The future of nuclear energy

J. Cugnon

Université de Liège, Département de Physique, allée du 6 Août 17, bât. B5, B-4000 Liège 1, Belgium
E-mail: J.Cugnon@ulg.ac.be

Abstract. Various aspects of the World energy problem indicate that nuclear energy will still be needed in the future. Conditions for a continued valuable use are discussed. Special attention is focused on the nuclear waste problem.

Keywords: Nuclear energy, Nuclear waste, Transmutation
PACS: 28.50.Hw, 28.41.Kw, 28.41.Te, 28.90.+i

1. INTRODUCTION

Although nuclear energy is a special topic of hadronic interactions, it is unfrequent to discuss such a matter in a meeting like this one. Particle physicists use to gather to discuss pure science, with little regards to the applications of their research. Setting in this meeting a discussion session on nuclear energy reveals that the issue of the future of nuclear energy appears more and more as a society problem, that cannot be ignored by nuclear and particle physicists.

In this introductory talk, I will present an overview of the main features that will influence the use of nuclear energy in the future. I will successively discuss the world energy problem, the necessary conditions for a valuable use of nuclear energy, the safety aspects, in particular the nuclear waste problem, and the strategy for the future.

2. THE WORLD ENERGY PROBLEM

1. World energy consumption. In year 2000, the world energy consumption raises to ∼10 Gtoe[1] and is steadily increasing, as shown in Fig.1. The energy consumption is unevenly distributed among the regions of the World (see Table 1). The breakdown of the energy sources is given in Table 2. By far, the main energy sources are fossil fuels. Energy resources are not uniformly distributed, as it is well known.

2. Prospectives. An important point is the (proved) energy resources. An indicative account is given in Table 3. The striking feature is that oil is running out, although the resources are probably underestimated. Oil shale may provide with another period of 40 years, but the extraction of this oil is still to be demonstrated. Nuclear energy based on present technology is in a better shape, but not that much.

---

[1] 1 toe = one ton of oil equivalent.

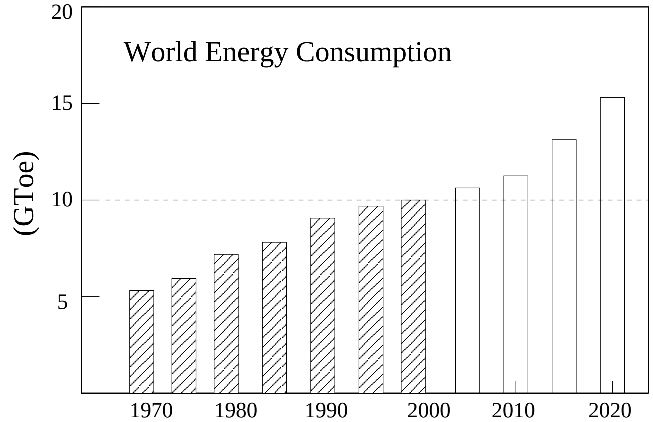

FIGURE 1. World energy consumption for the period 1970-2000 and projections for 2000-2020. Based on data from the International Atomic Energy Agency [1].

TABLE 1. Energy consumption in various regions of the World in year 2001.

	Energy consumption (Gtoe)	**Population (Billions)**	**Consumption indice (toe/capita)**
EU	1.50	0.380	3.95
Africa	0.52	0.812	0.64
Latin America	0.45	0.422	1.06
Asia (- China)	1.15	1.935	0.59
China	1.15	1.278	0.90
Former USSR	0.92	0.289	3.18
Middle East	0.38	0.169	2.31
USA+Canada	2.50	0.317	7.88
Rest	1.15	0.500	
World	10.20	6.102	1.67

If one includes the "estimated additional resources of type I", according to the Nuclear Energy Agency (NEA) classification [3], the horizon widens to 400 ans. If one turns to the fast reactor (FR) technology, which is not well developed up to now, another factor 10 would be gained.

