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Self-disposal option for highly-radioactive waste reconsidered

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ABSTRACT

Self-disposal option for heat-generating radioactive waste (HLW, spent fuel, sealed radioactive sources) known also as rock melting concept was considered in the 70s as a viable but alternative disposal option by both DOE in the USA and Atomic Industry Ministry in the USSR. Self-disposal is currently reconsidered with a novel purpose – to penetrate into the very deep Earth's layers beneath the Moho's discontinuity and to explore Earth interior. Self-descending heat generating capsules can be used for disposal of dangerous radioactive wastes in extremely deep layers of the Earth preventing any release of radionuclides into the biosphere. Descending of capsules continues until enough heat is generated by radionuclides to provide partial melting of surrounding rock. Estimates show that extreme depths of several tens and up to hundred km can be reached by capsules which could never be achieved by other techniques.

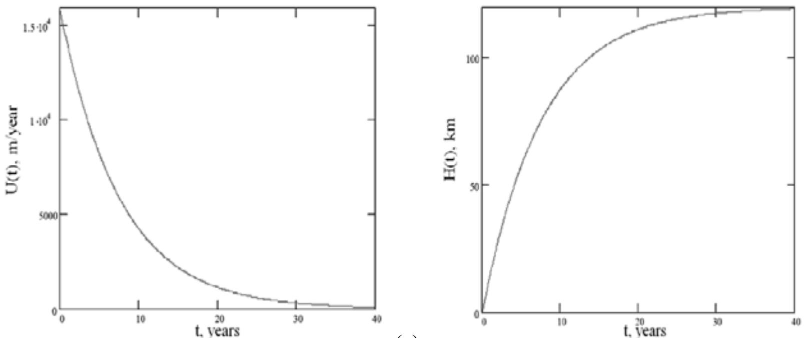
INTRODUCTION

Self-disposal or rock melting concept [1-4] utilizes the heat generated by decaying radionuclides of radioactive waste inside a heavy and durable capsule to melt the rock on its way down. The heat from radionuclides within the capsule partially melts the enclosing rock. If the average density of the capsule (mass divided by volume) is higher than that of molten rock, the melt will be displaced upwards past the heavier capsule [5-8]. Eventually the melt cools and solidifies i.e.. it vitrifies to form a glassy material or partly recrystallizes to form crystalline phases, therefore sealing the route along which the capsule has passed through. Descending or self-disposal continues while enough heat is generated by radionuclides to provide melting of the surrounding rock. Estimates show that extreme depths of several tens to one-hundred km can be reached by capsules, which could never be achieved by other techniques. Thus self-descending heat generating capsules could be used for self-disposal of dangerous radioactive wastes in extremely deep layers of the Earth preventing any release of radionuclides into the biosphere. This idea which was considered in the 70s as a viable alternative disposal option by DOE is reconsidered now [9]. In addition to that, self-descending capsules were recently proposed as a unique tool to explore the deep Earth interior including its mantle e.g. depths which are not accessible by current drilling techniques [10-13]. Acoustic monitoring of the capsules was suggested as a mean to reveal data about the structure of the Earth's interior.

THEORY

Self-descending was studied primarily in connection with self-disposal of radioactive wastes in USA, EU and in Russia [1–8]. The radiogenic heat from radioactive waste can be used for deep self-disposal of heat-generating high level radioactive waste (HLW) as well as highly radioactive spent sealed radioactive sources (SRS) [8, 10-14]. The radiogenic heat can also be used with a novel purpose – to penetrate with a tungsten self-sinking survey capsule into the very deep Earth's layers beneath the Moho's discontinuity [8, 11-13]. 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. It is typically assumed that a spherical capsule with radius R 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 within the capsule can be considered uniform over the entire volume of the capsule. If the capsule is made of a material which ensures good absorption of radiation, practically all of the energy released by the radioactive decay will be used for heating. The total power of heat released, Q_{tot}, then depends on the mass, M, of the heat-generating radionuclides and the specific heat release, Q_m, of the nuclide $Q_{tot}=MQ_m$. The specific heat release due to the decay of radionuclides within a capsule of radius R is then: $Q=3MQ_m/4\pi R^3$. The condition for self-sinking of the capsule is derived from requirement that the surface temperature of capsule is higher than the melting temperature of rock T_m [4, 8]: $q>q_{th}=3\chi(T_m-T_r)/R^2$, where χ is the thermal conductivity and T_r is the temperature of the rock far from capsule. 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 [3, 14], motion of the capsule in a partly cracked (fissured) rock is possible if the surface temperature of the capsule is higher than the melting temperature by a 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 = 950 °C (1223) K [4], the threshold thermal power is q_{th} = 16.2 kW/m^3. The total threshold power of a 1 m diameter self-sinking capsule is ~8.5 kW. The minimum amounts of two possible radionuclides ^{60}Co and ^{137}Cs necessary for self-sinking of that 1 m diameter spherical capsule into a granitic formation are 0.5 and 14 kg respectively. Hence the total volume of capsule (520 L) enables loading of a large amount of waste in addition to the radionuclides which provide the heat required for rock melting. Note that a sphere of ^{60}Co metal with an activity of 3.85 10^{18} Bq, which would yield ~1635 kW of heating power (e.g. hundred times above threshold), will be only about 0.3 m in diameter. The temperatures required for effective rock melting are well in excess of 1000 ºC, increasing with pressure, and ideally the capsule needs to withstand temperatures in excess of 2000ºC. Ceramic materials, although suitably refractory, tend to be poor heat conductors and would overheat [14], thus limiting thermal loading of capsules and hence descent rates and depth. The capsule should therefore be made of metal. It was proposed to use tungsten for this purpose [10-13]. Tungsten melts at 3410ºC, has a specific gravity of 19.3, is relatively inexpensive and is expected to have a low corrosion rate in silicate melts at high temperatures and pressures and low oxygen fugacity (i.e., the conditions that would prevail during descent through the crust and mantle). The capsule wall needs to be strong and thick enough to withstand corrosion and abrasion during descent and also to absorb the radiation from the heat source to ensure efficient heating by absorbing internal radiation. Abrasion during sinking through the melted rock is unlikely to be significant but most metals do corrode by reaction with silicate liquids at high temperature. The minimum wall thickness needed for adequate absorption of β and γ-radiation is ~ 0.1 m.

