BELARUS TEAM
FLOUR CRATERS

The problem is formulated as follows: «*If you drop a small object in flour, the impact will produce a surface structure, which looks like a moon crater. What information about the object can be deduced from the crater?*»

The formation of craters on moon and other planets is investigated quite thoroughly. Many observation and experimental data are given in literature. Empirical relations between parameters of a crater and characteristics of a body forming this crater were obtained on the basis of experiments and some physical phenomena. Material, in which the crater was formed, was also regarded. Special terms are introduced in the literature for convenience. In our case the flour, in which we throw bodies, will be called the *target*, and the thrown body - the *projectile*. Usually, influence of a projectile parameters on a target damage is investigated. We have to inverse the problem - we have to receive the maximum information about projectile on damage to the target.

Really, if small bodies are thrown in flour, the interesting formations can be observed. These craters are quite similar to craters on the Moon. To find the basic regularity of the target behavior under the impacts let us regard projectiles of the spherical shape. For observations we used projectiles, which parameters are represented in Table 1.

Table 1. Parameters of projectiles

Mass, g	**Diameter, cm**
5,6±0.1	2±0.1
6,8±0.1	2±0.1
12,8±0.1	2±0.1
19,1±0.1	3±0.1
37,8±0.1	4±0.1

Projectiles fell from heights of 10 cm up to 1.5 m were determined with accuracy of 5 mm. Diameter of a crater was measured with precision of 2 mm, and its depth - 2 mm. Density of a flour was determined to be equal to 480 ± 20 kg/m^3. The statistical error was about 15 %.

Investigating the shape of a crater we have found an interesting phenomenon. For projectiles fallen from the height of 10 - 80 cm the craters looks how it is shown on Fig 1. The shape of the crater is cylindrical feebly expanding to the top. But since the heights of 80 cm the cone is formed (see Fig. 2). Such crater reminds a cone, which is formed by the body moving in a medium with hypersonic velocity.

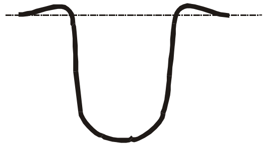
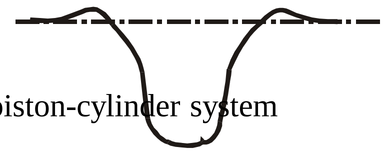


Figure 1. Crater, created by projectile, falling from height 10-80 cm

Thus, we have decided to explore flour properties. Let us give definition of flour, as a small-dispersible isotropic powder. To sonic wave velocity definition in powder at small strains the experimentally obtained relation called the Teit's formula is used.

$$P = \frac{\rho_0 c^2}{n}\left[\left(\frac{\rho}{\rho_0}\right)^n - 1\right], \qquad (1)$$



the piston-cylinder system

Figure 2. Crater, created by projectile, falling from height 80-150 cm

where *c* is the speed of an sonic wave in powder, *P* is the pressure applied to powder, ρ and ρ_o are current and initial density of flour, *n* is the coefficient should be experimentally defined. To find the dependence of flour density on applied pressure we used (Fig. 3). In the cylinder with a fixed bottom punch the flour *was poured, which mass had been measured. We imposed weights on the top punch and marked its immersion depth. We determined the density of flour under different pressures. As the result we have received a set of curves of dependence of Đ on the fraction* ρ over ρ_o. Then we approximated the data by the Teit equation. The results of experiment are represented on the Fig. 4. Thus, the sonic wave speed in flour is equal to 4 meters per one second. Such a speed is reached by projectile falling already from the height of 80 cm. At such a projectile speed there will be a shock wave of small intensity in the target, which velocity is approximately equal to velocity of an sonic wave. In result, the cone at the top of a crater should be formed, just what we had observed. So we can measure an apex angle of the cone, and we know projectile speed at the surface of the target. Therefore it is possible to estimate velocity of an acoustic wave in flour. On our estimations it is equal to 3.8 m/s.

Now let us consider the process of impact. The kinetic energy of projectile: 1) is spent on work against gravity at uprise of flour, 2) goes on thermal losses, on increasing of the target internal energy.

The latter losses can be calculated as square of an area under the diagram in PV - coordinates. These losses are of 2 % of a projectile kinetic energy.

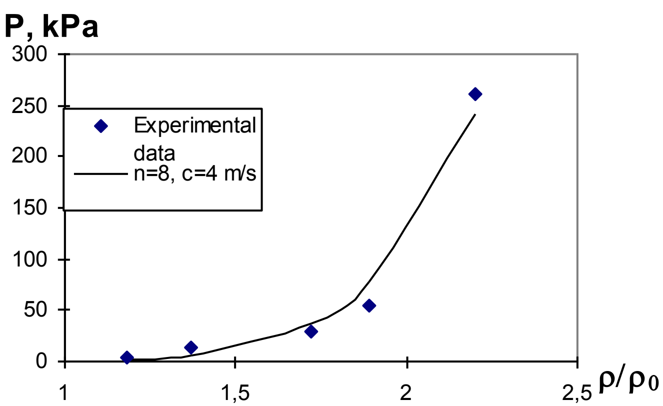


Figure 4. Dependence of pressure on flour dencity

The motion of the target substance while a crater is produced determines the crater size. We have investigated an ejection of the substance. For this purpose we put on the target surface powders of different colors similar to it on properties. We cut the crater and explored a motion pattern of the substance. The substance ejections according to our observations is schematically shown on Fig. 5. The air compressed at impact had blown flour nuggets along ballistic trajectories.

