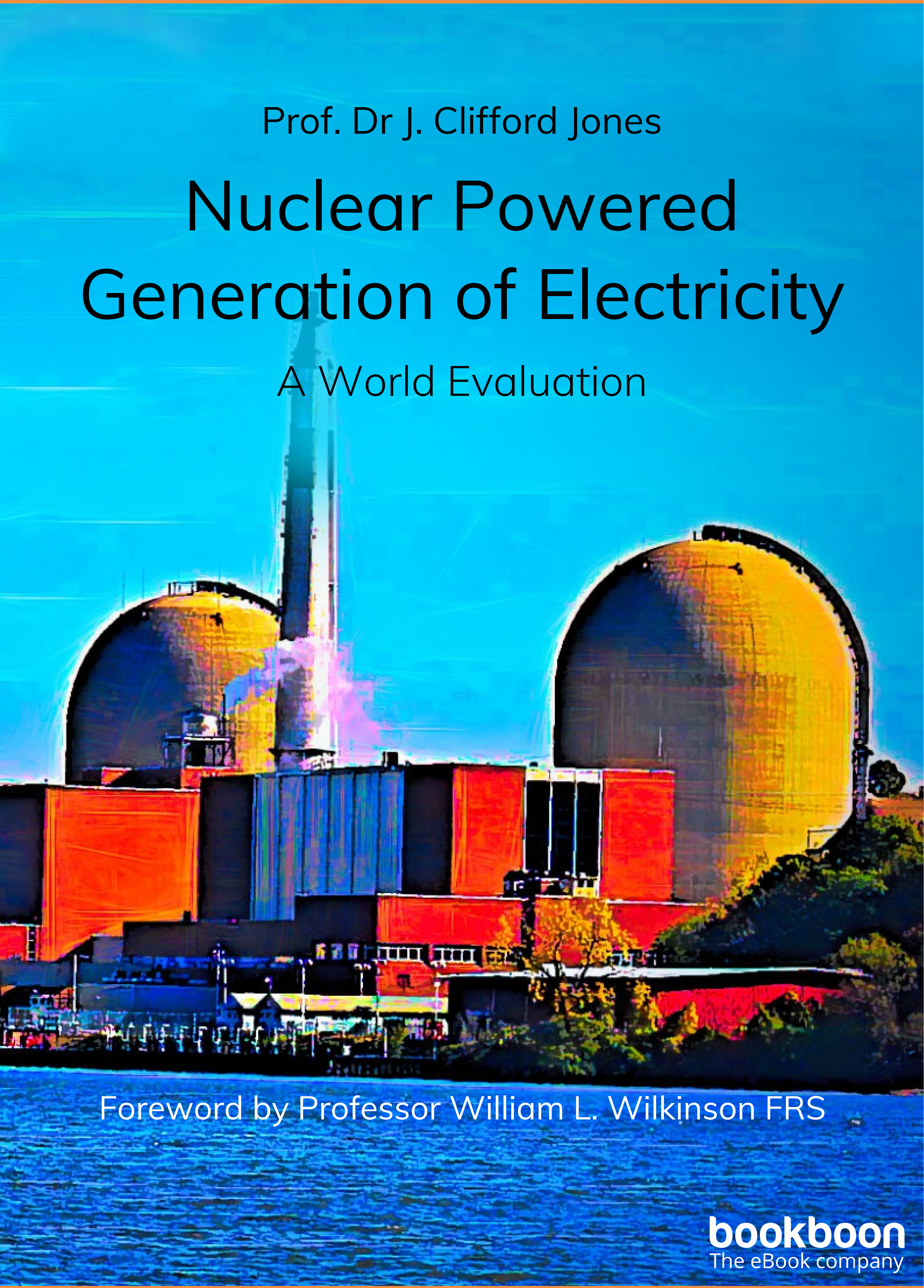
Prof. Dr J. Clifford Jones

Nuclear Powered Generation of Electricity

A World Evaluation



Foreword by Professor William L. Wilkinson FRS

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PROF. DR J. CLIFFORD JONES

NUCLEAR POWERED GENERATION OF ELECTRICITY

A WORLD EVALUATION

Nuclear Powered Generation of Electricity: A World Evaluation
1st edition

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Peer review by Professor William Wilkinson FRS

CONTENTS

Dedicated to
Shellie Jacobs
in gratitude for times shared with the author in
North America, Europe and the Far East.

FOREWORD BY PROFESSOR WILLIAM L. WILKINSON FRS

A reliable supply of electricity is essential to meet the modern needs of homes and industry. For many years this has been achieved by the burning of conventional fuels, mainly coal, oil and gas, but this is becoming unacceptable in many countries because of the impact of gaseous carbon emissions on health and the environment.

Nuclear powered electricity is both reliable and carbon free and is therefore important to fulfil future aims such as decarbonisation of transport. It is not only electric cars which will benefit from this but also other transports as well as many other industrial processes. Nuclear power has a vital role in supplying our current electricity needs as well as meeting our planned zero carbon emission target by 2050.

Nuclear generation of electricity has been developed in many countries over the past six decades. The UK claims the first nuclear power station, Calder Hall, which was commissioned in Cumbria some 60 years ago and which marked my first venture into the nuclear industry. My career was involved in the engineering challenges in the nuclear fuel cycle including manufacture of fuel and reprocessing of spent fuel. These engineering challenges continue with the decommissioning of first and second generation power stations and the treatment of legacy waste. Clifford Jones has produced a valuable and comprehensive account of the development of nuclear power worldwide from Calder Hall to the present time.

Nuclear generation of electricity is now a mature industry which can claim to be reliable, safe and affordable. Unfortunately, its development has been restricted in some countries, including the UK, by the irrational fears of the media and the public as well as by politicians who have not provided the industry with the necessary support. This is in sharp contrast to the situation in France which, for many years, has enjoyed the benefits of reliable nuclear generated electricity to meet the majority of its electrical demand. The adoption of nuclear power in other countries remains mixed. Whereas China is rapidly increasing nuclear generating capacity, there is still only a single nuclear power plant on the continent of Africa (at Capetown) and, as mentioned in Chapter 4 by the author who is an Australian national, nuclear powered electricity is absent in both Australia and New Zealand.

I am happy to commend this book to readers. I can imagine that students of energy matters as well as policymakers will derive benefits from consulting it.

W. L. Wilkinson FRS

Knutsford, England.

February 2020.

Professor William Wilkinson FRS was Chairman of the British Nuclear Industry Forum from 1992–1997 and President of the European Nuclear Forum from 1994–1996.

1 GENERAL INTRODUCTION

1.1 BACKGROUND ON NUCLEAR FISSION

In conventional fuels heat release is by oxidation, which is a chemical process. With nuclear fuels the origin of the heat is difference is the binding energy between the parent and daughter nuclides.

Processes in the fission of uranium-235 include [1]:

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{141}_{56}Ba + ^{92}_{36}Kr + 3^{1}_{0}n$$

There are 235 bound nucleons on the left. The binding energy per nucleon is 7.59 MeV [2] giving a total of 1783 MeV. There are 233 bound nucleons on the right. For ^{92}Kr the binding energy per nucleon is 8.51 MeV [3] and for Ba it is 8.32 MeV [4]. The energy from the nuclear reaction is then:

$$[(92 \times 8.51) + ((141 \times 8.32)] - 1783 \text{ MeV}$$

$$= 173 \text{ MeV or } 71 \text{ TJ per kg of Uranium-235.}$$

That is about the energy released on the burning of 10000 barrels of petroleum products. The mass conversion to energy is

$$[173 \times 10^{6} \times 1.6 \times 10^{-19} \text{ J}/(3 \times 10^{8})^{2} \text{ m}^{2}] \text{ kg} = 3 \times 10^{-28} \text{ kg.}$$

In a combustion process there is a change in chemical composition in going from reactants (e.g. natural gas) to CO_2 and H_2O products, and the composition change is accompanied by an energy change (ΔH or ΔU in conventional symbols) manifest as heat. In nuclear fission such as that in the equation above, energy is redistributed between binding energy of nucleons and kinetic energy of fission fragments and there are also 'prompt γ rays'.

The barium and krypton nuclides formed from uranium-235 fission are radioactive. The former has a half life of 18 minutes and the latter a half life of 3 seconds. Both are β emitters and γ rays are produced in the decay chain. The γ rays are distinguished from those from the fission itself, called prompt γ rays as noted above. These further processes can be incorporated into the total energy of the fission process bringing it to slightly above 200 MeV [1].

When, as in the case of uranium-235, neutrons released as a result of fission enable a reaction to be sustained the nuclide is said to be fissile and the term chain reaction applies. Uranium-235 is the only naturally occurring fissile substance. Plutonium-239, which features frequently in this book, is fissile but is present in no more than a trace in naturally occurring plutonium and if required as a nuclear fuel has to be produced from uranium-238 which is itself classified not as fissile but as fertile. That is according to:

$$^{238}_{92}U + ^{1}_{0}n \rightarrow ^{239}_{92}U \rightarrow ^{239}_{93}Np \rightarrow ^{239}_{94}Pu$$

In a reactor producing plutonium from uranium-238 there is a concurrent fission reaction to $^{234}_{90}Th$ plus an alpha particle. The low binding energy per nucleon of the latter is the origin of the accompanying energy release which is what enables this process to be used in electricity generation. Uranium-238 though not fissile is fissionable as well as being fertile: if supplied with neutrons it is capable of fission but not of sustaining a chain reaction. Uranium-233 is fissile but is absent from natural uranium and has to be obtained from the fertile thorium-232; there are several examples of this in the subsequent chapters. The abundance of uranium-235 in natural uranium is 0.72%. Many plants use enriched uranium. Low enriched uranium (LEU) has uranium-235 up to 5% and high enriched uranium has uranium-235 up to 20% [5]. Uranium, plutonium and thorium are actinides, the term given to chemical elements in the atomic number range 89 to 103. They are sometimes referred to as that in accounts of their use in nuclear energy. In a reactor the fuel is contained in fuel rods which are held in place in a fuel assembly by spacer rods. Control rods, which function by neutron absorption, occupy the spaces between the fuel rods and can be raised or lowered. Another isotope of uranium is uranium-236, and this can be formed in a nuclear reactor by the process:

$$^{235}U + n \rightarrow ^{236}U$$

which is concurrent with the fission. The decay products of uranium-236 include xenon, which therefore accompanies krypton in the gaseous products from a nuclear reactor. There is a return to this point in Chapter 4. Uranium-236 does not occur naturally, and its presence in a sample of uranium is proof positive that the uranium has been in a nuclear reactor. It is not fissionable with thermal neutrons (see below).

1.2 NEUTRON SPEEDS AND NEUTRON ECONOMY

Whether a particular neutron-nuclide encounter leads to capture depends on the neutron speed. Care with terminology is needed in the classification of neutron speeds. Fast neutrons are fast because they have energy from the nuclear process in which they were released. Thermal neutrons have only the energy characteristic of the temperature of their surroundings like molecules of an ideal gas do. Usually the term 'slow neutrons' means neutrons having lost some but not all their energy on release. Such neutrons are sometimes (e.g. [6]) described as 'not completely thermalised'. Occasionally (e.g. [7]) 'slow neutrons' is used synonymously with 'thermal neutrons'. Thermal neutrons have energies of around 25 keV. Fast neutrons have energies up to about 20 MeV and if decelerated by collisions so that they become 'slow' in the sense explained above have energies down to > 1 MeV. [8]. Intentional slowing down of neutrons is by a moderator, a term which occurs frequently in this book.

A reactor for fission of uranium-238 requires fast electrons. That is in contrast to fission of uranium-235 which requires thermal neutrons. Neutrons 'drive' nuclear fission and neutron economy – effective direction of neutrons at target nuclides by avoidance of their absorption by surfaces – needs to be practised. An assembly of fissile material will need time to become self-sufficient in neutrons, at which stage it has achieved criticality. This is explained more fully in the next chapter with a particular nuclear reactor as an example. There it is emphasised that 'critical mass' does not depend solely on the mass.

The idea that neutrons from the fission of uranium-235 might be diverted to plutonium production from uranium-238 is an obvious and attractive one as it would mean concurrent electricity and nuclear fuel production. The term breeder reactor would apply to that [9], [10]. It is possible for the rate of nuclear fuel production in such a reactor to exceed the rate of fuel usage.

1.3 FURTHER COMMENTS

This chapter has set out some of the ideas which occur frequently in the book. Sometimes in subsequent chapters an idea or principle against the background of a particular application. For example, what has been said about criticality in this chapter will be followed in the next chapter by a discussion of the analogy between criticality in nuclear processes and criticality in combustion (chemical) processes. That is in the coverage of the Shippingport nuclear power plant in Pennsylvania. Mixed oxide fuel (MOX) is introduced in Chapter 3 when nuclear power in France is described.

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2 EARLY* NUCLEAR POWER PLANTS

2.1 CALDER HALL AND OTHER UK NUCLEAR POWER PLANTS WITH MAGNOX REACTORS

2.1.1 INTRODUCTION

A Magnox reactor uses graphite as a neutron moderator and has gaseous carbon dioxide as the heat exchange fluid, that is, the fluid by means of which heat from the nuclear reaction is made available for steam raising. ‘Magnox’ is also the name of a magnesium alloy, and in a Magnox reactor this material is used as nuclear fuel cladding. Eleven power plants using Magnox reactors came into being in the UK in the 1950s, the first of which was Calder Hall in the north west of England. There has been no use of Magnox reactors in power generation anywhere since 2015 [1]. Magnox reactors use fast neutrons and yet have a moderator. That is because to slow down the neutrons is good for neutron economy. As shown in the previous chapter the speed range of fast neutrons is wide, and those in a Magnox reactor remain in this range on moderator exit.

2.1.2 BACKGROUND TO CALDER HALL

It was adjacent to a nuclear fuels production plant at Winsdscale in Cumbria. Windscale was commissioned as a facility for making Plutonium-239 from Uranium-238. This was at a time shortly after ‘Victory in Japan’ had been effected by the use of nuclear weapons. Britain was importing uranium from places including the Belgian Congo, Canada and South Africa so as to make from it Plutonium-239 for use in weapons. Recall the figure of 173 MeV for the fission of uranium-235 given in the previous chapter. The figure for plutonium-239 fission is 210 MeV making for a greater energy release per unit weight fissioned. Fairly immaterial in electricity generation that is an obvious advantage in nuclear weaponry, which is why plutonium-239 is preferred for such applications.

The manufature of plutonium for nuclear weapons then was the raison d’être of Windscale, and heat from the accompanying fission was used to make electricity by steam generation. Heat is obtained from the uranium-235 fission process outlined in the previous chapter.

Below is an early image of Calder Hall. It was in operation over the period 1956-2003. The fuel at Windscale was natural uranium clad with a magnesium alloy as noted. It initially had two Magnox reactors and this was later increased to four, providing electricity for the grid by export of heat to the nearby power station.

* Commissioned before circa 1965.

Calder Hall power station shortly after commissioning. It had four 60 MWe Image taken from [2].

Each reactor at Windscale enabled of the order of 46 MW of electricity to be generated [2]. At Calder Hall the burnup – quantity of heat released per unit amount of nuclear fuel – was low, about 500 MW days per tonne [3]. Burnup rates of 2000 MW days per tonne or higher are possible with such a reactor [4]. That was not a deficiency: low burnup is always used where the primary process is plutonium-239 production, as the neutron supply necessary for a higher burnup also promotes the conversion of plutonium-239 to plutonium-240 [5]. The burnup rate at Calder Hall can be expressed as a percentage and this is below.

$$500 \text{ MW days} = 4.3 \times 10^{13} \text{ J.}$$

One tonne of natural uranium contains 7.2 kg of uranium-235.

Using the value of 71 TJ for the heat from a kilogram of Uranium-235 (see Chapter 1) the heat from a tonne of the nuclear fuel is:

$$71 \times 10^{12} \times 7.2 \text{ J} = 5.1 \times 10^{14} \text{ J}$$

$$\text{Percentage burnup} = [(4.3 \times 10^{13})/(5.1 \times 10^{14})] \times 100 = 8$$

See also the concluding paragraph of section 4.1.

Examination of some data relating to the non-nuclear part of this power plant is below.

Information is taken from [2]. At each of the four Magnox reactors at Windscale/Calder Hall the gas flow rate was 891 kg s^{-1}. The gas enters the reactor at 140°C and leaves it at 336°C.

Using a rough value of 1000 J kg^{-1}°C^{-1} for the specific heat, the rate at which heat is transferred from the nuclear reactor to the carbon dioxide is:

$$891 \text{ kg s}^{-1} \times 1000 \text{ J kg}^{-1}{}^{\circ}\text{C}^{-1} \times (336 - 140)\ {}^{\circ}\text{C} = 175 \text{ MW}$$

So the performance is 175 MW_{th} and 46 MW_e or:

$$(46/175) \times 100 = 26\% \text{ efficiency.}$$

The calculation could have been refined by closer attention to the value of the specific heat of CO_2 across the temperature range.

2.1.3 THE 1957 FIRE AND ' COCKROFT'S FOLLY'

On 10th October 1957 a fire began at a graphite neutron moderator at one of the reactors at Windscale [6]. Neutron impact has an effect on graphite in a way resembling the introduction of strain, the Wigner effect, and this can be reversed by annealing. Annealing was taking place at one of the graphite moderators at Windscale on the day of the accident [7]. There was concern about release of harmful substances, in particular Iodine-131. That is produced in uranium-235 fission and is a synthetic isotope, being totally absent from naturally occurring iodine. Iodine-131 is produced in the fission product decay chains both of uranium-235 and plutonium-239. In a nuclear reactor, the reactor wall prevents release of radioactive substances into the surroundings. It was only because of the accident that there was an issue at Windscale.

Some of the heat exchange gas at a Magnox reactor finds its way into the atmosphere via a stack. Between the gas and the reactor core are both the Magnox alloy and the graphite rods, and these prevent contamination of the gas either by unprocessed fuel or by nuclides having been formed in the nuclear reactor. Even so J.D. Cockroft (Nobel Prize in Physics, 1951), who was Director of the UK Atomic Energy Research Establishment at the time of the commissioning of Windscale, required that each of the two stacks there be retrofitted with a filter. Those doubting the need for that referred to the edict as 'Cockroft's folly'. Having as noted been retrofitted and not part of the original stack design the filters were very conspicuous, and they became known as 'Cockroft's follies' (see below).

One of the two 'Cockroft's follies'. Image taken from [8].

Those sceptical about the need for the filters were probably right in that in operation of the Magnox reactor contaminants from the fuel rods would not enter the heat exchange gas. The filters proved their worth however at the 1957 fire. The consequences would have been more serious if the filters had not been there, even though Cockroft was thinking of day-to-day operation and not of such an emergency when he insisted on their installation. They were removed in 2014 prior to demolition of the stacks the following year. If the filters required by Cockroft been installed 30 years later they would have been seen as being consistent with 'inherent safety'. The concrete shield against γ radiation at Calder Hall weighed thousands of tons, and the point is made in [9] that its use would not be feasible in a shipping application of nuclear power.

2.1.4 OTHER POWER PLANTS IN THE UK USING THE MAGNOX REACTOR (ALL NOW OUT OF SERVICE)

That at Chapelcross in Scotland was in service over the period 1959-2004 and produced 240 MW of electricity from a total of four reactors [10]. Like Windscale/Calder Hall with which it is contemporaneous, it was primarily a plutonium production facility. Natural uranium was the nuclear fuel. A quantity of 60 TWh of electricity was produced annually at Chapelcross over its 45 year life representing an average production of 150 MW_e.

The Magnox reactor at Berkeley in Gloucestershire operated from 1962 to 1989. It had two reactors and supplied the city of Bristol (current population 0.54 millions) with electricity [11]. It was the first of the Magnox plants in the UK to face decommissioning. The Bradwell Magnox power plant in Essex had two reactors with a combined electricity production of 242 MW from natural uranium fuel [12]. It was in service from 1962 to 2002. In nuclear decommissioning, dismantlement and demolition are followed by a care and maintenance (C&M) period whereby structures not safe to remove because of radioactive contamination are left in situ to allow time for natural decay of the contaminants. This will involve frequent monitoring and inspection of such structures ('care and maintenance'), sometimes called the quiescent phase of the decommissioning. Decommissioning of the Magnox plant at Bradwell is at the C&M stage. That has involved covering each of the two reactors with a weatherproof material (see below) which will remain in place for up to a century [12].

The Magnox reactors after fuel rod removal at Bradwell, England at the C&M stage of decommissioning. Note the covers. Image taken from [12].

Hunterston A power station in Scotland, also commissioned to produce Plutonium-239 for weapons, was in service from 1964 to 1990. It is estimated that the quiescent phase of its decommissioning will end in around 2125 [13].

