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Stocks and Flows of U and Pu in a World with 3.6 TWe of Nuclear Power

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Stocks and Flows of U and Pu in a World with 3.6 TWe of Nuclear Power

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Abstract
Integrated energy, environment, and economics models project that worldwide electrical energy use will increase to ~12 TWe in 2100 and nuclear power may be required to provide 3.6 TWe at this time. If pulverized coal without carbon sequestration were employed instead, the resulting incremental long-term global temperature rise would be about 2/3 deg C. Calculations are presented of the stocks and flows of uranium and plutonium associated with the scenario where this energy is provided by nuclear power. If only light-water reactors (LWRs) are used, the scenario consumes about 33.4 Mt of mined uranium. Continuing to operate the reactors in place in 2100 through the end of their assumed 60 year lifetime raises this to 59 Mt, 4.7x the NEA/IAEA Redbook estimate for total discovered + undiscovered uranium. The waste corresponds to about 86x the legally defined capacity of Yucca Mtn. A case is also considered where a transition is begun to fast-spectrum reactors in 2040, both for a "balanced" system of LWRs and transuranic (TRU) burners with conversion ration (CR) = 0.5, and for a system of breeders. In the latter case we find that CR = 1.21 is adequate to replace all LWRs with breeders by 2100, using solely TRU from LWRs to start up the reactors – assuming reprocessed fuel is available for use two years after its removal from the reactor. The stock of plutonium circulating in the fast reactor system in 2100 is comparable to that which would have been buried in the LWR-only case. One year of fueling corresponds to 2,000 – 6,000t of Pu. Fusion energy, if first brought on line in mid-century, could in principle replace fast reactors in this scenario.

1. Introduction

Global warming and nuclear war both represent significant risks to human civilization and to the earth's ecosystem. Nuclear power has the potential to mitigate the risk of the former but also to exacerbate the risk of the latter. Here we summarizes work[1] that studies this tradeoff quantitatively. Section 2 provides a brief evaluation of the literature on energy, environment and economics modeling, in order to assess the projected use of nuclear power. Section 3 then uses a standard climate model to estimate the impact of nuclear power on global warming. Section 4 assesses the stocks and flows of uranium and transuranics (TRU) in a scenario in which this power is provided exclusively by Light Water Reactors (LWRs). Section 5 considers a transition starting in 2040 to Fast-spectrum Reactors (FRs). Section 6 notes the potential role for fusion energy, if it is developed by mid-century.

2. Projected use of nuclear power

Different energy, environment and economics models make different assumptions about the future availability and cost of the various energy sources. Different runs of the same model make differing assumptions about restrictions on CO_2 emissions. It is interesting, however, that the amount of *electrical power* production and use across many models and many assumptions varies relatively little. Edmonds et al.[2] explain the lack of variability with respect to restrictions on emissions by noting that restricting CO_2 in their model runs results in significant reduction in total energy production, but a closely counter-balancing increase in the *fraction* of energy produced in the form of electricity. This is because electrical power generation stations are one of the most practical targets for CO_2 emissions reductions.

Clarke et al.[3] have gathered together 97 model runs from 15 different energy/environment/economics models by research groups around the world, running a wide range of different CO_2 emissions constraints. The spread of resulting projections for electrical power use, shown in figure 1, is remarkably constrained, with the greatest differences being between models rather than between constraint scenarios. The projected %/year rate of growth is somewhat less than was experienced in the period 1980 – 2006.

