NUCLEAR ENERGY

NUCLEAR POWER AND THE ENVIRONMENT

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Received October 29, 2004

At the beginning of their development, the use of railroads, the tramway, the underground, the automobile, the first airplane, all raised not only a great skepticism, but also a strong fear or even hostility on the part of the general public, the media and some officials. Contrary to the development of other technologies, in the beginning there was even support and enthusiasm about the possibilities of the wide uses of nuclear energy. However, the voices against the use of nuclear power increased with time. Now the future of nuclear power is dependent on reversing this situation. The present paper addresses the role of nuclear power in the global energy sector in a broader context, that of sustainable social and economic development and the environmental impacts arising from the use of different sources of energy. The main objective of this paper is to provide clear and complete information and to demonstrate that nuclear power is a mature technology that has environmental advantages. The paper is destined to the energy community, energy policy and decision makers, environmentalists and the wider public in order to understand and accept the benefits of nuclear as a fundamental energy source toward sustainable development and a better standard of life. The decisive fact that nuclear power is environmentally benign, makes it an energy source consistent with the goals of sustainable development and environmental protection that should be taken into consideration in discussing the future energy mix in different countries. A special attention is accorded in the paper on the subject of radioactive waste management disposal where are provided top-level information, because this seems to be the warmest subject of the moment.

INTRODUCTION

It is well known that general public and the media still question the desirability and the need for nuclear power, despite the impressive development of it over the last four decades, its environmental advantages as compared to practical alternatives for electricity production, and its economic competitiveness in many countries. The fact that all energy systems of any kind have an impact on the environment is usually unknown or deliberative not discussed by the opponents.

If one looks back through the history of human race, it becomes obvious that man has improved life on this planet by engaging in activities that changed his environment to some degree. Examples of such activities are the use of fire, the development of agriculture, the construction of buildings, the mining of materials, the construction of the canals and dams, the operation of the factories and so on. Whereas it is generally accepted that there is no human endeavor without some effect or some risk to the environment, it is also clear that, on the whole, man has improved radically his standard of existence by engaging in these activities and creating, as a result of them, the industrialized technological society in which we live. The word “effect” means, in a sense, a change. Until the 1960, mankind did not give much thought to the environmental effects. Perhaps, the reason for such behavior was the apparent continuous, until that time, improvement of the standard of living, and the not so apparent continuous deterioration of the environment, as judged primarily by quality of air and water. The environmental movement started in the 1960s and raised the society’s concerns about the changes caused in our biosphere by human activities. It became clear that business as usual could not and should not continue. In many cases, certain activities had to stop, and they did stop indeed (e.g., some dams were not built); in others, standards had to be established to protect the quality of air and water and, by implication, to protect people, the industry had to follow the procedures necessary to comply with those standards. To ensure that the necessary changes would be implemented by industry, by state and institutions, and by individuals, in many countries have been created the Environmental Protection Agencies.

The generation of electricity is one of man’s activities that are indispensable in our life. There is no doubt that the use of electricity has benefited man and improved life tremendously. From lighting to heat, from communication to music, from industrial tool to medical instruments, electricity permeates every aspect and every second of our lives and is making them better. But, like any other human activity, the generation of electricity produces undesirables’ effects. The abandonment of the electricity in order to avoid the detrimental environmental effects is obviously not a viable alternative. However, everybody – either directly involved in this enterprise, or indirectly reaping the benefits of it – should be concerned about possible detrimental environmental results. Our society, like an individual, should not accept any harmful activity that does not lead to a benefit believed to be worth more than its harm. Once a decision is made to proceed with the production of a product or a service, the process chosen should be the most environmentally benign, other factors being equal.

The paper discusses the environmental effects caused by the various methods of producing electricity, including especial the nuclear power and the final disposal of the burn fuel as main environmental effect. In every case, the effects for the total cycle of the process are considered. For example, the effects
from an oil-fired plant include not only those from the direct burning of the oil, but also the effects of pumping the oil from the ground. In the same order of ideas, the effects from the manufacturing of material used in the generation of electricity (metals, concrete, etc) are also taken into account. In this way the reader will be able to put all of the risks into proper perspective.

Discussion of the various methods of generating electricity and their corresponding environmental effects will make clear there is no method that is integral environmentally benign. Since this is the case, the electrical needs of a country are satisfied by choosing methods of generation that are environmentally acceptable, despite their detrimental effects, but also satisfy two other very important factors. One is economics and the other is assurance of fuel supply and both factors play a crucial role in the decision-making process of every country when an electricity generation method is chosen.

