Rend. Fis. Acc. Lincei (2014) 25:119–126
DOI 10.1007/s12210-013-0247-z

ANTHROPOCENE - NATURAL AND MAN-MADE ALTERATIONS OF THE EARTH

Nuclear energy and Anthropocene

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Received: 23 April 2013 / Accepted: 5 July 2013 / Published online: 15 October 2013

Abstract After a short introduction on the basic physical problems of the application of nuclear physics to unfortunate military scopes and to civil production of nuclear energy we will consider their relatively recent and possible important impact on Anthropocene. Special emphasis will be devoted to the present continuous production of nuclear wastes and to their disposal, particularly in deep storage locations.

Keywords Nuclear energy · Nuclear wastes · Disposal · Deep storage

1 Introduction

The effects of nuclear energy in Anthropocene are relatively recent and can be due in principle both to fission and fusion. The military application of nuclear fission led about seven decades ago to the nuclear test in New Mexico followed by the tragic events of Hiroshima and Nagasaki. From then the application of fission and fusion to nuclear tests produced considerable and sometimes hidden effects in the environment. Since about six decades interest was also addressed to the civil production of nuclear energy which has now reached a considerable percentage in the energy balance of many countries. This has been accomplished so far only by fission, and the hopes of civil production by fusion have been so far frustrated. We will therefore be concerned here only to the former of these processes.

The potentiality to produce nuclear energy can be easily understood by inspecting Fig. 1 where the binding energy of a nucleus is divided by its atomic number A. It can be seen that the most stable nuclei present a maximum mean binding energy when A is around 60. As a consequence energy can be obtained either by splitting heavy nuclei like ^{235}U (fission) or unite light ones (fusion).

2 Nuclear fission

Civil nuclear energy by fission is mainly produced by capture on ^{235}U of *thermal* neutrons with a very low energy (about 0.025 eV).

$$\mathbf{n}_{\text{thermal}} => {}^{235}\mathbf{U} + \mathbf{X} + \mathbf{Z} + m\,\mathbf{n}_{\text{fast}}$$

where **X** and **Z** are fission fragments and the number m of generated neutrons is in average of 2.47. The energy of these neutrons is, however, too large to produce further fissions and has to be reduced by means of a suitable moderator (Carbon, H_2O, D_2O etc.). Moderated neutrons can then produce further fissions and give rise to the *chain reaction* shown in Fig. 2.

The role played by Uranium isotopes in nuclear fission is reported in Table 1. The captured thermal neutron delivers to the nucleus an excitation energy which should be larger than the activation energy needed to produce fission. Only the 233 and 235 isotopes of Uranium obey this rule, with isotopic abundances of 0.005 and 0.72 %, respectively. The abundance of the former is too low for its use in a reactor, unless produced in other ways, while the one of ^{235}U can be sufficient in some reactor, like the first one built by Fermi, but it

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This contribution is the written, peer-reviewed version of a paper presented at the conference "Anthropocene—Natural and man-made alterations of the Earth's fragile equilibrium", held at Accademia Nazionale dei Lincei in Rome on November 26–27, 2012.