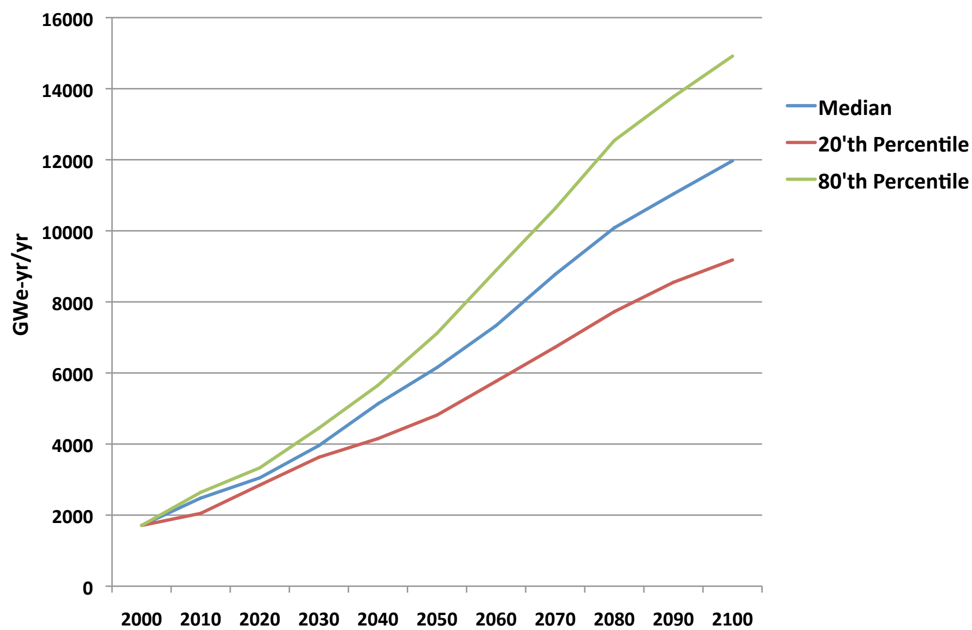

Figure 1: Projected range of electrical energy production per Clarke et al.[3]

Here we will assume, along with these models, that the dominant use of nuclear energy will be through electrical power production, including for electrically-powered transportation. The spread in nuclear electrical energy production in these models is greater than that of total energy, with the 20 - 80'th percentiles arriving at about a factor of 2 variation, each, from the median, as shown in figure 2.

The nuclear energy production of the median case corresponds rather closely to a curve drawn from current use to that projected for 2100, using a linearly varying fraction of the total electrical energy production, from 14% today to 30% in 2100. This curve will be used in the following analyses, with the recognition that while it is unbiased by either pro or anti-nuclear sentiment, it cannot be viewed as a firm projection but rather as a reasonable estimate given the range of assumptions in current models. The range of these projections is evidently quite large. The assumed curve represents an increase by a factor of 12 from 300 GWe-years of energy production per year (the ordinate of figures 1 and 2) today to 3600 GWe-years per year in 2100. This analysis published in 2009 does not include effects of the accident at Fukushima Daiichi.

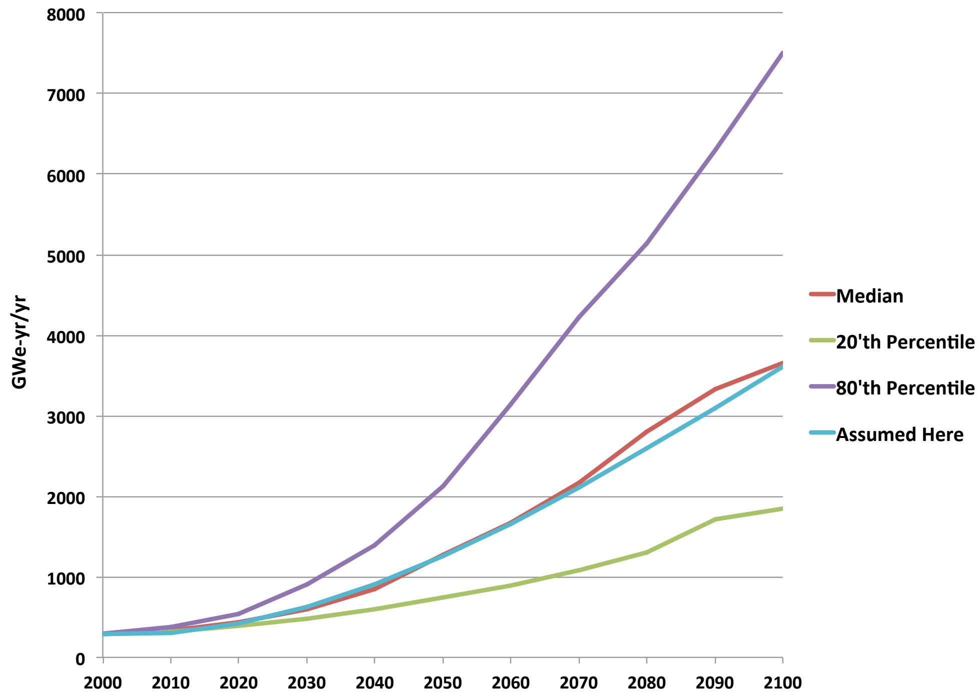

Figure 2: Projected range of nuclear electrical energy production per Clarke et al.[3] and assumed here.

