Climate Change, Nuclear Proliferation and Fusion Energy

R. J. Goldston 1), L. R. Grisham 1), G. W. Hammett 1)

1) Princeton Plasma Physics Laboratory, Princeton NJ 08543, USA
E-mail contact of main author: rgoldston@pppl.gov

Abstract. Analysis of the energy and environment literature suggests that ~12,000 GW of electrical power production is projected for 2100, with relatively little scatter between models and scenarios, and that nuclear power could make a significant contribution by providing ~ 30% of world electrical power in 2100. The annual fueling of plutonium for a 3600 GWe fleet of fast-spectrum fission reactors is approximately equal to the content of one million first-generation nuclear weapons, presenting a daunting challenge to disarmament and non-proliferation regimes. If fusion begins to enter commercial operation in 2050 and grows at a rate ≤ 0.9%/yr of the world electric market (fission grew from 1975 – 1990 at 1.2%/year of the then electric market), it can provide the projected nuclear electrical power in 2100 with much lower proliferation risk.

1. Introduction

Nuclear power has the potential to produce energy with minimal atmospheric emission of carbon dioxide. It also has the potential to facilitate the proliferation of nuclear weapons. The damage to humanity and the world environment from either climate change or nuclear war would be severe. Both could have devastating impacts on the heritage passed on to future generations. This paper uses recent energy, environment and economics modeling for the period up to 2100 to estimate the scale of a meaningful role for nuclear energy in mitigating climate change, and then uses calculations of stocks and flows of fissile materials based on recent technological studies to assess the associated proliferation risks.

2. Integrated Energy, Environment and Economics Modeling

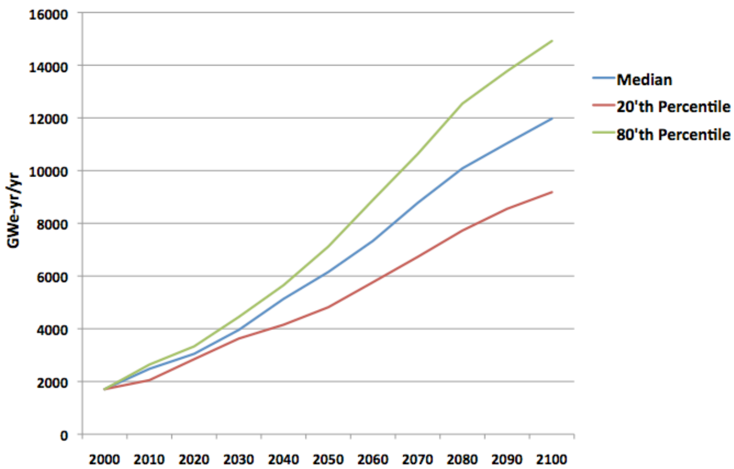

FIG. 1. Electrical power production from EMF 22 models.

The database from the Energy Modeling Forum 22 (EMF 22) study [1] provides a basis for projecting future electrical energy use. Published in late 2009, it includes modeling results from a large number of major groups around the world, taking into account multiple energy sources and opportunities for improvements in efficiency. CO_2 constraints were varied from business-as-usual (no constraint) to atmospheric concentration as low as 450 ppm equivalent. Overshoot of CO_2 concentration compared with the ultimate goal was allowed or disallowed, and early participation in emissions constraints was assumed only for developed countries, or for all countries. The projection for electrical energy production, across the wide range of models with this wide range of constraints, was surprisingly stable. In highly carbon-constrained cases energy use was reduced, but this was compensated by increased electrification of energy supply. The median projection of electrical energy production from the EMF 22 database is shown in figure 1, while the 20^{th} and 80^{th} percentiles provide a sense of the variation over models and constraints. Adding to the credibility of this projection, the average worldwide logarithmic growth in the median case from 2010 to 2100 is moderately less than has been experienced over the last 30 years.

The five-fold increase of electrical power production from 2010 to 2100 shown in figure 1 will be difficult to achieve while also minimizing carbon emissions. Below we consider a strawman case, generally consistent with the EMF-22 modeling scenarios, where 40% of electrical production in 2100 is provided by combustion coupled with carbon sequestration, 30% is provided by tapping natural energy flows and 30% is provided by nuclear energy.

