Potential Environmental Risks of the Next Generation of Nuclear Power Plants

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October 2006

Introduction

There are many different designs and sizes of reactors that have been developed during the 50 years of commercial operation of the civil nuclear industry. These reactors can be classified into different age and design related groups: Generation I, II, II, and IV. The oldest reactors, Generation I, are expanded versions of the original plutonium production reactors from the 1950s. Currently, the only reactors of this class in operation are the remaining RMBKs[2] (in Lithuania and Russia) and the UK's Magnox stations. The majority (95%) of reactors in operation today are the Generation II and include the Pressurized Water Reactors (PWRs), Boiling Water Reactors (BWRs), Gas Cooled Reactors, Pressurized Heavy Water Reactors and Fast Breeder Reactors. The Generation III reactors are now being further developed and deployed in a number of countries, while Generation IV designs are current only in the design stage.

There are many ongoing and in some cases increasing design and operational problems for the Generation I and II reactors. One of the most important aspects for consideration is the safety and economic impact of the aging process. The physical conditions of reactor operation, as high temperatures, pressures, stresses and neutron bombardment can have an impact on the ability of materials to function as required. This can for example lead to cracking and breaking of pipework or the corrosion of components. The current trend of attempting to increase the operation lives of reactors and also a tendency to increase the output from stations will test the operator's and regulator's ability to control this aging process. However, this briefing will not focus on the aging issue, however, further information is available in the Greenpeace report 'Nuclear Reactor Hazards'[3].

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[1] This briefing note is based on the report, Nuclear Reactor Hazards; Ongoing Dangers of Operating Nuclear Technology in the 21st Century. Report Prepared for Greenpeace International, by Helmut Hirsch, Oda Becker, Mycle Schneider and Antony Froggatt, April 2005. Additional informal, in the form of updated material was provided by the author.
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[2] Some bodies classify these reactors as Generation II

[3] http://www.greenpeace.org/international/press/reports/nuclearreactorhazards

Generation III

The Generation III are the so-called "Advanced Reactors", four of which are already in operation in Japan, and more are under construction or planned. About 20 different designs for Generation III reactors are reported to be under development. Most of them are "evolutionary" designs that have been developed from Generation II reactor types with some modifications, but without introducing drastic changes.

The European Pressurized Water Reactor (EPR)

The EPR is a pressurized water reactor that has developed from the French N4 and the German KONVOI reactor line, the latest Generation II reactors which were taken into operation in those countries.

The goals stated for EPR development are to improve the safety level of the reactor (in particular, reduce the probability of a severe accident by a factor of ten), achieve mitigation of severe accidents by restricting their consequences to the plant itself, and to reduce costs.

However, this has not been achieved in all areas and compared to its predecessors, the EPR displays several modifications which constitute a reduction of safety margins including:

- The volume of the reactor building has been reduced by simplifying the layout of the emergency core cooling system, and by using the results of new calculations which predict less hydrogen development during an accident.
- The thermal output of the plant was increased by 15 % relative to the N4 by increasing core outlet temperature, letting the main coolant pumps run at higher capacity and modifying the steam generators.
- The EPR actually has fewer redundant trains in safety systems than the KONVOI plant; for example, its emergency core cooling system has only 4 accumulators (pressure tanks) whereas the KONVOI plants' has 8 such tanks.

The protection of the plant against airplane crash is equivalent to that of the German KONVOI plants and hence does not reach a new, higher safety level.

Problems are already plaguing the construction at the world's only EPR project, at Olkiluoto in Finland. These problems are already predicted, only 18 months after the groundbreaking ceremony, to have caused a year delay in the expected start up of the unit. In July 2006, the Finish regulator (STUK)[4] produced a critical report on these construction problems, which include:

- 'The time and amount of work needed for the detailed design of the unit was clearly underestimated when the overall schedule was agreed on'.

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[4] Management Of Safety Requirements In Subcontracting During The Olkiluoto 3 Nuclear Power Plant Construction Phase Investigation Report 1/06 1 Nuclear Reactor Regulation Translation 1.9.2006. STUK

- Problems have been found in the base slab for the reactor base, namely that it was found to be porous. Areva have tried to blame this on the subcontractors, but STUK have said that the problems in the base slab show that quality standards were not made clear to the subcontractor. The report said that there was also no overall manager for the base slab work.
- Regarding the lining of the slab 'requirements concerning quality and construction supervision have been surprising news to the manufacture'.
- Furthermore, according to the report Areva NP 'was not sufficiently familiar with the Finnish practices at the beginning of the project'.