3. Climate change mitigation benefits of nuclear power

The total amount of nuclear energy produced from 2010 to 2100 in the scenario we have adopted is about 150 TWe-years. A typical pulverized coal plant without carbon capture and storage emits[4] about 6.7 MtCO_2/GWe-yr, so if such plants were to provide 150 TWe-years of power this would correspond to 1000 GtCO_2, which would result in an increase of about 80 ppm in atmospheric concentration of CO_2 in 2100[5]. The Intergovernmental Panel on Climate Change estimates[6] that this additional CO_2 would cause a rise of long-term (multi-century) equilibrium global-average surface temperature of 0.64° C, with an uncertainty range of a factor of 1.5 in either direction. This range is termed by the IPCC the "likely" (>2/3 probability) prediction. For perspective it should be noted that many scientists consider an increase in global average temperature of 2° C to be highly risky, so 2/3° C could represent a significant impact.

The above estimate of 2/3° C temperature rise may be too high, however, because in the absence of nuclear power there would be less total electrical power produced and not all substituted power would come from the highest carbon-emitting sources such as pulverized coal. On the other hand, the climate-impact estimate here can also be seen as too low, in that the substitute 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 further emission of 768

GtCO2 post-2100. Furthermore, presumably nuclear power would not be available as an energy source thereafter.

The model we use here, and elsewhere, for committed energy production is based on assuming steady exponential growth until the moment when further plants are no longer constructed (in this case no further "substitute" plants are constructed post-2100). Then the remaining committed energy production integrated over time as each plant is turned off at its end of life is given by[7]

$$E_{com} = P_{max}\tau_p \left[\frac{m\tau_p - \left(1 - e^{-m\tau_p}\right)}{m\tau_p\left(1 - e^{-m\tau_p}\right)} \right]$$

where P_{max} is the maximum power at the time when no further plants are constructed, τ_p is the plant lifetime (assumed here to be 60 years) and *m* is the exponential growth rate in inverse years. Checks of this model against detailed analysis of different cases, with *m* chosen to fit power production $\tau_p/2$ years before the end of new construction, show accuracy to a few %.

4. Light Water Reactor Scenario – Stocks and Flows

We start by considering a case where all of the nuclear power shown in figure 2 is supplied by LWRs, using a once-through fuel cycle. For the stocks and flows of uranium and TRU we assume 4.5% fuel enrichment and 0.25% enrichment of tails. We further assume 33% efficiency, giving a requirement for 205t of natural uranium to produce 1 GWe-yr of electrical energy. Production of 22.1t of initial Heavy Metal (iHM) per year requires 153 tSWU of separative work. Within this fuel is 1t of ^{235}U. For the assumed burnup of 50 GWd/tiHM, we find that the production rate of transuranics is 321kg/year of which 295kg is plutonium.

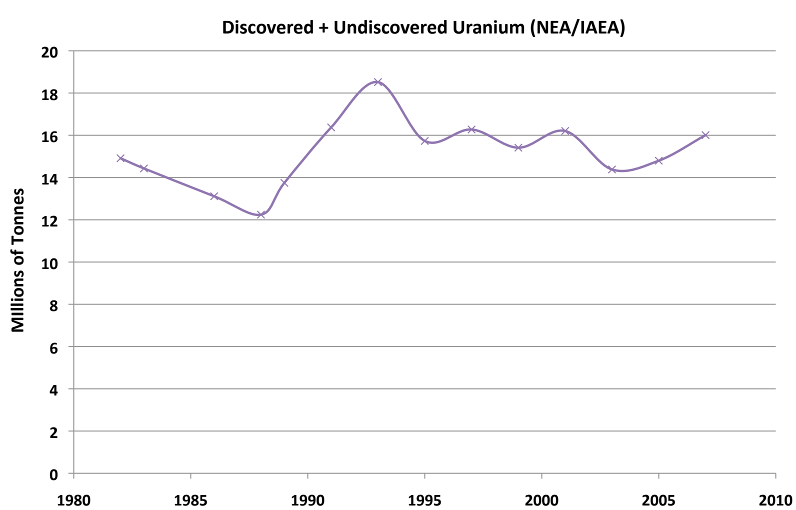

Figure 3: Total discovered + undiscovered uranium reported in NEA/IAEA Red Books, since estimates of undiscovered resources have been included.

