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PROBING OF THE INTERIOR LAYERS OF THE EARTH WITH SELF-SINKING CAPSULES

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It is shown that self-sinking of a spherical probe in the form of a capsule filled with radionuclides, whose decay heats and melts the rock in its path, deep into the Earth is possible. Information on the formation, structure, and shifts deep in the Earth can be obtained by recording and analyzing acoustic signals from the recrystallization of the rock by the probe. It is shown that such capsules can be placed at a prescribed depth. Self-sinking probes can be used to study the formation of deep layers in the Earth, prospect for minerals, and study underground motions in seismically active regions.

The great interest in the interior structure of the Earth is not diminishing but many details of the Earth's structure are still undetermined [1–7]. Thus, the sources which maintain the Earth's heat balance, the role of ^{40}K in this balance [2], and the nature of the high fluidity of the magma at a definite depth [4, 5] remain unclear. Only near-surface layers of the Earth are accessible for direct observation, as a result of which many details of the Earth's structure remain unknown.

Modern technology permits drilling superdeep wells on continents (up to 10–15 km deep). The deepest exploratory well Bertha Rogers (USA) is 9583 m deep, and the scientific well KTW-Oberpfaltz (Bavaria) has reached a depth of 9101 m. According to the international program of deep-water drilling, the deepest well has been drilled in the Pacific Ocean south of Costa Rica (2105 m below the ocean bottom). Drilling of the Kola superdeep scientific well began in 1970. Its projected depth is 15 km. Although drilling stopped at a depth of 12261 m in 1991, it still remains the deepest well in the world [6, 7]. Drilling superdeep wells takes years and is very expensive.

Reaching a large depth poses insurmountable barriers for drilling mainly because of increasing pressure and temperature. At great depths, the difference between the hydrostatic pressure of a column of the drilling solution and the lithostatic pressure due to the mass of the rocks becomes substantial, which causes the walls of the well to collapse. The high temperature in the deep interior of the Earth remains one of the chief factors limiting the drilling depth. The thermal stability of the drilling equipment does not exceed 573 K, so that modern technical means do not make it possible to drill wells for a long time to a depth where the temperature is above this value. At the same time, as the depth increases, the rock temperature increases, for example, at the bottom of the Salton Sea well (USA) 3220 m the temperature reached 628 K, so that drilling becomes impossible at very large depths. There are also serious technical difficulties with spontaneous curving of deep wells during drilling. For example, the Kola well at a depth of about 12 km deviated from the vertical by 840 m, and the KTB-Oberpfaltz well at a depth of 9101 m deviated by 300 m [6, 7].

Various possibilities for reaching a great depth in the Earth are being examined theoretically. An example is explosive penetration to the deepest layers [3]. At the present time, the greatest achievement would be reaching the Mohorovicic

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boundary (Moho discontinuity), where the transmission velocity of seismic waves changes sharply (above the Moho discontinuity the velocity of longitudinal waves is 6.3 km/sec and the velocity of transverse waves is 3.7 km/sec, below the discontinuity the values are 8 and 4.3 km/sec, respectively). It is believed that the Moho discontinuity is a phase transition from a low- to a high-temperature form of basalt. Reaching the Moho discontinuity and studying its characteristics are of great practical value, since it is precisely here that 99% of all deep-focus earthquakes are engendered. The Moho discontinuity lies at the bottom boundary of the basalt layer, i.e., at a depth of only 4–6 km below the oceans, 20–30 km below continents, and up to 70 km in mountainous regions [1]. In the present paper, we shall show that modern technology makes it possible to reach such depths for research.

It has been suggested [3] that a ~10 W acoustic probe be directed into a giant fused mass of iron 10^8–10^{10} kg which moves down through the crack produced by a nuclear explosion with a power of several megatons. The practical implementation of this project is not being studied because of the enormous cost and technical difficulties. The aim of the present work is to indicate the fundamental possibility of directly probing the Earth at great depths by detecting sound waves from capsules which sink by melting rock. Such a probe is filled with radionuclide in an amount ensuring that the rock along the path of the probe will be heated and melt as the probe sinks. Observations can be made on the probe by detecting acoustic signals, caused by melting and subsequent crystallization of the rock, motion of the capsule, and radiation and thermal effects. Placement of probes at a prescribed depth, where the probes will serve for a long time as deep acoustic sources, would make it possible to obtain information about the structure of the deep layers of the Earth and provide continuous information about underground motions. Such information is especially valuable for seismically active regions.

