"Super-Size Me!"

The Role of Sodium-Cooled Fast Reactors in a Large-Scale Nuclear Economy

This paper provides an overview of the challenges of a transition to a "super-sized" nuclear power economy, a world where extensive use of nuclear energy is made in the electricity generation sector, with a market share large enough to significantly displace fossil fuel consumption and address global warming. In the context of an atmospheric concentration stabilization scenario at 550ppm, I develop a 'large-scale nuclear' scenario corresponding to fast and steady increase of the share of nuclear power generation. I focus more specifically on the potential contribution of one promising nuclear technology, the sodium-cooled fast neutron reactor (SFR), and a specific fuel cycle that could be built based on such a technology, the full actinide recycle balanced closed fuel cycle. Attention is then given to the main barriers that could deter this technology to be deployed at widespread scales. Four factors are identified: the safety of plant operations, the economics of the fuel cycle for electricity generation, the question of waste management, and the risks of proliferation. The 2003 MIT 'The Future of Nuclear Power' study concluded that 'once through' cycles were the most economical solution and should be pursued in the short term. The main conclusion of this paper is that, though this economic disadvantage will hamper its development in the middle-run, SFR design presents very strong advantages in terms of waste management and proliferation control. The integrated fast reactor technology, based on a SFR design integrated with an on-site pyroprocessing plant, that could render these two issues much more manageable from a policy perspective, should hence become an integral part of worldwide energy policies at the horizon of Generation IV reactors.

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1. INTRODUCTION

The worldwide shift in public perception about global warming has rehabilitated the idea that nuclear power is a crucial energy source for our future. A question arises: to what extent could nuclear energy become a solution to global warming? In the context of an atmospheric concentration stabilization scenario at 550ppm, I develop a 'large-scale nuclear' scenario corresponding to a steady increase of the share of nuclear power generation, and evaluate the different challenges the nuclear industry would be facing.

I focus more specifically on the potential contribution of one promising nuclear technology, the sodium-cooled fast neutron reactor (SFR), and a specific fuel cycle that could be built based on such a technology, the full actinide recycle balanced closed fuel cycle. Four factors that could hamper the widespread development of this technology are identified: the safety of plant operations, the economics of the fuel cycle for electricity generation, the question of waste management, and the risks of proliferation.

For each of these policy decision-making variables, I detail and weigh the benefits and drawbacks that would stem from the use of the SFR design in the build-up of a large-scale nuclear economy. I assert that, because of its very positive waste management and proliferation control features, an integrated fast reactor based on a SFR design with on-site pyroprocessing could become the reference scenario for Generation IV nuclear power at the horizon 2030.

2. THE NEXT GENERATION OF NUCLEAR POWER

Global warming and the role of nuclear power generation

The major role played by anthropogenic emissions in the process of global warming is now clearly recognized by the scientific community. The upcoming IPCC report, whose executive summary was published in February 2007, concluded for the first time that global warming is an "unequivocal" phenomenon and that human activity is its main driver, "very likely" causing most of the observed rise in temperatures (IPCC, 2007). The amount of carbon in the atmosphere the world could tolerate is far from being agreed upon. In order to keep the effects of global warming down to a manageable level, the current focal benchmark among scientists is that emissions should be curbed so as to maintain atmospheric concentration of CO_2 at a level of 550 ppm, twice as much as the pre-industrial concentration, from a current level of 380 ppm (Socolow and Lam, 2007).

Power generation technologies will play a crucial role in carbon emissions abatement strategies. Electricity production accounts for over 40% of current carbon emissions worldwide, while nuclear power generation accounts for only 16% of the 14,000 TWh currently produced each year (Paltsev, Reilly, Jacoby et al., 2005). Such a technology has an obvious potential for carbon mitigation (apart from secondary emissions during the construction phase, nuclear power generation is virtually carbon-free), but most projections are basing their forecasts on the hypothesis that nuclear power generation won't be developed further than its current level, due to the strong anti-nuclear current in the public opinion.

Forecasts are hence based on a widespread use of carbon capture and storage technologies, which are, contrary to nuclear power generation, not yet tested nor deployable in the middle-run. Figure 1 presents for example the evolution of the power generation sector in a scenario with stabilization of the atmospheric concentration at 550 ppm computed by MIT's EPPA model, in which the nuclear power capacity is assumed to be renewed but not expanded due to the 'combination of economic/policy issues' that such a sector raises (Paltsev, Reilly, Jacoby et al., 2005).

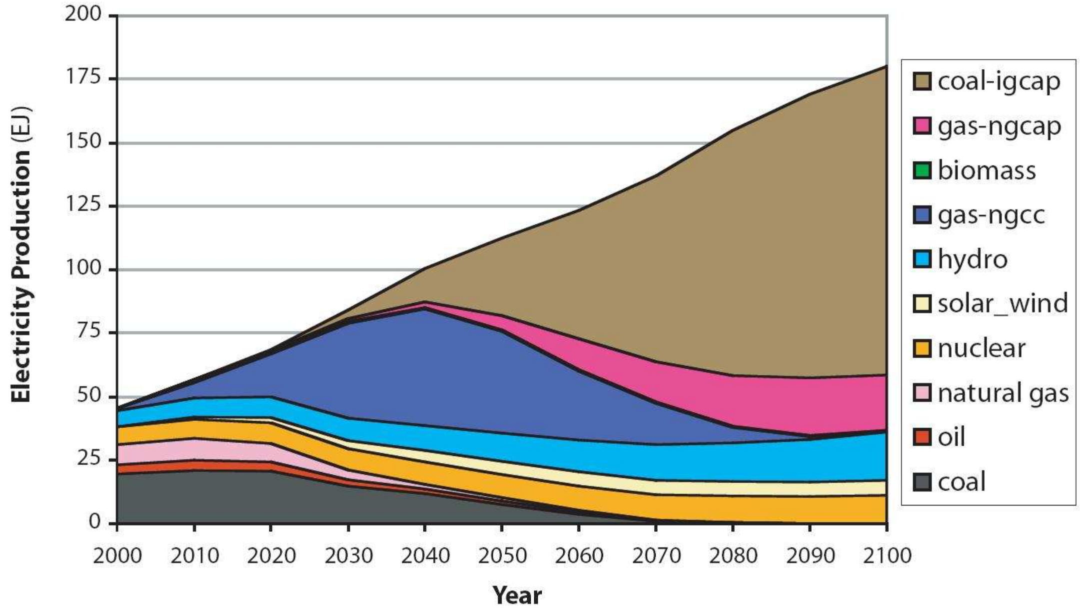

Figure 1: Power generation forecast in the 550 ppm with constraint nuclear[1]

Public opinion on nuclear energy is however evolving mostly because of the role this technology could play to help alleviate global warming. While the decision on how to balance these benefits and the risks nuclear is associated with is a political decision that will be specific to each country, voices from the environmentalist movement that favor nuclear energy are now frequently hear (e.g. Dr. Moore, founder of Greenpeace and at a time a prominent anti-nuclear activist, now declares that 'benefits fare outweigh the risks'). What scale should nuclear power generation be developed at in order to play a significant role in carbon emissions abatement?