The next section deals on short with all the established methods of generating electricity, except nuclear, discussing the environmental effects. The effects from nuclear-fueled plans are presented further in a section dedicated to environment with an especial attention to the disposal of spent fuel which represents “apple of discord” in relation with public. The last section is destined to the conclusions obtained by a comparison of all of the various environmental effects, showing the environmental advantages of nuclear power.

**VARIOUS TYPES OF ELECTRICITY GENERATING SYSTEMS AND THEIR ENVIRONMENTAL EFFECTS**

Fossil fuels are coal, oil and natural gas. Fossil fuels are burnt to heat water in a boiler to produce steam. The steam drives a turbine, which rotates the electrical generator, thus producing electricity. The major environmental effects resulting from the use of fossil fuels are the release, during the burning process, of substances like fly ash, CO₂, nitrogen oxides, sulfur dioxides and traces of heavy metals. Table 1 provides a recent compilation of waste products from coal and oil fuel [1]

<table>
<thead>
<tr>
<th></th>
<th>Coal</th>
<th>Oil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual consumption of fuel</td>
<td>2.3 million [tons]</td>
<td>9.2 million [barrels]</td>
</tr>
<tr>
<td>Annual production of waste</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bottom ash</td>
<td>50,000</td>
<td>–</td>
</tr>
<tr>
<td>Fly ash retained</td>
<td>248,000</td>
<td>–</td>
</tr>
<tr>
<td>Sulphur retained</td>
<td>46,000</td>
<td>–</td>
</tr>
</tbody>
</table>

(continues)
As a result of the emissions from fossil fuels, particularly coal and oil, two major problems have been created. One is the greenhouse effect and the other, the rain acid. Persons directly involved with the extraction of the fuel from the ground are also affected. Finally, there are adverse effects from the production of the materials used for extraction, transportation and storage of the fuel, as well as for the construction of the plant itself. Table 2 [1], with the risks per megawatt-electric-year and a 70% capacity factor is reproduced in order to provide some idea of the value of the numbers involved.

The term “greenhouse effect” is used to describe the potential change of the earth temperature as a result of the change in the atmosphere. The atmosphere of

<table>
<thead>
<tr>
<th>Risks</th>
<th>Gathering and Handling Fuel</th>
<th>Transportation</th>
<th>Electricity Production</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Occupational:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Accidental</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Death</td>
<td>(0.7 to 1.5) $\times 10^{-3}$</td>
<td>(1.6 to 5.0) $\times 10^{-3}$</td>
<td>(1.3 to 9.0) $\times 10^{-5}$</td>
<td>(2.5 to 6.7) $\times 10^{-3}$</td>
</tr>
<tr>
<td>Injury</td>
<td>0.04 to 0.07</td>
<td>(1.3 to 4.8) $\times 10^{-2}$</td>
<td>(1.6 to 8.5) $\times 10^{-3}$</td>
<td>0.056 to 0.083</td>
</tr>
<tr>
<td>Man-days lost</td>
<td>8 to 16</td>
<td>1- to 32</td>
<td>0.16 to 0.97</td>
<td>20 to 51</td>
</tr>
<tr>
<td>Disease</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Death</td>
<td>(0 to 7.5) $\times 10^{-4}$</td>
<td>–</td>
<td>–</td>
<td>(0 to 0.75) $\times 10^{-4}$</td>
</tr>
<tr>
<td>Disability</td>
<td>(4.2 to 8.4) $\times 10^{-3}$</td>
<td>–</td>
<td>–</td>
<td>(4.2 to 8.4) $\times 10^{-3}$</td>
</tr>
<tr>
<td>Man-days lost</td>
<td>0.2 to 5.0</td>
<td>–</td>
<td>–</td>
<td>0.2 to 5.0</td>
</tr>
</tbody>
</table>

* Per MW(e)-year and a 70% capacity factor.
Nuclear power and the environment

The earth allows the heat of the sun to reach the planet and retains the earth heat in such a way that the temperature of our planet stays about constant. If the composition of the atmosphere changes, the possibility arises that this heat-exchanging process may become unbalanced and act like a greenhouse, trapping the heat and not letting it escape, in which case the temperature of the earth may change and result in adverse global climatic effects [2]. The following energy balance may be written:

\[
\text{(Solar Energy Reaching the Earth) = (Energy Radiated Back to Space)}
\]

Or equivalent:

\[
\pi R^2 (1 - A) S = 4 \pi R^2 \sigma T^4
\]

Where:
- \( R \) = radius of the earth,
- \( A \) = Aledo of the earth,
- \( S \) = solar radiation flux (W/m\(^2\)),
- \( \sigma \) = Stefan-Boltzmann constant = \( 5.67 \times 10^{-8} \) W/m\(^2\),
- \( T \) = temperature of the earth (K).

