Super-Deep HLW Self-Disposal Option -11065

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ABSTRACT

The possibility of super-deep (below 5 km) self-disposal is analysed which is based on utilisation of radiogenic heat of decaying waste radionuclides from high-level radioactive waste (HLW) or spent sealed radioactive sources (SRS). Super-deep self-disposal does not require dedicated disposal facilities and provides a minimal footprint with an increased safety of disposal and non-proliferation characteristics. Utilisation of heat generated by relatively short-lived radionuclides of SRS diminishes the environmental uncertainties of self-disposal and increases the safety of this concept. Self-sinking HLW capsules could be launched from the bottom of sea, shallow or relatively deep boreholes. Super-deep self-disposal can be used also with a novel purpose – to penetrate into the very deep Earth's layers beneath the Moho's discontinuity and to explore Earth mantle.

INTRODUCTION

The renaissance of the nuclear industry is associated with the renaissance of a bright concept which could be an alternative to existing options for solving the nuclear waste problem: self-disposal or rock melting concept [1-4]. Self-disposal utilizes the heat generated by decaying radionuclides of radioactive waste inside a heavy and durable capsule to melt the rock on its way down. As the heat from radionuclides within the capsule partially melts the enclosing rock, the relatively low viscosity and density of the silicate melt allow capsule to be displaced upwards past the heavier body as it sinks [5-8]. Eventually the melt cools and vitrifies or recrystallizes, sealing the route along which the body passed. Descending or self-burial continues until enough heat is generated by radionuclides to provide melting of surrounding rock. Estimates show that extreme depths of several tens and 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-burial of dangerous radioactive wastes in deep layers of the Earth preventing any release of radionuclides into the biosphere. This idea which was considered in the 70s as a viable but alternative disposal option (DOE) is now a part of current environmentalism [9]. Environmentalists such as Jesse Ausubel cites Russian and British research into self-disposal of nuclear waste "with shells most likely made of tungsten and heated by their radioactive contents to the point where, once disposed of in deep holes in the Earth's crust, they would melt the surrounding lithosphere and bury themselves several miles deep" [9]. In addition to that, self-sinking capsules were proposed to explore the deep Earth interior including its mantle e.g. depths which are not accessible by current drilling techniques [10-13]. It was noted that acoustic monitoring of the capsules could reveal data about the structure of the Earth's interior with scientific importance of the order of an expedition to Mars [9].

SELF-DESCENDING CONCEPT

Self-descending method has been studied primarily in connection with self-burial of radioactive wastes in US and Russia [1–8]. Although self-burial has not yet been used for radioactive waste disposal the method is analyzed in detail and model experiments are described [1-8, 14]. The radiogenic heat from radioactive waste can be used for super-deep self-disposal of heat-generating high level radioactive waste (HLW) [1-8] as well as highly radioactive spent sealed radioactive sources (SRS) [10]. The radiogenic heat can be also 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 [11-13]. In both cases the sealed radioactive sources can serve as carriers, providing enough heat to keep the enhanced temperature during several years and to melt the surrounding rocks enabling self-sinking of metallic capsules into the very deep layers of Earth.

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 regarded as 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 decay will be used for heating. The total power of heat release Q_{tot} then depends on the mass M of the heat-generating radionuclides and the specific heat release Q_m of the nuclide:

$$Q_{tot} = MQ_m \qquad \text{(Eq. 1)}$$

Numerical values are presented in Table I for radionuclides which appear promising for heating a self-sinking capsule and are the main components of the radioactive wastes [15].

Table I. Parameters of heat-generating radionuclides.

Radionuclide	^{60}Co	^{90}Sr	^{137}Cs
Half-life, $T_{1/2}$ (y)	5.27	28.5	30.17
Heat generated, Q_m (kW/kg)	17.4	0.158	0.605
Decay product	Ni	Zr	Ba

Note that the decay products of these radionuclides are nongaseous, which avoid possible complications due to excess pressure. The specific heat release caused by radionuclide decay within a capsule of radius R is:

$$q = \frac{3MQ_m}{4\pi R^3} \qquad \text{(Eq. 2)}$$

The condition for self-sinking of the capsule as a result of melting through the surrounding rock is given by Logan's ratio [4]:

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

where χ is the thermal conductivity; T_m is the melting temperature; and T_r is the temperature of the rock. 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, 16], 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 = 950 °C (1223) K [4], and the threshold thermal power is hence q_{th} = 16.2 kW/m^3. The total threshold power of a 1 m diameter self-sinking capsule is therefore ~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 x 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 [16], thus limiting thermal loading of capsules and hence descent rates and depth. The capsule should therefore be made of metal and 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 liquids at high temperatures and pressures and low oxygen fugacities (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 of the probe. 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.