Three different scenarios can be outlined:

- <u>Status quo:</u> nuclear power generation capacity is maintained at its current level during the next century, with limited new constructions compensating for the gradual phase out of plants reaching the end of their lives. This means a sustained level of around 430 plants of the current size, or a more important number of smaller plants, totaling 2,400 TWh. In 2050, nuclear energy would hence fall to

[1] Source: Paltsev, Reilly, Jacoby et al., 2005. MIT's EPPA model (Emissions Prediction and Policy Analysis), the computable general equilibrium model used to produce these forecasts, has embedded constraints on nuclear power generation, on the basis of the current political situation of nuclear power generation.

less than 9% of power generation market share. Such a scenario could be justified in two cases: either policies to curb global change are weak or turn out to be facilitated by technological advance; or public perception of nuclear energy, potentially frightened by new incidents, deter governments and industry from a full-scale development. Most of the increase in supply would hence be met by fossil fuels technologies with capture and storage of carbon dioxide.

- Limited new development: nuclear power generation capacity would undergo a steady development, reaching widespread development in developed countries, at a level of around three times the current capacity. This scenario is kin to the one detailed in MIT's *Future of Nuclear Power* report (Deutch Moniz et al., 2003), and would lead to around a thousand 1,000 MWe reactors distributed around the world, for a total capacity of around 8,300 TWh and a 25% market share in 2050. Such a scenario would entail a steady growth of nuclear capacity after the next 15 years, during which capacity is bound to be flat due to the lack of new projects already on track. Over the 2020-2050 period, this scenario entails that twenty 1,000 MWe plants would be built worldwide per year.

- Large-scale development: nuclear power generation capacity expansion would, in this case, be the main instrument of carbon emissions mitigation in the next century. Such an expansion could be a six-fold growth from the current basis, reaching 16,000 TWh and a 50% market share by 2050, where the nuclear park would comprise of around two thousand 1,000 MWe plants. To reach such a penetration level, nuclear plants would need to be built at a pace of fifty to sixty plants a year worldwide during the peak years, which has the potential to congest the industry, and would saturate the electrical power generation markets in developed countries while making significant entry in LDCs.

The focus of this paper is on the last scenario. Though it is less likely to be ultimately effectively deployed than the second one, its drastic implications for the nuclear economy are useful to try to assess the challenges faced by governments and the industry if this industry was to reach a whole new scale. Studying how the promising Sodium-cooled Fast Reactor technology could respond to such a challenge would hence allow us a better understanding of the role of Generation IV reactors in the climate and energy policies of the next century.

Challenges for a nuclear future

Such a steady growth of nuclear energy in the near future would cause two types of problems: conventional challenges that nuclear technologies have traditionally faced, and new challenges arising from the scale factor pertaining to this widespread deployment.

Among conventional challenges, four of them have dominated the debate over nuclear energy in the past, and are of capital importance for its potential future development (Deutch, Moniz et al., 2003):

- Safety: the general safety of nuclear power plants operation, especially pertaining to the risks of release of radioactive material in the atmosphere, be it from a failure of operations (e.g. Chernobyl and Three Miles Island) or from external aggressions (e.g. natural disasters, terrorism).

- Economics: the cost of nuclear power generation, especially compared to other electricity generation technologies over the life of plants, taking into account the full cost of construction, operations and decommissioning (and lately the cost potentially imposed in the near future on carbon dioxide emissions).

- Waste disposal: the disposal of used nuclear fuel rods, as well as the disposal of radioactive material after the decommissioning of power plants, poses specific issues of public health and protection from radioactivity, and of long-term containment management (some radioactive fission products have a half-life of the order of a million years).

- Proliferation threats: nuclear power plants operations involve the procurement and the disposal of radioactive material – especially plutonium – that could potentially be used by terrorist organizations or rogue states to obtain either nuclear weapon capability, or the ability to threaten other nations with its dissemination.

Coupled to these problems is the issue of scale. Deploying nuclear technologies to the "super-sized" extent we are studying here would obviously exacerbate most of these problems. Most critically, in order to jump-start the build-up of nuclear capabilities, governments and industries worldwide would need to overcome the hurdle of public acceptance. Even if it could be very useful in order to abate carbon dioxide emissions, environmentalists are still very reluctant to accept increased use of nuclear power generation. This calls for both a sustained transparency and pedagogy effort from institutional stakeholders, in order to reconstruct public trust in these technologies, and sustained research and development in order to solve or mitigate the four issues I have listed. We shall see in next section what next generation technologies could do in order to address this question.

Generation IV nuclear power generation technologies

Nuclear technologies were first used for power generation in the 1950s and 60s, with a first generation of early prototype reactors. The so-called 'second generation' reactors were the first to be developed at a commercial scale, starting in the 1970s, forming the large commercial power plants that are still operating today. Generation III, appeared in the 1990s and with advances still underway, has started to be deployed and is under consideration by several countries. This third generation includes a number of near-term evolutionary designs that will offer significant advances in safety and economics, and will most likely be extensively deployed from now to 2030. Worldwide research effort is now bearing on an innovative fourth generation of nuclear energy to be deployed past that horizon. Three major factors allow a classification of the most promising Generation IV technologies:

The Generation IV International Forum, an international organization of countries that undergo Gen IV R&D, has selected six technologies that appear as the most promising and near-term at the 2030 horizon. These six technologies are classified around three factors:

- Core temperature: from 500ºC (indicated for electricity generation applications, because lower temperature means less issues of corrosion and material safety) to around 1000ºC (best suited for Hydrogen production through water electrolyse, which might become a major role for nuclear in a Hydrogen economy).

- Actinide burning: fast neutron breeder reactors rather than thermal ones have the right properties for this mission, which consists in accelerating the decay of major and minor actinides that where the product of subsequent fission in a thermal reactor.

- Size: from small reactors for distributed generation, to middle and large scale centralized grid-connected power generation.

SFR are ‘cold’ core, fast breeder, large-scale reactors, which are the best suited for electrical generation in a closed fuel-cycle (recycling). It is hence a reference technology for carbon emissions mitigation. We shall see in the next section how it could help to address the challenges of scale of the next century’s nuclear economy.

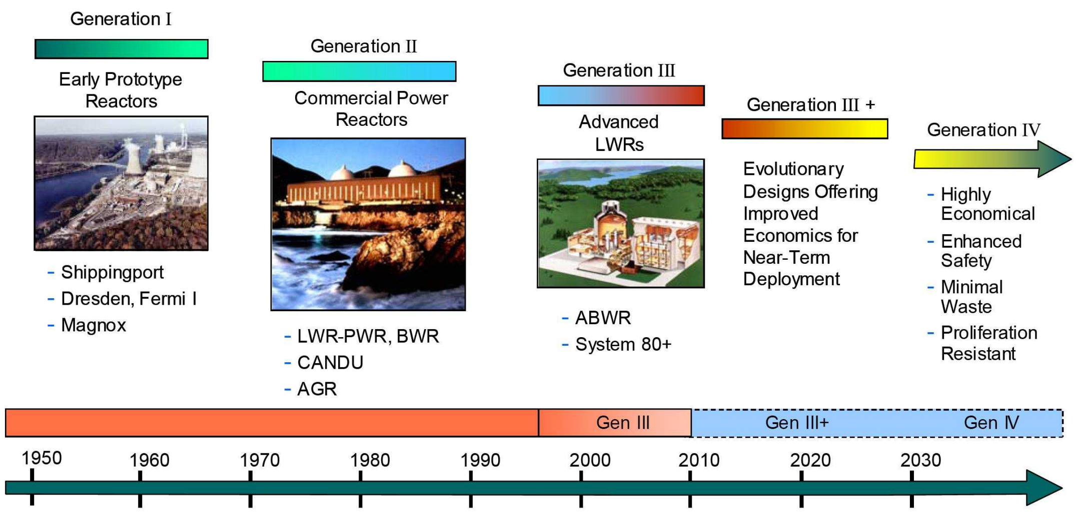

Figure 2: Generation I to Generation IV nuclear technologies[2]