Rocks are characterized by solidus T_s and liquid T_l temperatures. Because of that the rock would not have to be heated above T_l e.g. to melt completely for the denser and heavier capsule to sink through it. It is known that the viscosity of magmatic melts tends to decrease dramatically when the percentage of crystals falls below that at which rigid crystal networks form [15]. This has been shown experimentally to be between 30% and 40% content of crystals [18]. Therefore the descent rates and depths need to be calculated accounting for this gradual decrease of viscosity. The most appropriate value for T_m in estimates would be [12]: $T_m = T_s + 0.4(T_l - T_s)$. We are nevertheless using herein similarly to [10-12] the overestimating assumption that the heat of fusion of rock is the full heat to completely melt it, and that $T_m \approx T_l$. The estimates obtained are hence rather conservative and demonstrate the feasibility of the concept. Because of that the calculated values for descent rates, terminal depths and total sinking times are absolute minimum values. The self-descending through oceanic lithosphere and through continental lithosphere were recently considered in [12] for the purpose of interior Earth exploration. A simpler case is the penetration via oceanic lithosphere. The lithosphere beneath the ocean basins is relatively well known, consisting of a basaltic crust underlain by peridotitic mantle. Admittedly there are local variations, especially with different varieties of peridotite, however the thermal properties of these are very similar. The gradual sinking of a capsule to increasingly deeper layers by melting rock can be calculated by numerical methods [8, 14]. An approximate calculation is possible with some approximation analytically [3, 6-8]. The time of motion of a capsule in rock can be determined quite accurately. Indeed, the power of thermal sources decreases with time exponentially, $q(t)=q(0)\exp(-\lambda t)$, where $q(0)$ is the initial specific power of the sources, λ is the decay constant $\lambda = 0.693/T_{1/2}$, and $T_{1/2}$ is the half-life of the radionuclide. The self-sinking of the capsule stops when the threshold specific power is reached. Consequently, the time of motion of the capsule is given by: $\tau=1.44T_{1/2}\ln[q(0)R^2/3\chi(T_m-T_r)]$. For $t > \tau$ the capsule can no longer melt the rock in its path and remains stationary in the rock. Capsules will be heated by the radiogenic heat to high enough temperatures to begin melting the surrounding rock and, when the melt fraction reaches a critical value, the capsule will begin to sink through the partial melt due to its higher specific gravity. The velocity at which the capsule sinks can be estimated analytically for a capsule with isothermal heat sources at small Stefan numbers, i.e., in a typical case of not very rapid sinking [3, 6]: $U(t) = U(0)\exp(-\lambda t)\Theta(\tau - t)$, where $\Theta(\tau - t)$ is the is the Heaviside unit step function.



(a) (b)

Fig. 1. The velocity of penetration into granite of a self-descending 1 m diameter tungsten capsule (a); Penetration depth (km) into granite of a self-descending 1 m diameter tungsten capsule heated by decaying ^{60}Co (3.5 EBq) (b).

