New Types of Nuclear Reactors

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New reactor designs are being proposed that claim to offer considerable improvement over existing reactors with little supporting evidence.

All nuclear reactor types – conventional uranium, plutonium of 'fast neutron' reactors, fusion and thorium – pose serious risks of contributing to the proliferation of nuclear weapons.

Introduction

New nuclear reactor types are being promoted with claims that they will produce less nuclear waste than conventional reactors, reduce weapons proliferation risks, and reduce the risk of serious accidents. While there is certainly scope for considerable improvement on all three fronts, the claims should be treated with some scepticism.

It is uncertain whether new reactor types will be developed, with the very large R&D costs being one of the major obstacles. Reactor types with the greatest likelihood of deployment are those which are relatively minor modifications of existing reactor types; as such, any advantages over existing reactors will be marginal.

If new reactor types are developed, they are unlikely to be commercially deployed for some decades (other than those which are minor modifications of existing reactor types).

While new reactor types are being promoted as advantageous in relation to waste, weapons and safety, closer inspection of R&D programs suggests that the primary aim is to lower the cost of nuclear power.

Indicative of this emphasis on improving economic competitiveness is the list of objectives of 'advanced' reactor types provided by the Uranium Information Centre and the World Nuclear Association:[1]

- a standardised design for each type to expedite licensing, reduce capital cost and reduce construction time,
- simpler and more rugged design, easier to operate and less vulnerable to operational upsets,
- higher availability and longer operating life,
- economically competitive in a range of sizes,
- further reduce the possibility of core melt accidents, and
- higher burn-up to reduce fuel use and the amount of waste.

To the extent that the nuclear power industry is able to improve its cost competitiveness by means other than technological innovation, this will reduce the incentive to develop new reactor types. Methods of improving cost competitiveness in the absence of technological development are:

- reducing regulatory requirements and the attendant costs;
- the imposition of carbon taxes or other disincentives to the use of fossil fuels; and
- further subsidisation of nuclear power e.g. with R&D funding and favourable insurance arrangements such as the US Price Anderson Act.

Improving the economics of nuclear power may come into conflict with the other stated objectives in relation to weapons, waste and safety. Most importantly, there is little reason to believe that minimising proliferation risks will be a priority in the development of new reactor types. A number of the 'advanced' reactor concepts being studied involve a 'closed' fuel cycle that involves reprocessing and thus the actual or potential separation of weapons-useable plutonium (or weapons-useable Uranium-233) from irradiated fuel or targets.

Passive or 'inherent' safety systems can improve overall plant safety, such as the use of gravity rather than (failure-prone) pumps to feed coolant into the plant as required. However, overblown and unsubstantiated claims about future reactor designs with (some) passive safety systems has attracted scepticism and cynicism even from within the nuclear industry, with one industry representative quipping that "the paper-moderated, ink-cooled reactor is the safest of all" and noting that "all kinds of unexpected problems may occur after a project has been launched".[2]

Importantly, safety depends on social as well as technological factors. The Massachusetts Institute of Technology (MIT) Interdisciplinary Study states: "We do not believe there is a nuclear plant design that is totally risk free. In part, this is due to technical possibilities; in part due to workforce issues. Safe operation requires effective regulation, a management committed to safety, and a skilled work force."[3]

Serious, unresolved problems remain on all three fronts – regulation, management, and workforce skills. The safety culture varies considerably within and between nations operating nuclear power plants. As the MIT study notes: "It is still an open question whether the average performers in the industry have yet incorporated an effective safety culture into their conduct of business." (Ansolabehere et al., 2003)

Generations I-II

Among commercial nuclear power plant types, four generations of reactors are commonly distinguished.
Generation I were prototype commercial reactors developed in the 1950s and 1960s. They mostly used natural uranium fuel and used graphite as moderator. Most, but not all of them have already been decommissioned although some Magnox reactors are still operating.

The vast majority of the 441 power reactors in commercial operation worldwide today belong to Generation II. They include the following (with parentheses indicating the number in operation, fuel, coolant and moderator)

- Pressurized Water Reactors (268 in operation - enriched uranium dioxide fuel - water coolant - water moderator)
- Boiling Water Reactors (94 - enriched uranium dioxide - water - water)
- Gas-cooled reactors (Magnox and AGR) (23 - natural or enriched uranium - carbon dioxide coolant - graphite moderator)
- Graphite Moderated Boiling Water Reactors (12 - enriched uranium dioxide - water - graphite)
- Pressurized Heavy Water Reactors (40 - natural uranium dioxide - heavy water - heavy water)
- Fast Neutron Reactors (4 - plutonium and uranium dioxide - liquid sodium - no moderator).