According to the United Nations organisation, the World population will be of 7.5 ± 0.4 Billions of people in 2020 and is expected to increase further. The low variant scenarios predict a maximum around 9 Billions in the second half of this century. The energy demand is expected to increase from 10 Gtoe to 13-17 Gtoe in the year 2020 (see Table 1). The main increase will come from developing countries, in which 1.6 Billion people are in "energy poverty".

It is hard to say what kind of energy resources will be developed or will be prominently chosen in the future. Three kinds of factors, economical, technological and societal, are influential. First of all, the trends will mainly depend on the supply and demand mechanism, which, however, may be strongly affected by price policy

TABLE 2. Share (in percents) of total primary energy supply in year 2001.

Source	Oil	Coal	Gas	Renewable and waste	Nuclear	Hydro	Geothermal and wind
Percentage	35.8	23.0	20.9	10.8	6.8	2.2	0.5

TABLE 3. Proved recoverable resources, established in 1999 [2]. Note that they are given in metric tons, except for natural gas. The last column gives the number of years after which these resources will be exhausted if their respective present consumption rates are maintained.

Source	**Amount**	**Number of years**
Coal	796 Gt	220
Lignite	189 Gt	237
Oil	143 Gt	42
Oil shale	$\sim$100 Gt	
Natural gas	151 Gm^3	63
Uranium	3.28 Mt	100
Nuclear (fast reactors)		21000

(we will disregard this aspect in the rest of this paper). Technological developments may drastically change the respective importances of the various energy sources. Solar energy is often cited as an example, but experts do not foresee a rapid breakthrough. Fusion energy is another quoted example, but the first full-scale reactor is not expected before fifty years.

The pattern may also be strongly influenced by slow but profound changes which are presently reshaping our societies. Let me just mention three of them:

- *Environmental concerns.* The most obvious one concerns the reduction of greenhouse effect gases, in order to prevent a global climate change. This presumably implies a reduced use of fossil fuels.
- *Sustainable development.* An obvious application of this principle calls for a development of renewable (and soft) energy sources. The latter account for 15% of the present energy consumption (see Table 2) and they are not expected to rapidly contribute for substantially more. Let me shortly comment on each of them separately. It is estimated that the hydroelectric capacity can be increased by a factor 5, but investments are slow and present other problems. Wood already contributes to about 7% and can hardly be doubled, hitting evident environmental problems. Biomass has an enormous potential ($\sim$6 Gtoe/year), but tapping it would divert its use from agricultural purposes. Solar energy is very diffuse. Solar photovoltaïc technology is developing well, but the installed power amounts to only 600 MW and is not expected to amplify rapidly. Wind energy is expanding very rapidly and is promising: it has passed from 2 GW to 18 GW in the last 30 years. Geothermal energy is

not important and is developing very slowly. Tidal energy and other sources are only in the experimental stage.
Of course, the principle of sustainable development has other facets. For instance, it advocates looking for increased efficiency of technological devices. In western countries, a strong effort has been made in this direction during the last years, both in the industry and in domestic use. But at the same time the energy demand has kept growing. More profoundly, the principle of sustainable development challenges our model of development and calls for other less energy-demanding ones.

- *Changes in society management.* Western countries have undergone a strong mutation in the last 25 years, almost unknown of the populations. They have shifted from a centralized undebatable management (governments were considered to work from the wealth of nations and to do the right choices without referring to the populations) to a local participative style of management. This mutation will have, for sure, implications for future options concerning energy, although it is hard to figure out which ones [4].

Concluding this Section, one can state that there is a strong chance that the energy demand will still be increasing for many years, especially due to the rise of developing countries. The weight that will be given to the various energy resources is hard to predict. Due to the foreseen pressure for a reduced use of fossil fuels and the presumably slow development of so-called alternative sources, it is expected that we will have to rely to all energy sources, including nuclear energy.

