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Climate Change, Nuclear Power and Nuclear Proliferation: Magnitude Matters

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Climate Change, Nuclear Power and Nuclear Proliferation: Magnitude Matters

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Abstract

Integrated energy, environment and economics modeling suggests that worldwide electrical energy use will increase from 2.4 TWe today to ~12 TWe in 2100. It will be challenging to provide 40% of this electrical power from combustion with carbon sequestration, as it will be challenging to provide 30% from renewable energy sources derived from natural energy flows. Thus nuclear power may be needed to provide ~30%, 3600 GWe, 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, without a dramatic change in the proliferation risks of such systems, at the end of the century global nuclear proliferation risks are much greater, 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.

climate change, nuclear power, nuclear proliferation

1. 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 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 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 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 by Williams and Feiveson (1990), Feiveson (2004), Feiveson *et al.* (2008), Socolow and Glaser (2009) and Feiveson (2010).

2. Integrated Energy, Environment and Economics 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 we focus 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*. (2006), 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% to 60%. These effects very nearly balance each other, providing a stable projection for future electricity production.

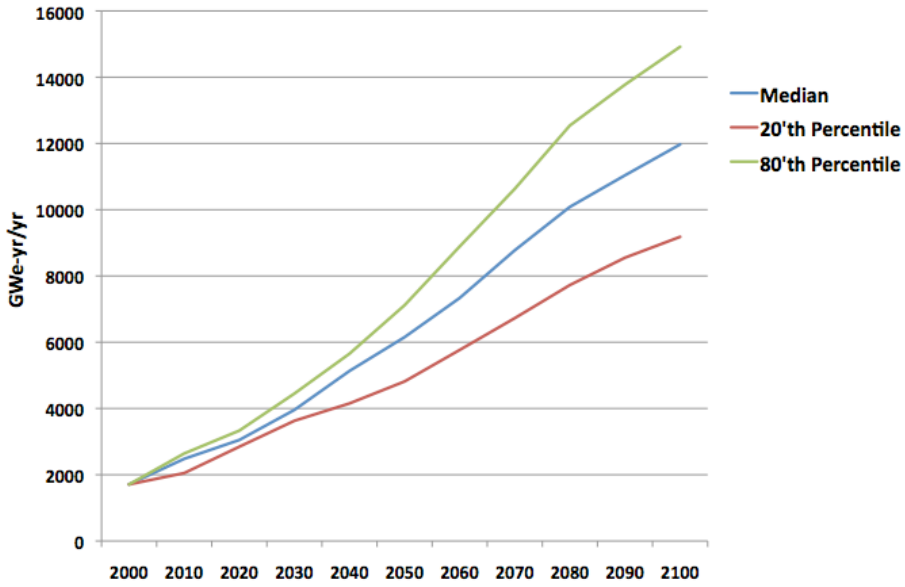


Figure 1. Electrical power production from EMF 22 models. "GWe-yr/yr" is used to indicate electrical power production, as opposed to production capacity, often denoted "GWe".

It is valuable to look beyond Edmonds's results of 2006 to the most recent analyses, and to a wider range of models. The database from the Energy Modeling Forum 22 (EMF 22) study (Clarke *et al.*, 2009) is a source of such information. 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. 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; 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 full early participation was assumed. The projection for world electrical energy production, 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 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 20'th and 80'th percentiles refer to the range of results over all models[i] and all constraints. The average logarithmic growth in the median case from 2010 to 2100 is somewhat less than was experienced 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. For perspective, according to online DOE Energy Information Agency data, world electrical power production in 2007[ii], was 2142 GWe-yr total: 1482 GWe-yr (69.2%) from conventional thermal sources plus biomass and waste, 296 GWe-yr (13.8%) from nuclear, 342 GWe-yr (15.9%) from hydroelectric and 26 GWe-yr (1.2%) from wind, geothermal, solar, tide and wave.

The 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 (Blanford *et al.,* 2009, Calvin *et al*., 2009a, Calvin *et al.*, 2009b, Gurney *et al.*, 2009, Krey *et al.*, 2009, Loulou *et al.,* 2009, Russ *et al.,* 2009, van Vliet *et al*., 2009) indicate a great deal of variation in the mix. There is, however, a clear trend towards higher 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 of 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.

Sections 3 and 4, below, provide a basis for estimating that of the 12,000 GWe-yr/yr projected in 2100, 40% may be able to be provided by combustion, including of biomass, with a large fraction of sequestration, and 30% may be able to be provided by renewable electrical power obtained from tapping natural energy flows: hydro, wind, solar, geothermal, *etc.* Sections 5 and 6 examine the implications, particularly for nuclear proliferation, of providing the remaining 30% with nuclear fission and/or fusion. The electrical energy fractions discussed here are quite similar to detailed recent results from the MiniCam model[iii] (Kim *et al.,* 2008) for a case where the atmospheric concentration of CO_2 was constrained to 550 ppm. 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, with total time profile given by the median case 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 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 12x increase in nuclear power from 2010 to 2100.

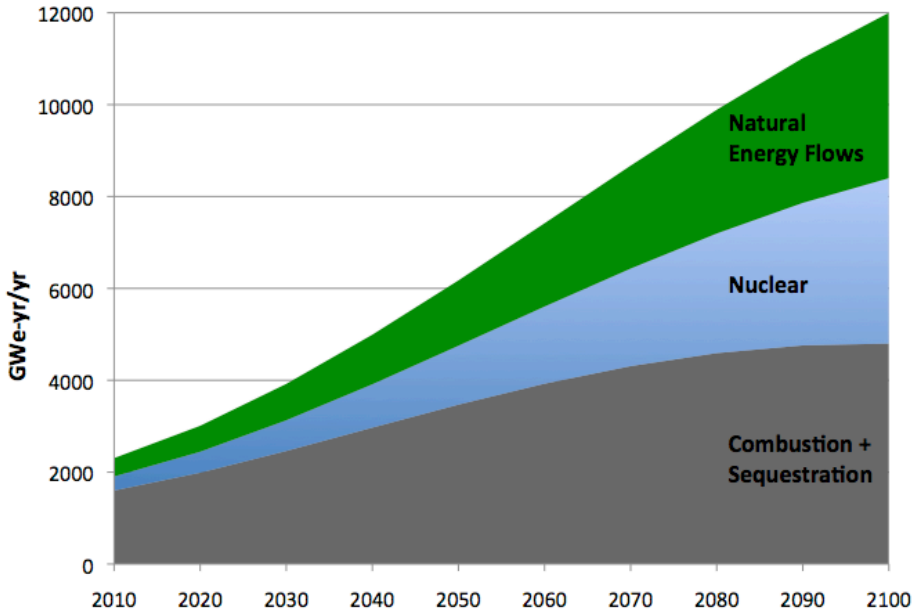


Figure 2. Assumed electrical energy production time profiles.

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 (IPCC, 2005) 0.762 $kgCO_2/kWh$ or 6.68 $MtCO_2/GWe\text{-}yr$.[iv] The increased total emission of 1000 $GtCO_2$ would result in an increase of about 80 ppm in atmospheric concentration[v] of CO_2 in 2100 compared to a case without the increased emission. The Intergovernmental Panel on Climate Change (2007a) estimates that this would cause an additional increase of equilibrium global-average surface temperature of 0.64^oC with an uncertainty range from 0.43^o C to 0.96^o C. 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. It is difficult to be quantitative about the impacts of long-term changes such as these, but for example it is reported (IPCC, 2007a) that a ~1^o C change in global surface-average temperature in 2100 makes the difference between "Most corals bleached" and "Widespread coral mortality". A ~2^o C change makes the difference between "Up to 30% of species at increasing risk of extinction" and "Significant extinctions around the globe". A

~2.5^{o} C change 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^{o} C to 0.96^{o} 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 Sections 3 and 4 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 (Clarke, 2009b). Furthermore, if the demand for electrical power shown in figure 1 is an overestimate, for example due to improved end-use efficiency, then the need for nuclear energy would be reduced. 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 Appendix 1).

3. Combustion and Sequestration, including Biomass:
320 TWe-yrs by 2100, 4800 GWe in 2100

As summarized in recent reports (IPCC, 2005, MIT, 2007, Socolow, 2005) 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 $MtCO_2$ using subsurface storage in saline aquifers 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 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 (2005) at a lower limit of 1850 $GtCO_2$. The range of published projections is quite varied (MIT, 2007) with the upper limit of technically potential storage in some cases as much as an order of magnitude higher. 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 (Appendix 1),

with no sequestration beyond their lifetimes, this increases to about 3200 $GtCO_2$, more than 70% above the IPCC lower-limit estimate.

Carbon capture and storage (CCS), where applied, reduces the net efficiency for extracting electrical energy from coal by ~25%. CCS is currently in the range of 90% efficient at capturing CO_2 produced, so that CO_2 emissions per net kWhe are reduced by about 87%, not 100%. [CO_2 emissions per kWhe from renewable electrical energy and from nuclear power are estimated by the IPCC (2007b) to be much less.] 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 (2005) reports that, because of mismatches between CO_2 sources and potential sequestration locations, "by 2050, given expected technical limitations, around 20 – 40% of global fossil fuel CO_2 emissions could be technically suitable for capture, including 30 – 60% of the CO_2 emissions from electricity generation." In this context, the achievement of 40% electrical energy production in 2100 from combustion, with very low net emission of CO_2, appears to be an important, but nonetheless challenging, goal.

4. 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% 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 (IPCC, 2007b), large-scale hydropower will provide about 6% of world electricity in 2100. Other sources based on hydrological flows such as tides and wave power are not projected to be major contributors.

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 U.S. by 2050 (MIT, 2006).

We posit here that 30% of world electrical production may come from renewable energy obtained by tapping 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 over days and weeks 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 (Traube *et al.,* 2008), necessitating demand reductions and/or significantly increased generating capacity. A U.S. study (USDOE, 2008) targets 20% 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. Some argue, on the other hand, that a factor of ~ 2 higher fraction, ~ 40%, can be achieved with improved technologies before technical limits are reached (Reeves *et al.*, 2003). China, Europe, India, Japan and Korea, representing about half of the world's population, have ~16% of the wind resources per capita of the U.S. (Clarke *et al.,* 2009b). The most populous nations, China and India, have ~5%. It appears from this that a 20% world-average contribution from intermittent energy sources, and a total world-average contribution of 30% from renewable electrical energy tapping natural energy flows, represent important, but nonetheless challenging, goals.

