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FEATURES OF SINKING OF RADIOISOTOPE DEVICES IN ICE STRATUM

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Sinking of radioisotope devices in ice due to different thermal mechanisms of energy transfer is analyzed in this work. Features of heat transfer from the device to the surrounding ice by thermal conduction and direct heating by gamma radiation are considered by the example of sinking devices with radionuclides ^{90}Sr, ^{137}Cs and ^{60}Co. For the device model in the shape of a sphere containing nuclides listed above, the sinking parameters including the threshold heat power required for melting of ice and the descent velocity depending on heat power and the size of the sphere have been assessed.

Ice research, self-sinking, radioisotopes, ice melting, heat transfer mechanisms, thermal conduction, direct heating due to gamma radiation

INTRODUCTION

The modern methods of natural ice research include various measurements effected by probing and ice drilling; the possibilities of aerial photography and satellite survey are also widely used. As known, the thickness of the ice cover of the Earth may reach 4,700 m (the ice cover of Antarctica) [*Voitkovsky, 1999*]. Application of the method of sinking a device into rocks based on using the radiation energy of radio nuclides [*Kashcheev et al., 1992; Logan, 1974; Gibb, 1999; Arutyunyan et al., 2014; Arutyunyan, 2014, 2016*] to sinking a measuring device into ice will allow penetration into the ice masses up to 4 km deep and more. Together with the respective measuring equipment, this method may be used for investigating hard-to-reach areas in the ice masses, which are located at large depths and for obtaining information on the physical and chemical characteristics of ice and their change with the depth. Such measurements may be conducted locally in certain areas of the territory investigated, in particular, in order to test and update the data obtained by other methods.

The method of self-burial of radioactive waste (RW) of the nuclear plants due to its heat emission in the rocks, such as granite, basalt and other, has been discussed in [*Logan, 1974; Kashcheev et al., 1992; Gibb, 1999; Gibb and Ojovan, 2005*]. The RW is proposed to be placed in a capsule. The energy produced due to radioactive decay of the radionuclides contained in the RW is to be used for melting the surrounding rock. Ousting the melt formed due to gravity, the capsule descends into the rock depth. This method potentially allows immersion of RW into the deep strata of the lithosphere, up to the mantle.

In the patents [*Arutyunyan et al., 2014; Arutyunyan, 2014, 2016*], methods and devices are proposed for immersion into rocks based on heat-emitting elements with certain radionuclides (including those contained in RW), having the necessary characteristics to ensure heat production over a long period of the time of sinking the device. Such sinking devices may serve as carriers of useful load, for example, of measuring instruments than can be used for investigation.

Depending on the characteristics of radionuclide radiation, the geometry and the material of the device, there may be different mechanisms of the transfer of the emitted energy to the surrounding rock to melt it. It is supposed in the above papers and patents that heat transfer to the environment is carried out primarily by way of thermal conduction, as a result of the greater amount of radiation becoming absorbed inside the device or container used for sinking.

In this study, sinking a device containing radionuclides into a mass of ice is discussed, when thermal conduction or direct heating of ice by γ-radiation acts as the main mechanism of energy transfer. Transfer of radiation emitted by radionuclides followed by absorption of radiation by material is understood as direct heating due to radiation. Analysis was carried out by the example of sinking devices based on different radionuclides, the radiation characteristics of which, together with the structural details of the devices, allow implementation of the said mechanisms of energy transfer.

THE ICE SINKING MODEL OF A SINKING DEVICE

It is supposed in this study that sinking into an ice mass is carried out with a device schematically shown in Fig. 1. Radionuclides ensuring heat emission are placed in a spherical layer between the internal and external shells made of steel or alloys based on heat-proof metals Mo, Nb, Ta, etc. For the purpose of evaluations, it is assumed that the thickness of the internal and external shells is 3 mm; the mass of the radionuclides in the spherical layer is determined by the required heat sink capability.

Among the radionuclides contained in the radioactive waste of nuclear plants and those used in the industry and in medicine are ^{60}Co, ^{90}Sr (with the daughter nuclide ^{90}Y) and ^{137}Cs (with the daughter nuclide ^{137m}Ba), the characteristics of which are shown in Table 1 [*Babichev et al., 1991; ICRP..., 2008*]. The values of energy intensity are given in the table in supposition of equilibrium of parent nuclides with their decay products. Due to rather high values of energy yield per one decay act, high energy intensities are characteristic of these radionuclides. The half-life period values intermediate compared to other radionuclides allow the required energy intensity to be maintained throughout a long period of time. Considering the said characteristics, we will consider the radionuclides given in Table 1 as sources of thermal emission in the ice sinking devices.