MELTING OF ROCKS

In reality rocks do not melt at a single temperature T_m as assumed above, but rather over an interval between the solidus T_s and liquidus T_l temperatures. The rock would not have 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 [17]. This has been shown experimentally to be between 30% and 40% 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 probably be [12]:

$$T_m = T_s + 0.4\,(T_l - T_s) \qquad \text{(Eq. 4)}$$

Reasonably good data are available for the solidus and liquidus temperatures of most common rock types under anhydrous melting conditions but are much sparser for hydrous melting. Melting in the presence of water, or even hydrous minerals, greatly lowers both the solidus and liquidus temperatures of silicate rocks. It is likely therefore that the use of data for anhydrous melting will lead to conservative underestimates of both sinking rates and depths of penetration. Also note that because rocks are mixtures of different mineral phases that do not melt uniformly over the solidus – liquidus interval, it would not be strictly correct to linearly apportion a fraction of the heat of fusion, although this would probably be a reasonable first approximation. 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

$$T_m \approx T_l \qquad \text{(Eq. 5)}$$

The estimates obtained are hence conservative and give a rather demonstration of 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 [12]. A simpler case is the penetration via oceanic lithosphere. The lithosphere beneath the ocean basins is relatively straightforward, 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 simple model of oceanic lithosphere is given in Table II [12].

Table II. Parameters of oceanic lithosphere [12].

Depth	**Rock type**	**Pressure**	**Temperature**	**Density**	**Thermal conductivity**	**Heat capacity**	**Heat of fusion**	**Thermal diffusivity**	**Solidus**	**Liquidus**
D (km)		P (kbar)	(Ambient), (°C)	ρ (kg/m^3)	λ (W/m, °K)	C_p (J/kg, °K)	L (J/kg)	K (m^2/s)	T_S (°C)	T_L (°C)
0	Basalt	0.001	25	2900	1.590	782	307730	7.013 10^{-7}	1079	1358
7	Basalt	1.930	128	2900	1.590	895	307730	6.126 10^{-7}	1114	1370
7	Peridotite	1.930	128	3234	3.389	895	383734	1.171 10^{-6}	1134	1721
30	Peridotite	8.250	464	3234	3.138	982	420669	9.881 10^{-8}	1200	1772
100	Peridotite	27.500	1256	3234	2.720	~1067	509324		1453	1901
145	Peridotite	40.000	1544	3234	3.222	?	566893		1628	1958

The gradual sinking of a capsule to increasingly deeper layers by melting rock can be calculated by numerical methods [8, 16], and an approximate calculation is possible with acceptable accuracy analytically also [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

$$\tau = 1.44 T_{1/2} \ln \frac{q(0)R^2}{3\chi(T_m - T_r)} \qquad \text{(Eq. 6)}$$

For $t > \tau$ the capsule can no longer melt the rock in its path and remains stationary in the rock.

SELF-DESCENDING THROUGH ROCKS

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 [3, 6]:

$$U(t) = U(0)\exp(-\lambda t)\Theta(\tau - t) \qquad \text{(Eq. 7)}$$

where $\Theta(\tau - t)$ is the is the Heaviside unit step function and U(0) is the initial descending velocity:

$$U(0) \approx \frac{4Rq(0)}{3\rho_m[L + c_p(T_m - T_r)]} \qquad \text{(Eq. 8)}$$

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 (see Table II). The depth at which the capsule sank down can be estimated from:

$$H(t) \approx \frac{4Rq(0)[1 - \exp(-\lambda t)]}{3\lambda\rho_m[L + c_p(T_m - T_r)]} \qquad \text{(Eq. 9)}$$

