https://doi.org/10.7494/miag.2022.4.552.7

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Modern means of underground transport – technical and economic effects and benefits to the working environment resulting from the operation of VOLTER monorail battery-powered locomotives

Battery-powered means of transport are increasingly being used in underground mining. The article describes a suspended VOLTER battery-powered locomotive designed for the transport of equipment, materials and people. The technical and economic effects related to the operation of this innovative solution in comparison with diesel locomotives, including energy (fuel) costs and maintenance time, are presented. The article also describes the benefits to the working environment connected with the use of battery locomotives resulting from the lack of exhaust emissions and a significant reduction in noise and heat generation, which improves the climatic conditions in comparison with diesel locomotives.

Key words: *suspended transport, battery locomotive, energy costs, operating costs, working environment, climatic conditions*

1. INTRODUCTION

Manufacturers of mining equipment are increasingly developing and implementing machines with battery drives. Locomotives, suspended locomotives, haulage and transport vehicles, and other machines are testament to the development of underground electromobility. The new generation of batteries with lithium cells improves technical and economic effects as well as environmental benefits of electric drives compared to diesel ones.

In particular, battery-powered transport systems are increasingly being used in underground mining. They are a response to the challenges related to:

- extension of transport and access routes for personnel,
- increase in the power of installed machines and devices,
- increasingly stricter requirements for the working environment,
- the need to minimise carbon footprint and greenhouse gas emissions,
- the need to optimize production costs.

The flagship product of Becker-Warkop Sp. z o. o. in this area is the VOLTER monorail battery locomotive [1].

2. DESCRIPTION OF THE VOLTER BATTERY-POWERED LOCOMOTIVE

The VOLTER battery locomotive with a friction drive is used to transport people, materials, and equipment during transport works, e.g. installation and salvage of longwall equipment. The locomotive in a configuration without operator's cabins is only used for transporting loads.

The VOLTER/X/Y (where: X-number of drives, Y-number of operator's cabins) battery locomotive is intended for operation in underground mining excavations in non-methane and methane fields, in the excavations included in 'a', 'b' or 'c' degree of methane explosion hazard and in the excavations included in 'A' or 'B' class of coal dust explosion hazard.

Figure 1 shows the basic construction of the VOLTER locomotive with operator's cabins. The locomotive can also be operated without cabins as a manoeuvring locomotive (Fig. 2).

Fig. 1. Basic configuration of VOLTER/4/2 locomotive

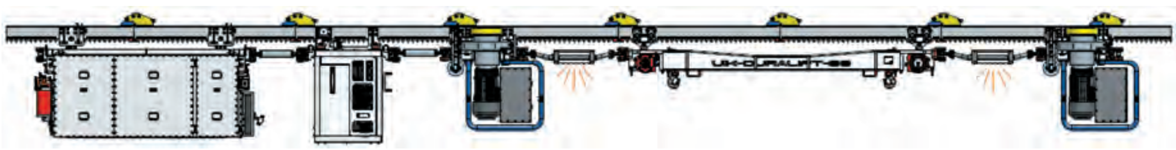

Fig. 2. VOLTER/2/0 manoeuvring locomotive equipped with a transport beam and mobile lighting of material stations

2.1. Drive and braking system

Each drive unit is equipped with two electric drives (a motor with an inverter), a gear and friction drive wheels. The drive is transmitted by frictional coupling of the drive wheels with the rail. The drive wheels are pressed by a hydraulic cylinder, which presses the rocker arm towards the axis of the track through a lever. The gear connected to the electric drive and the friction drive wheel is fixed in the rocker arm. Figure 3 shows a single electric drive of BWNE type.

Fig. 3. BWNE electric drive

The braking system is used as a parking and emergency brake. Brakes are released after applying pressure to the brake release actuator, which moves the brake shoes away from the rail. The auxiliary unit includes an electric drive (inverter motor), which drives the hydraulic pump supplying the locomotive hydraulic controls.