The total requirement for natural uranium to supply the LWRs in this scenario is 33.4 Mt.

Including the committed fuel requirement (see Section 3) brings the total to 59 Mt. The Nuclear Energy Agency of the OECD, together with the IAEA, estimates world uranium resources in a bi-annual series of "Red Books"[8]. These documents are based on national self-reporting. If one sums all categories of conventional uranium resources irrespective of price, including speculative, undiscovered resources (which have been reported since 1982), the total uranium projection has been relatively stable over the last 25 years at about 16Mt, as shown in Figure 3. During this time period about 1.1 Mt has been mined. There is much speculation and uncertainty as to how much uranium can practically be made available, particularly as the cost of natural uranium contributes very little to the cost of electricity from fission. It is possible that uranium will ultimately be available at an acceptable cost from seawater. Nonetheless, the requirement for 3.7 times the quoted total discovered, speculative and undiscovered uranium resource calculated here gives some pause.

Potentially more problematic is the amount of nuclear waste produced. By 2100 the total waste committed corresponds to 86 times the legislatively determined limit for Yucca Mountain. While there is reason to believe that a few geological repositories will be opened, worldwide, in the next decade or so, the scale of this challenge has to be viewed as daunting.

Next we use the calculated stocks and flows to quantify the materials that might become available for nuclear weapons proliferation in this scenario. In 2100 the total separative work required is 551,000 tSWU/yr. Since 5.4 tSWU is required to produce a single IAEA-defined[9] "Significant Quantity", SQ, of highly enriched uranium, HEU, at 90% enrichement, from natural uranium (with 0.3% enriched tails), this corresponds to the enrichment capability for about 100,000 SQ per year, a very large number. One can be concerned about leakage of widespread enrichment technology to clandestine facilities and about rapid breakout scenarios for declared, but well protected facilities. A second concern is the production of plutonium, which is 1060t/yr in 2100. While this is by definition "reactor grade" Pu, the U.S. has declassified that such Pu is usable for weapons and the IAEA considers it on an equal footing with "weapons grade" Pu. 1060t/yr corresponds to 132,000 SQ/yr. This material is mixed with highly radioactive fission products, and so is considered self-protecting with regard to theft by sub-national groups for a period of over 50 years. However the IAEA indicates that a state actor would require only 1 - 3 months to process it for use in weapons. The total waste produced corresponds to about 6M SQ.

When Reagan and Gorbachev spoke, Reagan liked to quote the Russian proverb "Trust, but Verify". Gorbachev was partial to the proverb "When there are too many guns around, they start firing by themselves." With such a large amount of explosive nuclear material available globally, it seems to this author that deep disarmament would be extremely difficult to achieve. Figure 4 shows a map of the nations that have nuclear energy programs and those that have requested assistance from the IAEA to establish new nuclear energy programs.

Nations which have not put into force an Additional Protocol with the IAEA, which strengthens the IAEA's capability to inspect undeclared facilities, include: Argentina, Bolivia, Brazil, Venezuela; Egypt, Iran, Israel (not a signator of the Nuclear Non-Proliferation Treat, NPT), Saudi Arabia, Syria; Cambodia, Malaysia, Thailand, Vietnam; South Korea, North Korea (left the NPT); Pakistan (not a signator of the NPT), India (not a signator of the NPT).

