APPENDIX E: NUCLEAR ENERGY—PRESENT AND FUTURE

NUCLEAR POWER PLANT FEATURES

A nuclear power plant produces electricity using heat energy, as do coal and gas fired power plants. The difference for a nuclear power plant lies in the way the heat is created.

Nuclear reactors rely on a controlled process of nuclear fission to produce heat. Nuclear fission is the term applied to an atomic nucleus splitting into smaller elements, releasing neutrons and a large amount of energy.

Nuclear fission produces much more energy than chemical combustion—in the range of 10 000 to 20 000 times more in mass terms. Nuclear fuel is very energy dense: one tonne of uranium fuel yields the same amount of electric power as 20 000 tonnes of black coal or 8.5 million cubic metres of gas. The same nuclear fuel is used in a reactor for up to five years.[1]

In order to safely harness this heat energy and convert it into electricity, special highly engineered pressure vessels, called nuclear reactors, are required.

The key elements of a nuclear reactor are illustrated in Figure E.1.

FUEL ZONE

All nuclear reactors are fuelled by a material that is capable of sustaining nuclear fission. Most commonly this is an isotope of uranium, ^{235}U. The fuel needs to be put into a robust form, such as a ceramic or metal alloy, or encased in graphite, due to the high temperatures of the fuel. Nuclear fuel assemblies are specifically designed for particular types of reactors and are made to exacting standards (refer to Appendix C: Further processing methods).

