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Research Article

A Study of Self-Burial of a Radioactive Waste Container by Deep Rock Melting

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Aiming at the problem of radioactive waste disposal, the concept and mechanism of self-burial by deep rock melting are presented. The rationality and feasibility of self-burial by deep rock melting are analyzed by comparing with deep geological burial. The heat threshold during the process of contact melting around a spherical heat source is defined. The descent velocities and burial depths of spherical waste containers with varying radius are calculated. The calculated depth is much smaller than that obtained in the related literature. The scheme is compared with the deep geological burial that is currently carried out by the main nuclear countries. It is found that, at the end of melting, a radioactive waste container can reach deep strata that are isolated from groundwater.

1. Introduction

According to the latest report from the OECD/NEA [1], nuclear energy will be the only choice to replace the carbon fuels and satisfy the global energy needs. However, for nuclear energy, the problem of radioactive waste disposal is inevitable. The problem has existed for more than half a century since the development of the first nuclear power plant. There are available deep geological disposal solutions in France, Sweden, Finland, or USA, but at the moment there is no operating facility available for radioactive waste from civil use of nuclear energy. In 2020 also first disposal operating facility is expected in Finland. At the present time, most of the waste has to be stored temporarily, and the long-term storage has been proven to be safe and efficient. A lot of countries are in process of long-term storage prolongation from 50 to 100 years [1].

The peculiarity and difficulty with the disposal of spent nuclear fuel (SNF) lie in its high radioactivity and longevity. The most popular schemes being researched for waste disposal are the transmutation and the deep geological burial [1]. The transmutation is a type of nuclear reaction, in which a long-life radioactive nuclide is changed into a steady-state or short-lived nuclide so that the amount of radioactive waste is much reduced and its disposal is much simplified. The significance of transmutation also lies in its efficient use of valuable nuclear resources such as ^{238}U and ^{232}Th. However, research on the transmutation has not advanced beyond its earliest stages because of its complexity so that the future of this technology is still unclear. Deep geological burial is one of the most popular schemes at present. In this scheme, the spent fuel should be vitrified and compacted first and then is put into a special spherical container made of stainless steel or cement. It is unnecessary to make directly a perfect compact sphere from the spent fuel or radioactive waste. The container is buried in the deep borehole in a repository and filled with some special material such as Ca-Bentonite or just closed for the future use of these wastes, so that the nuclides are prevented from reentering the ecosystem over a defined time period. For the deep geological burial, to avoid losing significant amounts of the radioactive contents due to the abrasion, corrosion, or/and local melting during the “deep rock melting” phase, it is a key guarantee that the spherical container filled with the spent fuel should be made of the special stainless steel with high performance. Certainly, nobody wants to have high-level radioactive waste spread over large volumes of the Earth’s mantle. So research on deep geological burial is being actively carried out in the main nuclear countries, and it is also recognized as an effective scheme by the international nuclear society [2]. The first repository in Yucca Mountain in the United States was expected to be opened in 2010. However, this scheme has faced public opposition. The main problem or danger lies in the relatively shallow burial depth, within 1000 meters of the surface for economic reasons, and the fact that the container is the only barrier between the nuclides and the groundwater, so that the trust of the public still cannot be established [2]. For the above reasons, the program has been delayed for a long time and in some countries it has even been suspended.

2. Self-Burial by Deep Rock Melting

The deep geological burial is one of the rather popular schemes at present. An alternative scheme for deep geological burial is self-burial by deep rock melting, in which the radioactive decay heat of spent fuel preserved in the spherical container is used to make a waste container melt into the deep rock. This concept has a long history with a great deal of research [3–10] showing that self-burial by deep rock melting is feasible both theoretically and practically. Much more attention has been paid to this kind of scheme recently and it may develop into an ideal scheme for SNF disposal in the near future.