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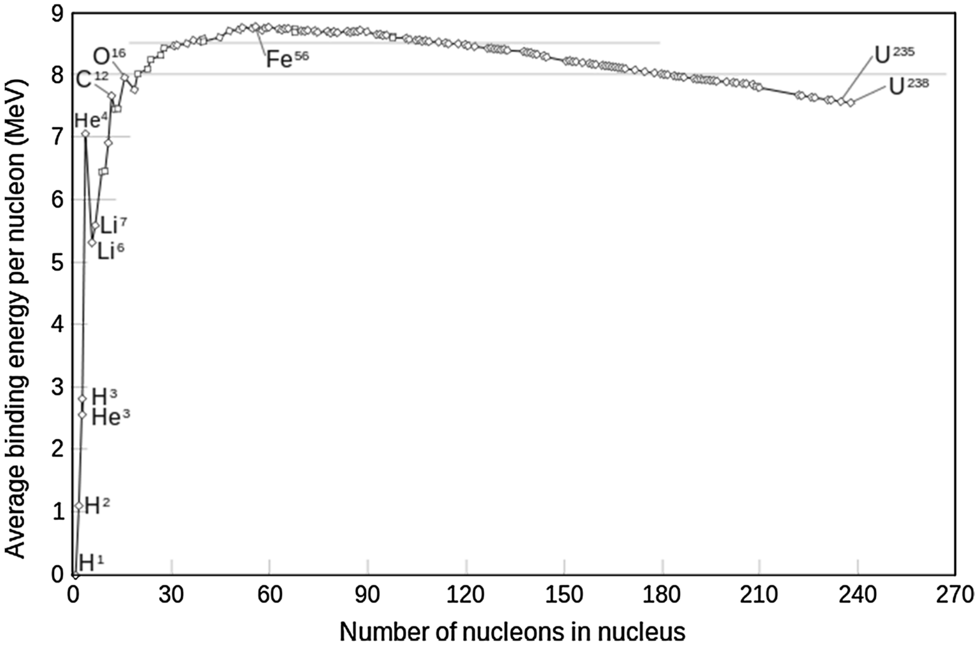

Fig. 1 Mean binding energy as a function of atomic number

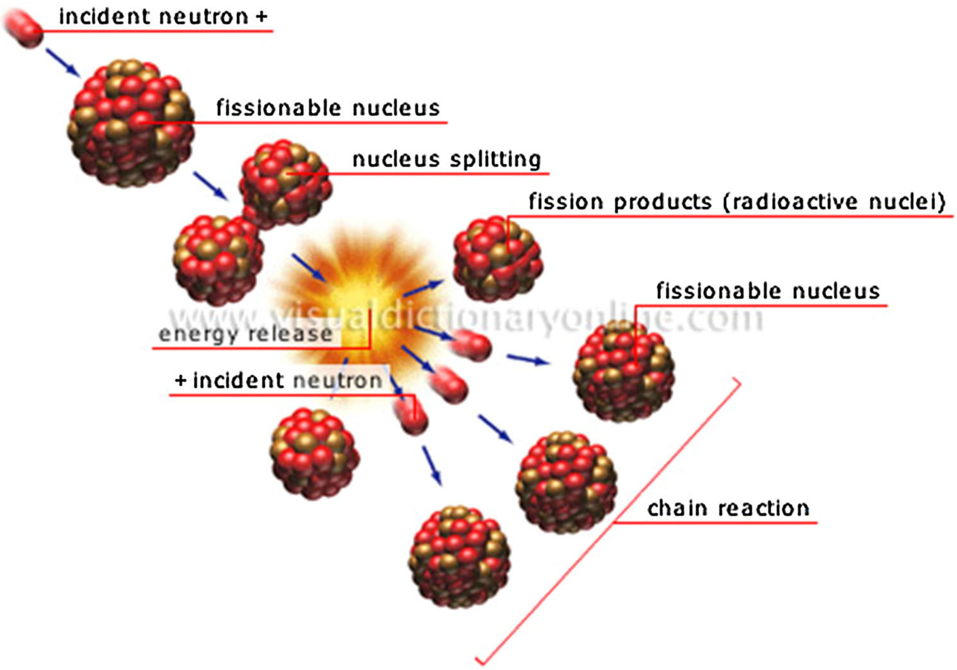

Fig. 2 Scheme of nuclear fission chain

Table 1 Properties of some relevant isotopes

Nucleus	Binding energy	Activation energy	σ (barn)
^{232}Th	4.8	6.7	$<10^{-6}$
^{233}U	6.8	5.85	531.8
^{235}U	6.5	5.9	579
^{238}U	4.8	5.8	2.7×10^{-6}
^{239}Pu	6.5	6.3	742

has to be enriched in most of the power reactors presently running. One can note the attractive properties of the artificial isotope ^{239}Pu which we will consider later.

