it is immediately evident that $\delta^2F < 0$, i.e., the solution found corresponds to a local maximum.

To answer the second question an algorithm was developed for maximization of Eq. (2) by the iteration method. (All solutions of the nonlinear integral equation (4) cannot be obtained analytically.) With various initial section shapes this algorithm invariably led to the solution found above. This permits the conclusion that we have obtained a complete solution.

Calculation of the maximum interaction force for the cross section determined here gives

$$F_{\max} = \frac{2\sqrt{2}}{3\pi^{3/2}}\mu_0\frac{I^2}{\sqrt{S}} = 2.1277\frac{I^2}{\sqrt{S}}\,(\text{N/m}).$$

For comparison, we note that for two circular conductors pressed against each other (of given section) the interaction force comprises 83% of the maximum value.

EXPERIMENTS ON INDUCTIVE-STORE CURRENT SWITCHING

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UDC 621.316.5

Considerable interest attaches to the scope for using inductive stores for systems of Θ-pinch type with liners. A feature of the store operation in that case is the low inductance of the solenoid with the liner at the current-switching stage, which enables one to perform the switching with comparatively little energy loss.

One of the complicated problems is current interruption [1, 2]. Here we describe an inductive store with transformer output that can be used with liner compression, and we discuss results on the current switching. These experimental studies may be useful in the design of large systems with inductive stores.

Experimental Apparatus. The apparatus (Fig. 1) is a two-section inductive store ($L_{1.1}$, $L_{1.2}$); each section consists of 33 turns of diameter 660 mm made of aluminum rod of cross section 30 × 30 mm and connected in series. The sections have a center tap, which passes via the discharge gaps P_2 and P_3 to the ground line. The discharge gaps are adjusted for a breakdown voltage of ∿5.5 kV and serve to prevent overvoltages on the turns arising if one or more of the trips does not operate or breaks down. The sets of trips (two for each winding) are connected in series with the sections. The overall inductance of the primary winding is $5 \cdot 10^{-4}$ H. The store is supplied by the discharge current from the capacitor bank C_1 with a total stored energy of 1.2 MJ at a maximum voltage of 5 kV. The maximum charging current is ~60 kA, which corresponds to an energy of ∿1 MJ. The capacitor bank is connected to the store by the mechanical trip P_1 with solid insulator.

The energy output to the load is by means of a transformer circuit with parallel connection of the turns in the secondary winding, which consists of two turns of diameter 690 mm and length 10^3 mm, each of which encompasses one section. The turns are made of St.3 steel of thickness 8 mm with a collector for connecting the cables. The current in the secondary winding (after opening the primary circuit) passes via a cable feeder to the load. The accelerating solenoid is of steel and consists of one turn with an internal diameter of 150 mm and a length of 120 mm. We examined only the current switching in these experiments, so a metal insert of ∅148 mm was used instead of the liner.

The store operates as follows: after P_1 has operated (Fig. 1), the charging begins. When the necessary current is reached, the trips K_1-K_4 operate and the current is diverted to the wires F_1-F_4, which explode and open the circuit of the primary winding, and then a multiplied current appears in the secondary winding. To equalize the voltages on the trips, each is connected to a sectional resistor R_1-R_4 = 3 Ω in such a way that each trip is shunted by a resistance of 1 Ω.

Moscow. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 6, pp. 117-121, November-December, 1981. Original article submitted October 13, 1980.