Self-burial is essentially a process of contact melting of phase change material (PCM) around a heat source followed by recrystallization of the molten wake. Contact melting has been widely studied by many scholars [11–20]. The melting and recrystallization process is illustrated schematically in Figure 1 [5, 21]. A container filled with SNF is preburied in rock at a certain depth. Radioactive decay heats the surrounding rock to its melting point. The container melts downward through the rock and the molten wake recrystallizes as its temperature drops below the melting point. When there is insufficient heat of decay to heat the rock to its melting point, the melting stops. During the above process, three protective zones for the container [8] are formed from inside to outside. The first zone is the partially melted and then recrystallized rock, the second zone is the zone of metamorphic recrystallization and annealing, and the third zone is the zone of fractures filled by hydration reactions. Including the container, four near-field barriers come into being. When the melting ends, the radioactive waste is protected by the multibarriers, and any intact barrier can isolate the radioactive waste from the groundwater [8]. In addition, there is a rock barrier of thousands of meters beyond the four barriers. For self-burial by deep rock melting, only a shallow borehole is needed, and the harmful effect of the heat of radioactive decay need not be taken into consideration. And a single borehole can be used to dispose of a radioactive waste container.

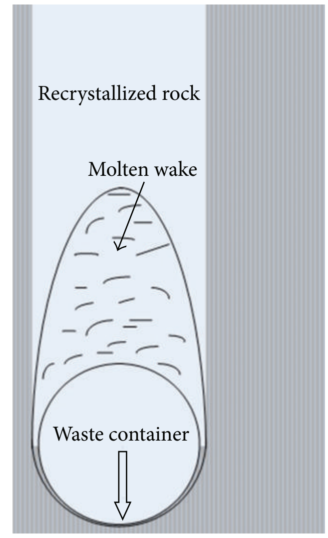

Figure 1: Self-burial process of a radioactive waste container by deep rock melting.

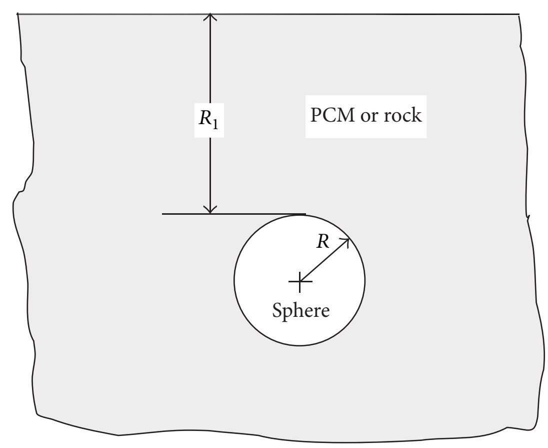

Figure 2: Schematic of sphere of radius R buried in the PCM (or rock).

3. Analysis and Discussion

In some literature related to contact melting, the melting process is shown to continue until the container reaches the core of the Earth [12]. However, this result is obviously impossible because of gravity and Earth's structure. The problem is addressed by introducing the concept of heat threshold. A spherical container with radius R and surface temperature T_1 is assumed to be surrounded by PCM with thickness R_1, thermal conductivity λ, and initial temperature T_2, as shown in Figure 2. It is assumed that (1) the time-dependent term in the heat conduction equation can be neglected, (2) all transfer of heat by convection and advection can be neglected, and (3) the latent heat of fusion can be neglected. Then according to [22], the heat transferred from the sphere can be expressed as

$$Q_s = \frac{4\pi\lambda\left(T_1 - T_2\right)}{1/R - 1/\left(R + R_1\right)}. \quad (1)$$

Melting occurs only under the condition $T_1 \geq T_m$, so the minimum heat needed is

$$Q_{\text{th}} = \frac{4\pi\lambda\left(T_m - T_2\right)}{1/R - 1/\left(R + R_1\right)}, \quad (2)$$

where Q_{th} is the heat threshold of the sphere. Compared with the size of sphere, the depth of burial can be regarded as infinite, so, in (2), $1/(R + R_1) \approx 0$. For a heat source with constant heat rate, whether melting occurs can be determined by the previous equation. As for melting by a container filled with the radioactive waste, the emitted heat decreases as the nuclides decay, and the melting ceases when the heat yielded by radioactive decay reaches the heat threshold.