Hinkley Point A power station in south west England followed closely behind Calder Hall and like it used natural uranium as fuel. It had two reactors and was in service from 1965 to 1999. (Hinkley Point B nuclear power station is still in service having commenced power production in 1976. It is not included in this discussion because it does not use the Magnox reactor.) Trawsfynydd nuclear power station in Wales was in service from 1965 to 1991 and had two Magnox reactors [14]. At Dungeness A power station in Kent power production ceased in 2006 after forty years. Decommissioning is expected to enter the C&M stage in 2027 [15]. Dungeness B nuclear power station, which does not use the Magnox reactor, remained in service after Dungeness A ceased production. Sizewell A nuclear power station in East Anglia was in service from 1966 to 2006, and again a C&M period of the order of a century is expected . Oldbury nuclear power station in Gloucestershire operated from 1967 to 2011 and had two fully conventional Magnox reactors with graphite moderators and CO_2 as the heat exchange fluid. Wylfa nuclear power station in Anglesey off the Welsh coast is the most recent (2015) of the Magnox reactors to exit service. The first nuclear power plant in Italy, called 'Latino', used a Magnox reactor as will be described later in the book.

2.1.5 FURTHER COMMENTS

Calder Hall was the first commercial nuclear power generating plant in the world, and Magnox is 'Generation 1'. Coverage in an early chapter of the book is therefore appropriate. The Shippingport Atomic Power Station in Pennsylvania is legitimately described as 'the world's first atomic electric power plant devoted exclusively to peacetime uses' [16]. It was part of President Eisenhower's 'Atoms for Peace' policy. Calder Hall was not 'devoted exclusively to peacetime uses' as it was primarily as producer of plutonium-239 for weapons. The SM-1 reactor in Virginia narrowly preceded Shippingport in supplying electricity to the grid for general distribution but that was not is sole *raison d'etre*: it was an activity of the US Army Nuclear Power Program [17]. Its capacity was only 2 MW and it was originally conceived as being portable. The Shippingport power station is fully described in the next section.

2.2 SHIPPINGPORT, PENSYLVANIA

2.2.1 BACKGROUND

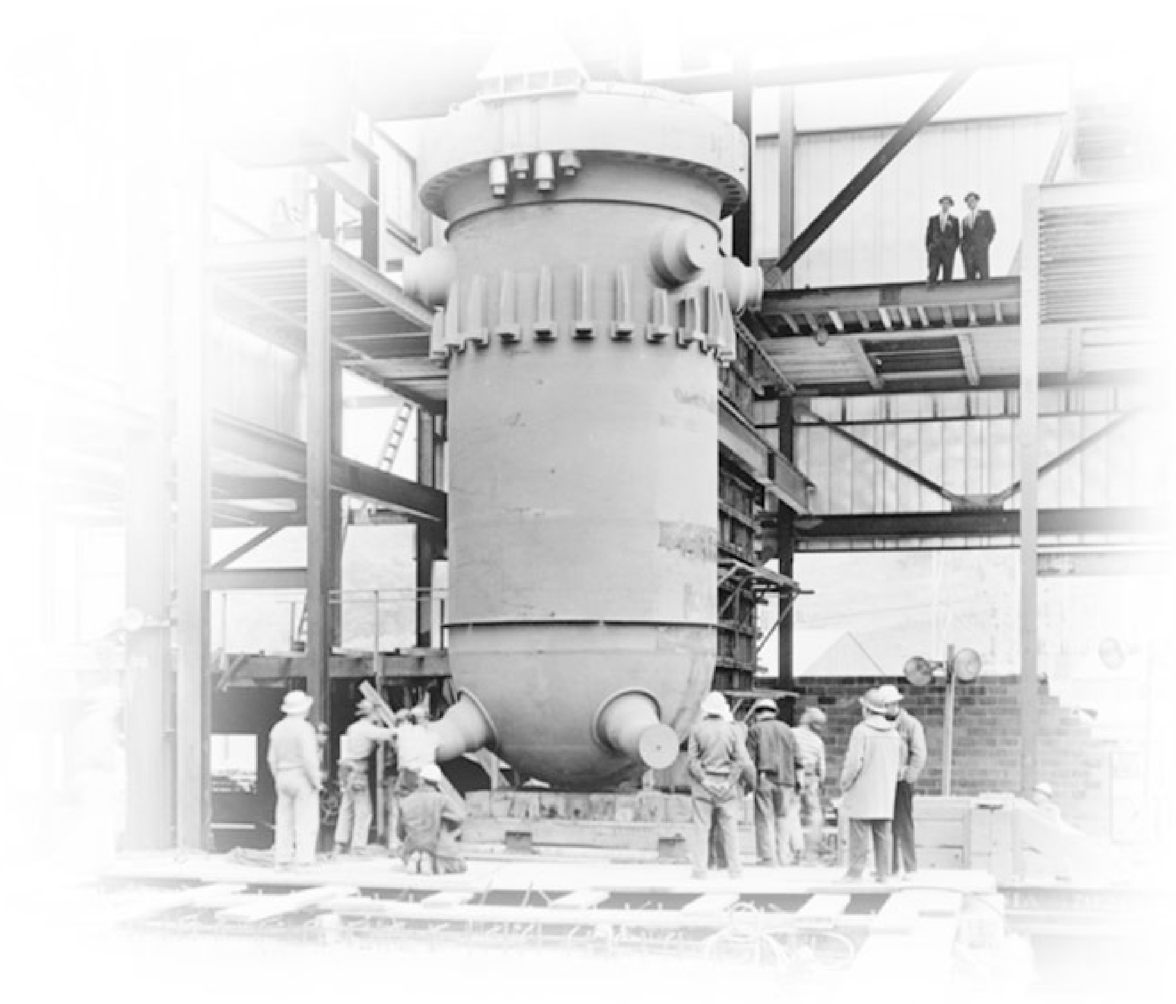
In a boiling water reactor (BWR) heat from the nuclear fuel is used to supply the heat of vaporisation of the water, there being only one water stream. Another way of saying that is that the reactor coolant becomes the turbine working substance. The alternative is supply of the heat to pressurised light water and heat exchange from that to the water undergoing evaporation in what is termed a pressurised water reactor (PWR), and in such a reactor the water also acts as a neutron moderator. Shippingport (like SM-1) was a PWR facility, and at the initial operation in 1957 the fuel comprised 165 pounds of high enriched uranium as 'seed' and 14 US tons of natural uranium as a 'blanket' [18]. The seed and blanket contributed about 50:50 to the heat release and critical conditions prevailed, that is, the reaction was sustained by supply of neutrons from the fuel. Generalising the discussion, attainment of criticality is not dependent on the fuel quantity and composition only. Many of the neutrons released are not involved in further fission but are lost, and such loss can be reduced by attention to the surface/volume ratio of the fuel as admitted to the reactor. Criticality can also be 'helped along' by use of a neutron reflector [19]. In combustion, which has a chemical not nuclear origin, criticality – whether or not a particular burning mass will ignite – depends on the surrounding temperature. The higher the ambient temperature the greater the propensity to ignition. In a nuclear fission process criticality depends on the behaviour of the surroundings towards neutrons. The more reflective they are towards neutrons the more readily the critical mass is attained. This all follows from what was said in the introductory chapter about the importance of neutron economy. The power plant at Shippingport used dry saturated steam at 1800 p.s.i. (= 12.4 MPa) [20]. From steam tables, the equilibrium temperature is 328°C. The power station was in service up to 1982.

The oft-repeated statement that Shippingport was the first nuclear power plant directed solely at peacetime activity is quite sound as its role was purely electricity production for homes and industry. At Calder Hall and other Magnox plants the primary intention was plutonium production for weapons. At Shippingport the neutrons after moderation would have been too slow for plutonium-239 production from uranium-238.

2.2.2 OPERATING DETAILS

The single reactor, built by Westinghouse, used pressurised water as heat exchange fluid ('coolant') making it a pressurised water reactor (PWR) and as noted pressurised water also served as a neutron moderator. The pressurised water (in the 'primary water circuit') was initially at about 270°C and rose by about 40°C through heat transfer from the reactor. It was then passed along to heat water for steam raising (in the 'secondary water circuit') followed by electricity generation at 60 MW at a steam turbine using a Rankine cycle. The boundary between one 'circuit' of water and the other prevented any contamination from the reactor from entering the secondary water a.k.a. service water which, of course, ultimately contacts the atmosphere at the cooling towers (of which there were two at Shippingport). Electricity from the power station was supplied to Pittsburgh. Whether one regards it as satisfactory terminology or not, the water which is evaporated in a nuclear reactor is often referred to as the reactor coolant. If this is simply referred to as the coolant it is very important that it and the water for the cooling tower are not confused. The latter is in the non-nuclear part of the plant and undergoes no thermodynamic cycle.

The illustration below shows the reactor vessel at the Shippingpoint power plant. The vessel, of course, held the fuel rods, the control rods and the heat transfer fluid, and it was 10.7 m in height. In April 1989, seven years after the power station ceased operation, the vessel was buried in the Hanford Nuclear Reservation in Washington State having been taken there by barge [21]. Protesters were encountered along the route, as is par for the course.



The reactor vessel at Shippingport prior to installation. Image taken from [22].

There is a brief return to Shippingport in section 2.7.

2.3 THE OBNINSK NUCLEAR POWER PLANT

This was in operation from 1954 to 2002 (therefore predating Calder Hall, with which it had the common factor of plutonium-239 production) and was close to Moscow [23]. Its output of electricity was 5 MW produced at an efficiency > 20%. The fuel was enriched uranium (5% uranium-235). It had water as the heat exchange fluid and graphite as the neutron moderator. Other, larger reactors of this type came into operation and are known as light water graphite reactors (LWGR), a term which occurs several times in this book. Perhaps the primary significance of the plant at Obninsk is that it was the prototype LWGR. The reactor was known as AM-1 where AM stands for Atom Mirny = peaceful atom, an expression highly reminiscent of that coined by President Eisenhower.

The Obninsk nuclear power plant on the day of a visit by Yuri Gagarin (third from the left on the front row). Image taken from [24].

2.4 TŌKAI 1 NUCLEAR POWER PLANT

A report from 1957 prepared for the US Atomic Energy Commission [25] is entitled 'Comparison of Calder Hall and PWR reactor types' and in the report PWR is synonymous with Shippingport. Distinction is on the basis of heat exchanger fluid (CO_2 for Calder Hall, light water for Shippingport) and neutron moderator (graphite for Calder Hall, light water for Shippingport). Note is also made of the point made previously in this text that natural uranium is the nuclear fuel at Calder Hall and enriched uranium the seed fuel at Shippingport. Magnesium was the material used in the fuel cladding at Calder Hall and Zirconium at Shippingport. Zirconium is much more expensive than magnesium. In a PWR, where water contacts the cladding, corrosion is much severer than in a Magnox reactor where only gaseous CO_2 contacts it, and that was seen as a plus for Magnox.

By the time the report was published, PWR at Shippingport was a *fait accompli* as was Magnox at Calder Hall. A major part of the reason for the study was to advise on which type of reactor Japan should go for when it began nuclear powered electricity generation. In fact the Tōkai 1 nuclear power plant, the first in Japan, was of the Magnox type [26]. It operated from 1966 to 1998 at 160 MW_e. Japan ceased to be an occupied country in 1952, but there was US involvement in its post-war reconstruction until considerably later. That probably explains the anomaly of a USAEC study for the benefit of Japan.

2.5 YANKEE ROWE (MASSACHUSETTS) POWER PLANT

This was in operation from 1960 to 1992 and had a capacity of 167 MW [27]. It used a PWR and light water as a neutron moderator. The plate below shows the reactor at Yankee Rowe on arrival from manufacture by Babcock & Wilcox prior to its installation in the vertical position.

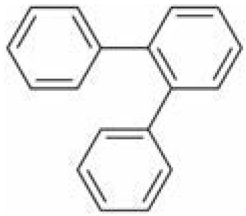
Reactor vessel at the Yankee Rowe nuclear power plant. Image taken from [27].

This power plant was originally intended to operate for at least 40 years, but was closed down after considerably less time than that. The difficulty was in the vessel and its embrittlement. Reference to any generic diagram of a PWR will show that the axial length of the fuel rods is much less than that of the reactor vessel holding them, and the parts of the vessel inside wall at the same vertical level as the fuel rods (the 'beltline region' of the reactor) will be particularly susceptible to embrittlement by flux of escaped neutrons. See also the discussion of the Leibstadt nuclear power plant in Switzerland.

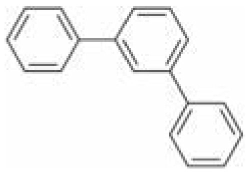
2.6 PIQUA NUCLEAR GENERATING STATION [28]

Located in Piqua Ohio 80 miles from Cincinnati, this operated at 11 MW for distribution over the period 1963-66. In fairness it was seen as being a demonstration project so the short period of service does not necessarily mean that it was a failure. It was however the only foray the US Atomic Energy Commission made into organic cooled reactors. As shown in the illustration this power plant used an organic heat transfer fluid at Piqa and this also acted as a neutron moderator.

The reactor building at the Piqua power station. Image taken from [28]. The coolant was a mixture of terphenyls (see facing column).



ortho-terphenyl



meta-terphenyl

para-terphenyl

The three isomers of terphenyl. Image taken from Wikipedia.

2.7 EARLY NUCLEAR POWER PLANTS IN CONTINENTAL EUROPE

These are listed in tabular form below and comments follow.

Chinon power plant, France [29].	Commissioned in 1964-66 with three 'gas and graphite' reactors using natural uranium, all of which had been decommissioned by 1990. Currently uses a PWR (see the next chapter) .
Arbeitsgemeinschaft Versuchsreaktor (AVR) Jülich, Germany [30].	Producing 15 MW of electricity from 1967-1988 at which time Jülich was in the German Federal Republic a.k.a.
 AVR reactor in Jülich, Germany. Image taken from Wikipedia.	Bundesrepublik Deutschland, BDR or West Germany. Pebble bed reactor: enclosure of the enriched uranium fuel in graphite which therefore acts as a neutron moderator. Thorium-232 also present. Helium as the heat exchange fluid. See also the description of the HTMR-100 small modular reactor in Chapter 8.
Dodewaard nuclear power station, the Netherlands [32]. Facing: The Dodewaard nuclear power station as it now stands in partly decommissioned state. Image taken from [33].	In operation 1968-1997. BWR. 55 MW of electricity.  Operational from 1964-1990 at 260 MW of electricity. PWR.

Enrico Fermi nuclear power plant, Trino, Italy [34]. Also in Italy: Garigliano nuclear power plant, operational from 1964-1982. Latina nuclear power plant, operational from 1963-1987. Details of each in the main text.	Closure three years after a referendum in which it was decided not to build new nuclear power plants in Italy [35].

The original reactors at Chinon clearly had a great deal in common with Magnox reactors – CO_2 as a heat exchange fluid, graphite as a neutron moderator – and were known as Uranium Naturel Graphite Gaz (UNGG) reactors. They were later to be used at other French nuclear power plants including that at **Saint-Laurent-Nouan**, commissioned 1969 and now using PWR. No UNGG reactors remain in service anywhere. (See also the coverage of the Bugey nuclear power plant in Chapter 3).

In the AVR (second row of the table) there was thorium-232 present additionally to the enriched uranium as noted in the table. Thorium-232, itself fertile, on neutron capture gives uranium-233 which is fissile and does not occur naturally. This is an example of breeding, using not uranium-238 but thorium-232. The AVR was seen as providing useful guidance in the development of these more recent reactors. There is more on uranium-233 in section 6.1.2.

There is major interest in thorium as a nuclear fuel in India as described in Chapter 6. Even so, there has up to the present time been surprisingly little interest in electricity using thorium as a nuclear fuel*. There was a breeder reactor using thorium in use at Shippingport PA over the period 1977-1982 [31], a later period than that of the other reactors in this chapter.

It initially contained uranium-233 (fissile) and thorium-232 (fertile), and after the five year operating period there was 1.4% more of the fissile nuclide than initially [36]. Neutrons from the fissile nuclide were slowed down by a reactor before application to the fertile nuclide. The reactor provided heat for electricity and used water as the heat exchange fluid. In the AVR heat from the helium is used to make steam to produce electricity at a turbine operating by the Rankine cycle. For the helium itself to enter a gas turbine and produce electricity operating by the Brayton cycle is obviously possible. There is a return to this theme in Chapter 8.

The remaining Dodewaard nuclear power station structure shown in the table will wait forty years from dismantlement and removal, and can be compared with Bradwell (section 2.1.4). The Garigliano nuclear power plant was of the BWR type and produced electricity at 150 MW [37] .

The Latina power plant originally used a Magnox reactor. In 1972 this was replaced by a CIRENE reactor, an Italian design applied for the first time at Latina having been developed there [38]. This used light water as a heat exchange fluid and heavy water as a neutron moderator. Magnox of course uses carbon dioxide and graphite respectively. Heavy water is often a better choice than light water as a neutron moderator as it has a lower propensity to neutron absorption and that makes for neutron economy. The larger the neutron absorption cross section of a material the more probable it is that a neutron encountering it will be captured. For thermal neutrons, light water and heavy water have neutron absorption cross sections of respectively 0.66 and 0.0013 barn [39] where 1 barn = 10^{-28} m^2. Graphite, also frequently used as a neutron moderator as noted, has a value of 0.0035 barns [39].

* ‘It’s possible to have a Ph.D. in nuclear reactor technology and not know about thorium energy.’ Attributed to Kirk Sorensen, a leading expert in the field [27].

It was mentioned that saturated steam is used at Shippingport and this is so anywhere. Superheating of the steam in nuclear power generation (PWR or BWR) has not yet gone beyond 'concepts' e.g. [40] in which it is proposed that a fossil fuel might be used to effect the superheating and [41] in which it is suggested that solar energy might be so used. The book will now move on to a country-by-country coverage of recent and current nuclear power generation, starting with countries of the EU. MH-1A nuclear power plant entered service during the period covered by this chapter but on account of its having been a floating nuclear power plant it will be described in Chapter 8.

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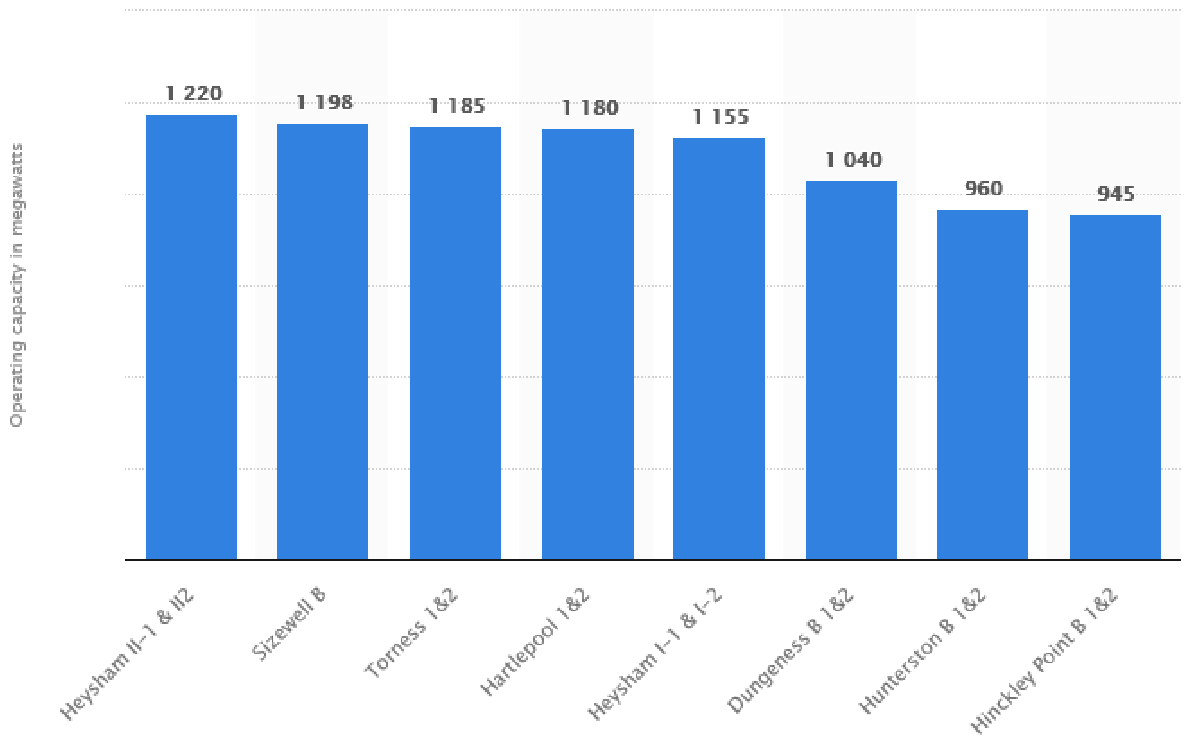
3 COUNTRIES OF THE EU AND NON-EU EUROPEAN COUNTRIES

3.1 THE UK

Brexit came into force just as this book went to press, and the UK will be covered in this chapter. The illustration below gives details of UK nuclear power stations in descending order of capacity. Note that the capacities do not vary greatly.



UK nuclear power plant locations and capacities. Taken from [1].

There are two nuclear power plants at Heysham each having two reactors, and they feature separately in the diagram above. The first (Heysham I) came into operation in 1983 and the second (Heysham II) in 1988. Each of the total of four reactors has cooling with carbon dioxide and neutron moderation by graphite and so owes something to the Magnox design, but unlike the Magnox reactors those at Heysham use enriched uranium as fuel. Such reactors are often referred to as Advanced Gas-Cooled Reactors (AGR) [2] and unlike Magnox reactors they were not commissioned as a means of making plutonium (see section 2.1.2).