The maximum sinking depth, corresponding to stopping of the capsule at t=τ is therefore:

$$H(\tau) \approx \frac{1.9 T_{1/2} R q(0)}{\rho_m [L + c_p (T_m - T_r)]} [1 - \frac{q_{th}}{q(0)}] \quad \text{(Eq. 10)}$$

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:

$$T_0 = T_m + \frac{4}{3\kappa c_p} \left(\frac{\eta q(0)^4 R^5}{2g(\rho_c - \rho_m)(L + c_p (T_m - T_r))\rho_m^4} \right)^{1/3} \quad \text{(Eq. 11)}$$

where κ is the thermal diffusivity of the rock, g is the acceleration of gravity, η 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 [19]:

$$\eta(T) = A_1 T \left[1 + A_2 \exp\left(B / RT\right)\right]\left[1 + C \exp\left(D / RT\right)\right] \quad \text{(Eq. 12)}$$

where R is the absolute gas constant and parameters A_1, A_2, B, C and D are directly related to the enthalpies and entropies of formation and motion of configurons [20]. 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.

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. Fig. 1 shows schematically a self-descending capsule [10].

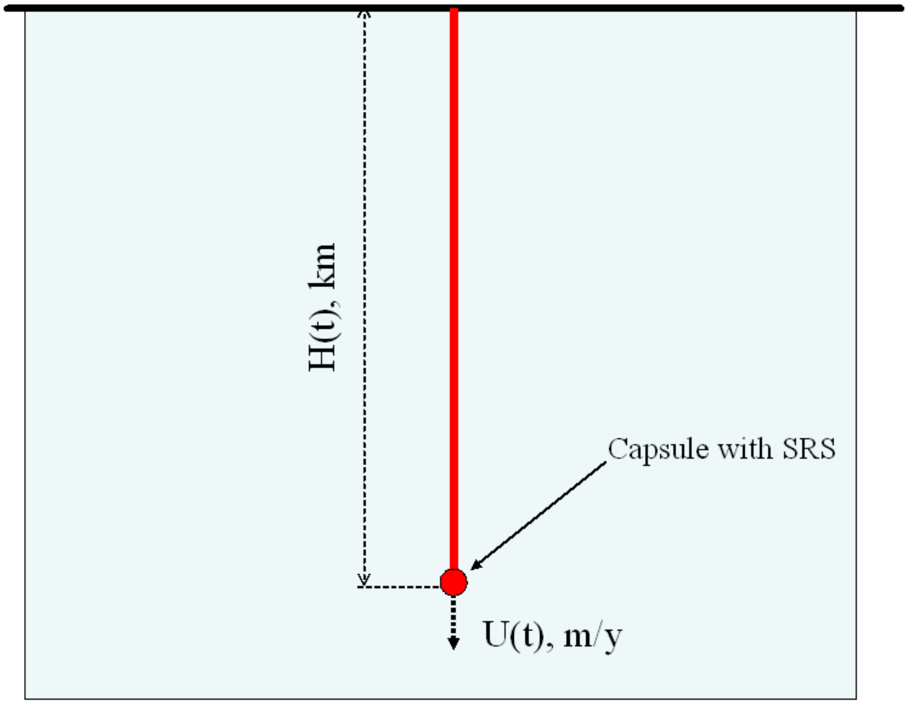

Fig. 1. A schematic of self-sinking heat-generating capsules.

Table III shows estimated self-burial parameters for 1 m diameter tungsten capsules containing ^{60}Co radionuclides with following characteristic parameters used: average rock density ρ_m=2.7 g/cm^3, heat capacity c_p=1 J/g K, heat of fusion L=418 J/g, heat conductivity χ=0.01 W/cm K, melting temperature T_m =1200°C, temperature far from capsule T_r = 20 °C. The average capsule density was taken ρ_c=12.7 g/cm^3.

Table III. Self-descending parameters of tungsten capsules.