2.2. Control

The operation of the locomotive is controlled by the BWKS control box (in the manoeuvring version) or the control station in the operator's cabin.

Optionally, the battery locomotive can be additionally equipped with a wireless control and radio communication system as well as mobile lighting for passenger stations and material stations.

2.3. Battery unit

A VOLTER battery unit is an explosion-proof device in a flame-proof enclosure. A VOLTER lithium battery is used to power the locomotive drives.

The battery unit includes systems intended for monitoring, protection, supervision and control of individual locomotive devices. The battery compartment is equipped with lithium cells grouped in 20 boxes. Each box contains 8 cells, which are monitored in terms of voltage and temperature by individual control modules. The control modules communicate with the supervisory part located in the apparatus box and are also responsible for the cell charging process and for sending operating parameters to the control system.

The advantage of the VOLTER battery is the charger integrated with it (installed in a special compartment of the battery enclosure), to charge the cells directly from the mine power grid with a three-phase voltage of 500 V or 1000 V. The mine grid is connected through a quick connector installed in the flameproof enclosure which significantly speeds up the connection/disconnection process. The charging time is up to 4 hours. The drive system of the VOLTER locomotive enables operation with energy recuperation, i.e. energy recovery back to the battery when travelling on a decline or when braking [1].

Table 1 shows the basic technical parameters of the VOLTER battery locomotive [1].

Table 1

Basic technical parameters of the VOLTER battery locomotive

Parameter	Value
Pulling force	max. 25 kN (for single friction drive) max.100 kN (for four friction drives)
Maximum speed	2.0 m/s
Min. horizontal turning radius	4 m
Min. vertical turning radius	8 m
Max. inclination of travelling track	± 30°
Admissible profiles of travelling track rails	I155(I140E), I140V95, I250 types or other compatible of approved type
Rated charging voltage (directly from the mains)	500 V, 1000 V
Battery type (VOLTER)	lithium
Battery energy	143.5 kWh
Power of one drive motor	11 kW
Locomotive power with 4 friction drives (two motors)	88 kW
Static braking force	min. 1.5 x pulling force
Locomotive dimensions with 4 drives (height × width × length)	1,275 × 800 × 15,340 mm
Locomotive kerb weight – version with cabins and 4 drives	11,310 kg (4 friction drives)

3. TECHNICAL AND ECONOMIC EFFECTS RESULTING FROM THE OPERATION OF VOLTER BATTERY-POWERED LOCOMOTIVES

To illustrate the benefits of operating VOLTER battery locomotives, the operating costs and maintenance time of a battery locomotive were compared with those of a diesel locomotive. The analysis was based on locomotive operation data from the Budryk and the Szczygłowice mines. The analysis results are presented in Tables 2 and 3 and in Figure 4.

The above data show that:

- electricity/fuel cost per 1 km is 20.21 PLN higher for a diesel locomotive,
- annual operating cost of a diesel locomotive (in the cost groups analysed) exceeds the cost of a battery locomotive six times,
- annual maintenance time is 308 man-hours shorter for a battery locomotive.

Table 2

Comparison of energy (fuel) costs of a VOLTER battery locomotive with a diesel locomotive

	Diesel locomotive	Battery locomotive	Comparison
Average fuel/energy consumption per 1 km	3.75 l	4.9 kWh (Szczygłowice) 5.63 kWh (Budryk)	–
Fuel/energy cost per 1 km	3.75 l × 6.38 PLN = 23.93 PLN	4.9 kWh × 0.66 PLN = 3.23 PLN 5.63 kWh × 0.66 PLN = 3.72 PLN	20.70 PLN (Szczygłowice) 20.21 PLN (Budryk)

Table 3

Comparison of selected annual operating costs of a VOLTER suspended battery locomotive with a diesel locomotive