A document relating expressly to Heysham [3] gives an account of refuelling procedures for nuclear reactors. This uses a 'refuelling machine', which consists of a crane capable of horizontal movement as well as a vertical. Refuelling can be carried out with (off-load refuelling) or without (on-load refuelling) cessation of reactor operation and it is noted that there has been off-load refuelling at Heysham II.

Sizewell B power station on the East Anglian coast has a PWR, the only one in the UK [4], and uses enriched uranium. It began supplying to the grid in 1995. As recorded in section 2.1.4, previously there was a Magnox reactor at the same location known as Sizewell A, and this was decommissioned in 2006. Whether heat is made available by chemical (conventional fuel) or nuclear means electricity generation using a steam turbine is according to the Rankine cycle. With coal-fired power plants efficiency usually means overall efficiency, that is, the electrical energy produced divided by the heat from the coal. It would be less straightforward to express efficiencies in that way for nuclear power plants where burnup is across a wide range and so strongly influenced by neutron supply. The efficiency of a nuclear power plant almost always means the Rankine efficiency, which depends on the enthalpy of the steam at turbine entry and at turbine exit.

The two turbines at Sizewell B are each 660 MW and that there are similar turbines at Drax, once the largest coal fired power station in the UK and now using biomass fuel, has been noted and commented upon [5]. Sizewell B practices offline refuelling. The Torness nuclear power plant in south east Scotland has two AGRs [6] as does the facility at Hartlepool [7]. There has been online refuelling at Torness.

At nuclear power plants, used nuclear fuel can stored under water in the 'used fuel pool', the size of which can determine the total period of service of the power plant. (See the discussion in Chapter 4 of the Laguna Verde nuclear power plant in Mexico.) The used fuel pool at Sizewell B approached its capacity in 2015, and continued operation of the plant was made possible by the use of dry storage of spent fuel in vessels comprising a metal canister encased in steel and concrete.

Dungeness I and II are discussed in section 2.1.4 as is Hunterston A. Hunterston B power station, on the west coast of Scotland, has two AGRs [8]. Decommissioning of this power plant is expected to begin in 2023. The same date is set for the decommissioning of Hinkley point B in south west England, which also has two AGRs. (See also the discussion of the Chooz B nuclear power plant in France.) Hinkley Point B also featured in Chapter 2.

There is no nuclear power generation in Ireland, either in Ulster or in Eire.

3.2 FRANCE

Nuclear power contributes 72% of the electricity produced in France [8]. The Chinon power plant, now long decommissioned, was described earlier in this book. French nuclear power plants currently in operation are listed in the table below which is followed by comments. All of the power stations in the table are operated by Électricité de France (EDF) sometimes with a co-operator.

Belleville nuclear power plant, central France [9].  The twin cooling towers at Belleville. Image taken from [10].	2 × 1300 MW PWRs supplied by Framatome, HQ in Paris. Commissioned 1988-89. Decommissioning expected in 2028-2029.
Blayais nuclear power plant [11].	4 × 910 MW PWRs. Commissioned 1981-83. Two of the reactors licenced for MOX (see main text).
Cattenom nuclear power plant [16] north east France, 10 km from the Luxembourg border.	4 × 1300 MW PWRs. Commissioned 1987-1991.
Paluel nuclear power plant, Normandy.  Image taken from Wikipedia.	4 × 1330 MW PWRs. Commissioned 1984-1986. Located at the English Channel.
Bugey nuclear power plant [18].	2 × 880 MW PWRs. 2 × 910 MW PWRs. Originally a 540 MW reactor using CO_2 and a graphite neutron moderator. Closure of all of the reactors in the near future.

Tricastin nuclear power plant.  Greenpeace protest at Tricastin in 2013. The words in bold capitals mean 'Ready to pay the price?'. Image taken from [20].	4 × 915 MW PWRs [19]. Commissioned 1980-81.
Chooz B nuclear power plant.  Chooz B nuclear power plant. Image taken from [24]. Water for power generation is taken from the Meuse River in the foreground.	2 × 1500 MW PWRs. Commissioned 2000 [22]. Chooz A, also PWR, shut down and being decommissioned [23].  Final removal of one heat exchanger from Chooz A. Image taken from [25].
Civaux nuclear power plant near Poitiers [29].	2 × 1450 MW PWRs. Water from the nearby River Vienne.
Dampierre nuclear power plant [31].	4 × 890 MW PWRs. Commissioned 1998-99. Supplied with water from the River Vienne.

Cruas nuclear power plant [33].  Cooling tower art at the Cruas nuclear power plant. It required 4000 litres of paint. Image taken from [34].	4 × 915 MW PWRs. Commissioned 1983-84. Water from the Rhône River.  One of several replacement heat exchangers installed at Cruas in 2017 (more details in the main text). Image taken from [35].
Gravelines nuclear power plant [36].	6 × 900 MW PWRs. Commissioned 1980.
Golfech nuclear power plant [37].	2 × 1363 MW PWRs. Commissioned 1991.
Nogent nuclear power plant [38].  Cooling towers at the Nogent nuclear power plant, 120 km S.E. of Paris. The river is the Seine. Image taken from [39].	2 × 1300 MW reactors. Commissioned 1987.
Penly nuclear power plant near Dieppe [41].	2 × 1382 MW. Commissioned 1990.
St. Alban nuclear power plant [42].	2 × 1335 MW. Commissioned 1986-87.
St Laurent nuclear power plant [43].	2 × 956 MW Previously referred to as having used UNGG. PWR since 1990.

Note the Loire River at the bottom left of the illustration of the Belleville nuclear power plant. Water for the plant is taken from this. Reference [11] gives 26380 GWh as the amount of electricity produced at the Blayais nuclear power plant (next row of the table). Comparing with the maximum possible amount according to the nameplate capacity, which is:

$$3640 \times 10^{-3}\ \text{GW} \times (365 \times 24)\ \text{h} = 31886\ \text{GWh}$$

the capacity factor is:

$$(26380/31866) \times 100\% = 83\%$$

a value confirmed in [10] in which it is stated that a capacity factor over the lifetime of the power plant of about 75% would be expected.

It is noted in the table that two of the reactors at Balyais are licenced for use of mixed oxide fuel (MOX). There is some interest in France of interest that in the use of mixed oxide fuel (MOX) in nuclear power generation [12]. MOX comprises plutonium from nuclear waste with a suitable uranium-containing fuel, for example low enriched uranium (LEU). A digression into MOX follows. In the Magnox reactors of the 1950s, manufacture of plutonium was the primary process with electricity generation as a bonus. That is not so with more recent nuclear power generation which, nevertheless, does produce plutonium. Two thirds of it is plutonium-239 which is fissile [13] and is almost absent from naturally occurring plutonium as noted in Chapter 1. A popular web site states [14] ‘One gram of plutonium 239 can generate as much electricity as one ton of petrol’. This is examined below.

First of all, ‘as much electricity’ will be taken also to mean ‘as much heat’.

1 ton = 907 kg. This amount of petrol will release 907 × 45 MJ = 41 GJ of heat on burning.

Reference [15] gives a fission energy for plutonium-239 of 210 MeV (see also section 2.1.2). 1 g of the isotope will release on fission:

The Avogadro number

↓

$$(1/239) \times 6 \times 10^{23} \times 210 \times 10^{6} \times 1.60 \times 10^{-19}\ \text{J} = 84\ \text{GJ}$$

↑

eV to J

so the statement in [13] is correct to within a factor of two and errs in favour of the nuclear fuel.

There is more on MOX fuels in later chapters, especially those relating to the USA and to Japan.

The Cattenom power station (next row of the table) averages (since 2014) 35547 GWh annually giving a capacity factor of:

$$[35547\ \text{GWh}/(5200 \times 10^{-3}\ \text{GW} \times 365 \times 24\ \text{h})] \times 100\% = 78\%$$

The proximity of the Paluel nuclear power plant to the English Channel is noted in the table. A notable accident in the ‘slips, trips and falls’ category occurred at this power plant in 2016 when a 465-tonne steam generator being removed prior to replacement dropped on to the floor of the reactor enclosure [17]. There were no serious consequences.

The gas cooled reactor with a graphite moderator once used at Bugey (next row of the table) was of the UNGG design which as noted in a previous chapter was once used at Chinon. At Tricastin (next row of the table) water supply is from an adjacent canal reinforcement of which, to make it safer in the event of an earthquake, will have been carried out by 2022 [21].

Chooz B is operated by EDF and by Sena (Société d'énergie nucléaire Franco-Belge des Ardennes). The turbines (two) at Chooz B are in the Arabelle series manufactured by GE, and the range now extends to 1750 MW of electricity [26]. Steam turbines of this capacity are not used in power generation from conventional fuels. An Arabelle turbine is under construction for use at Hinkley Point in England, [27], where one nuclear power plant (A) has been decommissioned and another (B) will be decommissioned in the early 2020s. The newbuild power plant at Hinkley Point will be called Hinkley Point C and will use two PWRs. That is a move away from AGR which as noted is a descendant of Magnox. The Flamanville nuclear power plant in France, not yet commissioned, will use an Arabelle steam turbine [28]. This theme is continued in the discussion in Chapter 7 of the Taishan nuclear power plant in China.

At the Civaux nuclear power plant (next row of the table), which also uses Arabelle steam turbines, there were water supply issues during the unusually hot summer of 2019 [30]. The Dampierre power plant (next row of the table) was considered for future decommissioning costs which, it was argued [32], can be applied to other French nuclear power stations. A figure of €300 million per GW of capacity for decommissioning of the nuclear power plants in France was thus arrived at, and it is pointed out [32] is lower than such estimates for Germany and the UK.

With reference to the Cruas nuclear power plant (next row of the table), a reminder that in a PWR steam generation is by heat transfer from water having itself received heat from the nuclear fuel is helpful. That is why such heat exchangers are often called steam generators and a single reactor can have multiple 'steam generators' in that sense. Three new ones were installed at one of the reactors at Cruas in 2017, one of which is illustrated in the table. In an interesting example of process integration, fluid exiting the turbines at Gravelines nuclear power plant is diverted to local aquafarming. At the very early planning stage of the Golfech nuclear power plant UNGG reactors were proposed. In the event PWRs were used as recorded in the table.

The Nogent nuclear power plant has been identified as a possible scene for industrial symbiosis, that is, supply of heat from the turbines to local industry [40]. That a card and paper factory is located 3.2 km from the plant and a malt factory 2.4 km from it is noted. The study extends to a number of the other nuclear power plants featuring in this section of the book, for example Gravelines where there is a pharmaceuticals plant only half a kilometre away. Supply of heat to that would have to be additional to the supply to aquafarming. Low-quality steam would have to be the means of export of heat from the power plants to such external users. In 2019 EDF announced its intention to add two advanced PWRs to its national structure and Penly (next row of the table) is a possible location for these.

The nameplate capacities in the table add up to ~ 55 GW. If Flamanville is included the total is 58 GW. The discussion will now move on to Spain, which has a 400 mile border with France. It has a nuclear electricity generating capacity about 12% that of France.

3.3 SPAIN

Again a tabular approach with comments, annotations and illustrations will be followed. Only nuclear plants still in service will feature.

Almaraz nuclear power plant [44].	2 × 1000 (approx.) MW PWRs. Commissioned 1981-83.
Ascó nuclear power plant [46].  Dry spent fuel storage at Ascó. Image taken from [47].	1 × 933 PWR and 1 × 943 PWR. Commissioned 1984-86.
Trillo nuclear power plant [48].	1 × 1066 MW PWR. Commissioned 1988.
Cofrentes nuclear power plant [49].  Image taken from [49].	Commissioned 1985. One 1092 MW boiling water reactor (BWR).

Vandellós II nuclear power plant [50].  Post-turbine water from Vandellós II in a channel awaiting discharge into the sea. Image taken from [51].	1 × 1087 MW PWR. Replaced Vandellós I which was 'graphite and gas' and similar to UNGG [52].

It is expected that at the Almaraz nuclear power plant (first row of the table) one reactor will close permanently in 2027 and the other in 2028 [45]. It is also expected that the year 2035 will see total cessation of nuclear powered electricity in Spain. Like Sizewell B in England, the Ascó nuclear power plant (next row) practices dry storage of spent fuel (see illustration in the table). At Trillo (next row of the table) plans in the 1980s for a second, equivalent reactor did not come to fruition. The reactor at Cofrentes (next row of the table) is a BWR, so the steam is generated by heat from the reactor without an intermediate water stream as in a PWR. Nor in a BWR is there carbon dioxide as a heat transfer fluid as in a Magnox reactor. In a BWR, once water has evaporated because of heat from the nuclear reaction the steam itself transfers heat to the influx water and so does the job of a heat transfer fluid. It differs from the action of carbon dioxide in that with the latter there are no phase change effects ('latent heat'). Vandellós II nuclear power plant (next row of the table) is at the Mediterranean coast.

The Spanish term for nuclear fuel is combustible nuclear, where here 'combustible' is a noun. This usage is also common in Argentina. This is perhaps no more potentially misleading than to talk of the burning of a nuclear fuel, and that is perfectly standard.

3.4 THE NETHERLANDS

The only nuclear power plant in the Netherlands is that at Borssele [53]. It has a 482 MW PWR and has since 2014 used mixed oxide (MOX) fuel [54] concurrently with enriched uranium. Initially, eight MOR fuel assemblies were installed in the PWR there and twelve more have been installed annually since (it was not necessary to take the reactor out of service for that). There can be hundreds of fuel assemblies in a PWR reactor.

3.5 GERMANY

The map below shows the location of nuclear power plants in Germany and includes those operating and those having exited service. Those out of service, with dates of cessation of operation in brackets, are Brunsbüttel (2007), Krummel (2009), Unterweser (2011), Grafenrheinfed (2015), Biblis (2011), Gundremmingen (2017). Those still in service will be considered in turn. Sometimes, as at Neckarwestheim and at Isar, one reactor is currently in service there having previously been more than one.

Taken from [55].

The Brokdorf nuclear power plant, commissioned in 1986 [56], has one PWR capable of producing 1440 MW of electricity which uses MOX in some of its fuel assemblies. Water for the plant is taken from the nearby River Elbe and returned there. The Grohnde nuclear power plant uses a single PWR producing 1403 MW of electricity. Some of its 193 fuel assemblies contain MOX fuel [57]. The Emsland nuclear power plant also has a PWR with 193 fuel assemblies [58]. Its capacity is 1363 MW. Applications for the dismantlement of Neckarwestheim and Phillipsburg have been submitted [59]. A single 1410 MW BWR operates at Isar. The attitude of Germany towards nuclear power hardened as a result of the 2011 earthquake in Japan and its effects on the Fukushima nuclear power plant [60]. A separate part of this book describes nuclear power in Japan.

3.6 BELGIUM

There are two nuclear power plants in Belgium: Doel with four reactors and Tihange with three, and the combined capacity is 5.9 GW of electricity [61]. The Doel nuclear power plant is 25 km from Antwerp and the details of its reactors are below. Information has been taken from [62].

Doel 1: 412 MW of electricity, commissioned 1974.
Doel 2: 454 MW of electricity, commissioned 1975.
Doel 3: 1056 MW of electricity, commissioned 1982.
Doel 4: 1041 MW of electricity, commissioned 1985.

They are all PWRs. For a period, waste from the reactors was processed into MOX which was then used for reactor 3. Tihange nuclear power plant has three PWRs which were installed over the period 1975-85 and have a combined generating capacity of 3 GW [63].

3.7 BULGARIA

The Kozloduy nuclear power plant (KNPP) in Bulgaria originally had six reactors but now operates with only two, both PWRs [64]. Their combined output is 2000 MW. A canal transfers water 7 miles from the Danube to the power plant for steam raising. The PWRs are VVER (Vodo-Vodyanoi Energetichesky Reaktor), of Russian design [65]. Such reactors are termed VVER-X where X is the nameplate capacity in MW of electricity. Those at KNPP are VVER-1000. A VVER-1000 reactor has 163 fuel assemblies and 312 fuel rods per assembly. Electricity generated by nuclear fuels has been exported to Greece. VVER continues into the discussion of the Czech Republic below. VVERs also feature in the chapter on Russia.

3.8 THE CZECH REPUBLIC

This has two nuclear power plants: Dukovany (below left) with four VVER-440 reactors and Temelin (below right) with two VVER-1000 reactors [66].

Dukovany. Image taken from [67].

Temelin. Image taken from [68].

Gadolinium oxide Gd_2O_3 is sometimes incorporated into fuel rods in nuclear energy production to achieve control by 'neutron poison'. This is blended with the nuclear fuel and restricts its reactivity where that is desirable. Recently Dukvany has gone to a fuel containing some Gd_2O_3 in addition to enriched uranium [69]. It is called RK3+ modified VVER-440 fuel. Gd_2O_3 is 'burnable', by which is meant the following. Gadolinium-157 is very effective at absorbing neutrons and in so doing it goes to gadolinium-158 which is an extremely poor neutron absorber. That means that neutron poisoning and production of neutrons from the fuel decline together, making for stability [70]. Another element used in neutron poisoning is boron (see the discussion of the Davis-Besse nuclear power plant in Ohio). Slovakia, also part of the former Czechoslovakia, has the Bohunice nuclear power plant and the Mochovce nuclear power plant. Each has two VVER-440 reactors [71].

3.9 FINLAND

There are two nuclear power plants in Finland, both in the south of the country [72]. One is Loviisa where there are two VVER-440 PWRs and the other is Olkiluoto where there are two 880 MW BWRs. In relation to Loviisa, use of VVER reactors in a country which was never part of the Eastern Bloc is moderately prevelant (see also the discussion in Chapter 5 of the Kola nuclear power plant in Russia and that of the Bushehr nuclear power plant in Iran in Chapter 7.) During a recent outage for refuelling of one of the reactors at Olkiluoto, ten TRITON 11™ fuel assemblies were installed each containing 109 fuel rods [73]. These use of water as a moderator was by means of water rods in the assemblies. That a neutron poison might be used to absorb neutrons from a nuclear fuel we have already seen, but it might be desired to control 'parasitic absorption' of neutrons by the spacer grid, which supports the fuel rods in a fuel assembly consistently with neutron economy. Such control can be realised by the spacer grid design (avoidance of excess quantity) and the material used to fabricate it (a small neutron capture cross section), and TRITON 11™ makes provision for this [74].

'Neutrons in motion are the starting point for everything that happens in a nuclear reactor.' So states a World Nuclear Organisation document [75], and in the introductory chapter of this book it was stated that neutrons 'drive' a nuclear process. What has been said in the preceding paragraphs of this book is totally consistent with that. There is a return to Finland in the final section of the chapter.

3.10 SWEDEN

The Ringhals power plant has one BWR and three PWRs and at nameplate capacity 4 GW is the largest power plant of any sort in Scandinavia [76]. This BWR has been in use for over 40 years. Also in Sweden is the Forsmark nuclear power plant which has three BWRs and a total nameplate capacity of 3.3 GW [77]. The Oskarshamn nuclear power plant on Sweden's Baltic coast now has only a single BWR, which is capable of producing 1450 MW of electricity and one of the largest BWRs in service [78].

Water streams in a nuclear reactor will briefly be reviewed. In a BWR a single water stream receives heat from the nuclear fuel and becomes steam. In a PWR a stream of water receives heat from the nuclear fuel and passes on the heat at a heat exchanger ('steam generator') to another stream which evaporates to form steam. Where, was explained above in relation to TRITON 11™, there are 'water rods' as neutron moderating devices that is another 'stream'. That is in the 'nuclear part' of the power plant. In the 'non-nuclear part' is water for removal of heat from steam having exited the turbine, which might be seawater as it is at all of the nuclear power plants in Sweden. If during a spate of hot weather the sea is warm that can affect cooling tower performance, and in the very hot summer of 2018 that necessitated shutdown of one reactor at Ringhals and reduction in output at Forsmark (though all three reactors remained in operation). Oskarshamn was not affected: it takes its seawater from a deeper level of the sea than the other two do, and the steep temperature profile of the sea ensures supply of cooler water.

3.11 SWITZERLAND

These are listed in the table below, which is followed by comments.

Beznau nuclear power plant [79].  Greenpeace activists at Beznau in 2014. Image taken from [80].	2 × 635 MW PWRs, entering service in 1969 and 1972 respectively.
Mühleberg nuclear power plant [81].	1 × 373 MW BWR. Commencement of operation in 1972.
Gösgen nuclear power plant [83].	1 × 1000 MW PWR (below). In service since 1979.  The reactor at Gösgen. Image taken from [84].
Leibstadt nuclear power plant [86].	1 × 1000 MW BWR. Operating since 1979.

The Beznau nuclear power plant is on an artificial island on the Aar river, from which water for steam production is obtained. The Mühleberg nuclear power plant is to be shut down for decommissioning at the end of 2019 [82], the first such decommissioning in Switzerland. Decommissioning is not on the agenda at Gösgen (next row of the table) where modernisation of the reactor protector system, which enables the reactor to be shut down by movement of the control rods to their maximum depth, is to take place at the next refuelling which is expected to be in 2022 [85]. It is intended that the reactor at the Leibstadt nuclear power plant (next row of the table) will operate until 2039, that is, for sixty years. It has been pointed out however [87] that if this is to happen improved fuel rod cladding will be necessary, otherwise the reactor itself might become unserviceable through neutron embrittlement. The reason for that is conversion of the kinetic energy to thermal on neutron impact.

