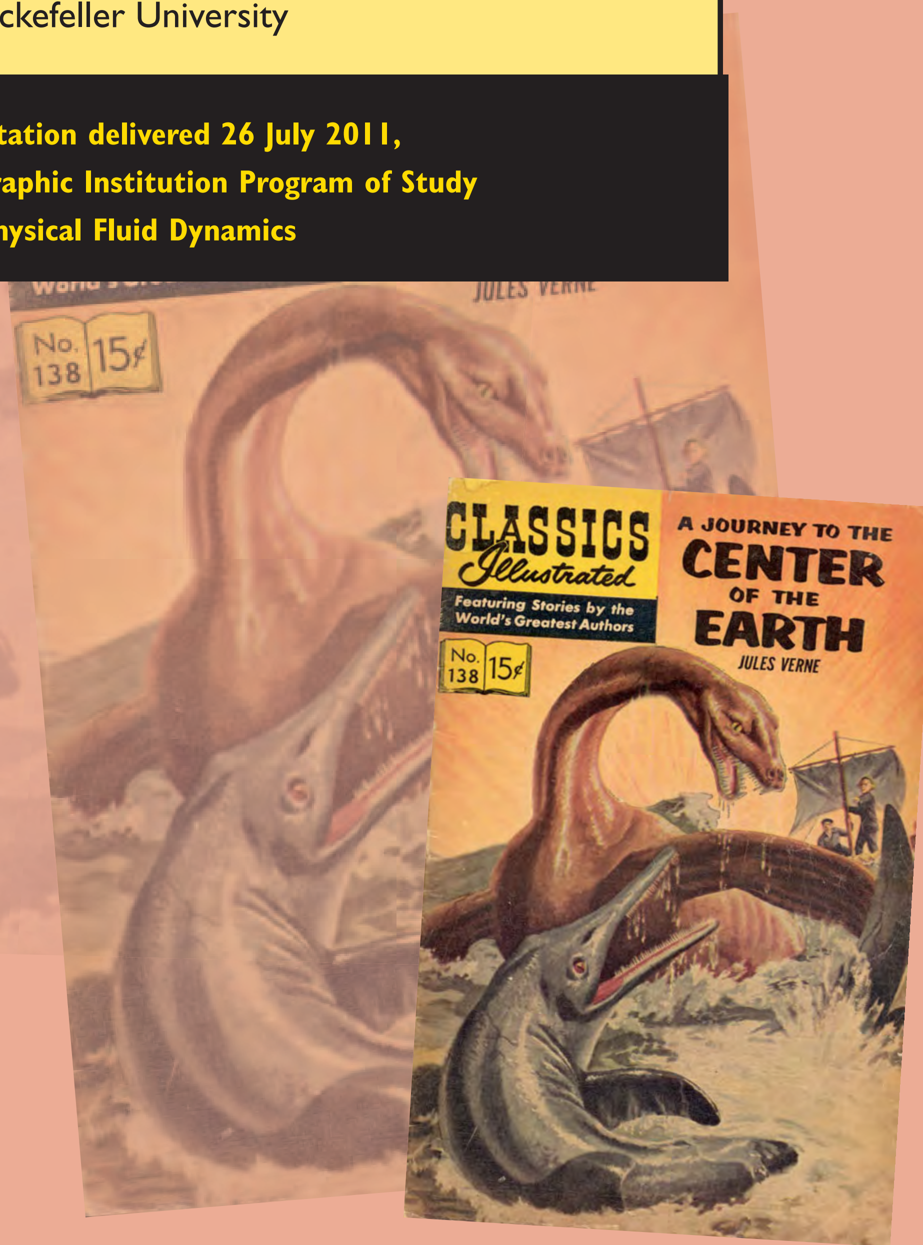
Self-Sinking Capsules to Investigate Earth's Interior and Dispose of Radioactive Waste

Jesse H. Ausubel

Program for the Human Environment,
The Rockefeller University

**Seminar presentation delivered 26 July 2011,
Woods Hole Oceanographic Institution Program of Study
in Geophysical Fluid Dynamics**



Abstract

The concept of self-burying capsules can be adapted to super-deep disposal of the most hazardous waste. Deep self-disposal involves loading of waste together with a powerful heat-generating radionuclide into a sealed metal (probably tungsten) capsule and placing it at the bottom of a shallow borehole. By radiogenic heat generation, the capsule will melt surrounding rock and descend. Extreme depths of many tens of kilometers 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 by detection of the acoustic signals generated by melting and re-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.

Jesse Ausubel is Director, Program for the Human Environment, The Rockefeller University, 1230 York Avenue, New York, N.Y. 10065. http://phe.rockefeller.edu/.

This talk draws on a PowerPoint presentation delivered 26 July 2011 at the Woods Hole Oceanographic Institution Program of Study in Geophysical Fluid Dynamics and written in collaboration with Catherine Fisher, summer intern with The Rockefeller University and engineering student at the University of Michigan (class of 2014), now an engineer at Apple Computer.

Thanks to Edward A. Spiegel (Columbia University), Norman Lebovitz (University of Chicago), and P. J. Morrison (University of Texas, Austin) for the opportunity to present this seminar.

The views expressed in this paper are those of the author.

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Suggested citation:

Ausubel, Jesse H. 2015. "Self-sinking capsules to investigate Earth's interior and dispose of radioactive waste." Seminar presentation 26 July 2011, Woods Hole Oceanographic Institution Program of Study in Geophysical Fluid Dynamics.

Technical experts, science fiction writers, and environmental advocates have all famously considered a self-descending spherical body in a melting environment not as a solution but as a problem. In connection with nuclear reactor core meltdown, this phenomenon is the so-called China Syndrome (**Figure 1**). Let's step back and consider the China Syndrome as a solution.

Like all fields, study of self-sinking capsules has a history. See the bibliography for some notable contributions, on which I rely. My mentor in many dimensions of science, Italian physicist Cesare Marchetti, introduced me to self-sinking capsules. In recent years a geophysicist of Russian origin now working at the University of Sheffield in the UK, Michael Ojovan,[1] has led the advance of the small field and tutored me. I am grateful to Mikhail for allowing me to share some of his work. I also wish to thank an undergraduate engineering major from the University of Michigan, Catherine Fisher, who has worked this summer with me as a research intern. The idea of self-sinking capsules was invented and first studied at the Euratom Center of the Institute for Environmental Protection and Research, near Milan, in the early 1960s by Marchetti and colleagues, and subsequently has been explored in the USA, UK, and especially Russia.

I have become engaged in the potential of self-sinking capsules as one of the proponents of a new cooperative international research program encouraged by the Alfred P.