3 Nuclear wastes

The main problem and challenge in the present and especially in the future civil and unfortunately military

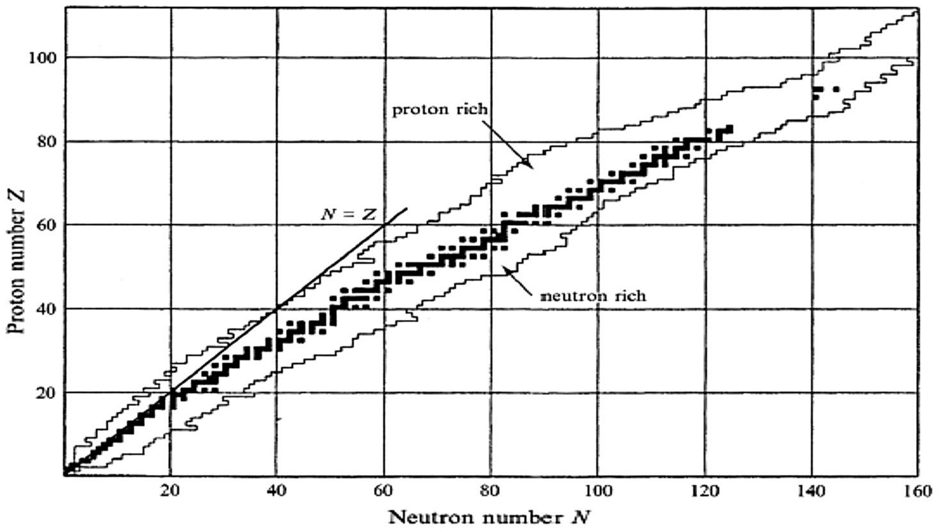

Fig. 3 Proton versus neutron number. Stable nuclei are shown in *black*

development of nuclear energy stays in the unavoidable production of radioactive isotopes: the so called *nuclear wastes*. In heavy nuclei, the presence of neutrons with respect to protons has to be larger to keep them together, overcoming the larger coulomb repulsion (Fig. 3). This is less true for fission fragments much richer in neutrons and therefore unstable. They are below the line of the stable nuclei evidenced in the figure and tend to stability with a chain of beta decays of generally increasing half lifetime.

The presence of these isotopes of both civil and military origin adds to the natural radioactive environment as shown in Fig. 4. Present environmental radioactivity is in fact due to.

1. *Fossil* radioactivity from pre-existing atoms like Uranium, Thorium or Potassium
2. *Cosmogenic* radioactivity due to activation by interactions of Cosmic Rays
3. *Anthropogenic* radioactivity due to isotopes produced mainly by nuclear explosion or tests, by the production of nuclear energy or even of radioisotopes for medical and/or other civil applications

4 Nuclear reactors

A draft of the first nuclear reactor constructed by Fermi in the swimming pool of the University of Chicago and secretly sketched against the strict military secrecy laws is shown in Fig. 5. We would like to stress that the scope of this reactor was not the production of energy, but just to prove the possibility to produce a chain reaction for