5. Nuclear Power: Fission and Fusion: 150 TWe-yrs by 2100, 3600 GWe in 2100

The above discussion illustrates the challenges associated with producing 70% 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. This provides support to evaluate a nuclear power scenario that produces 30% of the world's projected electrical energy needs in 2100, up from 14% in 2007, while total electrical energy production increases by a factor of five. Here we will discuss the leading fission technologies, light water reactors and fast-spectrum reactors based on the use uranium fuel, followed by a discussion of fusion energy. In all cases we will focus on proliferation risks.

Thorium may provide an alternative fuel for nuclear fission, with larger crustal abundance than uranium and some attractive nonproliferation and waste advantages (IAEA, 2005b). Thorium itself is not fissile, but can be transmuted by thermal neutron capture to ^{233}U, 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 Feiveson (2004) and Feiveson *et al.* (2008), which consider the proliferation risks associated with various alternative fission reactor technologies, including those fueled with thorium.

5.1 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 maintaining the chain reaction rather than being absorbed without producing subsequent 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% ^{235}U (the naturally-occurring fissile isotope of uranium) to about 4.5%. As discussed in Appendix 2, about 200t of natural U is needed to provide 1 GWe-yr, with 0.25% ^{235}U concentration in uranium tails, a relatively aggressive level to maximize uranium utilization. If all of the nuclear power in the scenario of figure 2 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.* (2008) of 35 Mt. If the uranium required to complete operation of the LWRs in use in 2100 is included (see Appendix 1), with no further LWR construction, the required mined uranium increases to 59 Mt.

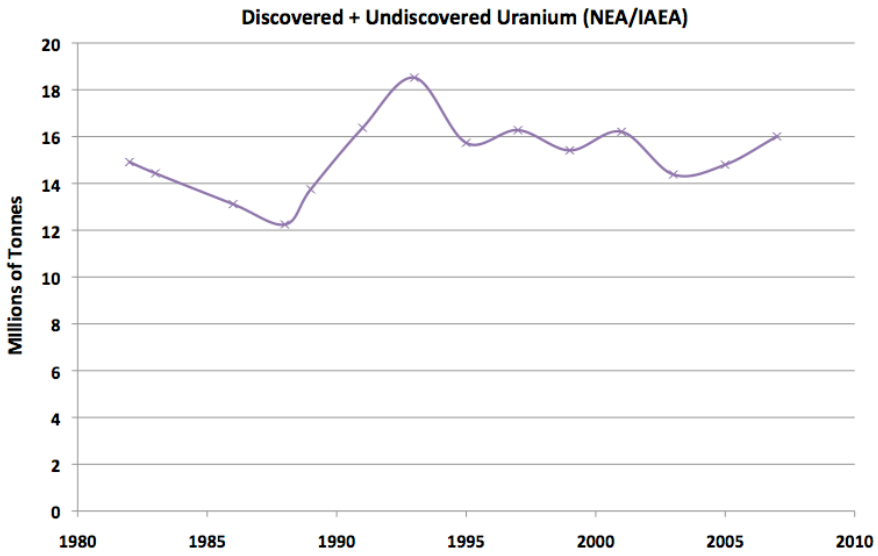


Figure 3. Total discovered + undiscovered uranium reported in IAEA/NEA Red Books, since estimates of undiscovered resources have been included. During this time period 1.1 Mt of U was mined (OECD 2006, 2008).

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 (OECD, 2008) summarized data from 2007, and whose history to 2005 was summarized in 2006 (OECD, 2006). These documents are based on national self-reporting of highly 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 3.

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 (Deffeyes *et al.*, 1980, Schneider and Sailor, 2008) on future conventional uranium reserves, particularly because the price of electricity from LWRs is very weakly dependent on the price of mined uranium. Based on simple models, and very limited geological data, their results suggest that 60 Mt of uranium may be available at acceptable prices. Furthermore, essentially unlimited unconventional uranium sources such as seawater (Seko *et al.*, 2003) may eventually become available at an acceptable price. 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, 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 factor of 38 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 U.S. 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 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. In Table 1, "Pu+MA" denotes plutonium plus minor actinides, such as neptunium and americium, which can also be used to produce nuclear weapons (Albright and Barbour, 1999). 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: Proliferation-relevant parameters of LWR systems to provide the nuclear power profile specified in figure 2.

Proliferation risks can be divided into three categories (GIF, 2006):

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 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 "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, 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 Pu 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 of order 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 than currently, so many new nations will need to join the nuclear "club", and indeed 61 nations without nuclear power[vi], 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 (von Hippel, 2010). 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 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, 1250 t/yr of ^{235}U would be provided to LWRs in the form of LEU, assumed here at 4.5% enrichment (Appendix 2). The IAEA (2001a) 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% ^{235}U), an SQ is defined as a quantity containing 25 kg of ^{235}U. For Pu, an SQ is 8 kg, practically irrespective of its isotopic composition[vii]. The USDOE has indicated that it is possible to make nuclear weapons with as little as 4 kg of weapons-grade Pu.

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 ^{235}U in HEU that could be produced with the anticipated enrichment plants. Enrichment capability is measured in kg Separative Work Units (Benedict *et al.*, 1981). About 5550 kgSWU are required for 1 SQ of HEU (Gilinksy *et al.,* 2004), and 153,000 kgSWU for 1 GWe-yr of LWR power, at 4.5% enrichment with 0.25% ^{235}U 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% of the anticipated world market in 2050, can be reconfigured to produce 1380 SQ/yr, of ^{235}U at 90% enrichment. It is relatively straightforward to verify that a commercial enrichment facility is not producing HEU, but breakout into HEU production can be rapid (Glaser, 2008).

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 (Gilinksy *et al.*, 2004) 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 (Socolow and Glaser, 2009, Glaser, 2010).

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 (Appendix 2), 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 production rate of 400t/year corresponds to 46,000 SQ of Pu/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 Pu. The IAEA (2001b) estimates 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 (2008), based on his analyses in the context of the Generation IV International Forum (GIF, 2006), proposed for the Global Nuclear Energy Partnership fission initiative (NNSA, 2008) classifying reactor-grade Pu as having "medium" proliferation resistance, while weapons-grade plutonium (with a high concentration of ^{239}Pu relative to other Pu isotopes) would have "low" proliferation resistance. This assessment was based on a statement by the USDOE: "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 Pu is treated equivalently with weapons-grade Pu in IAEA controls. The construction of nuclear weapons using reactor-grade Pu are "not different in kind from those involved in using weapons-grade plutonium, but only in degree." (Mark, 1993). 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" (Mark, 1993, Garwin, 1998, Gilinsky *et al*., 2004). 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, provide higher-grade plutonium. More rapid implosion using technologies developed after 1945 also improves performance. In 1962 the U.S. successfully detonated a nuclear weapon using reactor-grade Pu, and the U.S. Department of Energy (USDOE, 1997) has stated 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 Pu.

Clearly, used fuel would need 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 safeguares could be a strong temptation for a state 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 into a stalemate, a considerable benefit. The analyses of the motivations and behavior of North Korea by Sigal and Wit (2009) and of Iran by Ehteshami (2009) 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 the U.S. Global Nuclear Energy Partnership (GNEP) (USDOE, 2007) and IAEA “fuel bank” (IAEA, 2005) 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 (Glaser, 2010).

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 we will next consider "fast-spectrum" fission and then fusion scenarios, in which these new technologies begin to be commercialized around mid-century, 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^{o} C – 0.51^{o} C, subject to the caveats described above. In particular, it might 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 this potential temperature rise against the increased proliferation risks discussed so far.

5.2 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[viii]. Alternatively, a neutron-transparent coolant such as He may also be usable. Such systems take as a design goal converting ^{238}U to Pu isotopes and minor actinides (TRU) while burning only TRU, not ^{235}U. Thus they would require no mined uranium. If designed for the purpose they can also be started up using enriched uranium (MIT, 2010) rather than TRU, and then transition to TRU burn.

The development of fast reactor 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 research and development on fast-spectrum systems, through the Generation IV International Forum (GIF, 2009), through other multilateral agreements, and through national deployment of prototype fast-spectrum systems.

The conversion ratio (CR) of a fast reactor 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 (Piet *et al.,* 2009), 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 ~ 1.9, which would result from capture of all of the remaining neutrons by ^{238}U producing ^{239}Pu, is inevitably reduced by the loss of neutrons from the reactor core or by their absorption through parasitic capture in fuel or 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 (Hoffman *et al.*, 2006).

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." (USDOE, 2005) Thus we consider scenarios in which fast spectrum fission reactors burning TRU come on line commercially in 2040. Other nations may be driven by different considerations than the U.S. 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 fast reactors can be started up as this used fuel is reprocessed to extract Pu and MA's and is then fabricated into TRU fuel for the fast reactors. As shown in the dynamical equations of 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 we only start FR's using TRU, not enriched uranium.

In these analyses we also neglect country-to-country variations of uranium supplies and of access to used fuel, 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 4a - 4d we consider both breeder (CR > 1) and burner (CR < 1) FRs: first, FR "breeder" cases with the ratio CR $\leq$ 1.5 that allows fast reactors to take over maximally from LWRs 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. We consider for each of these classes two residence times 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 centrally located reprocessing centers. These analyses extend the insightful work by Dixon *et al.* (2007), analyzing U.S. - only scenarios, which employed these values for τ_F.