The spent fuel of the typical reactor AC-600 [23] is chosen for analysis. For this reactor, the heat power is 1930 MW, the total weight of fuel UO_2 is 66800 kilograms, and the refueling period is 18 months. The weight and density of the spent fuel are assumed to be the same as the initial fuel; namely, the weight and density of the spent fuel are 66800 kilograms and $\rho = 10\,\text{g/cm}^3$. The spent fuel can exactly be filled into a spherical container with radius $r = 116.9$ cm. The expression of radioactive decay heat for the per unit mass spent fuel is [24]

$$q = \frac{0.005P_0 a\left[\Gamma_s^{-b} - \left(\Gamma + \Gamma_s\right)^{-b}\right]}{M}, \quad (3)$$

where M is the total weight of the spent fuel, P_0 is the heat power of reactor, Γ is the operating time, Γ_s is the shutdown time, $a = 27.43$, and $b = 0.2962$. The main parameters of the rock used as the PCM are given as follows [12]: $\lambda = 0.042\,\text{W/(cm}\cdot{}^\circ\text{C)}$, $\rho_m = 2.7\,\text{g/cm}$, $c_p = 1.05\,\text{J/(g}\cdot{}^\circ\text{C)}$, $L = 420\,\text{J/g}$, $T_2 = 0^\circ\text{C}$, and $T_m = 1200^\circ\text{C}$. Spheres with radii $R = r$, $2r$, $3r$, $4r$ are used for analysis, which should be made of the material (such as most stainless steel) with higher melting point than $T_m = 1200^\circ\text{C}$. The variation of the decay heat of waste in these spheres is presented in Figure 3, and the corresponding heat thresholds are 74, 148, 222, and 296 kW with melting time 4.94, 15.72, 30.00, and 47.18 a, respectively. Considering the time for storage and transportation, namely, the fact that the spent fuel cannot be disposed of immediately, the time Γ_s between the shutdown and the start of self-burial is taken as 0.5, 1, and 2 a, respectively.

The physical model and coordinates for the contact melting of a hot sphere container in the rock are shown in Figure 4. The sphere with radius R and constant surface temperature T_1 is placed in and forced down through the solid PCM whose temperature is uniform, initially remaining at a temperature T_2, smaller than the melting point T_m.

At time $t \geq 0$, the melting begins because of the temperature difference between the sphere and the solid PCM. The density difference between the sphere and the melt is assumed to be large enough to produce a continual descent of the sphere. The motion of the sphere at a vertically downward velocity U_0 is accompanied by the generation of liquid at the melting surface, and the liquid is pushed up through a narrow layer. It is assumed that (1) the melt layer is very thin (i.e., $\delta \ll R$) and the viscous forces are dominant as well as $\partial^2/\partial h^2 \ll \partial^2/\partial s^2$ and (2) heat transport by convective flow is negligible as compared with that by heat conduction in the quasisteady liquid layer. Based on the above assumption, Emerman and Turcotte derived the theoretical descent velocity and depth of the sphere container as follows:

$$U_0 = \frac{4}{3}\frac{R\rho q}{\rho_m L'}, \qquad H = \frac{4}{3}\frac{R\rho q}{\rho_m L'}t, \quad (4)$$

where $L' = L + c_p(T_m - T_2)$. The descent velocities of the four spheres are presented in Figure 5, respectively. The melting depths for the four radii are presented in Figures 6, 7, and 8 for $\Gamma_s = 0.5$, 1, and 2 a, respectively.

It is found that an increase of sphere radius can remarkably prolong the melting time and increase the final depth,

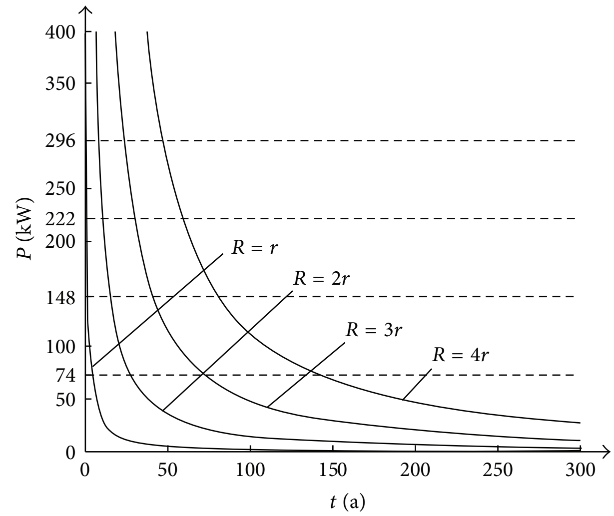

FIGURE 3: Heat variation and corresponding threshold of spherical containers of radioactive waste with radii 116.9 cm, 233.8 cm, 350.7 cm, and 467.6 cm.