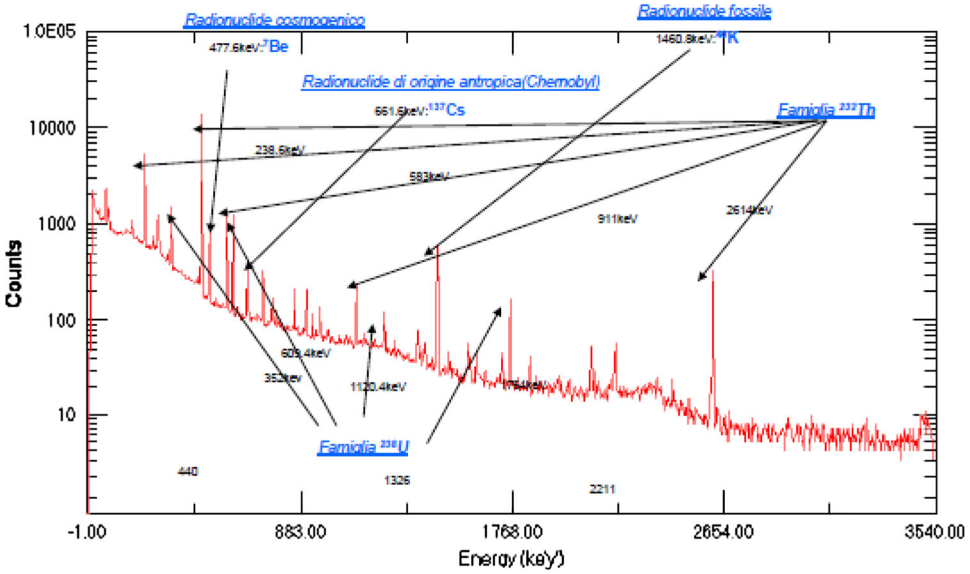

Fig. 4 Present gamma spectrum of the sum of fossil, cosmogenic and anthropogenic radioactivity

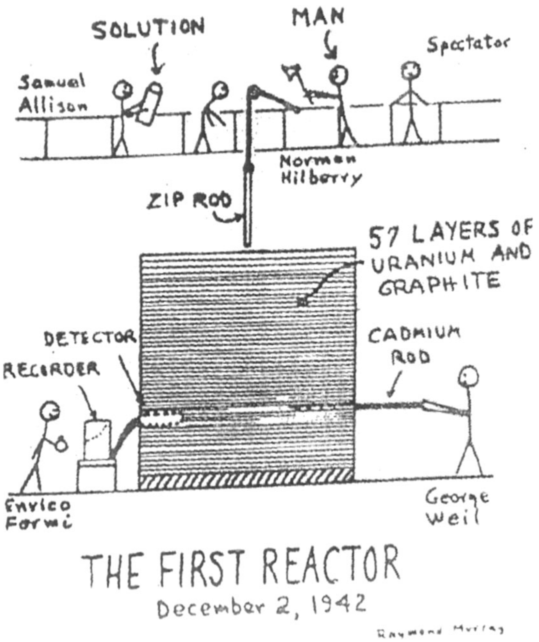

Fig. 5 The first reactor

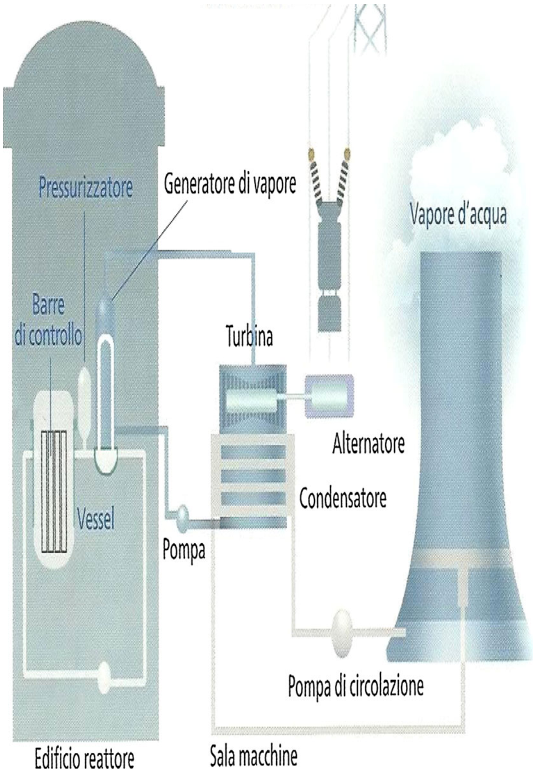

Fig. 6 A present power reactor

military purpose. This brought to the *nuclear military era* with great efforts for the development and test of nuclear weapons. It was only with the sixties that interest was devoted to reactors specifically constructed for the production of energy (Fig. 6).