Table 1: Most promising Generation IV technologies as selected by the GIF

Generation IV System	**Acronym**
Fast-spectrum neutron reactors	
Gas-Cooled Fast Reactor System	GFR
Lead-Cooled Fast Reactor System	LFR
Molten Salt Reactor System	MSR
Sodium-Cooled Fast Reactor System	SFR
Thermal neutron reactors	
Supercritical-Water-Cooled Reactor System	SCWR
Very-High-Temperature Reactor System	VHTR

[2] Source: Generation IV International Forum, 2002

3. THE TECHNOLOGY OF SODIUM-COOLED FAST REACTORS

The Sodium-Cooled Fast Reactor (SFR) system features a fast-spectrum reactor and a closed fuel recycling system. Its coolant is sodium, a molten metal, and it operates through a breeder fission reaction. Such a technology is of particular interest not only for electricity generation but also for the management of high-level wastes, specifically plutonium and other actinides: it is the nearest term actinide management system, and is estimated to be deployable by 2015.

The physics of fast breeder nuclear reactors

A fast neutron reactor is a category of nuclear reactor in which the fission chain reaction is sustained by fast neutrons (energies of the order of 1 MeV), opposed to thermal neutrons (for which energy is given by thermal agitation term $k_B T$; this yields a an energy of around 0.025 MeV at 300ºC) (Tester Drake Golay et al., 2005). Fast neutron reactors do not need neutron moderators, but must use fuel that is relatively rich in fissile material when compared to that required for a thermal reactor. The consequence of the lack of a moderator is that there is a much larger excess of neutrons not required to sustain the chain reaction in a fast reactor (higher neutron economy). These neutrons can be used for other purposes than the generation of energy through fission, for example to treat long half life waste through transmutation, or to produce extra fuel through breeding reactions, such as:

$$n + {}^{238}U \rightarrow {}^{239}U \rightarrow {}^{238}Np + \beta + \gamma \rightarrow {}^{239}Pu + \beta + \gamma$$

If the 'breeding ratio', the ratio of fertile material (here ${}^{238}U$) transformed into fissile material (here ${}^{239}Pu$) per neutron, is higher than 1, the reactor produces more fuel than it consumes. Fast reactors are often characterized by such high breeding ratios: they are in this case designed as 'fast breeder reactors'. Fertile material, particularly ${}^{238}U$, deliberately provided to the reactor, is continuously turned into fissile material by the breeding reaction. After their initial fuel charge of plutonium, these reactors hence require only minimal natural (or even depleted) uranium feedstock as input to their fuel cycle. Such reactors, and the fuel reprocessing technologies, are at the basis of what has been termed the 'plutonium economy': a closed fuel cycle nuclear power generation system with fast reactors breeding plutonium and burning other actinides stemming from thermal reactors waste fuel, integrated with reprocessing facilities.

Engineering features of SFR nuclear reactor technology

<u>Cooling mechanism</u>

Water cannot be used as the primary coolant for fast reactors, since it acts as a moderator, slowing neutrons to thermal levels and preventing the breeding of uranium-238 into plutonium 239. Fourth generation fast neutron reactors are hence based on experimental coolants. SFR designs use liquid metal sodium for that purpose.

The use of sodium metal as a primary coolant permits SFR to offer a relatively large thermal inertia and a large margin to coolant boiling, which are important safety features for nuclear reactors, and to operate at essentially atmospheric pressure. It allows relatively low core temperatures, around 550ºC. Figure 3 presents a flow chart of a sodium-cooled fast reactor power generation plant (GIF, 2002).

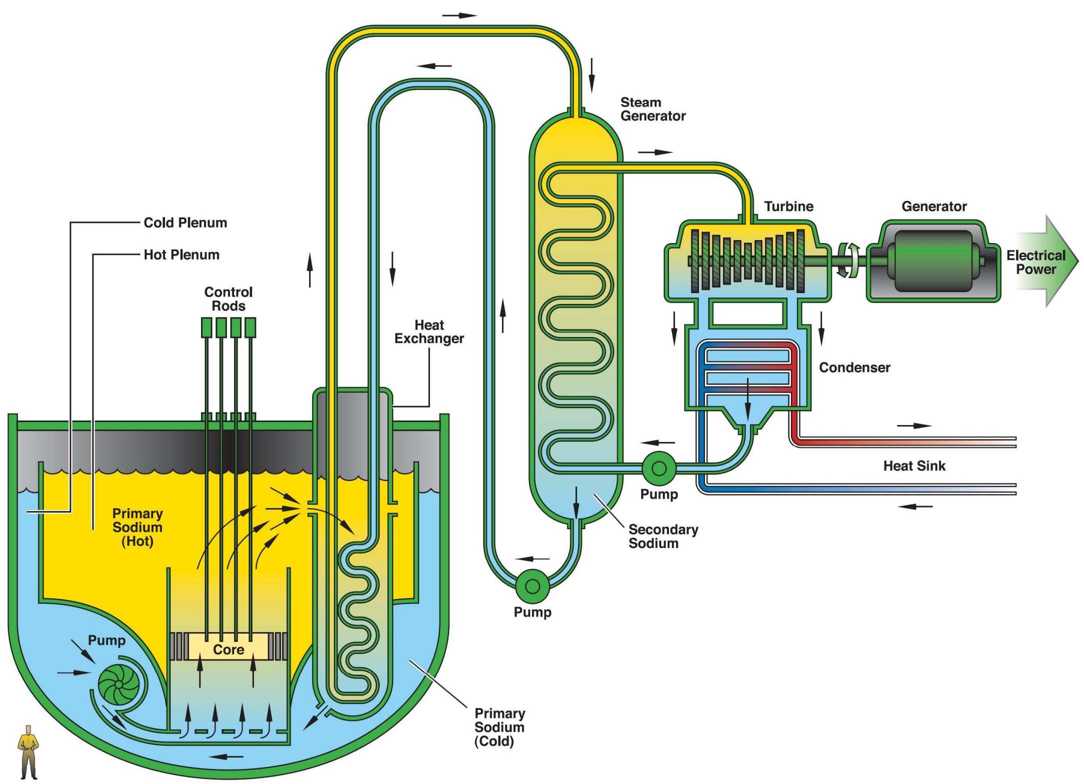

Figure 3: Sodium-cooled fast reactor[3]

[3] Source: Generation IV International Forum, 2002

Safety mechanisms

The main source of safety concern raised by such reactors is that sodium entering in contact with air and water undergoes a fast and violent chemical reaction. To limit the potential for such reactions and their consequences a secondary sodium system acts as a buffer between the radioactive sodium in the primary system and the steam or water that is contained in the conventional Rankine-cycle power plant, so that sodium-water reactions that may occur in case of a leak do not involve a radioactive release. A certain number of passive safety mechanisms were developed to increase the safety of such designs, and the long term prospects for SFR in terms of safety. However, it should be emphasized that SFR design presents inherent safety advantages over conventional light water reactors thanks to the use of liquid sodium as a coolant (Nuclear News, 1992).

