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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.