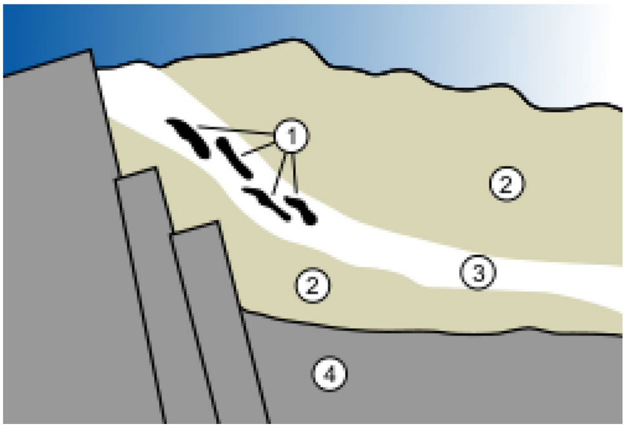

Fig. 7 The Oklo 1 reactor: *1* Nuclear reactor zones. *2* Sandstone. *3* Uranium ore layer. *4* Granite

It could be of some interest for geologists that nuclear reactors existed in Nature! In present reactors the natural abundance of ^{235}U (0.72 %) has to be increased by about three times to allow the chain fission reaction to occur in a reactor, but a moderator has to be present. Billions years ago ^{235}U and ^{238}U existed with the same amount, but the abundance of ^{235}U decreased more rapidly than for ^{238}U due to the lower half lifetime (0.704 instead than 4.47 Gigayears). In geological times the ratio between isotopes 235 and 238 was therefore much larger than the present one, but a chain fission could only occur in presence of a suitable moderator. In some case, however, water was present. A known and proved case was the *Oklo reactor* in the African region of Gabon shown in Fig. 7 where apparently a moderator like water or granite was present. The occurrence of this reactor about 1.7 Gigayears ago was geological suggested, but later also proved by specific measurements which revealed a geologically abnormal lack of ^{235}U and the presence of isotopes which could only be produced by a chain reaction. (Curtin University 2012).

Two major disasters due to nuclear reactors took place so far: one in 1987 in Chernobyl (then USSR) and recently in Fukushima (Japan).

The effect on environmental radioactivity by the Chernobyl accident in Milan is shown by our gamma ray spectrum of Fig. 8 recorded then. One can notice the presence of the radioactive isotopes of Iodine, Ruthenium and Cesium in addition to the lines due to natural radioactivity. We would like to note that, due to its relatively long lifetime (30.07 years), a minor contribution from ^{137}Cs due to the Chernobyl accident is still present in air particulate in Italy.

Despite the much larger distance from Fukushima we were able to detect recently the contamination of the isotopes of Cesium and Iodine (Clemenza et al. 2012) as shown in Fig. 9.

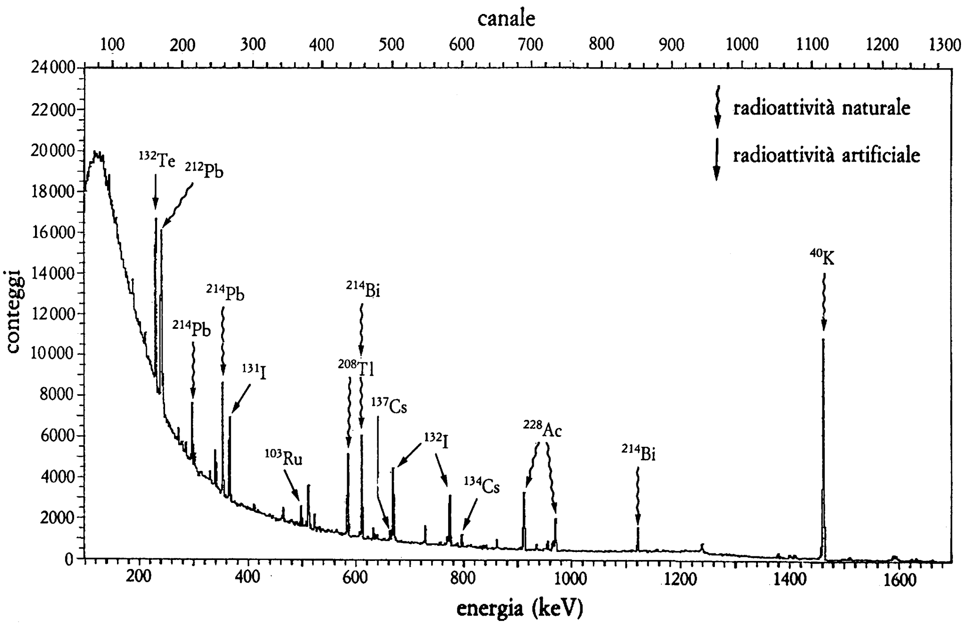

Fig. 8 Additional environmental radioactivity due to the Chernobyl incident in 1986

