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Viewpoint

New perspectives on nuclear power—Generation IV nuclear energy systems to strengthen nuclear non-proliferation and support nuclear disarmament

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HIGHLIGHTS

- Generation IV systems are developed for long-term sustainable electricity production.
- New perspectives are capabilities to manage nuclear waste from nuclear power and aid disarmament.
- Simulations show how a country can launch fast reactors to control and reduce plutonium stocks.
- Safeguards-by-Design principles should be deployed, facilitating effective nuclear safeguards.

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ABSTRACT

Recently, nuclear power has received support from environmental and climate researchers emphasizing the need to address factors of global importance such as climate change, peace and welfare. Here, we add to previous discussions on meeting future climate goals while securing safe supplies of energy by discussing future nuclear energy systems in the perspective of strengthening nuclear non-proliferation and aiding in the process of reducing stockpiles of nuclear weapons materials.

New nuclear energy systems, currently under development within the Generation IV (Gen IV) framework, are being designed to offer passive safety and inherent means to mitigate consequences of nuclear accidents. Here, we describe how these systems may also be used to reduce or even eliminate stockpiles of civil and military plutonium—the former present in waste from today's reactors and the latter produced for weapons purposes. It is argued that large-scale implementation of Gen IV systems would impose needs for strong nuclear safeguards. The deployment of Safeguards-by-Design principles in the design and construction phases can avoid draining of IAEA resources by enabling more effective and cost-efficient nuclear safeguards, as compared to the current safeguards implementation, which was enforced decades after the first nuclear power plants started operation.

1. Perceived roles of nuclear power

Recently, leading climate researchers have stated in an open letter (Caldeira et al., 2013) that, “There is no credible path to climate stabilization that does not include… nuclear power.” Failing to address the issue of climate change because of the drawbacks of nuclear power is not an option. The US secretary of state, John Kerry, recently stated, “When I think about the array of global climate – of global threats – think about this: terrorism, epidemics, poverty, the proliferation of weapons of mass destruction – all challenges that know no borders – the reality is that climate change ranks right up there with every single one of them.”

In *World Energy Outlook 2013*, The International Energy Agency (IEA) (2013) predicts considerable growth in primary energy demand until 2035. With fossil fuels predicted to dominate energy supplies in 2035, there is great concern regarding climate change, especially in light of The International Panel on Climate Change (IPCC) (2013) report, which describes unprecedented atmospheric concentrations of greenhouse gases, increased temperatures, melting glaciers and elevated sea levels, and in which the IEA acknowledges severe threats to the ‘2° Carbon budget’. In the newly released summary report, The International Panel on Climate Change (IPCC)

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(2014) states that necessary reductions of CO_2-equivalent emissions are characterized by a tripling to nearly a quadrupling of the share of zero- and low- carbon energy supply such as nuclear energy. Decarbonizing is a key component to reaching these reduced emission levels, and in the IPCC models, the share of low-carbon electricity supply increases from the current share of approximately 30% to more than 80% by 2050. Specifically, IPCC notes that nuclear power could make an increasing contribution to the low-carbon energy supply, but that risks associated with e.g. waste management, nuclear weapons proliferation and public acceptance exist.

The IEA expects the increased energy demand to be supplied by a combination of all primary energy sources; with fossil fuels and renewables dominating the energy supply, and nuclear power being an important secondary source of energy. However, it has also been suggested that nuclear power should take on a more dominant role. The issue of nuclear power to counteract global warming has been raised previously (Nature, 2004), with Gen IV nuclear energy systems being proposed to provide sustainability for large-scale production of nuclear energy (Nature, 2012).

Nuclear power opponents often raise concerns regarding waste issues and the risk for release of radioactive material associated with accidents, while proponents claim the benefits are larger than the drawbacks. Furthermore, the connection between nuclear power and nuclear weapons is often debated, and non-proliferation issues are raised (Nature, 2004). An expansion of nuclear power and introduction of Gen IV systems to counteract global warming will add to such concerns; especially since the implementation of Gen IV systems requires large reprocessing and recycling capabilities, which are sensitive technologies in terms of non-proliferation. On the positive side, Gen IV systems may also be a tool for disarmament, offering efficient reduction of the current stockpile of weapon materials through its capability to convert high-enriched uranium as well as plutonium to less sensitive material. This aspect also makes Gen IV systems a possible tool for managing the plutonium inventory contained in civilian spent nuclear fuel.

