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Climate Change, Nuclear Power, and Nuclear Proliferation: Magnitude Matters

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Integrated energy, environment, and economics modeling suggests that worldwide electrical energy use will increase to ~12 TWe in 2100. Due to limitations of other low-carbon energy sources, nuclear power may be required to provide ~30% of world electrical energy by 2100. Calculations of the associated stocks and flows of uranium, plutonium, and minor actinides indicate that the proliferation risks at mid-century, using current light-water reactor technology, are daunting. There are institutional arrangements that may be able to provide an acceptable level of risk mitigation, but they will be difficult to implement. If a transition is begun to fast-spectrum reactors at mid-century, the global nuclear proliferation risks become much greater by 2100, and more resistant to mitigation. Fusion energy, if successfully demonstrated to be economically competitive, would provide a source of nuclear power with much lower proliferation risks than fission.

INTRODUCTION

Nuclear power has the potential to produce very large amounts of electrical energy with minimal atmospheric emission of carbon dioxide. It also has the potential to facilitate the proliferation of nuclear weapons. The damage

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to humanity and the world environment from either climate change or nuclear war would be very severe. Both could have devastating impact on the heritage passed on to future generations. This paper uses recent energy, environment, and economic 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 key characteristics of such an undertaking. A quantitative time-dependent perspective is provided on the nuclear proliferation risks that would result, for comparison with the climate change risks that would be mitigated by nuclear power. This supplements earlier work in this area by Williams and Feiveson,[1] Feiveson,[2] Schneider and Sailor,[3] Feiveson et al.,[4] Socolow and Glaser,[5] and Feiveson.[6]

INTEGRATED ENERGY, ENVIRONMENT AND ECONOMIC MODELING

Nuclear energy is viewed primarily as a source of electrical power, although the high temperature process heat that may be producible in some designs could facilitate production of hydrogen or biofuels. Here the focus is on the electricity market. The dominant contribution of nuclear power to the transportation sector may in any event be through plug-in hybrid and electric vehicles.

Projections of future electricity use, while subject to the large uncertainties of any long-term forecasts, are relatively robust against variations in the projected requirement for limitation of CO_2 emission. In the study of electrification by Edmonds et al.,[7] as CO_2 emissions are more severely restricted, overall energy use is depressed. However, at the same time, the ratio of electrical power production to total final energy use in 2100 increases from 32 percent to 60 percent. These effects very nearly balance each other, providing a stable projection for future electricity production.

It is valuable to look beyond Edmonds's results of 2006 to the most recent analyses, and to a wider range of coupled energy, environment, and economic models. The database from the Energy Modeling Forum 22 (EMF 22) study is a source of such information.[8] Published in late 2009, it includes modeling results from a large number of different groups around the world, taking into account multiple energy sources and opportunities for improvements in efficiency of end-use. The study examined a wide range of cases: CO_2 constraints were varied from business-as-usual (no constraint) to atmospheric concentration as low as 450 ppm equivalent; temporary overshoot of CO_2 concentration beyond the ultimate goal was allowed or disallowed; and early participation in emissions constraints was assumed only for developed countries, or full early participation was assumed. The projection for world electrical energy use, across a wide range of models with this wide range of constraints, was surprisingly stable. The variation between models was greater than the variation vs. CO_2 and

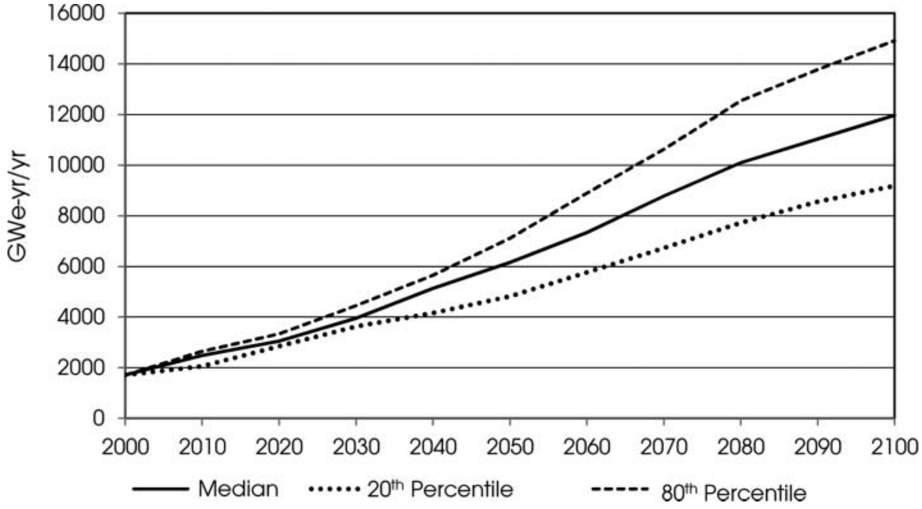


Figure 1: Electrical power production from EMF 22 models. "GWe-yr/yr" is used to indicate electrical power production, as opposed to production capacity, often denoted "GWe".

other constraints, and the direction of variation of electrical energy production as a function of the severity of the CO_2 constraint was not consistent. The median projection of electrical energy production from the EMF 22 database is shown in Figure 1. The 20th and 80th percentiles refer to the range of results over all models and all constraints.[9] For perspective, the average logarithmic growth in the median case from 2010 to 2100 is somewhat less than was experienced historically between 1980 and 2006.

While Figure 1 provides a basis, however uncertain, for considering future electrical energy needs, it does not provide a basis for estimating how much nuclear power will be needed. The full calculated mix of electrical energy sources for the various model runs was not provided to the EMF 22 study database, and the published descriptions of the EMF 22 model results indicate a great deal of variation in the mix.[10–17] There is, however, a clear trend towards a higher fraction of nuclear power, greater carbon sequestration, and more renewable energy as CO_2 concentration limits become more stringent. Overall it appears that combustion with carbon capture and storage, including biomass, is the largest contributor to electricity production in the carbon-constrained model runs, with renewable energy obtained from tapping natural energy flows such as hydropower, wind, and solar generally contributing somewhat less. Nuclear in different reported model runs contributes more or less than these renewables.

The discussions on combustion, sequestration and renewable electrical power that follow provide a basis for estimating that of the 12,000 GWe-yr/yr projected in 2100, 40 percent may be able to be provided by combustion, including of biomass, with a large fraction of sequestration, and 30 percent may

Table 1: Electric energy sources

	2007		2100	
Combustion	1482 GWe-yr/yr	69.2%	4800 GWe-yr/yr	40%
Nuclear	296 GWe-yr/yr	13.8%	3600 GWe-yr/yr	30%
Hydro	342 GWe-yr/yr	15.9%	700 GWe-yr/yr	6%
Other Renewables	26 GWe-yr/yr	1.2%	2900 GWe-yr/yr	24%
Total	2046 GWe-yr/yr	100%	12,000 GWe-yr/yr	100%

be able to be provided by renewable electrical power obtained from tapping natural energy flows: hydro, wind, solar, geothermal, etc. The primary goal of this article is to examine the implications, particularly for nuclear proliferation, of providing the remaining 30 percent with nuclear fission and/or fusion. The electrical energy fractions discussed here are quite similar to detailed recent results from the MiniCam model for a case where the atmospheric concentration of CO_2 was constrained to 550 ppm.[18,19]

In order to model simply a quantitative evolution of the energy system, the fraction of each electrical energy source (not the quantity of each) is assumed to vary linearly from its current value to its assumed value in 2100 (see Table 1), with total time profile given by the EMF-22 median case shown in Figure 1.

The resulting time profiles for each source are shown in Figure 2. The integrated electrical energy production from combustion is 320 TWe-years, from

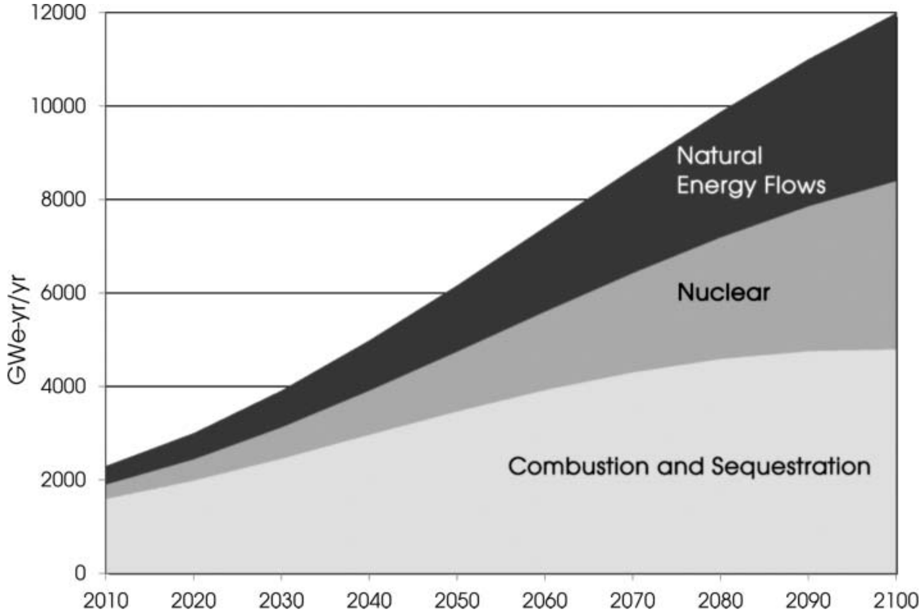


Figure 2: Assumed electrical energy production time profiles.