3. Electrical Power from Combustion with Carbon Sequestration

As summarized in recent reports [2, 3, 4] subsurface injection of carbon dioxide is a well-developed technology, although not at the scale required for power generation in the GWe range. A single 1 GWe-yr/yr coal-fired power plant with a lifetime of 60 years would need to sequester about 450 Mt CO_2 under an area of about 150 km^2. Substantial R&D is needed to determine the potential of various geological formations for retention of CO_2 at this scale, without significant leakage over hundreds of years. Even with successful R&D, there will certainly be licensing issues associated with the potential safety and environmental impacts of such large undertakings.

The total world's total technical potential for CO_2 storage in geological formations, not considering economic feasibility, is estimated by the Intergovernmental Panel on Climate Change [2] at a lower limit of 1850 Gt CO_2. The range of published projections is quite varied [3] with the upper limit of technically potential storage in some cases as much as an order of magnitude higher. If we assume a linear time variation of the fraction of electricity from combustion from today to 2100 and include the storage commitment associated with the remaining lifetime of the plants existing in 2100, about 3200 Gt CO_2 storage is required. This is more than 70% above the IPCC lower-limit estimate of technical potential.

Carbon capture and storage (CCS) reduces the net efficiency of extracting electrical energy from coal by ~25%. CCS also is currently in the range of 90% efficient at capturing CO_2 produced, so that CO_2 emissions per net kWh are reduced by about 87%. 4800 GWe generated using coal and CCS would emit 4 Gt CO_2/year, which is beyond the total world CO_2 emissions from electricity production in carbon-constrained scenarios. Even taking into account future improvements in CCS technology, large scale production and combustion of biomass-based fuel would be needed, in parallel with coal, to achieve acceptable net emissions. Overall, the achievement of 40% electrical energy production in 2100 from combustion plus sequestration represents an important, but challenging, goal.

4. Electrical Power from Natural Energy Flows

The dominant non-carbon-emitting electrical energy source today is hydropower, providing about 16% of world electrical production in 2007. While hydropower has potential for growth in the future, it is not likely to be able to track the factor of five increase projected for 2100. If it grows by a factor of two, to its realistic limit [5], large-scale hydropower will provide about 6% of world electricity in 2100. Other hydrological sources such as tides and wave power are not projected to be major contributors. The low thermal conductivity of rock, the difficulty of drilling deep into igneous and metamorphic rock, and induced seismicity have been raised as serious concerns for deep geothermal power, although some studies indicate a large potential total capacity, with the possible production of as much as 100 GWe in the U.S. by 2050 [6].

We assume that 30% of world electrical production will come from natural energy flows in 2100 (3600 GWe), including perhaps 10% from steady sources such as hydropower and geothermal, and 20% from intermittent energy sources such as wind and solar. The fraction of intermittent energy that can practically be incorporated into a regional electrical system is controversial. Large, strong grids can average variable production over large areas, but energy storage to smooth out the natural time variability of intermittent sources is speculative. Even if wind and solar power are averaged over the entire Great Plains "wind belt" region of the U.S., from Texas to North Dakota, total power output drops below 11% of peak capacity during 10% of the time [7], necessitating demand reductions and/or significantly increased generating capacity. A USDOE study [8] targets 20% electrical power production from wind by 2030, but requires a significant upgrade to the U.S. electric grid that may be difficult to implement. Some argue, on the other hand, that a factor of ~ 2 higher fraction can be achieved before technical limits are reached [9]. Since many regions of the world, including China, Europe, India, Japan and Korea, are much less well endowed with wind resources per capita than the U.S. [10], it appears that a 20% world-average contribution from intermittent energy sources represents an important, but challenging, goal.

Of course the above estimates are very uncertain, but they do motivate evaluation of the proliferation risks characteristic of a level of nuclear power of order 3600 GWe in 2100. Nuclear power could contribute significantly to reducing CO_2 emissions either by circumventing the limitations of other energy sources discussed here or by reducing the overall cost of emissions reduction as deduced from economic models [10].