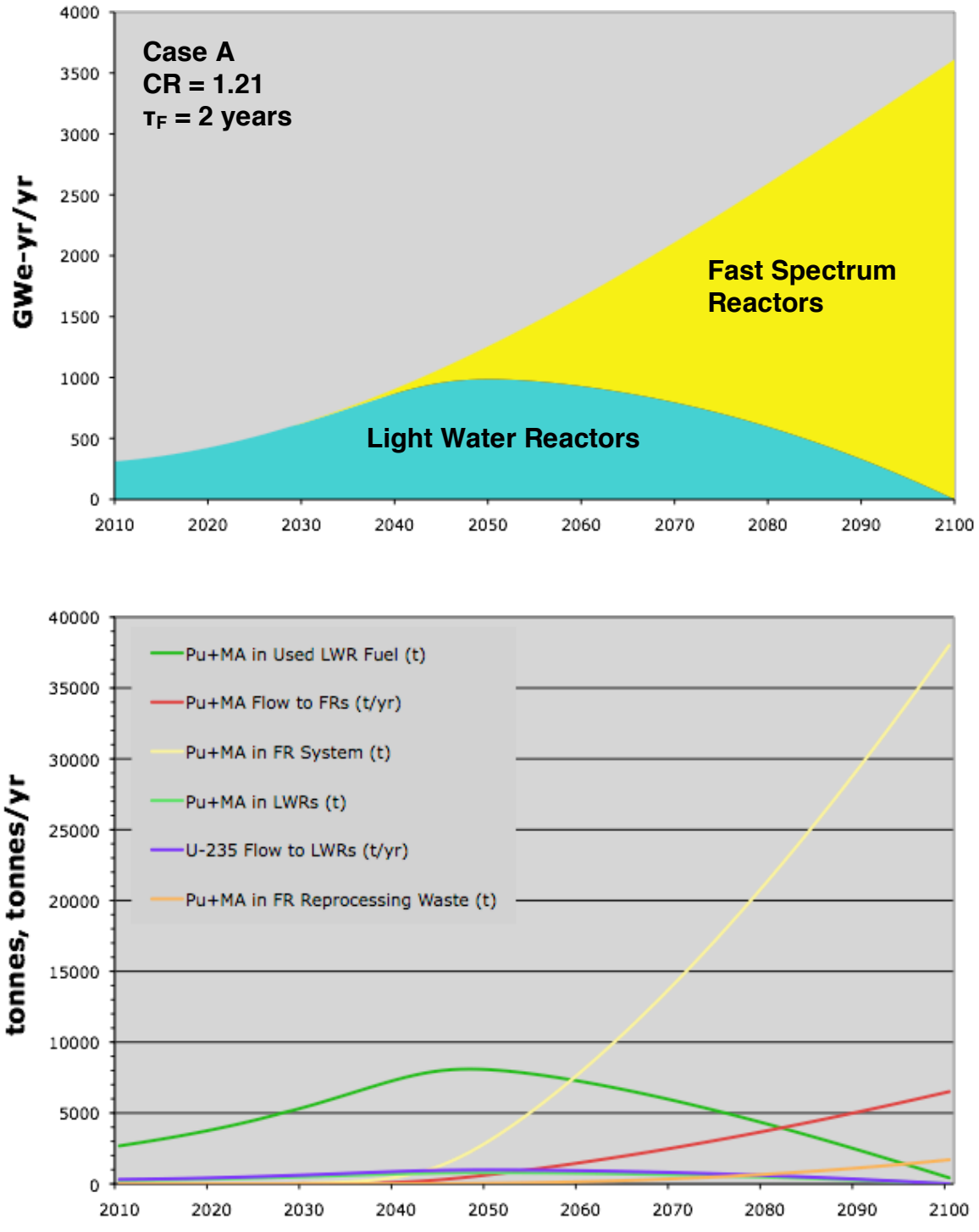


Figure 4a. Power production and stocks and flows of Pu+MA and ^{235}U for CR = 1.21, τ_F = 2 years.

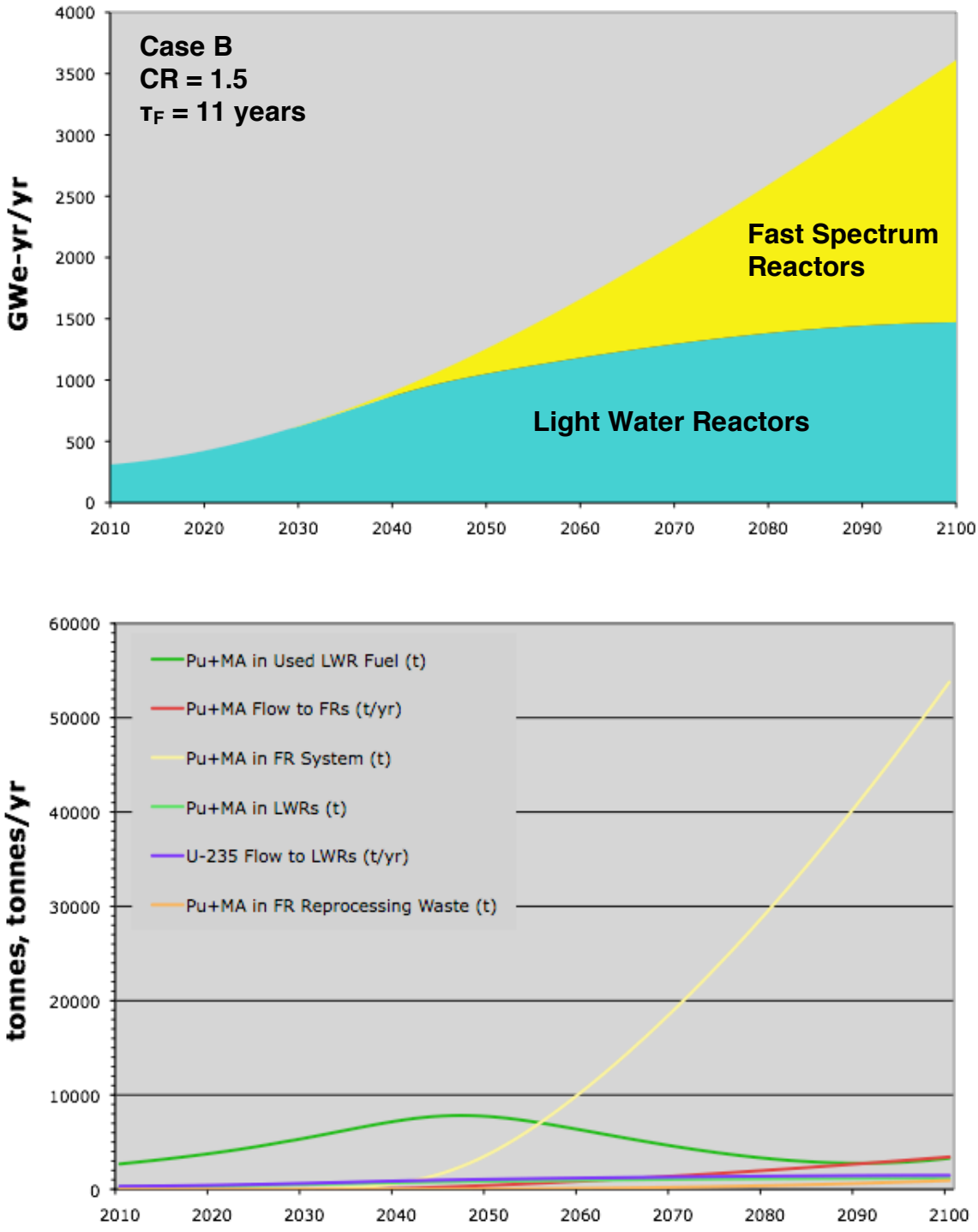


Figure 4b. Power production and stocks and flows of Pu+MA and ^{235}U for CR = 1.5, τ_F = 11 years.

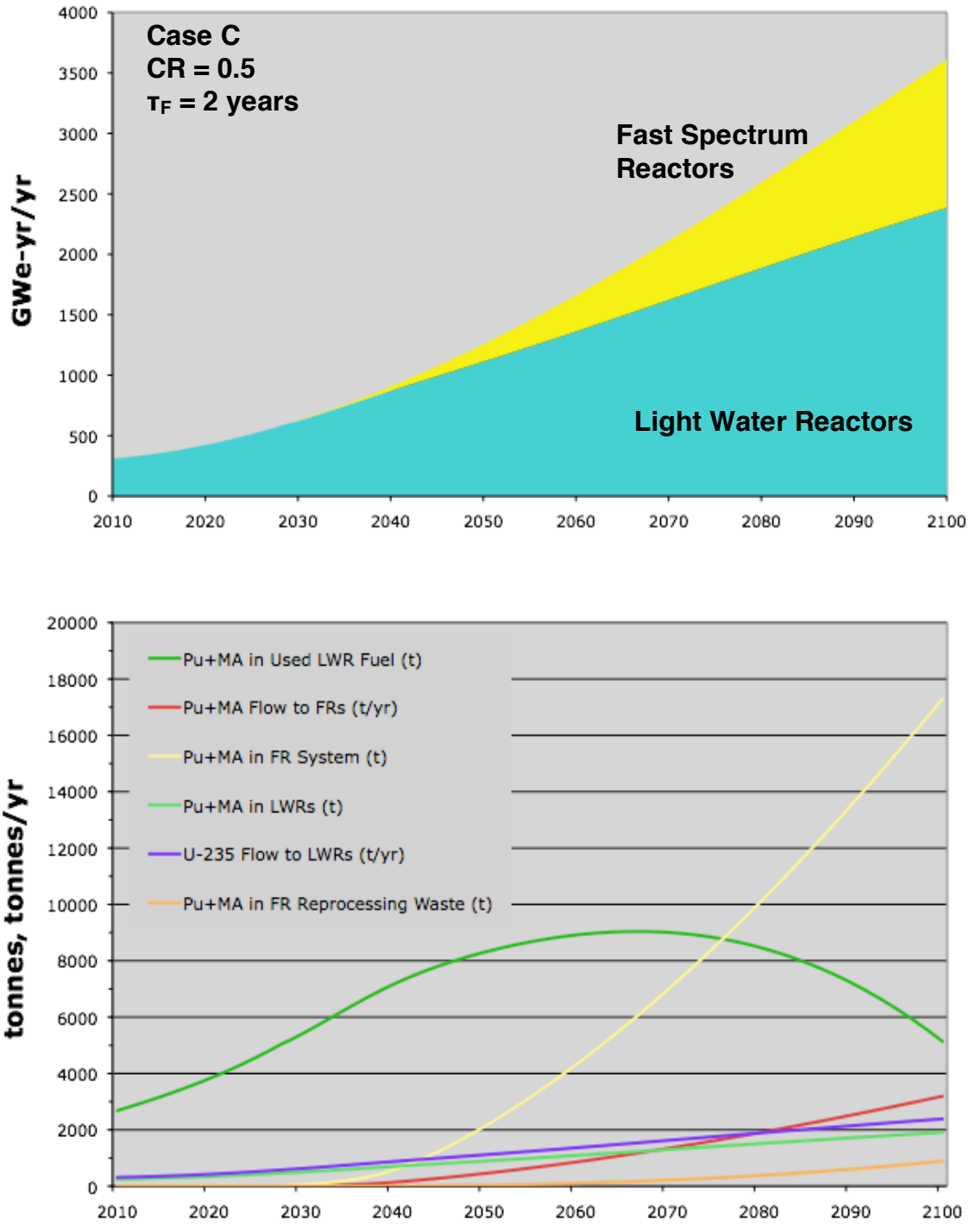
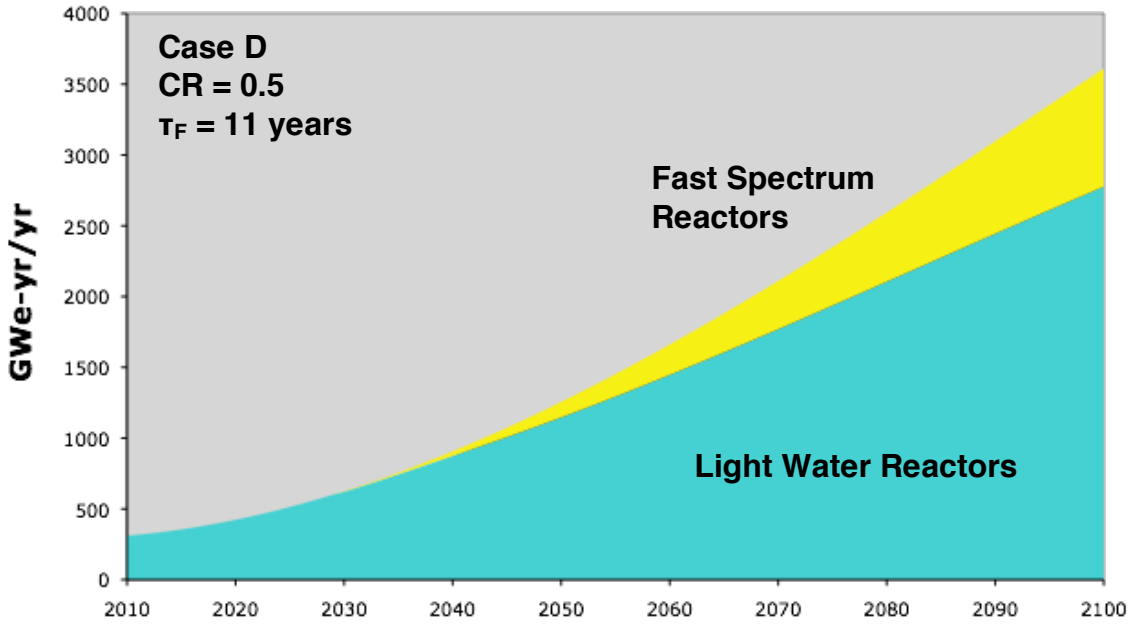