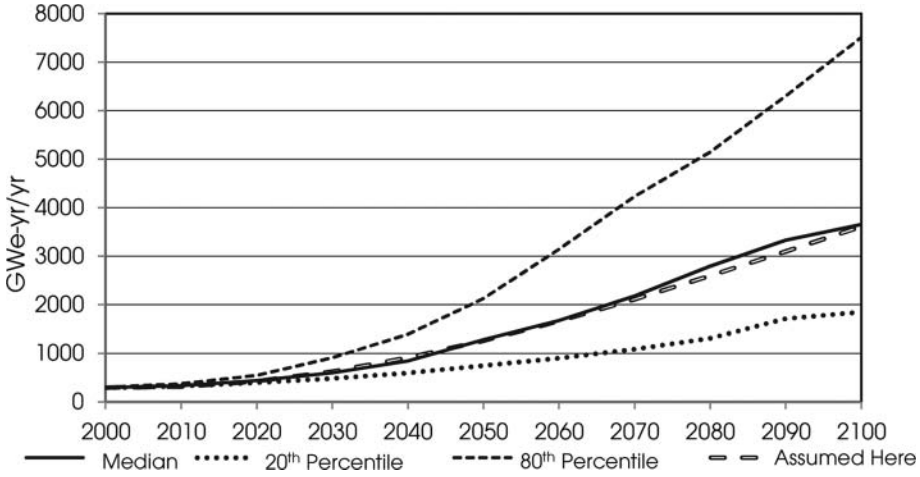


Figure 3: Nuclear electrical power production from EMF 22 models, and assumed here.

nuclear energy is 150 TWe-years, and from renewable electrical power obtained by tapping natural energy flows, 160 TWe-years. It is informative to note that this constitutes a 12× increase in nuclear power from 2010 to 2100.

Interestingly, the EMF-22 database does give a projection specifically for total nuclear electric power production (including an electric equivalent of a small amount of nuclear hydrogen),[20] of 3650 GWe-yr/yr in 2100, with however a very wide range of variation from the 20th to the 80th percentiles of 1850 to 7510 GWe-yr/yr, as shown in Figure 3. The time curve of the EMF-22 median value of nuclear electric power production is very close to the time curve assumed here, using the logic described above.

The fractions and time profiles shown in Figure 2 cannot be viewed as predictions, but they can be used to illustrate the scale of the problem at hand and its consequences. For example, from the climate perspective, one can estimate the impact of 150 TWe-years of electricity production from coal without sequestration, as a substitute for the nuclear power shown in Figure 2. A typical pulverized coal plant emits 6.68 $MtCO_2$/GWe-yr.[21,22] (This emission includes only operation, ignoring the small contribution from other lifetime emissions such as associated with construction, mining, and transportation.) The increased total emission of 1000 $GtCO_2$ due to supplanting nuclear with unsequestered combustion of coal would result in an increase of about 80 ppm in atmospheric concentration of CO_2 in 2100 compared to a case without the increased emission.[23] The Intergovernmental Panel on Climate Change estimates that this would cause an additional increase of long-term equilibrium global-average surface temperature of 0.64°C with an uncertainty range from 0.43°C to 0.96°C.[24] This range of a factor of 1.5 in either direction is termed by the IPCC the "likely" ($>2/3$ probability) prediction.

The global-average surface temperature approaches its equilibrium value over a period of several centuries, and it is difficult to quantify the impacts of long-term changes such as these, but for example it is reported that approximately a 1°C change in global surface-average temperature in 2100 makes the difference between "most corals bleached" and "widespread coral mortality."[25] A roughly 2°C change makes the difference between "up to 30 percent of species at increasing risk of extinction" and "significant extinctions around the globe." A change in the range of 2.5°C makes the difference between "tendencies for cereal productivity to decrease in low latitudes" and "productivity of all cereals decreases in low latitudes."

The 0.43°C to 0.96°C estimate of temperature rise is likely too high, because in the absence of nuclear power there would be less total electrical power produced and not all substituted power would come from high-carbon-emitting sources such as pulverized coal. If the limits to combustion with sequestration and to renewable energy obtained from tapping natural energy flows discussed in the sections on combustion and sequestration, and on renewable electrical power below are not hard, but only lead to increased costs for these sources, and if carbon emission limits are hard, then economic models replace nuclear power with other low-carbon energy sources, at increased overall cost to the world economy.[26] It should be recognized, however, that the climate-impact estimate here can also be seen as an underestimate, in that if the limits to other energy sources are hard, the non-sequestering coal-fired plants operating in 2100, unless they are decommissioned before end-of-life or retrofit with carbon capture and storage, would represent a commitment to emission of a further 768 $GtCO_2$ post-2100 (see on-line Appendix 1).[27]

COMBUSTION AND SEQUESTRATION, INCLUDING BIOMASS: 320 TWe-YRS BY 2100, 4800 GWe IN 2100

As summarized in recent reports, subsurface injection of carbon dioxide is a well-developed technology, although not at the scale required for power generation in the GWe range.[28–31] A single 1 GWe-yr/yr coal-fired power plant with a lifetime of 60 years would need to sequester about 450 $MtCO_2$ using subsurface storage in saline aquifers under an area of about 150 km^2. Substantial research and development (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 be licensing issues associated with the potential safety and environmental impacts of such large undertakings and "Not Under My Back Yard" will be a significant constraint.

The total world's technical potential for CO_2 storage in oil and gas fields, in unmineable coal seams and in deep saline formations, not including consideration of economic feasibility, is estimated by the Intergovernmental Panel on Climate Change (IPCC) at a lower limit of 1850 $GtCO_2$.[32] The range of published projections is quite varied with the upper limit of technically potential storage in some cases as much as an order of magnitude higher.[33] The scenario shown in Figure 2 would require 2300 $GtCO_2$ of storage. If the storage commitment associated with the remaining lifetime of the plants existing in 2100 is included (on-line Appendix 1), with no sequestration beyond their lifetimes, this increases to about 3200 $GtCO_2$, more than 70 percent above the IPCC lower-limit estimate of technical potential. This estimate, however, assumes that all combustion is of coal, and all is sequestered. Combustion of natural gas produces about 50 percent less CO_2 per kWh, and all carbon emissions will not be sequestered, particularly in the near future. Projections for the relative contributions of coal and natural gas to future electrical energy production are highly variable.

Carbon capture and storage (CCS), where applied, reduces the net efficiency for extracting electrical energy from coal by about 25 percent. CCS is currently in the range of 90 percent efficient at capturing CO_2 produced, so that CO_2 emissions per net kWhe are reduced by about 87 percent, not 100 percent. (CO_2 emissions per kWhe from renewable electrical energy and from nuclear power are estimated by the IPCC to be much less.[34]) 4800 GWe, all generated using coal and CCS, would emit 4 Gt CO_2/year, which is beyond the total allowed world CO_2 emissions from the sum of all energy and industrial processes in carbon-constrained scenarios. Even taking into account future improvements in the efficiency of coal-fired power plants and in CCS technology, large scale production and combustion of biomass-based fuel (which results in net reduction in atmospheric CO_2 if the energy used to harvest the biomass is low enough) would be needed, in parallel with coal, to achieve acceptable net emissions.

Furthermore, the IPCC reports that, because of mismatches between CO_2 sources and potential sequestration locations, “by 2050, given expected technical limitations, around 20–40 percent of global fossil fuel CO_2 emissions could be technically suitable for capture, including 30–60 percent of the CO_2 emissions from electricity generation.”[35] In this overall context, the achievement of 40 percent electrical energy production in 2100 from combustion, with very low net emission of CO_2, appears to be a very challenging goal, and difficult to exceed.

RENEWABLE ELECTRICAL POWER FROM TAPPING NATURAL ENERGY FLOWS: 160 TWe-YRS BY 2100, 3600 GWe IN 2100

The dominant non-carbon-emitting electrical energy source today is hydropower, providing about 16 percent 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 overall increase in electrical power production projected for 2100. If it grows by a factor of two, to its realistic limit, large-scale hydropower will provide about 6 percent of world electricity in 2100.[36] Other sources based on hydrological flows such as tides and wave power are not projected to be major contributors. As shown in Table 1, a more than 100-fold increase in power from tapping non-hydrological natural energy flows is therefore assumed.

The low thermal conductivity of rock, the high difficulty of drilling very deep into igneous and metamorphic rock, and induced seismicity have been encountered as 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 United States by 2050.[37]

We are positing here that 30 percent of world electrical production may come from renewable energy obtained by tapping natural energy flows in 2100 (3600 GWe), including perhaps 1/3 from steady sources such as hydropower and geothermal and 2/3 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. Wide, strong grids can average variable production over large areas, but energy storage to smooth out the natural time variability of intermittent sources over days and weeks is speculative. Even if wind and solar power are averaged over the entire Great Plains “wind belt” region of the United States, from Texas to North Dakota, total power output drops below 11 percent of peak capacity 10 percent of the time, necessitating demand reductions and/or significantly increased generating capacity.[38] A U.S. study targets 20 percent domestic electrical power production from wind by 2030, but requires a significant upgrade to the U.S. electric grid that may be difficult to implement.[39] Some argue, on the other hand, that approximately 40 percent can be achieved with improved technologies before technical limits are reached.[40]

Large fractions of wind power, however, are only achievable in regions with high wind resources. China, Europe, India, Japan, and Korea, representing about half of the world’s population, have approximately 16 percent of the wind resources per capita of the United States.[41] The most populous nations, China and India, have approximately 5 percent.

A similar set of concerns pertains to solar power, which is also spatially and temporally intermittent. A wide and strong electric grid can be helpful, but there are serious limitations to this approach. For example the Desertec project proposes to provide a large fraction of the electric needs of Europe using wind and solar farms in North Africa.[42] However a project of this sort would represent a significant security risk for Europe, as highlighted by recent events in the region. In general, it is not at all clear that nations will accept putting control of a large fraction of their electric power supply in the hands of others.

It appears from the above analysis that a 20 percent world-average contribution from intermittent energy sources, representing an increase by about a factor of 100 in such power production, and a total world-average contribution of 30 percent from renewable electrical energy tapping natural energy flows, are very challenging goals. While projections in this area are highly controversial, the goal presented here may be difficult to reach or exceed.