5. Electrical Power and Proliferation Risks from Light Water Fission Reactors

The far-dominant current fission reactor technology is light-water reactors (LWRs), which are considered here. This technology is mostly employed using a once-through fuel cycle, in which uranium is first mined from the earth and then enriched from its natural concentration of 0.7% ^{235}U to about 4.5%, called low-enriched uranium, LEU. About 200t of natural U is needed to provide 1 GWe-yr from LWRs. If the fraction of nuclear power from LWRs is assumed to ramp linearly from its current value of 14% to 30% in 2100, 59 Mt of U would be required, including that needed to complete operation of the reactors in use in 2100.

NEA and IAEA "Red Book" [11] estimates of total discovered plus undiscovered U have been relatively stable at about 16 Mt U since they were first reported in 1982. However there is considerable disagreement in the literature [12, 13] on future conventional uranium reserves, particularly because the price of electricity from LWRs is very weakly dependent on the price of mined uranium. Furthermore, unconventional uranium sources such as seawater [14] may become available at an acceptable price. On the other hand, there is considerable variation from country to country in uranium resources relative to projected consumption. Since many nations perceive a strong need for domestic energy supplies, concerns remain about early depletion of uranium, even in the face of overall optimistic projections.

Table 1 summarizes some of the parameters relevant to proliferation risks of an LWR system designed to provide the full nuclear power specified in our scenario. Parameters for the years 2050 and 2100 are listed, anticipating the possibility that other technologies, such as fast-spectrum fission or fusion power plants, could provide a significant fraction of nuclear power beyond 2050. In Table 1, "Pu+MA" denotes plutonium plus minor actinides, such as neptunium and americium (which can also be used to produce nuclear weapons [15]). Sometimes in this context Pu + MA are indicated as "TRU", transuranics. Minor actinides typically represent less than 10% of the total TRU in used nuclear fuel.

	2010	**2050**	**2100**
Power (GWe-yr/yr)	300	1250	3600
Fueling (t/yr ^{235}U)	300	1250	3600
Pu+MA Production (t/yr)	100	400	1150
Pu+MA in Waste (t)	2600	11,200	49,000

TABLE 1: Parameters of a LWR system to provide 30% of world electrical power needs in 2100.

Proliferation risks are conventionally divided into three categories [16]:

1) Clandestine production of weapons materials in undeclared facilities
2) Covert diversion of weapons materials from safeguarded facilities by host states
3) Breakout by host states from non-proliferation obligations and subsequent use of previously safeguarded facilities and/or weapons material for military purposes.

There are also risks associated with the theft by sub-national groups of weapons material from nuclear facilities, with or without insider cooperation.

The largest risks for future LWR systems are associated with A) clandestine enrichment of uranium using advanced technologies such as centrifuges, B) breakout and use of previously safeguarded enrichment facilities to produce weapons materials, and C) breakout and use of Pu and possibly minor actinides from used nuclear fuel. The concerns about Iran's development of centrifuges for uranium enrichment center on risks A) and B), while North Korea's development of nuclear explosives is a case of risk C).

Taking the year 2050 as an example, the enrichment capability to provide 1250t ^{235}U in the form of low-enriched uranium (LEU) for LWRs would be adequate to produce 34,500 SQ of highly-enriched uranium (HEU) per year, where 1 SQ is defined by the IAEA [17] as "the approximate amount of nuclear material for which the possibility of manufacturing a nuclear explosive device canot be excluded." A single large centrifuge-based enrichment facility that could produce LEU for 50 GWe-yr/yr of LWR power, 4% of the anticipated world market in 2050, can be reconfigured to produce 1380 SQ/yr, of HEU [18]. It is relatively straight-forward to verify that a commercial LEU enrichment facility is not producing HEU, but breakout into HEU production can be rapid [19]. Even more problematic, a clandestine enrichment facility using the P-2 centrifuge technology developed in Pakistan, with a footprint of about 550m^2 and drawing about 100 kWe, can produce 1 SQ of 90% enriched HEU per year [14] starting with natural uranium, and over 5 SQ/yr starting with LEU. Current commercial centrifuge technologies are even more compact and efficient. Facilities based on either technology would be difficult to detect.