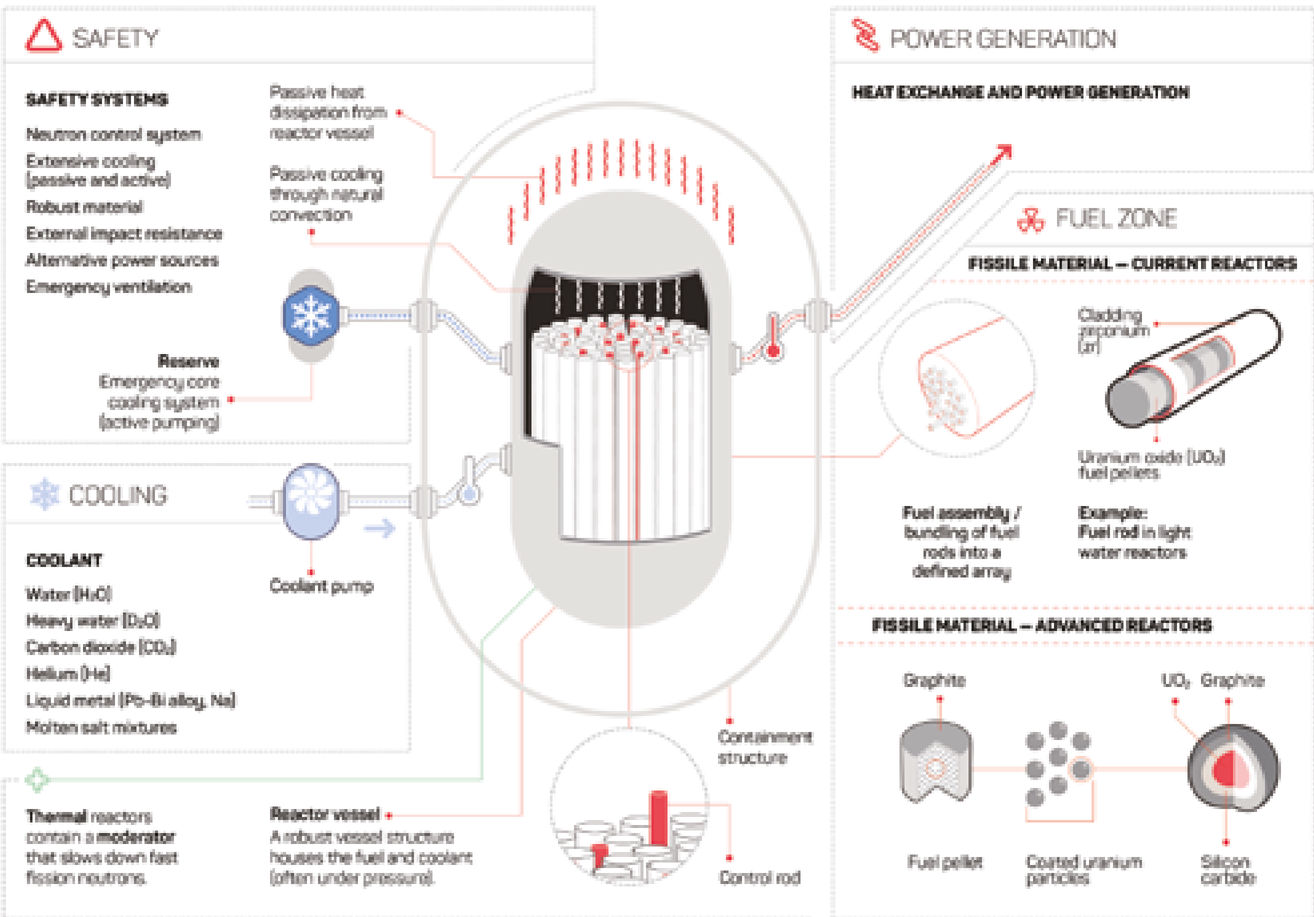

Figure E.1: Key elements of a nuclear reactor

The three main fuel assembly types currently produced are for pressurised water reactors (PWR), boiling water reactors (BWR) and CANDU pressurised heavy water reactors (PHWR). The key elements in a nuclear fuel system and the physical differences in fuel assembly designs are shown in Figure E.2.

COOLANT

Coolants are necessary in a reactor to absorb the heat from the fuel and to transfer that energy to the turbines. Most reactors have multiple cooling circuits and use water, either light or heavy, as the coolant. Some reactors use a gas, such as helium or carbon dioxide. Some advanced reactors use other kinds of coolants, such as liquid metals.[2]

HEAT EXCHANGE AND POWER GENERATION

The heat generated from the fission process in the reactor core is converted into high pressure steam, either directly or in a steam generator, which is fed through conventional steam turbines, similar to those used in coal power plants. The steam expands and causes the turbines to rotate, which in turn drives a generator that produces electricity. Commercial power plants are connected to a high voltage grid to distribute the electricity across a wide geographical area.

LOAD FOLLOWING

Nuclear power plants are typically operated as baseload generators that run continuously at full power. 'Load following' is an operational mode where the electricity output of a power plant is adjusted to reflect the changing electricity demand. Some of the currently operating nuclear plants are configured to have some load following capability; however, it is more economical to run them at full power. Furthermore, operating at full power is less demanding on both the plant equipment and the fuel.[3]

COOLING WATER REQUIREMENTS

Water requirements vary according to features of the particular reactor design, including the operating temperature and the type of cooling system employed.[4] A 'once-through' cooling system involves withdrawing water from a nearby sea, river or major inland water body and circulating large volumes through a condenser(s) in a single pass. The water is then discharged back into the original water source a few degrees warmer without much loss (through evaporation) from the amount initially withdrawn.

Alternatively, cooling may be carried out by 'recirculation': that is, water initially withdrawn from the sea, a river, etc., is recirculated from the condenser to a cooling tower and back to the condenser. A cooling pond works in much the same way.[5] Recirculation is much more efficient in its use of water, compared with the once-through system.