NUCLEAR POWER: FISSION AND FUSION: 150 TWe-YRS BY 2100, 3600 GWe IN 2100

The above discussion illustrates the challenges associated with producing 70 percent of the projected world's electrical energy needs in 2100, with low CO_2 emissions, from a combination of combustion with CCS, including biomass, and renewable energy obtained by tapping natural energy flows. It is not claimed here that these goals are impossible, or even that they definitely cannot be exceeded. However in concert with the EMF-22 study results, this analysis provides support to evaluate a nuclear power scenario that produces 30 percent of the world's projected electrical energy needs in 2100, up from 14 percent in 2007, while total electrical energy production increases by a factor of five from today. Here the leading fission technologies, light-water reactors, and fast-spectrum reactors based on the use of uranium and transuranic fuels are discussed, followed by a discussion of fusion energy. In all cases the focus is on proliferation risks.

Thorium, which is not discussed here, may provide an alternative fuel for nuclear fission, with larger crustal abundance than uranium and some attractive nonproliferation and waste advantages.[43] Thorium itself is not fissile, but can be transmuted by thermal neutron capture to Uranium-233, a fissile isotope usable both for power production and in nuclear weapons. The technology for the thorium fuel cycle has proven to be difficult, and has not yet been fully developed. Since the possible characteristics of the fuel cycle for thorium, and its proliferation risks, have not been studied as thoroughly as those for uranium, fission reactors based on the use of thorium are beyond the scope of this investigation. The reader is referred to previous works that consider the proliferation risks associated with various alternative fission reactor technologies, including those fueled with thorium.[44,45] In general the study of fission energy here can be viewed as providing a background against which advantages of alternative nuclear fission technologies can be measured.

LIGHT WATER REACTORS

The far-dominant current fission reactor technology is light-water reactors (LWRs). In these systems conventional water is used both to remove fission-produced heat from the reactor and to slow down the fission-produced neutrons to thermal energies, where they have a high probability of inducing fission and so maintaining the chain reaction, rather than being absorbed without producing fission. 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 percent Uranium-235 (the naturally-occurring fissile isotope of uranium) to about 4.5 percent. As discussed in on-line Appendix 2, about 200 t of natural uranium is needed to provide 1 GWe-yr, with 0.25 percent Uranium-235 concentration in depleted uranium tails, a relatively aggressive level to maximize uranium utilization. If all of the nuclear power in the scenario of Figure 3 were provided by LWRs, this would require mining of 33.4 Mt, comparing well with the estimate for a similar scenario by Feiveson et al. of 35 Mt.[46] If the uranium required to complete operation of the LWRs in use in 2100 is included (see on-line Appendix 1), with no further LWR construction, the required mined uranium increases to 59 Mt.

The Nuclear Energy Agency (NEA) of the Organization for Economic Co-operation and Development (OECD), together with the International Atomic Energy Association (IAEA) have estimated world Uranium resources in a broadly referenced bi-annual series of "Red Books," whose 2008 edition[47] summarized data from 2007, and whose history to 2005 was summarized in 2006.[48] These documents are based on national self-reporting of uneven geological studies. If one sums all categories of conventional uranium resources irrespective of price, including speculative, undiscovered resources (which have only been reported since 1982), the total uranium projection has been relatively stable over the last 25 years, as shown in Figure 4.

This NEA/IAEA estimate of uranium resources would represent a significant limitation on using LWRs with the once-through fuel cycle to meet the nuclear energy requirements of our scenario. However there is considerable disagreement in the literature with the NEA/IAEA estimate of future

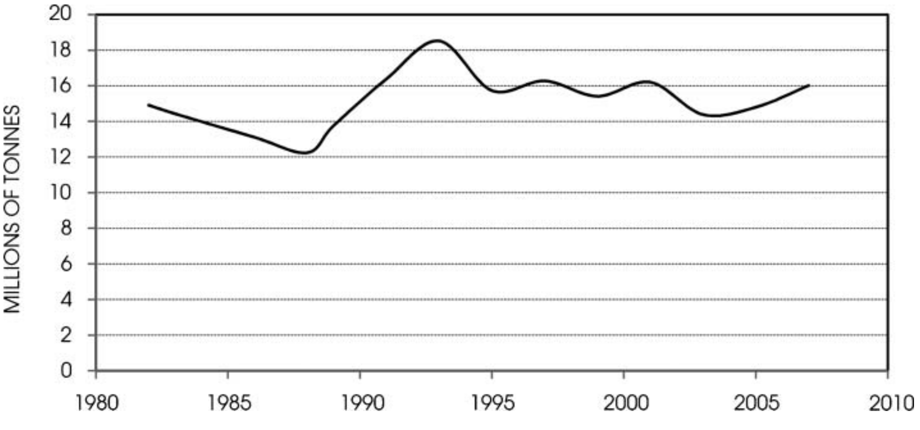


Figure 4: Total discovered + undiscovered uranium reported in IAEA/NEA Red Books, since estimates of undiscovered resources have been included. During this time period 1.1 Mt of U was mined. Source: OECD 2006, 2008.

conventional uranium reserves.[49,50] This is particularly so because the price of electricity from LWRs is very weakly dependent on the price of mined uranium at current levels. Based on simple models, and very limited geological data, these analyses suggest that 60 Mt of uranium may be available at a price approximately 5 times current levels. This would increase the price of electricity by about $0.01/kWh. Furthermore, essentially unlimited unconventional uranium sources such as seawater may eventually become available at prices in this range or somewhat above.[51] Nonetheless, 59 Mt for the full scenario is a factor of 3.7 above NEA/IAEA estimates of total world resources and could be difficult to supply. By 2050 only 6.6 Mt will have been consumed, with a further 10 Mt committed, roughly consistent with the total NEA/IAEA estimate. It should be recognized, however, that there is considerable variation from country to country in uranium resources relative to potential consumption. Since many nations perceive a strong need for adequate domestic energy supplies, despite the possibility of stockpiling uranium fuel significant concerns remain about early depletion of uranium resources.

A second factor which could limit the ability of LWRs with once-through fueling to support the scenario of Figure 2 is the production of nuclear waste. If all of the specified nuclear power were provided by LWRs, the nuclear waste created worldwide by 2100 would correspond to the equivalent of about 48 times the statutory limit proposed for the U.S. repository at Yucca Mountain. An additional 38 times that limit would be associated with the estimated remaining lifetime of the installed LWR systems in 2100. No geological storage facility has yet been licensed in the world for commercial high-level nuclear waste, and the Yucca Mountain geological storage facility has been “taken off the table” by the United States. Despite encouraging progress in Sweden, Finland, and France, the prospect of needing to license 86 times the capacity of Yucca Mountain, worldwide, remains daunting.

Calculations such as these lead to the consideration of different nuclear fission technologies, most prominently those employing a fast (as opposed to thermal) spectrum of neutrons, which have the potential to use uranium more efficiently and to reduce the longest-lived nuclear waste. A second alternative is fusion energy, powered by the fusion of light nuclei into helium, which is not limited by uranium resources and does not produce waste requiring geological burial. Before turning to these technologies, let us consider the proliferation risks associated with LWRs at this scale.

Table 2 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. In Table 2, “Pu+MA” denotes plutonium plus minor actinides, such as neptunium and americium, which can also be used to produce nuclear weapons.[52] Sometimes in this context Pu + MA are indicated as “TRU,” transuranics. Minor actinides typically represent less than 10 percent of the total TRU in used nuclear fuel.

Table 2: Proliferation-relevant parameters of LWR systems to provide the nuclear power profile specified in Figure 3

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

Proliferation risks can be divided into three categories:[53]

A) Clandestine production of weapons materials in undeclared facilities

B) Covert diversion of weapons materials from safeguarded facilities by host states

C) Breakout by host states from nonproliferation obligations and subsequent use of previously safeguarded facilities and/or weapons material for military purposes.

There is also risk associated with the theft by sub-national groups of weapons material from nuclear facilities, with or without insider cooperation. In risk analysis for nuclear power systems, this risk is considered separately, under the category of "physical protection."

In nations that are signatory to the Nonproliferation Treaty and in particular to its Additional Protocol that allows inspection of non-declared facilities, there is little risk of clandestine production of weapons materials in small fission reactors, because these can be detected, for example, by their emissions. There is also relatively little risk of covert diversion of materials from declared LWR facilities, because fuel rods can be counted and monitored by the International Atomic Energy Agency (IAEA) with a high degree of confidence. With an increase of an order of magnitude in nuclear power production, and many more nations producing nuclear power, however, maintaining the same absolute level of error in accounting would be more challenging. The risk of theft of nuclear materials by sub-national groups for the production of nuclear weapons is relatively small, since the incoming fuel for LWRs is low-enriched uranium (LEU), not easily converted by a sub-national group to the highly enriched uranium (HEU) needed to produce nuclear weapons, and the plutonium and minor actinides in the used nuclear fuel are mixed with highly radioactive fission products. The used fuel is deemed "self-protecting" against theft and subsequent use for nuclear explosives by sub-national groups for a period on the order of 100 years. Even after this period used fuel is bulky and radioactive, and can be readily accounted. With adequate resources, it should be possible to detect rapidly a deficit of used nuclear fuel from cooling ponds, dry casks or even repositories, either due to diversion by a host nation or due to theft. It should be recognized, however, that the IAEA's current budget of 122 M€/yr, to verify 908 facilities under safeguards or containing safeguarded materials, is clearly over-stretched, limiting what can be accomplished. Furthermore national resources committed to deterrence of theft are often characterized as inadequate to the challenge.

To address climate change, nuclear energy will need to become much more widespread, so many new nations will need to join the nuclear "club," and indeed 61 nations without nuclear power,[54] including developing nations around the globe such as Bolivia, Madagascar, and Yemen, have begun to explore the option of nuclear power through discussions with the IAEA.[55] This presents the danger of greatly multiplying the number of nations with access to weapons materials.