The second major concern with LWR technology is the presence of significant quantities of TRU in used fuel. 1 GWe-yr of LWR operation produces approximately 320 kg of TRU, including about 295 kg of Pu. The 11,200t of TRU available in used fuel in 2050 corresponds to 1.3 million SQ of Pu. The TRU production rate of 400t/year corresponds to 46,000 SQ of Pu/year. To address climate change, nuclear energy will need to become much more widespread than currently, so many new nations will join the nuclear "club", and indeed 61 nations without nuclear power, including developing nations such as Bolivia, Madagascar and Yemen, have begun to explore the option of nuclear power through discussions with the IAEA [20]. A new nuclear nation that had produced only 1 GWe of nuclear power for a decade would have in its possession 370 SQ of Pu. The IAEA [17] estimates that the time for a host state to produce nuclear weapons, starting with used nuclear fuel, is 1 – 3 months. While the expected nuclear explosive yield of reactor-grade Pu is much more variable in a first-generation device than that of weapons-grade, it is nonetheless highly destructive even in the probable case of a minimum-yield "fizzle" [21, 22, 18], with a blast radius ~ 40% that of a fully successful detonation. Reactor-grade Pu is treated fully equivalently with weapons-grade Pu in IAEA controls. Partially irradiated fuel, which would be available in a breakout scenario, or the ends of fuel rods, which are less exposed to neutron irradiation, provide higher-grade plutonium. More rapid implosion using technologies developed after 1945 also improves performance.

There are proposals for international control of both enrichment and spent fuel handling. These have met with resistance, however, from nations expressing desire for full control over their nuclear fuel cycle, a right expressly provided in the Non-Proliferation Treaty [23].

6. Electrical Power and Proliferation Risks from Fast-Spectrum Fission Reactors

Table 1 also illustrates the waste management challenge associated with LWRs. The total TRU waste planned for the U.S. Yucca Mtn. facility was to be about 1000t. The committed TRU waste production, including completion of operation of facilities existing in 2100, would be about 85,000t. Since no such facility has yet been licensed in the world for commercial nuclear waste, the prospect of licensing 85 is daunting.

Limitations of uranium supply and/or of the ability to store used nuclear fuel are perceived as potential drivers for adopting nuclear fission reactors that operate with a fast spectrum of fission-produced neutrons, sometimes called "fast reactors". These can in principle convert ^{238}U to Pu isotopes and minor actinides (TRU) while burning only TRU. (Other less-well-developed options, such as thorium-uranium breeders are not discussed here.) The conversion ratio (CR) of TRU-based fast reactors is defined as the production rate of TRU divided by the TRU burn rate. For example CR = 1 denotes a system which produces as much TRU as it consumes. The range of CR that may be accessible is from 0.5 to 1.5, although the limits are under study; TRU-based fuel is still in development.

In 2005 the U.S. Advanced Fuel Cycle Initiative had as one of its goals, "Develop and make available the fuel cycle technology needed for commercial deployment by 2040 of fast spectrum reactors ..." [24]. Thus we consider scenarios in which fast spectrum fission reactors burning TRU come on line commercially in 2040. The world will have a large resource of used nuclear fuel by 2040, so fast reactors can be started up from this fuel, without further mining of U. The time evolution of the implementation of these reactors is controlled by the source of TRU, the conversion ratio (CR) of the fast reactors and the residence time of fuel in the reactor, in cooling, and then in reprocessing and fabrication. Figure 2a, b shows the result of an analysis similar to the that of [25], which addressed U.S.-only scenarios, but now for an international scenario. We find that for a CR of 1.21 and a rapid fuel cooling, reprocessing and fabrication time of 2 years, it is possible to transition fully from an LWR-based nuclear power system to fast reactors by 2100. This case is quite successful at achieving the goals specified for fast – spectrum nuclear reactors. The total required mined U is 12.3 Mt, less than the total "Redbook" discovered + undiscovered uranium. The TRU waste from LWRs is effectively burned, with a much lower TRU waste from the reprocessing stream, assuming 1% processing losses. Fission products, however, set a lower limit on waste storage needs [26].