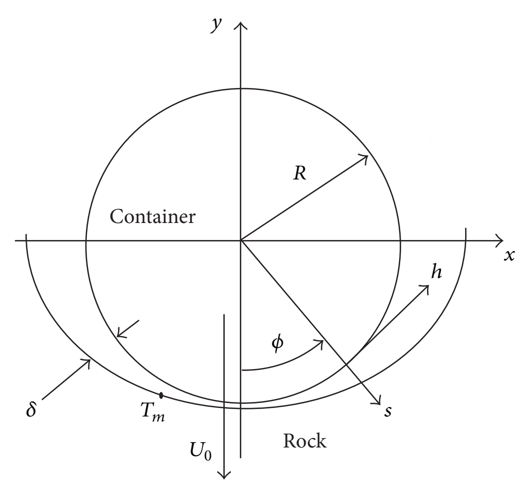

FIGURE 4: Physical model and coordinates for melting of sphere container in rock.

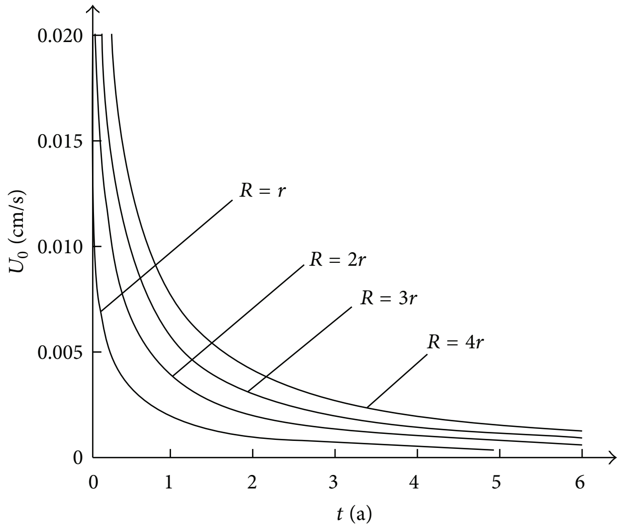

Figure 5: Melting velocity of spheres with different radius.

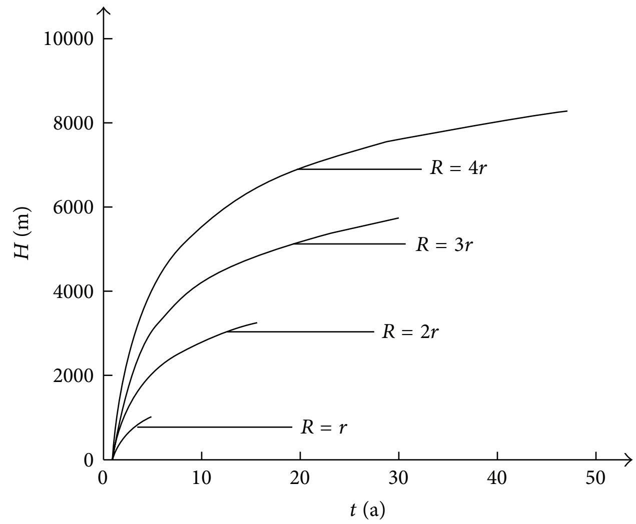

Figure 7: Melting depth of spheres with different radius while Γ_s = 1 a.

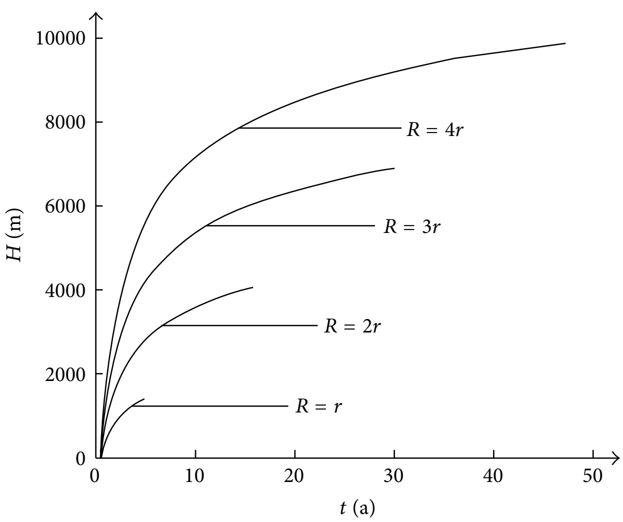

Figure 6: Melting depth of spheres with different radius while Γ_s = 0.5 a.