1 Michael I. Ojovan, Department of Materials, Imperial College London, www3.imperial.ac.uk/people/m.ojovan.

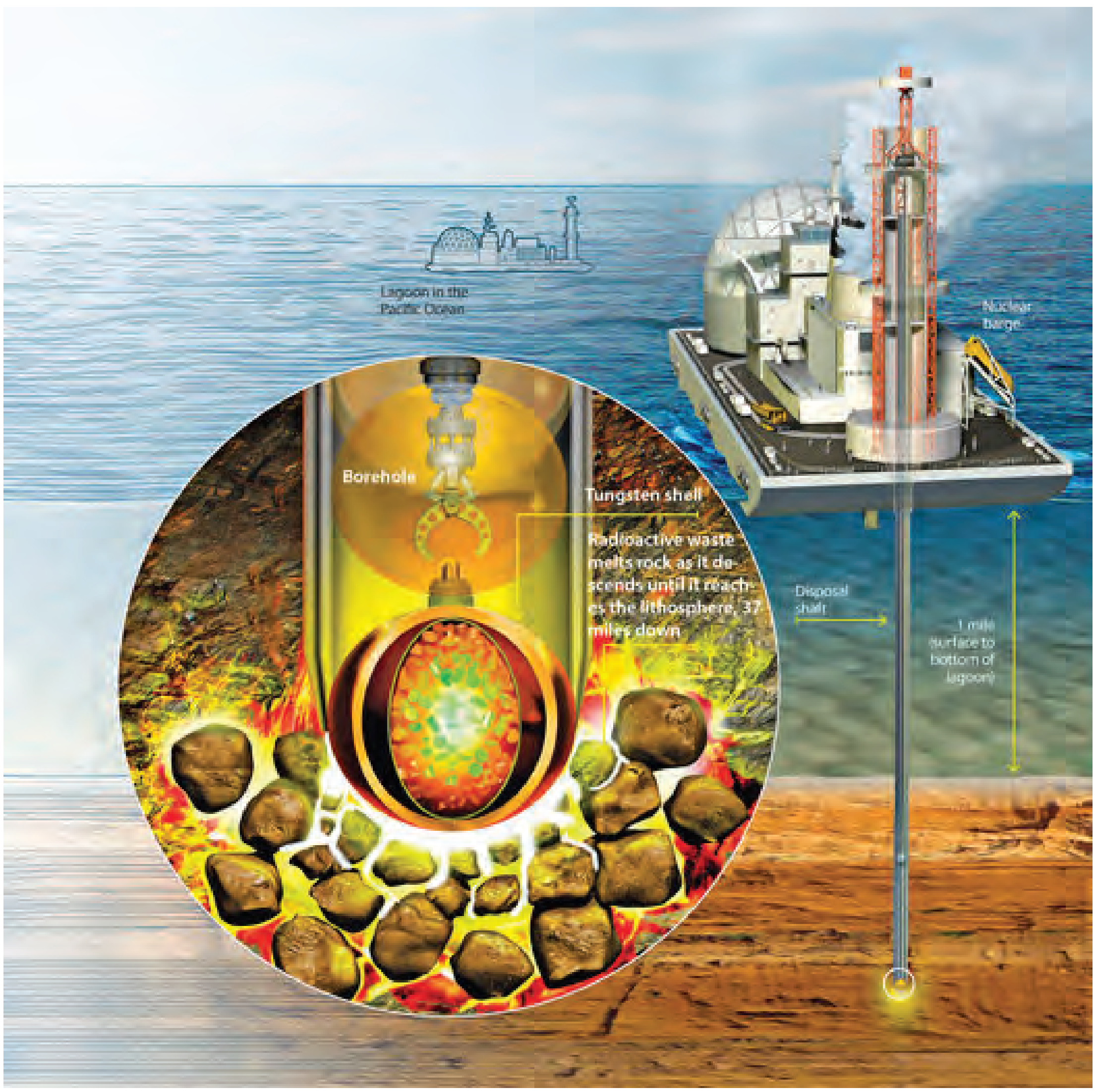


Figure 1. Self-sinking capsules for waste disposal. Self-descent of a spherical body by melting of rock through which it passes has been considered in context of nuclear reactor core melt down, so-called China Syndrome, but it could be a solution for deep burial of wastes.
Credit: *Popular Science*; Artist: Kevin Hand.

Sloan Foundation, the Deep Carbon Observatory (DCO),[2] which aims to transform our understanding of the carbon deep in Earth. The DCO encourages advancement of approaches to observe the deep crust and upper mantle, the reservoirs and fluxes of carbon in those regions, the origins and behavior of hydrocarbons and related fluids at high temperatures and pressures, and the extent of the deep biosphere.

Somewhat surprisingly, human knowledge of the composition and structure of Earth's interior through direct observation and sampling remains limited to the uppermost 12 km. Geologists have sampled the top 2 to 3 km of the crust extensively at outcrops and by excavations, mines, and boreholes. From 3 to 12 km, sampling is restricted to a handful of very deep boreholes on land and in the seafloor, some drilled by basic researchers and others by prospectors for oil, natural gas, and minerals. Scientists of the Soviet Union drilled the deepest hole, to more than 12 km, in the Kola Peninsula (**Figure 2**).

A complementary technology to boring holes is melting rock or engineering self-sinking and self-disposing capsules. The basic idea makes use of the heat generated by decaying radionuclides of radioactive waste, such as cobalt, inside a heavy and durable capsule to melt surrounding rock on its way down (**Figure 3**). As the heat from the capsule partially melts the enclosing rock, the lowered viscosity and density of the silicate melt allows the capsule to sink. Eventually the melt cools and vitrifies or recrystallizes, sealing the route along which the body passed. Descent or self-burial continues as long as radionuclides generate enough heat to melt surrounding rock. Calculations and simple experiments suggest that depths of several tens of kilometers or even a hundred kilometers could be reached by the capsules, a depth that other techniques could never achieve.

The self-descending, heat-generating capsules could bury dangerous radioactive wastes in layers of Earth whose depth prevents any release of radionuclides into the biosphere. Although humanity has still not mapped the limits of the biosphere, no one proposes that it spans the entire crust. The capsules would not be retrievable.

Because the capsules penetrate into Earth's deep layers, they also offer a chance to explore the Mohorovičić discontinuity, or Moho, and the mantle (**Figure 4**). The Moho bounds the crust and mantle and is defined as the discontinuity or layer at which descending seismic waves accelerate. A higher density material below the discontinuity presumably causes the acceleration. Density calculations suggest that a material with density similar to olivine-rich rock such as peridotite underlies basaltic ocean crust and granitic continental crust.

The depth of the Moho varies greatly between sea and land and within the land (**Figure 5**). On land, the Moho ranges between about 30 and 70 km deep, so the Kola hole probably did not even reach halfway to the mantle.

Below the ocean the Moho generally ranges between about 10 and 30 km deep, and even somewhat thinner