3. CONDITIONS FOR A VALUABLE USE OF NUCLEAR ENERGY

Applying the notion of "sustainability" to energy production by nuclear means, one can formulate these conditions as follows:

1. No rapid exhaustion of resources. It would not be wise to mutiply the numbers of reactors of the present technology by a factor of, say 10, in view of the proved U resources. Furthermore, a light water reactor (LWR) working in "open cycle", i.e. without a recycling of useful matter in spent fuels, consumes less than 1% of the potential fission energy (^{238}U is practically untouched). This argues in favour of using fast neutron reactors (FR), where rapid neutrons can fission ^{238}U. This technology exists, but is not well developed and more complex. It probably cannot compete valuably as long as U is cheap and abundant.

2. No unacceptable risk. This point mainly covers the operational risks and the problem of proliferation. I will elaborate on these points in the next Section.

3. No generation of untractable problems for future generations. This implies taking care of the waste problem. The latter will be discussed below.

4. SAFETY PROBLEMS

There are three main safety problems.

1. Reactor safety. Because it escapes to our senses, radioactivity is frightening. However, in normal operation, a nuclear reactor is among the large energy-producing installations the one whose impact on workers, population and environment is the weakest [5]. What really scares the population is a major accident, especially after the Chernobyl catastrophy, even if it can be argued that this has been a Soviet as much as a nuclear accident [6]. To dissipate the fears of the public, one has to demonstrate the feasibility of a technology that would not release radioactivity even in the case of melt-down of a reactor core. This requirement is at the base of the future so-called Generation III reactors, of which the French-German EPR reactor (whose conceptual project is currently in the optimisation phase) is a example.

2. Proliferation. ^{239}Pu or other radioactive materials can be diverted from the fuel cycle for military or terrorist purposes. The solution to this problem rests on the control by the International Atomic Energy Agency (IAEA). However, the recent Iranian example indicates that this control is not without limit. Another acute problem is generated from the rise of centrifuge-based technology for separation of ^{235}U, which seems to be accessible to countries with medium technology industry. Surely, the solution to this problem passes by an increased role of the IAEA and possibly by new treaties of non-proliferation.

3. Wastes. The highly-radioactive products consitute the real problem, since the reprocessing of low and medium-radioactive wastes is now industrially mastered. In addition, the absence of any real application of accepted and durable method for storing the highly-radioactive wastes leaves the impression that there is no solution to this problem. This is not the case, as it is shown in the next Section.

5. WASTE PROCESSING. SOLUTIONS FOR THE FUTURE

5.1. A short reminder about waste classification

To simplify the presentation, one may distinguish between low-level (LLW) and high-level wastes (HLW). LLW contain radio-elements of short lifetime (less than 30 years) and mainly originate from laboratories, hospitals and industry. HLW are mainly coming from spent fuel and some structural materials of nuclear reactors. Spent fuel contains U+Pu, minor actinides and fission products. In addition, one has to include wastes from U extraction and from enrichment process. Sometimes, U and Pu are not considered as wastes, since they can be used as fuel for future FR's.

Almost everywhere, LLW are conditioned in special containers and stored in surface or near-surface depositories. HLW pose the most serious problem, because they release heat, have a large activity and contain many long-lived isotopes. I will

TABLE 4. Inventory of the main isotopes yearly produced by an typical LWR reactor, three years after unloading of the reactor.

