# COSMOGONIC RESEARCH — CHANGE OF THE PARADIGM: THE HIGH VELOCITY PENETRATOR

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**Abstract**

We suggest a fundamental change of paradigm in cosmogonic research: Instead of using instruments derived from terrestrial analogues, the development of tools should from the beginning be focussed on space application. An example where this new paradigm can be applied is the development of *Small High Velocity Penetrators* (SHVP). Such penetrators as research devices of a new generation may turn out to be very useful for many tasks in experimental cosmogony. Actually single components of such systems have already successfully passed many tests. They are economically accessible, and their realization within the framework of modern technologies is feasible without basic difficulties.

## 1 Introduction

In many fields, space research adopts an "anthropomorphic–geomorphic" paradigm: the use of methods, concepts and analogues adapted from (and sometimes feeding back to) terrestrial experience, and the key role of humans in near–Earth space and lunar programmes. The authors argue that this paradigm may ultimately be inappropriate, resulting in high costs, technical failures and a limitation of space research programmes.

Instead of copying terrestrial technologies, and sometimes literally also the field geologist, the authors argue for a change of paradigm leading to the creation of technologies and methods tailored specifically to the needs of space research (energetics, speeds, ambient conditions, timescales, communications, weight limitations, reliability and costs) and capable of solving problems of fundamental importance. While such technologies and methods largely still await their creators, one noteworthy development in this direction is the concept of a *Small High–Velocity Penetrator* (SHVP).

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The most general requirements for such devices and their systems are as follows:

- Shock resistance and long overloads with axial accelerations: $\approx 10^4$ g
- Lateral accelerations: $\approx 2000$ g
- Ambient temperature: $50 - 1500$ K
- Structure of the environment can be homogeneous, or it can be complex (even three–phase)
- Density of geological medium: $10^2 - 10^4$ kg m$^{-3}$
- Electrical conductivity: from dielectric to metal
- Operational lifetime: 10 minutes – 10 years
- Mass of $0.2 - 15$ kg for SHVP or $0.1 - 10^4$ kg for devices of other type
- The form is defined by its functional purpose and external conditions; length/diameter ratio $\sim 1 - 10$
- Angular rotation velocity: $0 - 10^3$ s$^{-1}$

The device should be fully autonomous with regard to energy, communications, motion control, and operational modes of the scientific equipment. Naturally, the specific scientific task determines the actual requirements.

## 2 Design and performance of high–speed penetrators

A high–speed penetrator moves in the target geological medium with a speed greater than the speed of P–waves in the medium. Such a penetrator should be small, its mass being defined by the capability of chemical propulsion systems, which in the case of the Moon would be $\approx 2000$ kg (for Mars $\approx 500$ kg). The high–velocity penetrator has advantages in terms of manufacturing techniques, tests, scientific efficiency and costs.

It can have an impact speed of up to 2500 m/s, depending on the characteristics of constructional materials and shape. The penetration depth at $10^4$ g impact load would be at least 60 m. For merely economic reasons, its diameter $d$ should not exceed $120 - 130$ mm, i.e. the caliber of a modern artillery gun. For cavitation penetration and necessary lengthening (by about a factor of 10) the weight of payload will go up to $\approx 1$ kg excluding service systems (telemetry, battery). The high–speed penetrator is an ideal system for carrying out geophysical research: seismic, thermal, some electric, magnetic and electromagnetic measurements. Some geologic–geochemical problems, like e.g. the search and analysis of fluids and some types of elemental analysis, can be also be addressed. While initially foreseen for application to the Moon, Mars, Venus and Mercury, subsequent development will be more challenging in terms of science payload, mass, structure and number of penetrators. One view of the future development of a *Small High–Velocity Penetrator* (SHVP) is described below.