2 See https://deepcarbon.net/home.

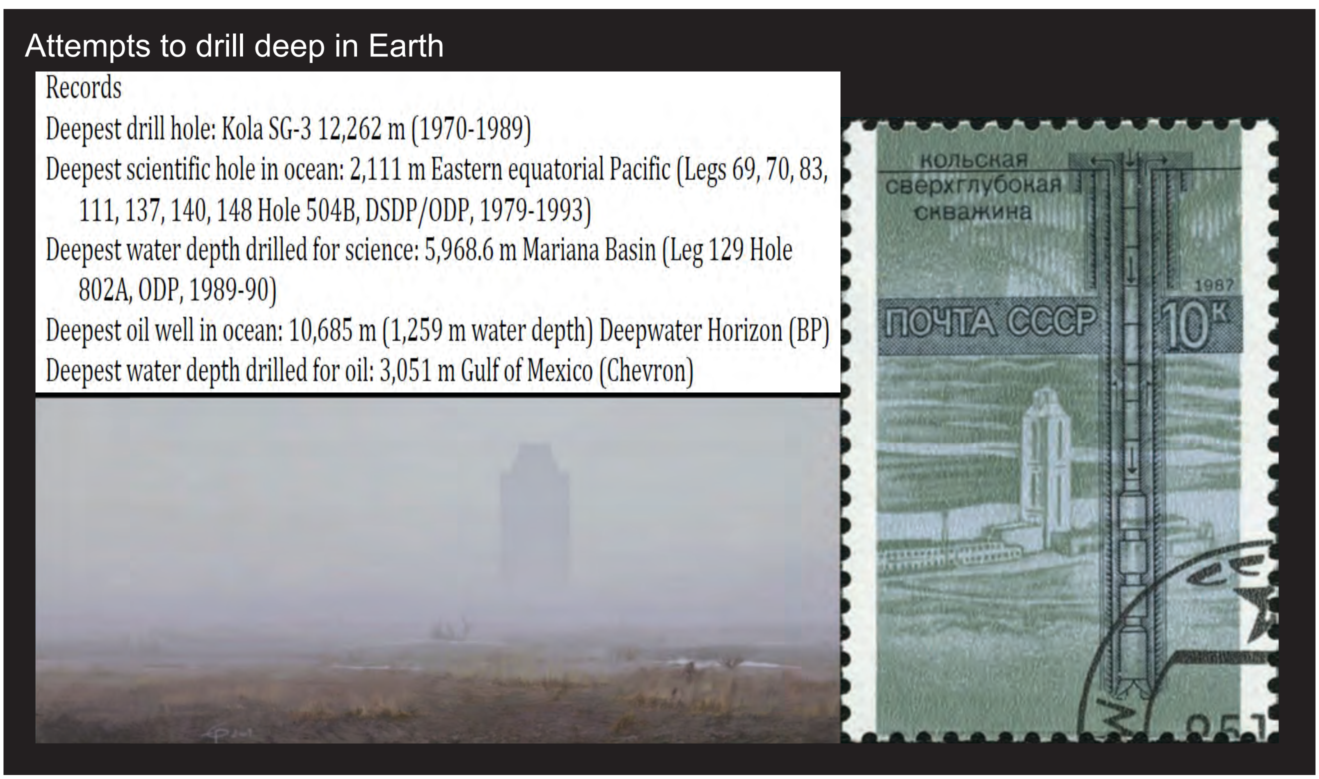


Figure 2. Kola Peninsula station and stamp.

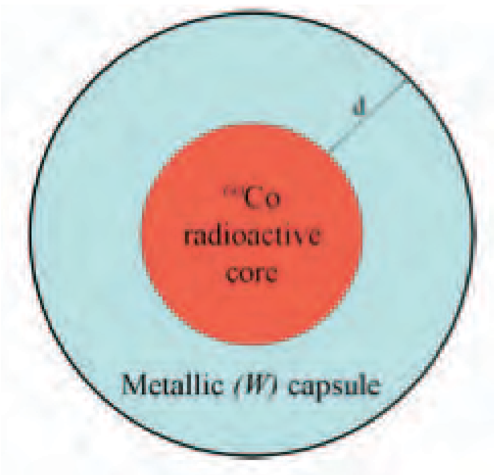


Figure 3. Self-sinking capsule, cobalt in tungsten example.
Source: Ojovan et al., 2010.

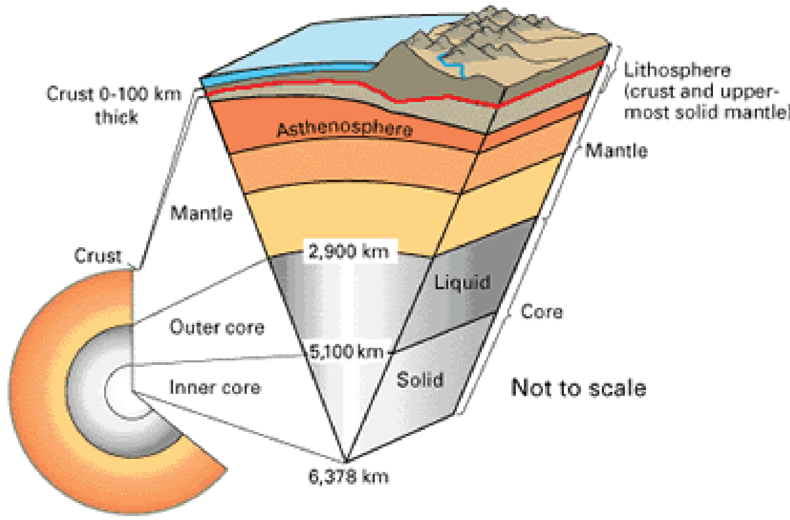


Figure 4. The mantle: A goal for exploration, and for safe disposal. Mohorovičić discontinuity in red.
Source: "Mohorovičić Discontinuity - The Moho," http://geology.com, 27 June 2011.

regions exist where new, young seafloor forms (**Figure 6**). Because of the thinner crust, efforts to reach the Mohole to retrieve a sample of pristine mantle concentrate on ocean drilling, and teams of geologists and engineers are carefully scrutinizing three potential sites in the Pacific [**Figure 7,** see also **Table 1**]. Factors such as water depth, rock temperature, and possible volcanism as well as crustal thickness affect site preference.

In fact, a great dream of geologists is to retrieve a sample of pristine mantle, and it could happen within a decade or so. The first hole could cost a lot, $500 million or more. Inevitably there must be a first hole, but of course comparisons will greatly enhance the value of what we might learn from the first hole and the cores extracted from it. So, if a complementary and less costly technology allows us to explore more than just one hole even if without

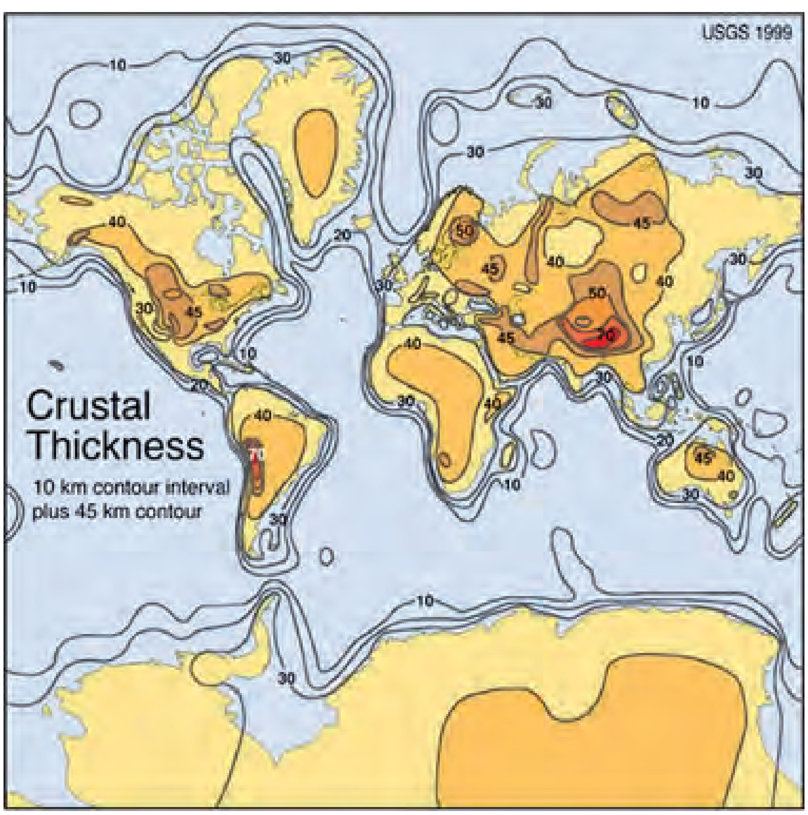


Figure 5. Depth to Moho on land and seafloor.
Source: "Mohorovičić Discontinuity - The Moho," http://geology.com., 27 June 2011.