The following experiment had demonstrated the role of air at an ejection. The flour was located under a bell, from which air was extorted. As a result of impact the mine with vertical walls was formed, and ejections were not practically observed. After a crater was produced the energy to eject was not enough, and the high layers of the target were uplifted and partially turned round. The initial surface level was raised. Thus, the size of a crater is a function of a projectile kinetic energy and the share spent on formation of a cavity.

On the mechanism of stopping crater formation motion the craters are divided on strengthening and gravitational ones. In the first case the sizes of craters are determined by strength properties of the target. Energy is spent on work against strength of a target material. They are, for example, microcraters and craters formed by high-speed impact on metals. According to calculations and experimental data given in the literature, the size of a crater is proportional to a root cubic of a projectile kinetic energy:

$$R \propto E^{1/3} \qquad (2)$$

In case of gravitational crater formation the motion of soil is determined in basic by strength properties of a target, but the stopping of crater formation motion happens because of transition of a kinetic energy of target particles to potential one in a gravitational field. For example, there are craters in dry sand. Also a gravitational crater served formation of a cavity at slope of a water drop in water can be regarded as an example of. The kinetic energy of a drop is spent on energy of a vacuity and acts against forces of surface tension. Increasing the cavity sizes the contribution of work against surface tension becomes small, and the projectile energy is connected with radius of a crater by the next relationship

$$R \,\square\, (rg)^{-1/4}E^{1/4}. \qquad (3)$$

In our case, when the motion of target substance is determined by its strength properties, and the stopping of crater formation motion happens on the gravitational mechanism. Therefore dependence of crater radius on a projectile kinetic energy follows from combination of equations (2) and (3):

$$R = \beta(\rho g)^{-\left(1-\frac{3}{k}\right)}E^{\frac{1}{k}}, \qquad (4)$$

where $3 < k < 4$.

We had approximated by the obtained data the relationship (4) and had received, that $k = 3.75$, and ($\beta = 1.05$) (Fig. 6).

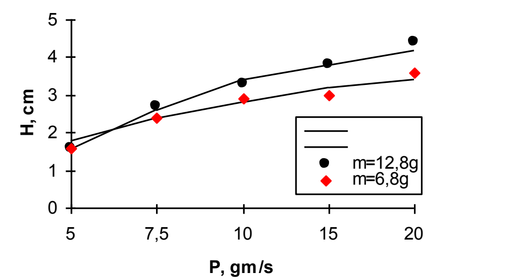


Figure 7. Dependence of crater depth on projectile impulse

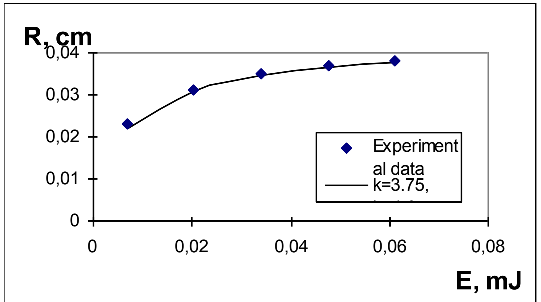


Figure 6. Dependence of crater radius on kinetic energy

At hypersonic speeds of projectile the share of energy going on cavity formation decreases. And the crater depth increases, whereas its diameter practically does not vary (Fig. 7). Thus, the formula (4) is true only for the case of subsonic speeds. At hypersonic velocities the main role in crater formation belongs to a projectile momentum. Unfortunately, we did not have quite much experimental data to find an equation, by which we could approximate, the obtained dependences.

At a obliane impact new qualitative changes are not observed. The depth of a crater is determined by vertical component of projectile velocity. Therefore we had investigated only vertical drop. Only since an angle of 20°±5° to surface the crater itself is not formed, and the furrow is formed at impact.

It is possible to tell about the projectile shape on its trace at the bottom of a crater. By the shape of a crater it is possible to measure maximum sizes in a projectile diameter, and also it is possible to estimate the area of its lateral surface. By the shape of a crater it is possible to determine, for example, how the cone drop - downwards by basis or not. At falling of the cylinder downwards by basis similar to crater shape is formed, as in case of spherical projectile, only the bottom of a crater is formed flat. At falling of the cylinder by a lateral area the ejection happens, in basic, from under lateral area, and practically it is not observed on the part of the bases.

In result, basing on said above, we have determined experimentally projectile parameters under the shape of a crater, formed in flour. We took projectile spherical with originally unknown parameters. Projectile freely dropped from various heights. Initial density of flour was of 480 kg/m^3. The results of calculations for one projectile are given in tab. 3.

Table 2. Projectile parameters determine

Projectile parameters, measured by other methods			**Projectile parameters, measured from reaction of a flour on impact**		
Size, mm	Speed[1)], m/s	Kinetic energy, mJ	Size, mm	Speed, m/s	Kinetic energy, mJ
21	2.5	25	20	–	30
21	3.1	40	22	–	50
21	3.7	68	21	–	70
21	4.2	97	22	4.1	–
21	4.7	138	23	4.8	–

Conclusions:

By the shape of a crater formed by projectile, we can determine the following:

1. The maximum sizes of projectile in diameter.
2. If the crater above represents a cone, on an angle of a cone it is possible to determine the relation of projectile velocity and velocity of sonic wave. If the velocity of sonic in the target is known, it is possible to receive value of projectile velocity
3. If the projectile velocity is subsonic, it is possible to estimate projectile kinetic energy.