Fuel options

SFR can operate with two different fuels: MOX (mixed oxides of plutonium and uranium) and metal alloy (mixed uranium-plutonium-zirconium). Mixed oxide, or MOX fuel, is a blend of plutonium and of natural, reprocessed or depleted uranium, which behavior is close from the classical low enriched uranium (LEU) fuel. MOX is the fuel that is currently produced by conventional reprocessing facilities (PUREX technology), while the metal alloy would be produced using pyroprocessing technologies.

The specificity of sodium-cooled fast reactors is that they are breeder reactors. Their main interest is hence that, if used under this breeder configuration, they can 'produce more fuel than they consume', i.e. they will burn the MOX or metal alloy fuel rods in a classical fashion, but the high neutron population will escape this 'seed' to enter the 'blanket' of ^{238}U that lies outside the core, where it will undergo the breeding reaction, turning the uranium in ^{239}Pu. Once the fuel in the 'seed' is burnt, such a reactor only needs a reprocessing facility that will separate the fission products from the spent fuel rods and the plutonium from the blanket to recombine it with a marginal external input of ^{235}U to produce fresh MOX or metal alloy.

A second interesting feature of fast reactors is that they can 'burn' nearly all actinides. They could hence be used downstream from thermal reactors, in order to burn the transuranides that poison the spent fuel of such plants. A very interesting feature of such a process is that it allows the burning of several long-lived radioactive nuclides that would instead have to be stored on the very-long run in waste disposal facilities, hence yielding the double benefit of an increased energetic efficiency and a decreased waste management burden. Finally, this actinide burning property is interesting from a geopolitical point of view, since it would allow fast reactors to burn plutonium from the waste management reserves or dismantled nuclear missiles warheads. We will come back on this property in the last section.

As a conclusion, SFR designs have interesting fuel options that position them as an important part of the nuclear power policies of the next decades. However, in order to become useful, such properties must be integrated in a whole fuel cycle, comprising of mining and enrichment facilities as well as reprocessing plants and several types of reactors. We now turn over to the issue of fuel cycles.

Closed fuel cycle options: the Plutonium economy

Reprocessing technologies

To utilize the benefits of fast reactor technologies, the nuclear industry needs fuel reprocessing facilities. It has currently developed two different technologies that would allow the construction of a full fuel cycle: aqueous technologies, and pyroprocessing.

The aqueous reprocessing technologies are base on a long and successful experience with PUREX process technology (Plutonium and Uranium Recovery by Extraction), currently used in several countries. A scheme of the technology is presented on figure 4. An important characteristic of PUREX technology is that it is used not only for fast reactor but as reprocessing facility for thermal reactors. They hence are dimensioned for important volumes of spent fuel (thermal reactors utilize only ^{235}U and a small portion of ^{238}U that is bred to ^{239}Pu, hence produce large quantities of spent fuel for comparable electrical capacities). Reprocessing plants thus usually have important capacities that entail that they are used in remote reprocessing cycles. This imply spent fuel transportation, which can create public uproar (e.g. La Hague plant in France). The high level waste form from advanced aqueous processing is vitrified glass, for which the technology is well established.

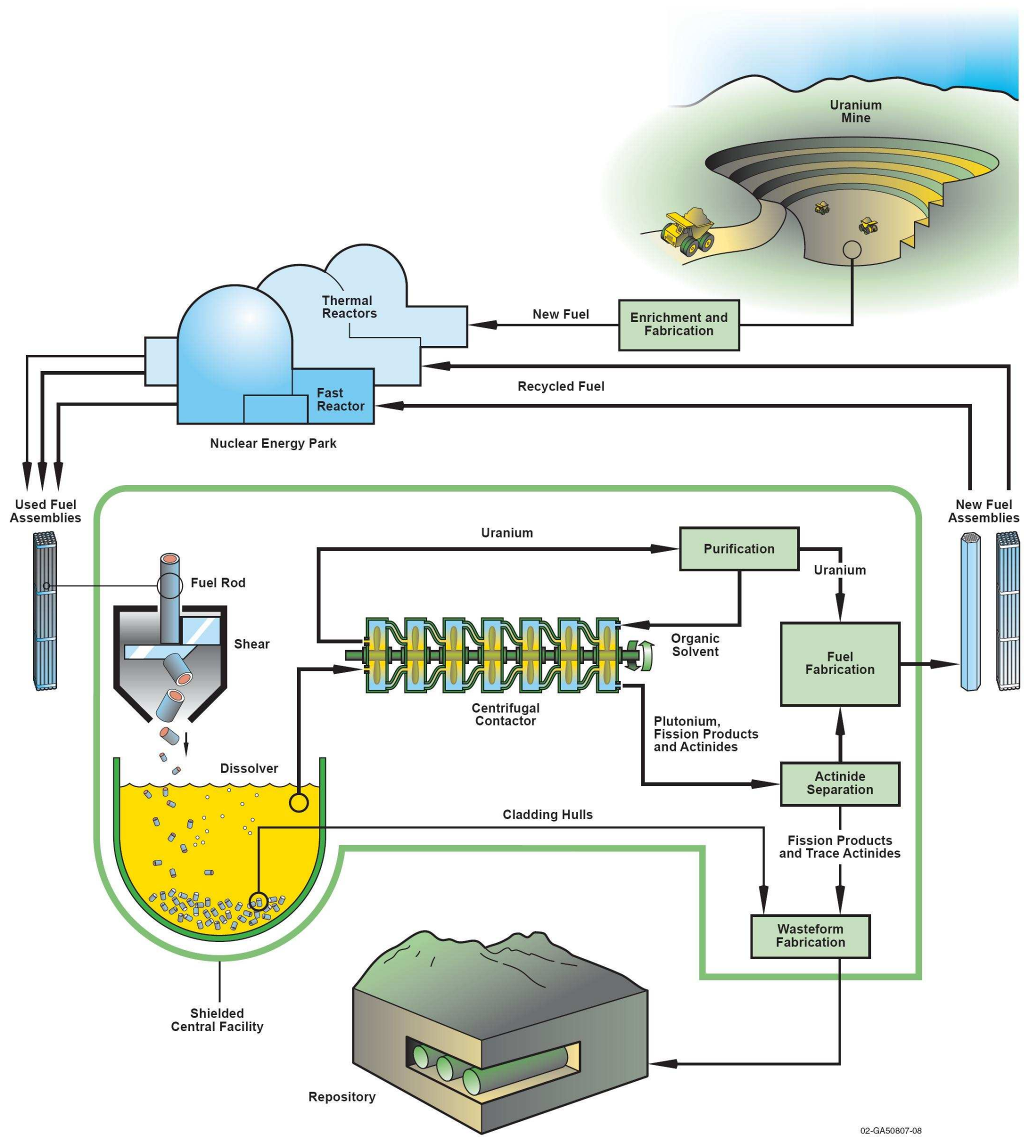

Figure 4: advanced aqueous reprocessing[4]