From the proliferation point of view, a favorable result is that U enrichment is no longer needed after 2100. However, the rising yellow line in figure 2b indicates that the pool of Pu + MA in active process includes about 4 million SQ of Pu, comparable to the total geologically stored waste in the LWR-only scenario. Furthermore this scenario involves the fueling of fast reactors with about 750,000 SQ of Pu per year, about one million times the Pu reported to have been used in first-generation U.S. weapons. Currently the IAEA standard for uncertainty in closing the material balance of a plutonium reprocessing plant is 1% [17]. Even with enhanced monitoring, surveillance and containment to detect off-normal operation or diversion of materials, failure worldwide to account for 1% of 750,000 SQ per year, 7500 SQ per year, could create an unstable international environment where nations would be highly suspicious of the activities of others and so perceive the need to take precautionary actions themselves. This would present an extreme challenge to any disarmament regime.

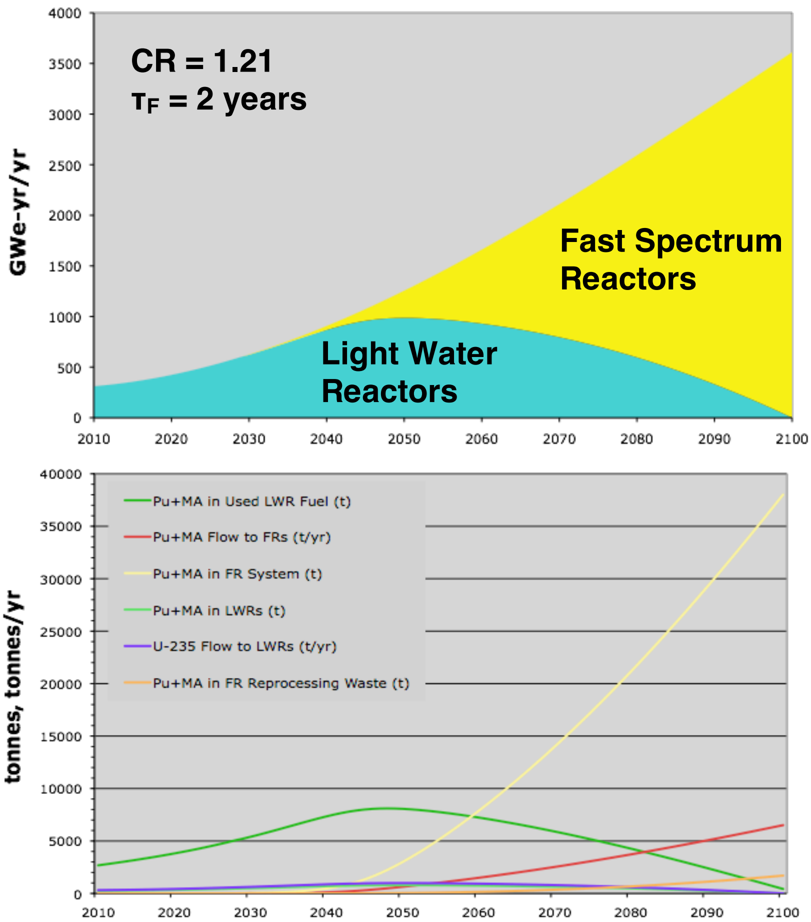

FIG. 2a, b. Power production and stocks and flows of Pu + MA and ^{235}U for fast-spectrum reactors.

Are there approaches to resolving the risk of diversion in a world with such large stocks and flows of Pu and minor actinides? Because of the magnitude of these flows, to assure against national diversion or insider-aided theft, the standards for material accountancy at reprocessing plants would need to be improved by at least two orders of magnitude, which may not be practicable. Are there approaches to resolving the risk of breakout from non-proliferation agreements? This seems at least equally problematic. Consider that the startup fuel for 1 GWe of fast reactor capacity requires ~8t of Pu or ~1000 SQ. The temptation to use this fuel for military purposes could be very strong, particularly for a state that perceived itself to be under existential threat, even from conventional weapons. The IAEA estimate [13] is that 1 – 3 weeks is required to process such fuel into the form needed for a weapon.

7. Electrical Power and Proliferation Risks from Fusion

Figure 3 shows a scenario for the application of fusion power for electricity production after mid-century. The maximum growth rate of fusion power in this scenario is 0.86%/year of the world electricity market, which is less than the growth rate of fission power 1975 - 1990, 1.2%/year of the electricity market at that time. The doubling time is at all points ≥ 3 yrs. 15.8 Mt of uranium is mined for LWRs, equal to the IAEA/NEA projected total resource.