Parameter	Diesel locomotive	Battery locomotive
Fuel/energy per month (calculation based on 415 km/month)	415 km × 3.75 l × 6.38 PLN/l = 9,928.88 PLN	415 km × 5.62 kWh × 0.66 PLN = 1,539.32 PLN
Fuel/energy per year (calculation based on 4,980 km/year)	12 × 9,928.88 PLN = 119,146.50 PLN There are also additional costs related to transport of fuel from the surface and its distribution in underground mines	12 × 1, 539.32 PLN = 18,471.82 PLN Can be charged anywhere underground the mine
Filters and other parts	Air, fuel, hydraulic and engine oil filters, injectors, V-belts: 9,510.66 PLN	Hydraulic system filter: 873,00 PLN
Oils	Hydraulic and engine oil: 2,474.90 PLN	Hydraulic and transmission oil: 1,994.14 PLN
Other consumables	Coolant and extinguishing chargé: 2,923.70 PLN	None
Total annual costs	134,055.76 PLN	21,338.96 PLN

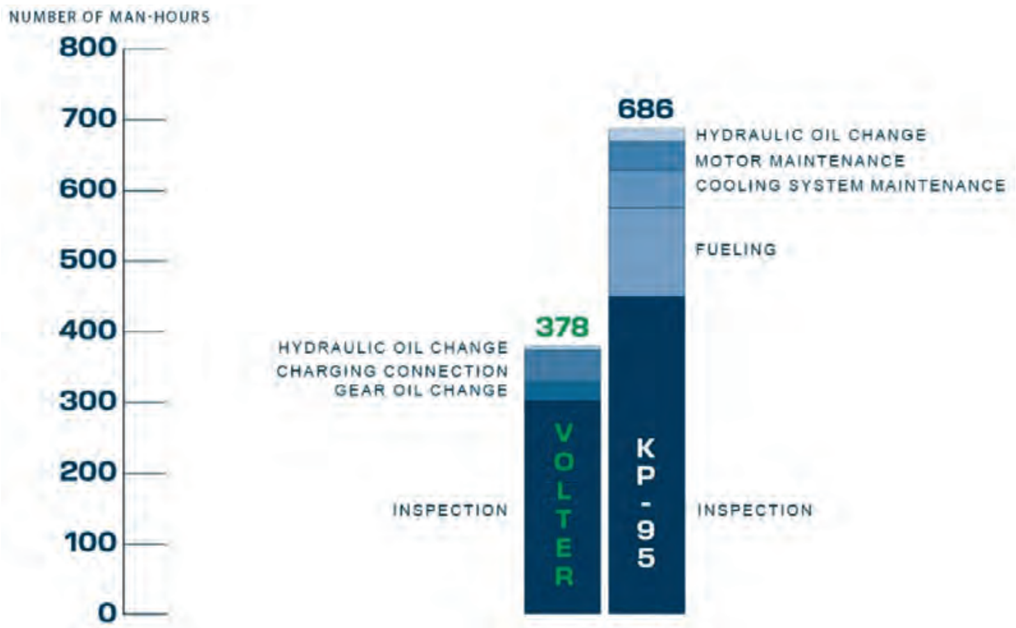

Fig. 4. Comparison of time necessary for maintenance of a battery locomotive and a diesel locomotive per year

4. BENEFITS TO THE WORKING ENVIRONMENT RESULTING FROM THE OPERATION OF BATTERY-POWERED LOCOMOTIVES

The use of battery-powered machines brings the following benefits to the working environment:

- Elimination of exhaust gases, which results in a smaller amount of air required to dilute them. It is assumed that when using machines with diesel engines, 0.06 to 0.08 m^3/s of air flow per 1 kW of installed power is required to dilute exhaust gases (according to The Southern African Institute of Mining and Metallurgy).
- Less noise and vibration improves work comfort of the locomotive operators and the transported personnel.
- Operation of locomotives does not interfere with the operation of fire safety systems (CO sensors).
- Reduction of heat emission in comparison with diesel locomotives has a significant impact on the improvement of climatic conditions in the excavations. This issue is presented in more detail further in the article.