Figure 4c. Power production and stocks and flows of Pu+MA and ^{235}U for CR = 0.5, τ_F = 2 years.



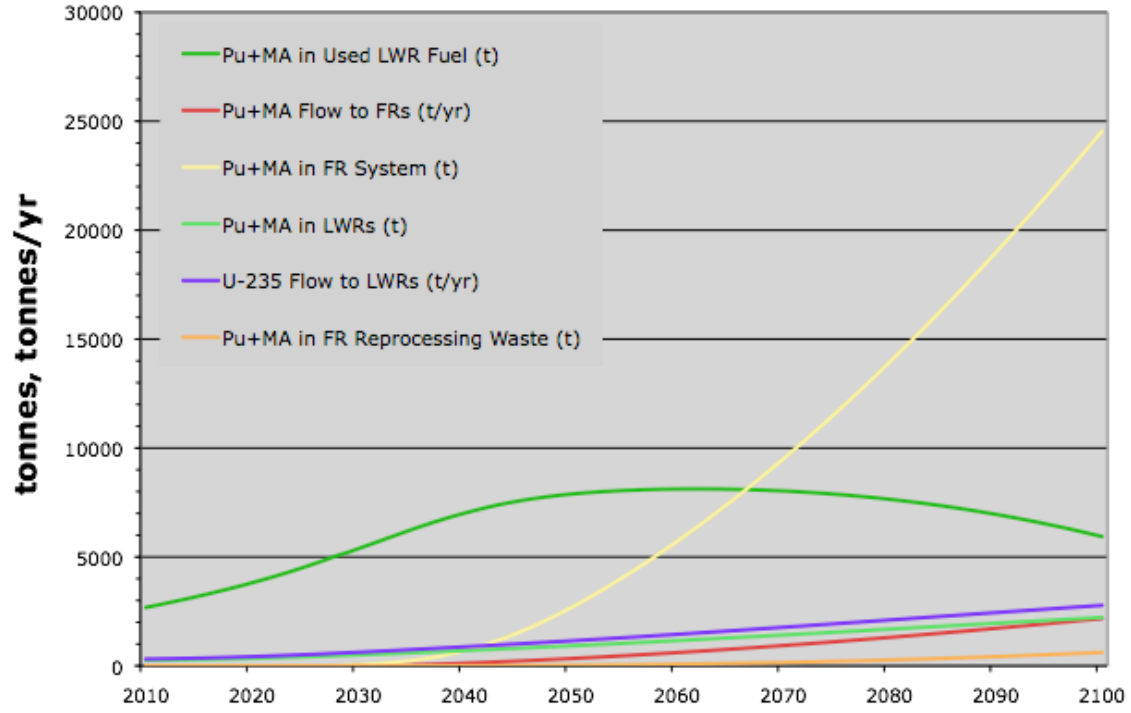


Figure 4d. Power production and stocks and flows of Pu+MA and ^{235}U for CR = 0.5, τ_F = 11 years.

Figures 4a - 4d show results for these cases, using the evolution equations for stocks and flows described in Appendices 2 and 3. In general one observes that longer fuel residence times result in slower growth rates for fast reactors. This stems from the fact that a fast reactor typically contains four (τ_R) 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 τ_F = 2 years, as assumed in Case A, all LWR nuclear power can be replaced with FRs having CR = 1.21. At CR = 1.5, to achieve this goal requires $\tau_F \leq 6$ years. At τ_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 τ_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 (Appendix 3) fast reactors with CR = 0.5 would only account for ~39% 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 2 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. We start by analyzing the degree of success towards the goals considered for fast spectrum reactors, extension of uranium resources and reduction of waste.

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 16 Mt, unlike the LWR-only scenario which required 59 Mt even if no further reactors were 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 2. 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 strongly limited by the availability of TRU, if the FRs are designed to be able to

start operation with enriched uranium fuel, and then transition to TRU. If we consider an FR capable of 1 GWe-yr/yr output with CR = 1 and τ_F = 11 years, it will begin to supply its own fuel only after it has been provided with 15 years worth of fueling. Ignoring differences between ^{235}U and TRU fuel, this would require about 27t of ^{235}U, or about 5800t of mined U, assuming 20% enrichment in ^{235}U with 0.25% in the tails. Thus to start up 1000 GWe-yr/year of such systems would require about 5.8 Mt of mined U. In the extreme case, 3600 GWe-yr/year of fast reactors could be started up using 21 Mt of mined uranium, about 30% 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 900kg of ^{235}U 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 3600 GWe-yr/yr fast reactor system with τ_F = 11 years would be in the range 100,000t, about twice the maximum value in table 2.

	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
^{235}U 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

Table 2: Parameters of fast-reactor scenarios relevant to extending resources and reducing waste, as well as to proliferation risks.

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 0.32t of TRU waste, while 1 GWe-yr of FR operation requires fueling roughly in the range of ~2t 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%, or ~0.02t, that is anticipated to be lost in the reprocessing and fabrication steps, assuming successful development of these processes. This results in a factor of ~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 4a - 4d, because it must be cooled for ~6 years (Dixon *et al.*, 2007) before reprocessing.]

One should be cautious, however, because this waste assessment 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 ~300 years, outside of the repository (Wigeland *et al.*, 2006). It also appears that in an oxidizing environment such as predominates at Yucca Mtn., as opposed to the reducing environment now recommended by the IAEA for geological repositories (IAEA, 2003), the mobility of the long-lived ^{99}Tc and ^{129}I fission products relative to Pu and minor actinides could make them a significant radiological safety concern (Piet *et al.*, 2007).

Now we consider the proliferation risks of the FR cases in figures 4a - 4d. 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 1). 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 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 τ_F = 11 years, it would be about 11 million SQ. This is an example where magnitude certainly matters. 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 (Piet *et al.*, 2009), "...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 2 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. ^{238}U from natural or even depleted uranium provides the material to be converted to Pu. 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 Pu and minor actinides indicated in Table 2. 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 Pu per year. Case D, with the lowest fueling rate, corresponds to 250,000 SQ of Pu per year. Currently the IAEA standard for uncertainty in closing the material balance of a plutonium reprocessing plant is 1% (IAEA, 2001b, IPFM, 2008). 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% 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 others 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 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. 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 the used fuel. Extremely large quantities of Pu, some significant fraction of 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 (Kang and von Hippel, 2005), and can be rapidly chemically separated and used for weapons, in contrast to the ^{235}U 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 ~8t of Pu 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 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 Pu waste quantity from an LWR, ~2t (250 SQ) / GWe-yr *vs*. 0.3t (37 SQ) / 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 (IAEA, 2001a).

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 2 and the LWR scenario through 2050 discussed near the end of Section 5.1, the estimated change in long-term equilibrium global-average surface temperature of substituting pulverized coal plants, without carbon sequestration, is 0.2^{o} C – 0.45^{o} C, again subject to the caveats discussed above.

5.3 Fusion

Power can be produced by "fusing" heavy forms of hydrogen to form helium (Nutall, 2009, von Hippel and Goldston, 2011). In laboratory experiments up to 16 MWt has been produced for periods of order 1 second, demonstrating the scientific feasibility of producing fusion energy using magnetic fields to confine hot fusion fuel (Hawryluk, 2002). 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 MW of thermal power from fusion for periods of up to one hour, which will demonstrate the technological feasibility of fusion energy. In the U.S. 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, but also with a mission to demonstrate the scientific feasibility of fusion by using the inertia of tiny exploding pellets to confine them for long enough to provide 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 (Moyer, 2010), for which there are solutions under development (Hazeltine *et al.*, 2010). There is 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 (Maisonnier *et al.*, 2005, Najmabadi *et al.,* 2006). Very considerable R&D is required to move from scientific

feasibility to technological feasibility to practical demonstration (FESAC, 2003, USBPO, 2009) allowing commercialization by mid-century. 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 5 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%/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. In this scenario 15.8 Mt of uranium is mined for LWRs, equal to the IAEA/NEA projected total resource.