The SHVP design is determined by many parameters. Empirically, it is possible to present a set of dependencies as given below:

$$\begin{array}{lllll} R = R(G); & P = P(k); & I = I(k); & k = k(N); & \\ G = G(N); & I = I(t); & R = R(L); & G = G(t); & \\ I = I(N); & R = R(V_i); & E = E(G); & G = G(V_i); & D = D(V_i) \end{array}$$

where the variables have the following meaning:

$R$ – Delivery costs of the SHVP to the zone of capture by a gravitational field of a space body

$G$ – Weight in standard units (1 standard unit = the minimal weight of SHVP: $\approx 0.1$ kg)

$N$ – Number of scientific tasks

$I$ – Scientific information obtained from use of of SHVP

$P$ – Performance reliability of scientific programmes

$k$ – SHVP number

$t$ – Duration of functioning after landing

$V_i$ – Speed of impact onto the surface of a body

$L$ – Distance between $i$-th and $(i+1)$'th penetrator

$E$ – Energy in SHVP systems (for example in batteries) received from transformation of kinetic energy at the time of landing

$D$ – penetration depth

Even without quantitative definition of the dependences given above, it is possible to present qualitatively their forms. They are illustrated in Figures 1 – 11. So, $R = R(G)$ (Figure 1) at $G = 1 - 3$ can have delivery costs $R = 0$; the reason is that for the launch of heavy commercial satellites, for advertising purposes, the company can allocate small weight free–of–charge. The freely transported mass may be enough for a first SHVP with a particular payload. Further, $R$ is defined by the cost of the minimal weight of a rocket with a small payload, and only over a certain certain range of $G$ a transition to a heavy expensive carrier is required.

The function $G = G(N)$ has the following features: there are always 1 – 3 scientific tasks (for example, seismic and thermal measurements), demanding negligible weights; a further increase of $N$ leads to the necessity to choose another, heavier rocket that allows the number and type of devices to be varied before reaching a critical value of $N$ demanding a new carrier (Figure 2). General information also increases monotonically with growing $N$, but successful selection of the devices leads to a qualitative difference for constant $N$ (curves 1, 2). Reliability of performance $P$ of scientific tasks of the expedition

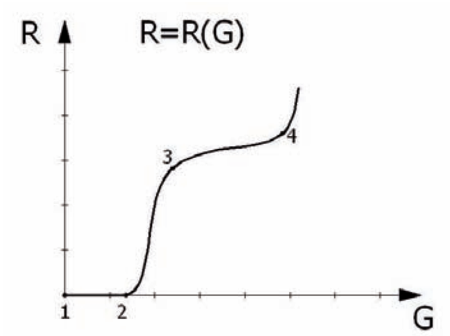


*Figure 1: Cost of penetrator delivery depending on their weight. 1–2: penetrators have insignificant weight, delivery together with commercial satellite; 2–3: using of the independent carrier; 3–4: the serial carrier with accelerating blocks of penetrators; 4: special system for orbit delivery and acceleration of the penetrator; 6: weight of penetrator in standard units, (1 s.u. = 0.1 kg.*

is extremely sensitive to the number $k$ of SHVP. With $k = 1$ it is difficult to provide $P > 0.75$, but using $k \geq 3$ and correct selection of $N$ makes it is simple to receive $P > 0.99$, see Figure 4. Depending on the selection of useful payload (type of devices), growth of the general scientific information $I$ with increasing time of functioning is limited to a certain level (Figure 5, curves 1–3).

With growth of the speed of landing $V_i$ the costs of the mission sharply fall, while $I$ and depth $D$ of penetrating grow (Figure 6). With growth of number of SHVPs their information grows, but after some $k$ the curve levels out (Figure 7). The costs of the expedition are almost constant at insignificant distances between neighbouring SHVP ($\approx 3 - 10$ km). With increasing $L$ (up to radius of a hemisphere of the target body) $R$ grows and information $I$ has a more complex dependence (Figure 8). During decelerating and penetrating into the ground, part of the original kinetic energy can be transformed into the elasto–mechanical and/or electrical energy $E$ (Figure 9). With increasing $T$ the weight of the SHVP grows, but with automatic switching operating modes of devices it can be limited (Figure 10). The weight $G$ of the SHVP grows smoothly with increasing $V_i$, and it grows faster when a critical treshold value of about $V_i \geq 2200$ m/s is exceeded (Figure 11). This is caused by the need that in the high velocity regime additional safety devices to reduce overloads must be implemented.