4.1. Influence of diesel machines on climatic conditions in excavations

In internal combustion engines, the process of internal fuel combustion takes place and the power transferred to the drive is equal to the calorific value of fuel, several times greater than the effective power of the engine. Diesel machines transfer about three times more heat to the environment than machines powered by electric motors of the same effective power [2].

The calorific value of diesel oil, which is the fuel in diesel engines of underground machines, is 45.6 MJ/kg. Fuel consumption in locomotive diesel engines is approx. 0.229 kg per hour of operation and per 1 kW of engine power. Therefore, according to the calculation below, 2.9 kW of power resulting from the chemical energy of the fuel is consumed per 1 kW of engine power.

$$\frac{0,229 \cdot 45,6 \cdot 1000}{3600} = 2,9 \text{ kW paliwo/1 kW silnik} \quad (1)$$

About 1/3 of the energy calculated above is converted into effective work of the machine, and 2/3 of the calculated energy is converted into heat. About 1/3 of the heat is emitted from the hot engine, 1/3 from the exhaust gases. The heat generated as a result of combustion is transferred to the air in a sensible form (increase in temperature) and in a latent form (increase in humidity). As a result of the combustion of 1 litre of diesel oil, approximately 1.1 litres of water vapour is released. It can be assumed that 10–25% of the emitted heat results in an increase in temperature, and 75–90% results in an increase in air humidity [2]. The increase in temperature and humidity is calculated according to the formulas below.

$$\Delta t = \frac{(0.1 - 0.25) \cdot \Delta Q}{V \cdot \rho \cdot c_p} \quad (2)$$

$$\Delta X = \frac{(0.75 - 0.90) \cdot \Delta Q}{V \cdot \rho \cdot r_w} \quad (3)$$

where:

- Δt – increase in air temperature [°C],
- ΔX – increase in air humidity [g/kg] of dry air,
- ΔQ – energy stream converted into heat in a machine powered by a diesel engine [kW],
- V – volumetric flow rate of air in excavation [m^3/s],
- ρ – air density [kg/m^3],
- c_p – air specific heat [kJ/kg · K] c_p = 1,005 kJ/kg · K,
- r_w – heat of water vaporization at temperature t [kJ/g] $r_w = (2502.5 - t \cdot 2{,}386) \cdot 10^{-3}$ kJ/g.

High efficiency of electric drives means that they emit much less heat to the excavation in comparison to diesel railways. The comparative analysis of heat increase for 1 km of a heading driven (Fig. 5), in which 28°C is stable along its entire length without the operation of the railway, showed that the temperature increase at the exit of the excavation related to the operation of a diesel railway was 1.5°C. In the case of an electric railway, it is about 0.1°C, while the increase in air humidity is 4.6 g/kg and 0.5 g/kg, respectively [3].

The calculations take into account the continuous operation of the railway in an excavation. It was assumed that 20% of the heat generated by the machine is transferred to the air in a sensible form, and 80% in a latent form. It was additionally assumed that the heat generated during the operation of the railway is not taken out of the excavation together with the excavated material, i.e. the maximum possible heat gain in the excavation was taken into account. The total heat gain (sensible and latent) in the analysed heading was 181.0 kW and 18.5 kW, respectively, for the diesel and electric railway [3]. In order to neutralize the heat gain (sensible and latent) when using a diesel railway, a cooling power of over 180 kW is needed.

One of the unquestioned advantages of electric railways is the lack of water vapour emission, which increases air humidity.

If it is necessary to use air cooling in excavations, its humidity is of key importance. If it is high, a greater part of the cooling capacity of the air-conditioning system coolers is spent on lowering air humidity (air drying) than on lowering the temperature.