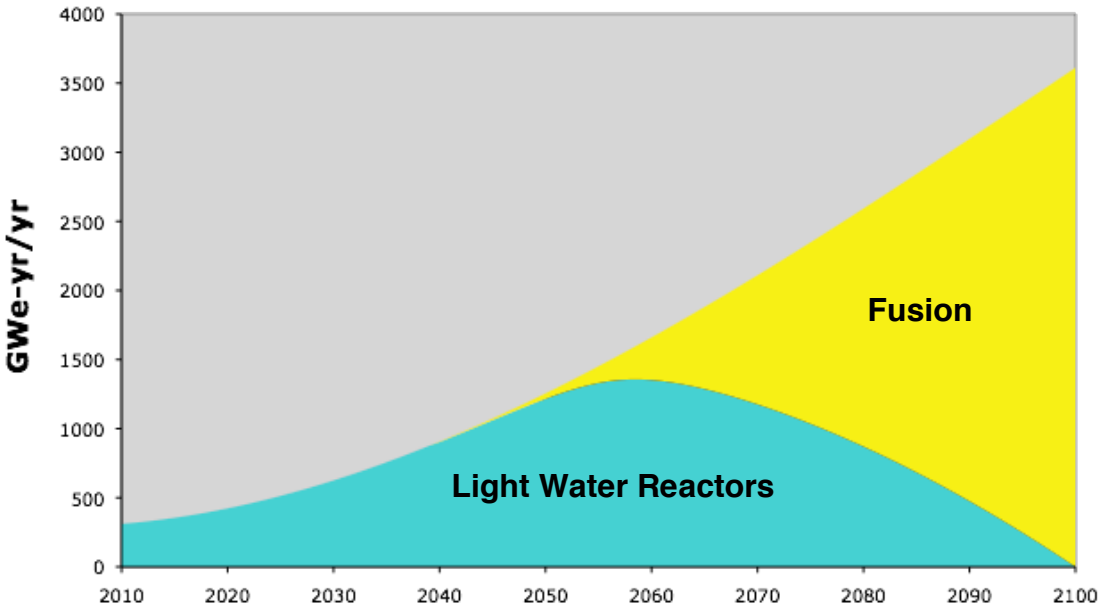


Figure 5. Nuclear power production from light water reactors, transitioning to fusion.

Fusion has significant nonproliferation advantages relative to fission (Goldston *et al.,* 2009). 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. 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. Furthermore, 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 these weapons materials in a declared facility would not be a serious risk.

Fusion systems contain significant quantities of the heaviest isotope of hydrogen, tritium. If a small amount of tritium were diverted from a fusion system it could be used to boost the yield

of fission weapons, including those based on reactor-grade Pu. Tritium itself, however, does not provide access to nuclear weapons capability, explaining why it is not controlled under the Nonproliferation Treaty. Unlike reactor-grade Pu, tritium is not considered to be an entry-level component of nuclear proliferation.

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. His threat is to begin to produce such materials. It would be technically feasible to convert a conventionally designed pure fusion power plant to begin to produce ~1 SQ of ^{239}Pu or ^{233}U per week, after inspectors had been expelled. This can be compared with the situation for fast-spectrum fission reactors where, for 1 GWe-yr/yr capacity, ~ 2t or 250 SQ of Pu is in hand at any time for yearly refueling. More importantly, 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.

5.4 Fusion-Fission Hybrid Transmuters

In the scenario of figure 5, with no further processing of the used nuclear fuel from the LWRs, 27,000t of TRU and associated fission products remain worldwide, requiring geological repositories with capacity of ~27 times the proposed statutory limit of Yucca Mounain.

It has been proposed to use accelerator-driven neutron sources to drive sub-critical 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 (Freidberg and Finck, 2010). Here we consider one of the more well-developed concepts (Stacey, 2009), based on a subcritical fast reactor driven by fusion neutrons (see Appendix 4) burning the left-over TRU from LWRs. Figure 6 shows the TRU stocks and flows associated with this concept, as applied to the scenario of figure 5. For simplicity we have assumed that a constant fraction of all nominally fusion systems until 2100 would be fusion-fission hybrid TRU burners. 9.9% is the required fraction to put all of 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 Pu 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 ~39% of a steady-state system in which they burn the waste from LWRs. If the technology is developed to make the scenario of figure 6 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 4c and 4d with fewer burner reactors, but without a qualitative proliferation advantage. In steady state, burner fast reactors at CR = 0.5 must constitute ~39% of a steady-state "balanced" fleet, corresponding to a "support ratio" of LWR power production to FR power production of 1.6 (Appendix 3). The equivalent steady-state support ratio for the fusion-fission hybrid systems (Appendix 4) is 3.6.

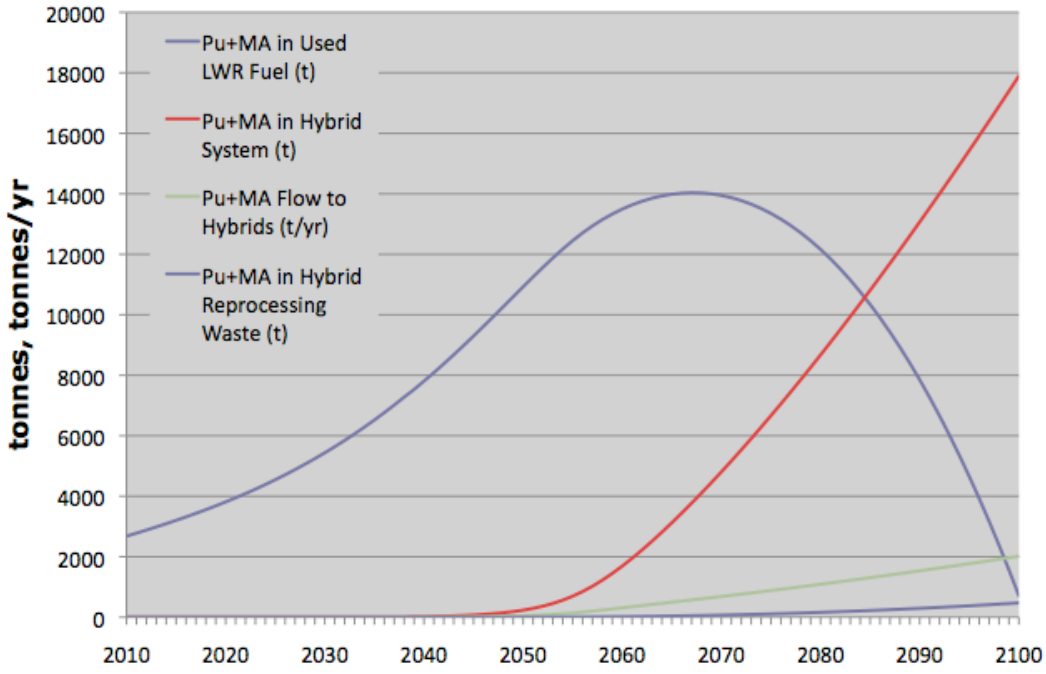


Figure 6. Stocks and flows of Pu+MA in fission-fusion hybrid case.

6. Conclusions

Nuclear energy may be needed to provide ~30% 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 from 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 $0.43^{o}C - 0.92\,^{o}C$. 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. Reduced demand for electricity compared with the projections discussed here would also reduce the need for nuclear electricity.

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 weapons-usable material and the difficulty in 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. The risk from fusion is only associated with breakout from safeguards, and appears to be the most manageable, since no fissile material is available at the time of breakout.

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[i] Downloaded on December 7, 2009. One model appeared to have a miscalibration, providing results for year 2000 electricity production low by more than by a factor of three, and was not included.
[ii] http://tonto.eia.doe.gov/cfapps/ipdbproject/IEDIndex3.cfm accessed on January 14, 2010
[iii] MiniCam is now GCAM. http://www.globalchange.umd.edu/models/minicam/

[iv] Note that "Mt" in this paper denotes millions of metric tonnes, not to be confused with "MT", which is often used in the U.S. fission literature to denote metric tonnes. "Gt" here denotes billions, 109s, of metric tonnes.
[v] Using the 3-reservoir model in the RICE-99 spreadsheet, downloaded from http://www.econ.yale.edu/%7Enordhaus/homepage/dice_section_V.html on 1/25/10
[vi] The 61 nations are: Albania, Algeria, Australia, Azerbaijan, Bangladesh, Belarus, Chile, Ecuador, Egypt, Estonia, Georgia, Ghana, Gulf states, Indonesia, Iran, Ireland, Israel, Italy, Jordan, Kazakhstan, Latvia, Libya, Malaysia, Mongolia, Morocco, Namibia, New Zealand, Nigeria, Norway, Philippines, Poland, Portugal, Syria, Thailand, Tunisia, Turkey, Uganda, Venezuela, Vietnam and Yemen.
[vii] "Reactor-grade" Pu that emerges with a mixture of Pu isotopes from LWRs is considered by the IAEA to be adequate for the production of nuclear explosives. Only mixtures with > 80% ^{238}Pu are excluded, and since Pu is dominantly produced and transmuted by neutron capture starting from ^{238}U, little ^{238}Pu is available in the nuclear fuel cycle.
[viii] The maximum energy loss, ΔE_n, in an elastic collision of a neutron with a nucleus in the coolant is given by $\Delta E_n/E_n = 4A/(A+1)^2$, where A is the atomic number of the target nucleus. For A >> 1 this becomes small. The hydrogen in water is a very effective at reducing neutron energy.

APPENDICES

General notes to Appendices:

1) In all cases the designation "Mt", accepted for use with the S.I. system, denotes millions of metric tonnes. This is to be distinguished from "MT" which is often used in the U.S. literature to denote metric tonnes.
2) In all cases power production, *e.g.,* P_{LWR} and P_{FR}, is measured in GWe-yr/yr, to be interpreted as actual electric power production, as distinguished from the commonly quoted electrical power capacity. For example 111 power plants each with 1 GWe capacity, operating at capacity factor 0.9, produce 99.9 GWe-yr/yr.
3) All flows assigned to year *n* are assumed to occur on January 1 of year *n*, and all stocks assigned to year *n* are assumed to be assayed at mid-year, July 1, of year *n*.

Appendix 1: Committed Energy Production

Ignoring startup effects, in a system of power plants that has been operating at a nearly steady power level for a period of time long compared to plant lifetimes, the average plant will be at the mid-point in its lifetime. Thus the amount of additional energy that is committed to be produced by the existing plants during their remaining lifetimes, after time t_0 when further construction ceases, is $E_{com} = P(t_0)\,\tau_{PP}/2$, where $P(t_0)$ represents the power level at time t_0 and τ_{PP} is the expected power plant lifetime.