(For a description of Generation II reactors see World Nuclear Association, 2005.[4] For description and critical analysis, see Hirsch et al.[5]

Generation III

Throughout the world there are around 20 different concepts for the next generation of reactor design, known as Generation III. Most of them are “evolutionary” designs that have been developed from Generation II reactor types with some modifications. A smaller number of proposed Generation III reactor types are more innovative.
Only in Japan are there any commercial scale reactors of Generation III in operation - the Advanced Boiling Water Reactors, which are modifications of existing reactor types.

The next most advanced design is the European Pressurised Water Reactor, which is being built in Finland and may be also sited in France. According to Hirsch et al.,[6] this design is a slightly modified version of current reactor designs operating in France and Germany, with some improvements, but also with reduction of safety margins and fewer redundancies for some safety systems.

Other examples of Generation III reactor types are: various pressurised water reactor types, the pebble bed modular reactor, boiling water reactors, heavy water reactors, gas cooled reactors, and fast breeder reactors.

Hirsch et al. conclude that: “All in all, “Generation III” appears as a heterogeneous collection of different reactor concepts.[7] Some are barely evolved from the current Generation II, with modifications aiming primarily at better economics, yet bearing the label of being safer than current reactors in the hope of improving public acceptance. Others are mostly theoretical concepts so far, with a mixture of innovative and conventional features, which are being used to underpin the promise of a safe and bright nuclear future – while also not forgetting about simplification and cost-cutting.”

Generation IV

Under the leadership of the US, the “Generation IV International Forum” (GIF) was established in 2000. The GIF also includes Argentina, Brazil, China, Canada, France, Japan, Russia, South Africa, South Korea, Switzerland, the UK, and EURATOM.

A parallel initiative is the IAEA-led International Projects on Innovative Nuclear Reactors and Fuel Cycles (INPRO), established in 2000.[8]

Generation IV reactor types generally represent considerable departures from conventional reactor technology. Development to the point of commercial deployment will necessarily involve major financial investments over a period of some decades.

While electricity generation is the primary focus, there is also some interest in the development of reactor types suitable for hydrogen production and nuclear waste treatment.

Currently, there are six reactor designs being considered, including:

- Gas-Cooled Fast Reactor System
- Lead-Cooled Fast Reactor System
- Molten Salt Reactor System
- Supercritical-Water-Cooled Reactor System
- Sodium-Cooled Fast Reactor System
- Very-High-Temperature Reactor System

Hirsch et al. summarise the gap between rhetoric and reality in relation to Generation IV designs: “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.[9] 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.”

It is beyond the scope of this paper to describe and analyse all of the Generation III and IV reactor types but some of the best-known types are discussed below - the Pebble Bed Modular Reactor, plutonium breeder reactors, fusion power, and thorium-powered systems.

Pebble Bed Modular Reactors (PBMR)

Of the more innovative Generation III reactor types, the best known is the Pebble Bed Modular Reactor (PBMR).[10] PBMRs are helium cooled and graphite moderated and intended to be built in small modules. Pressurised helium heated in the reactor core drives turbines that attach to an electrical generator.

While the PBMR is in some respects innovative, it also shares features with high temperature gas cooled reactors (HGTR). The HTGR line has been pursued until the late 80s in several countries; however, only prototype plants were ever operated (in the USA, UK and Germany), all of which were decommissioned after about 12 years of operation at most.

China operates an experimental PBMR with a larger (200 MWe) ‘demonstration’ reactor planned. A pilot PBMR is planned in South Africa. Internal documents from South African utility giant Eskom, leaked in 2005, point to considerable financial risks in the development of PBMR technology. The US-based company Exelon withdrew its involvement in the development of PBMR technology in 2002.

PBMR proponents claim major safety advantages resulting from the heat-resistant quality and integrity of the small fuel pebbles, many thousands of which are continuously fed from a silo. Each spherical fuel element has a graphite core embedded with thousands of small fuel particles of enriched uranium (up to 10% uranium-235), encapsulated in layers of carbon.

The safety advantages of PBMR technology include a greater ability to retain fissile products in the event of a loss-of-coolant accident. While this configuration is potentially advantageous compared to conventional reactors, it does not altogether avoid the risk of serious accidents; in other words, claims that the system is ‘walk-away safe’ are overblown. Familiar commercial pressures can undermine the safety advantages; for example there are plans to develop PBMR reactors with no containment building.

In relation to weapons proliferation (Harding, 2004):[11]

- The nature of the fuel pebbles may make it somewhat more difficult to separate plutonium from irradiated fuel, but plutonium separation is certainly not impossible.