3.12 HUNGARY

The Paks nuclear power plant 100 km south of Budapest has four VVER-440 reactors [88]. Expansion by two more reactors is under way [89]. These will be of the VVER genre though with some innovations and are expected to have a service life of 60 years [90].

3.13 SLOVENIA

The only nuclear power plant in this country is that at Krško which has one 696 MW PWR [91] using enriched uranium (up to 5% uranium-235) as fuel. Some of the electricity from it is exported to Croatia. Connected to the grid in 1983, the plant was expected to remain in service until 2023 [92]. Recent very positive reports on the condition of the reactor have encouraged a bid for an extension. Modifications required for the extension are in the 'non-nuclear' category, for example lighting and ventilation [93]. Such improvements have in any case been implemented quite widely in the nuclear power industry since 2011 when the Fukushima nuclear power plant in Japan was disabled by an earthquake..

3.14 ROMANIA

The Cernavoda nuclear power plant in the south east of the country has two CANDU 650 MW reactors [94]. CANDU means **Can**ada **D**euterium oxide **U**ranium: a Canadian design using natural uranium fuel and heavy water [95]. Deuterium in the acronym means deuterium oxide, heavy water. There is of course no elemental deuterium (D_2). This design of reactor obviously fits the desriptor PHWR. Light water is an effective neutron moderator, but it also absorbs neutrons, a point made in the previous chapter. With natural uranium as fuel this absorption can mean that there are too few neutrons for sustained reaction, therefore enhanced uranium fuel has to be used instead. With heavy water as moderator this neutron loss is avoided. That enables natural uranium to be used as the fuel. This is central to the CANDU concept. It is possible for a nuclear power plant to use heavy water for neutron moderation and light water as the reactor coolant. This will be discussed in the chapter dealing with India. More details of the CANDU reactor are, appropriately, given in the coverage of nuclear power in Canada, in particular in section 4.2.1.

3.15 BULGARIA

The Kozloduy nuclear power plant in the north west of the country has two VVER-1000 reactors [96]. They are expected to remain in service until the middle of the 21st Century. There were previously four other such reactors in service at Kozloduy and these are being decommissioned. Substances including metals and concrete contaminated with radioactive materials have to be got into a form suitable for long term disposal, and at the decommissioning at Kozloduy this is being achieved by plasma heating to consolidate such substances into a slag [97]. Recycling of the materials is precluded, and in some regulatory climates the view might be taken that carbon credits for the production of equivalent amounts of such materials are payable.

3.16 EU COUNTRIES WITHOUT CURRENT NUCLEAR POWER GENERATION

In alphabetical order these are Austria, Croatia, Cyprus, Denmark, Estonia, Greece, Italy, Latvia, Lithuania, Poland and Portugal. It would be legitimate for Austria to associate herself with the discovery of nuclear fission. The phenomenon was first reported in a letter to Nature in February 1939 authored by Lise Meiner and her nephew Otto Frisch [98]. Meitner was born in Vienna and graduated from the university there, and it was she who coined the term nuclear fission.

3.17 NON-EU COUNTRIES IN EUROPE

Such countries are Albania, Andorra, Armenia, Azerbaijan, Bosnia and Herzegovina, Georgia and Iceland. The only one producing nuclear power is Armenia. That is the Metsamor power station 'in the shadow of Mount Ararat' [99] an illustration of which is below. It currently operates one VVER-440 reactor. In 2016 this single reactor provided 33% of Armenia's electricity; the balance was from hydroelectric and gas, each about a third of the total.

The Metsamor power station in Armenia. Image taken from Wikipedia.

3.18 FURTHER COMMENTS

In 2021 work will begin on the construction of the Hanhikivi nuclear power plant in Finland, with a view to commencement of electricity supply to the market in 2028 [72]. There are no other grassroots nuclear power plant constructions under way in the EU at present. The Hanhikivi nuclear power plant will have one VVER-1200 reactor. It is close to the Baltic Sea, water from which will be used in the cooling towers. It is intended that it will remain in service until the 2070s, which will be 20 years beyond the centenary of the Obninsk nuclear power plant.

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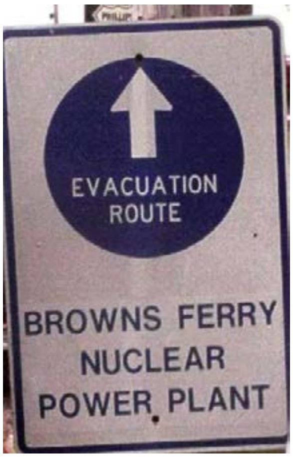
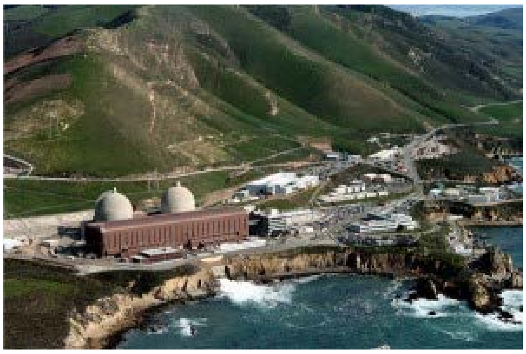
4 THE AMERICAS

4.1 USA: LISTING BY STATE

This is in the table below, which is followed by further information and comments. Again, only nuclear power plants currently in operation will be covered.

State.	Details of nuclear power plants.
Alabama.	Browns Ferry nuclear power plant. 3 BWRs, combined capacity 3297 MW [1]. Operated by the Tennessee Valley Authority.  Image taken from [2].
Arkansas.	Arkansas Nuclear One nuclear power plant. 2 PWRs, combined capacity 1776 MW [4].

State.	**Details of nuclear power plants.**
Arizona.	Palo Verde (PV) nuclear power plant. 3 × 1450 PWRs [5]. The largest nuclear power plant in the US.  PV nuclear power plant in Arizona. The body of water in the background is a reservoir for cooling tower water which, like the reactor water, is obtained from waste water (see main text). Image taken from [7].
California.	Diablo Canyon nuclear power plant. × 1110 PWRs [8].  Note the two reactors and the coastal location. Image taken from [9].
Connecticut.	Millstone nuclear power plant, located in Long Island Sound. Two PWRs, total capacity 2 GW [10].
Florida.	St. Lucie nuclear power plant. × 1000 MW PWRs [12]. Turkey Point nuclear power plant. 2 × 875 MW PWRs [13]. Fossil fuel generated electricity at the same site.

<table>
<tr><th>State.</th><th>Details of nuclear power plants.</th></tr>
<tr><td>Georgia.</td><td>Alvin W. Vogtle nuclear power plant.
2 × 1150 MW PWRs [17].
See also the discussion in Chaper 7 of the
Sanmen nuclear power plant.

Edwin I. Hatch nuclear power plant.
2 × 875 MW BWRs [20]. Each in service since the 1970s.</td></tr>
<tr><td>Illinois.

All owned by
Exelon Nuclear.</td><td>Braidwood nuclear power plant.
× 1175 MW PWRs [22].
Byron nuclear power plant .
2 × 1250 MW PWRs [26].

Byron nuclear power plant, showing the reactors and
the cooling towers. Image taken from [28].

Clinton nuclear power plant.
1 × 1062 MW BWR [29].

Clinton nuclear power plant, showing the distinctive sky blue reactor
building (left, a.k.a. a shield building). Image taken from [30].

Dresden nuclear power plant.
2 × 900 MW BWRs [33].

LaSalle nuclear power plant.
2 × 1150 MW BWRs [35].

Quad Cities nuclear power plant.
2 × 910 MW BWRs [37].
Commissioned in 1984.</td></tr>
</table>

State.	Details of nuclear power plants.
Iowa.	Duane Arnold nuclear power plant. 1 × 600 MW BWR [39]. Closure expected in 2020.
Kansas.	Wolf Creek nuclear power plant. 1 × 1200 MW PWR [41].  Wolf Creek nuclear power plant. The water in the foreground is a cooling pond (see main text). Image taken from [42].
Louisiana.	Waterford nuclear power plant ('Waterford Steam Electric Station'). 1 × 1240 MW PWR [43]. Closed down during Hurricane Katrina. River Bend nuclear power plant. 1 × 990 MW BWR [44]. Remained in operation during Hurricane Katrina. Both power plants authorised to remain in service until the 2040s [45]
Maryland.	Calvert Cliffs nuclear power plant. 2 × 850 MW PWRs [49].

State.	Details of nuclear power plants.
Michigan.	Enrico Fermi nuclear power plant. 1 × 1120 BWR [53]. Expected to continue operating until 2045.  Enrico Fermi nuclear power plant with Lake Erie in the foreground. Image taken from [54]. As reported in the chapter on the EU, there is also an Enrico Fermi nuclear power plant in Italy. Donald C. Cook nuclear power plant. 1 × 1020 MW PWR. 1 × 1090 MW PWR [55]. Palisades nuclear power plant. 1 × 850 MW PWR. Closure expected in 2022 [57].
Minnesota.	Monticello nuclear power plant. 1 × 650 MW BWR [59]. Prairie Island nuclear power plant. × 520 MW PWR [60].
Mississippi.	Grand Gulf nuclear power plant. 1 × 1400 MW BWR [62]. Commissioned in 1985.
Missouri.	Callaway nuclear power plant. 1 × 1150 MW PWR [63].

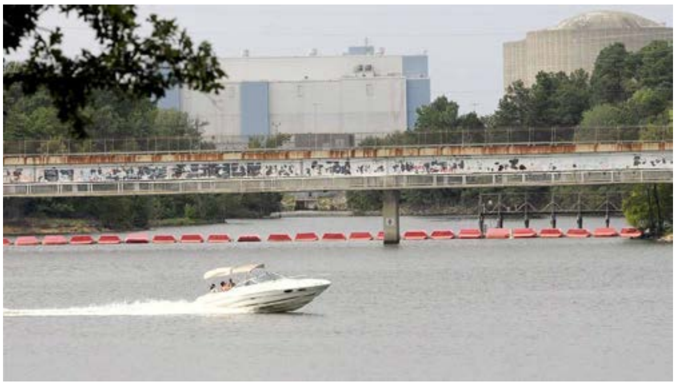
<table>
<tr><th>State.</th><th>Details of nuclear power plants.</th></tr>
<tr><td>Nebraska.</td><td>Cooper nuclear power plant.
1 × 810 MW BWR [66].

Cooper nuclear power plant, adjacent to the Missouri River. Image taken from NY Times.</td></tr>
<tr><td>New Hampshire.</td><td>Seabrook nuclear power plant.
× 1250 MW PWR [68].</td></tr>
<tr><td>New Jersey.</td><td>Hope Creek nuclear power plant.
1 × 1250 MW BWR [73]. Commissioned 1986.
Salem nuclear power plant.
2 × 1150 MW PWRs [74]. Commissioned 1977 and 1981.

The two are on the same site in Lower Alloways Creek NJ (see illustration below).

The Hope Creek BWR (left) and the two Salem PWRs (right). Delaware River in the foreground. Image taken from [75].</td></tr>
</table>

State.	Details of nuclear power plants.
New York.	Nine Mile Point nuclear power plant. In Scriba NY on the shore of Lake Ontario, 290 miles from Manhattan. 1 × 613 MW BWR. 1 × 1277 MW BWR [77]. Indian Point Energy Center (IPEC) nuclear power plant. In Bucahanan NY, 43 miles from Manhattan. 2 × 1020 MW PWRs [79] Cessation of operation expected in 2021 [80].
North Carolina.	Brunswick nuclear power plant. 2 × 930 MW BWRs [82]. McGuire nuclear power plant. 2 × 1185 MW PWRs [83]. Shearon Harris nuclear power plant. 1 × 928 MW PWR [84].  Shearon Harris nuclear power plant. Image taken from Wikipedia. See also the annotation on Three Mile Island in the row on PA.
Ohio.	Davis-Besse nuclear power plant. 1 × 894 MW PWR [85]. Perry nuclear power plant. 1 × 1256 MW BWR [88]. Both operated by FirstEnergy Solutions.

State.	Details of nuclear power plants.
Pennsylvania.	Beaver Valley nuclear power plant. 2 × 852 MW PWRs [89]. Limerick nuclear power plant [89]. 2 × 1090 MW BWRs Peach Bottom nuclear power plant. 2 × 1065 MW BWRs [89]. Susquehanna nuclear power plant. 2 × 1180 MW BWRs [89]. The Three Mile Island nuclear power plant in PA, where there was a major incident in 1979 which is frequently referred to, ceased electricity production in September 2019 [90]. In 2010 the electrical generator which had been used with the failed reactor at Three Mile Island was, after refurbishment, installed at the Shearon Harris nuclear power plant in North Carolina.
South Carolina.	Catawba nuclear power plant. 2 × 1185 MW PWRs [93].  Catawba nuclear power plant showing its lakeside setting and the two reactors. Image taken from [94]. H.B. Robinson nuclear power plant. 1 × 741 MW PWR [97]. Oconee nuclear power plant. 3 × 850 MW PWRs [99]. Virgil C. Summer nuclear power plant. 1 × 973 ME PWR [100].

State.	Details of nuclear power plants.
Tennessee.	Sequoyah nuclear power plant. 2 × 1220 MW PWRs [102]. Watts Bar nuclear power plant. × 1165 MW PWRs [103].
Texas.	South Texas Nuclear Project (STNP) power plant. 2 × 1280 MW PWRs [106]. Entered service 1988-89.  The STNP power plant in 2017. Image taken from [107]. Comanche Peak nuclear power plant. 2 × 1210 MW PWRs [108].
Virginia.	North Anna nuclear power plant 2 × 800 MW PWRs [114]. Surry Nuclear Power Plant. 2 × 838 MW PWRs [115].
Washington.	Columbia nuclear power plant. 1 × 1207 MW BWR [116,117].
Wisconsin.	Point Beach nuclear power plant 2 × 591 MW PWRs [118]. Both reactors in service since the early 1970s.

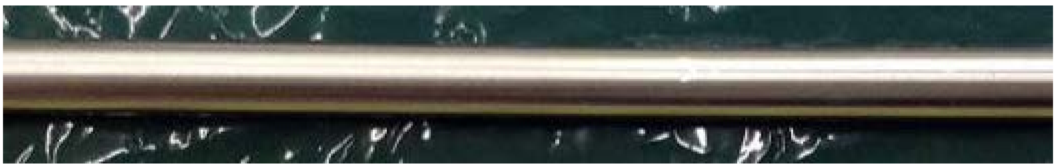
The Browns Ferry nuclear power plant when it first entered service in 1973 with a single BWR was the largest nuclear power plant in the world. The second reactor came into operation in 1974 and the third in 1976. Units 2 and 3 at the plant use nuclear fuel made from surplus weapons-grade uranium, which is high enriched uranium (HEU). That is diluted with natural uranium to make blended low enriched uranium (BLEU) for use at Browns Ferry. In the early days of operation of this nuclear power plant, actually in March 1975, there was a serious fire at Unit 1 when insulating material in an electrical cable tray was ignited [3]. It was noted in section 2.2.1 that in a BWR heat from the reactor provides directly the heat of vaporisation to produce steam, there being no 'steam generator' in the sense of that term in nuclear engineering. At the Browns Ferry accident the fire at the cable tray affected the power supply to the pumps conveying water to the reactor. By the time these failed the ECCS - Emergency Core Cooling System – pumps had been brought into operation but even so there was a rapid drop in the level of water in the reactor and the reactor had to be shut down.

Arkansas Nuclear One is expected to be in operation until well into the 2030s. It is noted in [4] that no new nuclear reactors for power production are under construction in or for the US. The pressurised water reactors at Palo Verde (next row of the table) are of the type termed System 80, which was developed by Combustion Engineering, HQ in Chattanooga

TN. This nuclear power plant is highly unusual in its desert location and distance from water supply. Its water for steam raising is derived from the municipal waste water of Phoenix AZ and is purified before use [6]. The Diablo Canyon nuclear power plant in California (next row of the table) uses for steam raising desalinated seawater [9]. The desalination plant also provides household water for the local area at times of drought.

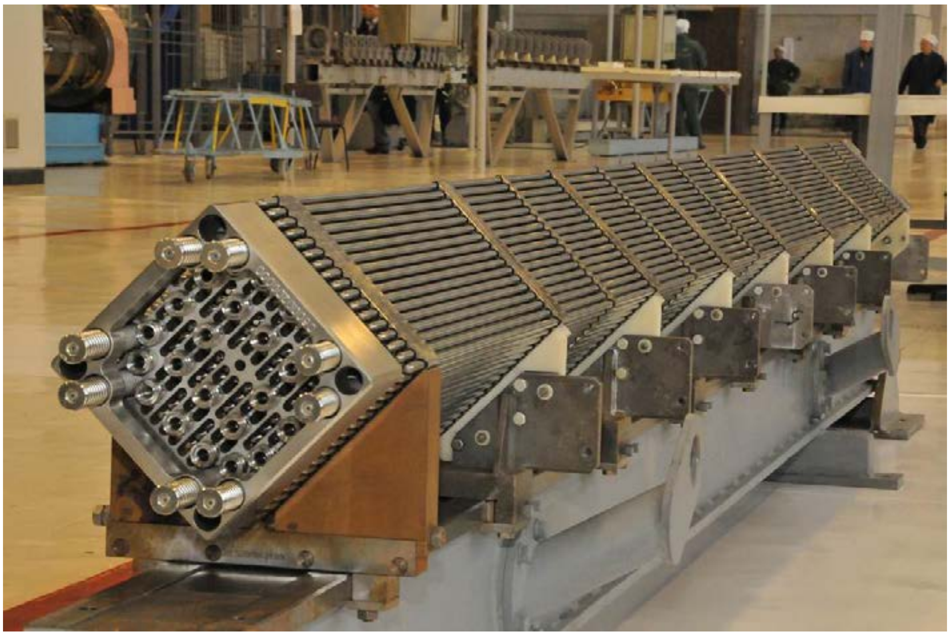
The Millstone nuclear power plant in Connecticut is expected to remain in operation until circa 2030 [11]. One of the PWRs there has been in service since 1975 and the other since 1986. Both of the nuclear power plants in Florida (next row of the table) were shut down at the approach of Hurricane Irma in 2017 [14]. Its speed on reaching the Florida coast was 185 m.p.h., placing it in Category 5 on the Saffir-Simpson scale [15]. A nuclear reactor is in shut down status when it is subcritical, achievable obviously by neutron control. This can be brought about by use of the control rods or by a neutron poison such as boric acid (see section 3.8) [16].

The Alvin W. Vogtle nuclear power plant in Georgia (next row of the table) will have two more reactors in operation by the early 2020s. These are Westinghouse AP1000® PWRs, each of capacity 1100 MW [18]. The advantage of these over predecessor designs is very much in the safety as evaluated by risk analysis [19]. The frequency of core damage by overheating in an AP1000® PWR has been estimated as 5.1×10^{-7} per year of operation. This unprecedentedly low figure for the frequency of core damage in a nuclear power reactor has been reviewed by the US Nuclear Regulatory Commission and accepted by it [19]. The 'large release frequency' for the AP1000® PWR is given as 5.61×10^{-8} per year of operation [19]. During a refuelling outage in 2018 at one of the reactors at the Edwin I. Hatch nuclear power plant two samples of IronClad, a material developed by GE in association with Oak Ridge National Laboratory, were installed in it. Neither contains fuel [21]. IronClad (below) is composed of iron, chromium and aluminium and is intended to become a material for cladding. Next time the reactor is refuelled the IronClad will be removed and examined, valuable R&D into its future use in cladding. One of the samples installed at Edwin I. Hatch had the structure of an empty fuel rod and the other was a solid bar.



IronClad, proposed material for fuel rod cladding currently being tested at the Edwin I. Hatch nuclear power plant in Georgia. Image taken from [21].

The nuclear power plant at Braidwood IL (next row of the table) was the first in the US to use the Russian TVS-Kvadrat fuel assembly [23]. Developed for VVER reactors, these have been increasingly applied to PWRs from western manufacturers including Westinghouse, so much so that manufacture of TVS-Kvadrat fuel assemblies has begun in the US. There are now 25 such fuel assemblies in service there [24]. ‘Kvadrat’ is Russian for ‘square’ and TVS stands for ‘**t**opli**v**naya **s**borka’ which means ‘fuel assembly’. The assemblies *are* square in cross section, the fuel rods being in a 17 × 17 arrangement as shown below. (See also the discussion of the Mitsubishi Advanced Pressurised Water Reactors in Chapter 4 and the discussion of the Rostov nuclear power plant in Chapter 5.)



The TVS-Kvadrat fuel assembly. The nuclear power plant at Braidwood IL was its proving ground in the US. Image taken from [25].

Byron nuclear power plant in Illinois is the tenth largest in the US and has been producing electricity since the mid 1980s [27]. At the Clinton nuclear power plant the dome on the reactor building (see the illustration in the table) is free standing, being held to the lower, cylindrical part of the structure only by gravity [31]. That helps relieve stress in the event of acoustic resonance during startup of the steam line after a refuelling [32]. The Dresden nuclear power plant in Illinois uses ATRIUM™ 10XM advanced boiling water reactor fuel [33]. This also uses fuel assemblies with a square cross section, though with a 10 × 10 arrangement of the fuel rods [34]. Dresden was the first nuclear power plant in the US after Shippingport and originally had a single BWR. The LaSalle nuclear power plant was commissioned in 1984.