This simple result can be generalized for a continuously exponentially growing or decaying system in which all further construction ceases at time t_0. The power production curve before time t_0 is given by

$$P\left(t < t_0\right) = P\left(t_0\right)e^{m\left(t-t_0\right)} \qquad \text{Eq. A1.1}$$

where $m > 0$ is the annual growth rate, and $m < 0$ the annual decay rate. New construction and decommissioning must have the same exponential time dependence, so we find

$$\frac{dP\left(t < t_0\right)}{dt} = mP\left(t_0\right)e^{m\left(t-t_0\right)} = C_0e^{mt} - D_0e^{mt} \qquad \text{Eq. A1.2}$$

Since each plant must be decommissioned τ_{PP} years after it was commissioned, we also have

$$D_0e^{mt} = C_0e^{m\left(t-\tau_{PP}\right)} \qquad \text{Eq. A1.3}$$

from which we can find that the decommissioning rate is given by

$$D_0e^{mt} = \frac{mP\left(t_0\right)e^{m\left(t-t_0-\tau_{PP}\right)}}{1-e^{-m\tau_{PP}}} \qquad \text{Eq. A1.4}$$

This formula is valid even beyond t_0, since plants constructed prior to that time still need to be decommissioned at the originally projected rate, until the last plant is decommissioned at $t = t_0 + \tau_{PP}$ and $P = 0$. Unlike simple exponential decay, the decommissioning rate is maximum at $t = t_0 + \tau_{PP}$, and P reaches zero. We can then integrate the decommissioning rate to find the power profile after new construction ends:

$$P\left(t > t_0\right) = P\left(t_0\right)\left[1 - \frac{e^{-m\left(t_0+\tau_{PP}\right)}}{1 - e^{-m\tau_{PP}}}\left(e^{mt} - e^{mt_0}\right)\right] \qquad \text{Eq. A1.5}$$

This can finally be integrated over the remaining committed energy production from time t_0 to time $t_0 + \tau_{PP}$ to give the total committed power production:

$$E_{com} = P\left(t_0\right)\tau_{PP}\left[\frac{m\tau_{PP} - \left(1 - e^{-m\tau_{PP}}\right)}{m\tau_{PP}\left(1 - e^{-m\tau_{PP}}\right)}\right] \qquad \text{Eq. A1.6}$$

For the estimates given in the main text τ_{PP} is taken to be 60 years, and m is chosen to fit the annual power production 30 years before the designated commitment point. Committed additional CO_2 emissions, mining and used fuel production for different types of power plants can be computed from E_{com}.

To check the effect of the approximations used in deriving equation A1.6, an explicit calculation was performed for the committed energy after 2100 in the scenario where LWRs provide all of the nuclear power of figure 2. Linear decline was assumed for currently existing plants between today and 2050, allowing specific decommissioning and construction dates to be defined as needed to fill the remainder of the power curve. The explicitly calculated committed power in 2100 agrees with equation A1.6 to 2%.

Appendix 2: Equations for Stocks and Flows of Uranium, Plutonium and Minor Actinides Associated with Light Water Reactors

A2.1 TRU in Existing Used Nuclear Fuel

The TRU in existing used nuclear fuel, denoted $TRU_{UNF}(0)$ in the following equations, is required as an initial condition in the time-dependent calculations of TRU in used nuclear fuel. It was estimated at 2580t of TRU on the basis of the IAEA Overview of Global Spent Nuclear Fuel Storage (Fukuda *et al.*, 2003), the IAEA (2009) Nuclear Technology Review and the Global Fissile Material Report (IPFM, 2009).

A2.2 Uranium Fueling

The natural uranium consumed to produce 1 GWe-yr of nuclear electricity from LWRs, denoted U_c in the following equations, was evaluated at 204.7t, based on Figure A-4.2 in the MIT (2003) "Future of Nuclear Power" report and associated calculations, assuming a relatively aggressive 0.25% ^{235}U concentration in the enrichment tails to maximize uranium utilization, and 4.51% fuel enrichment. The MIT report assumes 33% efficiency for the LWRs, which is adopted here. Adjustment was made for the assumed capacity factor of 0.9. The 204.7t of natural uranium required for 1 GWe-yr, enriched to 4.51%, with 0.25% tails, corresponds to 22.15t of initial heavy metal (iHM) fuel. 6.89 kg of Separative Work (SWU) is required for each kg of this fuel. Within this fuel is almost exactly 1t of ^{235}U, so the annual flow of ^{235}U to LWRs, in tonnes, is almost exactly equal to P_{LWR} in GWe-yr/yr.

It was assumed that 1 year is required for processing, enrichment and fabrication between the time uranium is considered to be "mined" and when it is used as fuel. Since the residence time of fuel in LWRs is assumed to be 4.5 years, when a net new reactor is started in the calculations, 4.5 yearly loads of U are assumed to be required. For simplicity, if a reactor is decommissioned and another commissioned in the same year, it is assumed that only one year of fresh fuel is required for those reactors, that year.

A2.3 TRU Stock in LWRs

Time-averaging of the composition of LWR fuel during burn from 0 to 50 MWd/kg (Glaser, 2009) provides an estimate of the inventory of TRU in a 1 GWe LWR. Taking into account a capacity factor of 0.9, this gives the TRU stock for 1 GWe-yr/yr of electricity production of

$$TRU_{LWRc} = 0.80\text{t} \qquad \text{Eq. A2.1}$$

The total stock of TRU in LWR cores is then simply $TRU_{LWRc}P_{LWR}(n)$

A2.4 TRU Flow to LWR Used Nuclear Fuel Stock

The flow of TRU from LWRs to the total stock of LWR used nuclear fuel per GWe-yr was estimated on the basis of the MIT report, Table A4-1, assuming burnup of 50 GWd per metric tonne of initial heavy metal, and adjusting for the assumed 0.9 capacity factor. The LWR production rate of TRU, denoted $TRU_{p,LWR}$ in the following equations, equals 0.3207t/yr, of which 0.295t is Pu. When the count of reactors is reduced it is assumed that TRU_{LWRc} flows to the used nuclear fuel, but if a reactor is decommissioned in the same year that another is commissioned, then only $TRU_{p,LWR}$ of TRU is assumed to be produced from those reactors, that year, and to flow into the stock of LWR used nuclear fuel.

The proposed statutory capacity of Yucca Mountain is 70,000t of heavy metal, of which 1.447% or 1013t, is TRU.

A2.5 Evolution Equations for Stocks and Flows

The evolution equations are formulated as difference equations, with time-step of 1 year. As noted above, all flows(n) are considered to occur on January 1 of year n, and all stocks(n) are evaluated on July 1 of year n.

Taking into account the assumed one-year delay between mining and fueling, the change in the stock of mined uranium is given by

$$U_m(n) = U_m(n-1) + U_c P_{LWR}(n+1) + 3.5 U_c Max\left[P_{LWR}(n+1) - P_{LWR}(n), 0\right] \quad \text{Eq. A2.2}$$

where $U_m(-1)$ is set at zero, so that $U_m(0)$, supplying the uranium for the first year of operation in the calculation is included. (The last term includes a factor of 3.5, rather than the full residence time of 4.5 years, because the previous term is evaluated at time $n + 1$.)

The evolution of the stock of TRU in LWR used nuclear fuel due to LWR operation is given by:

$$\begin{aligned} &TRU_{UNF}(n) = TRU_{UNF}(n-1) \\ &+TRU_{p,LWR} P_{LWR}(n-1) + TRU_{LWRc} Max\left[P_{LWR}(n-1) - P_{LWR}(n), 0\right] \end{aligned} \quad \text{Eq. A2.3}$$

Note that when FRs are included in Appendix 3, they will add important terms to this equation.

Appendix 3: Equations for Stocks and Flows of Plutonium and Minor Actinides Associated with Fast Spectrum Fission Reactors

A3.1 TRU Fueling Flow to FRs

The burnup rate (BU_{FR}) and TRU mass fraction (f_{TRU}) for a modern TRU-burning fast reactor design has recently been calculated as a function of conversion ratio (CR). The annual fueling rate, in metric tonnes, required to produce 1 GWe-yr can be calculated from these as

$$L_{FR}(t) = \frac{1\ GWe}{\eta_{th}} \frac{365.25 d}{BU_{FR}(GWthd/t)} f_{TRU} \quad \text{Eq. A3.1}$$

The thermal efficiency, η_{th}, for these designs is estimated at 38%. Figures 2-20 and 2-21 in Bays *et al.* (2009) provide BU_{FR} and f_{TRU} as functions of CR, but numerical values are not available. Figure A2-1 provides a fit to L_{FR} based on values read from these figures, used in

the following calculations. Only *CR* values between 0.5 and 1.5 have been used in the calculations.

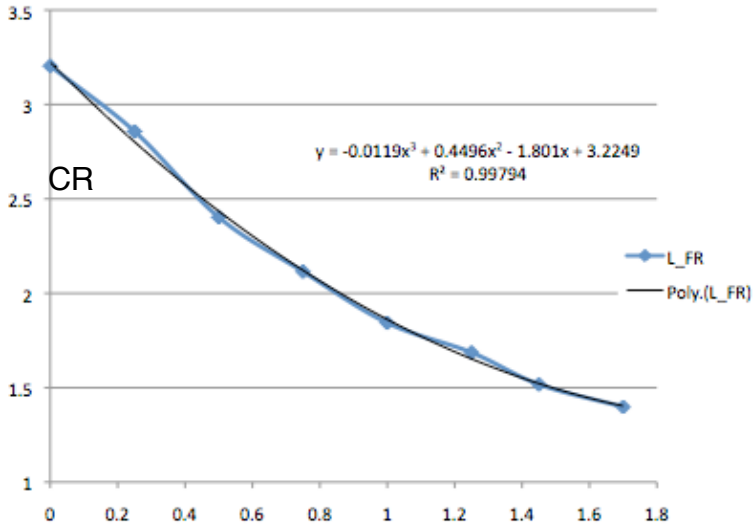

Figure A2-1. L_{FR}, the TRU load to fast reactors in order to produce 1 GWe-yr of electrical energy, from graphically reported calculations for burnup and fraction of TRU in fast reactor heavy metal, as a function of conversion ratio, *CR*.

The residence time of the fuel in the reactor is assumed to be $\tau_{FR} = 4$ years, taking into account capacity factor, and consistent with estimates of damage tolerance by Hoffman *et al.*, 2006. (Note that in these calculations τ_{FR} is constrained to integer values.) It is assumed that each additional GWe-yr/yr of installed FRs requires a load of $\tau_{R,FR}L_{FR}$.