If one assumes that \( A = 0.3 \) and \( S = 1367 \) W/m\(^2\), then \( T \) has to be 256 K. Since the mean temperature of the earth was measured as being 289 K, this increase of 33 K is attributed to atmospheric gases.

There are five gases that make the earth atmosphere retain heat and thus contribute to greenhouse effect. They are: carbon dioxide (CO\(_2\)), methane (CH\(_4\)), nitrogen oxide (NO\(_2\)) and two chlorofluorocarbon (CFCl\(_3\) and CF\(_2\)Cl\(_2\)). From these, it is estimated that CO\(_2\) is responsible for about half of the greenhouse effect [3]. It is reported that the global concentrations of CO\(_2\) have increased more than 25% since the mid-1800s, from 280 part per million (ppm) in the mid-to late-nineteenth century to more than 350 ppm today. Mauna Loa Observatory, Hawaii, has reported [4] that the result of measurements shows not only the increase in CO\(_2\) from the atmosphere, but also the monthly averages. Seasonal variations are the result of CO\(_2\) being removed from the atmosphere during the growing season in the northern hemisphere, and then released during the autumn and winter. Fig. 1 [5] shows a rise of more than 10% since 1958. The current rate of increase, is 1 ppm per year (\( 2.3 \times 10^{12} \) kg of carbon dioxide).

Analyses of air trapped in ice cores in Antarctica indicate that there was little, if any, change in the carbon dioxide for many centuries before the nineteenth century and the industrial revolution. More than one-quarter of the previously mentioned increased in the CO\(_2\) in the atmosphere has occurred in the past ten years.

A segment of the scientific community has been aware of the CO\(_2\) problem for many years. For instance, the great chemist Svante-Arhenius had recognized the potential seriousness of the problem early in the last century. His calculations and predictions, although a bit higher, are surprisingly in agreement with today estimates.
However, at the beginning of the new millennium, there is no conclusive evidence and no scientific unanimity as to whether the greenhouse effect is present and, if it is, what its effect will be. There is at least one study [6] that compared the temperatures measured by satellite with those predicted by an international used computer model of climate change. During 1980–1996 the measurements show a decline, whereas the computer model predicts a temperature increase. Living the uncertainty aside, one can bring the following arguments against air pollution of any sort. The earth atmosphere is finite in volume and mass. If the activities of the human race continue to infuse in it quantities of CO$_2$, NO$_x$, etc., the composition of the atmosphere will change and the present “equilibrium” will be disturbed eventually. As a result the earth heat balance may change. The question is in what way? Will the new temperature be higher or lower? Either trend will be detrimental to the biological space. More than that, once the trend becomes real, it will not be possible to reverse it quickly: it will take time and a substantial global effort to return to the pre-greenhouse state. Therefore, the prudent approach is to reduce the pollutants that go into the atmosphere by (a) curtailing the activities that generate pollutants and by (b) replacing the polluting industrial activities with others that are environmental benign. Fortunately, the world leaders have recognized the potential problem and in three major conferences, Rio de Janeiro, Brazil, Kyoto, Japan and Johannesburg, South Africa, have signed agreements aiming at keeping our air at least as clean as it today.
As concerns the acid rain the term is used to describe the transformation of sulfur dioxide (SO$_2$) and nitrogen oxides (NO$_x$) in the atmosphere into sulfuric (H$_2$SO$_4$) and nitric (HNO$_3$) acids, respectively [7]. In addition, it has to say that part of the nitric oxides contribute to the production of the ozone, which is positive fact. These sulfuric and nitric oxides are emitted of course, during the combustion of fossil fuels, primary coal and oil. The sulfuric and nitric acids are transported considerable distances by air currents before they fall back on the earth. Thus, this form of pollution affects not only the population close to the center using the fuel, but also people far away from it. Acid rain crosses state as well as national boundaries. The acids falling on the earth, either on the ground or on trees or on water, cause deleterious effects. There are many localities in the developed states where the adverse ecological effects of acid rain on the environment are visible and measurable in terms of fish kills, deforestation, and destruction of life in rivers and lakes, and others. Certainly, for persons breathing the acid rains, respiratory problems may result.