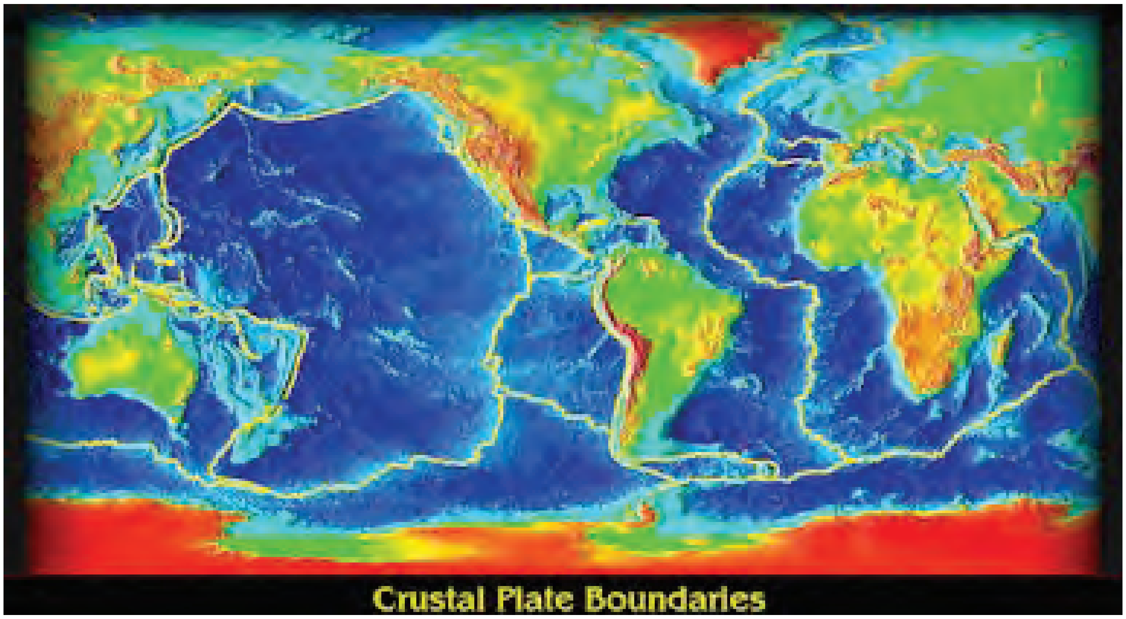


Figure 6. Crustal plate boundaries: Near mid-ocean ridges forming new crust, crust is thicker and hotter.
Source: National Geophysical Data Center (NGDC); also http://solarviews.com/cap/earth/plates.htm.

recovering a sample, great benefits could accrue to the overall program. Self-sinking capsules, if moderate in cost or funded for reasons in addition to basic research, could thus nicely enhance a Mohole program.

If societies are ever to permit deployment of the self-sinking capsules, they will require maximally secure calculations and preliminary experiments. One might state the essence of the geophysical fluid dynamics problem as melting around a migrating heat source. Let me walk you through the concept and some initial calculations.

Self-sinking capsule concept

A hot capsule can melt rock if the temperature of the surface of the capsule exceeds the melting temperature of the rock, and the average density of the capsule exceeds the specific mass of the rock. Assume that a spherical capsule is heated as a result of radioactive decay of a nuclide to a

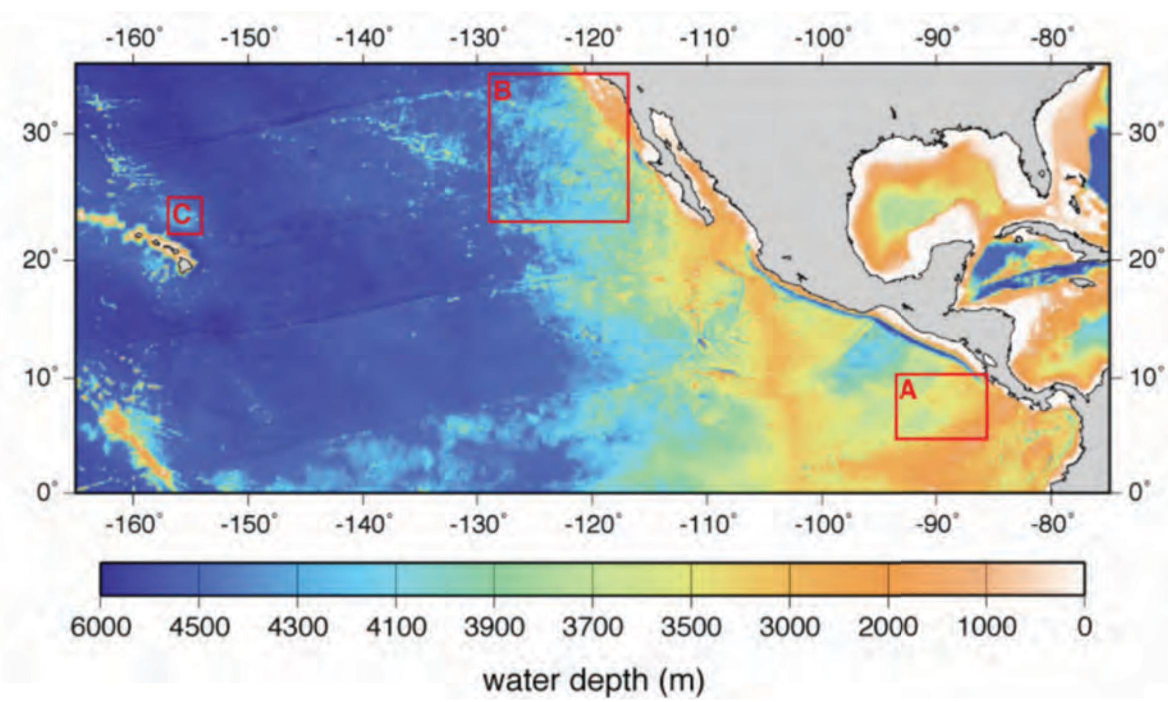


Figure 7. Mohole candidate sites: (A) Cocos Plate, (B) off southern/Baja California, (C) Hawaii.
Source: Teagle and Ildefonse. 2011.

Table 1. Regions of interest for preliminary site survey, with principal advantages and disadvantages.

Region	Advantages	Disadvantages
Off southern/Baja California	Large range of water depth Modest Moho T Higher latitude	Few data available Off-ridge volcanism
Cocos Plate	Shallowest water depth Well-known tectonics Sits within a corridor that includes a complete tectonic plate life cycle	Highest Moho T Faster than present-day fastest spreading rate Near equator
Hawaii	Lowest T Nearby a large port	Deepest water Near large hot spot Close to arch volcanism Near equator Lowest end of fast spreading rates

Source: http://www.sci-dril.net/10/56/2010/sd-10-56-2010.pdf.

temperature higher than the melting temperature of the relevant rock. Because of the intensity of the 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 that ensures good absorption of radiation, practically all the energy released by decay will be used for heating.

The total power of heat release then depends on the mass of the heat generating radionuclides and the specific heat of the nuclide. **Table 2** shows numerical values for three radionuclides appear promising for heating a self-sinking capsule, and they are the main components of the radioactive wastes. Note that the decay products of the radionuclides are nongaseous and thus avoid possible complications due to excess pressure.

Table 2. 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

The heat release caused by radionuclide decay within a capsule of a given radius can be estimated, and also the condition for self-sinking of the capsule as a result of melting through the surrounding rock by a ratio of thermal conductivity, melting temperature, and rock temperature. Capsules with a power of heat release less than the threshold do not melt the surrounding rock and, consequently, remain stationary.