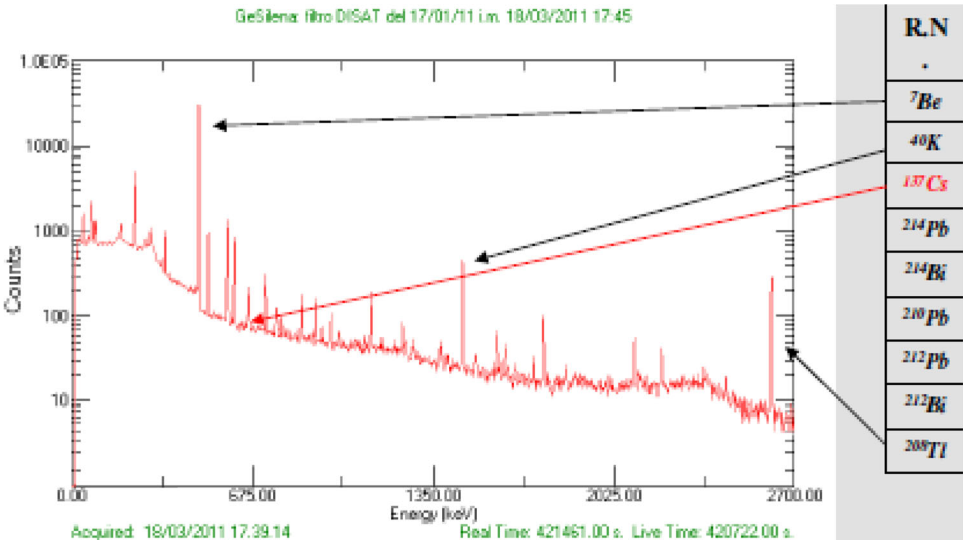

Fig. 9 Evidence in Milan particulate of the effects of the Fukushima incident

5 Disposal of nuclear wastes

Nuclear wastes come from various sources: military and civil reactors, nuclear tests and pacific application of nuclear physics (medical, agricultural, industry). We will not be concerned here with the third, since it is negligible with respect to the first two. A great amount of wastes were produced at the beginning of the nuclear era especially in USA and in USSR for their competition in the production of atomic bombs. In particular the dangerous plutonium was produced also as a reactor fuel in the worry of lack of Uranium. Further wastes were and are continuously generated for civil production of energy by the large number (almost 500) of operating power reactors. The concern is obviously related to the future destiny of nuclear energy and depends on the quantity and lifetime of the produced radioactive isotopes. We can roughly classify these radioactive nuclei according to their lifetime as shown in Table 2.

The general classification of nuclear wastes is unfortunately controversial and different among the various nuclear countries (Sook Jung et al. 2012). According to the International Atomic Energy Agency (IAEA) wastes can be classified as following:

1. High-level wastes (HLW): wastes containing larger concentrations of both short- and long-lived radionuclides than ILW and generally having an activity concentration of 10^4–10^6 Bq/g