Other sources of energy as hydroelectric, geothermal and solar although at first glance seem to be more attractive from point of view of environment impact, are however polluting in a considerable manner. For instance the environmental effects of hydroelectric power are: (1) ecological changes in the locality where the dam is built, (2) effects from the production of the large amount of materials needed for the construction of the dam (concrete, steel, etc) and (3) effects resulting from catastrophic dam failure that have occurred in the past in various parts of the world. As concerns the geothermal power again it may be said that certainly on a local level is not benign. But, there is noise and air pollution from hydrogen sulfide, ammonia and other effluents. Pollution of surface or groundwater may result from the disposal of wastes. Generating electricity by solar is still expensive and the environmental effects are twofold: (1) there may be an ecological local effect if a very large area is covered by collectors, (2) adverse effects may result from the production of the needed materials, as silicon that is a very intensive electricity process [8].

Less developed potential electrical power sources as tides, wind or fusion have also environmental problems. For instance fusion reactors, at least the first generation using deuterium-tritium reaction, will have radioactive products to dispose of and large quantities of tritium to handle routinely. In addition, a considerable mass of materials will be needed for the construction of a fusion reactor of the magnetic confinement type.

**NUCLEAR POWER PLANTS AND THEIR ENVIRONMENT**

Nuclear electrical generation plants are proving themselves daily throughout the world. Nuclear fission is highly stable, entirely predictable process, one of
Worldwide nuclear power is the third most used source of energy for electricity production, after fossil and hydropower. Nuclear power supplied 2448 TWh of electricity in 2000, or about 16% of total electricity generation worldwide [14].

Despite the generally proven successful operation of nuclear power plants, there is a public perception after the Chernobyl accident, that nuclear poses a great threat to the environment. But we have to notice that in fact, if the circumstances had permitted the discovery of nuclear fission prior to the extensive use of coal and oil to produce electricity, most of our electrical needs would now be satisfied with nuclear power! Indeed, the use of power plants fueled with coal and oil might have been prohibited since they would not have been able to satisfy stringent air quality standards to match the performance of nuclear plants.

Nuclear power is the only technology used for electricity generation that, from the very beginning of its development, took the environmental impacts into consideration. It is one of the human activities in which research on safety was developed together with its technology. Nuclear power plants are licensed from a safety point of view by independent governmental organizations and also subject to regional and local site approval procedure. Participation of public and nongovernmental organizations in both licensing and environmental procedures is allowed and just encouraged. Its impacts on the environment are almost nonexistent, if well managed.

In fact the environmental effects from the construction and operation of nuclear power plants fall into the following categories: (1) effects associated with the materials used for the construction of the plant, (2) effects associated with the nuclear fuel cycle (from mining of uranium to disposal of radioactive wastes), (3) radiation exposure of workers and public during normal operation of the plant, (4) potential radiation exposure during an accident that may result in the release of radioactive fission products to the environment. The first concern is no different for nuclear plants than it is for any other type of plant. On a per megawatt-electric basis, nuclear is not the most material-intensive construction, but the hydroelectric and solar are. Concern 2 is specific to nuclear because the nuclear fuel is radioactive. All available evidence indicates that the effect of the nuclear fuel cycle on the environment (weather, air, vegetation, people) is less than that from many other activities including the use of coal and oil [1, 9]. Concern 3 arises because some radioactive releases take place during the normal operation of nuclear power plant. The best way to estimate the effect of these releases is to compare them with those from other sources, Fig. 2. [10].

Coal-fired plants also emit radioactive materials routinely and are, therefore, responsible for some radiation dose to the public, as is shown in the Table 3 [8].
The forth concern is the most controversial one because of its probabilistic nature. The probability of a reactor accident that may release radioactive products to the environment has been the subject of many studies. The most recently is the NUREG-1150 [13], which represents the state of the art probabilistic risk assessment methodology. The best estimate for core damage is about $10^{-5}$ to $10^{-16}$ per reactor year. This number means very little standing alone, but it obtains significance if it is compared to the frequency of other accidents, some of them accepted routinely. Fig. 3.