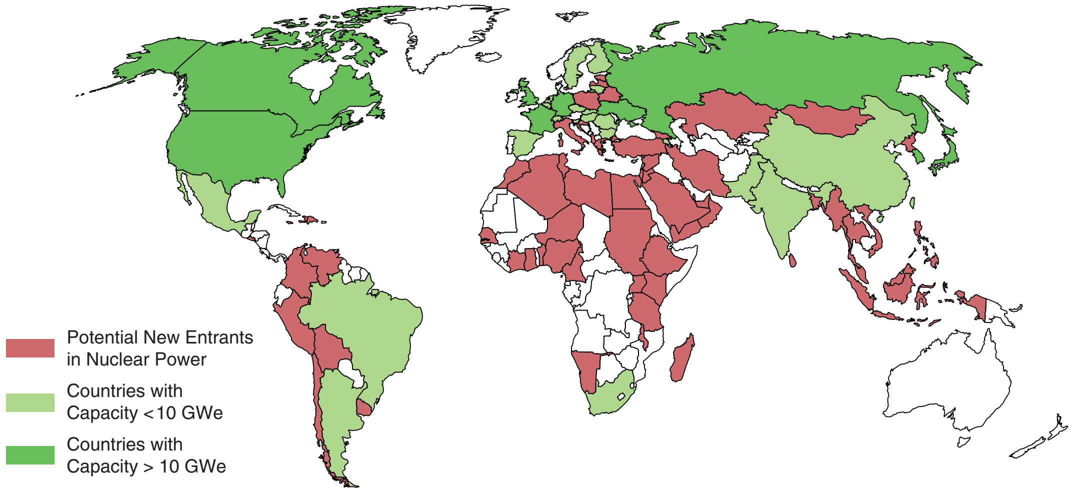

Figure 4: Nations with nuclear power programs in place and those that have requested assistance from the IAEA to establish nuclear power programs.

5. Fast-spectrum Reactor Scenario – Stocks and Flows

The leading approach considered for addressing the long-term fuel-supply and waste issues for LWRs is to move later in the century to reactors with fast neutron spectra, sometimes called Fast Reactors (FRs). FRs are characterized by their Conversion Ratio (CR) defined as the ratio of the mass of transuranics (plutonium plus minor actinides, TRU) produced to the mass of those burned. FRs with Conversion Ratio (CR) < 1 are defined as "burners" and can be used to burn the TRU waste from LWRs, greatly reducing the TRU that requires geological storage, while FRs with CR > 1 are "breeders" and can be used to not only to burn LWR TRU but also to breed fuel from ^{238}U, increasing the energy extracted from natural uranium by a large factor, and ultimately obviating the need for uranium enrichment. To track the stocks and flows associated with FRs we use a recent study[10] of the fueling requirements for sodium-cooled fast reactors, a leading architecture for FRs. Figure 5 presents the key result for the present analysis.

The stocks and flows of nuclear materials in a FR cycle are more complex than those in an LWR cycle, since material produced by FRs is reprocessed and re-inserted into the reactors. Following Dixon et al.[11], we assume 4 years of fuel residence time in-reactor. A crucial issue is the time it takes for processing the fuel before it is re-inserted, which depends strongly on the location where the processing take place. We again follow Dixon et al., and take an estimate of 2 years for on-site cooling, reprocessing and fuel fabrication, and – in strong contrast – 11 years for cooling, transportation to a centralized fuel recycling center, reprocessing, fuel fabrication, and return to the fast reactor. We assume a processing loss of 1% of TRU per cycle. Figure 6 shows two cases, a breeder case with local reprocessing, and a burner case with centralized reprocessing. In the case of breeders with CR= 1.21, and a rapid fuel cycle, it is possible to load all the TRU from

LWRs into the FR fuel cycle and *turn off* the last LWR in 2100. In the case of the burners, the long fuel cycle requires so much TRU that the equilibrium ratio of burners to LWRs of 39% is far away even in 2100, when all available LWR TRU has been loaded into the FRs.

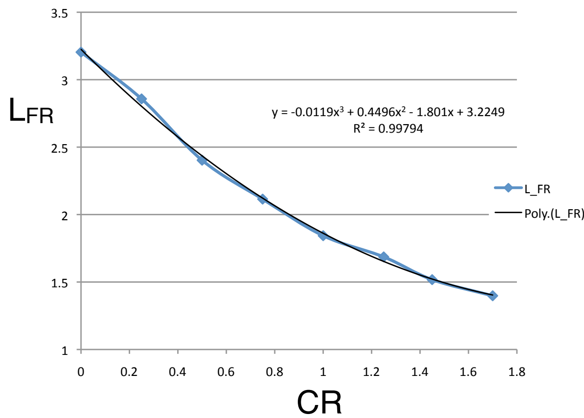

Figure 5: Load of TRU, in tonnes, required to produce 1 GWe-yr in a fast reactor, as a function of conversion ratio, CR. A realistic range of accessible CR's may be from about 0.5 to about 1.5.