	Isotopes	**Period (years)**	**Loading (kg)**	**Unloading (kg)**
Uranium	^{235}U	$7.08\ 10^8$	751	221
	^{236}U	$2.34\ 10^7$	-	88
	^{238}U	$4.47\ 10^9$	20734	20204
Plutonium	^{238}Pu	87.7		3.3
	^{239}Pu	24119		123.1
	^{240}Pu	6569		47.5
	^{241}Pu	14.4		25.4
	^{242}Pu	$3.7\ 10^5$		10.5
Minor actinides	^{237}Np	$2.14\ 10^6$		8.8
	^{241}Am	432.2		4.4
	^{243}Am	7380		2.2
	^{244}Cm	18.1		0.5
	^{245}Cm	8500		0.06
Fission products (medium-lived)	^{90}Sr	28		10.5
	^{137}Cs	30		24.3
Fission products (long-lived)	^{79}Se	70000		0.11
	^{93}Zr	$1.5\ 10^6$		15.5
	^{99}Tc	$2.1\ 10^5$		17.7
	^{107}Pd	$6.5\ 10^6$		4.4
	^{126}Sn	10^5		0.44
	^{129}I	$1.57\ 10^7$		3.9
	^{135}Cs	$2\ 10^6$		7.7
	^{151}Sm	93		0.33

concentrate on these wastes in the following.

5.2. The size of the problem

Nuclear wastes have a rather limited volume. A typical reactor (LWR, 900 MWe, burning rate of 33000MWd/t, 3.5 % enrichment) produces on the average about 20 tons of spent fuel per year. In a country like France, this means 20gr/year/capita compared to the 2.5t/year/capita of ordinary wastes. On the other hand, nuclear wastes are truly highly radioactive: three months after a shut-down, the activity of the core of a typical reactor is of the order of 1 GCi, corresponding to a release of heat at a rate of $\sim$8 MW.

It is interesting to look at the elements contained in the wastes. The inventory is given in Table 4. The largest part corresponds to U and Pu isotopes. If the latter are considered as fuel (see below), the weight is considerably reduced, but the radiotoxicity is not reduced in the same proportions. Let us look at the problem at the European scale. About 145 LWR's producing 880TWh per year (about 35% fo EU's electricity) generate about 2500t/year of spent fuel. Up to now these wastes are stored. The present total stockpile amounts to 37000 t, among which 330 t of Pu, 52t of minor actinides, 1500t of fission products including 46t of long-lived isotopes. Less data are available concerning military wastes (mainly Pu and tritium). The stockpile of military Pu is estimated to 260t, worldwile [7].

HLW are highly radiotoxic. Each ton corresponds to an equivalent dose of about 10^8 Sv. This should be compared with the radiation workers limiting dose, which has recently been reduced from 50mSv to 20mSv. The problem becomes more accute when the time evolution of the radiotoxicity is considered. This is illustrated by Fig.2, inspired from Ref. [8]. It needs more than 10 thousands of years for the radiotoxicity of HLW to reach down the radiotoxicity of natural uranium ore, the level which is generally considered to be necessary for a harmless release in the environment. If U and Pu are removed, this time reduces to a thousand years. If in addition minor actinides are also extracted, the necessary time is now of a few hundred years. The dashed curve indicates that this time is further diminished if long-lived fission products are removed.