Motion of the capsule in *fissured* rock is possible if the surface temperature of the capsule exceeds the melting temperature by some threshold value. This effect can be taken into account by an appropriate correction to the melting temperature. As an example, for granite rocks containing ~0.6% water and melting temperature T_m= 950°C, the threshold thermal power is q_{th} = 16.2 kW/m^3.

In a simpler setting, the total threshold power of a self-sinking capsule 1 meter in diameter might be ~8.5 kW. The minimum amounts of two possible radionuclides, ^{60}Co and ^{137}Cs, necessary for self-sinking of that spherical capsule into a granitic formation are only 0.5 kg and 14 kg, respectively. Hence, the total volume of a capsule enables loading of a large amount of waste in addition to the radionuclides that provide the heat required for rock melting. A sphere of ^{60}Co metal with an activity of 3.85 x 1018 Bq would yield ~1635 kW of heating power, a hundred times the threshold. Its diameter need be only about 0.3 m, the size of a basketball.

The temperatures required for surely effective rock melting would easily exceed 1000°C and increase with pressure, so ideally the capsule needs to withstand temperatures in excess of 2000°C. Ceramic materials, although suitably refractory, tend to conduct heat poorly and would overheat, thus limiting thermal loading of capsules and hence descent rates and depth.

The capsule should therefore be made of metal, and tungsten appears suited for this purpose (see **Table 3**). Tungsten melts at 3410°C, has a specific gravity of 19.3, and costs relatively little. It is expected to have a low corrosion rate in silicate liquids at high temperatures and pressures and low oxygen fugacities, the conditions that would prevail during descent through the crust and mantle.

Table 3. Properties of tungsten.

Atomic weight	183.86
Density @ 20°C (gm/cc)	19.3
Density @ 20°C (lb/cu. in.)	0.697
Melting point °C	3410
Boiling point °C	5530
Thermal conductivity @ 20°C (cal/cm/°C/sec)	0.40
Specific heat @ 20°C (cal/gram/°C)	0.032
Tensile strength @ Room temp (psi)	100,000 - 500,000
Tensile strength @ 500°C (psi)	75,000 - 200,000
Tensile strength @ 1000°C (psi)	50,000 - 75,000

The capsule wall needs strength and thickness 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 beta and gamma radiation is about 0.1 m, or 10 cm.

Melting of rocks

In reality rocks do not melt at a single temperature T_m as assumed earlier, 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. The viscosity of magmatic melts tends to decrease dramatically when the percentage of crystals falls below that at which rigid crystal networks form. This has been shown experimentally to range between 30% and 40% crystals. The descent rates and depths need to be calculated accounting for the changes of viscosity.

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. Therefore, the use of data for anhydrous melting likely leads to conservative underestimates of both sinking rates and depths of penetration. One can also elaborate the models to account for the fact rocks mix different mineral phases that do not melt uniformly over the solidus–liquidus interval. Because of the nature of the simplifying assumptions, values calculated so far for descent rates, terminal depths, and total sinking times are probably minimum values.

For both practical and scientific reasons, one wants to consider descent through both oceanic and continental lithosphere. The case of penetration through the oceanic lithosphere is simpler, because the lithosphere beneath the ocean basins is relatively straightforward, consisting of a basaltic crust underlain by peridotitic mantle. While conditions vary locally with different varieties of peridotite, their thermal properties are similar.

The simple model of the oceanic lithosphere is given in **Table 4**, whose parameters include depth, rock type, pressure, temperature, density, thermal conductivity, heat capacity, heat of fusion, thermal diffusivity, solidus, and liquidus.

Self-descent through rocks

The gradual sinking of a capsule to increasingly deeper layers by melting rock can be calculated by numerical methods. The *time of motion* of a capsule in rock can be determined quite accurately. The activity of thermal sources decreases with time exponentially depending on the initial activity of the sources, the decay constant, and the half-life of the radionuclide.

The *velocity* at which the capsule sinks can be estimated analytically for a capsule with isothermal sources with certain assumptions, for example, in a typical case of not very rapid sinking. Factors include the density of the melt, the latent heat of melting, and the specific heat capacity of the rock.

The depth to which the capsule sinks can be estimated as well. In fact, capsule parameters could be chosen beforehand so that the capsule stops at a specified or required depth. However, it is necessary that the capsule not be destroyed by excess heat generated by decaying radionuclides, i.e., the temperature of the capsule should not exceed its melting temperature.

Table 4. Properties to model oceanic descent. Source: Ojovan et al., 2010.

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[b]	782[c]	307730[b]	7.013 10^{-7}	1079	1358
7	Basalt	1.930	128	2900	1.590[b]	895[c]	307730[b]	6.126 10^{-7}	1114	1370
7	Peridotite	1.930	128	3234[a]	3.389[b]	895[c]	383734[b]	1.171 10^{-6}	1134	1721
30	Peridotite	8.250	464	3234[a]	3.138[b]	982[c]	420669[b]	9.881 10^{-8}	1200	1772
100	Peridotite	27.500	1256	3234[a]	2.720[b]	~1067[c]	509324[b]		1453	1901
145	Peridotite	40.000	1544	3234[a]	3.222[b]	???	566893[b]		1628	1958

The temperature of the capsule is maximal initially and can be derived for a metallic capsule from the thermal diffusivity of the rock, acceleration of gravity, dynamic viscosity of melted rock, and average density of the capsule, which accounts for both capsule and content materials, e.g., heat-generating material and waste to be disposed of.

The viscosity of melts decreases rapidly as a function of temperature. Higher fluidity of rock melts at higher temperatures limits overheating. The higher the capsule density, the less it overheats.

Moreover, the overheating increases rapidly with increasing capsule size. Estimates show that for metal capsules of about 1 m diameter the overheating is limited by hundreds of degrees, but these are the kinds of calculations that need to be checked and finally tested.

One can estimate self-burial parameters for 1 m diameter tungsten capsules containing ^{60}Co radionuclides with characteristic parameters. Parameters include activity, mass of the radionuclide, initial descending velocity, time of continuous descent, and finally depth of disposal. In ocean crust, 4.8 kg of ^{60}Co might descend for 18 years and reach 6 km, 48 kg for 36 years to 60 km, and 96 kg for 41 years to 120 km.

Table 5 shows the depth of penetration in ocean crust of a 1 m diameter tungsten capsule heated by ^{60}Co radionuclides with initial mass of 96 kg as a function of time. This capsule — or probing device — is calculated to move 41.2 years, achieving a depth of 120 km at its final point of penetration. Depths of 50 km would be investigated during the first 4 years of descent. **Figure 8a** shows the depth of penetration into granite, and **Figure 8b** shows the motion of the probe until its stop at final disposal depth at 120 km.

Note also the high initial descending velocities compared with conventional rotary drilling of scientific boreholes. The initial descent through the basaltic layer of just under 2 m/hour matches the rate of conventional rotary drilling of scientific boreholes, except no pauses occur for holidays, cleaning of equipment, or to minimize risks from severe storms or high waves. The ocean capsule would reach the Mohorovičić discontinuity in less than a half of year! The soonest borehole drilling is likely to reach the Moho is about 2020, so SSCs could arrive around the same time, with speedy development during the coming decade.

One can also model continental descent, which is of special interest to geologists (**Table 6** and **inset figure**). The capsule or probe would reach the mantle in just over a year and a half. The Kola drilling lasted nearly two decades to reach halfway.