There is currently a consensus that nuclear power will continue to provide the world with energy, but the role and time span are highly political questions. In this article, we aim to illuminate the non-proliferation aspects of Gen IV systems, including their capabilities for managing civilian and military stockpiles of fissile materials and the needs and opportunities for nuclear safeguards measures in these systems.

2. Gen IV nuclear energy systems and the civilian nuclear stockpile

The majority of the world's current fleet of commercial nuclear reactors utilizes a moderating material in the reactor core to reduce the energy of neutrons created in fission, which enhances the ability to maintain a fission chain reaction with relatively low fractions of fissile isotopes in the core (such as uranium-235 or plutonium). In the most common group of reactors of today – light-water reactors (LWRs) – water acts as both the moderator and the coolant, slowing down the neutrons while also transporting heat from the core to produce electricity. The LWRs have benefits in terms of safety and economy, but safety concerns have also been raised after e.g. the TMI (1979) and Fukushima (2011) accidents. Other drawbacks of LWRs are their questionable sustainability because of low utilization of natural resources (the fissile isotope ^{235}U only constitutes 0.7% of natural uranium) and the build-up of plutonium, being a man-made potential nuclear weapons material. Some countries recycle their fuel to make better use of the resources, but technical issues limit the number of cycles and operation of recycled fuel in LWRs still leads to an increase in total plutonium content.

To meet many of the concerns with current nuclear systems, intensive research is carried out all over the world, developing a new generation of nuclear systems, called Gen IV (Nature, 2012). An integral part of many Gen IV systems is metal-cooled reactors operating with a fast neutron spectrum, or in short, “fast reactors” (FRs), in which no moderator is present to slow down the neutrons. These reactor concepts address central issues for nuclear power, such as safety, sustainability, economy and non-proliferation. The drawbacks include a need for a higher fraction of fissile material in the core, whereas the benefits include a possibility to fission a wide range of heavy elements. Notable is that FRs can be configured to either create (breed) or consume (burn) heavy elements (transuranium elements), especially plutonium (U.S. DOE Nuclear Energy Research Advisory Committee and the Generation IV, 2002), which is of particular interest for non-proliferation.

Central to a Gen IV system with FRs is multiple recycling, giving a different fuel cycle than that for LWRs, as illustrated in Fig. 1, which enables the management of plutonium and other transuranium elements. However, introduction of multiple recycling also has strong implications on the safeguards system, as further discussed in Section 4.

When deploying the LWR fuel cycle, long-lived waste in the form of spent nuclear fuel, comprising fission products, plutonium and other heavy elements, will accumulate and constitute a proliferation hazard since it contains weapons-usable fissile material. From a states' perspective of proliferation risk to non-state actors, this material offers some degree of self-protection due to its intense radioactivity. However, over time, the self-protecting properties diminish as short-lived isotopes decay, leading to an increase in the proliferation risk with time. The introduction of FRs into the nuclear power supply has the possibility to change this picture by controlling the civil stockpile of plutonium instead of simply adding to it. This is illustrated using an example based on a country with 10 LWRs of 1 GW each, built during 1970–1990. It is assumed that the country wishes to maintain its electricity production capability, while transitioning the LWR system to a long-term sustainable Gen IV nuclear energy system being operational from 2050 and onwards, and simulations of this scenario have been performed. Five operational phases are illustrated in Fig. 2, showing the total plutonium stockpile (blue line) as a function of time.

The *first phase* covers the time period from 1970 to 2050, when only LWRs are in operation, adding to the plutonium stockpile (considered as waste in this nuclear fuel cycle). During this time, we assume that the oldest LWRs are replaced with new LWRs after 50 years life time (around 2020), and that the youngest LWRs of the first generation have a 60 year lifetime, operating until around 2050.

