencies (2) through (6).

The description provided above, covering the method, test rig, and procedure for measuring the functional parameters of rotary-percussive drills, allows for the quality assessment of the tested equipment based on the obtained results, both at the point of acquisition and subsequently during operational life. In this regard, the aforementioned procedure is recommended for the evaluation of rotary-percussive drills.

TESTING OF HYDRAULIC ROTARY HAMMER DRILLS

In drilling and bolting rigs, rotary-percussive drills are commonly used, while purely rotary drills are applied less frequently. Self-propelled drilling rigs are equipped exclusively with hydraulic rotary-percussive drills, whereas self-propelled bolting rigs may also be fitted with hydraulic rotary drills. However, due to higher investment and operating costs, as well as difficulties in unambiguously determining their operating parameters, rotary-percussive drills are more challenging to evaluate. Therefore, in accordance with the previously developed methodology, the most commonly used rotary-percussive drills in Polish mines were selected for testing. The technical (functional) parameters of these drills are presented in Table 1 (15, 16, 17, 18).

Table 1
The technical parameters of rotary hammer drills selected for testing

No	Manufacturer /drill type	Drill weight, kg	Drilling diameter mm	Drilling length, m	Supply pressure, bar	Flow rate, dm^3/min	Hydraulic power pack power, kW	Max impact energy J	Impact frequency Hz	Rotation speed, obr/min
1	WO-U/SAC1	151	28-64	4,610	150-250	62-80	55	375	40-60	0-300
2	WO-U/SAC2	170	28-64	4,610	200	60-77	55	267	60	0-385
3	WO-U/SAC3	170	28-64	4,610	230	75-92	55	330	60	0-340
4	WO-U/SM1	142	28-64	4,610	135	135	55	400	47	0-230
5	WO-U/SF1	189	28-89	4,610	190	110	55	---	91	0-320
6	WO-U/ST1	130	43-51	3,700	120-175	---	45	---	59	0-250
7	WO-U/ST2	210	43-64	3,700	120-220	---	45	---	67	0-250
8	WO-U/H1	75	28-64	4,610	160	65	55	250	75	0-400

It is readily apparent that the functional parameters of these drills vary significantly, and it is difficult to establish a common correlation between them – particularly regarding the impact energy values declared by the manufacturers. Consequently, these drills were tested directly at their operating sites.

Each drill was first equipped with appropriate sensors (pressure and flow rate transducers). Then, the force transducer was prepared and calibrated at the location where the respective drill was being tested. Following calibration, the drill was positioned such that the tip of the measuring rod rested on the force transducer, with its axis aligned parallel to that of the transducer. This setup enabled the activation of the measurement and data acquisition system, followed by the brief operation of the drill. During operation, signals from all measured quantities were recorded.

The recorded measurement signals-from the force transducer, the pressure transducers on the percussion mechanism and rotation motor supply lines, and the rotational speed of the rod-were collected for subsequent processing and calculation of the actual energy parameters of the tested drills using specialized software. The obtained test results are summarized in Table 2.

Based on the results presented in Table 2, it can be stated that the highest measured impact energy was recorded for the WO-U/SAC3 drill (E_u = 309 J), followed by WO-U/ST1 (E_u = 110 J), WO-U/H1 (E_u = 81 J), WO-U/SM1 (E_u = 77 J), and WO-U/ST2 (E_u = 77 J). The lowest impact energy among the tested drills was observed in the WO-U/SF1 model (E_u = 54 J). A similar trend is observed when comparing the mechanical efficiency of the percussion mechanism (η_{eu}), with the highest efficiency again corresponding to the WO-U/SAC3 drill, followed by WO-U/SM1 and WO-U/H1. The remaining drills show comparable mechanical efficiency.

In terms of hydraulic efficiency of the percussion mechanism (η_{fu}), the WO-U/H1 drill exhibited the highest efficiency, followed by WO-U/SAC3, WO-U/SF1, and the others. The overall efficiency of the percussion mechanism (η_{uu}) was also highest for WO-U/SAC3, followed by WO-U/H1. The remaining order is as follows: WO-U/SF1, WO-U/SM1, WO-U/ST1, with the lowest value observed for WO-U/ST2.