- Uranium (or depleted uranium) targets could be inserted to produce weapon-grade plutonium for weapons, or thorium targets could be inserted to produce uranium-233.
- The enriched uranium fuel could be further enriched for weapons.
- The reliance on enriched uranium will encourage the use and perhaps proliferation of enrichment plants, which can be used to produce highly enriched uranium for weapons.

Plutonium Breeder Reactors

Fast neutron reactors use plutonium as the primary fuel. They do not require a moderator as the fuel fissions sufficiently with fast neutrons to maintain a chain reaction. The various possible configurations include ‘breeders’ which produce more plutonium than they consume, ‘burners’ which do the reverse, and configurations that both breed and burn plutonium.[12]

There are various possible configurations of breeder systems. Most rely on irradiation of a natural or depleted uranium blanket that produces plutonium which can be separated and used as fuel.[13]

According to the World Nuclear Association (2004), worldwide experience with fast neutron reactors amounts to just 200 reactor-years and only “some” of that experience involves reactors in breeder mode. According to an IAEA scientist, the introduction of breeder reactors into the competitive electricity market is not expected before 2030, at which time breeders are expected to provide 1-2% of nuclear energy output, and this prediction may be “optimistic”.[14] Small breeder R&D programs are ongoing in a few countries (e.g. India, Russia, France) but in other countries the technology has been stalled or abandoned (e.g. the UK, the US, and Germany) or never developed in the first place. Japan’s plans for breeder reactors have been limited and delayed by accidents including the sodium leak and fire at the experimental Monju reactor in 1995.[15]

One reason for the limited interest in plutonium breeder power sources has been the cheap, plentiful supply of uranium. That situation may change, but while breeder technology certainly holds out the promise of successfully addressing the problem of limited conventional uranium reserves, it is doubtful whether the wider range of technical, economic, safety and proliferation issues can be successfully addressed.

Breeder technology is highly problematic in relation to proliferation because it involves the large-scale production and separation of plutonium (although separation is not required in some proposed configurations).[16] The proliferation of reprocessing capabilities is a likely outcome.

Interest in breeder and reprocessing technology in South Korea and China is arguably driven in part by concerns over Japan’s plutonium policies (which involve the large-scale separation and stockpiling of plutonium).[17]

Fusion Power

Fusion fuel - using different isotopes of hydrogen - must be heated to extreme temperatures of some 100 million degrees Celsius, and must be kept dense enough, and confined for long enough to enable fusion to become self-sustaining.

A major fusion R&D program is underway called the International Thermonuclear Experimental Reactor.[18] It involves the European Union, Japan, China, India, South Korea, Russia, and the USA. An experimental plant is to be built at Cadarache in the South of France.

Australian interest in fusion is concentrated in a coalition called the Australian ITER Forum.[19]

Fusion power remains a distant dream. According to the World Nuclear Association (2005C), fusion “presents so far insurmountable scientific and engineering challenges”.[20]

Australian proponents of fusion claim it is “intrinsically clean” and “inherently safe”.[21] However, in relation to radioactive waste issues, the World Nuclear Association states: “[A]lthough fusion generates no radioactive fission products or transuranic elements and the unburned gases can be treated on site, there would be a short-term radioactive waste problem due to activation products. Some component materials will become radioactive during the lifetime of a reactor, due to bombardment with high-energy neutrons, and will eventually become radioactive waste. The volume of such waste would be similar to that due to activation products from a fission reactor. The radiotoxicity of these wastes would be relatively short-lived compared with the actinides (long-lived alpha-emitting transuranic isotopes) from a fission reactor."[22]

In relation to safety issues, the World Nuclear Association points to potential problems identified by the American Association for the Advancement of Science (AAAS):[23] These include the hazard arising from an accident to the magnetic system. The total energy stored in the magnetic field would be similar to that of an average lightning bolt (100 billion joules, equivalent to about 45 tonnes of TNT). Attention was also drawn to the possibility of a lithium fire. In contact with air or water lithium burns spontaneously and could release many times that amount of energy. Safety of nuclear fusion is a major issue. But the AAAS was most concerned about the release of tritium into the environment. It is radioactive and very difficult to contain since it can penetrate concrete, rubber and some grades of steel. As an isotope of hydrogen it is easily incorporated into water, making the water itself weakly radioactive. With a half-life of 12.4 years, tritium remains a threat to health for over one hundred years after it is created, as a gas or in water. It can be inhaled, absorbed through the skin or ingested. Inhaled tritium spreads throughout the soft tissues and tritiated water mixes quickly with all the water in the body. The AAAS estimated that each fusion reactor could release up to 2×10^{12} Bequerels of tritium a day during operation through routine leaks, assuming the best containment systems, much more in a year than the Three Mile Island accident released altogether. An accident would release even more. This is one reason why long-term hopes are for the deuterium-deuterium fusion process, dispensing with tritium."