This level of criticism is remarkable in particular for two reasons:-

- The importance that the nuclear industry is placing upon the project: This is the only Generation III project underway in Europe and is being held up as an example of a renewed support for nuclear. Consequently, it would have been assumed that every care would have been taken to ensure the project ran to time and budget, as this was one of the main criticisms of historical nuclear programmes.
- Secondly, that construction has only just started. The laying of the base slab is the foundation of the whole project and so one of the first major milestones in any project. Problems at this stage do not give confidence in the ability of the project to remain on time and budget.

These problems are having an economic impact upon the project. As the project is a 'turn-key project' (one which TVO paid a fixed price for completion) the cost over-runs are being borne by the constructor (Areva). The full economic impact is not yet clear, although some reports suggest that it might cost the company upto €2 billion. However, what is already clear is that Areva's first half of 2006 profits were down €300 million as a result of the Olkiluto project.

Economic problems with Generation III project have also been experienced in the other design.
In Japan, General Electric estimated that the new 1300 MW Advanced Boiling Water Reactor could be constructed at a cost of $1528 per kilowatt. However, when the units were built for Tokyo Electric Power Company the construction costs were $3236/kW for the first unit and $2800//kW[5].

AP1000

The AP1000 gained a design certification in the US in late 2005. The reactor is based on the previously certified but never constructed the AP600. It is said that the AP 600 design has some safety improvement over current reactors but these gains are largely offset by steps taken to reduce capital costs. The AP 600 design was thought not to be economic and so it was transformed into an AP1000, by increasing the power output by 80% with only a 20% increase in construction costs. However, as a result, the AP-1000 has a ratio of containment volume to

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[5] Nuclear Power: Prospects for Commercial Reactors: CRS Report for Congress. July 27th, 2001.

thermal power below that of most of current PWRs, increasing the risk of containment overpressure and failure in a severe accident[6].

Generation IV

The U.S. Department of Energy (DoE) launched the “Generation IV International Forum” (GIF) in 2000. Today, ten member countries are participating in this initiative (Argentina, Brazil, Canada, France, Japan, Republic of Korea, South Africa, Switzerland, U.K., USA), as well as EURATOM. Their goal is to develop innovative nuclear systems (reactors and fuel cycles) likely to reach technical maturity by about 2030, but many suggest that this timetable is optimistic.

Concepts Selected for Generation IV

There are six concepts for the development of Gen IV that have been selected for further development in the framework of GIF. They are briefly discussed in the following.

GFR – Gas-Cooled Fast Reactor System:
The GFR system is a helium-cooled reactor with fast-neutron spectrum and closed fuel cycle. It uses helium a coolant, due to extreme temperatures (850 C outlet; compared to 300 for PWR and 500 for FBR). Consequently, ‘High temperatures and extreme radiation conditions are difficult challenges for fuels and materials’. It will use plutonium and burn actinides.

LFR – Lead-Cooled Fast Reactor System:
LFR systems are reactors cooled by liquid metal (lead or lead/bismuth) with a fast-neutron spectrum and closed fuel cycle system. A full actinide recycle fuel cycle with central or regional facilities is envisaged. A wide range of unit sizes is planned, from ´batteries` of 50–150 MWe, and modular units of 300-400 MWe to large single plants of 1200 MWe. The LFR battery option is a small factory-built turnkey plant with very long core life (10 to 30 years). It is designed for small grids, and for developing countries that may not wish to deploy a fuel cycle infrastructure. Among the LFR concepts, this battery option is regarded as the best, concerning fulfilment of Generation IV goals. However, it also has the largest research needs and longest development time.