Despite the Chernobyl accident, there is no industry in the world that can present the same excellent record of safety performances as the nuclear industry. All these safety and environmental features are incorporated in the final costs of nuclear power, including, in many countries, provisions for waste management and for future plant decommissions. This means that all safety and environmental
Table 3

Comparison of radiation doses to the population from a coal-fired and a nuclear 1000 MWe power plant

<table>
<thead>
<tr>
<th>Organ</th>
<th>Maximum Individual Dose (^a) [mrem/yr]</th>
<th>Population Dose (^b) [man-rem/yr]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Coal-Fired Plant (^c)</td>
<td>Nuclear Plant (PWR)</td>
</tr>
<tr>
<td></td>
<td>Stack Height 325 ft</td>
<td>Stack Height 650 ft</td>
</tr>
<tr>
<td></td>
<td>Stack Height 975 ft</td>
<td>Nuclear Plant (PWR)</td>
</tr>
<tr>
<td>Whole body</td>
<td>1.9</td>
<td>1.8</td>
</tr>
<tr>
<td>Bones</td>
<td>18.2</td>
<td>2.7</td>
</tr>
<tr>
<td>Lungs</td>
<td>1.9</td>
<td>1.2</td>
</tr>
<tr>
<td>Thyroid</td>
<td>1.9</td>
<td>3.8</td>
</tr>
<tr>
<td>Kidneys</td>
<td>3.4</td>
<td>1.3</td>
</tr>
<tr>
<td>Liver</td>
<td>2.4</td>
<td>1.3</td>
</tr>
</tbody>
</table>

\(^a\) At the plant boundary to be 500 m from the point of release.

\(^b\) Out to 55 miles for a site assumed to have a population of 3.5 million with that radius.

\(^c\) Assuming an ash release of 1% and coal containing 1 ppm uranium and 2 ppm thorium.

In addition, the nuclear power plant occupies only small surfaces of land and consumes small amount of fuel [11]. Also, its waste is small, confined and isolated from the environment [12].

Fig. 3. – Frequency of man caused events with fatalities greater than a number N, compared to estimated fatalities from the 100 nuclear power plants.

costs are internalized, which is certainly not the case with conventional thermal power plant. Even so, nuclear power remains competitive in many countries under this unequal condition of comparison.
We have to notice that in 2000, coal, oil and gas together supplied 86% of the energy consumed in the world; hydropower and other renewable sources, 7.5% and nuclear power, 6.5%. Although new gas fields are being discovered and the efficiency of extracting oil is increasing continuously, it is expected that these resources will begin to run out by 2050. Hence other sources of energy, including renewable energy (hydropower, solar, wind and biomass) and especially nuclear energy, will have to play a major role. A probable evolution of the total energy supply during the next 50 years estimated by experts of the oil industry is given in Table 4 [14].

<table>
<thead>
<tr>
<th>Year</th>
<th>Source</th>
<th>Gtoe</th>
<th>%</th>
<th>Gtoe</th>
<th>%</th>
<th>Gtoe</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Oil</td>
<td>3.7</td>
<td>40</td>
<td>5.0</td>
<td>36</td>
<td>3.5</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>Gas</td>
<td>2.1</td>
<td>22</td>
<td>4.0</td>
<td>29</td>
<td>4.5</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>Coal</td>
<td>2.2</td>
<td>24</td>
<td>3.0</td>
<td>21</td>
<td>4.5</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>Total fossil</td>
<td>8.0</td>
<td>86</td>
<td>12.0</td>
<td>86</td>
<td>12.5</td>
<td>70</td>
</tr>
<tr>
<td></td>
<td>Renewables&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.7</td>
<td>7.5</td>
<td>1.0</td>
<td>7</td>
<td>1.5</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>Nuclear</td>
<td>0.6</td>
<td>6.5</td>
<td>1.0</td>
<td>7</td>
<td>4.0</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>9.3</td>
<td>100</td>
<td>14.0</td>
<td>100</td>
<td>18.0</td>
<td>100</td>
</tr>
</tbody>
</table>

<sup>a</sup> Including hydropower.

One observes that the quote of the nuclear energy by 2050 is 3.4 times higher than the quote from 2000 and comparable with the quote of oil, gas and coal. These results are consistent with all other investigations made by nuclear organizations. The need for nuclear power could be even higher if the nuclear energy were used to generate more than just electricity (i.e., chemical fuels as hydrogen [15], heat district heat process, desalination, etc.).

However, the great merit of the nuclear energy is the environmental advantages that it has it. In this context it has to say that nuclear power does not produce CO₂ or other greenhouse gases, nor does it produce any SO₂, NOₓ, or other gases that contribute to acid rain. These characteristics of nuclear power are especially important in comparison to the coal fired generation of the electricity, which contributes with the 24% of all electricity generation in the world. As an example in comparison with a modern coal-fired power plant of the same size and with the advanced abatement techniques, a 1300 MWe nuclear power plant avoids annual emissions to the air of about 2300 t of particulates, 10 million tons of CO₂, 14000 t of SO₂, and 7000 t of NOₓ, the precise quantities being dependent on coal quality and other characteristics of the plant. Because
today 16% of the world electricity is generated using nuclear power, if this
electricity were to have been generated using coal, it would have resulted in
about 2.5 billion tons CO₂ annually. As a result, nuclear power is already avoiding
10% of present CO₂ emissions by all sources and 29% by the power sector –
Table 5 [14].