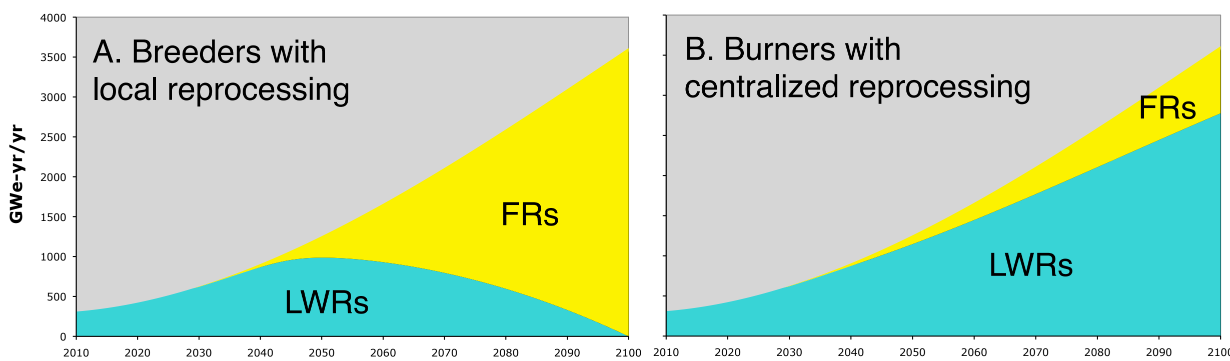

Figure 6. A) Breeder FRs with CR = 1.21 and local reprocessing, B) Burner FRs with CR = 0.5 and centralized reprocessing.

Table I shows that in case A the total mined uranium is only 12.3 Mt, while in case B the committed amount is 47.5 Mt, and continuing to grow. Of course the "burner" case is not designed to limit uranium use. Case A has zero enrichment requirement in 2100, while Case B requires 77% as much as the LWR-only case. The transuranics in waste are dramatically reduced in either case compared with the LWR-only case. One has to be cautious, however, in considering TRU as a measure of waste reduction. Fission products and their associated radiotoxicity are not significantly reduced per unit of energy production, except insofar as FRs are assumed to be somewhat more efficient in turning thermal energy into electricity (38% vs. 33%). In an oxidizing environment such as Yucca Mt., TRU is relatively mobile, while in a reducing, and particularly clay environment TRU appears to be largely immobilized[12,13]. Thus while the total long-term radiotoxicity is substantially reduced by burning TRU, the mobilizable toxicity may not be. Since 2003 the IAEA has recommended[14] that geological repositories be situated in reducing environments.

The stocks of TRU circulating in the two fuel cycles are impressive. Case A has 38,000t in circulation, comparable to the 49,000t to be buried in the LWR-only case. This corresponds to 4.5M SQ of Pu. Case B has 24,500t in circulation. Material in circulation in the FR cases is much more vulnerable to theft or diversion than the material in geological storage in the LWR case.

Table 1: Material Stocks and Flows, 2100

	A: Breeders	B: Burners	LWRs
Total U mined (Mt)	12.3	47.5 +	59
^{235}U Fueling (t/yr)	0	2,770	3,600
TRU in Waste (t)	2,220	6,550	49,000
TRU in FR System (t)	38,000	24,500	0
TRU Fueling (t/yr)	6,510	2,170	0

Also worrisome from a proliferation perspective is the TRU fueling rate. 6,510t/yr of TRU corresponds to about 750,000 SQ/yr of plutonium, and 2,170t/yr represents 1/3 of that. The IAEA standard for Material Unaccounted For (MUF) at a reprocessing plant is 1%. While surveillance and containment adds confidence beyond this number, a reported global level of MUF in the range of ~5000 SQ/yr could be destabilizing, particularly in a world seeking nuclear disarmament.