[4] Source: Generation IV International Forum, 2002

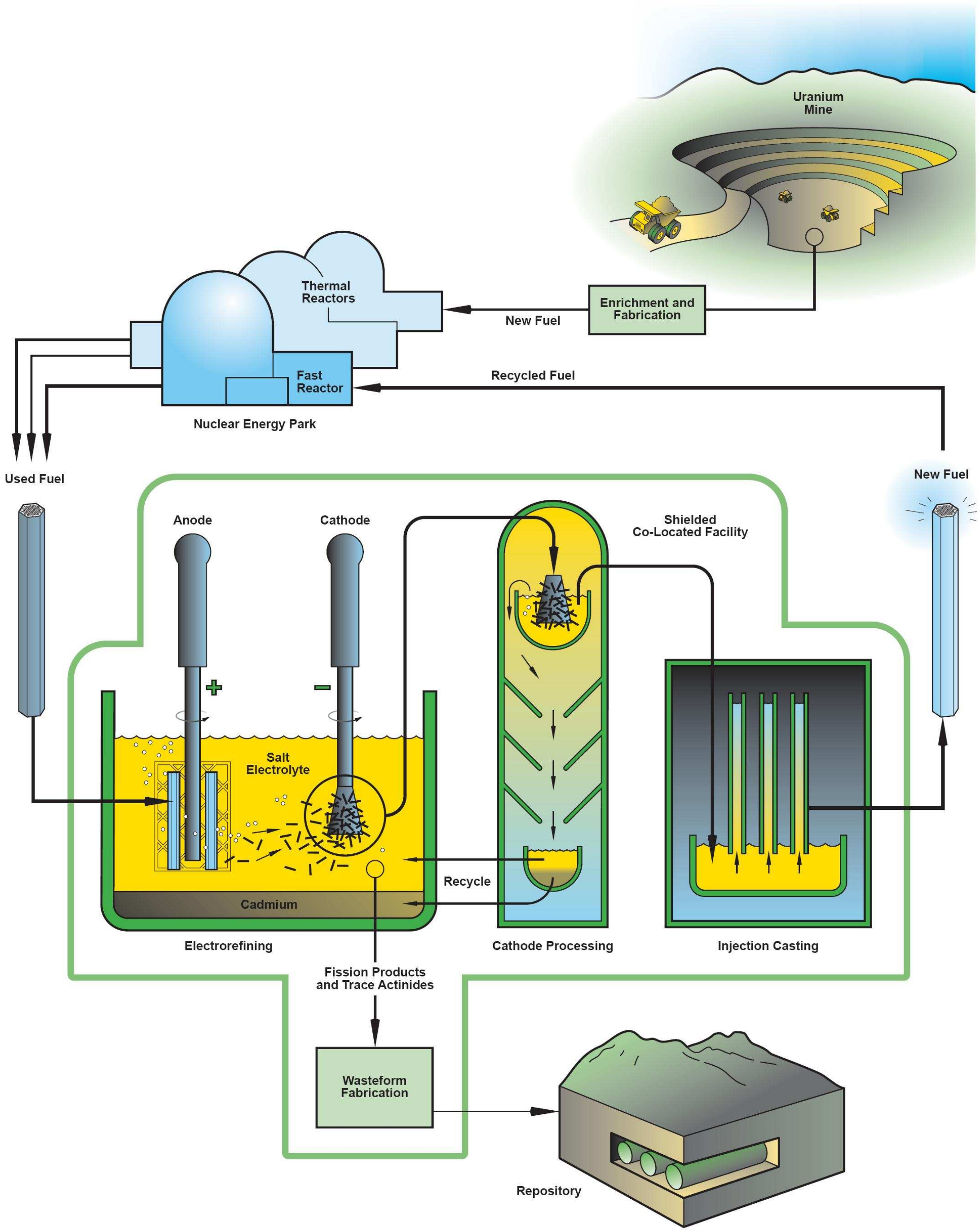

Figure 5: pyroprocessing[5]

[5] Source: Generation IV International Forum, 2002

The pyroprocessing technology has initially been developed jointly with the Integral Fast Reactor (IFR) program in the U.S. (started in 1984, stopped in 1994). It uses pools of molten cadmium and electrorefiners to reprocess metallic fuel (figure 5). Remote fabrication of metal fuel was demonstrated in the 1960s, but the technology could be used at small industrial scale exclusively for fast reactor spent fuel reprocessing directly on-site at the reactor. Significant work has gone into repository certification of the two high-level waste forms from the pyro-process, a glass-bonded mineral (ceramic) and a zirconium stainless steel alloy.

Open and closed cycles

A decision of capital importance for a future large-scale build up of the nuclear energy is the choice of the fuel cycle, i.e. not only what type of fuel is used, but also what reactors 'burn' it, how potential reprocessing loops are managed, and how spent fuel is managed. Three different scenarios for future nuclear cycles can be distinguished (Deutch Moniz et al., 2003):

- Once-through cycles: the nuclear energy system comprises only of thermal reactors that operate in a 'once through' mode (spent fuel is sent directly to the waste disposal facility).

- Closed fuel cycles with thermal reactors and one-time reprocessing: the nuclear energy system comprises only of thermal neutron, and waste products are separated from unused fissionable materials that are re-cycled as fuel into reactors (e.g. PUREX/MOX cycle used in France).

- Balanced closed fuel cycle with fast reactors: the nuclear energy system comprises of both thermal and fast neutron reactors, and thermal reactors consume LEU in a 'once-through' mode while a balanced number of fast reactors destroy the actinides separated from thermal reactor spent fuel.

Integrated sodium-cooled fast reactor cycle

The MIT report concludes that the 'once-through' fuel cycle has lower costs and best proliferation resistance while closed fuel cycles advantage is on long-term waste disposal and resource utilization. As the authors estimate that cost is the determinant issue, they advise that priority be given to the development of once-through cycles.

The major interest and main purpose of fast neutron reactors is however to allow the construction of balanced fuel cycles, the third type of cycle identified by the MIT study. I focus in the next section on the fuel cycle that makes the best use of the potential benefits of SFR design, an integrated closed cycle that could comprise of a SFR plant integrated with on-site pyroprocessing capability to burn the MOX produced from thermal reactor spent fuel, on the model of the late IFR. I investigate specifically what particular features of an integrated SFR-based closed cycle could tip the balance in favor of or against such a system, in the context of a worldwide large-scale expansion of nuclear power generation.