0021-8944/81/2206-0839$07.50

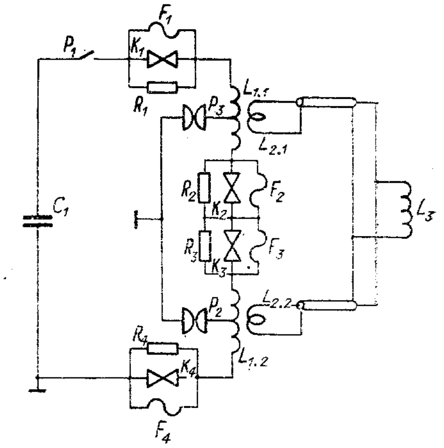

Fig. 1

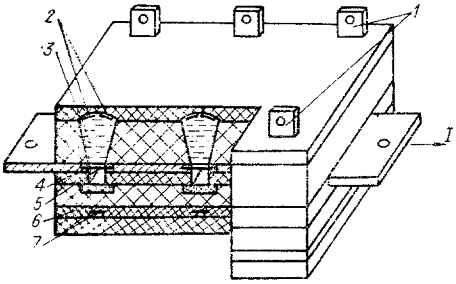

Fig. 2

The windings of the store are made in such a way that the condition $\tau_1 \gg \tau_p \gg \tau_2$ is met for the charging pulse, where τ_1 and τ_2 are, respectively, the decay times of the current in the primary and secondary windings, while τ_p is the length of the charging pulse. The magnetic energy stored within the primary winding is $E_0 = L_0 I_0^2$, where $L_0 = L_{1.1} + L_{1.2}$ and I_0 is the charging current.

Figure 2 shows the design of a trip, which is made in a fiberglass body. In the experiment we use four simultaneously operating trips, each of which has three fuses. The arc-extinguishing insulator in all the experiments was technical Vaseline 3 (Fig. 2), which was poured in in the hot state. The current leads 5 are broken by the flow of Vaseline flowing under the action of the explosion of the aluminum foils 2 of thickness $3 \cdot 10^{-2}$ mm, width 7 mm, and length 100 mm (two each per fuse). At the points of fusion, the current leads are made of aluminum foil of thickness 0.4 mm. The width of each fuse is 10 mm. The energy source supplying the foils is a capacitor bank with C = 90 μF, U = 28 kV, which is connected to the outputs 1. To provide synchronism in the operation of all the fuses, the capacitors are connected by a common discharge gap. To prevent erosion of the knife edges 4 after failure of the foils, each fuse is shunted by a copper wire of diameter 0.5-1.5 mm placed in quartz sand, or by copper foil 7 in the glass cloth 6, which enables one to reduce the voltage on the fuse at the moment of failure of the current lead and acts as an absorber for the energy dissipated in transferring the current in the secondary winding. The cross sections of the conductors are chosen on the basis of the current to be broken.

Results and Discussion. The operation of the switching system was examined mainly at charging currents up to 55 kA. Parts *a* and b of Fig. 3 show the waveforms for the charging current and the current in the secondary winding respectively (a capacitance of storage bank $C_1 = 6 \cdot 10^{-2}$ F, $U = 5 \cdot 10^3$ V). There is a small current in the circuit of the secondary winding during charging because of the current transformation arising from the small but finite value of τ_2/τ_p.

One of the necessary operating conditions is a small spread in the current interruption by all the fuses. For this purpose the drive circuit is switched by a common discharge gap. Also, the discharge circuits for all the foils were made as closely similar as possible. Considerable importance attaches to the casting of the insulator, because the presence of

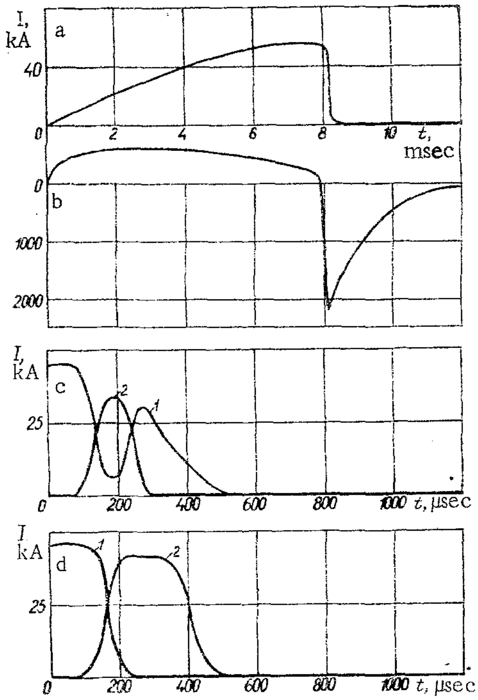

Fig. 3

air bubbles under the foils causes a marked increase in the volume of vapor after the explosion, while it reduces the pressure and correspondingly reduces the insulator flow rate. For this reason the foils were made as individual narrow strips, which reduces the possibility of air cavities. In experiments where wide foils were used (up to 23 mm in width and cross section 0.42 mm^2) we observed breakdown in the fuses caused by the spread in operation. Measurements showed that the fuses with narrow foils operated with a spread of not more than 10 μsec, which is much less than the current switching time and which does not cause over-voltages on the fuses. Considerable attention was devoted to the dimensions of the shunting wires. The wires should be of adequately low initial resistance to provide for current transfer. The mass is chosen such as to provide for energy absorption (the energy loss in switching), this energy being deposited on transferring the current in the secondary winding. The length of the wire was chosen from the necessary electrical strength of the explosion products.