SINKING CHARACTERISTICS IN IMLEMENTATION OF DIFFERENT THERMAL PHYSICAL MECHANISMS

Energy transfer by thermal conduction (^{90}Sr-based device)

The extrapolated range of β-radiation of radionuclides ^{90}Sr и ^{90}Y (the daughter product ^{90}Sr), corresponding to the maximum energy of emitted radiation 2.28 MeV, in the material contained between the sinking device shells is not more than several millimeters. If these radionuclides are used as a thermal source, it is to be expected that practically all the energy emitted during radioactive decay will be absorbed inside the device. Melting of the surrounding ice will take place due to transfer of thermal energy from the device by way of a thermal conduction mechanism.

A minimum value of the heat release power $Q_{\min}$ required for melting the surrounding mass may be obtained as [*Logan, 1974*]

$$Q_{\min} = 4\pi k R\left(T_{mlt} - T_{sm}\right), \tag{1}$$

where R is the external radius of the sinking device; k is the thermal conduction of the surrounding medium (ice in this case); T_{mlt} is the melting point of the surrounding medium; T_{sm} is the temperature of the surrounding medium. The value (1) corresponds to solution of a stationary thermal conduction equation. Dependence of the power of the heat release minimally required for ice melting on the device size $Q_{\min}(R)$ is shown in Fig. 2.

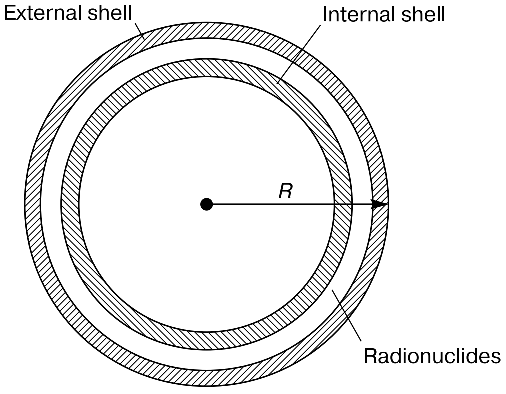

Fig. 1. The geometry of an ice sinking device (*R* is the external radius of the device).

Table 1. **Characteristics of radionuclides contained in RW**

Radionuclides	Density, g/cm^3	Half-life period, years	Specific energy release	
			W/g	J/g
^{60}Co	8.90	5.27	16.77	$4.0\cdot10^9$
^{90}Sr	2.63	28.8	0.92	$1.2\cdot10^9$
^{137}Cs	3.97	30.2	0.23	$3.2\cdot10^8$

With $Q >> Q_{\min}$, evaluation of the dependence of the heat release power required for sinking the device at the velocity v [*Arutyunyan et al., 2010; Chen et al., 2013*] may be obtained from the expression

$$Q = 2v\pi R^2\left[C\left(T_{mlt} - T_{sm}\right) + \lambda_{mlt}\rho\right], \tag{2}$$

where C, λ_{mlt}, ρ is the volumetric heat capacity, specific heat of fusion and ice density. Fig. 2, *a* demonstrates dependences of Q on the external radius of a device generated on the basis of (2), at different values of the sinking velocity.

The values of constants in the calculations were set based on [*Yen, 1981; Babichev et al., 1991; Voitkovsky, 1999*]: $\rho = 0.917\cdot10^3$ kg/m^3, $C = 1.77\cdot10^6$ J/(m$^3\cdot$K), $\lambda_{mlt} = 334.056\cdot10^3$ J/kg, $k = 2.1$ W/(m$\cdot$K), $T_{mlt} = 0$ °C; $T_{ice} = -60$ °C.

It can be seen from Fig. 2, *a* that, in order to ensure the sinking velocity of 1 km/year, the power of the heat release of about $5\cdot10^3$ W is required. This value of the power corresponds to the radioactivity of ^{90}Sr equal to $2.8\cdot10^{16}$ Bq.