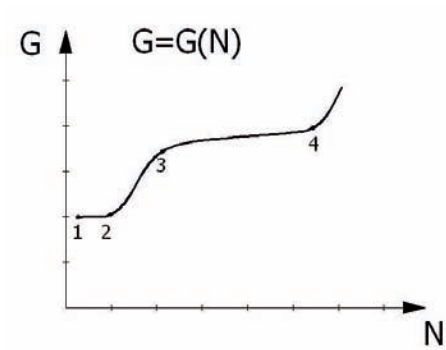


*Figure 2: Dependence of the penetrator weight on the number of scientific tasks. 1–2, 3–4: sites of complex use of scientific devices; 2–3, 4: increase in number of devices.*

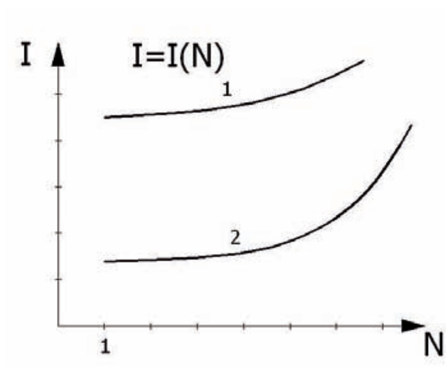


*Figure 3: Information of penetrator depending on number of scientific tasks. 1:Example of successfully selection of tasks (devices); 2: selection unsuccessful.*

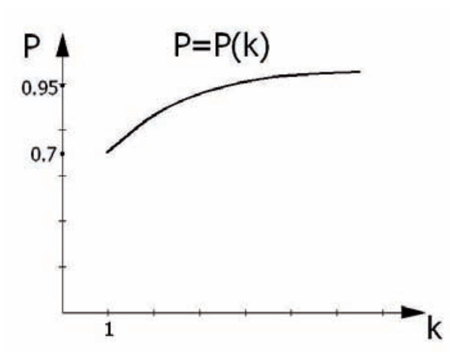


*Figure 4: Growth of reliability or a guarantee of performance of tasks of the expedition with increase in number of penetrators.*

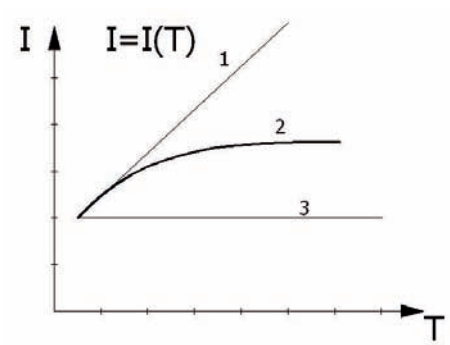


*Figure 5: Growth of the received information depending on a set of scientific devices and life time of penetrators. 1: Successful combination; 2: compromise; 3: unsuccessful.*

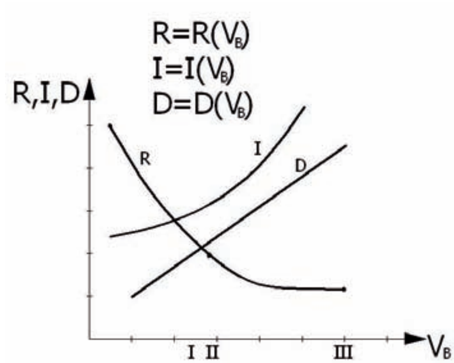


*Figure 6: Interrelation and the general course of the functions $R = R(V_i)$; $I = I(V_i)$; $D = D(V_i)$ depending on speeds of approach of SHVP to a day time surface. I: the first space speed case; II: the second space speed case; III: hurtle trajectory.*