A3.2 TRU Stock

The stock of TRU in a FR is a complex calculation, due to fuel shuffling, changes in reactivity, and other effects. Since $L_{FR} \sim 2B_{FR}$ and $|CR - 1| < 0.5$ in these calculations the effects of various approximations are in the few % range. Here we take an approximation that has the benefit that it allows an accurate check of stocks against flows - *i.e.,* in all fast reactors at all times the rate of growth of TRU is $B_{FR}(CR\text{-}1)$/GWe-yr. This gives on July 1st of any year an in-reactor inventory of $\tau_{R,FR}L_{FR} + B_{FR}(CR-1)/2$.

The total inventory of TRU in the fuel cycle depends on τ_F as discussed in the main text. We take τ_F to vary between 2 years, for on-site cooling, reprocessing and fuel fabrication, to 11 years for cooling, transportation to an centralized fuel recycling center, reprocessing, fuel fabrication, and return to the fast reactor as in Dixon *et al.* (2007). TRU in LWR used nuclear fuel that is to be used to fuel FRs is given an effective τ_F of 1 year.

A3.3 TRU Unload Flow from FRs

At η_{th} = 38%, 1 GWe-yr of electrical energy requires 2.632 GWth-yr of thermal energy. Since the fission of 1t of heavy metal results in 1000 GWth-d of thermal energy, this means that B_{FR}, the burned heavy metal per GWe-yr is 0.9611t. The amount of TRU unloaded after this much energy production is

$$B_{FR}CR + (L_{FR} - B_{FR}) = L_{FR} + B_{FR}(CR-1) \qquad \text{Eq. A3.2}$$

It is assumed that when an FR is decommissioned, and another is commissioned, the net unload flow is not affected. The unload flow from a net decommissioned FR would be

$$\tau_{R,FR}L_{FR} + B_{FR}(CR-1) \qquad \text{Eq. A3.3}$$

since it is assumed that the decommissioning would occur at the end of a burn cycle. Note, however, that in the the calculations of figures 4a - d there is never a net decrease of P_{FR}.

A3.4 Processing Losses

Many references assume 1% waste loss during reprocessing at the industrial scale. Consistent with these, in the calculations of this paper we take F_w = 0.01.

A3.5 Evolution Equations for Stocks and Flows

The total fueling flow needed for the FRs on Jan 1 of year n is given by

$$F_{FR}^{tot}(n) = L_{FR}P_{FR}(n) + \left(\tau_{R,FR}-1\right)L_{FR}\left[P_{FR}(n) - P_{FR}(n-1)\right] \qquad \text{Eq. A3.4}$$

whereas the total fueling flow available from prior operation of FRs is given by

$$\begin{aligned} F_{FR}^{FR}(n) &= \left[L_{FR} + B_{FR}(CR-1)\right]P_{FR}(n-\tau_F-1)/\left(1+F_w\right) \\ &+\left(\tau_{R,FR}-1\right)L_{FR}Max\left[P_{FR}(n-\tau_F-1) - P_{FR}(n-\tau_F),0\right]/\left(1+F_w\right) \end{aligned} \qquad \text{Eq. A3.5}$$

including the source from net decommissioning of fast reactors. The fueling flow from the stock of LWR used nuclear fuel is just the difference between these.

To get to the full TRU evolution equation, the additional contribution to TRU_{UNF} from LWRs must be included, as must loss to waste. Furthermore, the TRU_{UNF} must be reprocessed and fabricated into fuel, requiring an assumed period of 1 year. Taking this in account, we have:

$$\begin{aligned} TRU_{UNF}(n) &= TRU_{UNF}(n-1) \\ &-\left(1+F_w\right)\left\{L_{FR}P_{FR}(n+1) + \left(\tau_{R,FR}-1\right)L_{FR}Max\left[P_{FR}(n+1) - P_{FR}(n),0\right]\right\} \\ &+\left[L_{FR} + B_{FR}(CR-1)\right]P_{FR}(n-\tau_F) \\ &+\left(\tau_{R,FR}-1\right)L_{FR}Max\left[P_{FR}(n-\tau_F) - P_{FR}(n-\tau_F+1),0\right] \\ &+TRU_{p,LWR}P_{LWR}(n-1) + TRU_{LWRc}Max\left[P_{LWR}(n-1) - P_{LWR}(n),0\right] \end{aligned} \qquad \text{Eq. A3.6}$$

The total stock of TRU in the FR system at any time, n, is given by the sum of the TRU in the FRs, plus the total fueling for year $n+1$, multiplied by $(1+F_w)$, plus all $FR \rightarrow FR$ fueling in process for other years.

$$TRU_{FRS}(n) = \left[\tau_{R,FR} L_{FR} + 0.5(CR-1)B_{FR}\right] P_{FR}(n)$$
$$+\left(1+F_w\right) L_{FR} \left\{P_{FR}(n+1) + \left(\tau_{R,FR}-1\right)\left\{Max\left[P_{FR}(n+1) - P_{FR}(n), 0\right]\right\}\right\}$$
$$+\left[L_{FR} + B_{FR}(CR-1)\right] \sum_{m=n+1-\tau_F}^{n-1} P_{FR}(m)$$

Eq. A3.7

where we are not including the possibility of net reduction of FRs over time, since that does not occur in the calculations shown here, nor are we allowing for the case of overproduction from FRs, where the TRU unload from year $n - \tau_F - 1$ is greater than $(1+F_W)$ times the loading requirement for year n.

The flow of TRU to the waste stream is easily evaluated as F_w times the total flow to fueling FRs.

$$TRU_W(n) = TRU_W(n-1)$$
$$+F_w \left\{L_{FR} P_{FR}(n) + \left(\tau_{R,FR}-1\right) L_{FR}\left[P_{FR}(n) - P_{FR}(n-1)\right]\right\}$$

Eq. A3.8

again assuming no net decommissioning of fast reactors.

It is helpful, to check the numerical implementation of these equations, to evaluate the changes in stocks from the start to the end of the calculation, against the summed flows. For example, for cases with monotonically rising P_{FR}:

$$TRU_{UNF}(N) - TRU_{UNF}(0) = TRU_{p,LWR} \sum_{n=0}^{N-1} P_{LWR}(n) + TRU_{LWRc}[P_{LWR}^{\max}(1,N) - P_{LWR}(N)]$$
$$-\left(1+F_w\right) L_{FR} \left[\sum_{n=1}^{N} P_{FR}\left(n+1\right) + \left(\tau_{R,FR}-1\right) P_{FR}(N+1)\right] + [L_{FR} + B_{FR}(CR-1)] \sum_{1}^{N-\tau_F} P_{FR}\left(n\right)$$

Eq. A3.9

We can also sum the flows into and out of the TRU pool associated with the FR system, giving the result:

$$TRU_{FRS}(N) = \left(1+F_w\right) L_{FR} \left\{\sum_{n=1}^{N} P_{FR}\left(n+1\right) + \left(\tau_{R,FR}-1\right) P_{FR}(N+1)\right\} - [L_{FR} + B_{FR}(CR-1)] \sum_{n=1}^{N-\tau_F} P_{FR}\left(n\right)$$
$$+B_{FR}\left(CR-1\right)\left[\sum_{n=1}^{N-1} P_{FR}\left(n\right) + 0.5 P_{FR}\left(N\right)\right] - F_w L_{FR}\left[\sum_{n=1}^{N} P_{FR}(n) + \left(\tau_{R,FR}-1\right) P_{FR}(N)\right]$$

Eq. A3.10

These and other checks have been implemented in the calculations here. The results are accurate to numerical precision.

A3.6 Fraction of FR's in a "Balanced" Steady State System

From these equations is it straightforward to evaluate the fraction, f_{FR}, of total nuclear electric power in fast reactors with $CR < 1$ that will burn (and dispose as waste) exactly the TRU that is produced from a fraction $(1 - f_{FR})$ of total nuclear electric power in thermal reactors, in a steady-state situation. This amounts to solving the evolution equation for TRU_{UNF} (Eq. 3.6) for a situation in which all terms are independent of n.

$$f_{FR} = \frac{TRU_{p,LWR}}{TRU_{p,LWR} + B_{FR}(1 - CR) + F_w L_{FR}} \qquad \text{Eq. A3.11}$$

For $CR = 0.5$, $L_{FR} = 2.43$t , and $f_{FR} = 0.388$.

A3.7 Growth and Decay Rates of Fast Reactors with Zero TRU Input

One can use the above equations to consider growing or decaying situations with net zero input of TRU. This again amounts to solving equation 3.6, but now making only TRU_{UNF} independent of n (and neglecting any source from LWRs). For the growth case, one arrives simply at

$$CR_{m>0} = 1 + \frac{(1 + F_W)(1 + m\tau_{R,FR})(1 + m)^{\tau_F} - 1}{(B_{FR} / L_{FR})} \qquad \text{Eq. A3.12}$$

where $m > 0$ is the annual growth rate of FRs. For physical intuition, it is helpful to look at the limit of small m, which gives

$$B_{FR}(CR_{m>0} - 1) = L_{FR}\left[F_w + m(\tau_{R,FR} + \tau_F)(1 + F_w)\right] \qquad \text{Eq. A3.13}$$

The left-hand side is the amount of extra TRU produced per year per GWe-yr, while the right-hand side represents the needs for the next year in terms of sustaining the current FRs against loss to waste and the needed growth in stock of the reactors and the fuel reservoir, taking into account loss to waste.

Equation A3-12 has been tested against the time-dependent numerical calculation. Setting LWR power to zero, and using A3-12 for the relation between CR and m, there is no change in LWR used nuclear fuel, to numerical precision.

Equation A3-12 however is not in good agreement with equation 2 of Piet *et al*., 2009:

$$CR_{m>0} = e^{m(\tau_F + \tau_{R,FR})}\left[1 + m(\tau_{R,FR} - 1)\right]$$

even when setting $F_w = 0$. The derivation of this equation is not given. It is notable that the ratio B_{FR}/L_{FR} does not appear. The authors evaluate two cases with $m = 0.0175$. For $\tau_{R,FR} = 4$, $\tau_F = 2$, the "example for onsite recycling", $CR = 1.17$ is required per their equation 2, cited above, and for the case of $\tau_{R,FR} = 4$, $\tau_F = 11$, the "example for offsite recycling", $CR = 1.37$ is required.

Table A3.1 compares the results of the two equations in the limit $F_w = 0$.

m, τ_R, τ_F	$CR_{m>0}$ Eq. 2 of Piet et al. (2009)	B_{FR}/L_{FR}	$CR_{m>0}$ eq. A3.12, $F_W = 0$
1.75%, 4, 2	1.17	0.56	1.19
1.75%, 4, 11	1.37	0.63	1.47

Table A3.1. Comparison of eq. A3-12 from this work with Eq. 2 of Piet *et al.* (2009).