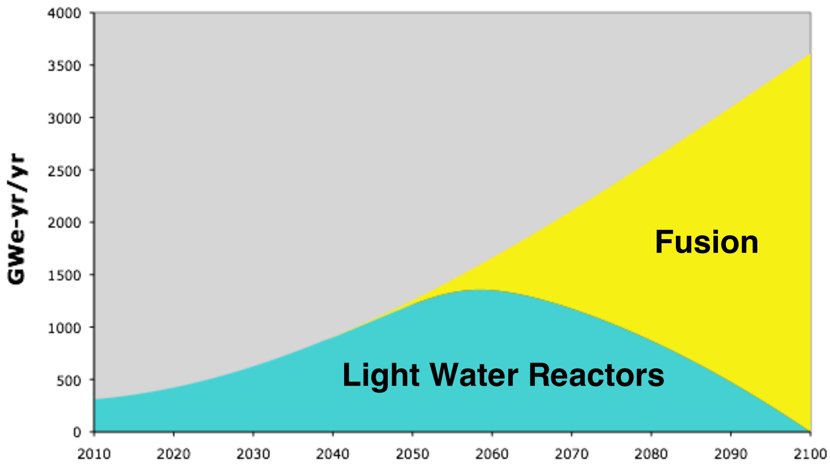

FIG. 3. Power production for LWRs followed by fusion.

Fusion has significant non-proliferation advantages [27]. While the energetic neutrons from fusion can be used to transmute ^{238}U to ^{239}Pu, or ^{232}Th to ^{233}U, this is very easy to detect and even prevent. First, fusion systems are easily enough detectable due to their size, energy use and effluents that clandestine use of a small fusion facility to produce weapons materials is not a realistic threat. Next, in normal operation a fusion power plant should have no uranium, thorium, plutonium or fission products at all. The detection of these at very low levels is straightforward, so covert production and diversion of fissile materials in a declared and safeguarded facility would not be a serious risk.

If a small amount of tritium were diverted from a fusion system it could be used to boost the yield of fission weapons, including in particular those based on reactor-grade Pu. Tritium, however, does not provide access to nuclear weapons capability in the absence of fissionable material, explaining why it is not controlled under the Non-Proliferation Treaty. Unlike reactor-grade Pu, tritium is not considered to be an entry-level component of nuclear proliferation.

Finally, the breakout scenario for fusion is qualitatively different from that for fission. At the time of breakout a fusion plant operator does not have any weapons material in hand. It would be relatively straightforward to convert a pure fusion power plant to produce ~1 SQ of ^{239}Pu or ^{233}U per week. However, it would also be straightforward to interdict such production, for example by destroying a cooling tower, electrical power conditioning system or cryoplant, none of which would pose a threat of nuclear contamination. This represents a strong contrast with the fission breakout scenario, where weapons material is already present in the host nation, and only aerial bombardment, with significant risk of dispersal of radioactivity over civilian populations, or invasion can interdict its use.

6. Conclusions

Nuclear energy would contribute significantly to reducing carbon emissions if it provided ~30% of world electrical power production by 2100. This can be achieved through a combination of light-water fission reactors, fast-spectrum fission reactors and potentially fusion. The very large scale and the associated broadening of the range of nations using fission power bring with them serious proliferation risks. The risks associated with light-water reactors at the needed scale are significant. The risks associated with fast reactors appear to be much greater and more resistant to management. If fusion is developed, it will provide an option with qualitatively lower proliferation risks.

This work was supported by U.S. DOE Contract # DE-AC02-09CH11.