The *second phase* starts in 2050 when the first FR is brought into operation, replacing the last LWRs from the first generation. These first FRs are operated in burner mode and thus consume plutonium. During this phase, the plutonium stockpile increases only marginally as the consumption in the fast reactors almost matches the production in the LWRs. Note that a fraction of the total plutonium inventory resides in FR cores rather than in storage (red line).

The *third phase* starts around 2100 when the last remaining LWRs are replaced with FRs operating in burner mode. The plutonium stockpile now quickly decreases as no LWRs produce plutonium anymore.

The *fourth phase* starts around 2200 when the plutonium stockpile in storage starts to run out. At this stage, the FRs are converted to breeders in order to be self-sustained with fissile material. The only added fuel is either natural uranium or other uranium types already in the system in terms of LWR spent fuel or depleted uranium. One may also consider fuelling the reactors with thorium in this phase. This self-sustaining phase of operation can in principle be extended indefinitely.

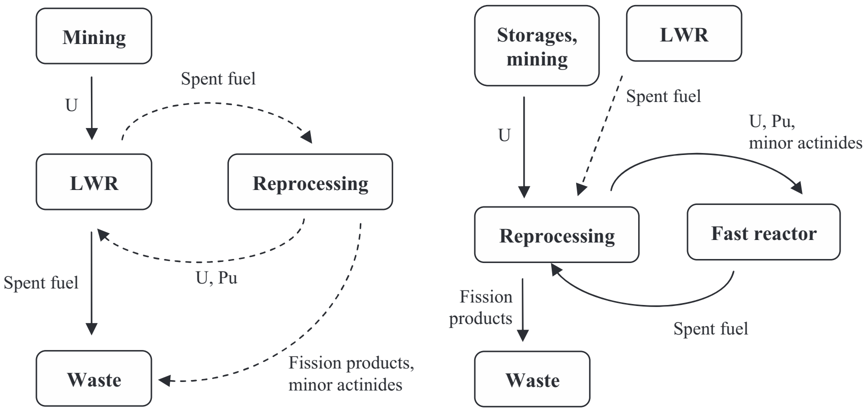

Fig. 1. The nuclear fuel cycle for the current nuclear energy systems, with once-through operation or limited recycling (left), compared to a Gen IV system with fast reactors and multiple recycling (right).

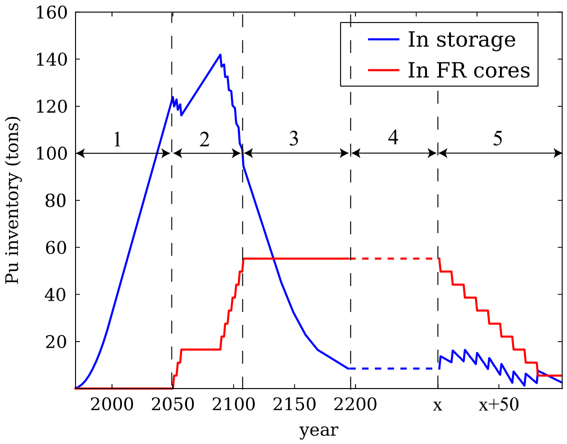

Fig. 2. Plutonium inventory in the simulated example, as a function of time and operation in LWRs and FRs. The blue line shows the plutonium in storage, while the red line shows the plutonium loaded into FR cores. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The *fifth phase* represents the phase-out of nuclear power where the FRs are gradually shut down, and the plutonium from all but the last reactor is burned in the remaining core. This phase takes around 50–100 years to complete, and the only remaining plutonium is that from the last FR core which may be disposed of in a dedicated subcritical transmutation reactor, leaving almost no plutonium for final storage.

In the example, the implementation of FRs operating in burner mode adds to the number of possibilities for the handling of spent nuclear fuel, where the current options are either storage in a repository or limited reprocessing and associated storage of waste products. Although placing the spent fuel in a dedicated repository may be a safe and reliable alternative, nuclear power opponents are critical and point out that proliferation risks associated with such storage facilities will increase, effectively turning them into “plutonium mines,” as the radiation barrier from the fission products decays with time (Lyman and Feiveson, 1998). The only way to ensure that the material will not be available for weapons production is by transmuting it, which is precisely what Gen IV reactor systems offer to do.