Mass of radionuclide, kg (MCi)	Specific heat power, kW/m^3	Initial heat power, kW	Initial descending velocity, m/y	Time of continuous descending, y	Depth of disposal, km
4.8 (5.4)	162	85	790	18.5	6
48 (54)	1620	850	7900	36	60
96 (104)	3240	1700	15800	41.2	120

Fig. 2 shows the depth of penetration of a 1 m diameter W-capsule heated up by ^{60}Co radionuclides with total activity 104 MCi (e.g. of the initial mass of active part 96 kg) 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. However 50-km depths will be investigated during firsts 4 years of study. Note that more accurate data show penetration under ocean to 107 km depth [12].

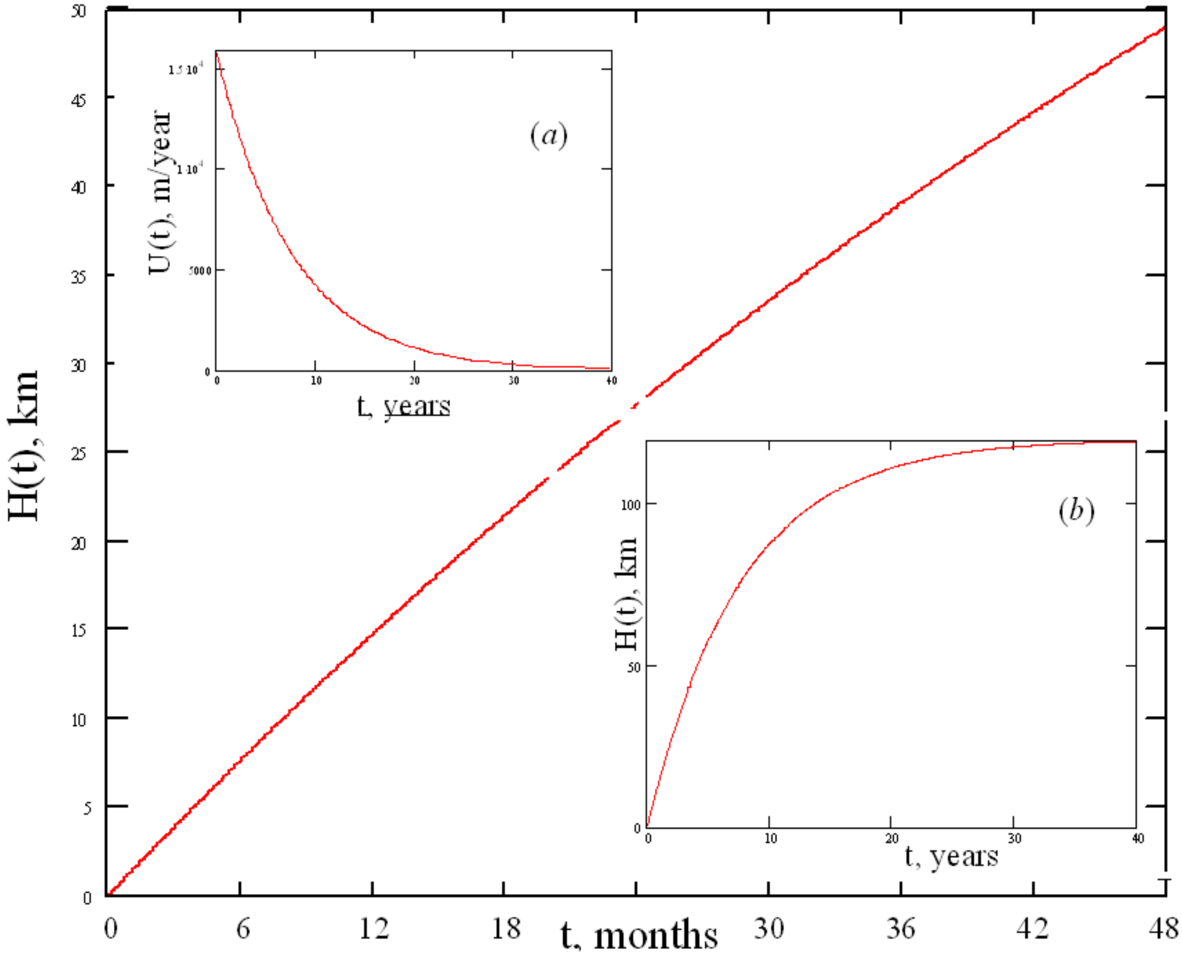

Fig. 2. Penetration depth (km) of a self-descending 1 m diameter tungsten capsule heated by ^{60}Co during first four years. Inserts show: (a) - the velocity of penetration into granite, (b) - the motion of probe until its stop at final disposal depth at 120 km.