If the cross section of the wire is small and does not correspond to the switch current, there is heating in the fuse at the same time as the arc is extinguished. The resistance of the wire increases, and as a result part of the current continues to flow through the fuse. Figure 3c shows waveforms from such an experiment (1 is fuse current and 2 is current in the shunting wire), where we used copper wires ∅ 1.04 mm. The conductivity falls after evaporation of the wire and there is a rise in current in the fuse. Although the arc is subsequently extinguished by the flow of insulator, the switching is slow ($\tau_S \approx$ 300 μsec), and the fuses dissipate considerable energy, which causes erosion of the knife edges. Experiments showed that the wire diameter shall be 1.5 mm for the charging current of 45-50 kA. In that case the wire remains cool throughout the transfer time (∿80 μsec) and takes up the current completely. The subsequent heating of the wire and consequent increase in voltage does not cause a current in the fuse (Fig. 3d). The current breakage time in the primary circuit is determined in the main by the heating and evaporation on the wire. This was ∿80 μsec with a charging current of 45 kA with copper wire of diameter 1.5 mm.

Copper wires exploding in quartz can withstand fields of 400-450 V/cm. Higher limiting fields (up to 600-650 V/cm) were obtained by exploding foil in glass cloth [3]. This design of shunting component is also less troublesome to assemble. A copper foil of length 420 mm, thickness $7 \cdot 10^{-2}$ mm, and width up to 30 mm is placed between two layers of glass cloth and gripped under the lower plate in the fuse (Fig. 2). This design reduces the inductance in the shunting circuit, and therefore the current-transfer time is reduced to 40-50 μsec (Fig. 4). Therefore, in most of the experiments the fuses were shunted by foils.

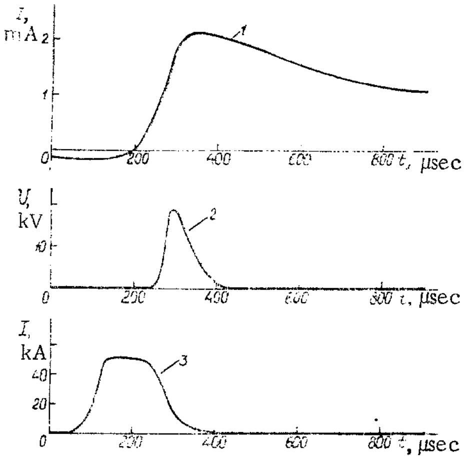

Fig. 4

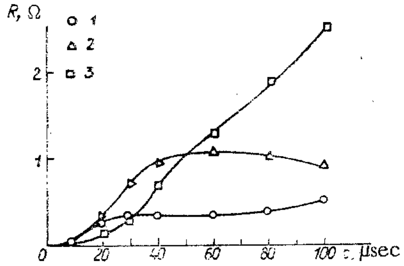

Fig. 5

Measurement on the voltage and current gave the resistance of the foil as a function of time. Figure 5 shows the corresponding curves for various sections of the foil. The origin is taken as the instant when the current in the foil decreases. When the cross section is small, the resistance tends to a limit after a certain rise and remains almost constant up to the end of the switching stage. This is obviously due a discrepancy between the mass of the foil and the energy deposited on switching the current in the secondary winding. As a result, the excess energy is deposited in the arc discharge arising within the assembly, which reduces the resistance. On examining the packs with the foils after the experiment, the explosion channel showed longitudinal damage due to the arc, and the damage was the more marked the less the section of the foil. In the case of a foil of width 30 mm with a charging current of 54 kA, the explosion channel after the experiment was a homogeneous fused mass arising from the vapors of the copper and the glass fiber. The resistance of such a foil increases almost linearly up to the end of the switching stage (Fig. 5, where I_0 = 54 kA, and the foil widths are 23, 26, and 30 mm for points 1-3, respectively).