Table 2 Classification of nuclear wastes according to their lifetime

Lifetime	Fission products
1–10 days	^{72}Zn, ^{67}Ga, ^{77}As, ^{82}Br, ^{90}Y, ^{95}Nb, ^{99}Mo, ^{103}Rh, ^{105}Rh, ^{109}Ag, ^{115}Cd, ^{115}I, ^{127}Sb, ^{131}Te, ^{131}I, ^{132}Te,^{129}Xe, ^{133}Xe,^{135}Xe,^{135}Ba,^{140}La, ^{143}Ce, ^{147}Pm, ^{14}Pm, ^{151}Eu, ^{153}Eu, ^{155}Eu, ^{161}Gd, ^{161}Tb, ^{166}Dy, ^{166}Ho
10–100 days	^{86}Ru, ^{89}Sr, ^{91}Y, ^{95}Zr, ^{95}Nb, ^{103}Ru, ^{115}Cd, ^{117}Sn, ^{124}Sb, ^{126}Sb, ^{125}Te, ^{129}Te, ^{131}Xe, ^{131}Cs, ^{143}Pr, ^{147}Nd, ^{151}Pmk, ^{156}Eu, ^{131}Te, ^{131}Te, ^{131}Te, ^{131}Te,
100 days–10 years	^{119}Sn, ^{123}Sn, ^{121}Te, ^{127}Te, ^{134}Cs, ^{144}Ce, ^{147}Pm, ^{154}Eu, ^{135}Eu, ^{151}Sm
$10^{-5} \times 10^{8}$ years	^{85}Kr, ^{90}Sr, ^{93}Zr, ^{93}Nb, ^{99}Tc, ^{107}Pd, ^{107}Cd, ^{107}Ag, ^{121}Sn, ^{126}Sn, ^{129}I, ^{135}Cs, ^{137}Cs, ^{131}Te,
$>5 \times 10^{8}$ years	^{82}Se, ^{87}Ru, ^{116}Cd, ^{130}Te, ^{114}Nd, ^{147}Sm, ^{152}Gd,

2. Intermediate level wastes (ILW): wastes requiring a greater degree of containment and isolation than that of nearer surface disposal
3. Low level wastes (LLW): these wastes are suitable for near surface disposal. They generally have a limit of 400 Bq/g on average (4,000 Bq/g for individual packages) for longer lived alpha emitting radionuclides

In a simplified approach two categories can be considered from the storage point of view:

1. Low level materials to handle strongly radioactive parts of reactors (e.g., cooling liquid, contaminated parts), radioactive sources even from nuclear medicine, industry etc., with limited lifetimes to be disposed for tens of years in pools or concrete structures
2. Actinides (in particular Plutonium) produced during fission, to be stored for geological time or reprocessed

One way to solve the problem of nuclear wastes is to limit their production with new types of reactors, or to reduce the produced ones by partitioning and transmutation (Ojovan and Lee 2005; Sook Jung et al. 2012). The former process consists in *separating* out of the spent fuel the radiotoxic components, the latter is based on *recycling* them in a way to minimize their toxicity and recover their contained energy in a useful way. We note that one or the Fukushima reactors was charged also with Plutonium. This *nuclear reprocessing* reduces the volume and the long-term radiation hazard and heat dissipation capacity needed. Reprocessing does not, however, eliminate the political and community challenges and require the need for the repository of nuclear wastes where they can be safely insulated from the biosphere for at least hundred thousand years (Pusch 1994; Ojovan and Lee 2005; Pusch 2008). We will be concerned here with the deep storage for geological times, because it can be closely connected with Anthropocene.

In USA, a country heavily involved since the beginning, like USSR, in the military applications of nuclear age many equipments were contaminated with amounts of radioactivity. This was mainly due to the production of nuclear weapons during WWII and the Cold War. They have been shipped to WIPP (Waste Isolation Pilot Plant) where the contaminants are permanently isolated and stored. This site is used even now to store nuclear wastes, but it is presently inadequate for the large amount of continuously produced radioactive material.

Many hopes were addressed in USA on the so called *Yucca project* (Fig. 10) initiated in 1978 for a long-term geological depository for spent nuclear fuel and high-level radioactive wastes. Recently, however, after animated litigation between the local agency for Nuclear Project of the State of Nevada and the Obama Administration the Yucca Project has been definitely canceled (New York Times 2011, May 9). This leaves United States civilians without