Note also that initial descending velocities are remarkable high 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].

DISCUSSION

Self-descending of a spherical body in a melting environment was considered mostly in concern with potential disposal of radioactive wastes and nuclear reactor core melt-down problem (so-called "China syndrome") [1-8]. It has been shown that ceramic capsules demonstrate significant overheating patterns which limit their heat loading and thus descending velocities [16]. We thus analyse self-descending of a metallic capsule which has almost homogeneous temperature distribution on its surface. Tungsten was selected as a suitable material to manufacture the probe capsule due to its refractory properties (melting temperature 3410°C), high specific weight (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 (Fig. 3).

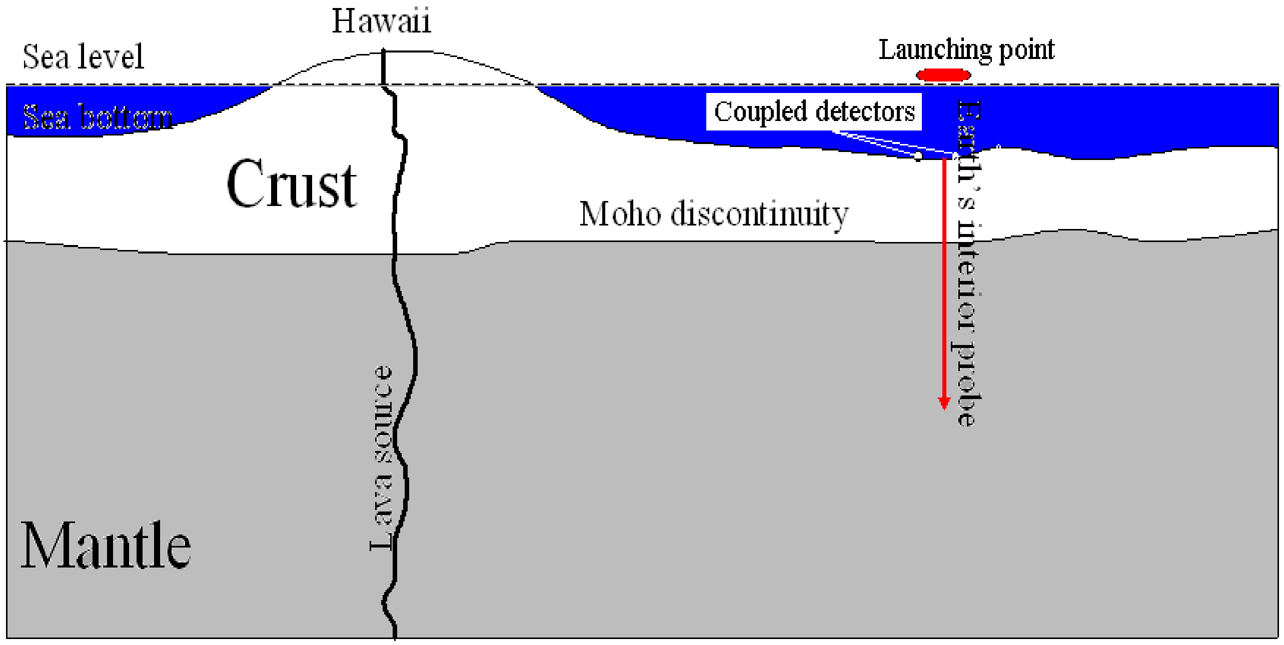

Fig. 3. Schematic of capsule launching.