At present, cooling water requirements of nuclear power plants exceed those of fossil fuel power stations by 20–25 per cent on average per m^3/MW hour (Table E.1). This is due to the lower thermal efficiency in most of the existing nuclear power plants, as they operate with lower steam pressures and temperatures. A number of newer nuclear technologies aim to minimise the use of water by, for example, maximising cooling tower concentrations.[6]

COMMON REACTOR TYPES

The two main types of reactor in operation today are the pressurised water reactor (PWR) and the boiling water reactor (BWR) which account for approximately 64 per cent and 18 per cent respectively of operating nuclear power reactors.[8] The key differences between these two types of reactor are:

- The PWR primary coolant is kept under high pressure, which stops it from boiling. A separate secondary circuit, with secondary coolant where steam is generated, is used to drive the turbine.
- In BWRs there is a single circuit in which the water is at lower pressure than in a PWR so that it boils in the core to create steam. This is then used to directly drive the turbines in the absence of a secondary coolant. Since the water in the core becomes contaminated with traces of radionuclides, the turbine is part of the reactor circuit and must be shielded.[9]

Table E.1: Water use for different cooling systems (m^3/MW/hour)

Cooling system	Once-through (withdrawal)	Cooling pond (consumption)	Cooling towers (consumption)
Nuclear	95–230	2–4	3–4
Fossil-fuelled	76–190	1-2	2
Natural gas/oil	29–76	–	1

Source: International Atomic Energy Agency (IAEA)[7]