3. Military nuclear weapons materials and disarmament challenges

Nuclear weapons are possessed by a limited number of countries in the world. There has been a decline in the global inventory due to the commitment by the U.S. and Russia to reduce their nuclear arsenals under a bilateral treaty (The New START Treaty, 2010). However, all of the five acknowledged nuclear weapons states (NWS) – the U.S., Russia, China, the UK and France – have either (i) major modernization programs under way for their nuclear weapons systems, (ii) are deploying new weapon systems, or (iii) have announced to do so in the future. No immediate changes in nuclear policy are expected for any of the five recognized NWS, or for India, Israel, Pakistan and North Korea, who are also considered to possess nuclear weapons (Stockholm International Peace Research Institute, 2013).

But can we in any way influence how disarmament policies are made? Nuclear physicists may offer little help in the political process, but we may assist by offering new ways to dispose of weapons material and boost confidence in the disarmament process itself, thereby making it less likely for states to embark on future armament endeavors.

With regard to fissile material, the five recognized NWS have produced both high-enriched uranium (HEU) and plutonium. India, Israel and North Korea have mainly produced plutonium and Pakistan mainly HEU (Stockholm International Peace Research Institute, 2013). Hence, in order to safely dispose of both weapons materials, we need solutions for HEU and plutonium. One successful example of disposing of HEU is the “Megatons to Megawatts” project, signed in 1993 and ended in November 2013, by the Russian Federation and the United States (The Megatons to Megawatts program). The purpose was to downblend 500 mt of HEU from Russian nuclear warheads and use it as fuel in commercial nuclear reactors in the U.S. This resulted in 10% of electricity in the U.S. being generated by Russian warheads, and a very successful demonstration of how political and technical tools can be combined to put HEU weapons material into safe custody.

Regarding the disposal of plutonium, there is a bilateral treaty between the U.S. and Russia in which each country has committed to disposing of 34 metric tons of weapons-grade plutonium. The treaty, the *Plutonium Management and Disposition Agreement*, was announced in the year 2000 and entered into force in 2011. Russia will convert the Pu into fuel and, starting in 2018, irradiate it in FRs, producing electricity. In the U.S., the surplus Pu was originally planned to fuel civilian light water reactors (2000 Plutonium Management and Disposition, 2010); however, after a review of the plutonium disposition program, alternative technologies are currently being evaluated (Fiscal Year, 2015).

One may note that irradiation of plutonium in LWRs reduces its quality from a weapons perspective, but it does not decrease the total amount in the fuel. Irradiation in Gen IV-type fast reactors does however offer to convert the plutonium to other elements. This is in line with nonproliferation policy objectives, identified by the US Office of Nonproliferation and International Security

(2008), showing that Gen IV nuclear energy systems are important for international nuclear security efforts.

4. Managing proliferation risks in Gen IV nuclear energy systems

Proliferation risk is a notation used to describe the risk of spreading nuclear material, nuclear technology (or nuclear weapons themselves) for nuclear weapons purposes. *Nuclear safeguards* denotes active measures taken to control and mitigate such risks by limiting the access to sensitive materials/technologies, keeping accurate and transparent accounting of materials, and performing nuclear inspections, etc.

When nuclear safeguards was introduced, it had to be adapted to the present conditions of the time. With Gen IV nuclear energy systems, we can do it the other way around, using appropriately designed nuclear safeguards solutions as preconditions for implementation. As described in Section 3, we also propose strengthening nuclear non-proliferation by reducing stockpiles of fissile material in fast reactors.

The implementation of Gen IV systems with FRs and closed fuel cycles, involves an extensive increase in recycling of nuclear fuel, identified as one of the most sensitive parts of the nuclear fuel cycle that requires significant nuclear safeguards resources, as e.g. currently manifested at the Rokkasho facility in Japan. Increased transport and handling of nuclear material, which is also sensitive, is as well expected. For these reasons, nuclear safeguards must be an essential part in the early design phase of new nuclear energy systems not to risk draining of IAEA safeguards resources.