MSR – Molten Salt Reactor System:
The MSR system is based on a thermal neutron spectrum and a closed fuel cycle. The uranium fuel is dissolved in the sodium fluoride salt coolant that circulates through graphite core channels. The heat, directly generated in the molten salt, is transferred to a secondary coolant system, and then through a tertiary heat exchanger to the power conversion system. It is primarily envisioned for electricity production and waste burn-down. The reference plant has a power level of 1,000 MWe. Coolant temperature is 700°C at very low pressure.
Of all six reactor systems, MSR requires the highest costs for development (1000 million US$). All in all, the interest of the GIF member states in the MSR is rather low. The high development costs and the required time frame could eliminate the MSR system from Generation IV altogether

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[6] Statement Submitted by David Lochbaum to the House Government Reform Subcommittee on Energy and Resources: “The Next Generation of Nuclear Power” . Union of Concerned Scientists 2005

SCWR – Supercritical-Water-Cooled Reactor System:
The SCWRs are high-temperature, high-pressure water-cooled reactors that operate above the thermodynamic critical point of water (i.e. at pressures and temperatures at which there is no difference between liquid and vapour phase). The reference plant has a 1700 MWe power level, an operating pressure of 25 MPa, and a reactor outlet temperature of 550°C. Fuel is uranium oxide. Passive safety features similar to those of the simplified boiling water reactor (SBWR) are incorporated.

SFR – Sodium-Cooled Fast Reactor System:
The SFR system consists of a fast-neutron reactor and a closed fuel cycle system. There are two major options: One is a medium size (150 to 500 MWe) reactor with metal alloy fuel, supported by a fuel cycle based on pyrometallurgical reprocessing in collocated facilities. The second is a medium to large (500 to 1,500 MWe) reactor with MOX fuel, supported by a fuel cycle based upon advanced aqueous reprocessing at a centralized location serving a number of reactors. The primary coolant system can either be arranged in a pool layout or in a compact loop layout. The outlet temperature is approximately 550 °C. According to GIF, the SFR has the broadest development base of all the Generation IV concepts. The existing know-how, however, is based mainly on old reactors, which have already been shutdown for various reasons (safety, economics, and resistance from the population).

VHTR – Very-High-Temperature Reactor System:
The VHTR system uses a thermal neutron spectrum and a once-through uranium fuel cycle. The reference reactor concept has a 600-MWth graphite-moderated helium-cooled core based on either the prismatic block fuel of the GT-MHR or the pebble bed of the PBMR. It is regarded as the most promising and efficient system for hydrogen production, either using the thermo-chemical iodine-sulphur process, or from heat, water, and natural gas by applying the steam reformer technology at core outlet temperatures greater than about 1000°C. The VHTR is also intended to generate electricity with high efficiency (over 50% at 1000°C). It is planned to drive the helium gas turbine system directly with the primary coolant loop. However, a high performance helium gas turbine has to be still developed. The VHTR requires significant advances in fuel performance and high-temperature materials.

Evaluation of Generation IV

Plutonium

According to GIF, a closed fuel cycle is celebrated as a major advantage of Generation IV concepts. This is because there is recognition that *'in the longer term, beyond 50 years, uranium resources availability also becomes a limiting fact, unless breakthroughs occur in mining or extraction technologies*[7]*'*. This is demonstrated by the graphic below, which suggests that under