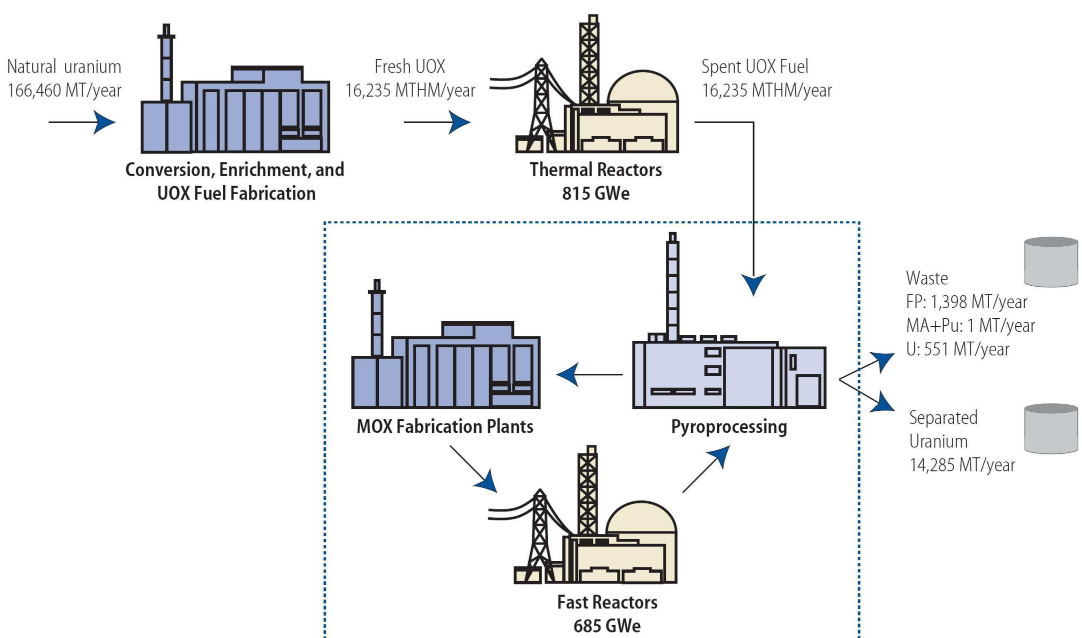

Figure 6: Balanced closed fuel cycle[6]

[6] Source: Deutch, Moniz, Golay et al., 2003. Figures are based on a 2050 three-fold expansion scenario.

4. SFR REACTORS IN THE LARGE-SCALE NUCLEAR ECONOMY

Safety of Nuclear Power Plant Operations

Safety of nuclear plants is the major impediment to a massive growth of nuclear electricity generation from a public acceptance point of view. Despite historical difficulties encountered by early prototypes of SFR, the proposed Generation IV SFR designs could enhance the safety of operations and enhance public acceptance, which is a determining factor both from a political and economic perspective.

<u>Safety records of Gen II and Gen III SFR reactors: a tale of two pities</u>

As they benefit from continuous development during the last 60 years, sodium-cooled fast reactors is the most technologically developed of generation IV. Their history is unfortunately, up to date, one of safety and economic failure (Public Citizen, 2007).

- <u>United States:</u> experimental SFR prototype Fermi 1 operated from 1963 to 1972, but suffered from serious problems, including a partial nuclear meltdown in October 1966 and a sodium explosion in 1970. It was hence closed in 1972. Another SFR reactor operated from 1982 to 1992 but was shut down in 2001.

- <u>United Kingdom:</u> a 250 MWe prototype SFR operated from 1974 to 1994 but suffered cracking of primary system components. In 1998, it was revealed that 170 kilograms of enriched uranium was missing, and the facility was closed.

- <u>France:</u> Phénix, a 233 MWe SFR, came online in 1973 and still operates. It encountered instability issues which raised safety concerns, and shut down for several years. It is due for permanent shut-down in 2009. Superphénix, a 1,200 MWe SFR, began operating in 1986, but was closed in 1997 as a result of continuing sodium leaks and cracks in the reactor vessel, and was permanently dismantled (the boilers were symbolically pierced).

- Japan: 280 MWe Monju reactor began operating in 1994, but was permanently shut down following a massive sodium leak and fire 1995. Another incident, in the fuel enrichment facility for a smaller experimental SFR, killed two workers and forced the local population indoors in September 1999.

- Russia: BN-350 (130 MWe) and its successor BN-600 (600 MWe) operated from 1972 to 1999, and starting from 1980. BN-350 experienced a major sodium-water reaction in a steam generator in 1973, and BN-600 has experienced several significant sodium leaks and the failure of the steam generator, but still operates.

- Germany: Construction of a 300 MWe SFR was completed in 1985, but widespread public opposition and political disagreement led to the project being decommissioned without ever having operated.

Safety prospects of Generation IV SFR reactors

As a conclusion, over twenty of these reactors have been built since 1951 in seven countries, all of which funded through government programs; only three reactors still operate (the French Phénix reactor, the Russian BN-600 reactor, and a small experimental reactor in Japan), mostly because of sky-rocketing costs and security issues linked to badly controlled risks stemming from the sodium design of the plants.

Generation IV designs address such concerns by incorporating passive safety mechanisms to decrease the likelihood of a meltdown in the event of a failure of primary safety mechanisms. For example, Gas Expansion Modules (GEM), that were first incorporated to the U.S. Advanced Liquid Metal Reactor design in the early 1990's, are hollow pressure tubes that are capped at the top and filled with Helium. Sodium coolant is allowed to fill the pressure tube when the coolant pumps are operating, but the Helium pressure would cause the Sodium level in the pins to drop and thus allow more neutrons to leak out of the core in the event of a coolant pump malfunction. The lower number of neutrons would cause less fission to occur and the power level would drop. Other passive safety measures of this kind have been envisioned for SFR and Generation IV reactors (Bleuel et al., 2007).

Moreover, even if the characteristic violence of reactions between sodium and water or air is frightening, it should be emphasized that the use of sodium as a coolant inherently presents significant safety advances compared to current LWR and BWR. First, sodium possesses exceptional heat transfer properties, which would not allow core meltdown to occur in such proportions as in Chernobyl. Second, liquid sodium is much less corrosive than water at the temperatures reached by at the reactor's core, which decreases the probability of coolant system leaks of failure of critical subsystems. Finally, since Sodium is liquid at 98ºC and gaseous at 882ºC, but is used in reactors operating around 550ºC, coolant tubes can be kept near atmospheric pressure, which is an element of safety and decreases the probability of industrial hazard (Lake et al., 2002, and Basdevant et al., 2002).

Economics

In a global world becoming more and more dominated by market forces, a major factor that will determine whether or not nuclear electricity will develop to its fullest extent is its cost. Comparison with other technologies are difficult today due to the uncertainty over upcoming regulations of carbon emissions. However, it is anticipated that under a proper regulatory and investment setting, nuclear energy may become cheaper than fossil fuels technologies. We investigate in this section the effects of a very large-scale development of nuclear power on its cost.

<u>Life-cycle cost analysis</u>

The true lifecycle cost of nuclear electricity is subject to much debate. Not only does it depend heavily on the reactor technology, fuel cycle type and generation capacity. Regulation, and its impact on the capital investment cost or the lead time of the plants, has a strong effect on the levelized cost of electricity, leading to very different pictures across countries. An element on which all energy economists agree is that there are two main determinants of the cost of nuclear electricity of the lifetime of a plant: the capital expenditure (which accounts for more than 50% of the cost of electricity), and the type of fuel cycle (once-through cycles are currently more economical).

The question we must consider is whether or not the large-scale development scenario we study will have an impact on the structure of such costs. Such a massive shift to nuclear power generation could have two major effects: putting pressure on the upstream uranium mining industry, and increasing the costs of construction. We examine in the next sections what responses the SFR technologies could bring to these challenges, and what issue they raise.