Table 5. Self-burial parameters for spent Savannah River Site (SRS) capsules. Source: Ojovan et al., 2010.

Capsule radius R, m	Radionuclide	Initial activity, PBq (MCi)	Number of 2PBq SRS	Approximate volume occupied by SRS in capsule, L	Initial specific heat power q(0), kW/m^3	Total heat power Q, kW	Initial descent velocity U(0), m/y	Time of continuous descent τ, years	Maximum depth of penetration H(τ), km
0.50	^{60}Co	200 (5,4)	~100	~1-2	162	85	790	18.5	6
0.50	^{60}Co	2000 (54)	~1000	~10-20	1620	850	7900	36	60

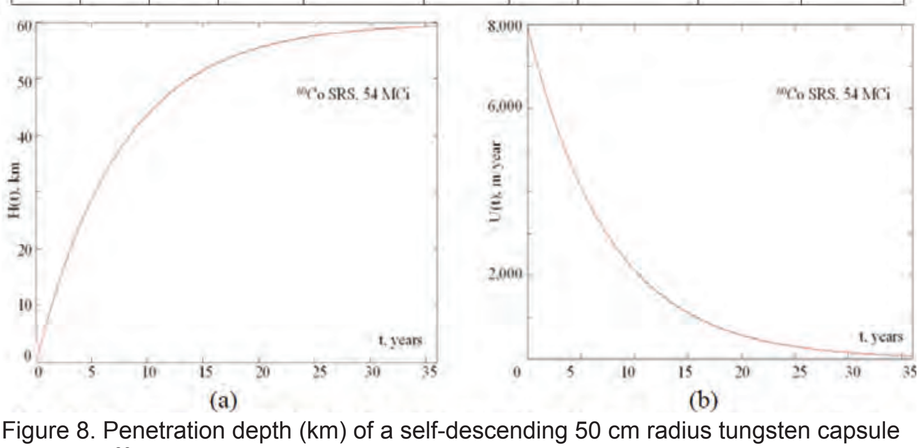


Figure 8. Penetration depth (km) of a self-descending 50 cm radius tungsten capsule heated by ^{60}Co SRS (a) and the rate of self-burial (b).
Source: Ojovan et al., 2010.

SSCs as sensors

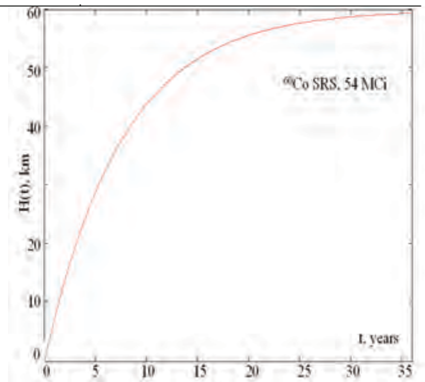
In 2003 David J. Stevenson proposed a "mission to Earth's core" in which a small probe embedded in a huge mass of molten iron would descend along a crack propagating under the influence of gravity. The Stevenson concept may overreach, but Ojovan et al. have investigated the possibility of exploring the deeper reaches of Earth's crust and upper mantle with a small, self-descending probe that melts the rocks and creates acoustic signals that could be detected at the surface, thus yielding information about the nature of the rocks through which the probe and the signals pass.

Melting and crystallization of rock generate intense acoustic signals in a wide spectrum of frequencies due to thermo-mechanical interactions that have been monitored experimentally. Melting of solid granite associates with characteristic acoustic signals of durations from a few microseconds to 30 milliseconds

Table 6. Descent of probe through continental lithosphere.

Depth range (km)	Rock type	Threshold power q_{th} (W/m^3)	Initial velocity U_0 (m/y)	Descent time (y)
0 – 10	Granite	39350	22787	0.45
10 – 17	Schist	37920	20919	0.79
17 – 22	Metapelite	27567	19477	1.06
22 - 27	Amphibolite	24048	17737	1.34
27 - 30	Mafic granulite	26749	14772	1.55
30 -100	Peridotite	46290	9472	28.6
100 – 101.5	Peridotite	34279	312	34.6

Modeling indicates initial sinking through granitic upper crust is over 30% faster than through oceanic basaltic layer. **Probe would reach the mantle in just over a year and a half.** It would attain a depth of 101.5 km before stopping after 34.6 years.
Source: Ojovan, 2010.



and amplitudes from 40 to 78 dB (**Figure 9**). On cooling, the processes of recrystallization and solidification produce high primary frequency signals (between 501 and 800 kHz) with relatively low amplitudes between 40 and 55 dB and short durations (mainly <100 microseconds µs). Registration of signals from the capsule by several coupled detectors on Earth's surface would provide permanent information on capsule motion as well as about Earth's layers above the capsule that signals travel through and hence on their geological structure and composition. With an appropriate library against which to compare the burial sounds, a profile of the crust and mantle near the path of descent would emerge.

One could add a signal source into the capsule, too. For example, an addition of a mixture of radium (^{226}Ra) and beryllium to the active part of the capsule could provide an intense source of neutron radiation through nuclear reaction, which enables continuous irradiation of rocks during descent (**Figure 10**). As a capsule could be placed at a given depth, it could provide information about underground motions, which might be particularly useful in seismically active regions.

An issue for the remote detection of the acoustic emission signals is the attenuation over the large distance that they have to be transmitted. The amplitudes of the signals recorded from granite samples in experiments did not exceed 80 dB at a distance of less than 40 cm from the source. Appropriate experimental assessment of the options for transmission of the generated acoustic emission signals,

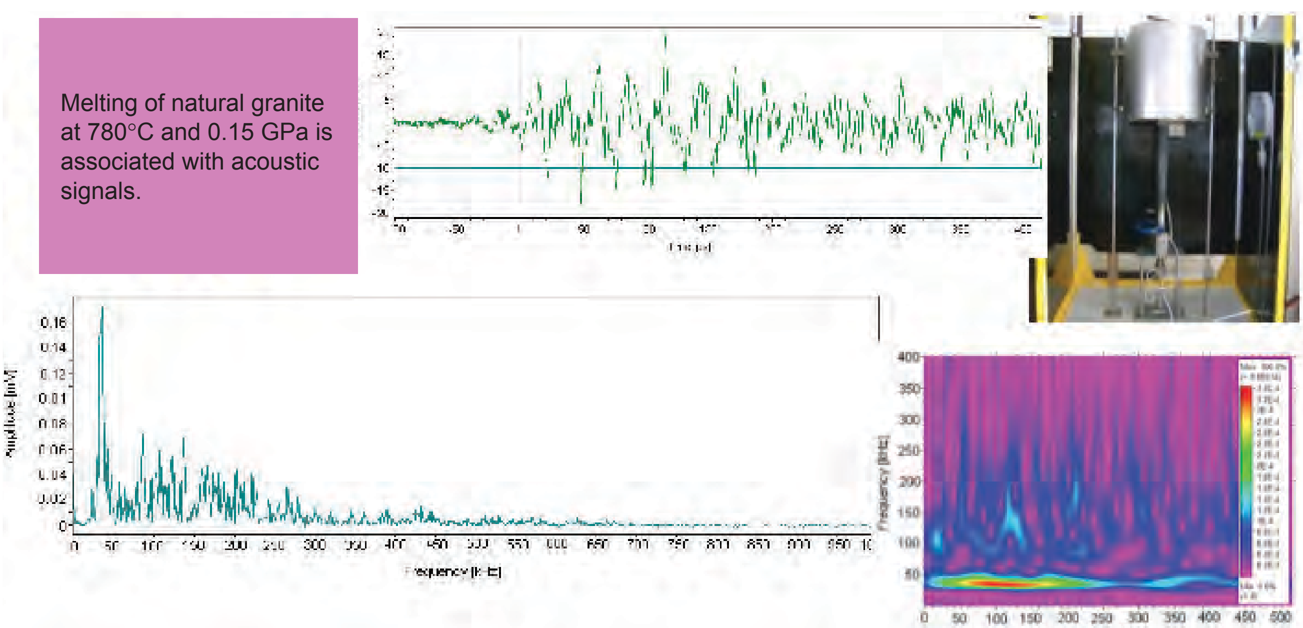


Figure 9. Acoustic emission signals. Signals associated with granite melting-crystallization were distinguished from equipment noise on basis of their primary frequencies of 39 kHz and in range between 101 and 300 kHz, particularly at 249, 244, 283, 205, and 112 kHz.
Source: Ojovan et al., 2010.

has to be conducted. On a positive note, solar probes and other technologies have made it possible to measure at very high temperatures (**Figure 11**).