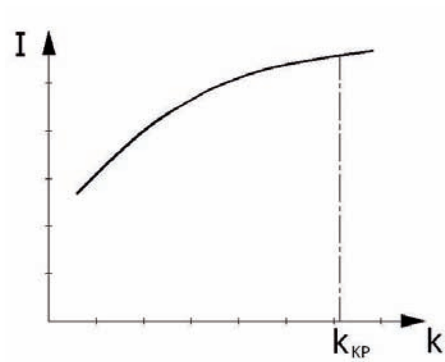


*Figure 7: Character of growth information with increase in number of SHVP. $k_c$ - critical number, after which curve I=I(k) levels out, $k_c \approx 10$.*

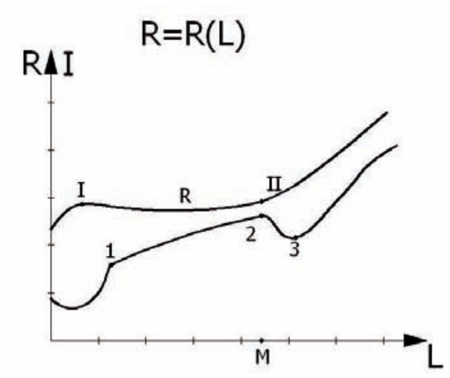


*Figure 8: Interrelation of cost and information of SHVP depending on distance l between the nearest SHVP. I – at using of system rotation; II – dump from the satellite of a space body; 1 – 2: formation and optimization of parameters for small aperture seismic group (SASG), 3: loss of properties of SASG.*

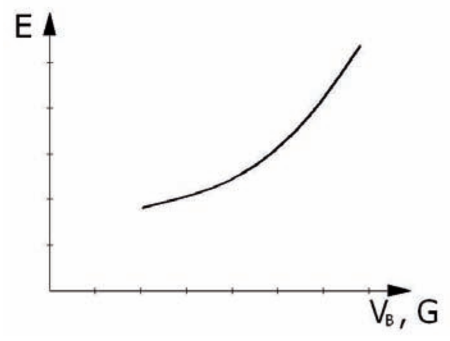


*Figure 9: Recuperation of kinetic energy E in time landing for SHVP in dependance of speed and weight.*

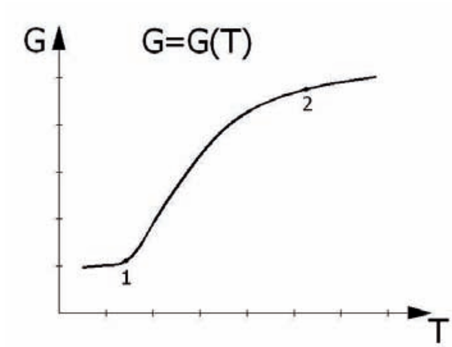


*Figure 10: Connection between of SHVP weight, devices and operating modes. 1, 2: changes point mode.*

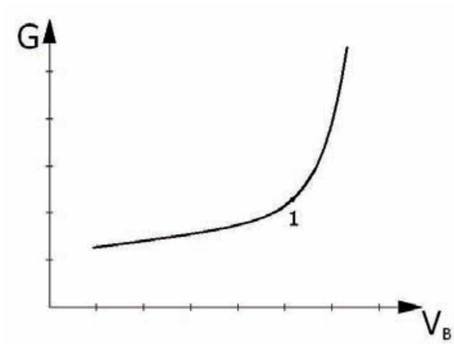


*Figure 11: Weight SHVP as function of speed of an impact on day surface. 1:* $V_i \geq 2000$ *m/s.*

The interrelation of the dependencies described above and illustrated in Figures 1 – 13, the addition of new factors, the development of materials and the perfection of the design alongside with new tasks will finally lead to a perfection of the shape of SHVP's as a new independent class of cosmogonic research devices.