Upstream Development

A question arises so as to the exhaustibility of nuclear fuel. The Generation IV Forum 2002 report as well as the MIT 2003 study estimate that the speculative worldwide resources of Uranium are sufficient to ensure the development of a large base of nuclear power plants in the next fifty years, even in the case of continued use of the 'once-through' cycle.

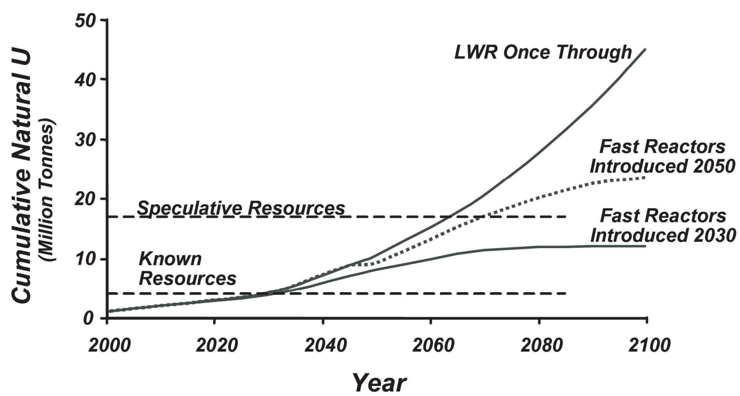

Figure 7: Long-run estimated world uranium resources utilization

The question of uranium scarcity may however arise in the long run. Closed cycles based on fast reactors are generally recognized as uneconomical under current conditions, because of the cost of reprocessing spent fuel, which is well higher than the price of new fresh fuel. If the supply for uranium became much more constrained than today, the rising market price of uranium would however shift the economics back in favor of closed cycle and reprocessing. SFR technology, which presents fewer advantages than conventional thermal reactors from an economic standpoint, would become an important energy policy tool, as they would enable a nuclear fuel breeding cycle (GIF, 2002).

Construction: Physical and Political Challenges

The second major impact of a fast and steady growth of the nuclear power generation installed basis would be to put a severe strain on the construction capabilities of the industry. The contracting firms would undoubtedly adapt to the spurring demand whatever the technology, and the physical challenges of such a fast growth would pass through to the cost of construction, which may rise with demand for nuclear plants. However, the whole legal and institutional infrastructure would also be strained be such a development. Because delays in capital intensive investments can prove very costly on a lifecycle basis, the determinant factor here is public acceptance. From a public perception point of view, the dismal history of sodium-cooled reactors may not help. Moreover, the need for fuel reprocessing facilities increases the capital expenditures for the integrated plant and may not ease the public debate. The economics of SFR technology in the case of a fast and steady growth of the industry may hence be less interesting than other simpler technologies such as the once through cycle.

Waste management and fuel recycling

The issue of waste management is twofold. A first aspect is the problem mid-term radioactive waste management and disposal. Spent fuel, as well as irradiated structure parts, must be dealt with in the short-run. Plants use interim repository: fuel rods for example are kept on-site in swimming pools for several years so that their temperature can decrease before long term storage. These issues must be faced today and fully incorporated in the plant design phase. The issue of decommissioning plants and managing irradiated core components or reclaiming the site is an integral part of this question, that is of immediate concern for the industry but receives little media echo.

On the contrary, the problem of long-run repository, which is widely perceived by the public as a major impediment to the future use of nuclear power, is not of immediate relevance yet, as governments worldwide have decided to take time and pursue research effort to make the best decisions on the question of long term repository. The issue of long-term radioactive waste is also much more dependant on the choice of fuel cycle. Very long run radioactive wastes (elements that have a decay half-life of the order of several thousand years) are mostly actinides nuclei and very stable radioactive fission products that appear in the fuel rods. The type of spent fuel, the amount of waste and the potential for reprocessing, all linked to the choice of fuel cycle, are very important factors for waste management.

The integrated SFR and pyroprocessing technology present a strong advantage for waste management when compared with conventional 'once-through' cycles and MOX/PUREX cycles: they allow for advanced reprocessing of the spent fuel and the burning of most actinides, which could lead to much shorter lived nuclear waste and much smaller volumes. Specifically, advanced waste management strategies include nuclides transmutation, decay-heat management and customized waste forms that permit more efficient and safer use of the repository capacity. Such a property may become key in the long run (beyond 2050) if the current repository space may become scarce in the face of the large scale growth of the industry. Estimates of waste volume from the MIT report adapted to our six-fold expansion growth scenario, listed in table 2, are eloquent.

Table 2: Radioactive waste volumes for large growth scenario[7]

<table>
<tr><th>Waste</th><th>'Once through'</th><th>Balanced closed cycle</th></tr>
<tr><td>Uranium</td><td>37 100 MT/y</td><td>730 MT/y</td></tr>
<tr><td>Plutonium</td><td>528 MT/y</td><td rowspan="2">~ 1 MT/y</td></tr>
<tr><td>Minor Actinides</td><td>48 MT/y</td></tr>
<tr><td>Fission Products</td><td>2045 MT/y</td><td>1860 MT/y</td></tr>
</table>

An even more interesting aspect of balanced closed cycles is that such technologies could not only help to decrease substantially the volume of long term waste,

[7] Figures are extrapolated for our expansion scenario (2000 GWe by 2050) from the 1500 GWe case in the appendix of the MIT survey. To account for technical progress, we assume that burn-up rate rises to 100 GWd/MTIHM in the 'once-through' case.

but also to lower drastically the time over which it should be monitored and stored. The GIF hopes that, using 'advanced fuel cycles using fast-spectrum reactors and extensive recycling, it may be possible to reduce the radiotoxicity of all wastes such that the isolation requirements can be reduced by several orders of magnitude (e.g., for a time as low as 1000 years) after discharge from the reactor' (GIF, 2002). This point is by far the most compelling technical argument in favor of a closed SFR cycle.

Security Concerns and Proliferation Risks

The problem of nuclear proliferation may be one of the most important geopolitical issues of our time, and its public perception is certainly a major impediment to the development of civil nuclear power generation technologies. This section investigates the nature of the issue, the geopolitical responses that have arisen and are currently discussed, and the role of technology in the debate on nuclear proliferation.

Plutonium: the link between civil and military technologies

Plutonium, under the form of its isotope ^{239}Pu, is a key fissile component in nuclear weapons. Only 15kg of weapon-grade Plutonium would be necessary to build a detonable weapon, using the least refined technologies such as the ones used over Hiroshima in 1945. The spectacular use of Plutonium in explosive devices requires very advanced engineering design and capabilities that may not be within the reach of most rogue states and terrorist organizations. However, small quantities of Plutonium may be used as threats through much less technology-intensive methods. Plutonium has a low chemical and radiological toxicity in a macro form, but proves deadly when inhaled in the form of dust or particulates, as this type of exposure allows alpha radiations to attack human tissues that would be protected by the skin. It could hence be used in radiological weapons, the so-called 'dirty bombs', conventional explosives that would spread Plutonium dust over inhabited areas, threatening the lives of the population (Blair, 2001).