The initial descending velocity is given by: $U(0)=4Rq(0)/3\rho_m[L+c_p(T_m-T_r)]$. Here ρ_m is the density of the melt, L is the latent heat of melting, and c_p is the specific heat capacity of the rock [12]. Fig. 1 (a) shows the penetration velocity of a 1 m diameter tungsten capsule heated up by ^{60}Co radionuclides with total activity 3.5 EBq (104 MCi), e.g. of the initial mass of active part 96 kg as a function of time. Note also that initial descending velocities are remarkable high and comparable with conventional rotary drilling of scientific boreholes. The capsule would reach the Mohorovicic discontinuity in less than a half of year which is a scientific and technical challenge [13]. Due to natural decay of radionuclides the heat power decreases until it becomes so low that the threshold specific power is reached. Further descending of capsule stops. The depth at which the capsule sank down can be estimated from equation:

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

The maximum sinking depth, corresponding to stopping of the capsule at t=τ. Fig. 1(b) shows the penetration depth of a 1 m diameter W-capsule heated up by ^{60}Co radionuclides with total activity 3.5 EBq as a function of time. This capsule (or probing device [11, 12]) will move 41.2 years achieving the depth 120 km at its final point of penetration into the Earth depth. Capsule parameters can be chosen beforehand so that the capsule stops at required depth. It is however necessary for the capsule not to be destroyed by excess heat generated by decaying radionuclides, e.g. its temperature T_0 should not exceed its melting temperature T_{mc}, e.g. for tungsten T_{mc} = 3410 ^{o}C (3683 K). The temperature of the capsule is maximal initially and can be found for a metallic capsule from:

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

where κ is the thermal diffusivity of the rock, g is the acceleration of gravity, η(T) is the dynamic viscosity of melted rock, and ρ_c is the average density of the capsule, which accounts for both capsule and content materials e.g. heat-generating and waste to be disposed of. The viscosity of melts is a rapidly decreasing function of temperature [17, 18]. Because of that the overheating is limited by higher fluidity of rock melts at higher temperatures. The higher the capsule density, the less it is overheated. Moreover, the overheating increases rapidly with increasing capsule size. Estimates show that for metal capsules of size ~1 m the overheating is limited by hundreds of degrees.

DISCUSSION

Self-descending of a spherical body in a melting environment was considered mostly in relation with potential disposal of radioactive wastes and nuclear reactor core melt-down problem (so-called “China syndrome”) [1-8]. Ceramic capsules demonstrate significant overheating patterns which limit their heat loading and thus descending velocities [14]. We thus suggest using metallic capsules which have almost homogeneous temperature distribution on their surface. Tungsten was selected as a suitable material to manufacture the probe capsule due to its refractory properties (melting temperature 3410^{o}C), high density (19.3 g/cm^3) and presumably low corrosion rate in silicate melts. Capsule's walls shall be enough thick to withstand to corrosion damage during motion: d $>r_{cor}\tau$, where d is the thickness of capsule shell, r_{cor} is the corrosion rate of material in melted rock. The walls of capsule (shell) shall also be enough thick to ensure efficient absorption of radiation emitted by decaying radionuclides and hence an efficient heating of capsule. Thicknesses larger than 10 cm are required to match these requirements. In order to achieve maximum penetrating depths the capsules can be launched from a ship in the sea, where the thickness of crust to be penetrated by capsule is minimal. Loading and weld sealing of capsule with radioactive sources can be done directly before launching, hence standard transport technique could be utilised. Capsules have a very limited Earth's disturbing volume (~m^3) and footprint area (~m^2). They utilise accessible materials of a very small volume (~0.5 m^3). The active part of capsule utilises readily accessible radionuclides such as ^{60}Co. The former is manufactured by neutron irradiation of metallic cobalt and widely used by industry, in medicine and research in form of SRS. In addition spent SRS can be utilised rather than new sources [10]. The capsule melts the surrounding rock on its way which re-crystallizes behind it. Melting and crystallization of rock generates intensive acoustic signals in a wide spectrum of frequencies due to thermo-mechanical interactions [19]. An addition of a mixture of ^{226}Ra and Be to the active part of capsule provides an intensive source of neutron radiation through nuclear reaction (α,*n*) which enables continuous irradiation of rocks during its descent into the depth. Registration of signals from the capsule by several coupled detectors will provide permanent information on capsule motion as well as about the Earth's layers above the capsule that signals travel through them and hence on their geological structure and composition. Capsules can be emplaced at given depths because of that they can provide information about underground motions, which would be particularly useful in seismically active regions including preventing earthquakes.

CONCLUSIONS

The self-disposal concept is suited for very deep (e.g. below 5 km) disposal of the most hazardous heat-generating waste. Self-disposal involves loading of waste together with a powerful heat-generating radionuclide into a sealed metal (tungsten) capsule and placing it at the bottom of a shallow borehole. Due to radiogenic heat generation, the capsule will melt surrounding rock and self-descend. Extreme depths of many tens km are assessed as readily achievable. These are greater than the levels that have been achieved by deep drilling techniques. The capsule descent could be tracked using detection of the acoustic signals generated by melting and solidification (vitrification and crystallisation) of the rocks around and above the capsule. Analysis of the detected signals should also be able to provide information about the deep interior of Earth that is currently inaccessible to direct sampling and augment data from other remote geophysical monitoring techniques.

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