\[ \text{Table 5} \]

CO₂ Emission Worldwide

<table>
<thead>
<tr>
<th>Emissions by the combustion of fossil fuels</th>
<th>25 billions tons of CO₂/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>World electricity production by nuclear power</td>
<td>2248 TWh (net) 2000</td>
</tr>
<tr>
<td></td>
<td>16% of total electricity generation</td>
</tr>
<tr>
<td></td>
<td>6% of total primary energy production</td>
</tr>
<tr>
<td>Amount of avoided CO₂ emissions due to the use of nuclear power in 2000</td>
<td>2.5 billion tons</td>
</tr>
<tr>
<td></td>
<td>10% of total CO₂ emissions</td>
</tr>
<tr>
<td>Recommendation from the Toronto conference (1988)</td>
<td>Cut tot. annual emissions by 20%</td>
</tr>
<tr>
<td></td>
<td>4 billion tons of CO₂ up to 2005</td>
</tr>
<tr>
<td>Power sector</td>
<td></td>
</tr>
<tr>
<td>CO₂ emissions</td>
<td>8.5 billion tons</td>
</tr>
<tr>
<td>Avoided emissions due to the use of nuclear power</td>
<td>29% of power sector</td>
</tr>
</tbody>
</table>

It has been argued that, from the environmental point of view, nuclear
power should not be compared with coal power plant, but with natural gas,
considered to be a cleaner source of energy. Not considering the issues of gas
availability and the assumption that the price of gas will stay low for many years,
some aspects need to be discussed when stating the gas is a “clean” technology.
Considering power generation, Fig. 4 compares a nuclear power plant with a gas
combined-cycle power plant [14].

The combustion of gas emits several air pollutants, such as SO₂, NOₓ, CH₄,
CO, and CO₂. In particular, the emissions of nitrogen oxides, one of those
responsible for acid deposition, and CO₂, the main greenhouse gas, are substantial,
as per Fig. 2. Considering the full energy chain, there are emissions of methane
(CH₄), during the extraction and transportation of gas. As methane is a much
stronger greenhouse gas than CO₂, transforming the amount of methane in CO₂
equivalent, the emissions of greenhouse gases from the use of gas in electricity
production might be of same order as those of the coal cycle. From these
considerations it can be said that the use of gas can not be reported as the
solution of the climate change problem.

Another environmental advantage of nuclear power is connected by the
waste disposal. This is the truth, in spite of negative perception of the public
concerning the radioactive waste management. Part of the waste resulting from
the burning coal, namely, toxic heavy metals such as arsenic, cadmium, lead and mercury, remains dangerous forever in the environment, contrary to the wastes of nuclear power generation, whose radioactivity decays with time. For instance a coal-fired plant of $2 \times 650$ MWe are responsible for 99 t/yr of arsenic, 40 t/yr of lead, 3 t/yr of cadmium, and 0.5 t/yr of mercury. The quantity of toxic metals emerging as waste by the combustion of coal is more than 10 times larger than the quantity of spent nuclear fuel, and over 30 times more than the separated high-level waste products if the fuel is reprocessed, resulting from the generation of the same amount of electricity by a nuclear power plant. Further, it must be emphasized that the relatively much smaller amount of nuclear waste is fully isolated from the environment. From coal generation, depending on the stack filtration system, 1–10% of the above amounts could be dispersed to the atmosphere together with CO$_2$ sulfur, and nitrogen oxides. A great part stays in the ashes. Usually, ashes are flushed with water to ash ponds, where elements may be leached and enter the aquatic environment. If the same standards as applied to nuclear power plants were applied to coal power plants, the dangerous wastes from coal generation would need to be removed and isolated. Coal power plant also emits naturally occurring radioactive nuclides to the atmosphere, because most coal contains thorium (6 t/yr) or uranium (3 t/yr) per 1300 MWe. As a consequence, paradoxical, sludge from coal power plant contains radioactive materials, not controlled as in nuclear power plants. A nuclear power plant normally delivers a smaller radiation dose per unit of energy produced than a coal-fired plant. Owing to the fact that nuclear is a highly concentrated form of

![Diagram showing annual fuel and waste disposal requirements of a 1300 MW(e) plant.](image-url)
energy, 1 t of nuclear fuel in a LWR for instance, produces the same amount of electricity as 20,000 t of hard coal of good quality, and therefore the volume of radioactive wastes is very small – Fig. 5.