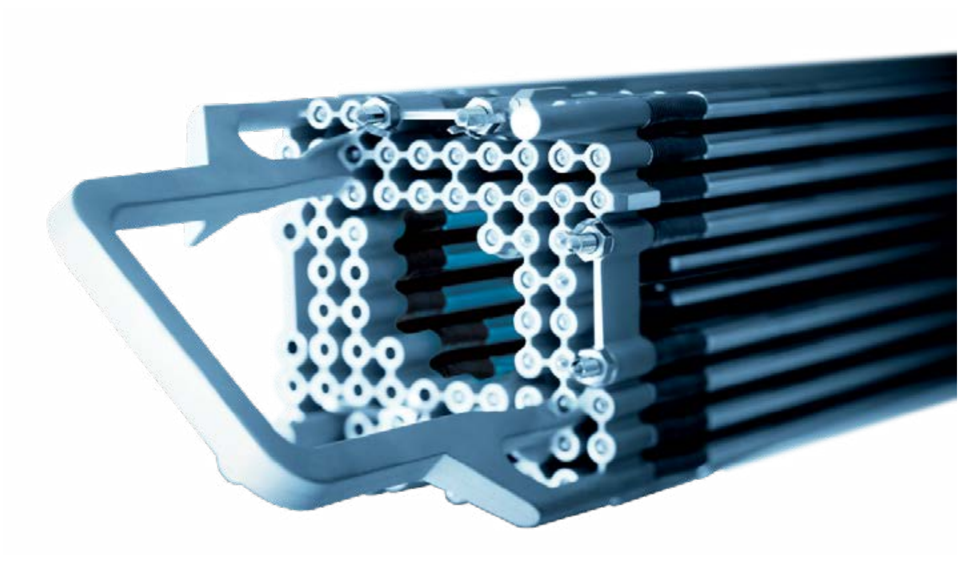
That in a BWR 'oscillations' in core power – rate of heat release – can occur is well known. The best known example of this was at the LaSalle nuclear power plant in March 1988 [36] when both random fluctuations and oscillations displaying periodicity were observed during a period of instability preceding emergency shutdown ('scram'). A document relating to the Quad Cities nuclear power plant, which follows LaSalle in the table above, states 'The reactor core, in conjunction with other equipment, is designed and operated to prevent the occurrence of uncontrolled [core] power oscillations' [38]. See also the account of the 1975 accident at the Browns Ferry nuclear power plant in Chapter 4.

The Duane Arnold nuclear power plant in Iowa (next row of the table) is scheduled for decommissioning as noted, and it is expected that Iowa will expand its wind power to make up the deficit [40]. Wolf Creek nuclear power plant in Kansas (next row of the table) has an artificial cooling pond with once-through cooling, that is, water for condensing the steam having been taken from the cooling pond is returned there at a higher temperature and evaporative losses are made up for by rainfall. During the warmer months the cooling pond can be topped up by water from the Neosho River. The power plant has no access to natural fresh or salt water for cooling.

Commissioned in 1985, the Waterford nuclear power plant had a new steam generator (in the sense of the term discussed in section 3.2 of this book) installed in 2012, an operation taking four months [46]. Below is a photograph taken during the steam generator replacement.

Installation of the new steam generator at the Waterford nuclear power plant, 2012-2013. The steam generator weighs 720 US tons and is 65 feet in length. Image taken from [46].

When applied to nuclear power generation the word 'fuel' often has less to do with the precise composition of the contents of the fuel rods than with the design and configuration of the fuel assembly. The River Bend nuclear power plant in Louisiana took delivery of a new 'fuel' in that sense in 2015 [47]. Manufactured by Global Nuclear Fuels in North Carolina this is called GNF-3 advanced fuel and consists of a fuel assembly of square cross section with a 10 × 10 assembly of fuel rods as shown below.



GNF-3 fuel assembly showing the 10 × 10 'lattice'. Image taken from [48].

The Calvert Cliffs nuclear power plant in Maryland (next row of the table) is one of a number in the US which have introduced ‘accident tolerant’ fuels, a term which was coined after the Fukushima accident in 2011 more details of which will be reported later in this text. In 2021 Calvert Cliffs will receive two ‘Enhanced Accident Tolerant’ fuel assemblies [50]. The basis of ‘accident tolerance’ is fairly simple. The nuclear fuel inside the rods is ‘doped’ with chromium oxide, and in a loss-of-coolant accident that restricts release of the product gases Kr and Xe, buying time before they can lead to a high pressure in the fuel rod [51]. This is a grain growth effect. In regular operation of a reactor the fission gases form bubbles between the grains. The dopant affects grain growth under loss of coolant conditions in such a way as to promote continued containment of the fission gas in bubbles, preventing its release. In an accident tolerant fuel, fuel rod cladding material of high thermal resistance is used. At Fukushima there were several hydrogen explosions, the hydrogen having originated with the steam at higher temperatures than it encounters in normal operation [52]. Such temperatures are less likely to occur if there is reduced heat transfer from the fuel rods. Chromium coated zirconium alloy is one of a number of cladding materials for accident tolerant fuels.

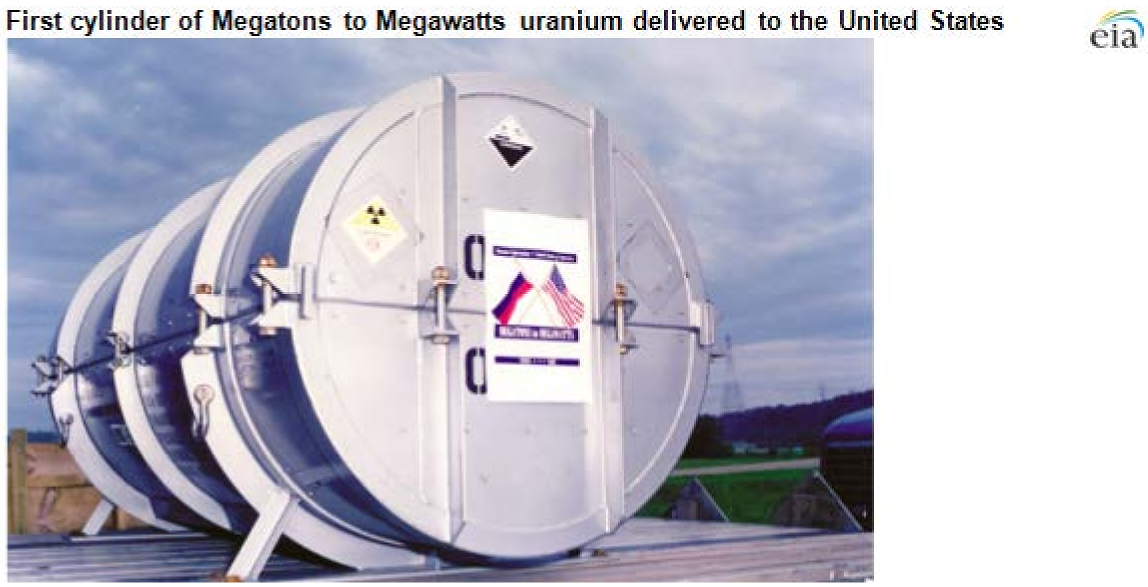
The Enrico Fermi nuclear power plant in Michigan (next row of the table) is on the shore of Lake Erie as shown in the illustration. Information in the table refers to the one reactor currently in service there, called Fermi 2, which was commissioned in 1988. The Donald C. Cook nuclear power plant has used ice condensation containment for its reactors [56]. This enables steam to be directed to baskets of ice in a loss of coolant incident, causing its condensation to the avoidance of pressure build-up and hydrogen formation. (See also the discussion of the McGuire nuclear power plant in North Carolina.) By the time it finally ceases operations the Donald C. Cook nuclear power plant will have been sold, and the purchaser will be responsible for the decommissioning. In order for that to be viable, the decommissioning cost will have to be below the sum allocated which is now in a decommissioning trust fund. The amount by which that exceeds the cost of a fully compliant decommissioning will be profit for the purchaser of the power plant in its redundant state [58]. The two nuclear power plants in Minnesota (next row of the table) are both operated by Xcel and are authorised to operate into the 2030s [61] beyond which extensions can be applied for, which is a likely course of events. Xcel currently operates two coal-fired power plants which it intends to have ‘shuttered’ by 2030. Even though the Xcel portfolio includes wind power and photovoltaic cells, continued nuclear powered generation will be necessary for the hoped for closure of the two coal-fired power plants. The reactor at Grand Gulf nuclear power plant in Mississippi (next row of the table) is extremely powerful. At a turbine efficiency of 35% the electrical power converts to 4 GW of heat.

In nuclear reactor engineering RVCH stands for **r**eactor **v**essel **c**losure **h**ead. This has to be lifted for refuelling [64]. The RVCH on the PWR at the Callaway nuclear power plant in Missouri (next row of the table) was replaced during an outage for refuelling in 2014 [65]. The new RVCH was made in Europe and taken to the US. Its journey to the power plant was partly by vessel and partly by road (see below).

Delivery of the new RVCH for the Callaway nuclear power plant. Left: Transportation by vessel along the Mississippi River. Right. Final transportation by road to the plant. Images taken from [65]. The RVCH weighs 180 tonnes and is 9 m in length (height).

The image in the next row of the table of the Cooper nuclear power plant in Nebraska shows its riverside location. During floods in March 2019 the river rose to within a metre of the plant [67]. Shutdown did not occur and there were no consequences. At the Seabrook nuclear power plant in New Hampshire (next row of the table) there are issues with the concrete at the containment structure and in the used fuel pool [69], both in the 'nuclear part' of the plant. The difficulty is ASR, alkali silica reaction. It is common enough in commercial and residential buildings, when the term 'concrete cancer' is sometimes applied. This is the first time that this has been observed at a nuclear power plant in the US. It has been observed [70] at the Tihange nuclear power plant in Belgium (see section 3.6).

The Cooper nuclear power plant was the first to use fuel from the Megatons to Megawatts Program [71] in which weapons grade uranium in the Russian nuclear arsenal was made suitable for power plant use and sold to the US (see illustration below). The programme ran from 1995 to 2013 and almost all of the nuclear power plants in the US became participants on the program. The program is seen as having been valuable in two ways. It provided about 10% of the fuel requirement of US nuclear power plants over a considerable period and it promoted dismantlement of Russia's nuclear weapons.



The first arrival, in 1995, of uranium in the US under the Megatons to Megawatts Program. Image taken from [72].

With reference to the Hope Creek and Salem nuclear power plants at Lower Alloways Creek in New Jersey, the cooling tower in the illustration in the table serves Hope Creek only [76]. Salem uses once-through cooling (see also the discussion of the Wolf Creek nuclear power plant in Kansas). Hope Creek postdates Salem in its commissioning, and fairly obviously it was concluded that the Delaware River could not support once-through cooling of both power plants. The smaller of the two reactors at the Nine Mile Point nuclear power plant in Scriba NY, having been in service since 1969, is the oldest nuclear reactor in power generation use in the USA [78]. It is expected that the Indian Point Energy Center nuclear power plant will be sold ahead of decommissioning which will therefore be the responsibility of the buyer as at the Enrico Fermi nuclear power plant in Michigan (see above) [81]. At the Brunswick nuclear power plant in North Carolina (next row of the table) water for steam generation is taken from the Cape Fear River and, after turbine exit, discharged into the Atlantic Ocean. The McGuire nuclear power plant uses water from an artificial lake originally part of a hydroelectric scheme. Like the Donald C. Cook nuclear power plant in Michigan, it has ice condensation for use in a loss of coolant incident.

At the Davis-Besse nuclear power plant in Ohio (next row of the table), boron in the form of boric acid has been used as a neutron poison (see section 3.8). In 2002 corrosion in the reactor vessel head due to contact with boric acid was discovered [86]. Over 30 kg of steel had in that way been lost from the vessel head. The reactor was taken out of service for two years, and the head was replaced with an unused one from the PWR at the mothballed nuclear power plant in Midland, Michigan, which was never completed [86],[87]. Viability in the medium term of the two nuclear power plants in Ohio has been assured by the award to the operator of $150 million per year in the form of zero emission credits [88]. That will continue up to 2026.

The future of the Beaver Valley nuclear power plant in Pennsylvania is very uncertain and closure in 2021 is probable [91]. It will have been in service for 45 years by then. The future of the Limerick nuclear power plant is brighter. Both of its reactors are authorised to operate until 2034, and no plans to bring forward the closure date have been announced. Similarly, the Peach Bottom nuclear power plant is expected to remain in operation until the middle of the 21st Century [92]. The Susquehanna nuclear power plant draws on the river of the same name for cooling. In what is a standard set-up, water from the river is heat exchanged with steam exiting the turbine. At the Catawba nuclear power plant in South Carolina (next row of the table) a novel material has been used for piping of service water replacing carbon steel pipe which has been in service at the plant for 30 years [95]. The replacement material is al-6xn® and is a stainless steel having a thermal conductivity of 11.8 W $m^{-1}K^{-1}$ [96]. That is only about a quarter of the value for a typical carbon steel.

On March 28th 2010 (coincidentally the 31st anniversary of the Three Mile Island incident) there was a fire at the H.B. Robinson nuclear power plant in South Carolina [98]. There was partial loss of power to the pump which takes water to the reactor, and the reactor shut down. The reactor being a PWR, water to the reactor does not become steam but exchanges heat with a further water stream at the steam generator which, as noted previously in the text, is a heat exchanger. The Oconee nuclear power plant in South Carolina is the fourth largest nuclear power plant in the US and was a participant in the Megatons to Megawatts program. At the Virgil C. Summer nuclear power plant in South Carolina the building of two new reactors was approved (see illustration below). Construction of the first of them began in March 2013, but it was not completed [101].

Construction work on reactor 2 at the Virgil C. Summer power plant in South Carolina. A 'containment ring' is being lowered into position. Image taken from [101].

Sequoyah nuclear power plant and Watts Bar nuclear power plant in Tennessee have been described [104] as 'sister plants'. Both are owned by the Tennesse Valley Authority. Each has ice condensation containment with the further feature of sodium tetraborate as a neutron poison (see section 3.8) which is present for the following reason. In the event of breakage of the pipe bearing pressurised water, water and steam contacting the fuel rod cladding can lead to loss of some of the the contents of the fuel rod and consequent transfer into the containment space [105]. Effects of that are mitigated by the presence of a neutron poison. Up to a point degradation of fuel rod cladding is not an issue in normal operation, but it creates this further hazard in a loss-of-coolant situation in a PWR.

The STNP power plant in Texas (next row of the table) operated at full power during Hurricane Harvey in 2017 [109]. Nuclear Regulatory Commission guidelines are that a nuclear power plant experiencing a hurricane shall be closed down if the wind speed exceeds 73 m.p.h. (Saffir-Simpson Category 1) and measured wind speeds at the plant were much lower than this, too low to be on the S-S scale at all [110]. Possible flooding was another factor, not so much of the plant as the roads to and from it if they became impassable. At the Comanche Peak nuclear power plant in Texas there were plans to expand by introduction of two new reactors. These were to have been Mitsubishi Advanced Pressurised Water Reactors (APWRs) each capable of generating 1700 MW of electricity [111-113]. They would have used fuel assemblies having 17 × 17 arrangement of fuel rods (see also the discussion of the nuclear power plant in Braidwood IL). The AWPRs obtain good return on the nuclear fuel by use of a neutron reflector (a 'nuclear factor') and by a good Rankine efficiency at the steam turbine (a 'non-nuclear factor'). In fact the APWRs for Comanche Peak still only have 'planned' status.

At the Surry nuclear power plant in Virginia, LEU is used as fuel [114]. In December 1986 four workers died from burns when there was escape of steam because of pipe rupture. This is the most serious accident in terms of fatalities in the history of the US nuclear electricity industry [115]. The accident did not of course have a nuclear origin, nor did it have a chemical one. The lethal factor was heat released by the water vapour on condensation. (See also the description of the Balakovo nuclear power plant in Chapter 5.)

'Uranium tails' are produced in the process of uranium enrichment and contain typically 0.3% of uranium-235. That contrasts with 0.72% of uranium-235 in natural uranium and (obviously) higher percentages in enriched uranium. The tails can themselves be enriched to produce nuclear fuel and there are proposals for the use of fuel from uranium tails at the Columbia nuclear power plant in Washington state (next row of the table). The longevity of the Point Beach nuclear power plant in Wisconsin is noted in the table. At present authority to operate extends to the early 2030s [119]. To raise the matter of decommissioning is not 'negative thinking', and for many engineering projects ease of eventual decommissioning has to be factored into commissioning. The estimated cost of decommissioning of Point Beach is $900 million at the 2018 value of the US dollar [119].

Both PWRs and BWRs are in use in the USA as recorded in the table. In 2013 the BWRs in aggregate had a burnup rate of 33.9 GW days per tonne of uranium and the PWRs in aggregate a had a burnup rate of 39.7 GW days per tonne of uranium [120]. These figures can be compared with those in section 2.1.2.

4.2 CANADA

4.2.1 ONTARIO

The Bruce nuclear power plant, adjacent to Lake Huron, comprises eight PHWRs – pressurised heavy water reactors – each of around 850 MW of electricity output [121]. As described earlier in this book, heavy water can be used as a neutron moderator, that is, it causes neutrons to decelerate without absorbing them like light water does. The reactors are of **Can**ada **D**euterium **U**ranium (CANDU) design, itself originating in Canada as explained in section 3.14 where use of such reactors in Europe is explained. Bruce is the largest nuclear power plant in North America and the second largest in the world. The reactor core in a CANDU reactor is called a calandria and uses natural uranium. It works in the following way. Horizontally positioned fuel rod bundles are supported in an outer tube called the pressure tube, and coolant (D_2O) passes through these and is heated by the fuel. Each of the pressure tubes is surrounded by another tube called a calandria tube through which heavy water as a neutron moderator passes. Carbon dioxide is passed through the annulus between the two tubes. It is sufficiently pressurised to provide thermal resistance to transfer of heat from the pressure tube to the calandria tube and its contents. The carbon dioxide is also partly for safety monitoring: D_2O in the efflux carbon dioxide would signify a leak. The heavy water from the pressure tubes passes to the steam generator where it loses heat to the light water which is used to make steam. The neutron moderator stream of heavy water is also cooled on exit. The drawing below shows the arrangement.

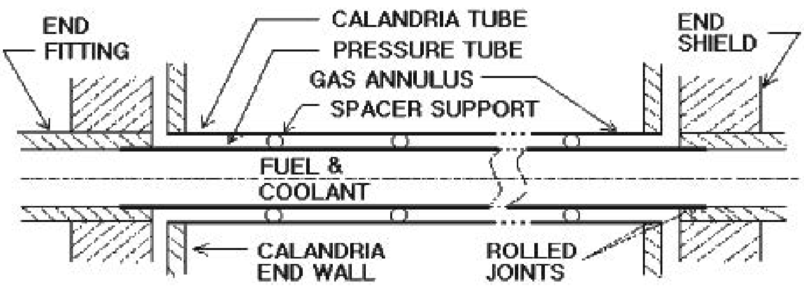
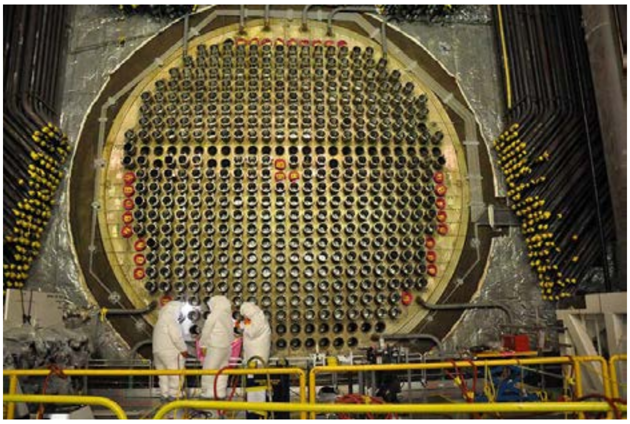


Image taken from [122].

In a CANDU reactor the pressure tubes are made of zirconium-niobium alloy and the calandria tubes of zirconium [124]. There will be hundreds of such parallel tubing arrangements ('fuel channels') in a calandria, as shown in the illustration below.



A calandria (reactor) at the Bruce nuclear power plant showing the array of fuel channels in cross section. Image taken from [123].

The Darlington nuclear power plant in southern Ontario has four 878 MW CANDU reactors [125]. Having been in service since the early 1990s, it is now undergoing refurbishment [126] both in the reactors (e.g. new fuel channels) and in 'non-nuclear' parts (e.g. new steam generators). That is with a view to operation of the power plant into the 2050s (see illustration below).

Image from a video promoting refurbishment at the Darlington nuclear power plant, accessible on https://www.youtube.com/watch?v=2dV83Se1lB8. The total cost of the refurbishment has been estimated as CA$ 12.8 billion [127].