To analyze the energy losses in the switching, the circuit of Fig. 1 may be represented by an equivalent circuit with series connection of the inductances L_0 and L_p, where $L_p = N^2(L_{2\cdot 1} + L_{2\cdot 2} + 4L_3) - L_0$; here $L_{2\cdot 1}$, $L_{2\cdot 2}$ are the inductances in the sections of the secondary winding, L_3 is the inductance of the solenoid, and N is the ratio of the numbers of turns on the primary and secondary windings in each section. The switching devices in this circuit are connected in parallel with L_p. Initially, there is no current in the circuit of L_p. Then the following is the expression for the energy losses in switching for the instant when current I_2 is maximal [2]:

$$\Delta E = E_0 L_p/(L_0 + L_p). \tag{1}$$

Here it has been supposed that the magnetic flux is conserved in the system. The expected value of the loss calculated from this formula should be $\sim$20%, which corresponds to $L_p \approx 1.2 \cdot 10^{-4}$ H.

In experiments, the losses can be determined from the energy balance in the store. The accuracy of this method is not very high, but the measurements show that the observed losses are somewhat greater than those calculated from (1), and evidently are due to additional losses arising from freezing of the field in the metal of the primary winding (the diffusion time is large by comparison with τ_s) and also losses on account of nonconservation of the magnetic flux.

Figure 4 shows the secondary current I_2, the voltage on the fuse, and the current in the shunting foil (curves 1-3, respectively). The voltage across a fuse appears at the time when the foil resistance is increasing rapidly and rises to 20 kV on each fuse.

With a charging current of 54 kA, the current amplitude at the output of the store is over 2 MA. After the maximum the current decays exponentially with a time constant $\tau_2 \approx 10^{-3}$ sec.

We are indebted to I. A. Ivanov for interest and to V. I. Kurnosova and K. V. Solomasov for assistance in the experiments.

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CONFINED EXPLOSION IN A POROUS MEDIUM

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UDC 622.235

1. Measurements have been made on the mechanical effects of confined explosions on monolithic rocks [1-5], and the maximal parameters of the explosion wave (mass velocity and pressure) have been related to the reduced distance, while information has been obtained on the damage zones. The results enable one to formulate relatively simple ways of forecasting the mechanical effects of explosion on monolithic rocks [1, 5]. On the other hand, the experimental data on explosions in porous media are restricted to laboratory results with sand [6, 7] and field studies [8, 9] with natural soft soils, which have enabled one to examine the damping of the compression waves [6, 8, 9] and the deconsolidating motion behind the front [7], which is responsible for the dilatancy [1, 5, 10]. It is extremely difficult to examine the damage zones in a material such as sand [11], and in laboratory experiments [3, 12] with pressed rocksalt the main attention was devoted to the decay of the mass velocities in the compression wave.

The available evidence on spherical explosion waves leads to the following conflict. For example, it is often asserted that the relationship between the maximum mass velocity and the reduced distance $\bar{r} = R/W^{1/3}$ (where W is explosion energy) for a monolithic rock (granite or rocksalt) is the same as for a porous medium such as sand. On the other hand, it is known [1,13] that there is a very low seismic performance in certain porous media (alluvium) surrounding an explosion focus.

This gives considerable interest to the mechanical effects of an explosion on a strong highly porous medium in which the damage areas can be identified quite simply. Artificial production enables one to select the properties to simulate actual rocks and also to locate measuring devices without disrupting the integrity.

2. The experiments on confined explosions were performed on blocks of artificial porous medium made from a mixture of KP-3 sand, lime flour, and waterglass. Heat treatment made the porous medium similar to strong but brittle rock. A cylindrical block of this medium had a height of 350 mm and a diameter of 300 mm and was contained in a metal vessel. The size of the block and the magnitude of the explosive charge were chosen such that the

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Moscow. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 6, pp. 121-129, November-December, 1981. Original article submitted September 23, 1980.

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