Self-Sinking Method. This method has been studied primarily in connection with self-burial of radioactive wastes. These projects are being developed in USA and in our country [8–13]. Although self-burial has not been used for radioactive wastes, in many publications the method is analyzed in detail and model experiments are described [9, 14].

Melting of the rock by a hot capsule is possible if the temperature of the surface of the capsule is higher than the melting temperature of the rock, and the average density of the capsule is higher than the specific mass of the rock. Let us suppose that a spherical capsule with radius R (m) is heated as a result of radioactive decay of a nuclide up to a temperature higher than the melting temperature of the rock. Because of the intense penetrating radiation, the distribution of heat sources can be regarded as uniform over the entire volume of the capsule. If the capsule is made of a material which ensures good absorption of radiation, almost all of the energy released by decay will be used for heating. The total power of heat release Q_{tot} depends on the mass M of the radionuclide and the specific heat release Q_m of the nuclide:

$$Q_{\text{tot}} = MQ_m = MQA, \tag{1}$$

where Q is the Q factor, W/Ci; A is the specific activity of the radionuclide, Ci/g. Their numerical values are presented in Table 1 for radionuclides which appear promising for heating a self-sinking capsule and are the main components of the radioactive wastes [15]. In addition, the decay products of these radionuclides are nongaseous, which makes it possible to avoid possible complications due to excess pressure. The specific heat release of a capsule of radius R is $q = 3MQ_m/4\pi R^3$. The condition for self-sinking of the capsule as a result of melting through the surrounding rock is

$$q > q_{\text{th}} = \frac{3\chi(T_m - T_r)}{R^2},$$

where χ is the thermal conductivity, W/(m·K); T_m is the melting temperature; and T_r is the temperature of the rock, K. Capsules with a specific power of heat release less than the threshold q_{th} do not melt the surrounding rock and, consequently, remain stationary. According to [11], motion of the capsule in fissured rock is possible if the surface temperature of the capsule is higher than the melting temperature by some threshold value. This effect can be taken into account by an appropriate correction to the melting temperature T_m. Specifically, for granite rocks, containing ~0.6% water, T_m = 1223 K [13], and the threshold thermal power q_{th} = 16.2 kW/m^3. The minimum amounts of two possible radionuclides ^{60}Co and ^{137}Cs necessary for self-sinking of a spherical capsule with radius 50 cm into granite are 0.48 and 97.7 kg, respectively; for ^{90}Sr

TABLE 1. Parameters of Promising Radionuclides for Heating by a Self-Sinking Capsule

Characteristic	^{60}Co	^{90}Sr	^{134}Cs	^{137}Cs
Half-life, yr	5.27	28.5	2.06	30.17
Activity, Ci/g	1130	136	1294	86.9
Q, mW/Ci	15.4	1.16	10.19	1.01
Q_m, kW/kg	17.4	0.158	13.2	0.0877

and ^{134}Cs the values are 53.8 and 0.64 kg. It is evident that existing industrial sources of high-radiation (with a volume of 0.52 m^3) with total thermal power 8.5 kW based on these radionuclides make it possible to reach the required melting parameters. In addition, as a result of the irretrievable placement of radionuclides in the deep layers of the Earth, spent sources, which at present are immobilized in metal matrices and are stored in surface storage sites [16], can be used as heat sources.

The gradual sinking of a capsule to increasingly deeper layers by melting rock can be calculated by numerical methods [17], and an approximate calculation is possible with acceptable accuracy analytically also [10, 11]. First, the time of motion of a capsule in rock can be determined quite accurately. Indeed, the power of thermal sources decreases with time exponentially $q(t) = q(0)\exp(-\lambda t)/T_{1/2}$, where $q(0)$ is the initial specific power of the sources and $T_{1/2}$ is the half-life of a radionuclide, yr. The self-sinking of the capsule stops when the threshold specific power is reached $q(\tau) = q_{\text{th}}$. Consequently, the time of motion of the capsule is

$$\tau = 1.44T_{1/2}\,\frac{q(0)R^2}{3\chi(T_m - T_r)}$$

(for $t > \tau$ the capsule can no longer melt the rock in its path and remains stationary in the rock). The velocity at which the capsule sinks can be estimated analytically for a capsule with isothermal sources for small Stefan numbers, i.e., in a typical case of not very rapid sinking [10, 11]:

$$U(t) \approx U(0)\exp(-\lambda t)\,\Theta(\tau - t) = \frac{4Rq(0)\exp(-\lambda t)\,\Theta(\tau - t)}{3\rho_m[L + c_p(T_m - T_r)]},$$

where $U(0)$ is the initial rate of sinking, m/yr; λ is the decay constant of the radionuclide; $\Theta(\tau - t)$ is the Heaviside unit step function; L is the latent heat of melting, J/g; ρ_m is the density of the melt, g/cm^3; and c_p is the specific heat capacity of the rock, J/(g·K). The penetration depth of the capsule by any prescribed moment in time $t < \tau$ can be estimated from the formula

$$H(t) \approx \frac{4Rq(0)[1 - \exp(-\lambda t)]}{3\lambda\rho_m[L + c_p(T_m - T_r)]}.$$

The maximum sink depth, corresponding to stopping of the capsule at $t = \tau$, is

$$H(\tau) \approx \frac{1.9T_{1/2}Rq(0)}{\rho_m[L + c_p(T_m - T_r)]}\left[1 - \frac{q_{\text{th}}}{q(0)}\right].$$

If the capsule parameters are chosen beforehand so that the capsule stops near the Moho discontinuity, then information about the nature of the layers of the Earth in this region and the processes occurring at depth can be obtained from the acoustic signals.

Capsule. The self-sinking of a hot capsule is initially studied assuming that the surface temperature of the capsule is uniform [9–11]. Actually, this corresponds to the case of a metallic capsule in which temperature uniformity is ensured by

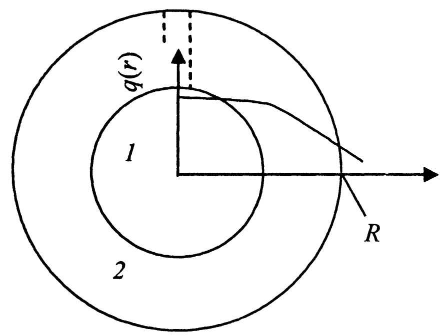

Fig. 1. Form of a self-sinking capsule: *1*) active material; *2*) capsule; $q(r)$ – distribution of heat sources in the capsule.

TABLE 2. Parameters of Self-Sinking Research Capsules in Deep Layers of the Earth

Parameter	^{60}Co	^{60}Co	^{60}Co	^{137}Cs	^{137}Cs
Capsule radius, m	0.5	0.5	0.5	0.5	0.75
Initial mass, kg	4.8	48	96	489	2155
Activity, MCi	5.4	54	104	42.5	187
Initial thermal power, kW/m^3	162	1620	3240	81	108
Total thermal power, kW	85	850	1700	43	191
Initial velocity, m/yr	790	7900	15800	395	790
Total time of motion, yr	18.5	36	41.2	75.3	96.5
Maximum self-sinking depth, km	6	60	120	17	34

the high thermal conductivity of the material. Its high mechanical and radiation resistance ensure that the capsule will survive several years of constant irradiation. As a result of the high lithological pressure at great depth, a spherical shape is preferred for the capsule (Fig. 1).

Self-sinking taking account of the nonuniformity of the temperature is described in [17]. It turned out that for a capsule made of a ceramic material the top part characteristically overheats, which substantially limits the initial load of thermal sources and thereby the rate of advancement. Promising metals are tungsten, which makes it possible to ensure high and effective loading of heat releasing radionuclides and to decrease the intensity of the external radiation field. Metallic tungsten probably has adequate corrosion resistance under conditions of contact with melted silicates at high pressure. The corrosion of the materials in contact with the rock melts under pressure is now being studied intensively for purposes of possible deep burial of radioactive wastes [18–21]. The results appear to be optimistic. For example, corrosion-resistant steel in granite melt at pressure 150 MPa corrodes to 10 μm in two months [21]. In order for the capsule not to fracture over the sinking time, the layers of the capsule must be thick enough (at least several centimeters for a characteristic corrosion rate ~0.1–1 mm/yr).

The temperature of the capsule is maximum initially and can be found for a metallic capsule from the formula [10]

$$T_0 = T_m + \frac{4}{3\kappa c_p}\left(\frac{\eta q(0)^4 R^5}{2g(\rho_c - \rho_m)(L + c_p(T_m - T_r))\rho_m^4}\right)^{1/3},$$

where κ is the thermal diffusivity of the rock, cm^2/sec; g is the acceleration of gravity, cm/sec^2; η is the dynamic viscosity of melted rock, Π (Π = 0.1 Pa·sec); and ρ_c is the average density of the capsule, g/cm^3.