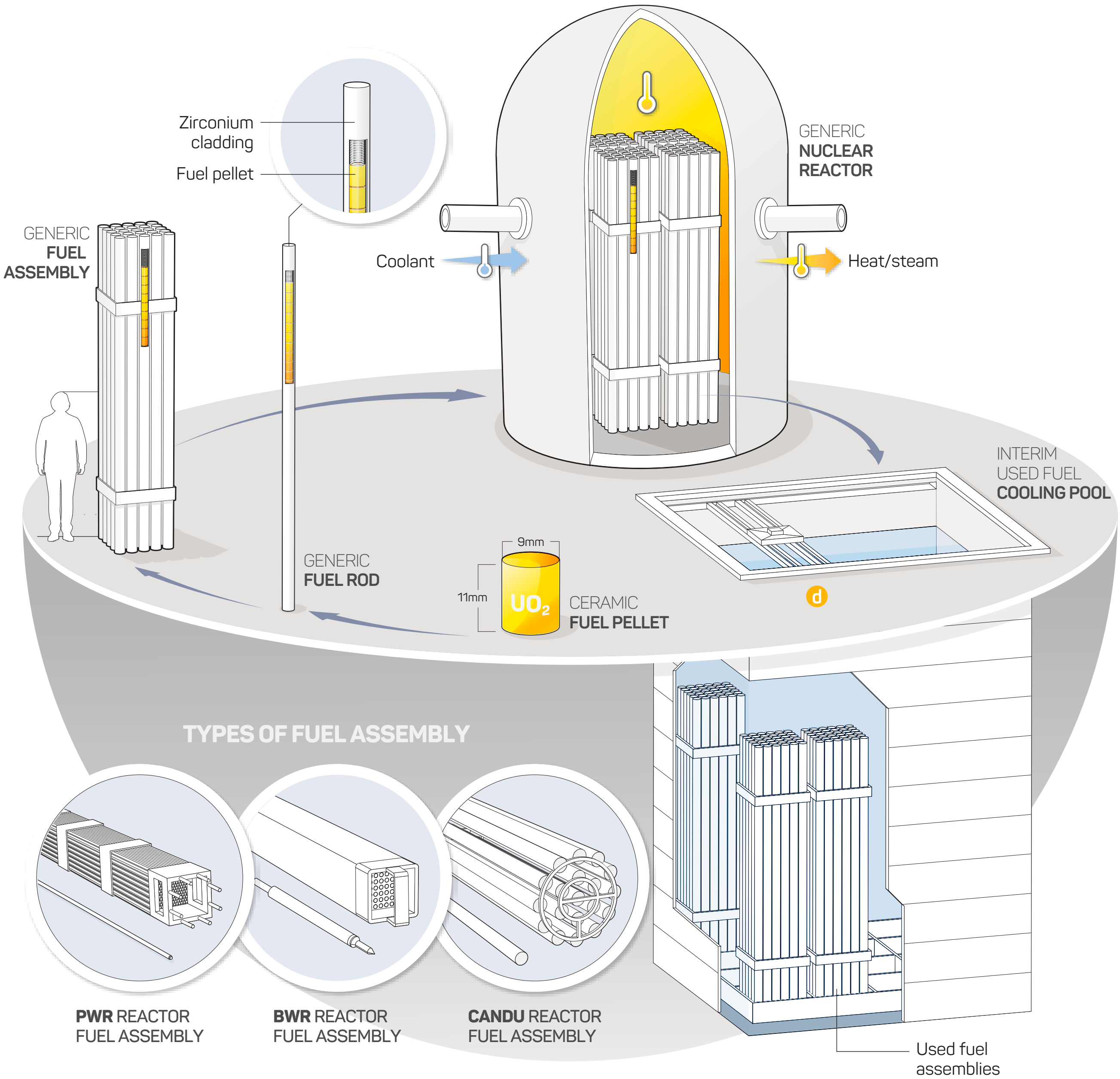

Figure E.2: A nuclear fuel system

NUCLEAR POWER PLANT SAFETY

SHUTTING DOWN A REACTOR AND DISSIPATING HEAT

Shutting down a reactor as part of normal operating procedures or in a fault or emergency situation involves inserting neutron-absorbing material into the core. This rapidly absorbs neutrons and stops the chain reaction and the production of heat from nuclear fission. In all commercial reactors this process is designed to occur automatically and without the need for human intervention.[10]

When the reactor has been shut down and the fission process stopped, it is still necesary to remove residual heat from the core and heat produced from the radioactive decay of the fission products in the fuel. Ongoing cooling is required to effectively remove the heat from the reactor core until the fuel is removed from the reactor.

Most commercial power reactors use water as the primary fuel coolant in closed cycles—those in which the water is recirculated to the reactor core after delivering heat to the turbine/generator system. Given the importance of maintaining adequate cooling for the fuel, reactors are also designed to supply additional coolant in the event of primary coolant loss.

In addition to the systems used for normal operations, all operating reactors are equipped with an emergency *active cooling system*, which makes available large amounts of supplementary water and multiple pumps with independent power supplies.

An emphasis in newer reactor designs is to provide additional fuel cooling using *passive cooling measures*. These rely exclusively on the fundamental physical effects of thermal expansion, gravity and the flow of heat to cooler zones. This can provide core cooling through natural circulation for extended periods without manual or mechanical intervention.[11]

Both active and passive safety systems can provide ongoing fuel and core cooling. However, passive systems to remove heat from the core reduce the dependence on active equipment (e.g. pumps and valves) and operator action in an emergency, and so are an increasingly important design feature for future reactors.

DEFENCE IN DEPTH AND REDUNDANT SYSTEMS

Modern nuclear power plants are designed to incorporate the 'defence in depth' concept. This means that no single human error or equipment failure at one level of defence, nor even a combination of failures at more than one level of defence, can escalate to jeopardise or lead to harm to the public or the environment.[12]

Defence in depth is based on having multiple barriers between radioactive materials and the workforce, the public and the environment, as well as redundancy and diversity of systems. The concept includes measures to protect the barriers themselves and ensures a high level of safety is reliably achieved through:

- high-quality design and construction of nuclear power plant systems
- equipment designed to prevent operational issues or human failures and errors developing into problems
- comprehensive monitoring and regular testing to detect equipment or operator failures
- redundant and diverse systems to control damage to the fuel and prevent significant radioactive releases
- provisions and countermeasures to reduce the effect of severe fuel damage
- improved human performance and a strong safety culture.

IMPACT RESISTANCE OF NUCLEAR REACTORS

Designers of nuclear power plants and the regulators that license plants have considered the potential for impact hazards that could challenge the safety and security of a nuclear power plant, such as terrorist attack and deliberate or accidental aircraft impact.[13]

In 2009 the US Nuclear Regulatory Commission amended its regulations to require applicants for new nuclear power reactors to perform a design-specific assessment of the effects on the facility of the impact of a large commercial aircraft.[14] In Europe, similar regulations are in place to ensure design standards take account of the hazards from impacts.[15]

While differences in detail exist among nuclear reactor types, the fundamental levels of external protection from an impact are:

- the external reinforcement of the outer containment structure
- thick steel construction of the reactor pressure vessel
- fuel and cladding designed to contain radioactive material in the core.