The hydraulic efficiency of the rotation mechanism (η_o) was highest for the WO-U/ST1 drill and lowest for WO-U/SF1, while the efficiency of the remaining drills was at a similar level.

Considering the above, it may be assumed that the tested drills varied in technical condition or degree of wear, with only the WO-U/SAC3 drill demonstrating the highest technical state.

It is recommended that, in the future, the parameters of new and technically sound drills be empirically determined, and the collected results be used as reference data during further operational use. This approach would support future evaluations of technical condition and facilitate maintenance-related decision-making.

When comparing the catalog (manufacturer-declared) parameters of the tested drills with the measured values obtained using the proposed method, significant discrepancies are observed. Therefore, it is recommended that the operational parameters of all drills be determined using a standardized methodology.

Table 2
Summary of measurement results for selected parameters of rotary-percussive drills

No	Drill type	m_{mw} [kg]	m_b [kg]	p_{zudr} [MPa]	q_{zudr} [dm³/min]	E_u [J]	f_u [Hz]	η_{eu} [J/MPa]	η_{fu} [(Hz·min)/dm³]	η_{uu} [(J·Hz·min)/(MPa·dm³)]	p_{zobr} [MPa]	q_{zobr} [dm³/min]	n_o [obr/min]	η_o [obr/(dm³·MPa)]
1	WO-U/SF1	189	5.20	11.2	27.7	54.0	33.9	4.82	1.22	6.97	2.90	34.2	110	3.22
2	WO-U/SM1	142	6.40	11.0	35.0	77.0	33.0	7.00	0.94	6.60	4.20	35.0	270	7.71
3	WO-U/SAC3	170	5.00	21.3	32.0	309.0	50.0	14.51	1.56	22.64	4.20	35.4	240	6.78
4	WO-U/ST1	130	3.34	22.5	45.0	110.0	50.0	4.89	1.11	5.43	3.50	35.6	280	7.87
5	WO-U/ST2	210	5.00	18.7	34.8	77.0	37.0	4.12	1.06	4.37	2.22	35.5	280	8.11
6	WO-U/H1	75	3.85	16.0	26.4	81.0	44.4	5.06	1.68	8.51	6.25	24.5	173	7.06

m_b – hammer mass, m_{mw} – drill mass, p_{zudr} – supply pressure of the percussion mechanism, q_{zudr} – flow rate of the percussion mechanism, E_u – impact energy, f_u – impact frequency, η_{eu} – mechanical efficiency of the percussion mechanism, η_{fu} – hydraulic efficiency of the percussion mechanism, η_{uu} – overall efficiency of the percussion mechanism, p_{zobr} – supply pressure of the rotation mechanism, q_{zobr} – flow rate of the rotation mechanism, n_o – rotational speed, η_o – hydraulic efficiency of the rotation mechanism.

SUMMARY

The developed method for empirically determining the energy and frequency of impact motors allows for the assessment of their technical efficiency. The method can be used for measurements at both stationary and mobile stations. It is particularly recommended for assessing the technical condition of hydraulic rotary-impact drills. An application of this method, an experimental procedure, and a measurement station have been developed for them. The mobile station facilitates research because it does not require disassembly of the drill. However, it should be remembered that the method for empirically determining the energy and frequency of impact motors is a comparative method, and its results can be used, compared, and analyzed if the tests are conducted using the method and station described earlier. Of course, this method can be used for other impact motors (rotary-impact drills), but only on dedicated stations.

The above observations and conclusions are confirmed by the results of tests on rotary percussion drills and their analysis. The tested drills achieved different impact energy and frequency values with comparable power supply parameters. Therefore, hydraulic and mechanical efficiency favor the WO-U/SAC3 drill, which has the highest efficiency. However, the weight of the drills should also be taken into account, as they burden the manipulators of drilling trucks, bolting rigs, and excavators.

REFERENCES

[1] Bęben A.: *Technika wiertnicza w odkrywkowym górnictwie skalnym*. Śląskie Wydawnictwo Techniczne. Katowice 1992.

[2] Szykowny K.: Określenie energii udaru młotów hydraulicznych na podstawie pomiarów wybranych parametrów pracy. AGH Kraków – Lubin 2006 (rozprawa doktorska).