The Pickering nuclear power plant on the shore of Lake Ontario has six 515 MW CANDU reactors [128]. Having been in service since 1971 it is one of the oldest nuclear power plants in the world, and cessation of operation in 2024 is expected [129].

4.2.2 NEW BRUNSWICK

The Point Lepreau nuclear power plant in New Brunswick close to the border with the US state of Maine has a single 705 MW CANDU reactor [130]. First supplying power in 1983, it closed for refurbishment in 2008 and returned to service in 2012 and this is expected to continue until about 2040. In the earlier years of its existence it sold some of its electricity to the US [131]. The point is often made (e.g. [132]) that Point Lepreau is the only nuclear power plant in 'Atlantic Canada'. There are none at all in 'Pacific Canada' even though there are parts of British Columbia which on a topographic basis would be very suitable for nuclear power plants [133]. There is uranium in BC, although it has not yet been mined. Large amounts of uranium have been produced in Saskatchewan. Canada was the world's largest producer of uranium until it was overtaken in 2009 by Kazakhstan [134].

4.2.3 EXTENSION TO OTHER MAJOR COMMONWEALTH COUNTRIES

Canada is a Commonwealth Realm, a term which replaced 'British Dominion' during the early part of the reign of Queen Elizabeth II. Two other notable 'Commonwealth Realms' are Australia and New Zealand, neither of which has nuclear generation of electricity. South Africa, formerly called the Union of South Africa, was once a British Dominion. The Koeberg nuclear power station in Cape Province has two 970 MW PWRs [135] of French design and is the most southerly nuclear power plant in the world. South Africa is the only African country with nuclear power generation capability.

4.3 MEXICO

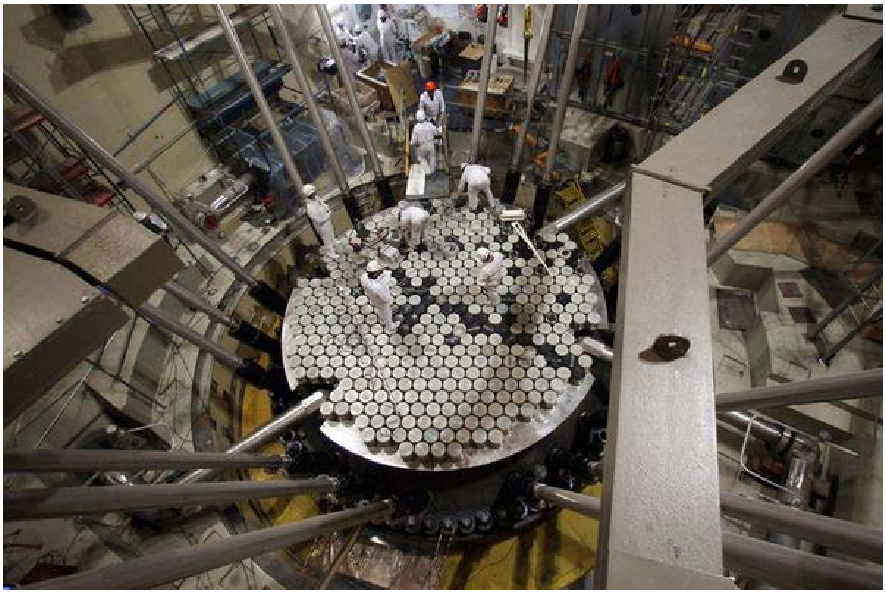
The Laguna Verde nuclear power plant in Mexico has two 810 MW BWRs [136]. Almost due north of it on the Gulf of Mexico rim is Bay City TX, the location of the South Texas Nuclear Project power plant (see below).

Locations of the STNP nuclear power plant (US) and the Laguna Verde nuclear power plant (Mexico) on the Gulf coast. Image taken from [137].

One of the reactors at Laguna Verde is scheduled to operate until 2029 and the other until 2034, and there will be space in an existing pool for all of the spent nuclear fuel over that time [138]. It was pointed out in Chapter 3 that this can be a factor in the life expectancy of a nuclear power plant. A fuel pool can also be used to store fuel during reactor outage, as has been the case at the Paluel nuclear power plant in France (see section 3.2).

4.4 ARGENTINA AND BRAZIL

These are the only two South American countries with nuclear electricity capability. There is no nuclear power generation in any of the countries of Central America. The Embalse nuclear power plant in Argentina has a single CANDU reactor which is supplied with natural uranium and produces 635 MW of electricity [139]. It recently returned to service after a three-year programme of refurbishment which included reconditioning of the calandria and new steam generators [140]. At the Atucha nuclear power plant 62 miles from Buenos Aires there are two PHWRs, not CANDU but Siemens [141]. They have in common use of heavy water both as a coolant and as a neutron moderator. Atucha I reactor produces 350 MW of electricity and Atucha II 745 MW. Use of the term 'calandria' meaning nuclear reactor is restricted to CANDU. Below is the reactor at Atucha II at the assembly stage. (See also section 8.4)



The Atucha II PHWR showing a cross section. Image taken from [142].

The Angra nuclear power plant near Rio de Janiero, the sole nuclear power plant in Brazil, has two Siemens PHWRs [143]. One of them produces 640 MW and the other 1275 MW. The power plant uses uranium from Brazil. Some is sent abroad to be enriched for use at Angra, and some is enriched locally at Resende.

4.5 FURTHER COMMENTS

The nuclear power plants in the US all have either PWRs or BWRs. Those in Canada all have CANDU reactors. Light water reactors and CANDU reactors for use with supercritical water are both under development [144]. Supercritical water is finding increasing application to power generation from conventional fuels, notably low-rank coals [145]. There the motive is enhanced efficiency and the good effect of that on CO_2 emissions. That of course does not apply to nuclear plants. One advantage of supercritical water in nuclear applications is the very high convection coefficients it displays [146]. In a BWR that would make for effective heat transfer in the reactor and in a PWR it would make for effective heat transfer at the 'steam generator'. This term has been put in inverted commas as supercritical water is not a form of steam but a phase distinct from vapour or liquid.

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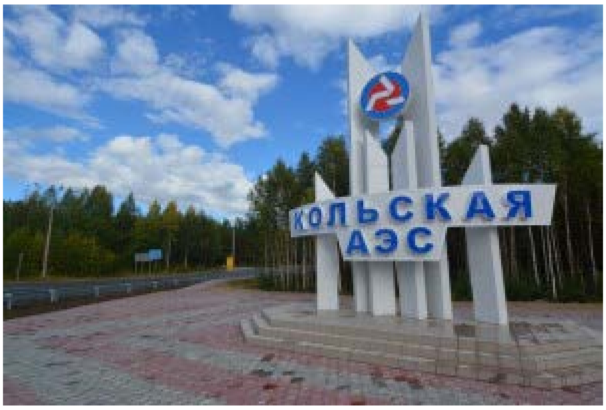
5 THE FORMER SOVIET UNION

5.1 RUSSIA

Nuclear power plants in in Russia are listed in the table below and other FSU countries are discussed later in the chapter. The sole nuclear power plant in Armenia, which is part of the FSU, featured in Chapter 3. The Akademik Lomonosov nuclear power plant in Pevek, Russia will be discussed in the chapter on small modular reactors. The supplier of nuclear fuel for the entire Russian nuclear power industry is TVEL, HQ in Moscow.

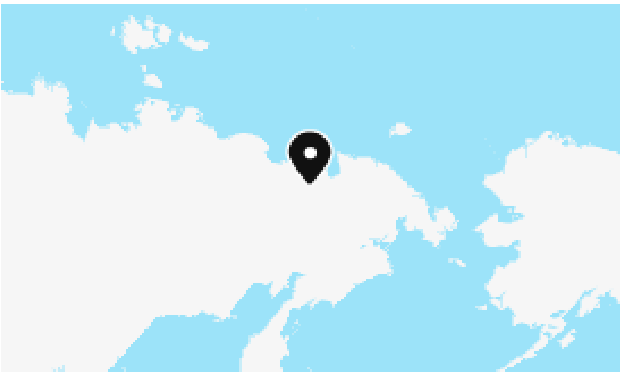
Name of the plant.	Details.
Balakovo nuclear power plant.	4 × 1000 MW VVERs [1]  View of the Balakovo nuclear power plant from across the Volga River. Image taken from [2].
Beloyarsk nuclear power plant.	Two fast breeder reactors. Combined output 1485 MW [3]. Use of MOX fuel.
Bilibino nuclear power plant.	The smallest nuclear power plant in the world. 3 × 12 MW EGP-6 reactors (see main text) [4].  Bilibino nuclear power plant. Image taken from [5].

Name of the plant.	Details.
Kalinin nuclear power plant.	4 × 1000 MW VVERs [7].
Kola nuclear power plant.	4 × 440 MW VVERs [8].  Entrance to the Kola nuclear power plant. Image taken from [9].
Kursk nuclear power plant.	4 × 1000 MW RBMK reactors [10]. See discussion in the main text.
Leningrad nuclear power plant.	1 × 1085 MW VVER [12].
Novovoronezh nuclear power plant.	In Central Russia. Four VVER reactors ranging from 417 MW to 1150 MW, total capacity 3747 MW [15].  Newly commissioned 1150 MW reactor at Novovoronezh. Image taken from [16].
Rostov nuclear power plant.	4 × 1000 MW VVERs [18].
Smolensk nuclear power plant.	3 × 1000 MW RBMK reactors [21].

It was noted in the coverage of other countries including the Czech Republic, Hungary and Finland that a VVER is a pressurised water reactor (PWR). Those at the Balakovo nuclear power plant in Russia (first row of the table) are termed VVER-1000. A description of the fatal accident due to steam release at a nuclear power plant in the US was given in Chapter 4. There was a similar occurrence at Balakovo in 1985 when 14 people were killed from exposure to steam. It was during the initial startup of the reactor before it was producing electricity for the grid.

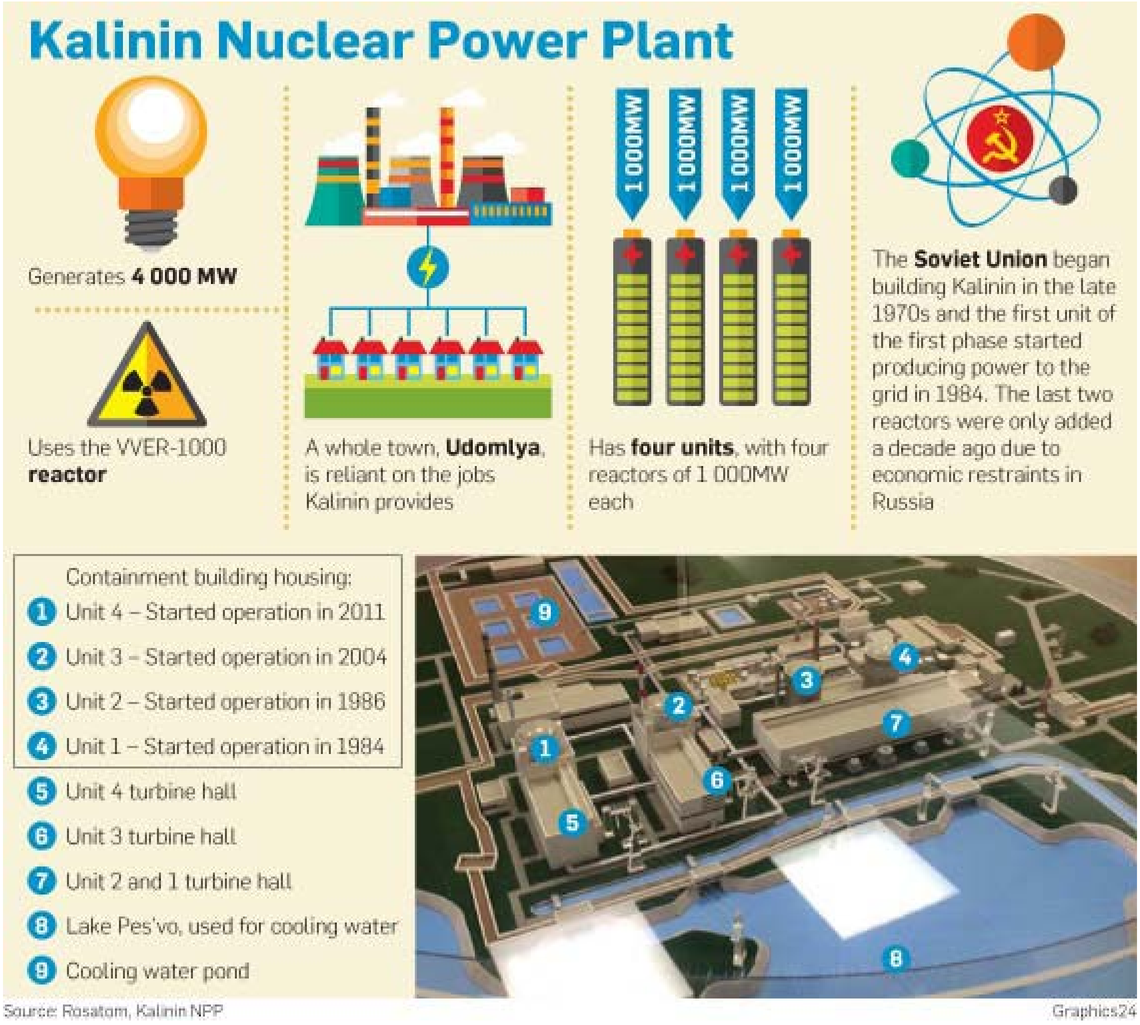
The Beloyarsk nuclear power plant (next row of the table) has two fast breeder reactors. Such reactors were briefly discussed in earlier sections of this book. Choice of sodium as the coolant has the advantage of the low neutron capture cross section of sodium-23 (0.5 barns). The importance of that in a breeder reactor is that the fertile material needs neutrons to produce a fissile material. The sodium coolant is heat exchanged with water to provide heat for steam generation and will itself before heat exchange be at a temperature of about 550°C. These are the only two fast breeder reactors in current operation. They are widely spaced in age and the older one is approaching the decommissioning stage.

The three very small reactors at the Bilibino nuclear power plant, which have been in service since the 1970s, are light water cooled and graphite moderated. They are in fact a small scale form of the RBMK reactor, which will be discussed later in the chapter. The illustration below shows the location of the Bilibino nuclear power plant, 687 miles from the coast of Alaska: it is the most northerly nuclear power plant in the world. Its role will shortly be taken over by the Akademik Lomonosov nuclear power plant.



Location of the Bilibino nuclear power plant. Image taken from [6].

The author has saved himself some work by reproducing the information sheet below on the Kalinin nuclear power plant (next row of the table). Some of its electricity goes to Moscow, which is a little over 100 miles away.



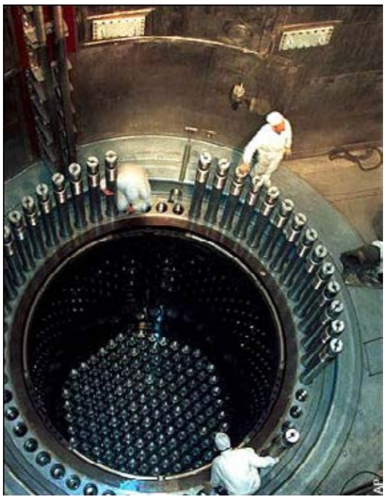
Taken from [7].

Two of the reactors at the Kola nuclear power plant (next row of the table) in north west Russia are the VVER 440/230 type, also used at the Loviisa nuclear power plant in Finland (see section 3.9). The two power plants are separated in location only by a distance of the order of 500 miles. Trouble-free operation at Loviisa was invoked in defence when there was opposition to extending the period of operation of the two VVER 440/230 reactors at Kola [8].

The RBMK (**r**eaktor **b**olshoy **m**oshchnosty **k**analny [11]) reactors at the Kursk nuclear power plant are light water cooled and graphite moderated. RBMK reactors were in use at the Chernobyl nuclear power plant in the Ukraine where in 1986 failure at one of the reactors led to the worst accident ever in the nuclear power industry. RBMK reactors operating since Chernobyl are required to have modifications, most notably to the fuel rods. At Chernobyl at the time of the accident the control rods were made of boron carbide tipped with graphite. The purpose of the graphite was displacement of coolant water as a control rod was lowered. The reactor at Chernobyl at the time of the accident was not in normal operation: it was undergoing a performance test. During fuel rod insertion before the boron component was fully lowered, the graphite component of the control rod accelerated the nuclear reaction and that was the initiating factor. The thermal neutron capture cross section of boron-10 is 3840 barns. (That of boron-11, the more abundant isotope, is almost six orders of magnitude lower.)

At the Leningrad nuclear power plant (next row of the table) there was until December 2018 a MW RBMK in service [13]. There are at the site of the Leningrad nuclear power plant three out-of-service RBMKs which will be decommissioned along with the recently closed down one. In 2010 (post-Chernobyl) production at the multiple RBMK reactors then in use at the Leningrad power plant was raised by use of uranium fuel with a greater degree of enrichment, 5% uranium-235 instead of 3% [14]. At the Novovoronezh nuclear power plant one reactor has, at the time of going to press, just been commissioned (see the illustration in the table), and it is expected to be in service until the 2070s. Fuel used at this power plant is 3.6% uranium-235 [17].

The four reactors at the Rostov nuclear power plant were commissioned respectively in 2001, 2010, 2015 and 2017. A cross section of a fuel assembly at Rostov is shown below. Note that is is hexagonal, whereas in Chapter 4 it was shown that some VVER reactors are square in cross section. This 'diversification' in VVER design is noted in [20].



Cross section of a fuel assembly at the Rostov nuclear power plant. Image taken from [19].

Two of the three RBMK reactors at the Smolensk nuclear power plant (next row of the table) predate Chernobyl. Their decomissioning by 2030 is expected [22]. It was because of Chernobyl that a fourth RBMK reactor at Smolensk was not in the event commissioned.

5.2 BELARUS

The Belarusian nuclear power plant is expected to begin electricity supply to consumers in early 2020 with a single VVER reactor producing 1194 MW [23]. An equivalent reactor will commence supply in mid-2020. Lithuania is opposed to the the nuclear power plant, not least because it is situated 23 km from the Belarus-Lithuania border and 55 km from the Lithuanian capital Vilnius, population 0.58 millions [24]. The Espoo Convention, full title 'The Convention on Environmental Impact Assessment in a Transboundary Context', was invoked. A possible retaliatory measure on the part of Lithuania would be refusal to allow export of electricity from the plant, for example to the other two Baltic States, via Lithuania. At present Lithuania herself imports electricity originating at gas fired plants from Belarus [25].

5.3 THE UKRAINE

There were three reactors at Chernobyl, all RBMKs, additional to the one where the accident occurred. They had all exited service by the end of the 20th Century. Below is a list of nuclear power plants in the Ukraine currently in service. All have VVER reactors to the exclusion of RBMK.

Khmelnitsky nuclear power plant.	2 × 1000 MW VVERs [26].  The two reactors at Khmelnitsky. Image taken from Wikipedia.
Rivne nuclear power plant.	Four VVER reactors ranging in capacity from 381 MW to 950 MW. Total 2385 MW [27].
South Ukraine nuclear power plant.	3 × 950 MW VVERs [29].
Zaporizhzhia nuclear power plant.	6 × 950 MW VVERs [31].  Zaporizhzhia nuclear power plant (the largest nuclear power plant in Europe) showing all six reactors. Image taken from [31]. Zaporizhzhia.

Construction of the second reactor at the Khmelnitsky nuclear power plant (first row of the table) was under way at the time of the Chernobyl accident. Its completion was delayed by a government proscription of new nuclear reactors in the Ukarine and the reactor did not come into operation until 2004. At the Rivne nuclear power plant there was an accident at a transformer in April 2019. The headline in an English newspaper on the fire at the Rivne plant [28] 'NUCLEAR INFERNO Panic after blaze rips through Ukraine nuclear power plant reactor built same year as Chernobyl nuke disaster' is a blatant example of irresponsible journalism. The fire at Rivne was not in the nuclear part of the plant at all. There is no possible basis for comparison of the incident with Chernobyl.

The primary supplier of nuclear fuel to the Ukraine has been TVEL. One of the reactors at the South Ukraine nuclear power plant (next row of the table) now contains nuclear fuel from two different suppliers, TVEL and Westinghouse [30]. In July 2018 one of the reactors at the Zaporizhzhia nuclear power plant (next row of the table) was supplied completely with fuel from Westinghouse, none from TVEL. This practice began because of uncertainties in supply from Russia after the Annexation of Crimea in 2014 [32]. See also the discussion of the Tianwan nuclear power plant in Chapter 7.

5.4 FURTHER REMARKS

None of the other FSU countries has nuclear power generation. It is pointed out in the previous section that a restriction was placed on expansion of nuclear power in the Ukraine because of Chernobyl. At the time of Chernobyl a nuclear power plant was under construction in the Azerbaijan Soviet Socialist Republic, now simply called Azerbaijan, and that was not completed [33]. As noted in Chapter 4, Kazakhstan is the world's largest producer of uranium. Production there in 2018 was 21705 tonnes [34]. The export market includes Canada, Russia and China [35]. When Kazakhstan was the Kazakh Soviet Socialist Republic, numerous tests of Soviet nuclear weapons took place there [36]. The only nuclear power there ever was in Kazakhstan used a 135 MW sodium cooled fast reactor which operated from 1973 to 1999 [37]. This had the common factors of fast neutrons and sodium cooling with the Beloyarsk nuclear power plant. Unlike Belyarsk it was not a fast breeder.