Sometimes it is convenient to solve for m in terms of CR. An iterative solution for $m > 0$, equivalent to $CR > 1 + F_w L_{FR}/B_{FR}$, can be found by gathering together higher order terms in m.

$$m_{>0} = \frac{\left(CR_{m>0} - 1\right)\left(B_{FR}/L_{FR}\right) - F_W - \left(1+F_W\right)\left\{(1+m\tau_{R,FR})(1+m)^{\tau_F} - \left[1+m\left(\tau_{R,FR}+\tau_F\right)\right]\right\}}{\left(1+F_W\right)\left(\tau_{R,FR}+\tau_F\right)}$$

Eq. A3.14

Only a few iterations on m (starting with $m = 0$) are required for accurate convergence.

Equation A3.12 is somewhat different for the decaying case, $m < 0$. Solving for the situation where no extra TRU accumulates from decommissioning FRs, but rather the TRU unloaded from operation in year $n - \tau_F - 1$ is just what is needed to fuel the FRs in year n, and allowing for FR decommissioning to return fuel to the stock of FR-derived TRU (consistent with the derivation of Eq. A3.6), one arrives at a slightly different formula for CR:

$$CR_{m<0} = 1 + \frac{\left(1+F_w\right)(1+m)^{\tau_F+1} + \left(\tau_{R,FR}-1\right)m - 1}{B_{FR}/L_{FR}}$$

Eq. A3.15

Of course in the limit $m \to 0$, $CR_{m<0} = CR_{m>0} = 1 + F_w L_{FR}/B_{FR}$.

The associated iterative solution for $m_{<0}$ is,

$$m_{<0} = \frac{\left(CR_{m<0} - 1\right)\left(B_{FR} / L_{FR}\right) - F_w - \left(1 + F_w\right)\left[(1+m)^{\tau_F+1} - 1 - \left(\tau_F + 1\right)m\right]}{\tau_F + \tau_{R,FR} + F_w\left(\tau_F + 1\right)} \qquad \text{Eq. A3.16}$$

Appendix 4: Equations for Stocks and Flows of Plutonium and Minor Actinides Associated with Fusion-Fission Hybrid Systems

A4.1 TRU Fueling Flow to Fusion-Fission Hybrids

The fusion-fission hybrid (FFH) system described by Stacey (2009) uses a modest fusion system, producing 180 – 240 MW of fusion power, to drive a sub-critical fast reactor producing 3000 MWth output power by burning TRU. Since this system should be capable of producing ~1 GWe, the consumption of TRU is B_{FFH} = 1.096t/GWe-yr. There is no concomitant production of TRU, since no fertile material is included in the fuel loading. The calculated burn-up fraction (Sommer *et al.*, 2010) is $BF_{FFH} \sim 23.8\%$, from which the total input load of TRU per GWe-yr can be calculated at L_{FFH} = 4.605t. The residence time of fuel in the system for this burnup is 2800 full-power days. Taking into account a reasonable duty factor this corresponds to $\tau_{R,FFH} \sim 9$ years.

A4.2 TRU Stock

Using the same simplified model for the TRU stock in FFH systems as in FRs, we have stock at mid-year in each FFH of $\tau_{R,FFH} L_{FFH} - BF_{FFH} L_{FFH} / 2$

A4.3 TRU Unload Flow from Fusion-Fission Hybrids

The amount of TRU unloaded after 1 GWe-yr of production is just $L_{FFH}\left(1 - BF_{FFH}\right)$. It is assumed that when an FFH is decommissioned, and another is commissioned, the net unload flow is not affected. When a net FFH system is decommissioned, its stock of TRU is returned to the pool of TRU.

A4.4 Processing Losses

As with FRs, processing losses are assumed to be 1%.

A4.5 Evolution Equations for Stocks and Flows

These equations are analogous with the FR equations of Appendix 3.

The total fueling flow needed for the FFHs on Jan 1 of year *n* is given by

$$F_{FFH}^{tot}(n) = L_{FFH} P_{FFH}(n) + \left(\tau_{R,FFH} - 1\right) L_{FFH}\left[P_{FFH}(n) - P_{FFH}(n-1)\right] \qquad \text{Eq. A4.1}$$

whereas the total fueling flow available from prior operation of FFHs is given by

$$F_{FFH}^{FFH}(n)=\frac{L_{FFH}}{1+F_w}\left\{\begin{array}{l}\left(1-BF_{FFH}\right)P_{FFH}(n-\tau_F-1)\\+\left(\tau_{R,FFH}-1\right)Max\left[P_{FFH}(n-\tau_F-1)-P_{FFH}(n-\tau_F),0\right]\end{array}\right\} \quad \text{Eq. A4.2}$$

including the source from net decommissioning of fusion-fission hybrids. (For simplicity we use the same symbol, τ_F, for the residence-time of the fuel in the reprocessing system as for FRs.) As with FRs, the fueling flow from the stock of LWR used nuclear fuel is just the difference between these.

To get to the full evolution equation, the additional contribution to TRU_{UNF} from LWRs must be included, as must loss to waste. Furthermore, the TRU_{UNF} must be reprocessed and fabricated into fuel, requiring an assumed period of 1 year. Taking these in account, we have, for the case of FFH systems, with no FR systems (we do not consider mixing the two):

$$\begin{array}{l}TRU_{UNF}(n)=TRU_{UNF}(n-1)\\-\left(1+F_w\right)L_{FFH}\left\{P_{FFH}(n+1)+\left(\tau_{R,FFH}-1\right)Max\left[P_{FFH}(n+1)-P_{FFH}(n),0\right]\right\}\\+L_{FFH}\left(1-BF_{FFH}\right)P_{FFH}(n-\tau_F)\\+\left(\tau_{R,FFH}-1\right)L_{FFH}Max\left[P_{FFH}(n-\tau_F)-P_{FFH}(n-\tau_F+1),0\right]\\+TRU_{p,LWR}P_{LWR}(n-1)+TRU_{LWRc}Max\left[P_{LWR}(n-1)-P_{LWR}(n),0\right]\end{array} \quad \text{Eq. A4.3}$$

The total stock of TRU in the FFH system at any time, n, is given by the sum of the TRU in the FFHs, plus the total fueling for year $n+1$, multiplied by $(1+F_w)$, plus all $FFH \rightarrow FFH$ fueling in process for other years.

$$\begin{array}{l}TRU_{FFHS}(n)=L_{FFH}\left[\tau_{R,FFH}-BF_{FFH}/2\right]P_{FR}(n)\\+\left(1+F_w\right)L_{FFH}\left\{P_{FFH}(n+1)+\left(\tau_{R,FFH}-1\right)\left\{Max\left[P_{FFH}(n+1)-P_{FFH}(n),0\right]\right\}\right\}\\+L_{FFH}\left(1-BF_{FFH}\right)\sum_{m=n+1-\tau_F}^{n-1}P_{FFH}(m)\end{array} \quad \text{Eq. A4.4}$$

where we are not including the possibility of net reduction of FFHs over time, since that does not occur in the calculations shown here, nor are we allowing for the case of overproduction from FFHs, where the TRU unload from year $n - \tau_F - 1$ is greater than $(1+F_W)$ times the loading requirement for year n, also not a case considered here.

The flow of TRU to the waste stream is easily evaluated as F_w times the total flow to fueling FFHs:

$$TRU_W(n)=TRU_W(n-1)+F_wL_{FFH}\left\{P_{FFH}(n)+\left(\tau_{R,FFH}-1\right)\left[P_{FFH}(n)-P_{FFH}(n-1)\right]\right\} \quad \text{Eq. A4.5}$$

again assuming no net decommissioning of FFH systems during the time of calculation.

Conservation equations can be derived to provide numerical checks, analogous to those for FRs:

$$TRU_{UNF}(N) - TRU_{UNF}(0) = TRU_{p,LWR}\sum_{n=0}^{N-1} P_{LWR}(n) + TRU_{LWRc}[P_{LWR}^{\max}(1,N) - P_{LWR}(N)]$$
$$-\left(1+F_w\right)L_{FFH}\left\{\sum_{n=1}^{N} P_{FFH}\left(n+1\right)+\left(\tau_{R,FFH}-1\right)P_{FFH}(N+1)\right\}+L_{FFH}\left(1-BF_{FFH}\right)\sum_{1}^{N-\tau_F} P_{FR}\left(n\right)$$

Eq. 4.6

and

$$TRU_{FFHS}(N) = \left(1+F_w\right)L_{FFH}\left\{\sum_{n=1}^{N} P_{FFH}\left(n+1\right)+\left(\tau_{R,FFH}-1\right)P_{FFH}(N+1)\right\}$$
$$-L_{FFH}\left\{\left(1-BF_{FFH}\right)\sum_{n=1}^{N-\tau_F} P_{FFH}\left(n\right)+\sum_{n=1}^{N-1} BF_{FFH}P_{FFH}\left(n\right)+0.5BF_{FFH}P_{FFH}\left(N\right)+F_w\left[\sum_{n=1}^{N} P_{FFH}(n)+\left(\tau_{R,FFH}-1\right)P_{FFH}(N)\right]\right\}$$

Eq. 4.7

These and additional numerical checks confirm the self-consistency of the given solutions for FFH systems.

A4.6 Decay Rate of Fusion-Fission Hybrid Systems with Zero TRU Input

Since the FFH systems described here do not produce net positive amounts of TRU, there is no analogous case to the maximum growth rate without TRU input that was considered above for FRs. However there clearly is a decay rate of the FFH system in which individual FFH reactors are turned off as waste is burned, in just such a manner that the fuel emerging from the TRU stock at all times is just what is needed for each future year, allowing for FFH decommissioning to return fuel to the stock of FFH-derived TRU (consistent with the derivation of equation A4.3). Starting from equation A4.3, we can solve for BF_{FFH}:

$$BF_{FFH} = 1-\left(1+F_w\right)\left(1+m\right)^{\tau_F+1}-\left(\tau_{R,FFH}-1\right)m$$

which has the physically intuitive limit as $m \rightarrow 0$ of $BF_{FFH} = -F_W$

We can also form an iterative solution for m:

$$m = \frac{-BF_{FFH}-F_w-\left(1+F_w\right)\left[\left(1+m\right)^{\tau_F+1}-1-m\left(\tau_F+1\right)\right]}{\left(1+F_w\right)\tau_F+\tau_{R,FFH}+F_w}$$

Eq. 4.9

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