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]. Fig. 4 shows an artistic impression of capsule launching [9]

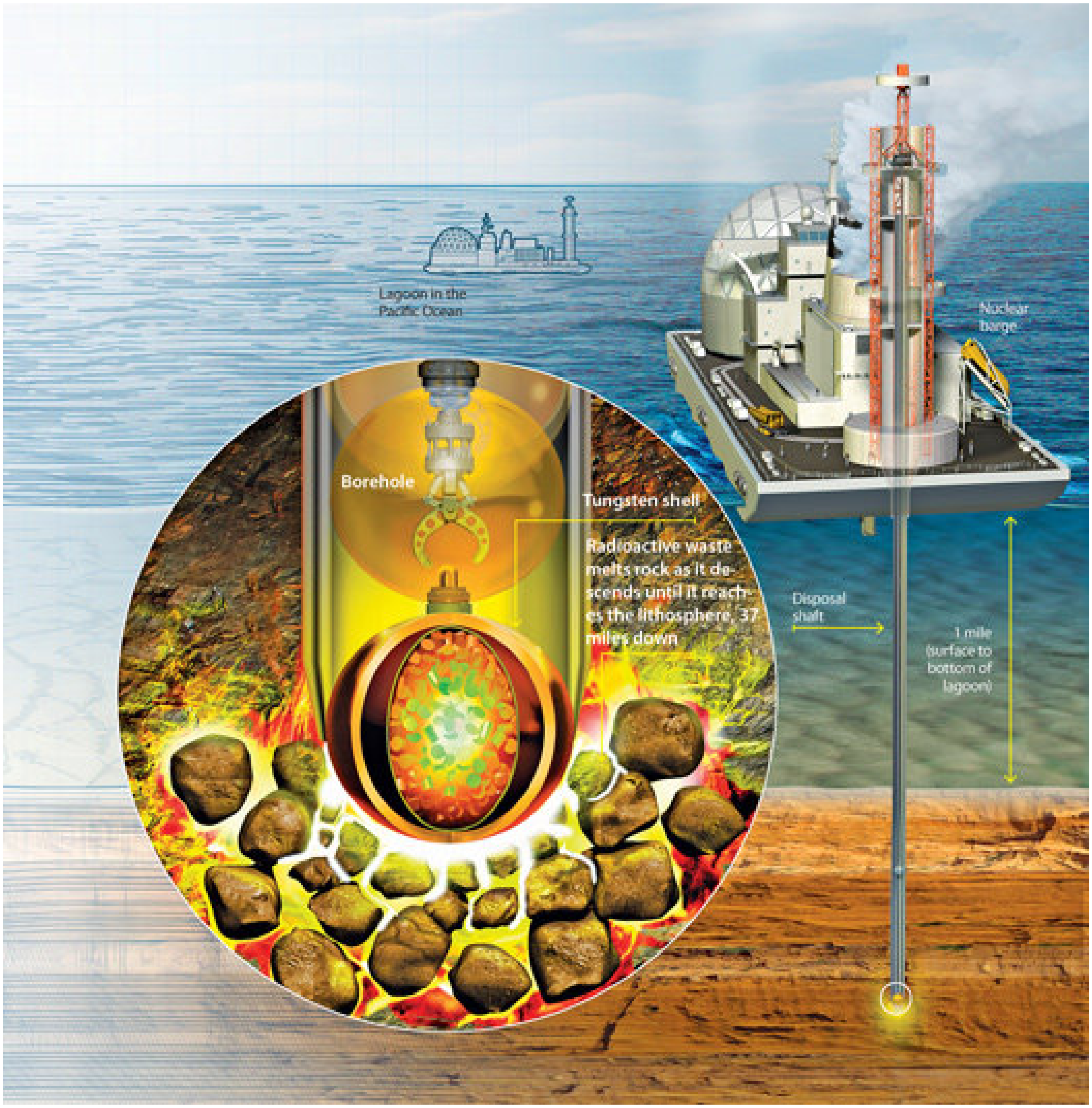

Fig. 4. An artistic view of capsule launching.

The capsule on its way melts the surrounding rock 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 [21]. 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 trough and hence on their geological structure and composition. As the capsule can be emplaced at a given depth it can provide information about underground motions, which would be particularly useful in seismically active regions.

CONCLUSION

The self-burial concept can be readily adapted to very deep and super-deep (below 5 km) disposal of the most hazardous waste. Deep 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 readily achievable for self-burial. These are greater than the levels that have been achieved by deep drilling techniques. The capsules could be tracked via detection of the acoustic signals generated by melting and crystallization 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. Moreover utilisation of spent SRS can help to resolve the problem of their safe disposal.

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