FRs additionally offer a major advantage, which is not often mentioned: breeder reactors producing their own plutonium during operation may eliminate the need for enriched-uranium based fuels and hence the need for uranium enrichment facilities. In 2004, the IAEA Director General El-Baradei already wanted to limit the use of this sensitive technology, acknowledging that it might be used to produce HEU for non-technically advanced nuclear weapons, which could be attractive for low-tech states or terrorist groups (ElBaradei, 2004). HEU may be produced using the same facilities and principles as those used to produce civilian nuclear fuel without requiring any facility modifications (Office of Nonproliferation and International Security, 2008; Implementation of the NPT, 2013), a concern which is currently relevant in Iran. The elimination of enrichment activities would thus constitute a big step forward for nuclear safeguards.

Still, conscious actions must be taken to mitigate proliferation risks in the implementation of Gen IV nuclear energy systems. We have selected a number of areas, where nuclear safeguards has a key role to play:

- *Technical research on separation techniques* that render the separated products and procedures less interesting for weapons production.
- *Design of the Gen IV reactor*, considering their ability to consume Pu from commercial and military sources, implying the need for a strong nuclear safeguards system. Another safeguards issue concerning the design of the reactor cores is to reduce the possibilities for modification from civilian to military use (Office of Nonproliferation and International Security, 2008).
- *Issues related to increased handling and transport* of sensitive material must be solved. Some argue that the anticipated spread of nuclear technology calls for strengthened export controls (Doyle, 2008) and adequate assistance on the implementation of legal and regulatory infrastructure to new states (U.N. Security Council Resolution, 2004). Others discuss the controversial restriction of construction and operation of fuel handling facilities to a small number of states, which would limit the distribution of sensitive technology (Yudin, 2011) but at the same time call for more transports.

There is clearly a need to take nuclear safeguards of the full nuclear fuel cycle system into account and we should work towards the goal to solely promote frameworks, processes and facilities designed with an inherent high resistance to proliferation. By putting *Safeguards-by-Design* (The International Atomic Energy Agency (IAEA), 2009) into practice, i.e. incorporating safeguards considerations in the initial stages of designing new nuclear facilities and nuclear energy systems, the efficiency of safeguards implementation can be increased at a reduced cost and with an increased acceptance among the operators.

In order for Generation IV nuclear energy systems to be part of the solution on how to electrify the world while making it safer, we must ensure that nuclear safeguards is prioritized by reminding national and international policymakers and research funding agencies of what is at stake. It should lie in the interest of all states to push these issues forward—they are not only an IAEA responsibility.

5. Looking ahead

There are many reasons to believe that nuclear power will play an important role in future society, together with a mix of other energy sources. Nuclear power offers to deliver large, reliable quantities of electricity associated with low greenhouse-gas emissions, which proves more important by the day. Accordingly, current large international efforts should be continued to develop Gen IV nuclear energy systems, with the aim to provide clean, long-term sustainable, safe, economic and efficient electricity production.

Among the new perspectives that Gen IV systems bring are their capability to contribute to the world's security in additional, valuable ways as compared to today's nuclear power, by offering means to control and reduce the amount of nuclear waste generated, and to aid the nuclear disarmament process by turning warheads into peaceful electricity. In this paper, we have shown an example of how a country with considerable use of nuclear power can launch fast reactors to control and reduce the amounts of plutonium generated, and thereby mitigating the proliferation hazard. The operation of these Gen IV systems can be extended until other climate-friendly, reliable energy systems are implemented, and accelerator-driven burners enable a complete destruction of the country's plutonium inventory.

There are many challenges associated with Gen IV nuclear energy systems; technical as well as political and social. In this context, nuclear safeguards and non-proliferation of nuclear weapons is highly important, especially as nuclear safeguards will become more challenging with an envisaged expansion of nuclear technology. Accordingly, Safeguards-by-Design principles should be implemented, allowing for more reliable, efficient and economic international safeguarding of sensitive materials.

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