![Fuel reprocessing and recycling diagram](image)

**Fig. 5. – SF reprocessing schematic.**

This important characteristic of the nuclear fuel cycle means that its waste volumes are very small compared with different alternatives as previously described. Hence, they can be adequately handled and treated. As a matter of fact, nuclear power is the only energy technology that treats, manages, contains and isolates its wastes in a way to fully protect human health and the environment. Solutions for final disposal of low-, medium-, and high level radioactive wastes are available and in use in several countries. New technologies for waste management and disposal are feasible and some are already under development.

Over the decades since the start of major radioactive waste research, a variety of disposal and other waste management options have been suggested [16]. Interest in the various options focuses on two ethical concerns: intergenerational equity (fairness and equity considerations between generations) and intragenerational equity (fairness and equity considerations within contemporary generations). A set of principles to be used as a guide in making ethical choices about waste management strategy are already in circulation as follows [17]: 1) the liability of waste management should be considered when undertaking new projects, 2) those who generate the wastes should take responsibility and provide the resources for the management of theses materials in a way that will not impose undue burdens on future generations, 3) wastes should be managed in a way that
secures an acceptable level of protection for human health and the environment and affords to future generations at least the level of safety that is acceptable today; there seems to be no ethical basis for discounting future health and environmental risks, 4) a waste management strategy should not be based on a presumption of a stable societal structure for the indefinite future, nor of technological advance; rather it should aim at bequeathing a passively safe situation that places no reliance on active institutional controls.

The principle of intergenerational equity requires that we show care for future generations by not placing them under undue burden to care for our waste. In addition, the current generation should not limit the options available for the next generations. The principle of intragenerational equity requires that the contemporary generations deriving the benefits immediately should pay its costs now by providing financial resources for handling the wastes in such conditions that everybody from the contemporary generation will be protected at a high enough level.

Concerning the waste management strategies of the most important representatives – spent-fuel (SF) and high level waste (HLW), we have to notice that reprocessing refers to the practice of extracting plutonium, uranium and undesirable fission products and actinides, Fig. 5 [17].

The plutonium is available for reuse as fuel in nuclear power plant (LWR or CANDU reactor) [11]. The uranium discharged from LWR may be recycled as fuel or may be used for other applications, but in more countries like Romania for instance, uranium discharged from CANDU reactor is considered to be a waste product in spite of the high content of plutonium, and the reprocessing is ignored [16]. Instead, in case of uranium from LWR, if the reprocessing is applied, the fission products and remaining actinides, which constitute only a small fraction of spent fuel, are incorporated into a suitable matrix such as glass for eventual disposal. Although reprocessing changes the characteristics of the waste form, reprocessing spent fuel does not alleviates the need for geological disposal.

However, decisions on whether to reprocess fuel are determined by the need to balance considerations such as the cost of different fuel cycle management options, the availability of indigenous fuel resources, the desire of maximizing the energy extracted from uranium, the capacity of interim storage for spent fuel and the energy value of recovered uranium and plutonium as feedstock for the manufacture of the new fuel. In this way, the question of whether or not to reprocess the SF from LWR and CANDU reactor is thus not fundamentally a waste management issue, how it was believed up to date.

Long-term surface storage, reprocessing, partitioning and transmutation (P&T) – the chemical separation, or partitioning, followed by reducing the quantity of long-lived radionuclides by changing, or transmutation, with nuclear reactions, long-lived radionuclides into short-lived radionuclides, or just stable elements- are potential components of the overall waste management strategy,
eventually leading to deep geological disposal. From this point of view, different waste management strategies for SF and HLW can be envisaged, namely: 1) extended or indefinite surface storage, 2) direct disposal (interim storage of SF followed by deep geological disposal with or without waste retrievability), 3) conventional closed cycle (interim storage followed by reprocessing and deep geological disposal with or without waste retrievability; after SF reprocessing, a geological disposal decision could be deferred, leading to the extended or indefinite storage of the resulting high-level liquid wastes or the conditioned vitrified HLW, 4) advances closed cycle (interim storage followed by reprocessing, P&T of minor actinides and long-lived fission products, and deep geological disposal with or without waste retrievability); after waste P&T, a deep geological decision could be deferred, leading to the extended or indefinite storage of the resulting partitioning and transmutation residues.