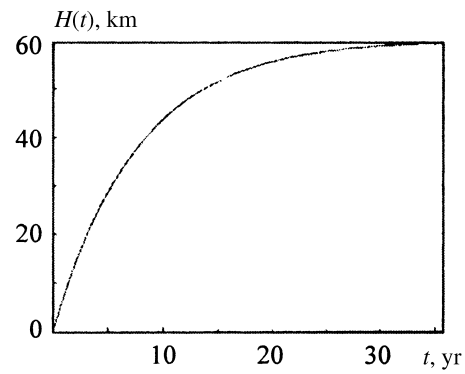

Fig. 2. Time dependence of the self-sink depth of a 1 m in diam. capsule with total ^{60}Co activity 48 MCi.

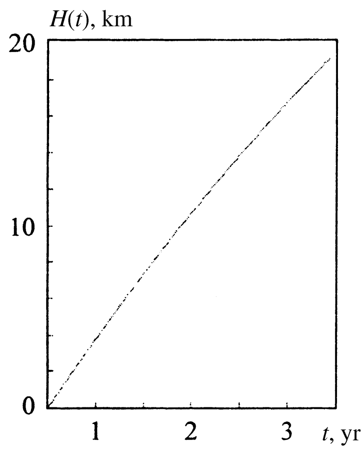

Fig. 3. Sinking of a capsule during the first 3 yr.

The condition for the capsule not to be destroyed by excess heat is $T_0 < T_{mc}$, where T_{mc} is the melting temperature of the cladding material, for example, for tungsten T_{mc} = 3683 K. The higher the capsule density, the less it is overheated; moreover, the overheating increases rapidly with increasing capsule size. Therefore small capsules are preferable, since the required sinking parameters can be achieved by increasing the specific heat release. Estimates show that for metal capsules of size ~1 m the overheating is limited by hundreds of degrees.

Sinking. The approximate sinking time and the sinking depth of a tungsten capsule filled with ^{60}Co or ^{137}Cs are presented in Table 2. For numerical estimates, the following average parameters of the rock and capsule were used: $\eta = 100$ П, $\rho_m = 2.7$ g/cm^3, $\kappa = 0.01$ cm^2/sec, $c_p = 1$ J/(g·K), $L = 418$ J/g, $\chi = 0.01$ W/(cm·K), $T_m = 1473$ K, $T_r = 293$ K, $\rho_c = 12.7$ g/cm^3 [10–13].

Figures 2 and 3 show that the Moho discontinuity can be reached in less than 1 yr; the region below the Moho discontinuity, which is inaccessible for direct probing, can be reached in 3 yr. This shows that a self-sinking capsule has advantages of simplicity and effectiveness compared with the moving-crack project [3]. At the same time, the capsule will operate for more than 10 yr as a constant moving source of acoustic waves. This could make it possible to judge the components of the motion of the interior layers of the Earth. To study deeper layers of the Earth, it is preferable to use self-sinking of a capsule directly from the ocean bottom. Another possibility is to start the capsule from an existing deep well. Filling the capsule with sources and sealing it can be done directly before release, which will make it possible to use standard shipping containers.

Acoustic Probing. The capsule melts rock in its path, and the melted rock recrystallizes behind the capsule. The melting and recrystallization of the rock are accompanied by powerful acoustic signals [22]. When a certain amount of ^{226}Ra and beryllium are loaded into a capsule, it is possible to irradiate as a result of the nuclear reaction (α, n) rock with neutrons with average energy 3.63 MeV, which is accompanied by additional emission of acoustic waves. The detection of acoustic signals can give information about the location of the capsule and the state of the rock transilluminated by the acoustic waves. It has been shown as part of the international project GENIUS on probing the Earth with neutrino radiation [23] that it is possible to detect acoustic signals several orders of magnitude weaker than the background radiation. Compared with radiation from neutrino reactions, a self-sinking capsule is a more powerful source of acoustic signals, which can be reliably traced from different points. It is believed [3] that an acoustic signal power of about 10 W is acceptable for deep measurements, and in addition the power of the acoustic signals from a capsule which melts rock in its path will be tens–hundreds of watts. Analysis of the spectrum of the signals will make it possible to add much to our understanding of the nature of the propagation of sound waves in the deep interior of the Earth.

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