Direct heating of ice by radiation (a device on the basis of ^{137}Cs and ^{60}Co)

Radionuclides ^{137}Cs and ^{60}Co are sources of γ-radiation. In radioactive decay of ^{137}Cs, radiation is

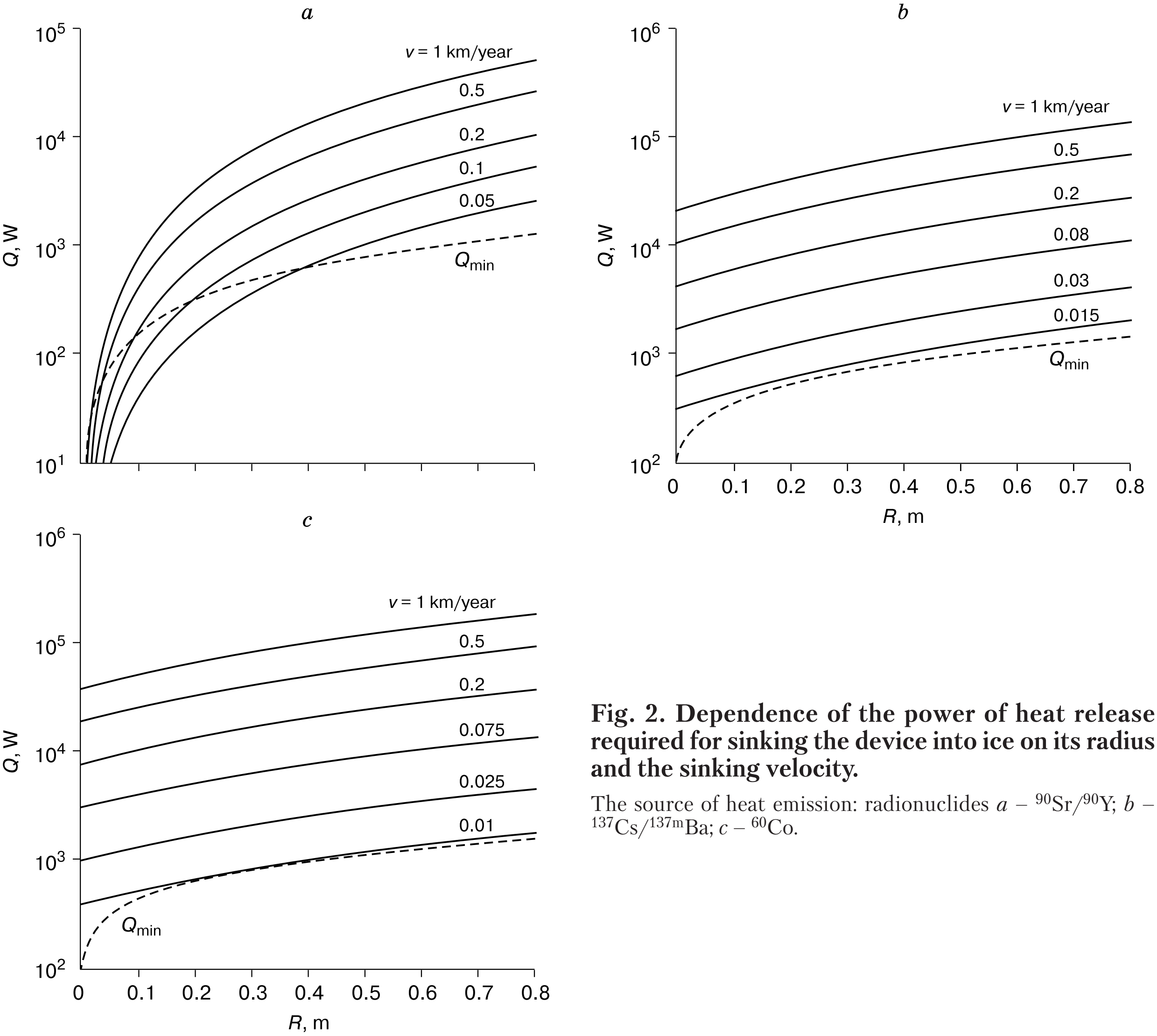

Fig. 2. Dependence of the power of heat release required for sinking the device into ice on its radius and the sinking velocity.