The P&T schemes bring together fuel-reprocessing plants, radionuclide separation plants, and various nuclear reactor types, (CANDU type, for instance, has especial merits), to produce nuclear energy while minimizing the creation of long-lived waste. But intensive research would be required to realize these schemes, which suggests that P&T is a technology that will take decades to come to fruition. The fact is that P&T programs are long-term projects that do not affect the present fuel strategy and that the concept cannot avoid the need for eventual deep geological disposal. The well-executed deep geological repositories are already deemed to be very convenient from the level of risks point of view. So, although the P&T would drastically reduce the hypothetical possible future consequences of unforeseen events, far into the future, should not be used as an excuse to postpone development of the deep geological disposal which will be needed anyway.

Long-term surface storage would allow the waste to remain easily monitorable and retrievable, thereby giving future generation’s greater freedom of choice and giving time for other waste management options to be developed. Another advantage is that the technology for waste surface storage already exists for low, intermediate, SF and HLW in many countries and is cheaper. On the other part, the disadvantage is that the long-term storage implies a commitment to active long-term management, passing the obligation for continuous supervision and maintenance to future generations and offers little protection against the long-term risks that could arise from the loss of social stability and control. One interpretation of the concept of sustainable development would support the extended storage approach, where one generation would pass on to the next generation a world with equal opportunity. According with this idea of a rolling present, the current generation would have the responsibility to provide to the succeeding generations the skills, resources and opportunities to deal with any problem the current generation passes on. However, if the present generation delays deep geological decisions because the surface storage is cheaper, it should
not expect future generations to make different decision. Such an approach in
effect would always pass responsibility for real action to future generations
and for this reason could be judged unethical [17].

The most attractive concept now is the phased deep geological disposal.
A primary motivation for this is based on the principle that the generation that
benefited from the activities that produced the radioactive waste should support
the cost of disposal. The safety of a disposal facility should not depend on its
long-term maintenance or even knowledge of its existence by future generations.
At the same time, it would be wrong to take steps that would totally foreclose all
other options that future generations might like to take up. A phased approach to
deep geological disposal, where the waste remained retrievable over an extended
period, might meet this need. The retrievability of waste allows future generations
to decide if there is a better alternative to geological disposal. The retrievability
is an important ethical consideration because deep geological disposal should not
be considered a totally irreversible process. The principle of sustainable
development requires a balance between the needs of the present and future
generations. In this context, many countries favor a stepwise approach to
repository development, whereby the present generation establishes a facility for
long-term management of the waste while allowing future generations the option
of adopting different management strategies, if they wish to do it. However, this
approach is more expensive and therefore is not considered by countries with
smaller financial potential. Speaking about Romania, we have to show that the
waste management strategy adopted for SF discharged from CANDU reactor is
the strategy no. 2 – direct disposal with an interim storage of SF followed by
deep geological disposal without waste retrievability. The interim storage
already exists at Cernavoda site and intensive research were performed about the
assessment of the deep geological repository in different host rocks as salt and
granite [18]. The site for the repository was not up to date fixed. Regarding the
low and intermediate waste a surface storage has been decided to be built at
Saligny site and a strong research activity is now in rolling [19].

CONCLUSIONS

No method of generating electricity exists that is without risk or without
any adverse environmental effects. Nuclear fission reactors used for generation
of electricity do not pose a greater threat, either to the people or the environment,
than the other methods employed for the same activity. In fact, the existing data
show that, with the exception of gas-fired plant, nuclear power fares better than
all the others, if all effects are taken into account. The public perception of the
future of the nuclear industry is often related to its negative perception of
radioactive waste management. The solution to this problem is to go into a process
of formal and informal consultation, communication and local involvement with public. So, it could become clear that phased deep geological disposal is a positive concept. Because it is essential to provide electricity to a world population approaching 10 billion people in the next 50 years, the nuclear power is a part of the solution that has the advantage of avoiding the wide variety of environmental problems arising from burning fossil fuels. Environmental problems that received the most attention have been “global warming”, which is changing the earth climate: acid rains, air pollution and the destructive effects of massive coal mining and oil spills on bio-systems. Non-electrical applications of nuclear energy, such as heat, potable water and hydrogen production, if further developed, would enlarge significantly nuclear energy contribution to avoid emissions of greenhouse gases. Without nuclear power, the long-term future of the global ecosystems is at risk. It is not claimed that an extended use of the nuclear power would be the only solution for avoiding global warming or other environmental damages originating from electricity production. It is asserted that nuclear power offers a significant contribution to a global energy balance with low emission of gases that cause climate change and that it should be used in a well-balanced combination with the energy conservation and renewable sources so that emissions of greenhouse gases can effectively be reduced.

REFERENCES