Some proponents of fusion falsely claim that fusion power systems pose no risk of contributing to the proliferation of nuclear weapons. In fact, there are several risks:[24]

- The production or supply of tritium which can be diverted for use in boosted nuclear weapons.
- Using the fusion reactor's neutron radiation to bombard a uranium blanket (leading to the production of fissile plutonium) or a thorium blanket (leading to the production of fissile uranium-233).
- Research in support of a (thermonuclear) weapon program.

Fusion power R&D has already contributed to proliferation problems. According to Khidhir Hamza, a senior nuclear scientist involved in Iraq's weapons program: "Iraq took full advantage of the IAEA's recommendation in the mid 1980s to start a plasma physics program for "peaceful" fusion research. We thought that buying a plasma focus device ... would provide an excellent cover for buying and learning about fast electronics technology, which could be used to trigger atomic bombs."[25]

Thorium

The use of Thorium-232 as a reactor fuel is sometimes suggested as a long-term energy source, partly because of its relative abundance compared to uranium.

Some experience has been gained with the use of thorium in power and research reactors – but far less experience than has been gained with conventional uranium reactors. The Uranium Information Centre states that: "Much development work is still required before the thorium fuel cycle can be commercialised, and the effort required seems unlikely while (or where) abundant uranium is available."[26]

According to the World Nuclear Association: "Problems include the high cost of fuel fabrication due partly to the high radioactivity of U-233 which is always contaminated with traces of U-232, similar problems in recycling thorium due to highly radioactive Th-228, some weapons proliferation risk of U-233; and the technical problems (not yet satisfactorily solved) in reprocessing. Much development work is still required before the thorium fuel cycle can be commercialised, and the effort required seems unlikely while (or where) abundant uranium is available."[27]

> Thorium fuel cycles are promoted on the grounds that they pose less of a proliferation risk compared to conventional reactors. However, whether there is any significant non-proliferation advantage depends on the design of the various thorium-based systems. No thorium system would negate proliferation risks altogether.[28]

Neutron bombardment of thorium (indirectly) produces uranium-233, a fissile material that can be used in nuclear weapons (1 Significant Quantity of U-233 = 8kg).

The USA has successfully tested weapons using Uranium-233 cores, and India may have investigated the military use of Thorium/Uranium-233 in addition to its civil applications.

The proliferation risk is exacerbated with existing and proposed configurations involving uranium-233 separation from irradiated fuel. As the World Nuclear Association notes: "Given a start with some other fissile material (U-235 or Pu-239), a breeding cycle similar to but more efficient than that with U-238 and plutonium (in slow-neutron reactors) can be set up. The Th-232 absorbs a neutron to become Th-233 which normally decays to protactinium-233 and then U-233. The irradiated fuel can then be unloaded from the reactor, the U-233 separated from the thorium, and fed back into another reactor as part of a closed fuel cycle."[29]

(A research reactor in India operates on U-233 fuel extracted from thorium that has been irradiated and bred in another reactor.)

The possible use of highly enriched uranium (HEU) or plutonium to initiate a Thorium-232/Uranium-233 reaction, or proposed systems using thorium in conjunction with HEU or plutonium as fuel present the risk of diversion of HEU or plutonium for weapons production.

Kang and von Hippel conclude that "the proliferation resistance of thorium fuel cycles depends very much upon how they are implemented". For example, the co-production of Uranium-232 complicates weapons production but, as Kang and von Hippel note, "just as it is possible to produce weapon-grade plutonium in low-burnup fuel, it is also practical to use heavy-water reactors to produce U-233 containing only a few ppm of U-232 if the thorium is segregated in "target" channels and discharged a few times more frequently than the natural-uranium "driver" fuel."[30] One proposed system is an Accelerator Driven Systems (ADS) in which an accelerator produces a proton beam which is targeted at target nuclei (e.g. lead, bismuth) to produce neutrons. The neutrons can be directed to a subcritical reactor containing thorium. ADS systems could reduce but not negate the proliferation risks.

Further Reading On New Reactor Types:

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World Nuclear Association:

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- Small Nuclear Power Reactors www.world-nuclear.org/info/inf33.htm
- Generation IV Nuclear Reactors www.world-nuclear.org/info/inf77.htm
- Advanced Nuclear Power Reactors www.world-nuclear.org/info/inf08.htm

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