The largest risks for future LWR systems are associated with 1) clandestine enrichment of uranium using advanced technologies such as centrifuges, 2) breakout and use of previously safeguarded enrichment facilities to produce weapons materials, and 3) breakout and use of plutonium and possibly minor actinides from used nuclear fuel. The concerns about Iran's development of centrifuges for uranium enrichment center on risks 1) and 2), while North Korea's development of nuclear explosives is a case of risk 3).

Taking the year 2050 as an example, 1250 t/yr of Uranium-235 would be provided to LWRs in the form of LEU, assumed here at 4.5 percent enrichment (on-line Appendix 2). The IAEA[56] defines a significant quantity (SQ) of fissile material as "the approximate amount of nuclear material for which the possibility of manufacturing a nuclear explosive device cannot be excluded. Significant quantities take into account unavoidable losses due to conversion and manufacturing processes and should not be confused with critical masses." For highly enriched uranium, HEU (> 20 percent Uranium-235), an SQ is defined as a quantity containing 25 kg of Uranium-235. For plutonium, an SQ is 8 kg, practically irrespective of its isotopic composition.[57] The U.S. Department of Energy has indicated that it is possible to make nuclear weapons with as little as 4 kg of weapon-grade plutonium (with a high concentration of Plutonium-239 relative to other isotopes).

The fuel for LWRs is in the form of LEU rather than HEU. Thus the quantity needed to evaluate the level of success required to safeguard against clandestine production or breakout, is really the amount of Uranium-235 in HEU that could be produced with the anticipated enrichment plants. Enrichment capability is measured in kg Separative Work Units (SWU).[58] About 5550 kg SWU are required[59] for 1 SQ of HEU, and 153,000 kg SWU for 1 GWe-yr of LWR power, at 4.5 percent enrichment with 0.25 percent Uranium-235 concentration in uranium tails. World enrichment capability in 2050 would thus correspond to the capability to produce about 34,500 SQ of HEU per year. A single large centrifuge-based enrichment facility that could produce LEU for 50 GWe-yr/yr of LWR power, 4 percent of the anticipated world market in 2050, can be reconfigured to produce 1380 SQ/yr, of Uranium-235 at 90 percent enrichment. It is relatively straightforward to verify that a commercial enrichment facility is not producing HEU, but breakout into HEU production can be rapid.[60]

Even more problematic, a clandestine enrichment facility using the P-2 centrifuge technology developed in Pakistan, with a footprint of about 550 m^2 and drawing about 100 kWe, can produce 1 SQ of 90 percent enriched HEU per year[61] starting with natural uranium, and over 5 SQ/yr starting with LEU. Modernized commercial centrifuge technologies are even more compact and efficient. Facilities based on either technology would be hard to detect, even with the Additional Protocol in place. Thus the broad dissemination of this and other advanced technologies for uranium enrichment and the broad legitimization of access to significant uranium supplies that could accompany a major expansion of nuclear power to many new nations is a serious concern, and should be controlled to the degree possible by the use of "black-box" systems in safeguarded multi-national facilities.[62,63]

The second major concern with LWR technology is the presence of significant quantities of plutonium and minor actinides (Pu + MA, or transuranics, TRU) in used fuel. At 50 MW-d/kg burnup, typical of LWRs, 1 GWe-yr of LWR operation produces approximately 321 kg of TRU (on-line Appendix 2), including about 295 kg of plutonium. The 11,200 t of TRU available in used fuel in 2050 corresponds to 1.3 million SQ of plutonium. The production rate of 400 t/year corresponds to 46,000 SQ of plutonium per year. A new nuclear nation that had produced only 1 GWe of nuclear power for a decade would have in its possession 370 SQ of plutonium. The IAEA estimates[64] that the time required for a host state to produce nuclear weapons, starting with used nuclear fuel, is 1–3 months, assuming that all other components were readied.

Bari,[65] based on his analyses in the context of the Generation IV International Forum,[66] proposed for the Global Nuclear Energy Partnership (GNEP)[67] fission initiative classifying reactor-grade plutonium as having "medium" proliferation resistance, while weapon-grade plutonium (with a high concentration of Plutonium-239 relative to other isotopes) would have "low" proliferation resistance. This assessment was based on a statement by the U.S. Department of Energy: "In the case of . . . a proliferant State we rate the barrier [from reactor-grade plutonium] as 'moderate' in importance: such a state would probably prefer to avoid if possible the burdens posed by isotopic deviations for design, fabrication, and maintenance of nuclear weapons, but it would also probably have the capabilities to cope with the burdens in ways that achieved a level of weapon performance adequate for the proliferant State's initial purposes."

By contrast with Bari's proposal, reactor-grade plutonium is treated equivalently with weapon-grade plutonium in IAEA controls. The construction of nuclear weapons using reactor-grade plutonium is "not different in kind from those involved in using weapon-grade plutonium, but only in degree."[68] While the expected nuclear explosive yield of reactor-grade plutonium is much more variable in a first-generation device than that of weapon-grade, it is nonetheless highly destructive even in the probable case of a minimum-yield "fizzle."[69–71] Partially irradiated fuel, which would be available in a breakout scenario or from the ends of fuel rods that are less exposed to neutron irradiation, would provide higher-grade plutonium. More rapid implosion using technologies developed after 1945 also improves performance. In 1962 the United States successfully detonated a nuclear weapon using reactor-grade plutonium, and the U.S. Department of Energy has stated[72] that "proliferating states using designs of intermediate sophistication could produce weapons with assured yields substantially higher than the kiloton-range made possible with a simple, first-generation nuclear device," using reactor-grade plutonium.

Clearly, used fuel needs to be carefully monitored in order to insure rapid detection of any violation of treaty obligations. On the other hand, short of military invasion, it is not practically possible to prevent a sovereign nation, in its own perceived supreme national interest, from breaking out of its nonproliferation agreements and accessing its own existing used fuel to produce nuclear weapons. Reprocessing plants prepared for operation can be hidden underground, and destroying a repository of used nuclear fuel by aerial bombardment could spread radioactivity over civilian populations, including those in neighboring countries. Breakout from safeguards could be a strong temptation for a state (or regime) that perceived itself to be under existential threat, even by conventional weapons alone. In some cases the attacking nation could respond by providing itself with nuclear arms, but even so, the rapid acquisition of nuclear weapons by both sides would turn an impending strategic defeat for the threatened state (or regime) into a stalemate, a considerable perceived benefit. Analyses of the motivations and behavior of North Korea[73] and of Iran[74] illustrate the attraction of nuclear weapons for states that perceive themselves to be under severe threat.

Recently the United Arab Emirates, as part of its proposal to build a first nuclear power plant, has indicated its willingness to return used nuclear fuel to its supplier. Arrangements such as this would help provide proliferation resistance at the so-called "back end" of the nuclear fuel cycle, although the need for fuel cooling before shipment would still leave a significant amount of material on site. It should be recognized, moreover, that the Nonproliferation Treaty is interpreted by its signatories to allow enrichment and reprocessing by all states, including non-weapons states, so major changes would be needed in international agreements to prevent nations from acquiring and applying these technologies. The difficulty faced by GNEP[75] and IAEA "fuel bank"[76] initiatives in attracting significant numbers of states willing to forgo enrichment and reprocessing for access to external fuel services is worrisome in this regard. The GNEP initiative would have defined states with the right to enrich and reprocess fuel, and others that would relinquish such rights. By contrast the IAEA initiative did not define such distinctions, but proposed that all enrichment and reprocessing activities be placed exclusively under international control. However even this proposal encountered strong resistance from developing countries.

Resistance to the needed strengthening of the nonproliferation regime stems in part from the slow rate of implementation of the disarmament clause of the existing Nonproliferation Treaty. However a large expansion and spread of nuclear power would make the disarmament process that much more difficult. The cooperative process of stepping away from nuclear weapons in a world with so much widely dispersed raw material for their production would be very difficult, because the magnitude and breadth of the system requiring control would be so daunting.

Since "fast-spectrum" fission and fusion scenarios, in which these new technologies begin to be commercialized around mid-century are considered next, it is valuable to consider, as an example, the climate impact of an LWR case which peaks in mid-century and uses all of the IAEA/NEA discovered + undiscovered uranium by 2100. Replacing that much nuclear power with pulverized coal plants without CCS would increase CO_2 concentration in 2100 by 44 ppm, with a predicted very long-term global-average surface temperature rise of $0.23–0.51^\circ$C, subject to the caveats described above. In particular, it may (or may not) be possible at increased cost to replace this level of nuclear power with accelerated programs of carbon-capture and storage and renewable electrical energy obtained from tapping natural energy flows.

Even with a much stronger nonproliferation regime in place, decision makers will need to balance the risks associated with temperature rise against the increased proliferation risks discussed so far, as well as the costs and uncertainties of accelerated alternative energy programs.

FAST SPECTRUM FISSION REACTORS

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," (FRs). This generally requires the use of heavy metallic coolants, such as sodium or lead, to limit the slowing-down of neutrons through collisions.[77] Alternatively, a neutron-transparent coolant such as helium may also be usable. Such systems take as a design goal converting Uranium-238 to plutonium isotopes and minor actinides (TRU) while burning only TRU, not Uranium-235. Thus they would require no mined uranium. If designed for the purpose they may also be able to start up initially using enriched uranium[78] rather than TRU, and then transition to TRU burn.

The development of FR systems based on TRU, and of the full associated fuel cycle with its highly complex radiochemistry, are significant technological challenges and the degree of success that will be achieved is not certain. However, many nations are pursuing R&D on fast-spectrum systems, through the Generation IV International Forum,[79] through other multilateral agreements, and through national deployment of prototype fast-spectrum systems.