Unique properties of SHVP's are:

1. An angle of approach to a surface in the range $15° - 90°$
2. Elements controlling terra–dynamics
3. Prompting and landing at practically any area of a "hemisphere" of a planetary body
4. Exact targeting to special points of a planet (top of mountains, volcano, canyons, inclined crevices, etc.) will lead to growth of information for carrying out of repeated expeditions.

A heavy high–speed penetrator demands an independent analysis, but one task is acquisition and delivery of a sample from surface geological structures and/or fluids into a low orbit or a return trajectory (a range of depths of $60 - 100$ m, speed of leaving from day time surface $V_l > 2000 - 3000$ m/s, see Galimov et al. (1999)).

## 3 Decrease in overloads and management of penetrating depth

Decrease in overloads during penetration with impact speeds of about 1 km/s can be achieved (Figure 12) as a result of application of gas dynamic shock–absorbers (Veldanov, 1997). At higher speeds of interaction, decrease in overloads can be achieved with the help of a cavitator spike at the tip of the penetrator, providing a cavity volume which reduces the area of contact of the module with the regolith (Veldanov et al., 1998). For impact speeds of about 2 km/s, the cavitator beam can be implemented as a solid rod, commensurable with the length of the penetrating module (perhaps ten times the length); this might be configured to unfold shortly before impact. For a cavitator spike two types are possible:

- Type A: *not deformable* (Figure 13a) – made of a strong highly rigid material (metal ceramic, strong carbon plastic); in this case the initial length of the cavitator beam is preserved during penetration, and it can have an initial length of $0.1 - 1$ m.
- Type B: *deformable or erodable* (Figure 13b) – made of metal or a composite material; in this case there is a reduction of the length of the penetrator during penetration, and its initial length, depending on the material used, can differ from several tens of centimetres up to several metres.

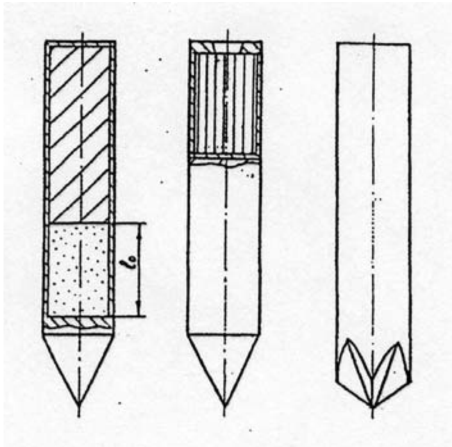


*Figure 12: Constructive receptions of reduction of overloads*

The change in diameter of the case of the penetrating module along its axis of symmetry should be defined by the diameter formed by the cavity volume to exclude contact of the case with the ground during initial, high speed penetration. The diameter of the cavity volume $D$ increases towards the tailward part of the penetrating module. Its increase can be determined via simulation of the impact (Veldanov et al., 1995). For engineering purposes, the diameter of the cavity volume in each of the considered cross–sections can be estimated using dependencies of the inertial expansion of the incompressible environment for the case of spherical symmetry. It can ve expressed by the following formula:

$$D = 2\cos\lambda \left[ 2.5\, x \sin\lambda \left( \frac{d_c}{2\cos\lambda} \right)^{1.5} + \left( \frac{d_c}{2\cos\lambda} \right)^{2.5} \right]^{0.4} \tag{1}$$

where

$x$ – distance from the tip of the cavitator to the considered section of cavity volume;

$\lambda$ – half angle of the cavitator point.

The body of the penetrating module in each of considered sections should not exceed the diameter $D$ of the cavity volume. Thus it can have a step–like or a smooth form (Figure 14).