[3] Sokolski M.: *Podstawy syntezy charakterystyk młotów hydraulicznych*, Oficyna Wydawnicza Politechniki Wrocławskiej, Wrocław 2013.

[4] Rammer R: New Method of Measuring Hydraulic Hammer Impact Energy. *The Only Magazine for the Breaking Business*, No. 1/97.

[5] Korzeń Z. I in.: *Analiza tendencji rozwojowych w budowie młotów hydraulicznych dla potrzeb górnictwa*. Prace Naukowe Politechniki Wrocławskiej, 42 seria Konferencje 7, Wrocław, 1984.

[6] Krauze K., Pluta J., Podsiadło A., Micek P.: Badanie ciężkich młotów hydraulicznych. VI Ogólnopolskie Sympozjum Pt. *„Badanie, konstrukcja, wytwarzanie układów hydraulicznych, Cylinder 96*”, Zakopane 1996.

[7] Krauze K., Pluta J., Maziarz M., Tylek R., Laska Z.: Stanowisko diagnostyczne młotów hydraulicznych. X Konferencja Naukowa Pt. *„Problemy rozwoju maszyn roboczych*”, zeszyt nr 2, Zakopane 1997.

[8] Krauze K., Micek P., Krawczyk S.: Metodyka badań młotów hydraulicznych na stanowisku laboratoryjnym. III Konferencja Naukowa Pt. *„Metody doświadczalne w budowie i eksploatacji maszyn*”, Wrocław – Szklarska Poręba 1997.

[9] Krauze K., Laska Z.: Diagnostyka młotów Rammer i Roxon na podstawie badań stanowiskowych. *I Międzynarodowa Konferencja „Techniki Urabiania 2001*” Kraków 2001.

[10] Krauze K., Sibielak M., Laska Z.: Wyznaczanie energii udaru młota hydraulicznego na podstawie pomiaru wartości ciśnień. *Ogólnopolska Konferencja „Cylinder 99”, Zakopane 1999*.

[11] Łuczko J., Ferdek U.: Drgania chaotyczne w mechanizmach wibroudarowych. *XI Konferencja Naukowa „Wibrotech 2003”*, Kraków 2003.

[12] Siwulski, T.; Warzynska, U.; Panowska, K.; Wolter, M. Improving the efficiency of a rock breaker hydraulic working system bychanging the structure of the hydraulic system. *MM Science Journal*. 2022, pp. 5738-5747.

[13] Antonchik V., Zabolotnyi K., Hankevich V., Maltseva V., Kuts O., Dyczko A.: Constructional changes of pneumopercussion machines for improving their efficiency. *Min. Mach*. 2022, vol. 40 issue 4, pp. 206-215. DOI: https://doi.org/10.32056/KOMAG2022.4.3

[14] Franca, L. F.P. A bit-rock interaction model for rotary–percussive drilling. *International Journal of Rock Mechanics and Mining Sciences* 2011, 48, 5, pp. 827-835. DOI: https://doi.org/10.1016/j.ijrmms.2011.05.007.

[15] Xi, Y., Wang, W., Fan, W., Zha, Ch., Li, J., Liu, G. Experimental and numerical investigations on rock-breaking mechanism of rotary percussion drilling with a single PDC cutter. *Journal of Petroleum Science and Engineering* 2022, 208, 8, 109227. DOI: https://doi.org/10.1016/j.petrol.2021.109227

[16] Zhang, X., Zhang, Sh., Luo, Y., Wu, D. Experimental study and analysis on a fluidic hammer – an innovative rotary-percussion drilling tool. *Journal of Petroleum Science and Engineering* 2019, 173, pp. 362-370. DOI: https://doi.org/10.1016/j.petrol.2018.10.020

[17] Karpov, V.N., Petreev, A.M. Determination of Efficient Rotary Percussive Drilling Techniques for Strong Rocks. *J Min Sci* 57, pp. 447-458 (2021). https://doi.org/10.1134/S1062739121030108

[18] Oparin, V.N., Timonin, V.V., Karpov, V.N. et al. Energy-Based Volumetric Rock Destruction Criterion in the Rotary – Percussion Drilling Technology Improvement. *J Min Sci* 53, pp. 1043-1064 (2017). https://doi.org/10.1134/S1062739117063114

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