The conversion ratio (CR) of an FR is defined as the production rate of TRU divided by the TRU burn rate. For example $CR = 1$ denotes a system which neither consumes nor produces net TRU. The range of CR that is likely to be accessible is perhaps from 0.5 to 1.5, although the limits are under study. Devices with $CR > 1$ are termed "breeders" of fissile fuel, and those with $CR < 1$ are termed "burners." The high end of CR is limited by neutron economy,[80] since about 2.9 neutrons are produced per fission in TRU, and one of these neutrons is necessarily consumed in further fission in order to sustain the chain reaction. The theoretical upper limit of CR of about 1.9, which would result from capture of all of the remaining neutrons by Uranium-238 producing Plutonium-239, is inevitably reduced by the loss of neutrons from the reactor core or by their absorption through capture in, for example, Plutonium-239 and fission products, and in internal reactor structures. The lower end of the CR range may be limited by the practical lifetime of TRU fuel cladding, or by safety issues that stem, for example, from the large swing in reactivity during burn at low CR and the small delayed neutron fraction of TRU.[81]

The U.S. Advanced Fuel Cycle Initiative has as one of its goals, "develop and make available the fuel cycle technology needed for commercial deployment by 2040 of fast spectrum reactors operating either exclusively as transuranics transmuters or as combined fuel breeders and transmuters."[82] Thus scenarios are considered here in which fast spectrum fission reactors burning TRU come on line commercially in 2040. Other nations may be driven by different considerations than the United States to move more quickly than this. For example China and India have rapidly growing energy supply needs and limited domestic uranium supplies.

The world will have a large resource of used nuclear fuel by 2040, so FRs can be started up as this used fuel is reprocessed to extract plutonium and MAs and is then fabricated into TRU fuel for the fast reactors. As shown in the dynamical equations of on-line Appendix 3, 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. In the present analyses FRs are only started using TRU, not enriched uranium.

In these analyses country-to-country variations of uranium supplies and of access to used fuel are neglected, considering the world's uranium and used fuel as world-wide resources. In the case of used fuel, this is likely to be optimistic since international exchange of used fuel, which has potential weapons use, will likely be restricted in significant ways. On the other hand access to uranium has historically been quite open, and fast reactors may be able to be started up with enriched uranium, as noted above. In Figures 5–8 both breeder ($CR > 1$) and burner ($CR < 1$) FRs are considered: first, FR "breeder" cases with the ratio $CR \leq 1.5$ that allows fast reactors to take over maximally from LWRs

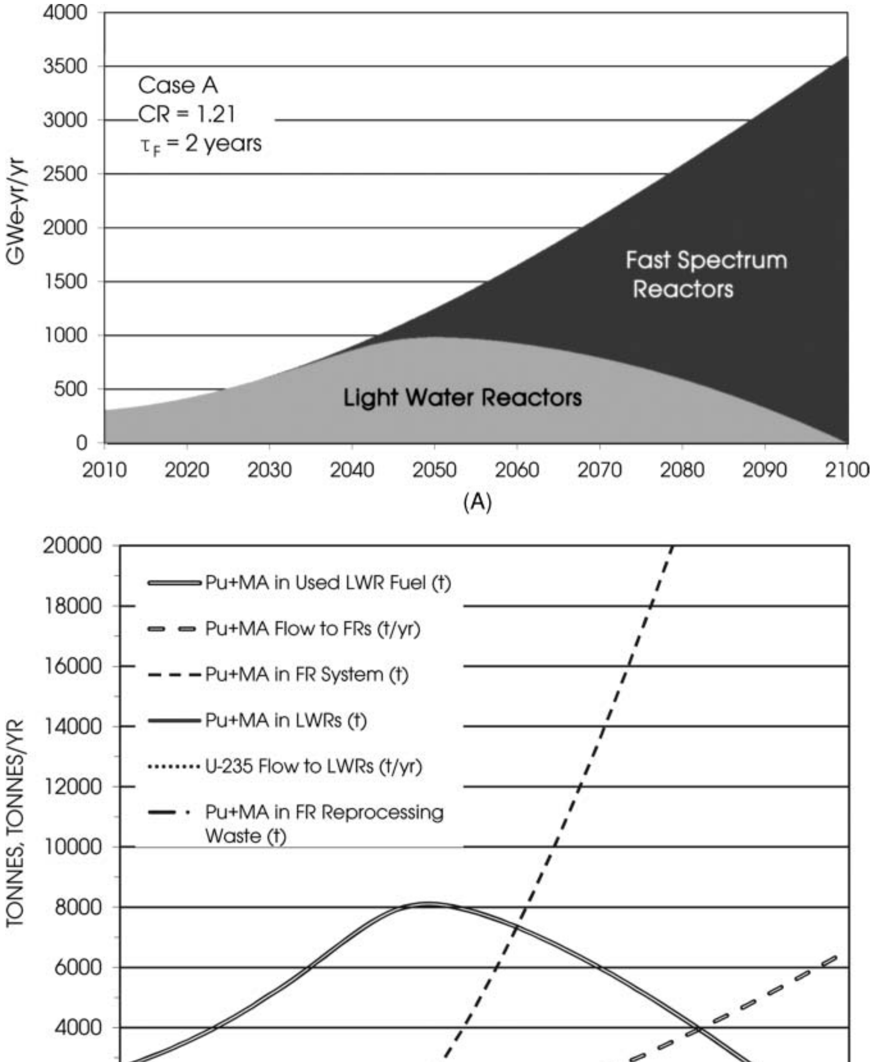


Figure 5A and B: (A) Power production and (B) Stocks and flows of Pu+MA and U-235 CR = 1.21, $\tau_F = 2$ years. In year 2100 the stock of PU+MA in the FR system reaches 38,010 tonnes.

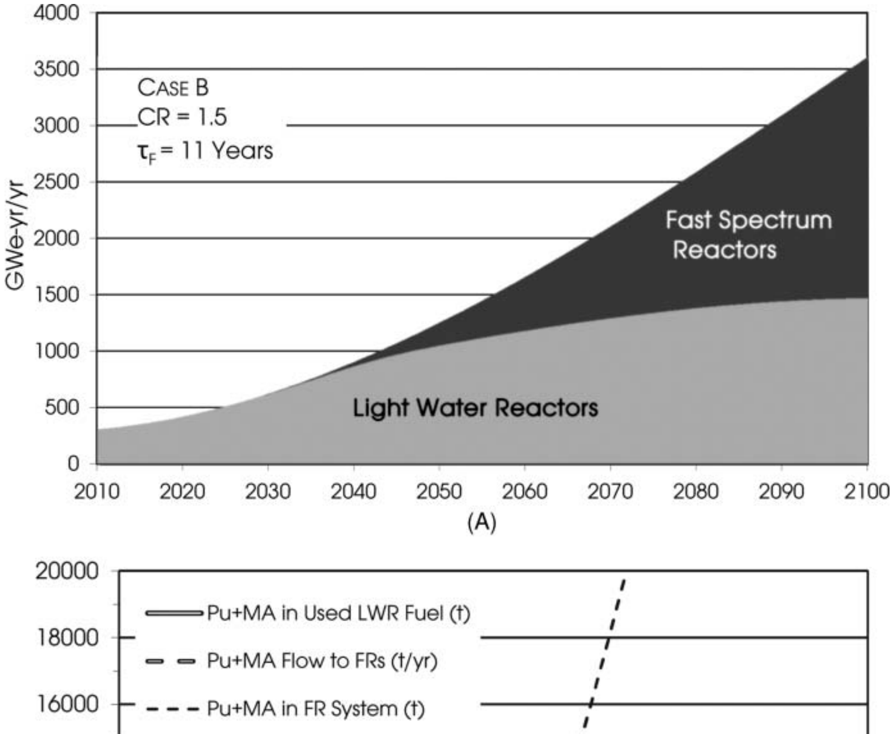


Figure 6A and B: (A) Power production and (B) Stocks and flows of Pu+MA and U-235 CR = 1.5, $\tau_F = 11$ years. In year 2100 the stock of PU+MA in the FR system reaches 52,432 tonnes.