Detailed analysis and modelling has been undertaken on impact events to predict potential damage to the reactor containment.[16] In a postulated aircraft crash, analyses confirmed that concrete walls in the external power plant structure (typically more than one metre thick) are strong enough to protect the fuel from impacts of large commercial aircraft.[17]

Figure E.3, a photo of the Flamanville PWR under construction in France, shows the inner steel containment structure prior to being covered in a thick concrete outer containment. This is typical of a modern light water reactor that is designed to resist and survive large aircraft impacts.

Figure E.4 shows the external containment structure of an existing PWR power plant.

In some newer designs the reactors are recessed into the ground to provide improved protection from impact hazards, as illustrated in Figure E.5. The reactors which are below ground level can be seen on the lower right.

EMERGENCY VENTILATION

In severe accident scenarios hazardous gases may be produced, most notably hydrogen which is potentially explosive. As a result, nuclear power plants also have chemical recombiners to control hydrogen build-up and also, if required, the ability to vent gas into the external reactor building.[18]

Figure E.3: Flamanville PWR plant under construction

Image courtesy of EDF

Figure E.4: External containment of an operating PWR plant

Image courtesy of EDF

Figure E.5: NuScale small modular reactor

Image courtesy of NuScale Inc.

SMALL LIGHT WATER MODULAR REACTORS

Most commercial nuclear plants operating have a generating capacity of about 1 GWe.[19]

A number of firms (see Table E.2) have sought to develop small reactors based on light water designs with generating capacities in the range of 300 MWe or less.[20]

It is thought that such reactors might have the potential to be integrated into a wider range of networks than large plants. Developers of these reactors are aiming to lower the typical construction costs associated with nuclear plants through serial fabrication at an off-site facility, with components brought together at the operational site for final assembly.

This modularisation of components leads such designs to be referred to as small modular reactors (SMRs).[21]

Light water SMR designs using proven light water reactor technology are in various stages of development, with the most advanced being in the licensing process.[22]

There are numerous light water SMR designs being developed, with the most common design features including:

- modular design and small size, lending itself to multiple units on the same site
- smaller output, reducing the level of radioactive inventory in the reactor
- less reliance on active safety systems and pumps to remove heat from the reactor, including during fault or accident conditions
- less cooling water required, so SMRs are more suitable for operating in remote regions and for specific applications such as mining or desalination
- compact design enabling off-site fabrication, if manufactured at a sufficient scale, which can facilitate implementation of higher quality standards and lead to lower construction costs
- below-ground siting of the reactor unit to provide improved protection from natural or external hazards such as aircraft impact
- reduced size of safety exclusion zones
- ability to remove the reactor modules for dismantling and decommissioning at the end of the operational lifetime.

Table E.2: Selected SMR designs under development

SMR type	Vendor/Developer	Country	Description
NuScale	NuScale Power LLC	USA	50 MWe Integral PWR module Deployed with up to 12 modules per plant.
SMART	Korean Atomic Energy Research Institute (KAERI)	South Korea	90 MWe Integral PWR unit Deployed with up to 2 units per plant
mPower	BWX Technologies Inc.	USA	180 MWe Integral PWR unit Deployed with up to 2 units per plant
Westinghouse	Westinghouse Electric Company	USA	225Mwe Integral PWR
ACP100	China National Nuclear Corporation (CNNC)	China	100 MWe PWR
Holtec	SMR LLC (subsidiary of Holtec International)	USA	160 MWe PWR

Source: World Nuclear Association[25]

On the current cost estimates, SMRs require less capital investment prior to producing returns compared with larger scale reactor designs.[23] However, there are no commercially operating examples of light water SMRs that can validate whether the design features listed above can be achieved collectively in a commercial context. In addition, those analysing SMR developments have identified hurdles and uncertainties facing development and commercial deployment including the following[24]:

- SMRs have a relatively small electrical output, yet some costs including staffing may not decrease in proportion to the decreased output.
- SMRs have lower thermal efficiency than large reactors, which generally translates to higher fuel consumption and spent fuel volumes over the life of a reactor.
- SMR-specific safety analyses need to be undertaken to demonstrate their robustness, for example during seismic events.
- It is claimed that much of the SMR plant can be fabricated in a factory environment and transported to site for construction. However, it would be expensive to set up this facility and it would require multiple customers to commit to purchasing SMR plants to justify the investment.
- Reduced safety exclusion zones for small reactors have yet to be confirmed by regulators.
- Timescales and costs associated with the licensing process are still to be established.
- SMR designers need to raise the necessary funds to complete the development before a commercial trial of the developing designs can take place.
- Customers who are willing to take on first-of-a-kind technology risks must be secured.

FAST REACTORS AND REACTORS WITH OTHER INNOVATIVE DESIGNS

Notwithstanding the commercial dominance of LWR designs, work has been undertaken for many decades to improve the sustainability and efficiency of nuclear fuel use in reactors for power production, since current designs utilise less than 1 per cent of the mined uranium. There is also interest in using different nuclear fuel sources such as 'burning' heavy radionuclides and depleted uranium, which are created as byproducts from used fuel reprocessing and fuel enrichment respectively.

For those reasons, different reactor designs have been developed that include:

- fuel forms that can operate at higher temperatures than the current zirconium-clad oxide fuels used in light water reactors
- fuel zones that use higher energy neutrons, the so-called 'fast spectrum'
- coolants that can operate at higher temperatures than water.

Reactors with these design features have operated since the 1960s, but principally as experimental, prototype or demonstration nuclear reactors.[26]

In recognition of the long period and costs involved in their further development, consensus was reached internationally in 2001 that no single country could overcome, in a timely manner, the technical and engineering challenges associated with advanced reactor developments and technologies. Nor could a single country commit the long term resources needed and afford the cost and risks associated with building the next generation of nuclear energy systems.[27]

That consensus led to the establishment of the Generation IV International Forum (Gen IV Forum) to support and manage international cooperation and collaboration on advanced reactor development.[28] Notwithstanding that consensus, some development continues to occur on a national basis.

The Gen IV Forum selected a grouping of six advanced reactor designs updated in January 2014 that are referred to as 'Generation IV' (Gen IV) set out below in Table E.3. The Gen IV Forum has agreed on a common set of high level goals or objectives:

- *Sustainability:* Meets clean air objectives and promotes long term availability of systems and effective fuel, minimising waste volumes and intergenerational burden
- *Economics:* Lifecycle cost advantages over other energy sources, with a comparable level of financial risk
- *Safety and reliability:* Excellence in safety and reliability through a very low likelihood of reactor core damage and removal of the need for an off-site emergency response
- *Proliferation resistance and physical protection:* Least attractive and desirable route for the diversion or theft of weapons-usable materials, and increased physical protection against acts of terrorism.

FAST REACTORS

Many of the Gen IV designs are fast reactors, which utilise fast neutrons rather than the slow or thermal neutrons used by commercial nuclear reactors in operation today. Fast reactors can fission ^{238}U as well as the ^{235}U and this means that more than 60 times more energy can be extracted from the original uranium compared to current reactors. They are also able to use some materials from high level waste as fuel.[30]

Most of the six selected systems employ a closed fuel cycle to increase fuel utilisation and reduce the amount of high-level waste that needs to be sent to a repository for final disposal. High operating temperatures for four of the selected Gen IV Forum systems enable thermochemical hydrogen production, which could prove to be important for future transport fuels.[31]

VERY HIGH TEMPERATURE GAS REACTOR

The very high temperature gas reactor (VHTR), which is one of the systems selected by the Gen IV Forum, is a graphite-moderated, helium-cooled thermal reactor. High outlet temperatures allow thermochemical hydrogen production.[32]