The source of heat emission: radionuclides *a* – ^{90}Sr/^{90}Y; *b* – ^{137}Cs/^{137m}Ba; *c* – ^{60}Co.

emitted with the energy 0.662 MeV, and the average number of γ-quanta per a decay act 0.85 (radiation is emitted by the radionuclide ^{137m}Ba, a daughter product of ^{137}Cs). Radionuclide ^{60}Co has γ-radiation with the energies 1.173 and 1.332 MeV, and the average number of γ-quanta per decay is 0.999 and 1.0, respectively. In using these radionuclides as sources of heat release, due to the high energy and, accordingly, to the high penetration of the emitted γ-quanta, the greater amount of the radiation will be absorbed outside the device in the surrounding ice. Thus, in this case, we can speak about realization of the direct ice heating mechanism by radiation as the main method of transferring energy released during the decay. Evaluations of the characteristic size of the area of energy absorption of γ-radiation δ_E in ice (the area corresponding to absorption of 90 % of the energy emitted by the source), carried out by the authors with the Monte Carlo method, were: $\delta_E = 51$ cm for radiation of ^{137}Cs, $\delta_E = 69$ cm for radiation of ^{60}Co.

To determine the parameters of sinking with radionuclides ^{137}Cs and ^{60}Co, spatial distribution of the volumetric power of heat release in the ice due to absorption of γ-radiation (the range $R \leqslant r \leqslant R_E$, where $R_E = R + \delta_E$) was approximated as

$$q(r) = \frac{a}{r^2} + b, \tag{3}$$

where the constants *a*, *b* were determined from the normalization condition of the total power of heat release $\int_R^{R_E} \left(\frac{a}{r^2} + b \right) 4\pi r^2 dr = Q$ and the condition of the volumetric heat power being equal to zero with $r = R_E$: $\frac{a}{R_E^2} + b = 0$. It was assumed that in the range $R_E \leqslant r \leqslant \infty$ the heat release source was absent.

The minimum power of heat release required for ice melting was determined from the solution of a stationary system of equations with the volumetric power of heat release (3) distributed in the surrounding ice:

$$Q_{\min} = \frac{4\pi k\left(T_{mlt} - T_{sm}\right)\left[R_E^2\left(R_E - R\right) - \left(R_E^3 - R^3\right)/3\right]}{R_E^2 \ln\left(R_E/R\right) + \left(R^2 - R_E^2\right)/2}. \quad (4)$$

The power of heat release required for sinking at a set velocity was determined from the expression (2), where the external radius of the device R_E was taken as the device size R, corresponding to absorption of the greater amount of the energy of γ-radiation.

Fig. 2, *b*, *c* demonstrates dependences of the power of heat release on the external radius R of the device with different values of the sinking velocity in the case of using radionuclides ^{137}Cs and ^{60}Co as energy sources. As previously, considered was the size of the device R, which constituted dozens of centimeters. It is shown in Fig. 2, *b*, *c* that, to ensure sinking of the device at the velocity v = 0.5 km/year, the power of heat release equal to about $5 \cdot 10^4$ W is required. Such a value of power may be obtained due to γ-radiation ^{137}Cs with the activity $5.6 \cdot 10^{17}$ Bq or ^{60}Co with the activity $1.1 \cdot 10^{17}$ Bq.

CONCLUSIONS

This study considers a method of device sinking into a mass of ice using radio isotope devices, when heat transfer from the device to the surrounding ice is carried out due to thermal conduction and direct heating of ice by radiation.

For the purpose of this analysis, as sources of heat release, radionuclides ^{90}Sr, ^{137}Cs and ^{60}Co were selected, contained in the RW of the nuclear power plants, industrial and medical radiation sources, having high specific power of heat release during a long period of device sinking. Differences in the characteristics of radiation of these radionuclides ensure realization of one of the two above indicated mechanisms as the main method of heat transfer to the melted ice. As β-radiation of ^{90}Sr and of its daughter product ^{90}Y is practically completely absorbed in the device, transfer of the thermal energy is carried out mostly by thermal conduction. Due to the high penetration of γ-radiation of ^{137}Cs and ^{60}Co, the major amount of the radiation goes outside the device, ensuring direct heating of the surrounding ice due to absorption of radiation.

The evaluations performed have shown that, to ensure device sinking at the velocity of about 1 km/year if the device is based on radionuclides ^{90}Sr, activity ~10^{16} Bq is required; to ensure this velocity developed by the device based on ^{137}Cs or ^{60}Co, activity of radionuclides is required to be equal to ~10^{17} Bq. Realization of the mechanism of direct heating of ice by γ-radiation in the ice sinking devices will contribute to reliability of the device functioning by reducing the thermal workload of the device components.

Radio isotope devices based on the said mechanisms of heat transfer to the surrounding medium allow long-term autonomous sinking of the device may serve as carriers of the workload as measuring instruments and may be used in conducting various investigations in the deep layers of ice, considering the advantages of measurements in close contact with the medium.

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