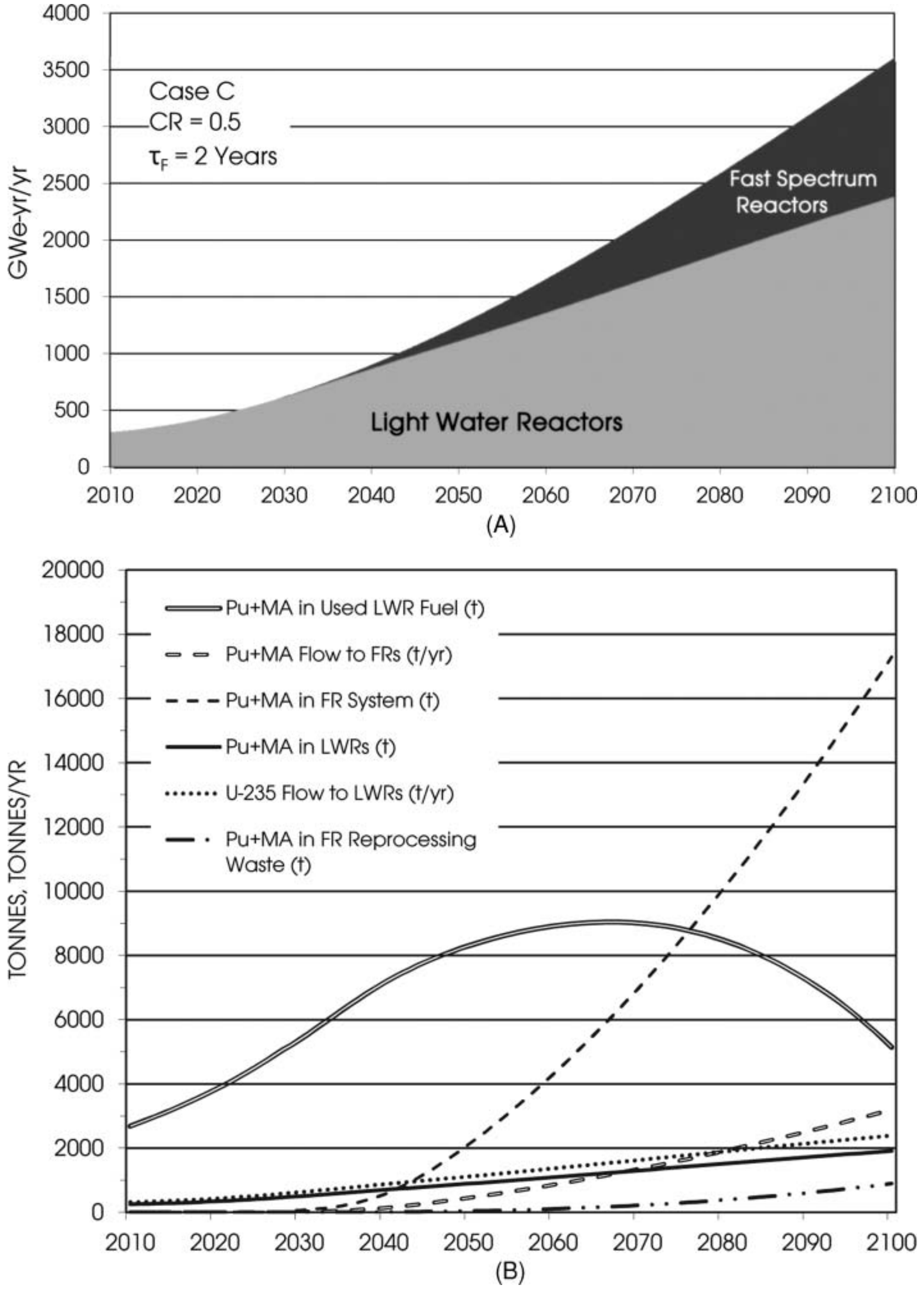
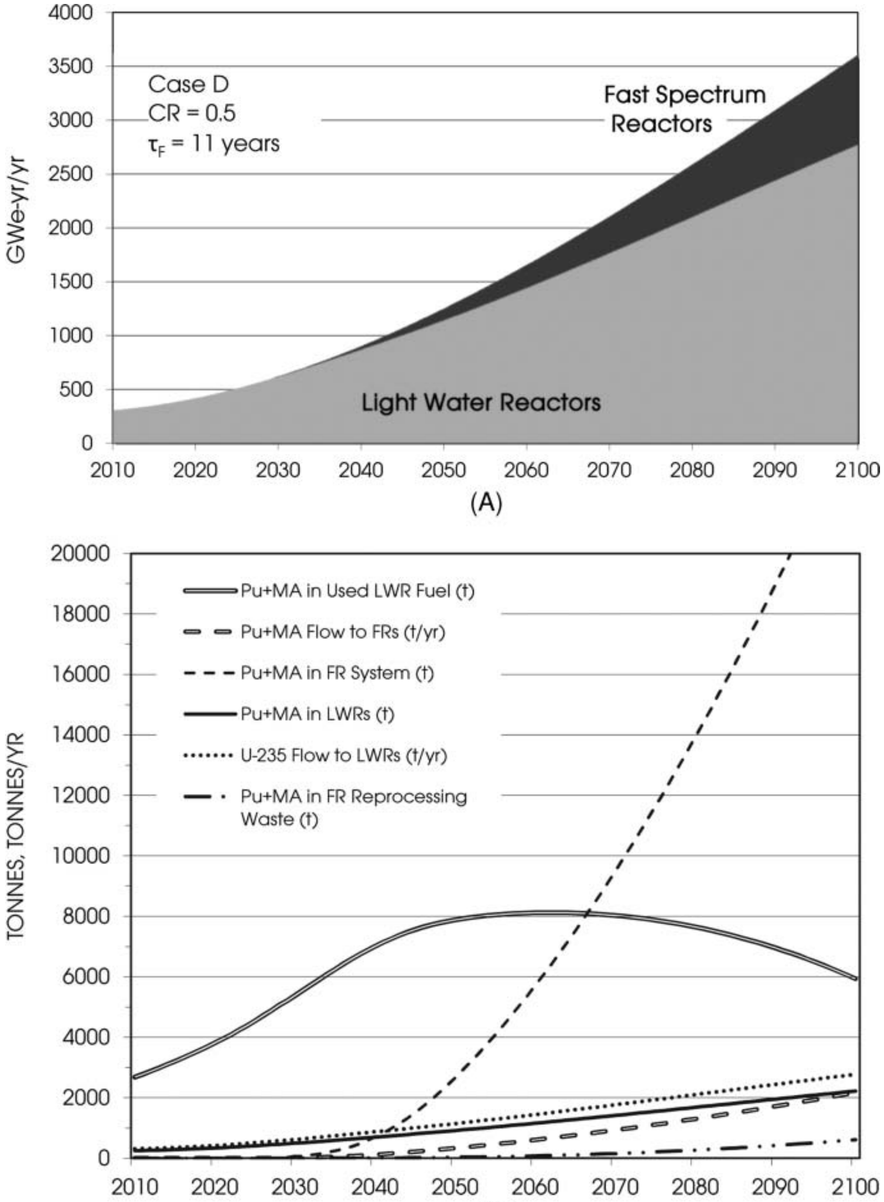


Figure 7A and B: (A) Power production and (B) Stocks and flows of Pu+MA and U-235 CR = 0.5, $\tau_F = 2$ years. In year 2100 the stock of PU+MA in the FR system reaches 17,292 tonnes.



(A)

(B)

Figure 8A and B: (A) Power production and (B) Stocks and flows of Pu+MA and U-235 CR = 0.5, $\tau_F = 11$ years. In year 2100 the stock of PU+MA in the FR system reaches 24,540 tonnes.

by the end of the century (but not sooner), also pulling essentially all LWR used fuel into the FR system by that date, and second, FR "burner" cases with CR = 0.5, which employ fast reactors to reduce TRU waste as LWRs continue to operate past 2100. For each of these classes two residence times are considered for used TRU fuel in the cooling/reprocessing/fabrication stages (τ_F): a minimum time of 2 years, which might be achievable with reprocessing facilities collocated at fast reactors, and an estimated time of 11 years, which might be required to provide adequate cooling to allow transportation of used TRU fuel to international reprocessing centers. These analyses extend earlier work[83] analyzing U.S.-only scenarios, which employed these values for τ_F.

Figures 5–8 show results for these cases, using the evolution equations for stocks and flows described in Appendices 2 and 3. In general, longer fuel residence times result in slower growth rates for fast reactors. This stems from the fact that a fast reactor typically contains four years worth of fuel, but the additional residence time in cooling ponds, transport, reprocessing, and fabrication (τ_F) requires substantial additional commitment of TRU for a continuously operating system. (No further allowance is made here for a reserve supply of fuel, perhaps one year's worth, which might be required by reactor operators.) With $\tau_F = 2$ years, as assumed in Case A, all LWR nuclear power can be replaced by 2100 with FRs having CR = 1.21. At CR = 1.5, to achieve this goal requires $\tau_F \leq 6$ years. At $\tau_F = 6$ years, with the assumed time for reprocessing and fabrication of only one year, the remaining five years for cooling and two-way transportation is likely to be inadequate for the use of international fuel recycling centers. In Case B, with $\tau_F = 11$ years, it is not possible to replace all LWRs by 2100.

It is also the case that lower CR results in fewer fast reactors. This is in part because in a "balanced" steady-state system in which the fast reactors steadily consume the TRU from LWRs (on-line Appendix 3) fast reactors with CR = 0.5 would only account for about 39 percent of the total power production. However it is also the case that the world's reserve of used nuclear fuel limits the total number of CR = 0.5 reactors that can be started up by 2100. The greater τ_F in Case D therefore reduces the number of fast reactors.

Table 3 provides some key results relevant both to the goals of fast reactors to reduce waste and extend the resources for fission, and also to proliferation risks. The degree of success towards the goals considered for fast spectrum

Table 3: Parameters of fast-reactor scenarios relevant to extending resources and reducing waste, as well as to proliferation risks

	Case A	Case B	Case C	Case D
CR	1.21	1.5	0.5	0.5
τ_F (yr)	2	11	2	11
Total U mined + Committed (Mt)	12.3	29.5	42.0 +	47.5 +
Pu+MA in Waste, 2100 (t)	2,220	4,210	6,030	6,550
Pu+MA in FR System, 2100 (t)	38,000	53,800	17,300	24,500
Uranium-235 Fueling, 2100 (t/yr)	0	1,470	2,390	2,770
Pu+MA Fueling, 2100 (t/yr)	6,510	3,420	3,190	2,170

reactors, extension of uranium resources and reduction of waste are analyzed first.

From the point of view of extending uranium resources, clearly Case A is successful, requiring less total mined uranium than the IAEA/NEA total (discovered plus undiscovered) resource of 16Mt, unlike the LWR-only scenario which required 59 Mt even if no further reactors are constructed after 2100. Case B is somewhat successful, and Cases C and D, because they are not designed to replace LWRs with FRs, not only far exceed the IAEA/NEA total, but are understated in Table 3. The "+" is meant to indicate that the "committed" resource associated with the existing reactors in 2100 far understates the very long-term commitment of a steady-state "balanced" system.

Note that the rate of transition to fast reactors could be accelerated, particularly in cases B and D which are limited by the availability of TRU, if the FRs are designed to start operation with enriched uranium fuel, and then transition to TRU. If an FR capable of 1 GWe-yr/yr output with CR $= 1$ and $\tau_F =$ 11 years is considered, it will begin to supply its own fuel only after it has been provided with 15 years worth of fueling. Ignoring differences between Uranium-235 and TRU fuel, this would require about 27 t of Uranium-235, or about 5800 t of mined uranium, assuming 20 percent enrichment in Uranium-235 with 0.25 percent in the tails. Thus to start up 1000 GWe-yr/year of such systems would require about 5.8 Mt of mined uranium. In the extreme case, 3600 GWe-yr/year of fast reactors could be started up using 21 Mt of mined uranium, about 30 percent more than the total "Redbook" estimate. With this resource, CR $= 1$ fast reactors designed to start up with enriched uranium would be able to take on the specified role later in the century in the absence of an earlier generation of LWRs. Since an LWR consumes about 900 kg of Uranium-235 per year, and produces about 325 kg of TRU, in general less mined uranium is required to transition to fast-spectrum reactors in the absence of a large build-up of LWRs. It should be noted, however, that the total Pu+MA in a 3600 GWe-yr/yr fast reactor system with $\tau_F = 11$ years would be in the range 100,000 t, about twice the maximum value in Table 3.