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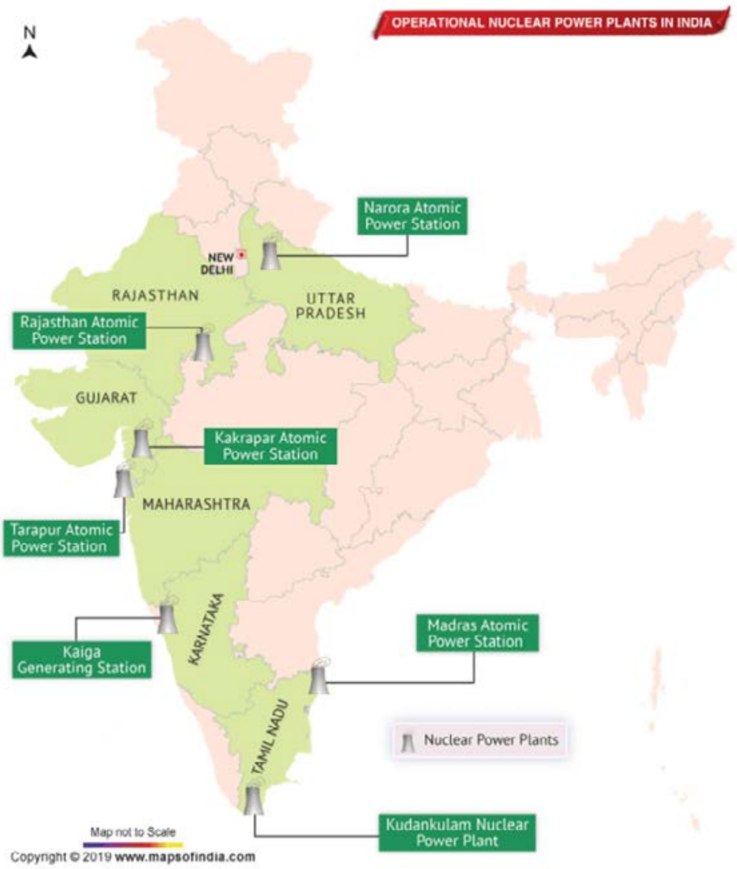
6 THE INDIAN SUBCONTINENT

6.1 INDIA

6.1.1 DETAILS OF THE POWER PLANTS



The map above is taken from [1] and is up to date. Descriptions of the respective nuclear power plants follow. The Narora nuclear power plant has two 220 MW CANDU reactors [2] which use natural uranium. The first entered operation in 1991 and he second in 1992. The location of the power plant is a small town on the bank of the River Ganges (see illustration below).

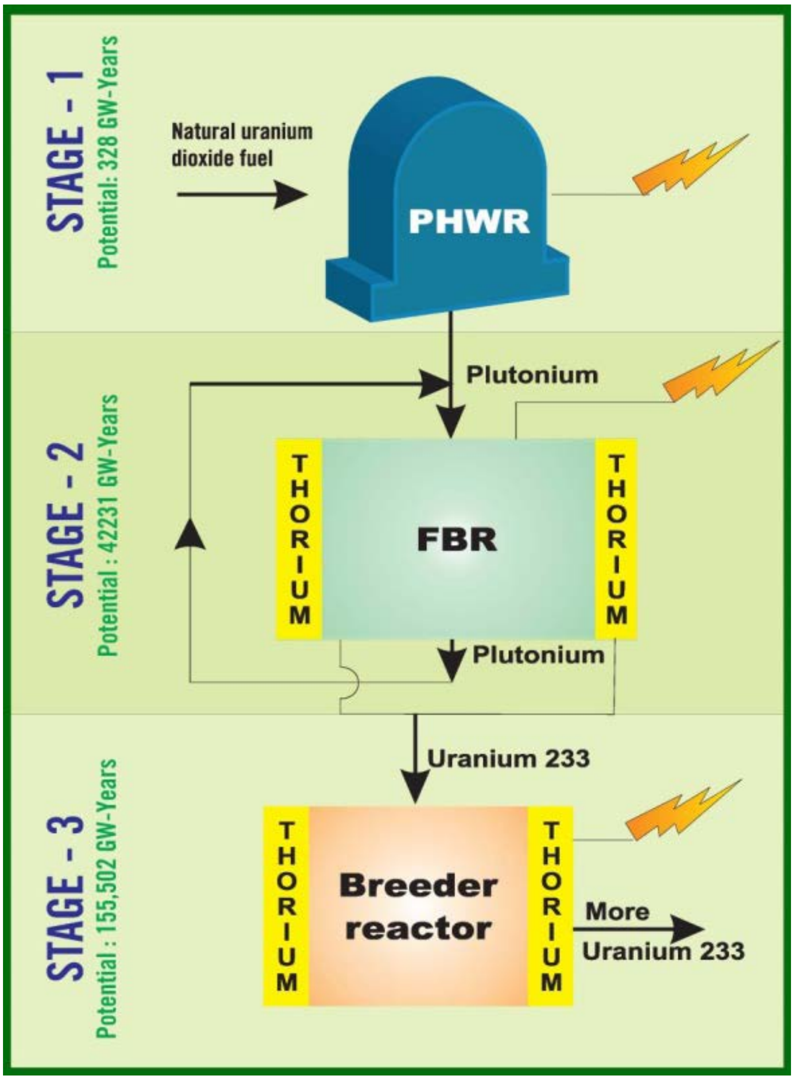
Narora nuclear power plant, showing its location on the Ganges. Image taken from [3].

Rajasthan nuclear power plant has one 100 MW CANDU reactor, one 200 MW CANDU reactor and four 220 MW CANDU reactors [4]. Under the Colombo Plan India obtained a CANDU reactor from the Atomic Energy of Canada Ltd. (AECL) and there was Canadian participation in setting it up at Rajathan [5]. A second CANDU reactor was obtained, but Canada withheld its involvement with this when in 1974 India conducted nuclear weapons tests at Pokhran. That was in contravention of a prior agreement with Canada that India's nuclear capability would be applied only to peaceful uses [6],[7]. More recently, reactors of CANDU design have been built in India ('indigenously supplied reactors' [8]). Electricity producers in the countries which use CANDU reactors have organised themselves into a CANDU Owners Group [9].

The Kakrapar nuclear power plant has two 220 MW CANDU reactors [10]. An 'indigenously supplied' 700 MW CANDU reactor at Kakrapar will come into service in the near future. The Tarapur nuclear power plant has two 160 MW BWRs and two 540 MW CANDU reactors [11]. The BWRs came into service in 1969, making Kakrapar India's oldest nuclear power plant. The Kaiga nuclear power plant has four 220 MW CANDU reactors [12] and is the only nuclear power plant in the world to have a rainforest location [13]. In a departure from the dominance of CANDU reactors in India, the Kudankulam nuclear power plant has two 1000 MW VVERs [14], one of which entered operation in 2014 and one in 2016. It is noted in [14] that by that time this type of reactor had, since its introduction 40+ years earlier, attained more than 15000 reactor-years of operation. The Madras nuclear power plant has two 170 MW CANDU reactors [15]. Its spent fuel goes to Tarapur for processing into plutonium.

6.1.2 INDIA'S THREE-STAGE NUCLEAR POWER PROGRAMME

India has major reserves of thorium [16]. As long ago as the 1950s India's 'three-stage nuclear power programme' was proposed [17] and the programme is still of interest. It is illustrated below.



Schematic of the three-stage nuclear power programme. Image taken from [18].

Stage 1 is standard use of uranium in a reactor with resulting plutonium-239. Stage 2 uses MOX containing natural uranium and the plutonium from stage 1. Further plutonium is produced from fission of the uranium component of the MOX and (a key point in the programme) there is excess plutonium which can can be removed for fuel use elsewhere. Fission of the plutonium-239 produces the fissile nuclide uranium 233, and more of this is produced by the action of fast neutrons on fertile thorium-232 which is present as a blanket. The uranium-233 from both sources is taken to step 3 where there is also further thorium-232 so a good composite fuel has been produced: neutrons from fission of the uranium-233 enable the thorium-232 to renew the uranium-233. All three stages produce energy from fission – from uranium-235 in steps 1 and 2 and from uranium-233 in step 3 – and can therefore be used to make electricity as indicated symbolically in the illustration. That as much as the potential fuel use of the plutonium from step 2 is a factor in the viability of the scheme.

This programme was conceived in order to bring India's thorium reserves into use. Its strength is that at two of its three stages throrium-232 is used in the production of uranium-233. In step 1 the heavy water will thermalize the neutrons from the fission so that they are at a suitable speed to sustain the fission, all quite standard. That attention has to be paid to neutron economy in the production or uranium-233 from thorium-232 is emphasised in [19]. Neutron economy is partly a configurational matter as described in Chapter 1. Another point naturally arises in one's mind: in this application slow neutrons are used with the thorium [19] and any moderating will require avoidance of accompanying neutron absorption.

6.2 PAKISTAN

There are two nuclear power plants in Pakistan (formerly West Pakistan), one of which has four pressurised water reactors (PWRs) and the other a single pressurised heavy water reactor (PHWR) [20]. The four PWRs at the Chashma nuclear power plant 195 miles from Islamabad each have a capacity of approximately 300 MW and are CNP-300 reactors of Chinese design, and Chashma was the first nuclear power plant outside China to use them. All existing CNP-300 reactors are of ~ 300 MW capacity. There is an intentional similarity of design between the CNP-300 PWR and the AP1000® PWR, although the capacity of the latter is over three time larger than that of the former. (See also the coverage of the Alvin W. Vogtle nuclear power plant GA in Chapter 4.) A prototype CNP-300 reactor commenced operation in China in 1985. It went into commercial service in 1991 and was withdrawn for renovation and upgrading in 2008. It has re-entered service, and is excepted the continue producing electricity only until 2020. The prototype reactor had 120 fuel assemblies and used fuel of 3.4% uranium-235 content [21]. The upgraded version uses a Gd_2O_3 'burnable' neutron poison (see section 3.8).

The Karachi nuclear power plant has a single CANDU reactor capable of producing 90 MW of electricity [19]. It has been in service since 1971. Expansion is under way there, and two 1000 MW PWRs of Chinese design called Hualong I reactors are being installed there [22]. Hualong I reactors will be discussed more fully in the chapter on China.

6.3 BANGLADESH

There are no currently operating nuclear power plants in Bangladesh. Two 1200 MW VVER reactors are under construction at Rooppur in western Bangladesh for entry into service in 2022-2023 [23]. The project is financed by a loan from Russia, and experience at the recently commissioned Novovoronezh nuclear power plant in Russia (see section 5.1) will be drawn on at Rooppur [24]. Once the plant is operating, spent fuel will be taken to Russia.

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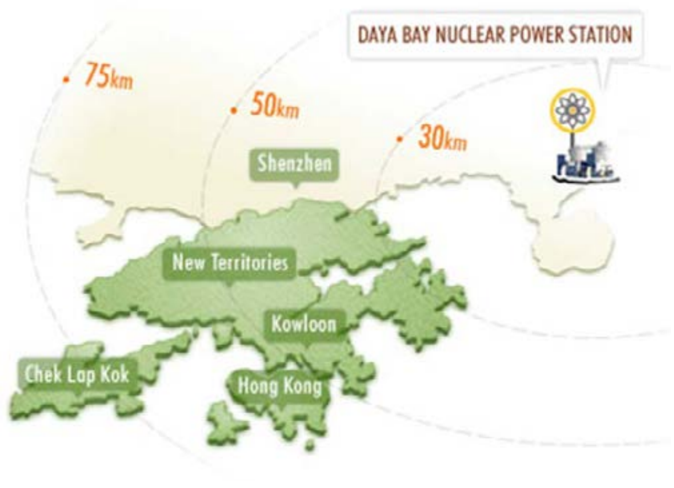
7 CHINA, TAIWAN, JAPAN AND SOUTH KOREA

7.1 CHINA

Nuclear power plants in use in China are listed in the table below, which is followed by comments.

Changjiang nuclear power plant. Province of Hainan.	2 × 650 MW PWRs [1]. In operation since 2015.  Positioning of the dome of reactor I at Changjiang. Image taken from [2].
China Experimental Fast Reactor (CEFR).	20 MW of electricity [3]. Fast neutrons through absence of a moderator.

Daya Bay nuclear power plant.	2 × 944 MW PWRs of French design [4].  Location of the Daya Bay nuclear power plant. More than half of the electricity from it is exported to Hong Kong. Image taken from [5].
Fangchenggang nuclear power plant. Close to the border with Vietnam.	2 × 1000 MW PWRs [6]. Both commenced electricity supply in 2016.
Fangjiashan nuclear power plant.	2 × 1100 MW PWRs reactors. See comments in the main text.
Fuqing nuclear power plant.	4 × 1089 MW PWRs [11].
Haiyang nuclear power plant.	2 × 1170 MW PWRs [12]. Commencement of operation 2018-2019.
Hongyanhe nuclear power plant.	4 × 1000 MW PWRs [15]. Entered service 2013-2016.
Ling Ao nuclear power plant. 1 mile from the Daya Bay nuclear power plant.	2 × 935 MW Framatome PWRs [16]. 2 × 1080 MW CPR-1000 reactors [16].

Ningde nuclear power plant. On the Chinese mainland mainland 236 miles from Taiwan.	4 × 1000 MW CPR-1000 reactors [18]. Two more reactors to be added.  Eventual configuration of the Ningde nuclear power plant with its six reactors (see comments in the main text). Image taken from [19].
Qinshan nuclear power plant.	Seven PWRs ranging in capacity from 300 MW to 677 MW [20].
Sanmen nuclear power plant. 205 miles from Shanghai.	Two Westinghouse AP1000® PWRs [24].
Taishan nuclear power plant.	Two 1850 MW PWRs [26].
Tianwan nuclear power plant.	4 × 1000 MW VVERs [28]. Entry into service 2006-2007.
Yangjiang nuclear power plant.	Two CPR-1000 PWRs. Two ACPR-1000 PWRs [30].

The PWRs at Changjiang (first row of the table) are CNP-600 reactors, of the same 'lineage' as the CNP-300 reactors which were described in the coverage of nuclear power in Pakistan. Each of the CNP-600 reactors contains 121 fuel assemblies. (See also the description of the ACPR-100 small modular reactor in the next chapter.) In the China Experimental Fast Reactor (next row of the table) the reactor core is immersed in sodium, making it a 'pool-type reactor'. The sodium receives heat from the nuclear reaction and is then heat exchanged with water. It uses fast neutrons as noted. In such a reactor the smaller likelihood of absorption of these compared with thermal neutrons is compensated for by use of high enriched uranium. The Daya Bay nuclear power plant (next row of the table) has an important role in the carbon accounting of Hong Kong. Hong Kong has one gas-fired electricity plant (Black Point) and one coal-fired one (Lamma). These obviously release CO_2, which of course electricity production at the Daya Bay nuclear power plant does not. The reactors at the Fangchenggang nuclear power plant are CPR-1000 reactors, usually considered to be of Chinese design [7] although it is recognised that it evolved from French designs having previously been in use in China [8]. Those at Fangjiashan nuclear power plant (next row of the table) are also CPR-1000. The Bradwell Magnox power plant in Essex was described in Chapter 2. There are plans for revival of nuclear power generation at Bradwell [9] with a Chinese built PWR called HPR-1000, which will also be used in an expansion of the Fangchenggang nuclear power plant [10]. The PWRS at the Fuqing nuclear power plant are also of CPR-1000 design and, by a policy closely mirroring Fangchenggang, future reactors there will be of HPR-1000 design.

The Haiyang nuclear power plant (next row of the table), which is almost 'brand new', uses AP1000® PWRs [13] like the Alvin W. Vogtle nuclear power plant in Georgia (see section 4.1). A proposed nuclear power plant in the UK which was not in the event completed, called the Moorside nuclear power plant and near Calder Hall, was to have used AP1000® PWRs [14]. In that event Sizewell B would have ceased to be the only PWR in the UK (see section 3.1). The PWRs at the Hongyanhe nuclear power plant are CPR-1000 and the plants uses desalinated seawater as coolant (the 'W' in 'PWR'!). That contrasts with desalination at the Diablo Canyon nuclear power plant in Arizona discussed previously. There the desalinated water is not for reactor use but for community use in a drought prone area. The Daya Bay and Ling Ao nuclear power plants are very close to each other and only 30 miles from Hong Kong, but the latter unlike the former does not supply electricity to Hong Kong [17].

The two additional reactors at the Ningde nuclear power plant (next row of the table) will be Hualong I reactors (see section 6.2). The four existing reactors are at a coastal location on the mainland, and the new ones will be on a nearby natural island linked by a breakwater as shown in the illustration in the table. The enclosed sea will afford a port for the facility. At the Qinshan nuclear power plant (next row of the table) five of the reactors are CNP reactors and the other two are CANDU reactors. These CANDU reactors are shown below.

The two CANDU reactors at the Qinshan nuclear power plant. Image taken from [21].

As stated more than once in previous parts of this book, natural uranium is the conventional fuel for CANDU reactors. Those at Qinshan use 'natural uranium equivalent fuel' [21], [22]. Natural uranium is 0.72% uranium-235, as already stated. Spent fuel from a reactor using enriched uranium can be separated into its elements by chemical means, commonly the PUREX process [23], and the uranium resulting is more abundant in uranium-235 than natural uranium, being typically 1%. Depleted uranium from elemental uranium enrichment is less abundant in uranium-235 than natural uranium, typically 0.3%. In natural uranium equivalent fuel these are blended to produce a fuel suitable for CANDU reactors called natural uranium equivalent fuel. At present the CANDU reactors at Qinshan are the only ones in the world using this fuel.

The Sanmen nuclear power plant has been supplying electricity since 2018 [25]. It has therefore 'pipped' in the use of the Westinghouse AP1000® PWR the Alvin W. Vogtle nuclear power plant (see Chapter 4). The Taishan nuclear power plant was the first to use the European Pressurised Reactor (EPR) and the UK, France and Finland are expected to follow. EPRs are in the French lineage of PWRs and differ from their forebears chiefly in scale: an EPR uses light water as heat transfer fluid and as neutron moderator and, like other designs of PWR, enriched uranium as fuel. A comparison of EPRs with the earlier N4 PWRs, scenes of use of which include the Chooz B power plant, is given in [27]. Both produce electricity at a rate in excess of a gigawatt. Either requires a steam turbine of sufficient capacity. The Taishan nuclear power plant will have two Alstom Arabelle steam turbines of 1755 MW capacity [28]. Chooz B also uses Alstom Arabelle steam turbines (see Chapter 3).

The Tianwan nuclear power plant uses TVS-2M fuel, which originates with TVEL in Russia (see section 5.1). Such fuel for use at Tianwan is however made in China under an agreement with TVEL [29]. The ACPR-1000 PWRs in use at the Yangjiang nuclear power plant (next row of the table) differ from earlier reactors in the series chiefly is their enhanced containment capability [31].

7.2 TAIWAN

There are two nuclear power plants in Taiwan currently in service. One is the Kuosheng nuclear power plant which has two 985 MW BWRs [32]. The other is the Maanshan nuclear power plant which has two 950 MW PWRs [33]. In section 3.1 of this book it was pointed out that spent fuel storage capacity is a factor in the longer term viability of a nuclear power plant. At Maanshan there is storage space for spent fuel, less so at Kuosheng [34]. When in November 2018 Taiwan held a referendum on continued use of nuclear generated electricity in Taiwan 59% of the vote was in favour [34].

7.3 JAPAN

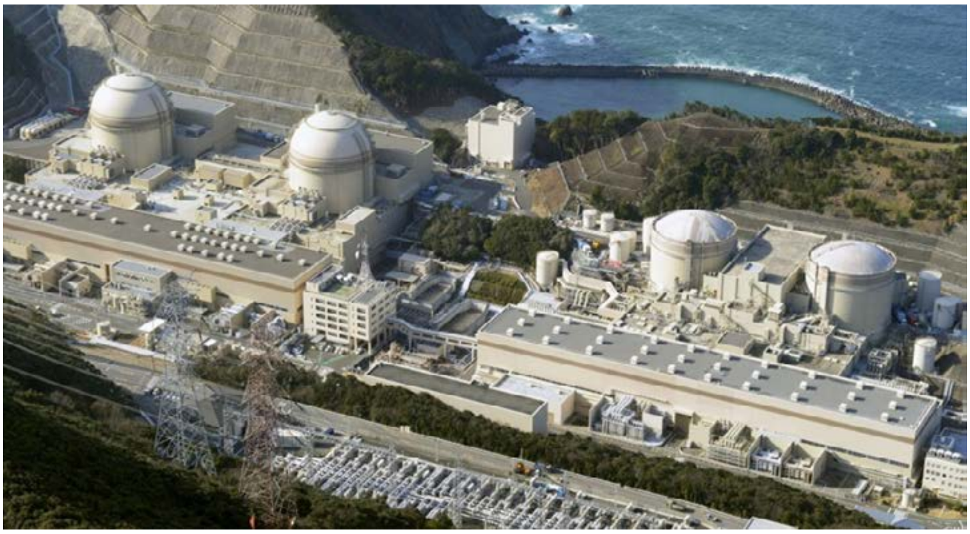
Many of the nuclear power plants in Japan are currently in suspended status or awaiting decommissisoning. In the latter group is Fukushima. Only the Japanese nuclear power plants currently in operation will be considered in this text. They are listed in the table below. Capacities given are current ones. All of these power plants have fewer operating reactors than originally.