The VHTR has some flexibility in fuel configuration, but no fuel recycling initially. Fuel is in particle form less than a millimetre in diameter, which may be incorporated into billiard ball sized pebbles or prismatic graphite blocks. The VHTR has potential for high fuel burn-up—around three to four times the level of current reactors. VHTR is planned to offer improved passive safety, low operation and maintenance costs, and modular construction features.[33]

VHTR can also 'burn' waste actinides if fuel is specially adapted and fabricated for this purpose.[34]

OUTLOOK FOR THE DEPLOYMENT OF FAST REACTORS AND OTHER INNOVATIVE DESIGNS

Presently there are no operational fast reactors or other innovative designs that can be used to validate their potential for commercial deployment.[35] Several countries have research and development programs for improved fast reactors, with some being in place since the 1950s, with significant challenges still to be overcome before commercial operation is achieved.[36]

Today India and Russia regard fast reactors as a priority in their nuclear programs. They also feature in the nuclear energy programs for Japan, China and France. Experimental prototype and demonstration reactor designs are currently in operation in several countries including Russia, China and India.[37]

Prototype and demonstration VHTR designs have previously operated in various countries, although all have been shut down.[38] A twin 105 MWe gas-cooled HTR-PM ('high temperature gas cooled – pebble bed modular') demonstration unit at Shidaowan in China commenced construction in December 2012 and is expected to start operation in late 2017.[39]

Based on the updated technology roadmaps published by the Gen IV Forum in 2014 for Generation IV designs, a reactor demonstration phase is expected to begin in approximately 2021 for the most advanced system.[40] This phase is expected to last at least 10 years and will require funding of several billion US dollars for each system. As a result, based on the published Generation IV planning basis, the earliest timescales for commercial deployment of fast reactors and other innovative designs is reported as 2031.[41]

The proposed Russian BN-1200 design, which is planned as the commercial design developed from the existing BN-800 demonstration sodium cooled fast reactor, may be in operation before then.[42]

In addition, the proposed Chinese twin 600 MWe HTR-PM reactor (which is made up of 6 x 105 MWe modules) at Ruijin city in China's Jiangxi province passed a preliminary feasibility review in early 2015. This design is based on the demonstration HTR-PM reactor, with construction expected to start in 2017 and grid connection expected in 2021.[43]

All the timescales described above are, however, subject to significant project, technical and funding risk, as with any complex technology development.

Table E.3: Reactor designs selected by the Generation IV International Forum

	Neutron spectrum (fast/ thermal)	Coolant	Temperature (°C)	Pressure[a]	Fuel	Fuel cycle	Size(s) (MWe)	Uses
Gas-cooled fast reactors	fast	helium	850	high	$^{238}U^{b}$	closed, on site	1200	electricity & hydrogen
Lead-cooled fast reactors	fast	lead or Pb-B	480–570	low	$^{238}U^{b}$	closed, regional	20–180[c] 300–1200 600–1000	electricity & hydrogen
Molten salt fast reactors	fast	fluoride salts	700–800	low	UF in salt	closed	1000	electricity & hydrogen
Molten salt reactor - Advanced high-temperature reactors	thermal	fluoride salts	750–1000	low	UO^2 particles in prism	open	1000–1500	hydrogen
Sodium-cooled fast reactors	fast	sodium	500–550	low	^{238}U & MOX	closed	50–150 600–1500	electricity
Supercritical water-cooled reactors	thermal or fast	water	510–625	very high	UO^2	open (thermal) closed (fast)	300–700 1000–1500	electricity
Very high temperature gas reactors	thermal	helium	900–1000	high	UO^2 prism or pebbles	open	250–300[3]	electricity & hydrogen

[a] high = 7–15 MPa
[b] = with some ^{235}U or ^{239}Pu
[c] 'battery' model with long cassette core life (15–20 years) or replaceable reactor module
Source: World Nuclear Association[29]

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Transcripts and submissions can be found at the Nuclear Fuel Cycle Royal Commission's website: www.nuclearrc.sa.gov.au/transcripts and www.nuclearrc.sa.gov.au/submissions