Furthermore, 1 GWe-yr/yr of plant capability requires 200 – 275 SQ of fuel per year. It is reasonable for an operator of a nuclear power plant to store at least one year's worth of fuel on site in advance of its use, to hedge against interruptions in the supply chain. Recycled fuel for a FR is not radioactively self-protecting, and no isotopic enrichment is required. The IAEA estimates that 1 – 3 weeks are required to process such material for use in weapons. The dispersal of ~ 500,000 SQ of nuclear explosive material in many areas of the world, available for short-term use, could be highly destabilizing. A disturbing feature of this scenario is that it cannot be mitigated by the use of international reprocessing centers, since the fuel must ultimately be delivered to the customer, wherever it has been reprocessed. This represents an important difference from international enrichment centers for LWRs, where the fuel delivered to a reactor requires further enrichment before it can be used in a nuclear weapon.

6. Fusion Scenario

The successful commercial development of fusion energy based on the DT reaction is not assured, but one can ask if a scenario exists in which fusion power plants could replace LWRs later in the century. The proliferation risks of fusion power plants would be significantly lower than those of either LWRs or FRs, assuming safeguards in all cases[15]. Figure 9 shows a scenario for the application of fusion power for commercial electricity production starting at mid-century, consistent with the stated goals of some nations involved in the international ITER fusion energy experiment. 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.

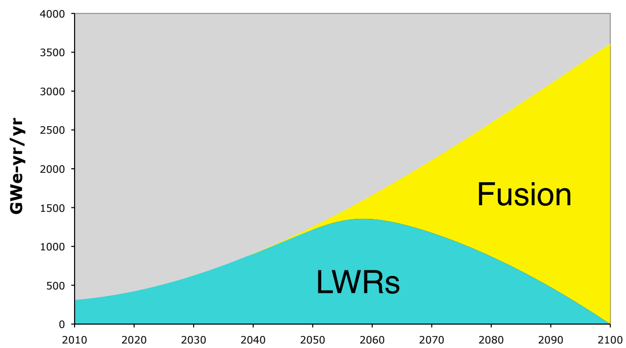

Figure 9. Scenario for fusion energy beginning commercialization at mid-century.

Proposals have been made to use the neutrons from fusion to transmute TRU waste from LWRs. This would entail stocks and flows of TRU in 2100 similar to those discussed for Case B above, and similar proliferation risks, but these stocks and flows would drop with a halving time of about 30 years, rather than continuing to grow as in both of the FR scenarios.

7. Conclusions

There are considerable uncertainties in the future application of nuclear power for the generation of commercial electricity. The median of a 2009 international study using 15 different energy/environment/economic models projected a median production level of 3600 GWe-yr/yr in 2100, with ~ factor of 2 spread in either direction. If this electrical power were produced instead by coal-fired power plants, the projected long-term global-average temperature rise, based on analyses by the IPCC, would be 2/3° C, with factor of 1.5 uncertainty, a significant impact. Arguments can be made that this estimate is either high or low.

The stocks and flows of uranium and plutonium for the production of this level of electrical energy are significant. In a case using only LWRs, the total committed uranium use is 59 Mt, about 3.7 times the NEA/IAEA "Red Book" total discovered, speculative, and undiscovered resource, but these estimates are disputed. The committed geological waste disposal is about 86x the legislated limit for Yucca Mt. The uranium enrichment required in 2100 would be capable of producing 100,000 SQ of HEU per year, so even small technology leakage or a small fraction of breakout would be very dangerous. About 132,000 SQ of Pu is produced in waste per year, and a total of 6.5M SQ would be placed in geological storage.

For a case where an LWR-only scenario is followed by breeder or burner fast reactors, we find that the amount of Pu in circulation in 2100 reaches 3 – 4.5M SQ. The amount of Pu delivered to fast reactors around the world would be a daunting 250,000 – 750,000 SQ per year.

Fusion energy systems, if successfully commercialized, could in principle replace LWRs starting in mid-century, with no additional stocks and flows of uranium and plutonium.

Analyses of this kind should be used by decision-makers to put the risks of global warming vs. nuclear proliferation into quantitative perspective, as well as to motivate research and development on nuclear technologies with substantially lower proliferation risks.

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