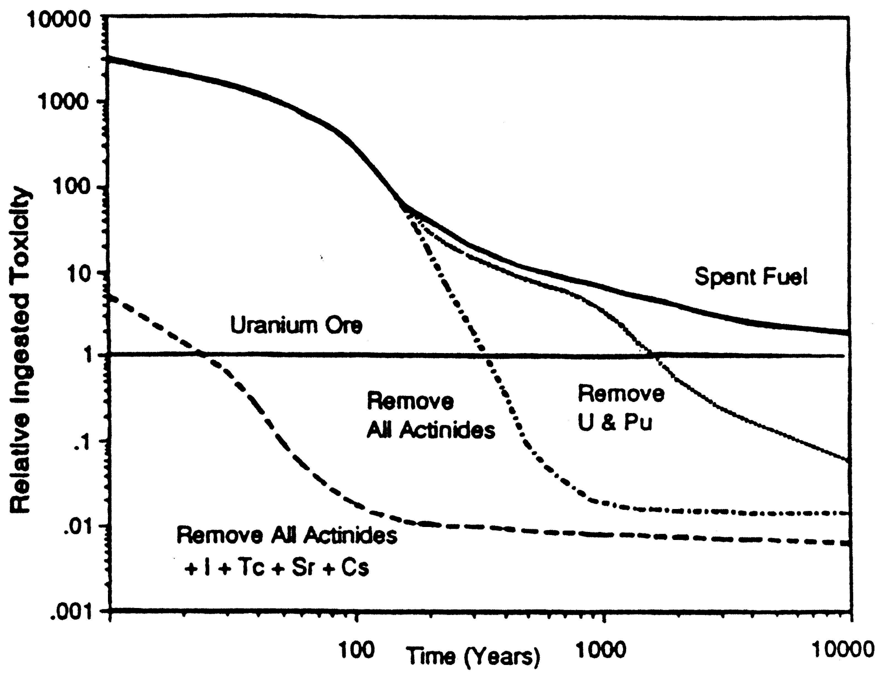

FIGURE 2. Evaluation of the (ingested) radiotoxicity of nuclear wastes coming from a typical reactor, relative to the uranium ore radiotoxicity. The different curves correspond to differentscenarios of partitioning. See text for detail.

5.3. Waste processing

Obviously, HLW coming from spent fuel require a very drastic protection against direct radiation exposure of population, release of radioactive fluids, excessive heating and criticality. Furthermore a strict inventory is of uttermost importance.

For the moment, spent fuel is kept on site, in water pools, for some time. Afterwards, it is sent either to a storage facility or to a reprocessing plant. In the first case, HLW are consolidated and stored in special containers. In the second case, HLW are reprocessed. This means that U, Pu, Np and some fission products are separated by a solvent extraction (PUREX) process from other HLW. U, Pu and Np are further separated. U can be sent to an enrichment plant to be re-used. Pu is partly incorporated in MOX (mixed oxyde) fuel to be burned in LWR's. Such a reprocessing is performed in the La Hague plant, in France, and in Sellafield, in United Kingdom. Reprocessing is often considered as a serious threat for proliferation, since separated Pu can be stolen. On the other hand, it is also claimed that this Pu is not "military grade". It indeed contains a substantial amount of ^{240}Pu, which emits neutrons in spontaneous fission (Pu for nuclear weapons is generally made in special reactors). But civil Pu is probably suitable to build some "nasty" bombs. Reprocessing presents some other advantages. It reduces the volume of HLW. Furthermore some isotopes, such as ^{85}Kr, ^{90}Sr or ^{137}Cs, which have industrial or medical applications, can be reclaimed from the wastes. It is also the case for some rare elements, for example Rd, Ru and Pd.

5.4. Solutions for the future.

The long run management of HLW is still a question of debate. Some countries, e.g. USA and Sweden, which do not reprocess their wastes, have opted for disposal in deep underground repositories. In USA, the site of Yucca Mountain is being prepared. Such repositories are arranged with a multibarrier approach: the first level is the waste conditioning itself (a glassy material), the second one is the container which should be compatible with the surrounding material, the third one is a layer of clay which should prevent intrusion of water and the fourth one is the geological site itself. It has to be suitable to minimize water flow and effects of heat generation. Repositories may be arranged in a reversible way, so that wastes may be reclaimed and reprocessed if future techniques make this possibility favourable.

When reprocessing is adopted, recycling of waste is envisaged. We have already indicated that U is reycled and that Pu is burned in ordinary reactors. However, Pu burning in LWR's is limited for reasons of reactor stability. Actually only about 7% of Pu can be incorporated in MOX. Furthermore, in LWR's, Pu is partly transformed into Cm and Am, by low energy neutron capture. The burning (by fission) of Pu (and of Am and Cm) is more advantageous in dedicated or "ordinary" FR's. The capture to fission ratio is much smaller for fast neutrons. However, fission cross-sections are not tremendeously high, so that burning takes more time.