From the point of view of reducing TRU waste all four cases are successful. This essentially stems from the fact, discussed in Appendices 2 and 3, that 1 GWe-yr of LWR operation produces about 0.32 t of TRU waste, while 1 GWe-yr of FR operation requires fueling in the range of 2 t of TRU (picked up from the LWR waste or created by the FRs), but the only TRU waste that needs to be disposed is the 1 percent, or about 0.02 t, that is anticipated to be lost in the reprocessing and fabrication steps, assuming successful development of these processes. This results in a factor of approximately 16 reduction in waste TRU per GWe-yr produced in a fast reactor as compared with an LWR. As the fast reactors begin by loading TRU from the LWRs, in this model the LWR power produces no waste of its own. (Note that LWR TRU does not go to zero in 2100 in Figures 5–8, because it must be cooled for about 6 years before reprocessing.)[84]

One should be cautious, however, because this waste assessment based solely on TRU is not complete. The mass of fission products produced per GWe-yr is about the same for LWRs and FRs, except for the modest anticipated increase in efficiency at the higher temperatures of fast reactor coolants. To gain a factor of 4–5 with respect to the thermal capacity of waste storage, cesium and strontium must be partitioned and stored for $\sim$300 years, outside of the repository.[85] It also appears that in an oxidizing environment such as predominates at Yucca Mountain, as opposed to the reducing environment now recommended by the IAEA for geological repositories,[86] the mobility of the long-lived Technetium-99 and Iodine-129 fission products relative to plutonium and minor actinides could make them significant radiological safety concerns.[87]

The proliferation risks of the FR cases in Figures 5–8 are considered next. What stands out most strongly in these figures is the rising line denoting the inventory of TRU in the FR system, including its storage and reprocessing facilities. Since FRs with $CR > 1$ create net TRU, and FRs with $CR < 1$ burn it, but slowly, the quantity of TRU in process is comparable to the quantity that would have been stored in dry casks or buried in geological repositories in the case of LWRs alone (see Row 4 of Table 2). Thus in the FR cases one has traded TRU casks and geological repositories for TRU pools of similarly large magnitude, but now being used and manipulated, and so entailing much more risk and requiring much more extensive safeguards. The pool size ranges from about 2 to 6 million SQ. For the case of 3600 GWe-yr/yr of fast reactors with $\tau_F = 11$ years, it would be about 11 million SQ. This is an example where magnitude certainly matters. The risk of covert diversion of a few SQ by nations or sub-national groups seems very high. It should be recognized as well that in all four cases one is committed to continuing growth of the active pool of TRU as energy use increases. Furthermore, stopping abruptly for any reason would result in a very large amount of waste to dispose. These results can be summarized epigrammatically,[88] "... one must put TRU 'in play' in order to reduce waste burdens. "Use it to lose it" and "don't stop!"

It is important to consider proliferation risks in terms of flows as well as stocks. Table 3 shows that Case A eliminates the need for uranium enrichment, because the only fissile fuels for the fast reactors in that scenario are the TRU from used LWR nuclear fuel and from the fast reactors themselves. Uranium-238 from natural or even depleted uranium provides the material to be converted to plutonium. This is a very favorable result. Case B has some effect, and presumably in the very long run would allow elimination of uranium enrichment. This could be accelerated by enriched uranium startup of FRs. Cases C and D, by construction, do not qualitatively affect this risk.

The largest concern in these cases is the flow of plutonium and minor actinides indicated in Table 3. Case A, the most attractive from the point of view of resolving other issues, involves the fueling of fast reactors with about 750,000 SQ of plutonium per year. Case D, with the lowest fueling rate, corresponds to 250,000 SQ of plutonium per year. Currently the IAEA standard for uncertainty in closing the material balance of a plutonium reprocessing plant[89,90] is 1 percent. Again, magnitude matters. Even with enhanced monitoring, surveillance and containment to detect off-normal operation or diversion of materials, failure worldwide to account for 1 percent of 500,000 SQ per year, 5000 SQ per year, could create an unstable international environment where nations would be very concerned about the activities of other nations and sub-national groups and perceive the need to take precautionary actions themselves.

Are there approaches to resolving the issue of diversion in a world with such large stocks and flows of plutonium 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. This may not be possible. A fundamental problem with the alternative solution of internationalizing the "back end" of the fuel cycle is that it necessitates—by definition—the transport of both used and reprocessed fuel. Extremely large quantities of plutonium, of order 500,000 SQ in fresh fuel, would be in transport every year, crossing international borders. This evidently creates its own set of diversion and theft risks. TRU in fast reactor fuel is not self-protecting,[91] and can be rapidly chemically separated and used for weapons, in contrast to the Uranium-235 in LWR fuel that requires further isotopic enrichment for military use.

Are there approaches to resolving the issue of breakout from nonproliferation agreements? This seems at least equally problematic. Consider that the startup fuel for 1 GWe-yr/yr of fast reactor capacity requires approximately 8 t of plutonium or 1000 SQ. In a world where the nuclear weapons states had disarmed to hundreds of weapons each, the temptation to use this fuel for military purposes could be very strong, particularly for a state or regime that perceived itself to be under existential threat, even from conventional weapons. The annual fueling for a fast reactor is much greater than the annual plutonium waste quantity from an LWR, approximately 2 t (250 SQ) vs. 0.3 t (37 SQ) per GWe/yr, and its processing would be even easier and faster for a host nation (1–3 weeks vs. 1–3 months for irradiated LWR fuel), since it would not be burdened with highly radioactive fission products.[92]

The proliferation risks associated with fast reactors, as currently understood, appear much greater than those associated with LWRs. Decision makers will need to balance these against the reduction in CO_2 emissions. If one considers that these FR scenarios make the difference between the total scenario of Figure 3 and the LWR scenario discussed near the end of the section on

LWRs, the estimated change in long-term equilibrium global-average surface temperature of substituting pulverized coal plants, without carbon sequestration, is 0.2–0.45°C, again subject to the caveats discussed above.

FUSION

Power can be produced by "fusing" heavy forms of hydrogen to form helium.[93,94] Fusion systems contain very little fuel, and produce little decay heat when the fusion reaction shuts down. Thus fusion energy systems cannot undergo an uncontrolled power excursion, as happened at Chernobyl, nor can they melt down, as happened at Three-Mile Island and Fukushima. There is also no significant limitation to fuel supplies, and fusion nuclear wastes should not require geological storage. These features contribute to the attractiveness of fusion power.

In laboratory experiments up to 16 MWt has been produced for periods on the order of 1 second, demonstrating the scientific feasibility of producing fusion energy using magnetic fields to confine hot fusion fuel.[95] Based on these scientific results, the ITER fusion experiment is under construction in Cadarache, France as an international collaboration of China, Europe, India, Japan, Russia, South Korea, and the United States. ITER is designed to produce hundreds of megawatts of thermal power from fusion for periods of up to one hour, which will demonstrate the technological feasibility of fusion energy. In the United States the National Ignition Facility has just come on line, with the primary mission to study the physics of advanced nuclear weapons in support of stewardship of the U.S. nuclear stockpile. It also has the mission to demonstrate the scientific feasibility of fusion energy production through "inertial confinement," in which the inertia of the fusion fuel in tiny thermonuclear explosions confines it for long enough to produce more fusion energy than laser energy delivered to the target.

ITER and NIF are fusion research facilities at the scale of fusion power plants. They are first-of-a-kind facilities, and have proven to be expensive, more so than originally planned. Critics tend to focus on specific technological issues such as production of tritium fuel or development of neutron-resistant materials,[96] for which there are solutions under development.[97] There is, however, an appropriate overall concern that fusion power plants will be large and complex high-tech facilities, and as a result their economic practicality cannot be assured at this time, despite favorable projections.[98,99] Very considerable R&D is required to move from scientific feasibility to technological feasibility to practical demonstration allowing commercialization by mid-century.[100,101] Despite these challenges, many of the nations in the ITER partnership have stated that they are targeting mid-century for the commercial application of fusion energy.

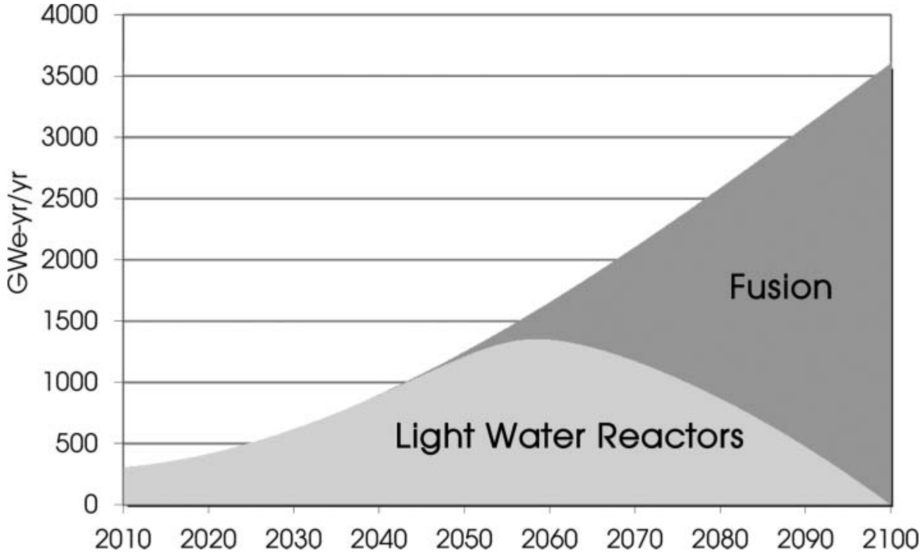


Figure 9: Nuclear power production from light-water reactors, transitioning to fusion.