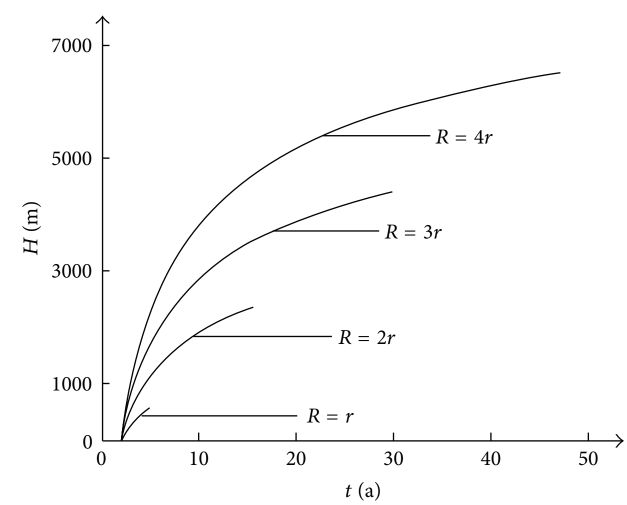

Figure 8: Melting depth of spheres with different radius while Γ_s = 2 a.

which also is affected by the time Γ_s. The shorter the Γ_s is, the deeper the final depth is. Therefore, to achieve the greatest depth of burial, the larger sphere container and shorter waste storage times should be chosen as consistent by other engineering constraints.

In the literature [12], the decay heat of waste is expressed by the Wigner-Way empirical formula as follows [24]:

$$q = 0.0622 H_0 \Gamma_s^{-0.2}, \quad (5)$$

where H_0 is the heat power per unit mass with values taken from the literature [12] to be 22.26, 2.226, and 0.2226 W/g. The radius of sphere and density of radioactive waste are taken to be 150 cm and 9 g/cm^3, respectively. With the above parameters, the heat threshold based on (2) is 95 KW. When H_0 = 22.26 W/g, the heat threshold is not reached even after 10^5 a, and, after 2000 a, the melting depth is 3006.7 km without considering the effect of waste storage time. However, when H_0 = 2.226 W/g, the melting time and final depth are 6953 a and 810.6 km, respectively, so the result in the literature [12] that the sphere container reaches the Earth's core in 30000 a is obviously incorrect. Similarly when H_0 = 0.2226 W/g, the melting time is only 25 d and final depth is merely 8.1 m, although the result in the literature [12] is that the sphere will reach the earth core in 500,000 a.

4. Conclusions

From the above analysis of the process of self-burial melting by deep rock melting, some conclusions can be drawn as follows.

(1) By the scheme of self-burial by deep rock melting, four protective zones or near-field barriers can be

formed to isolate radioactive waste from groundwater at the end of the melting process.

(2) A larger radius of the spherical container will remarkably prolong the melting time and increase the final depth of self-burial. In addition, the shorter the waste storage time is, the deeper the final depth of self-burial is.

(3) A container filled with radioactive waste can reach great depth by contact melting, and thick and safe near-field barriers can be formed. Self-burial by deep rock melting will be a valuable scheme for radioactive waste disposal.

(4) The descent velocity will depend upon the type of rock [9]. A high melting temperature is chosen in this study, which results in a minimum estimate of depth of self-burial. Although spent fuel is used in this analysis, in fact, any waste with decay heat bigger than the heat threshold can be used as the heat source for self-burial by deep rock melting.

Nomenclature

a, b: Constant
c_p: Specific heat J/(kg·°C)
g: Acceleration due to gravity m/s^2
H: Burial depth
H_0: Heat power per unit mass W/kg
L: Latent heat of melting J/kg
L': Equivalent melting latent heat $L' = L + c_p(T_m - T_\infty)$ J/kg
M: Total weight of spent fuel kg
P_0: Heat power of reactor W
q: Heat rate per unit mass W/g
Q_s: Heat power W
Q_{th}: Threshold of heat power W
R: Radius of sphere m
R_1: Thickness of rock m
t: Time s
T: Temperature °C
T_1: Surface temperature of container °C
T_2: Initial temperature of rock
T_m: Melting point of rock °C
U_0: Descent velocity m/s
Γ_s: Time between shutdown and start of self-burial s
Γ: Operating time s
λ: Thermal conductivity of rock W/(m·°C)
ρ: Average density of container kg/m^3
ρ_m: Density of rock kg/m^3.