Another possibility is the transmutation by so-called accelerator-driven systems (ADS). Transmutation is the transformation of long-lived isotopes to shorter-lived ones. For actinides this can be achieved by fission. An ADS is an assembly made of a subcritical reactor, a spallation source and a proton accelerator. The reactor works owing to the continuous supply of neutrons emitted by a spallation source (basically of piece of Pb-Bi) bombarded by high-energy protons. Since the reactor runs in a subcritical mode, it accomodates exotic fuels. Pu and minor actinides can thus be loaded in greater quantities than in the examples above. Several projects exist (see Ref. [9] for a review and a discussion of the merits of ADS's). The EU has recently launched the EUROTRANS project which has to evaluate the feasibility of the partitioning-transmutation cycle and to start the technical studies for a future demonstrator of ADS, that could be elaborated starting from the Belgian MYRRHA project [11].

Transmutation of fission products cannot be made by thermal neutrons because the capture cross-sections are too low. However many of these products show intense narrow resonances in the epithermal domain. They can then be transmuted by placing them in suitable locations in a reactor, corresponding to the appropriate neutron energies. The TARC experiment has shown that this method is promising [10].

Evidently combinations of these possibilities are foreseen. Even plans for the deployment of future FR's and ADS's in EU are drawn. ADS's are expected to start operating around 2050 and the amount of transuranic wastes is expected to stabilize at a level lower than the actual one in year 2070 [12].

One has to keep in mind that there are losses in the partitioning-transmutation procedures and that a small fraction of HLW (2-4%) will have to put in repositories, anyway.

6. CONCLUSION

The foreseeable World energy needs for the XXIst century, the environmental concerns and the long-waited and ethically justified access of poor countries to development make plausible a continued, if not enlarged, use of nuclear energy (unless our development model is radically revised), in spite of the fact that that some countries have opted, perhaps hastily, to a phasing out of their nuclear power. Of course, this choice should be accepted by the populations, which should be convinced of the advantages of nuclear energy and of the mastering of security and waste problems. This short overview indicates that there exist solutions to the last problems, even if they still need further investigations.

In my opinion, academic institutions have an important role to play concerning these issues. Basic research in nuclear physics should be pursued to support future technological developments. Studies on energy development scenarios should be refined. These institutions have also a role for public education. Especially, owing to their independence, they have to explain the advantages and disavantages of the energy options, in order to secure truly democratic choices. Finally, they have to form experts in nuclear sciences. Some countries, in view of a possible phasing out, are progressively neglecting these formations.

ACKNOWLEDGMENTS

I would like to thank Profs. David Blaschke and Jorg Hüfner, who urged me to present this lecture. I am also thankful to Dr. Hamid Aït Abderrahim for having provided me with some material and to Dr. Sylvie Leray for interesting discussions.

REFERENCES

1. *World Energy Outlook 2004* International Energy Agency publications, ISBN 92-64-10750-9 (paper) 92-64-10752-5 (CD-ROM), Paris, 2004.
2. World Energy Council, http://www.worldenergy.org/
3. Nuclear Energy Agency, http://www.nea.fr/
4. B. Barré, *Nucl. Phys. A*, **654**, 409c–416c (1999).
5. R. Wolfson, *Nuclear choices*, The MIT Press, Cambridge, USA, 1991, Chap.9.
6. B. Barré, L. F. Durret and B. Tinturier, *Le nucléaire durable*, Institut National des Sciences Appliquées, Paris, 2004.
7. D. Albright and K. Kramer, *Bulletin of the Atomic Scientists*, November/December 2004.
8. H. Takahashi and H. Rief, *Proceedings of the Specialists' Meeting on Acclerator-Based Transmutation*, PSI Zürich, March 1992.
9. W. Gudowski, *Nucl. Phys. A*, **654**, 436c–457c (1999).
10. S.Andriamonje et al., *Physics Letters B*, **458**, 167–180 (1999).
11. SCK-CEN Mol, Belgium, The MYRRHA project, http://www.sckcen.be.
12. H. Aït Abderrahim, *Proceedings of the International Conference on Nuclear Data for Science and Technology*, Santa Fe, USA, Sept. 2004, to be published.