Volumes

When SSCs are used for waste disposal, would the volumes of the capsules suffice? Used nuclear fuel gives rise to high-level waste, which may be either the used fuel itself in fuel rods or balls, or the separated waste resulting from reprocessing the fuel. If the used fuel is reprocessed, as from UK, French, Japanese, and German reactors, high-level waste comprises highly radioactive fission products and some transuranic elements with long-lived radioactivity. These are separated from the used fuel, enabling the uranium and plutonium to be recycled.

The problematic spent radionuclide sources such as heat-generating radionuclides and very long-lived radionuclides (americium, neptunium, curium, plutonium) form small volumes. A typical 1000 MWe light water reactor discharges about 20 m^3 (27 tons) of used fuel per year. Where that used fuel is reprocessed, only 3 m^3 of vitrified waste (glass) is produced. Nuclear power generation facilities worldwide produce about 10,000 m^3 of high-level waste including used fuel designated as waste. Normally, such high-level waste is vitrified into borosilicate (Pyrex) glass, encapsulated in heavy stainless steel cylinders about 1.3 meters high, and stored for eventual disposal underground. With the self-sinking capsules, vitrification becomes unnecessary and further sharply shrinks volumes. The content of the sinking sphere will be molten metals.

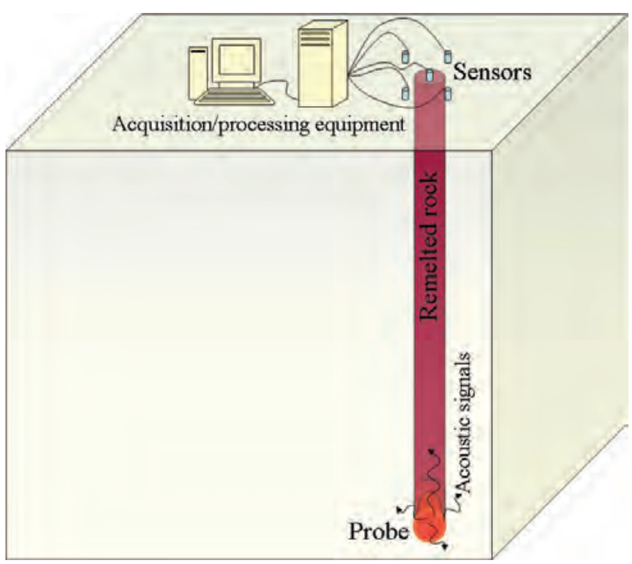


Figure 10. Acoustic tracking of self-sinking capsules. A few suitably positioned detectors continually monitoring signals reaching Earth's surface from probe would provide data on position and motion of probe as well as properties of rocks through which it was sinking and through which acoustic signals passed.
Source: Ojovan et al., 2010.

One could easily load the capsules with the tennis-ball sized fuel elements called pebbles that nuclear reactor designers favor for high-temperature reactors (**Figure 12**). Larger capsules are more difficult to engineer, while reactor processing and reprocessing easily produce small balls. Finally, a large reactor might drop just a handful of capsules per year for its waste disposal.

Further observations

To achieve maximum penetrating depths, the capsules could be launched from a ship at sea, where the thickness of crust to be penetrated by capsule is minimal (**Figure 13**). It remains to be understood whether depth of final burial, speed of descent, ease of initial insertion, or other attributes would most strongly determine system design.

Standard transport techniques could be used because loading and weld-sealing of the capsule with radioactive

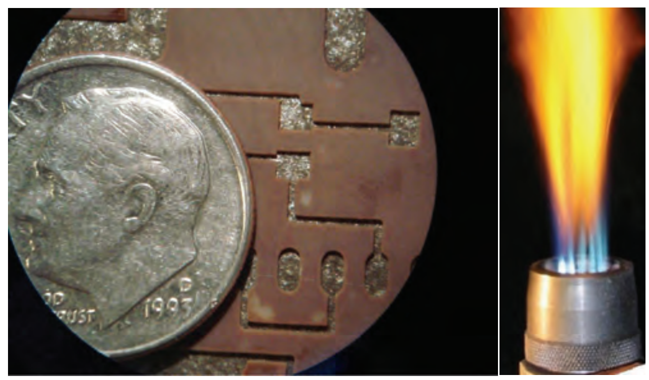


Figure 11. New circuit boards employing aerospace technology provide the ability to measure at extreme temperatures.

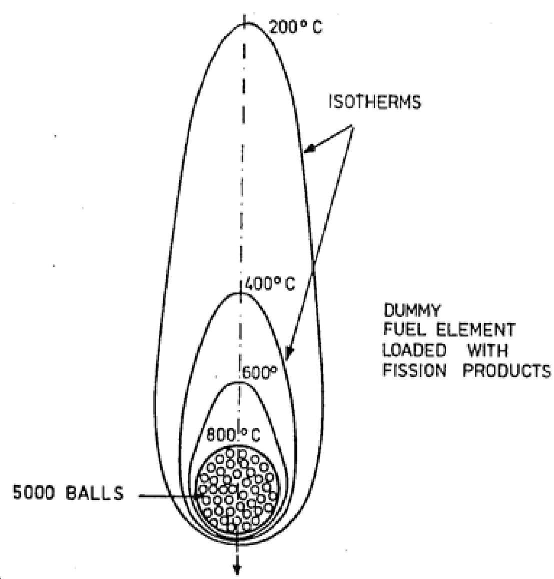


Figure 12. Self-sinking capsule loaded with pebbles or fuel balls after reprocessing.
Source: Marchetti, 1998.

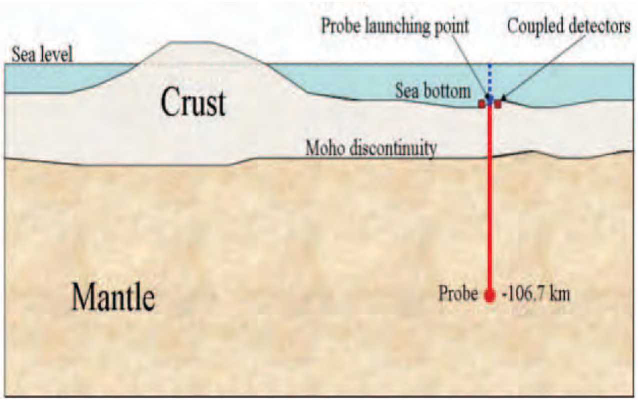


Figure 13. At-sea launching of self-sinking capsules.
Source: Ojovan, 2010.