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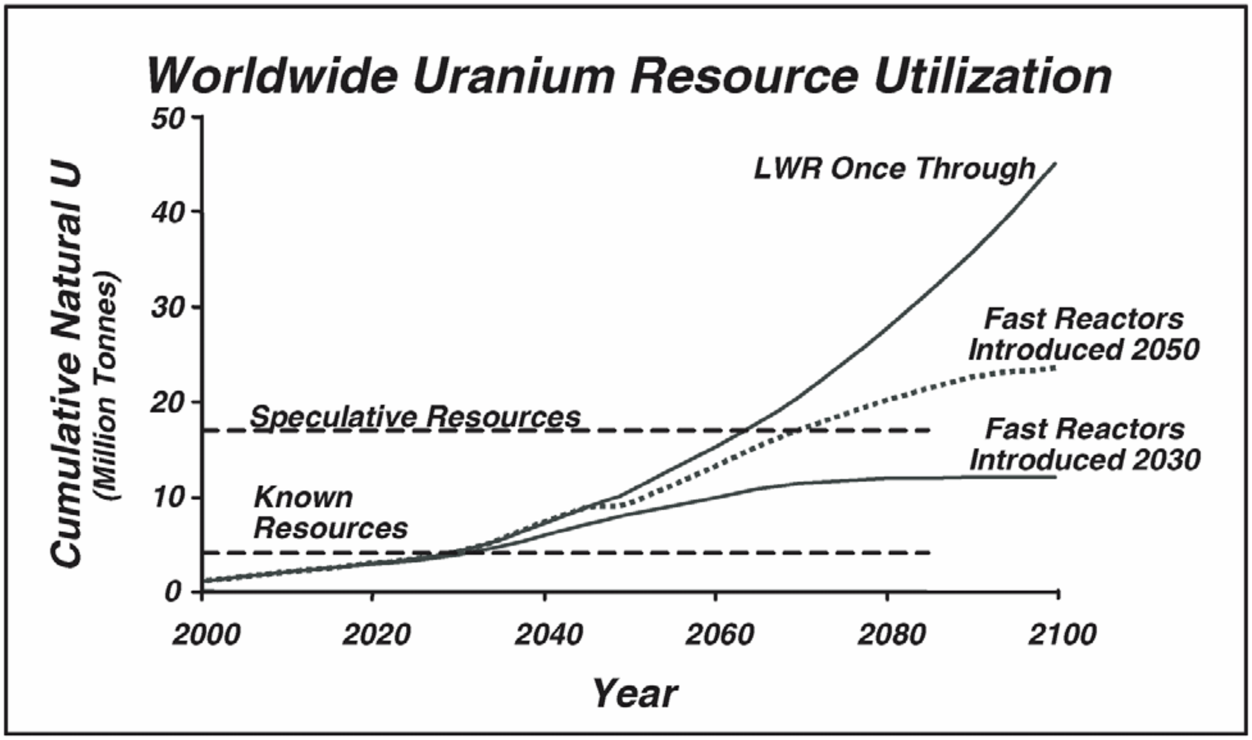
[7] A technology Roadmap for Generation IV Nuclear Energy Systems/NERAC Review Version, September 2002 page 13

current conditions the next Generation of fast breeders need to be being deployed in a couple of decades.



Source: A Technology Roadmap for Generation IV Nuclear Energy Systems (NERAC 2002)

This requires the reprocessing of spent fuel to extract the plutonium and then using plutonium as a fuel. This has significant proliferation implications, in particular if these types of reactors are widely deployed around the world. The reprocessing of plutonium has been widely criticised for its negative impact on the environment as well is its costs and security implications. The widespread introduction of the closed fuel cycle require a reversal of current anti-proliferation policy in a number of countries, including the United States, and a revision of current industry policy in most nuclear countries. A movement towards the deployment of Generation IV reactors utilising the closed fuel cycle would require large scale investment to construct reprocessing plants.

The costs of such fuel cycle concepts –the use of reprocessing - would be very high. According to “The Future of Nuclear” by the U.S. Massachusetts Institute of Technology[8], a convincing case has not yet been made that the long term waste management benefits of advanced closed fuel cycles involving reprocessing of spent fuel are not indeed outweighed by the short term risks and costs, including proliferation risks. Also, the MIT study found that the fuel cost with a closed cycle, including waste storage and disposal charges, to be about 4.5 times the cost of a once-

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[8] An Interdisciplinary MIT Study: John Deutch (Co-Chair), Ernest J. Moniz (Co-Chair), Stephen Ansolabehere, Michael Driscoll, Paul E. Gray, John P. Holdren, Paul L. Joskow, Richard K. Lester, and Neil E. Todreas; The Future Of Nuclear Power, January 2003

through cycle. Therefore it is not realistic to expect that there will ever be new reactor and fuel cycle technologies that simultaneously overcome the problems of cost, safe waste disposal and proliferation. As a result the study concludes that the once-through fuel cycle best meets the criteria of low costs and proliferations-resistance.

Furthermore, the Nuclear Control Institute (NCI) warned that transmutation of spent nuclear fuel is no guarantee against proliferation. The growing concerns about the safe and secure transportation of nuclear materials and the nuclear security of nuclear facilities from terrorist attacks is not adequately taken into account in any of the concepts.