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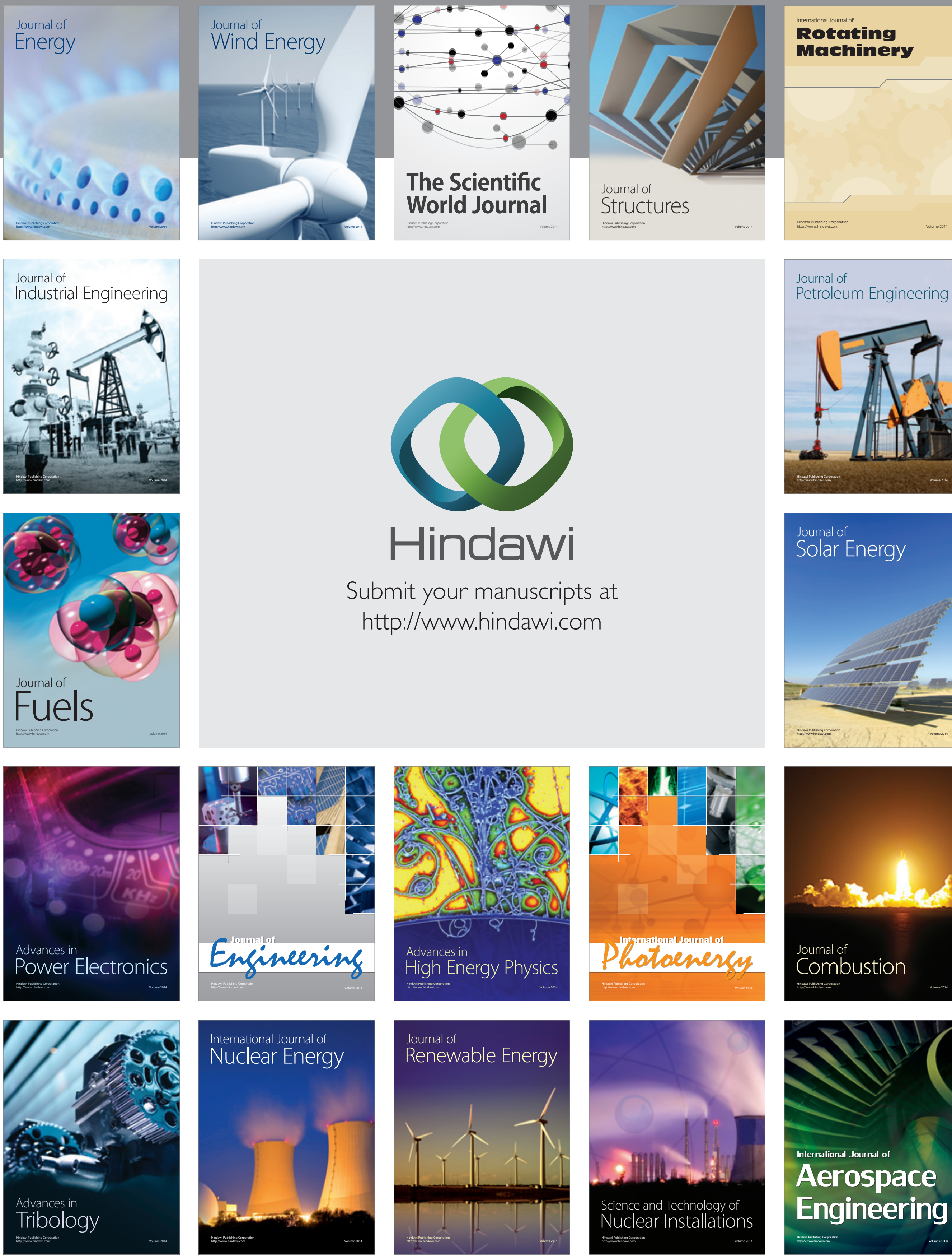
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