Nuclear proliferation, a concept which encompasses all threats stemming from the potential diverting of fissile material from its normal uses for malevolent purposes, has hence been a concern for scientists as soon as the first bombs were developed. Such concerns are usually associated in the public opinion with the cold war and the successive non-proliferation treaties that capped the build-up of nuclear warhead by the two superpowers. The dismantlement of the former Soviet Union did indeed raise concerns that large amounts of Plutonium from weapon heads may be diverted. Indeed it is estimated that total disarmament would yield 150 to 200 tons of weapon-grade Plutonium. However, the main concern about proliferation today stems from the civilian uses of nuclear technologies, as any nation conducting nuclear power generation based on closed fuel cycles and reprocessing using the traditional aqueous-based PUREX techniques could potentially divert plutonium towards weapons building (UIC, 2006).

In practice, commercial plutonium from reactors would require very sophisticated engineering to design effective weapons based on it, but the possibility must be and is seriously considered by the international community. Concerns about proliferation have led to joint diplomatic efforts on both the civilian and military fronts of the nuclear industry to control and regulate the use of nuclear technologies worldwide.

Geopolitical options proliferation risks mitigation

The current geopolitical situation over the issue of non proliferation is defined by two milestones: the Non-Proliferation Treaty, and the International Atomic Energy Agency. The Treaty on the Nonproliferation of Nuclear Weapons, known as the Nuclear Nonproliferation Treaty or NPT, was signed on July 1st 1968, and is now recognized by 189 countries including the five Nuclear Weapons States (NWS) recognized by the NPT: the People's Republic of China, France, the Russian Federation, the UK, and the USA. The NPT obligates the NWS not to transfer nuclear weapons or their technology to any non-nuclear-weapon state. Reversely, Non-nuclear-weapon States Parties accept not to acquire or produce nuclear weapons, and to accept safeguards to detect diversions of nuclear materials from peaceful activities to the military activities. Under these agreements, all nuclear materials in civil facilities must be declared to the IAEA, whose inspectors exercise routine monitoring and inspections. The IAEA was set up by unanimous resolution of the United Nations in 1957 to help nations develop nuclear energy for peaceful purposes. The IAEA regularly inspects civil nuclear facilities to deter diversion of nuclear material by increasing the risk of early detection. The main concern of the IAEA is that uranium not be enriched beyond what is necessary for commercial civil plants, and that plutonium which is produced by nuclear reactors not be refined into a form that would be suitable for bomb production (Schneider, 1994).

To address proliferation concerns, the U.S. Government has developed the 'spent fuel' standard that requires that Plutonium be never more easily usable for weaponizing that it would be when incorporated in used nuclear fuel. With the Global Nuclear Energy Partnership Strategic Plain (GNEP) it unveiled in January 2007, the U.S. Government, now promotes a 'nuclear fuel-cycle island' policy, according to which the five permanent members of the U.N. Security Council would control and centralize the facilities for nuclear fuel processing, and centralize fuel commercialization and reprocessing, with global flows of Plutonium occurring only at the 'spent fuel' grade (U.S. Dept of Energy, 2007). The major obstacle in terms of acceptability is the concerns for national security that other countries may nourish. The Non-Proliferation Treaty does not require ratifying countries to abandon civilian nuclear technologies, and implicitly authorizes them to develop their own facilities for fuel processing and recycling (Deutch et al., 2004). Abandoning such prerogatives entails the loss of one country's energy security in the hypothesis of a conflict with the five NWS. Such impediments are however specific to countries that have a hostile stance toward the international community on the geopolitical scene: it is likely that most of the countries would actually benefit from this loss of national sovereignty, as its direct corollary is the transfer of ownership over long term wastes to the NWS.

Whether or not this scheme would render proliferation more difficult as a whole is hence not obvious, especially since military and civilian technologies are very different, and since creating a functional bomb involves several technical hurdles that may be more challenging than the procurement Plutonium itself. As a conclusion, policy options are available for the international community to enhance the effectiveness of the control set by the NPT and IAEA on nuclear proliferation, but are conditional to technologies that would allow NWS to control the flows of spent fuel through reprocessing and waste disposal. Next section turns to the solution brought by SFR design under such context.

Technological options for proliferation risks control

Two main technological options have arisen: modified aqueous reprocessing systems based on evolutions of PUREX methods, and the pyroprocessing technology. Modified aqueous reprocessing technologies are proposed with added extra reagents which force minor actinide "impurities" to commingle with the Plutonium. Such impurities would not impact the performances of fast spectrum reactors but make turning the Plutonium into weapons extraordinarily difficult. Such systems as the TRUEX (Trans Uranic Extraction) and SANEX (Selective Actinide Extraction) are meant to address this issue (GIF, 2002).

The main advantage of SFR design lies in the use of integrated systems such as the former IFR on-site pyroprocessing system, which would reprocess metallic fuel directly on-site at the reactor. As we have seen in section 3, such systems would commingle all the minor actinides with both uranium and plutonium, so that the plutonium would stay under the form of ‘spent fuel grade’ fissile material. Moreover, such integrated system would be compact and self-contained, so that contrary to PUREX-based closed cycle, no plutonium-containing material would ever need to be transported away from the site (Stanford, 2005). Finally, a very interesting characteristic of a balanced closed cycle based on pyroprocessing and fast reactors is that it would be capable of burning the plutonium reserves stemming from potential disarmament, once the weapon-grade reserves would have been treated to reach a useable isotopic composition (UIC, 2006).

This kind of proactive proliferation control is the best solution technology can bring to international nuclear policy, and, as knowledge and engineering capabilities could be gradually acquired by threatening entities, it will become necessary to protect fissile material sources with schemes of that order. The ability to consume potentially proliferant products in the SFR reactors and the increased security they would bring when coupled with integrated pyroprocessing facilities that require no plutonium transportation is the most compelling geopolitical argument in favor of SFR.

5. CONCLUSION

We have shown in this paper that a transition to a "super-sized" nuclear power economy would be a rational move in the context of the stabilization of carbon dioxide atmospheric concentration at 550ppm, but could be undermined by significant challenges. We then evaluated the different contribution the sodium-cooled fast neutron reactor (SFR) and the full actinide recycle balanced closed cycle based on this design could make to emerging solutions to such major issues as cost, safety, waste management and proliferation.

The main conclusion of this paper is that though its economic disadvantage will hamper its use in the middle-run, SFR design presents very strong advantages in terms of waste management and proliferation control. In particular, the integrated fast reactor technology, based on a SFR design integrated with an on-site pyroprocessing plant could render these two issues much more manageable from a policy perspective.

The most interesting aspect of balanced closed cycles in the context of a large-scale nuclear economy is that such technologies could not only help to substantially decrease the volume of long term waste, but also 'the radiotoxicity of all wastes such that the isolation requirements can be reduced by several orders of magnitude (e.g., for a time as low as 1000 years) after discharge from the reactor' (GIF, 2002).

From a policy perspective, its ability to consume potentially proliferant products, and its natural integration with pyroprocessing facilities that would eliminate plutonium transportation naturally design SFR as an important future energetic option.

It remains clear that, in the short run, economics will prevail as the main concern for a renascent industry. Because of the dramatic improvements in waste disposal and proliferation control it could enable, the integrated SFR design with on-site pyroprocessing could become the future reference technology for Generation IV nuclear power.

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