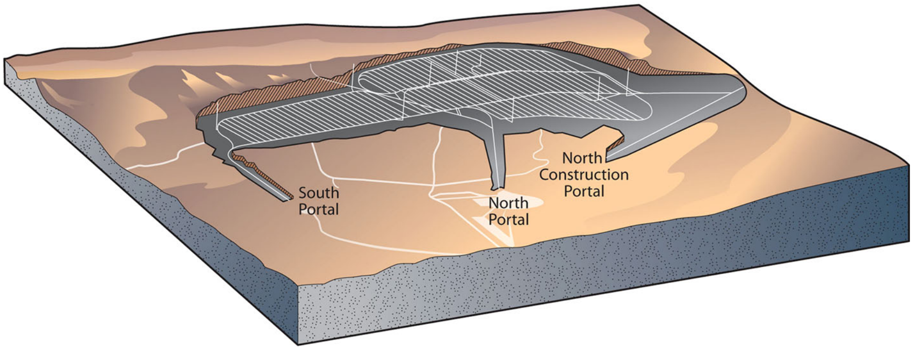

Fig. 10 The proposed Yucca site

Table 3 Presently studied sites for disposal of nuclear wastes

Country	Facility name	Location	Waste	Geology	Depth	Status
Argentina	Sierra del Medio	Gastre		Granite		Under discussion
Belgium			High-level waste	Plastic clay	~225 m	Under discussion
Canada	OPG DGR	Ontario	200,000 m^3 L&ILW	Argillaceous limestone	680 m	Licence application 2011
Canada			Spent fuel			Under discussion
China						Under discussion
Finland	VLJ	Olkiluoto	L&ILW	Tonalite	60–100 m	In operation 1992
Finland		Loviisa	L&ILW	Granite	120 m	In operation 1998
Finland	Onkalo	Olkiluoto	Spent fuel	Granite	400 m	Under construction
France			High-level waste	Mudstone	~500 m	Siting
Germany	Schacht Asse II	Lower Saxony		Salt dome	750 m	Closed 1995
Germany	Morsleben	Saxony-Anhalt	40,000 m^3 L&ILW	Salt dome	630 m	Closed 1998
Germany	Gorleben	Lower Saxony	High-level waste	Salt dome		Proposed, on hold
Germany	Schacht Konrad	Lower Saxony	303,000 m^3 L&ILW	Sedimentary rock	800 m	Under construction
Japan			High-level waste			Under discussion
Korea	Gyeongju		L&ILW		80 m	Under construction
Sweden	SFR	Forsmark	63,000 m^3 L&ILW	Granite	50 m	In operation 1988
Sweden		Forsmark	Spent fuel	Granite	450 m	Licence application 2011
Switzerland			High-level waste	Clay		Siting
United Kingdom			High-level waste			Under discussion
USA	Waste Isolation Pilot Plant	New Mexico	Transuranic waste	Salt bed	655 m	In operation 1999
USA	Yucca Mountain Project	Nevada	70,000 ton HLW	Ignimbrite	200–300 m	Proposed, canceled 2010

any long-term storage site for high-level radioactive waste apart WIPP.

Deep geologic disposal has been and is being studied by practically all nuclear countries since several decades, including laboratory tests, as shown by Table 3 (Wikipedia 2012). The need for safe disposal of high-level nuclear waste (HLW) has been in focus of the International Atomic Energy Agency and of a number of national authorities for decades. Various concepts have been proposed for deep deposition in salt, argillaceous and crystalline rock, but no large repository has yet been constructed. Many countries outside USA that focus on disposal of nuclear wastes are interested in the design developed by the Swedish Nuclear Fuel and Waste Company based on tunnels at about 400 m depth with large-diameter extending vertically from the tunnel. The plan is to place the waste in shallow places for tens of years after extraction to reduce radioactivity and the consequence release of heat and then to encapsulate them in a 400–500 deep repository in rock (Pusch and Weston 2012).

6 Conclusions

The future of the production of energy of nuclear origin is the object of animated economical, political, environmental and even ethical discussions. There is no doubt, however, that the major problem, despite in some way the future destiny of nuclear energy, is the need to dispose nuclear wastes. Even if new types of reactors capable to '*burn*' or reduce future wastes, the already existing, and most likely the future ones will require their disposal in deep cavities to avoid any contact with the biosphere.

On the other side excavation of a large and suitable deep cavern to house nuclear wastes presents great difficulties from the mechanical, environmental, geological, financial and even psychological point of views. The unexpected, at least for me, failure of the Yucca project is a clear example.

The efforts to investigate this problem and especially to find suitable solution are at present in my opinion insufficient and require a further increased collaboration of geophysics with physics and other fields of science. This is the message of nuclear energy to Anthropocene.

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