The cavitator tip should be made from a tough ceramic–metal alloy to maintain contact pressure with the target surface. For example, at $V_i = 2600$ m/s its strength should be $4 - 6$ GPa. The cavitator case (its tail cylindrical part) can be made from a less strong material (steel or Ti–alloy, for example). To reduce overloads at mechanical interfaces of the cavitator spike, it can be supplied with an elastic, plastic or gas dynamic shock–absorber (Veldamov and Naumov, 1999). The functioning of a type B cavitator made

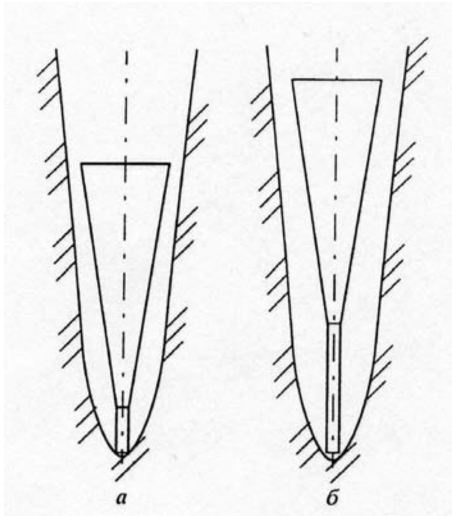


Figure 13: Kinds cavitator beams: A – not deformable, B – deformable

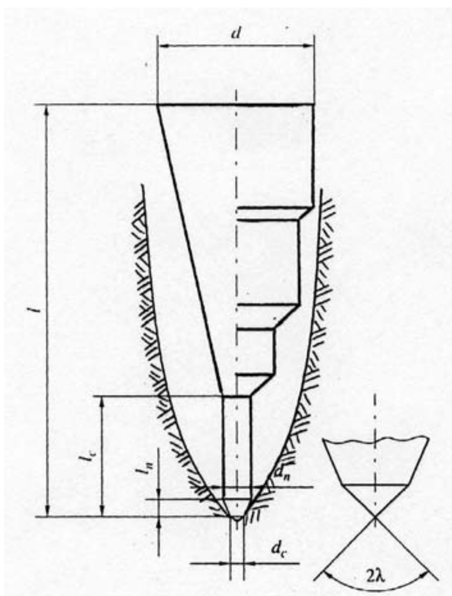


Figure 14: Forms of the penetrating modules entered in a cavity volume, their basic sizes.

from a material that deforms and collapses at the interaction with the ground will differ from that considered above. During initial penetration, the cavitator spike will be plastically deformed and collapse at the forward end. Therefore its length decreases during penetration. Thus, irrespective of the penetration speed, the overload of the penetrator will be determined by the dynamic limit of the destruction of the cavitator spike. On reduction of the penetration speed to some critical value $V_c$, deformation and destruction of the cavitator spike will stop, and we then have the non–deformable case (type A). The critical speed $V_c$, cavitator spike diameter $d_c$ and the change in length of the cavitator spike during penetration can be estimated from a continuum mechanical model given by Tate (1967) and Alekseevskii (1966):

$$V_c = \sqrt{\tfrac{2(\sigma - C)}{A}}\ , \quad d_c = \sqrt{\tfrac{4mgn_m}{\pi\sigma}}$$

where

A, C – characteristics of the penetration resistance of the ground (Veldanov, 1997; Veldanov et al., 1992); for regolith with stone inclusions $A \approx 1700$ kg/m$^3$, $\sigma = 1 - 1000$ MPa;

$m$ – weight of the penetrating module;

$n_m = 10^4$ g – maximal allowable overload for the penetrating module.

For use of a composite material with $\sigma = 5$ GPa the critical speed $V_c$ will be 2400 m/s, and the cavitator spike diameter $d_c$, for example, for penetrating modules of weight 500 kg and 2000 kg will be 0.10 m and 0.223 m, respectively. The advantage of deformable cavitator spikes is that the overload of the penetrating module will not exceed allowable values and at interfaces between deformable and rigid parts of the spike, the overload of the penetrator cannot exceed the value of $\sigma$. Therefore for the penetrating module with a deformable cavitator beam the additional shock-absorber is not required. Calculations show that the ultimate penetration depth in a regolith is about 100 m. For reduction of penetration depth it is necessary to impact the ground surface at an oblique angle (Figure 15). The effect of reduction of penetration depth in this case can be strengthened by addition of stabilizers with an asymmetric position with respect to the axis of symmetry. On interaction with the cavity walls the penetrator will experience a turning moment. Such a technique can also be used to orient a SHVP in the regolith parallel to its surface. There is an opportunity for reduction of penetration depth due to a curvature of its trajectory penetrating aside an obverse surface by performance of a forward part as the slanting cut (Figure 16). The angle of such a cut on the cavitator spike is a function of the ratio of the maximal allowable axial and lateral overloads, and also the coefficient of friction of the material of the cavitator with the regolith. It can be in the range 45° - 90°. The relation of a lateral overload to axial is equal:

$$\frac{F_N}{F_A} = \frac{1 - \mu \tan\lambda}{\mu + \tan\lambda} \tag{2}$$

where

$\lambda$ – angle of inclination of a slanting cut to the axis of the penetrator,

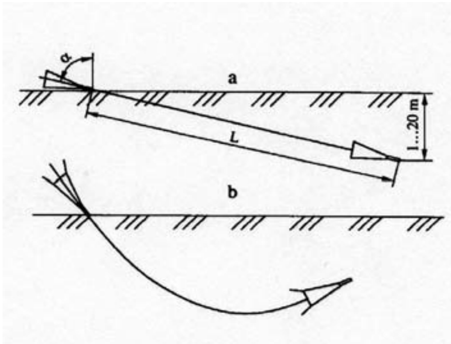


*Figure 15: Methods of reduction of depth penetrating in a soil. a: approach SHVP to a surface under big corner $\alpha$; b: application of the asymmetric stabilizer*

$\mu$ – coefficient of friction (Figure 17).

The angle $\lambda$ should be less than a critical value $\lambda_{cr}$ at which the relation given above relation is equal to zero (Figure 18). The radius of curvature $R$ of the trajectory is

$$R = \frac{mV^2}{F_N} = \frac{V^2}{N_n g} \tag{3}$$

where the maximal allowable lateral overload determined by the maximal lateral force is:

$$N_N = \frac{F_N}{mg} \tag{4}$$

At an allowable lateral overload $N_N = 2000$ and penetration speeds $1000 - 2600$ m/s, the radius of curvature is $50 - 300$ m. The opportunity for change of radius of curvature of a trajectory in the process of penetrating can be achieved by performance of a forward part cavitator spike with the corner of cut changing in the process of penetrating (Figure 19).

There is an opportunity for reduction of the overloads experienced by an instrument compartment by using a gas shock–absorber. The gas shock–absorber can be executed as a cavity ahead of the instrument compartment, filled with gas under pressure (Figure 20). It allows reduction of the maximal overloads during initial penetration. If the level of overloads for the gas shock–absorber exceeds allowable values, for example, on collision with a stone (Figure 21), under action of inertial forces the instrument compartment will make rigid connection with the cavitator spike. The overload experienced by an instrument compartment in this case will be determined by the geometrical sizes of the cavitator spike. In the case of reduction of overloads during passage through less strong layers of the target, the cavitator beam breaks contact with the instrument compartment and the gas shock-absorber functions once again to reduce overloads. The functioning of a penetrator with a gas shock-absorber is described by a system of differential equations (Veldamov and Naumov, 1999) including the equation of movement in the ground of the penetrator

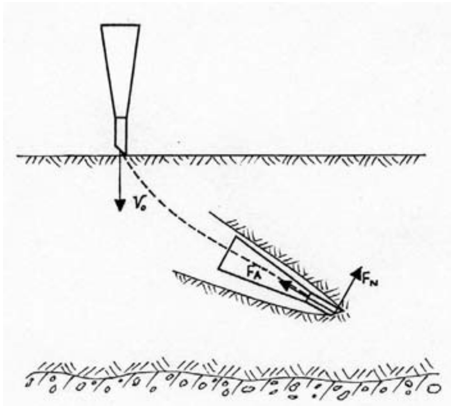


*Figure 16: Penetrating of SHVP with a slanting cut of cavitator beam.*

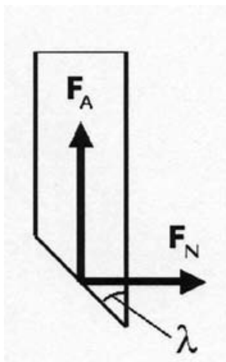


*Figure 17: Axial and lateral forces of resistance acting on a slanting cut of cavitator beam.*