References

[1] Clarke, L., Edmonds, J., Krey, V., Richels, R., Rose, S., Tavoni, M. International climate policy architectures: Overview of the EMF 22 International Scenarios, Energy Economics 31, S64, 2009
[2] Intergovernmental Panel on Climate Change (IPCC) Carbon Dioxide Capture and Storage, 2005
[3] Massachusetts Institute of Technology (MIT), "The Future of Coal", 2007
[4] Socolow, R.H., Can We Bury Global Warming, Scientific American, July, 2007
[5] Intergovernmental Panel on Climate Change (IPCC), Climate Change 2007: Mitigation, Oxford University Press, 2007
[6] Massachusetts Institute of Technology (MIT), "The Future of Geothermal Energy", 2006
[7] Traube, J., Hansen, L., Palmintier, B., Levine, J., Spatial and Temporal Interactions of Wind and Solar in the Next Generation Utility, Presented at WINDPOWER 2008 Conference and Exhibition, June 2008
[8] 20% Wind Energy by 2030: Increasing Wind Energy's Contribution to U.S. Electricity Supply, DOE/G0-102008-3567, July 2008
[9] Reeves, A., Beck, F., Wind Energy for Electric Power, Renewable Energy Policy Project, 2003
[10] Clarke L., Kyle P., M. Wise, et al., CO2 Emissions Mitigation and Technological Advance: An Analyis of Advanced Technology Scenarios (Scenarios Updated January 2009) PNNL-18075, 2009
[11] OECD Nuclear Energy Agency and IAEA, Uranium 2009: Resources, Production and Demand, 2010
[12] Deffeyes, K.S., MacGregor, I.D., World Uranium Resources, Scientific American January, p. 66, 1980
[13] Schneider, E.A., Sailor, W.C., Long-Term Uranium Supply Estimates, Nuclear Technology 162, p. 379, 2008
[14] Seko, N., Katakai, A., Hasegawa, S., Tamada, M., Kasai, N., Takeda, H., Sugo, T., Saito, K., Aquaculture of uranium in seawater by a fabric-adsorbent submerged system, Nuclear Technology 144, p. 274, 2003
[15] Albright, D., Barbour, L., Separated Neptunium 237 and Americium, in The Challenges of Fissile Material Control, Albright, D., and O'Neill, K., (editors), Institute of Science and International Security Reports, 1999
[16] Gen IV International Forum (GIF), Methodology for Proliferation Resistance and Physical Protection, Generation IV Nuclear Energy Systems, OECD Nuclear Energy Agency, GIF/PRPPWF/2006/005, 2006
[17] International Atomic Energy Agency (IAEA), International Nuclear Verification Series No. 3, IAEA Safeguards Glossary, 2001 Edition, IAEA, Vienna, 2001
[18] Gilinsky, V., Miller, M., Hubbard H., A Fresh Examination of the Proliferation Dangers of Light Water Reactors, The Nonproliferation Policy Education Center, 2004
[19] Glaser, A., Characteristics of Gas Centrifuges for Uranium Enrichment and Their Relevance for Nuclear Weapon Proliferation, Science and Global Security 16, p. 1, 2008
[20] von Hippel, F., The Uncertain Future of Nuclear Power, International Panel on Fissile Materials, 2010
[21] Mark, J.C., Explosive Properties of Reactor-Grade Plutonium, Science & Global Security, V.4, p.111, 1993
[22] Garwin, R.L., The Garwin Archive, Federation of American Scientists, 1998
[23] Glaser, A., 2010. The Civilian Nuclear Fuel Cycle in a Nuclear-Weapon-Free World: Challenges and Opportunities, in Elements of a Nuclear Disarmament Treaty, eds. Blechman, B.M., Bollfass, A.K., Henry L. Stimson Center
[24] U. S. Department of Energy (USDOE), Office of Nuclear Energy, Science, and Technology, Report to Congress – Advanced Fuel Cycle Initiative: Objectives, Approach, and Technology Summary, May 2005
[25] Dixon, B., Halsey, B., Kim, S., Matthern, G., Piet, S., Shropshire, D., Dynamic Systems Analysis Report for Nuclear Fuel Recycle, AFCI-SYSA-AI-SS-RT-2009-000053, Idaho National Laboratory, 2007
[26] National Academy of Sciences, Nuclear Wastes: Technologies for Separations and Transmutation, 2006
[27] Goldston, R.J., Glaser, A., Ross, A.F., Proliferation Risks of Fusion Energy: Clandestine Production, Covert Production, and Breakout, 9th IAEA Technical Meeting on Fusion Power Plant Safety, 2009