If nuclear power is to play a major role in meeting global energy needs, then there will need to be a massive scaling up of the current programmes. Nuclear power currently supplies around 6% of commercial primary energy consumption and 16% of electricity consumed. The Intergovernmental Program on Climate Change (IPCC) put forward a scenario in which nuclear power plays a more central role in reducing CO2 emissions and increases to 3000 GW of installed capacity in 2075 (providing 50% of the world's electricity) and then to 6500 GW in 2100 (75% of electricity). Under this scenario it would reduce by one fourth the CO2 emission predicted by 2100. Even assuming an operating life of around 50 years (beyond the current design life-time of most operating reactors), it would require the construction of around 7000 reactors in the next century, or 70 reactors per year. Given that, at the peak of the global nuclear industry in the 1980s, the highest number of reactors connected to the grid in a year was 33, this scenario is extremely optimistic. If only uranium fuelled reactor were used, this would result in 600 tonnes of plutonium being produced annually. However, given the number of reactors necessary and the extent of the known uranium reserves it is expected that plutonium fuelled reactors would have to be in operation. If plutonium fuelled reactors were deployed around 4000 tonnes of plutonium per year[9]. To put this in context the combined global military stockpiles of separated plutonium is around 150 tonnes[10]. Both of these scenarios have significant proliferation risks as reactors and the associated fuel cycle facilities would have to be deployed all over the world.

Nuclear regulators in the U.S. are not enthusiastic about the new reactor concepts. New nuclear power plants should be based on evolutionary, not revolutionary, technology, according to an NRC commissioner. The commissioner cautioned against *"too much innovation"* which would lead to new problems with untested designs, and urged the industry not to *"overpromise"* the capabilities of new reactor systems[11].

Technological Gaps

The Generation IV designs are currently, just that, paper designs. In order for even prototype versions to be built, technological breakthroughs in material development will have to be made. Below is a list of some of the barriers –technology gaps- currently facing the reactor developers:

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[9] Nuclear Power, Nuclear Proliferation and Global Warming, H.A. Feiverson, Forum on Physics and Society of the America Physical Society, January 2003

[10] Tracking Plutonium Inventories, Plutonium Watch Publication, David Albright and Kimberly Kramer, July 2005, revised August 2005, Institute for Science and International Security. http://www.isis-online.org/

[11] Platt's Nuclear News Flashes, March 08, 2005

GFR: The development of very-high temperature materials with superior resistance to fast-neutron is needed.

LFR: Fuel systems and materials with some gaps remaining for the 550 C options, and large gaps for the 750-800 C options.

Fuel cycle technology, including remote fabrication of metal alloy and TRU-N fuels need to be developed.

MSR: Has a number of technical viability issues that need to be resolved. The highest priority issues include molten salt chemistry, solubility of actinides and lanthanides in the fuel, compatibility of irradiated molten salt fuel with structural materials and graphite, and metal clustering in heat exchanges.

SCWR: Important technological gaps are in the areas of material and structures (including corrosion and stress cracking, strength, embrittlement and creep resistance), safety and plant design.

VHTR: Demonstrating the viability of the VHTR core requires meeting a number of significant technical challenges. Novel fuels and materials must be developed that: permit increasing the core outlet temperatures from 850 to 1000 and preferably higher; and permit the maximum fuel temperature reached following accidents to reach 1800 C

Furthermore, the problems of the Sodium Fast Breeder – which some believe should not be classified as a Gen IV project, as it has been deployed in some countries – highlight additional economics problems which these reactors will have to face, as it is stated that *‘a key performance issue for the SFR is cost reduction to competitive levels. The extent of the technology base [is known] yet none of the SFRs constructed to date have been economical to build or operate’.*

Safety Standards

A closer look at the technical concepts shows that many safety problems are still completely unresolved. Safety improvements in one respect sometimes create new safety problems. And even the Generation IV strategists themselves do not expect significant improvements regarding proliferation resistance.

But even real technical improvements that might be feasible in principle are only implemented if their costs are not too high. There is an enormous discrepancy between the catch-words used to describe Generation IV for the media, politicians and the public, and the actual basic driving force behind the initiative, which is economic competitiveness.

Timetable:

There are varying reports as to when the Generation IV reactors will be ready for deployment. However, the latest report by the US General Accounting office has concluded that the programme is unlikely to meet its 2021 deadline for deployment[12].