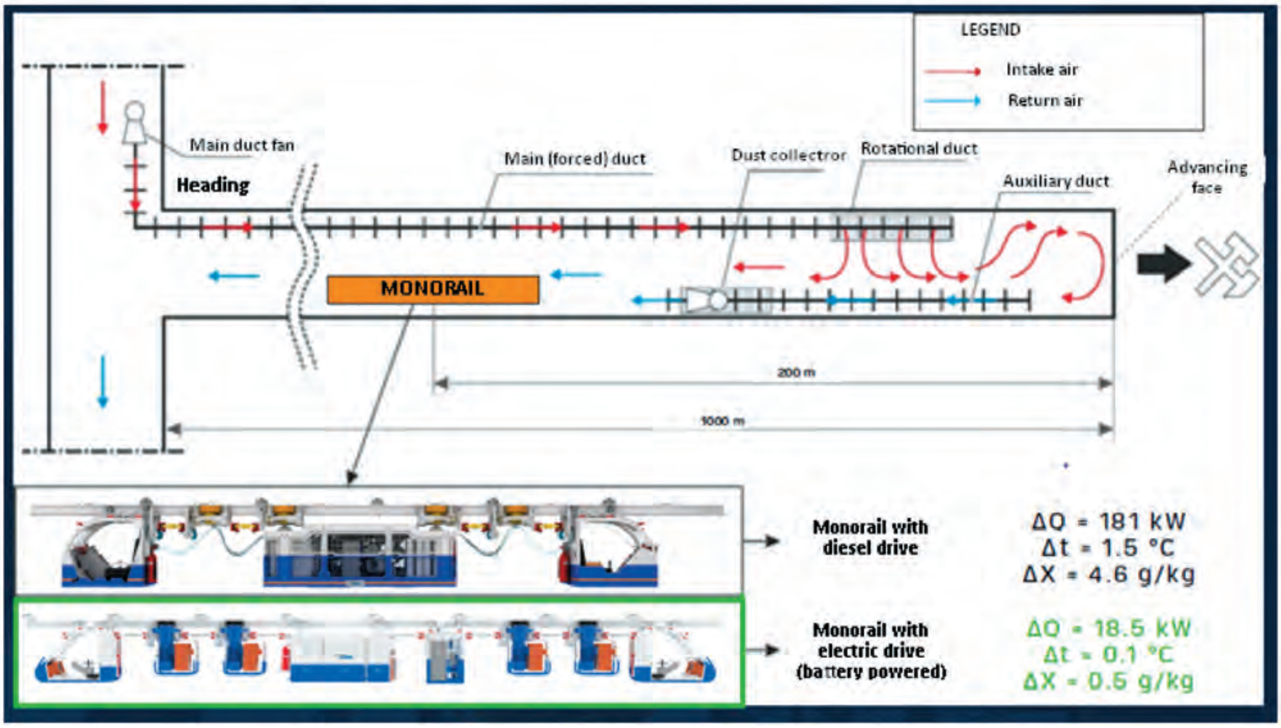

Fig. 5. Comparison of the impact of diesel locomotives and battery locomotives on climatic conditions in excavations

5. SUMMARY

The use of suspended VOLTER battery-powered locomotives brings the following technical and economic effects as well as benefits to the working environment in comparison with diesel locomotives:

- no exhaust emissions,
- low heat emission,
- quieter operation of the drive compared to a diesel drive,
- operation of locomotives does not interfere with the operation of fire safety systems (CO sensors),
- expensive logistics and diesel fuelling infrastructure is not required in the mine,
- lower operating costs,
- shorter time of necessary maintenance,
- possibility of charging the battery in excavations where electrical devices can operate in an explosion-proof enclosure,
- possibility of charging directly from the mine power grid with a three-phase voltage of 500 V or 1000 V,
- energy recovery when driving on a decline and when braking,
- monitoring of operating parameters and protections,
- remote control and data transmission,
- optional radio control.

Battery-powered suspended locomotives, due to their advantages, will gradually replace diesel locomotives in the coming years.

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