Genkai nuclear power plant.	1 × 559 MW PWR. 2 × 1180 MW PWRs [35].
Ikata nuclear power plant. S.E. Japan.	2 × 559 MW PWR. 1 × 890 MW PWR [37].  View of the Ikata plant showing the three reactors. Image taken from [38].
Ōi nuclear power plant.  Location of the plant. Image taken from [39].	2 × 1127 MW PWRs. See main text.
Sendai nuclear power plant.	2 × 890 MW PWRs [41]. The first nuclear power plant to re-enter service after the total cessation following Fukushsima.

Takahama nuclear power plant.	4 × 826 MW PWRs [44].  Containment strengthening work at Reactor 1 at Takahama. Image taken from [45]. The reactor is expected to return to service in mid 2020.

One of the 1180 MW PWRs at Genkai (first row of the table) uses plutonium from uranium-235 fission as fuel on a trial basis [35]. The plutonium-239 isotope is produced by neutrons from the fission and fertile uranium-238. In a nuclear reactor the time which elapses before this is made available for fuel use allows for conversion to other isotopes of plutonium, notably plutonium-240 which is not fissile [36]. Accordingly plutonium for nuclear fuel use is classified according to plutonium-240 content (the less plutonium-240 the better) and that will have been a consideration at Genkai. Plutonium-239 has a half-life of 24100 years, and the need to store it as nuclear waste is avoided if it is put to fuel use as at Genkai. One of the 559 MW units at the Ikata nuclear power plant (next row of the table) will exit service in the near future [38]. The 890 MW reactor has recently been using MOX fuel.

At the Ōi nuclear power plant (below) reactors 1 and 2 are no longer in service. Fuel from them was transferred to reactors 3 and 4, an undertaking requiring the permission of the Nuclear and Industrial Safety Agency in Tokyo. Reactors 1 and 2 contained 629 fuel assemblies, 264 of which were transferred to reactors 3 and 4 [40]. Reactors 1 and 2 were built by Westinghouse and reactors 3 and 4 by Mitsubishi Heavy Industries. All four reactors have the same thermal capacity (3423 MW) and that would have been a factor in the interchangeability.



Ōi nuclear power plant, from right to left reactor numbers 1, 2, 3 and 4. Image taken from [40].

The Sendai nuclear power plant will be out of service for several months in 2020 whilst anti-terrorism measures are introduced [42]. Such measures include a backup supply of coolant to the reactors in case of disruption through terrorist activity of the pressurised water which in normal operation receives heat from the nuclear process [43]. At the Takahama nuclear power plant (next row of the table) the container strengthening work is with a view to 40 years of further operation [45].

7.4 SOUTH KOREA

South Korea has major nuclear powered electricity generation. As previously in this book, a tabular presentation will be given.

Hanbit nuclear power plant.	6 × 1000 MW PWRs [46].
Wols(e)ong nuclear power plant.	Two OPR-1000 PWRs. Four 650 MW CANDU reactors [47]. Total capacity 4.6 GW_e.
Hanul (formerly Ulchin) nuclear power plant.	Four OPR-1000 PWRs. Two older PWRs of French design. Total capacity 5.9 GW_e [50]. Two APR-1400 PWRs 'on hold' [51] (see main text'.

Two of of the reactors at Hanbit are Westinghouse PWRs. Two are System 80 PWRs like those at Palo Verde in Arizona (section 4.1). Two are OPR-1000 PWRs [47]. These are 'descended' from the System 80 PWRs and are sometimes called System 80+. The fuel assembly in an OPR-1000 is a 16 × 16 square array of fuel rods [48]. The OPR-1000 can be used with MOX incorporating weapons grade plutonium requiring disposal instead of plutonium from a reactor as would be more common. Notwithstanding its ancestry, the OPR-1000 was originally called the Korean Standard Nuclear Power Plant. It was renamed OPR-1000 as that was thought to be more suitable for attracting foreign sales, although there are not and never have been installations of OPR-1000 reactors outside South Korea.

The oldest of the four CANDU reactors at the Wolseong nuclear power plant is currently licenced to operate until 2022, though the reactor is likely to exit service before then [49]. It has been operating since 1983. The reason for the 'on hold' status of the two APR-1400 PWRs at the Hanul nuclear power plant (next row of the table) is that the operator awaits clarification of the government's nuclear policy [52]. The is no nuclear powered electricity generation in North Korea.

7.5 FURTHER INFORMATION

China, Japan and South Korea have planned nuclear reactors as well as currently operating ones. Indonesia has nuclear power plants 'on the drawing board'. In Vietnam, construction of the Ninh Thuận 1 nuclear power plant was approved in 2014 although construction has not at the time of going to press begun. Even so its output is factored into longer term estimates of energy supply in Vietnam [53]. It is expected to have four 1200 MW VVER reactors. That is one of a number of VVER-reactors for use outside the former Soviet

Union and Eastern Bloc (see section 3.9) and another is the Bushehr nuclear power plant in Iran [54]. This has one VVER-1000 reactor which uses low enriched uranium. Iran is not an Arab country, but its location on the Persian Gulf gives it a common factor with some Arab countries. When in 2022-2023 the Barakah nuclear power plant in the United Arab Emirates enters service it will be the first nuclear power plant in the Arab world [55].

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8 SMALL MODULAR REACTORS

8.1 THE CURRENT SITUATION

The EGP-6 small modular reactor features in the description of the Bilibino nuclear power plant in Russia. As stated earlier, the EGP-6 is a version of the RBMK reactor. The Akademik Lomonosov nuclear power plant featured briefly at the beginning of Chapter 5. Now berthed at Pevek in the Russian Arctic, it has two 35 MW PWRs [1] and two steam turbines. It is often described as a 'floating nuclear power plant' and that is quite correct, but being permanently installed at Pevek it is floating without being mobile or portable. Each of the reactors has two steam generators, that is, heat transfer devices for raising steam from coolant exiting the reactor (see the account of the Cruas nuclear power plant section 3.1). The fuel assemblies at Akademik Lomonosov are triangular in cross section. The plant is expected to operate until about 2060.

Akademik Lomonosov is not the first floating nuclear power plant. The MH-1A nuclear power plant a.k.a. the Sturgis nuclear power plant was operated by the US Army over the period 1961-1976 [2]. Its structure was taken from an out-of-service cargo vessel and it used a PWR. The reactor produced 45 MW of heat becoming about 10 MW of electricity. Over the period of its service it supplied electricity at this rate to the Panama Canal Zone having been towed there. It used low enriched uranium fuel.

8.2 THE PROPOSED UK SMALL MODULAR REACTOR (UKSMR)

The UKSMR, a PWR under development by a group including Rolls Royce [3], will be capable of generating electricity at 400 to 450 MW. Moreover, whereas the EGP-6 is light water cooled and graphite moderated the UKSMR uses light water for cooling and for neutron moderation. Clearly, in spite of the common terminology 'small modular reactor' comparisons of the EGP-6 with the UKSMR are not helpful. If the criterion for classification of a reactor as an SMR is on capacity only the CNP-300 reactors in Pakistan and China (sections 6.2 and 7.1 respectively) can be so classified as can the 220 MW CANDU reactors in India (section 6.1.1). Fuel assemblies in the UKSMR are in a 17 × 17 square array. Below is an artist's impression of what a power plant using a UKSMR would look like.

Fururistic illustration of a power plant using a UKSMR. The enclosed structure would contain the reactor and the steam turbine. Image taken from [4].

8.3 NUSCALE (HQ IN OREGON) SMRS

A NuScale Power Module™ is a PWR and can produce 60 MW_e [5]. It uses low enriched uranium as fuel and 17 × 17 square fuel assembly configuration; refuelling is required every two years. The NuScale reactor can be delivered in 'knock-down' form comprising three components from scene of manufacture to scene of installation. More generally, in situ contruction from a small number of prefabricated parts is a possible criterion additional to capacity for classification as an SMR. Obviously multiple SMRs could be used at a single power plant to give electrical outputs comparable to that from a single large reactor, and this is envisioned [6]. It would be quite correct to refer to the SMRs in such a power plant as modules, and this was probably the origin of the term SMR. It would however be by no means incorrect to call the components comprising the knock-down kit 'modules', so the modular concept relates to both criteria.

8.4 EXAMPLES OF OTHER DESIGNS AND CONCEPTS

From the same stable as the ACPR-1000 PWR, the ACPR-100 SMR in demonstrations at the Changjiang nuclear power plant (section 7.1) has yielded 125 MW_e. The prototype of the CAREM-25 (Central Argentina de Elementos Modulares) PWR in fact produced 27 MW of electricity [7]. This SMR, which is 3.2 m in diameter and 11 m in width, used enriched uranium as fuel and had hexagonal fuel assembly geometry. Its control features included Gd_2O_3 as burnable poison (see section 3.8). A 100 MW prototype is expected to follow.

It is an integrated reactor, by which is meant that the stem generator in within the reactor vessel. There are plans for a SMR called the ARC-100 reactor at Point Lepreau in Canada [8], adjacent to the CANDU reactor currently in service there and described in section 4.2.2. It will use fast neutrons and a sodium coolant. It was noted in discussion of the Beloyarsk nuclear power plant in Russia (section 5.1) that liquid sodium is a poor absorber of neutrons, making its use advantageous. A value of 550oC was given in section 5.1 for the temperature of the sodium coolant in a nuclear reactor. At such a temperature liquid sodium has a thermal conductivity of thermal conductivity > 60 W m^{-1} K^{-1} and the fact that the heat exchange fluid *is* such a good conductor contrasts with the PWR and the BWR. The vapour pressure of the liquid sodium is below atmospheric as the the boiling point of sodium is 883^{o}C. These are advantages of sodium cooling additional to neutron economy.

The HTMR-100 reactor [9] is a South African design and has features in common with the early Arbeitsgemeinschaft Versuchsreaktor (AVR) described in section 2.7. It uses a pebble bed reactor, helium as a heat transfer fluid, graphite for neutron moderation and has thorium-232 in the fuel. That always requires an accompanying fissile nuclide (sometimes called a 'driver'), uranium-235 or plutonium-239. The thorium-232 itself produces uranium-233 which is fissile. '100' in the descriptor is heat release rate in MW, so the electricity production rate using steam is accordingly about 35 MW.

A more general point in relation to the use of helium as coolant, anticipated in section 2.7, will be made. In a conventional gas turbine ('combustion turbine') post-combustion gas is the fluid entering the turbine. If a nuclear fuel is used in a gas turbine a gaseous 'coolant' has to be used in the reactor for subsequent turbine entry [10]. There have been attempts to make electricity from such devices in which case the term GT-MHR – gas turbine helium reactor – applies. An example is the EM2 GT-MHR conceived by General Atomics (HQ in San Diego CA) [11]. The proposed reactor would generate at 265 MW_e and be capable of simple assembly in situ, consistently with the two requirements for SMR classification. Another proposed SMR using helium as coolant is the XE-100 pebble bed reactor commercial use of which by the mid 2020s is hoped for [12]. It will use steam generation. In terminology rather reminiscent of the retailing of beverages, this SMR is expected to be delivered to sites of installation as 'four-packs' [12] of 50 MW_e reactors: one such four-pack would provide 200 MW_e and a power plant having five four-packs would therefore be capable of yielding 1000 MW_e. The number of four-packs which a particular nuclear power plant could accommodate would be correlated, at the early planning stage, with the space available for the plant.

8.5 FURTHER INFORMATION

That concludes the discussion of SMRs. The chapter will conclude with a brief account of rectors at the conception or development stage only with outputs as low as 20 MW_e or less. These include the U-battery [13],[14], which like some of the other reactors in this chapter has helium as a heat exchange fluid. It uses TRISO fuel, consisting of sub-millimetre pellets having uranium fuel at their centre and carbon and silicon carbide coatings [15]. Such a configuration restricts fission gas release, a point touched on earlier in this book when the Calvert Cliffs nuclear power plant in Maryland was under discussion. It is hoped that the U-battery might be used in electrolysis to make hydrogen for vehicles powered by a hydrogen fuel cell. The hydrogen would be free of a carbon footprint, a big plus. That the U-battery uses helium as coolant has been noted. If the entire electricity generating operation is to be free of water that would only be possible if a gas turbine was used.

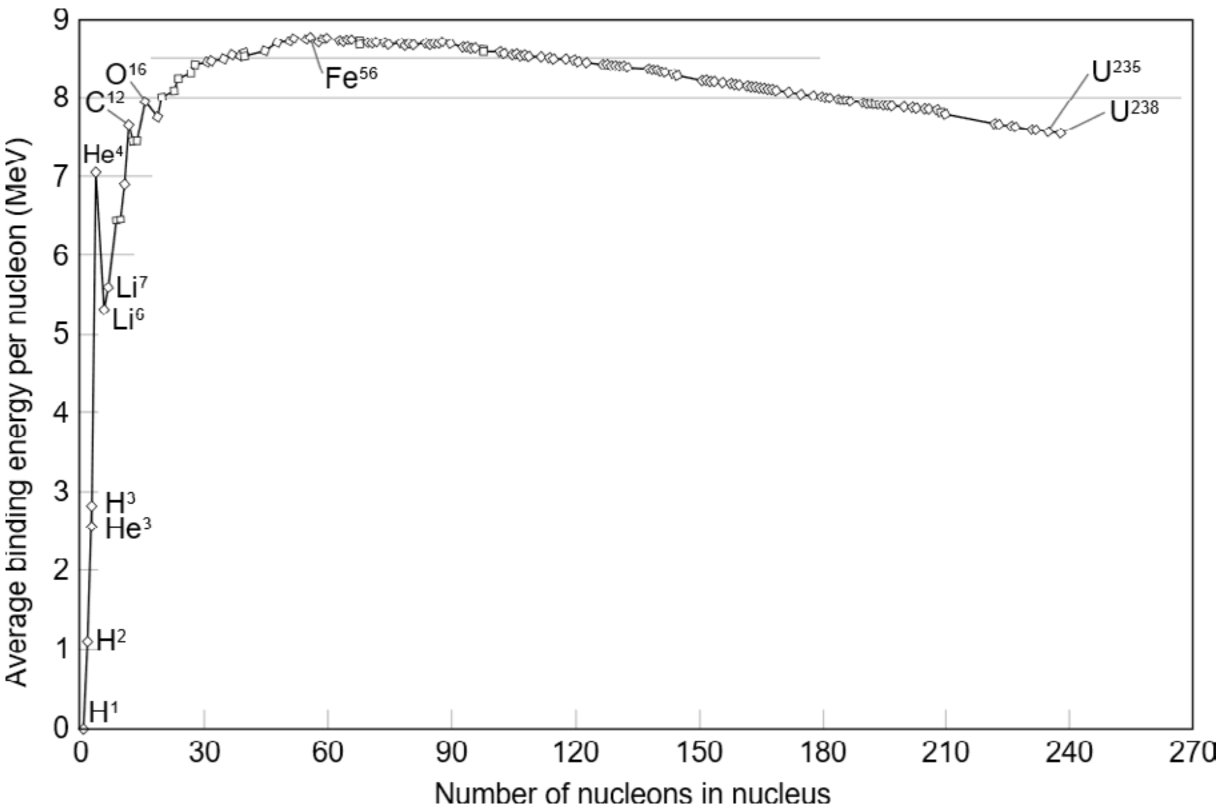
The Starcore reactor [16], which is being built to produce electricity in the range 20 to 36 MW, also uses TRISO fuel and helium coolant. The term VSMR – **v**ery **s**mall **m**odular **r**eactor – has been applied to it [17]. There is also the MMR™ – **m**icro **m**odular **r**eactor – with produces in the range 5-10 MW_e, under development by the Ultra-Safe Nuclear Corporation (UNSF) [18], [19]. This too uses helium as the exchange fluid, and it also uses graphite neutron moderation. It is not a molten salt reactor: these use a molten salt as the coolant, although there are none currently in service and they belong to an earlier era [20]. MMR™ is however, in event of its eventual commercialisation, expected to use molten salt thermal storage. Heat from the power generation at an MMR™ - energy from the reactor not converted to work from which electricity can be produced – will be transferred to a molten salt which will be held under insulated conditions until its heat is needed. That is correctly described as a heat battery [21]. The MMR™ uses TRISO fuel. TRISO fuel is in some degree a generic term and there is scope for variation in the precise composition of the nuclear fuel. That in the MMR™ was uranium enriched in the 235 isotope to 9% [22].

8.6 DIGRESSION INTO NUCLEAR FUSION

Heat from a nuclear fusion process could of course be used to raise steam for electricity generation, although this is not yet taking place anywhere. There is however so much activity into future use of fusion to make electricity that completeness in this book requires at least a mention of it. In the deuterium-tritium (D-T) reaction:

$$^{2}_{1}D + ^{3}_{1}T \rightarrow ^{4}_{2}He + ^{1}_{0}n$$

there is one fewer bound nucleon on the right of the equation than on the left. There is a further point to be considered which will be made with the aid of the diagram below which is fairly basic and has been widely reproduced (e.g. [23]).



Taken from [23].

For nuclides used in nuclear fission processes, those of uranium, plutonium and thorium, the binding energy per nucleon is always in the region of 8 MeV (although greater precision than that was achived in the calculation on fission energies in Chapter 1). For the much lighter nuclides in fusion reactions this is not so and there is a steep rise in binding energy per nucleon with atomic mass. The binding energy per nucleon of the nuclides in the equation above are as follows: deuterium 1.115 MeV, helium-4 7.073 MeV and tritium 2.827 MeV. The correctness of these the interested reader can easily confirm from the diagram. The energy of the fusion reaction is then:

$$[(4 \times 7.073) - (3 \times 2.827) - (2 \times 1.115)] \text{ MeV} = 17.58 \text{ MeV}$$

For 1 mol (2 g) of deuterium atoms this becomes 1.69 TJ.

Fusion reactions such as that exemplified in the equation above take place in a plasma at temperatures tens or hundreds of millions of degrees centigrade [24]. The plasma is contained by a magnetic field and where this is toroidal in shape the reactor is called a tokamak. There are altogether about thirty tokamaks in operation, with the common goal of providing findings and information which will lead to eventual power generation by fusion. They are all experimental: none of them is set up for electricity production for consumers. The collective noun for tokamaks is 'fleet'.

Because of the unimaginably high temperatures involved in fusion, there is a tendency to think of it as a process of extremes. The high temperature is necessitated by the need for the nuclei to overcome the coulombic forces between them so that fusion can take place. There is sufficient kinetic energy for that only at such temperatures. The colossal temperature of the plasma could not affect the wall of the reactor. That is because the mass of plasma in a tokamak is ultra-minuscule in comparison with the mass of the wall and this offsets the temperature difference [25]. The wall *can* be affected by impingement of neutrons from the fusion process. Being electrically neutral these exit the magnetic field and when they encounter the wall their kinetic energy is converted to thermal.

In experimental tokamaks rates of heat release are of the same order as those in coal or natural gas furnaces used in power generation. As an example, in the planning of the K-DEMO tokamak in South Korea two options being considered, 1700 MW of heat and 2400 MW of heat [26]. These if relating to a conventional fuel would be seen as quite moderate, not at all 'extreme'. A further perspective can be put on that. The magnetic field which contains the plasma is often in the range 2 to 10 tesla (T). That at the Joint European Torus (JET) in Oxfordshire, England is 4 T, which is within the range of magnetic fields used in magnetic resonance imaging (MRI) in hospitals. The plasma volume at JET is 100 m^3.

Tokamaks in current or planned operation additional to those mentioned above include the COMPASS-U tokamak in the Czech Republic, where the magnetic field is 5 T [27] and the HL-2M tokamak in China where the magnetic field is 2.2 T [28]. There are many others as noted. In a tokamak the temperature required for fusion has to be reached (often with energy from flywheel generation of electricity, as at the Joint European Torus). One of the major engineering challenges in making electricity from fusion viable is the need to obtain a greater quantity of electricity back from the fusion than that put in to set up conditions for the fusion. It was reported in 'Nature' in October 2019 [29] that in the UK work is about to commence on the design of a tokamak for commercial production of electricity. Even if there is plain sailing through design, construction and commissioning this tokamak is not expected to be even at the demonstration stage before 2040. There are similar enterprises in other countries including the US and China having the same sort of time scale. By 2040 over 80 years will have elapsed since the Atoms for Peace Conference, which was held in Geneva in 1958 [30]. One of the keynote speakers at that was Lev Artsimovich (1909-1973, 'father of the Tokamak' [31]). He was not sanguine in his expectations of electricity production from fusion: 'We must not underestimate the difficulties which will have to be overcome before we learn to master thermonuclear fusion' and '[the use of energy from nuclear fusion] will require a maximum concentration of intellectual effort and the mobilization of very appreciable material facilities and complex apparatus' [30].

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