Nuclear Fusion

In 2005 an agreement was reached on the siting of the next generation of fusion research. While conventional nuclear technology uses fission, the splitting of atoms, nuclear fusion requires the merging of different atoms to create energy. For decades research has been taking place to try and create and eventually control this process. The latest agreement is for the International Thermonuclear Experimental Reactor (ITER), a €10 billion (£6.5 billion) project, to be located in France. The technological, environmental and economic problems of fusion technology are huge and maybe insurmountable. The European Union's EURATOM Scientific and Technical Committee recently stated it would take twenty years before it could be determined whether fusion is a viable option for electricity supply in the 21st century at all[13]. While others suggestion that fusion is a '*long term energy option*', which will not be commercial until the 2nd half of the 21st Century[14].

The radioactive inventory of a fusion reactor is expected to be high, comparable to that of a fission reactor of the same size. Compared to a fission reactor, the fusion inventory is generally less toxic and shorter-lived because it consists of tritium and activation products, and contains no fission products and actinides. However, there are activation products with half-lives in the order of millions of years.

Accident mechanisms are different from those as fission power plants, but from the present viewpoint, accidents with catastrophic releases of radioactivity appear possible[15]. Tritium releases during normal operation are expected to be least ten times higher than those of pressurized water reactors; estimations vary by about three orders of magnitude.

Because of the high exposure to particle radiation and heat, the components of a fusion reactor which are facing the plasma must be replaced regularly. They constitute the main part of the radioactive wastes arising from fusion reactor and contain activated metal and tritium. Further radioactive wastes arise by contamination of other plant parts. As has been pointed out, on the other hand, the wastes are generally shorter-lived than those of nuclear fission. However, a particularly problematic nuclide often overlooked in analyses is beryllium-10, with a half live of

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[12] United States Government Accountability Office Testimony Before the Subcommittee on Energy and Resources, Committee on Government Reform, House of Representatives NUCLEAR ENERGY DOE's Next Generation Nuclear Plant Project Is at an Early Stage of Development Statement of Jim Wells, Director Natural Resources and Environment For Release on Delivery Expected at 1:00 p.m. EDT Wednesday, September 20, 2006 GAO-06-1110T

[13] Scientific and Technical Committee EURATOM: The Energy Challenge of the 21st Century: The role of nuclear energy; European Commission, Community Research, EUR 20634 EN, Brussels, 2003

[14] Energy from Fusion, European Commission, Community Research, 19315

[15] Schaper, A., G. Schmidt & R. Bähr: Emerging Nuclear Energy Systems, Their Possible Safety and Proliferation Risks; European Parliament, Directorate General for Research, Working Paper ENER 111 EN, Luxembourg, 12/1999

1.51 million years. All in all, long-term radioactive waste management will be required for fusion plants.

Conclusion:

There is a renewed interest in energy policy, due to increased awareness of the dangers of climate change and growing competition for shrinking energy resources. Consequently, nuclear power is being increasingly promoted.

New nuclear power stations in the future will predominantly be of the new designs, from Generation III and Generation IV series. In the case of Generation III designs these have made evolutionary changes from the reactors widely deployed today, while in the case of Generation IV significant – revolutionary – changes are being proposed.

Generation III reactors are largely only now being licensed and constructed. In the only two designs of reactors actually being deployed construction problems have lead to cost over-runs, a tendency which is all to prevalent in the current reactor programme. In the case of the EPR in Finland, the project is thought to be around one year late after less than 2 years of construction. Furthermore, economic constraints have in some cases resulted in design changes that have reduced the safety margins.

In the case of the Generation IV reactors, many of its design changes are driven by a realisation that uranium is a finite resource with an expected availability of only around 50 years at current levels of use. Therefore, the majority of the designs of reactors in this category are plutonium fuelled. This raises a large number of economic, safety and proliferation concerns. If a nuclear programme is to have a serious impact on CO2 emissions and security of supply then it will require an unprecedented wave of new construction. It has been estimated that if such a programme were to be deployed it would require plutonium fuelled reactors and would result in an annual production of plutonium more than 20 times greater than the current military stockpiles.

Further concerns are raised over the timetable of deployment for the Generation IV reactors, with the current designs requiring the development of new materials warranted by the physical conditions of operation.