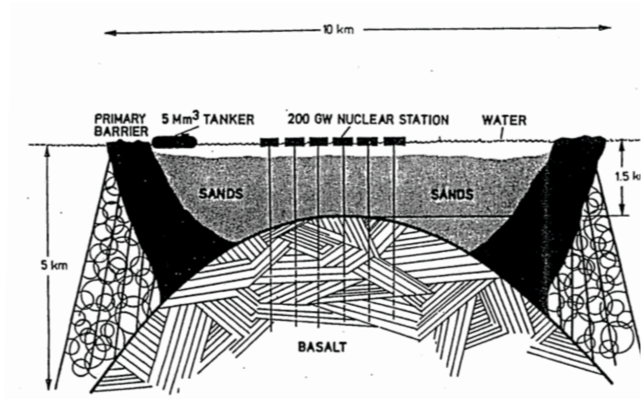


Figure 14. Energy Island: >1 TW power park with on-site disposal of waste in SSCs.
Source: Marchetti, 1977; 1998.

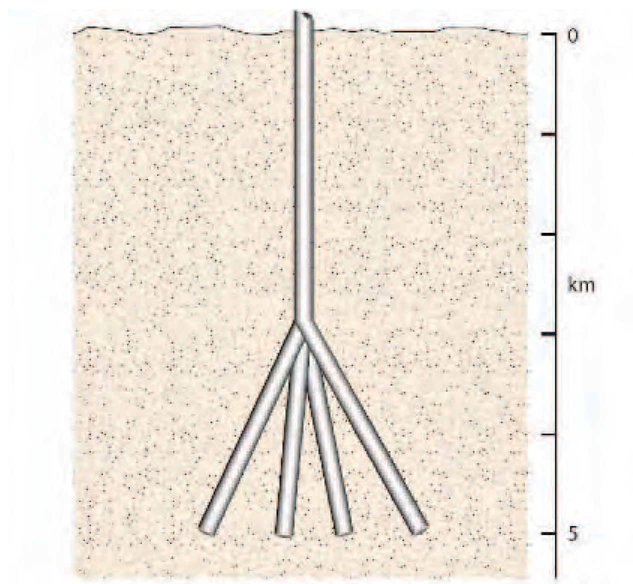


Figure 15. Fanned array to increase lifetime of borehole.
Source: Von Hippel and Hayes, 2010.

sources can be done directly before launching. In fact, the capsule could be prepared and even disposed of at the reactor site.

Marchetti has envisioned more complete, large systems, for example where a nuclear megapark of 1 terawatt operates on a Pacific atoll with on-site disposal of waste in self-sinking capsules directly below barges (**Figure 14**).

While Marchetti's vision may apply late in the 21st century, intermediate steps could increase the acceptability of SSCs for waste disposal, such as fanned arrays that could increase the lifetime and lower the cost of an initial infrastructure (**Figure 15**). Alternatively, capsules might congregate and mutually speed their descent, a behavior favoring a strategy of concentration. To increase safety, one might begin the descent in a "funnel" of perhaps 8000 meters on land or less in the seafloor filled with molten salt, so that capsules might for a while be retrievable.

To answer a recurrent worry, starting a volcano requires perhaps ten orders of magnitude more energy than a capsule would contain.

Summary

A system employing self-sinking capsules could have numerous advantages. Use of spent fuels can help to resolve the problem of their safe disposal. This strategy would not require long-term dedicated disposal facilities about which we would need to warn life for 250,000 or more years. In addition, it would increase safety of disposal, aid nonproliferation, enable launch from the bottom of the sea or from shallow or relatively deep boreholes, and accommodate mixtures of radionuclide and other contaminant species.

The capsules would also have a volume of only about 1 m^3 and a footprint of about 1 m^2. The capsules are constructed using about 0.5 m^3 of common materials. The active part of the capsule uses readily accessible radionuclides such as ^{60}Co, which is manufactured by neutron irradiation of metallic cobalt and is widely used industry, medicine, and research. Of course, spent sealed radioactive sources can be used rather than new sources.

Still, more thorough calculations and especially some experiments are needed. The Ispra lab of Euratom in the 1960s performed preliminary, encouraging experiments to check the equations by sinking electrically heated capsules in rock and salt masses. A new generation of more realistic experiments is needed to test the models of Ojovan and others.

To conclude, normally, high-level radioactive wastes generate considerable troublesome heat and require cooling. The self-sinking capsule concept could turn the China Syndrome on its head, into a solution. Let's calculate and experiment. Fluid dynamicists hold the key with their expertise about melting around a migrating heat source.

Bibliography

Notable contributions to the field

Cohen J.J., L.L. Schwartz, and H.A. Tewes. Economic and environmental evaluation of nuclear waste disposal by underground in situ melting. *Trans. Amer. Nuclear Soc.*18:194-195, 1974.

Donea, J., S. Giuliani, and L. Kestemont. Processus d'auto-enfouissement de recipients contenant des effluents radioactifs de haute activité, EUR 4903 f, Commission of the European Community, EURATOM Joint Research Center, Ispra, Italy, 1972.

Donea, J. Operation "Hot Mole." *Euro-Spectra* 11:102-109, 1972.

Kaccheev, V.A, A.S. Nikiforov, P.P. Poluektov, and A.S. Polyakov. On the theory of self-burial of high level waste. *Atomic Energy* 73: 215-221, 1992.

Logan, S.E. Deeper geologic disposal: A new look at self-burial. Proc. WM'99 Conference, 0-51pdf, 1999.

Stevenson, D.J. Mission to Earth's core -A modest proposal. *Nature* 423:239-240, 15 May 2003. doi:10.1038/423239a.

Ojovan, M.I., P.P. Poluektov, and V.A. Kashcheev. Super-Deep HLW Self-Disposal Option, WM'2011 Conference, 2011.

Ozhovan, M.I., F. Gibb, P.P. Poluéktov, and E.P. Emets. Probing of the Interior Layers of the Earth with Self-Sinking Capsules, *Atomic Energy* 99(2), 2005.

Sources of figures

Marchetti, Cesare. 1977. "Geoengineering and the Energy Island," Bolletino degli Ingegneri, XXV (8–9):3–10.

Marchetti, Cesare. 1998. "Energy Islands in the Final Configuration of the H2 Economy." Plenary lecture at the World Hydrogen Conference, Buenos Aires, 21–26 June 1998. http://www.cesaremarchetti.org/archive/scan/MARCHETTI-003.pdf.

"Mohorovicic Discontinuity - The Moho," http://geology.com, 27 June 2011.

National Geophysical Data Center (NGDC). See also http://solarviews.com/cap/earth/plates.htm.

Ojovan, Michael, Fergus Gibb, Pavel Poluektov, and Vladimir Kascheev. "Self-Sinking Capsules to Investigate the Earth's Interior." Reaching the Mantle Frontier: Moho and Beyond. The Carnegie Institute of Washington. 9-11 Sept. 2010.

Popular Science. http://www.popsci.com/technology/article/2010-06/future-environment-nuclear-revivalist.

Teagle, Damon, and Benoît Ildefonse. 2011. Journey to the mantle of the Earth, Nature 471, 437–439 (24 March 2011 doi:10.1038/471437a.

Von Hippel, David, and Peter Hayes. "Deep Borehole Disposal of Nuclear Spent Fuel and High Level Waste as a Focus of Regional East Asia Nuclear Fuel Cycle Cooperation." Austral Special Report 10-03A. 15 Dec. 2010.