Figure 9 shows a scenario for the application of fusion power for commercial electricity production starting at mid-century. The maximum growth rate of fusion power in this scenario is 0.86 percent/year of the world electricity market, which is less than the growth rate of fission power 1975–1990, 1.2 percent/year of the electricity market at that time. In this scenario 15.8 Mt of uranium is mined for LWRs, equal to the IAEA/NEA projected total resource.

Fusion has significant nonproliferation advantages relative to fission.[102] While the energetic neutrons from fusion can be used to transmute Uranium-238 to Plutonium-239, or Thorium-232 to Uranium-233, this is very easy to detect and even prevent. Fusion systems are easily enough detectable due to their size, energy use and effluents that clandestine use of a small fusion facility to produce weapon-materials is not a realistic threat. Furthermore, in normal operation a fusion power plant should have no uranium, thorium, plutonium, or fission products in the vicinity of the neutron-producing fuel. The detection of these at very low levels is straightforward, so covert production and diversion of these weapons materials in a declared and safeguarded facility would not be a serious risk.

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 fissile material. His threat is to begin to produce such materials. This is to be compared with the situation for fast-spectrum fission reactors where, for 1 GWe-yr/yr capacity, about 2 t or 250 SQ of plutonium is on hand at any time for yearly refueling. Furthermore, it would be straightforward to interdict fissile material production at a fusion power plant that had broken out from the safeguards regime, 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.

Fusion energy systems produce and subsequently consume significant quantities of the heaviest isotope of hydrogen, tritium, which is not available in nature. If tritium were covertly diverted from a fusion system it could be used by an advanced proliferating nation to boost the yield of fission explosives, including the primaries of thermonuclear weapons. Clandestine production of tritium using fusion is not a realistic concern, but fusion systems will have multi-kg tritium inventories, which would become available in a breakout scenario. Tritium itself, however, does not provide access to nuclear weapons capability, explaining why it is not controlled under the Nonproliferation Treaty. Some, however, have argued for such controls,[103] to cut off the production of tritium in nuclear weapons states and to limit access to tritium by advanced proliferating nations.

Plans for the production of tritium to maintain the U.S. tritium stockpile indicate that a single commercial-scale fission reactor can generate enough tritium ~1.5 kg/year to sustain the U.S. stockpile indefinitely.[104] An advanced proliferating nation could therefore build up and maintain a large stockpile of weapons, about 10 percent of the size of the U.S. stockpile in terms of tritium inventory, using a single very modest sized fission reactor. The same reactor could also be used to produce plutonium for weapons. The development of tritium-boosted weapons requires nuclear testing,[105] and thus breakout from the Nonproliferation Treaty, prior to the build-up of an arsenal. Therefore tritium production to supply boosted weapons, for example as part of a regional arms race, would not require covert diversion from a declared fusion facility. Such a build-up would be unlikely to be limited by access to tritium. Under these circumstances, the advantage of covert access to tritium from fusion energy systems, or through a fusion breakout scenario, would likely be modest.

The scientific basis of inertial confinement fusion overlaps with that of advanced nuclear weapons, so R&D, and ultimate deployment, of fusion energy systems based on this technology could present a risk of dissemination of sensitive information to proliferating nations with advanced capabilities. These risks need to be examined directly and transparently, as well as the means to minimize the dissemination of such information.[106]

In sum, the proliferation risks of fusion energy systems are qualitatively lower than those of the fission energy systems discussed here. However maintenance of this low level of risk requires the implementation of international safeguards. The extension of these safeguards to include tritium accounting, for both fission and fusion systems, should be considered.

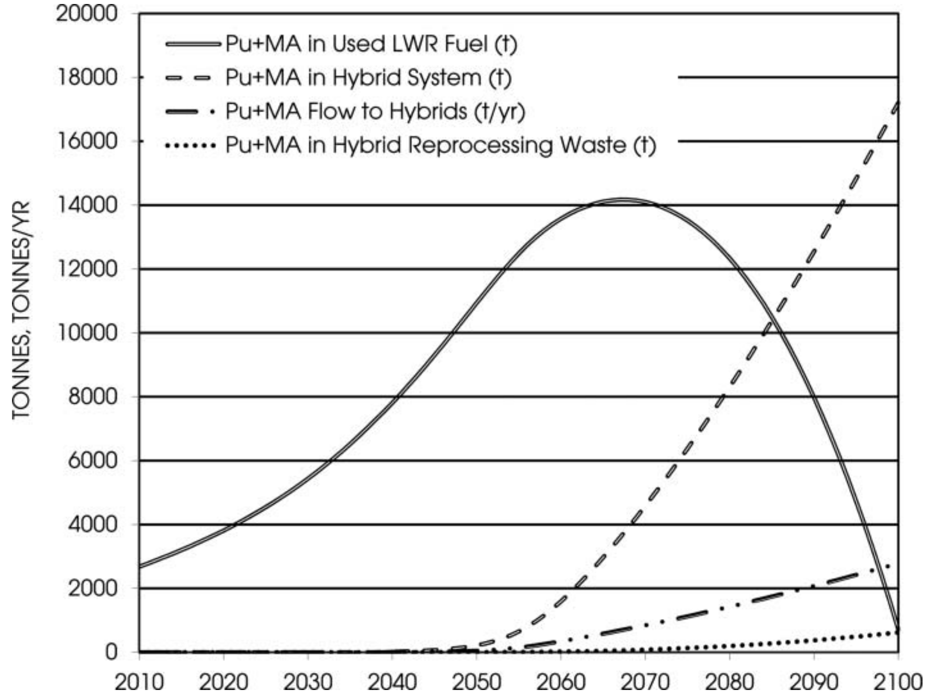


Figure 10: Stocks and flows of Pu+MA in fission-fusion hybrid case.

FUSION-FISSION HYBRID TRANSMUTERS

In the scenario of Figure 9, with no further processing of the used nuclear fuel from the LWRs, 27,000 t of TRU and associated fission products remain worldwide, requiring geological repositories with capacity of approximately 27 times the proposed statutory limit of Yucca Mountain.

It has been proposed to use accelerator-driven neutron sources to drive subcritical fission reactors to transmute, effectively to burn, TRU. Fusion systems can also produce neutrons, in principle with much lower energy input than accelerators, so studies have been undertaken to examine this option.[107] Here, one of the more well-developed concepts is considered,[108] based on a subcritical fast reactor driven by fusion neutrons burning the left-over TRU from LWRs (see on-line Appendix 4). Figure 10 shows the TRU stocks and flows associated with this concept, as applied to the scenario of Figure 9. For simplicity, it is assumed that a constant fraction of all nominally fusion systems until 2100 would be fusion-fission hybrid TRU burners. 9.9 percent is the required fraction to put all the world's used LWR nuclear fuel TRU into process by the end of the century.

This scenario shares the main proliferation risks of the fast reactor scenarios: large stocks and flows of plutonium and minor actinides. The advantage in this case is that as the TRU from the original set of LWRs is burned up, no further TRU is produced. After 2100, the stock and flow of TRU each drop by a factor of 2 every 30.6 years, rather than grow as nuclear power expands. Also in this scenario at most 1 in 10 power plants is ever a TRU burner, so the burners can conceivably be less dispersed than CR = 0.5 fast reactors, which constitute approximately 39 percent of a steady-state system in which they burn the waste from LWRs. If the technology is developed to make the scenario of Figure 10 an option, a judgment will be required as to whether this is safer, from a proliferation point of view, than depositing the used LWR nuclear fuel in geological repositories.

In principle, fusion-fission hybrids could instead play approximately the same role as the fast reactors in the CR = 0.5 scenarios shown in Figures 7 and 8, with a smaller fraction of power from burner reactors, 22% vs. 39 % (on-line Appendix 4), but without a qualitative proliferation advantage.

CONCLUSIONS

Nuclear energy may be needed to provide approximately 30 percent of world electrical power production, 3600 GWe-yr/yr, by 2100, although there is considerable uncertainty in this estimate. This level of power can be achieved through a combination of light-water reactors, fast-spectrum reactors and potentially fusion. However the magnitude of the undertaking is large, constituting a 12 times increase in nuclear electric power production compared with 2010. The very large scale and the associated broadening of the range of nations using nuclear power bring with them serious proliferation risks.

If the nuclear power profile shown in Figure 2 were replaced with pulverized coal plants without carbon capture and storage, the additional equilibrium global-average surface temperature rise would be 0.43–0.92°C. Alternatively if the potential limits to other low-carbon sources of electrical energy discussed here prove to be soft, it will be possible to replace nuclear energy, potentially early or late, with other low-carbon sources, albeit likely at higher cost to the world economy.

As choices are made about the future world energy economy, decision makers will need to balance the proliferation risks from nuclear power against its CO_2 mitigation. Light-water reactors carry significant risks associated with covert enrichment and breakout of declared enrichment facilities from safeguards, as well as breakout from safeguards of used fuel storage facilities. Institutional arrangements for management of these risks have been proposed, but are difficult to implement. Fast spectrum fission reactors carry significantly higher risk, due to extremely large above-ground stocks and flows of weapon-usable material and the difficulty of highly accurate accounting at reprocessing facilities. The above-ground stocks in active use are comparable in magnitude to those in storage in the LWR-only case. This gives rise to concerns both about covert diversion and about breakout. These risks appear more resistant to management. For example use of international reprocessing centers brings with it, necessarily, extensive cross-border transport of weapons-usable material. In order to play the role in carbon emissions reduction discussed here, the fueling rate for fast reactors in 2100 would be adequate to construct approximately 500,000 nuclear weapons per year. The risk of fissile material availability from fusion is only associated with operation after breakout from safeguards, which can be interdicted, and appears therefore to be the most manageable.

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