under the action of resistance forces and the pressure of the gas in the shock-absorber, and also the equation of movement of an instrument compartment under the action of the forces of inertia and the pressure of the gas. In such a shock–absorber, depending on penetration conditions there is an auto regulation of the overloads experienced by an instrument compartment (Figure 22). The gas shock-absorber can be implemented as a telescopic mechanism.

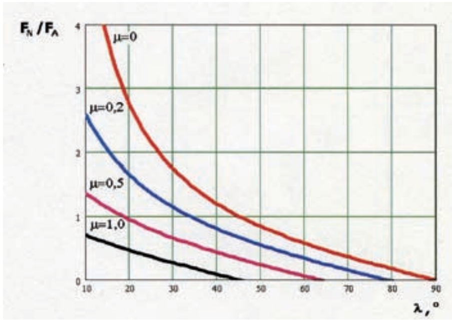


*Figure 18: Relation of lateral force of resistance to axial force depending on a corner of a cut.*

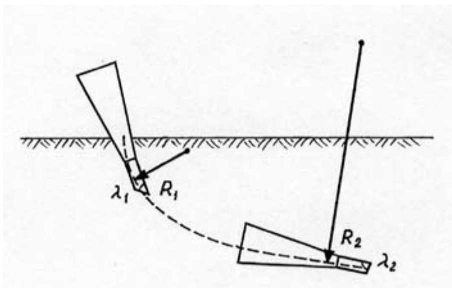


*Figure 19: Change of curvature of a trajectory depending on a corner of a slanting cut of cavitator beam.*

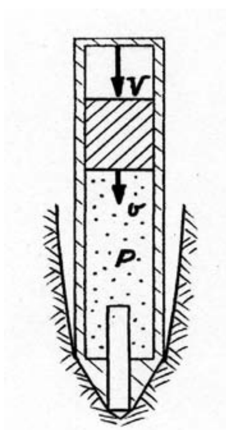


*Figure 20: Reduction of an overload with the help of a gas shock–absorber.*

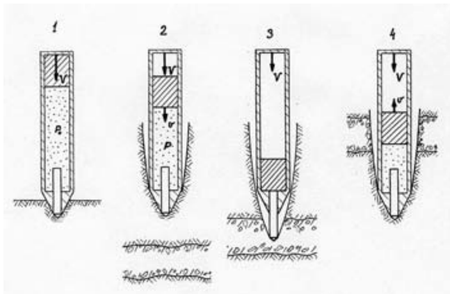


*Figure 21: Characteristic penetrating stages: 1 – the initial stage; 2 – work of the gas shock–absorber; 3 – work of cavitator beam; 4 – repeated work of the gas shock–absorber.*

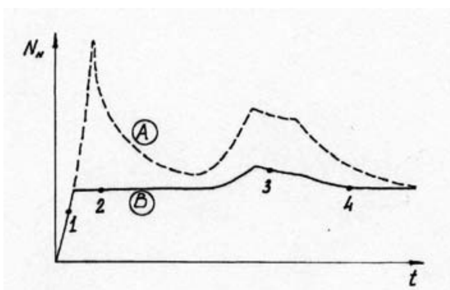


*Figure 22: An overload of an instrument container at absence (A) and presence (B) of a gas shock–absorber and the cavitator beam at characteristic stages of penetrating.*

## 4 Conclusion

SHVP as a next–generation research device is vital for many tasks of experimental cosmogony, and SHVPs have successfully passed many tests albeit as separate components; it is economically accessible, and its realization within the framework of modern technologies is feasible without basic difficulties. The problem of the use of SHVPs now depends on the psychology of the management of space departments!

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