WORLD NUCLEAR ASSOCIATION

2020/21

Pocket Guide

Environment • Radiation • Reactors • Uranium

Nuclear Power, Energy and the Environment

Energy and emissions, selected countries (2017)

Location	Population (million)	GDP (billion US$)	CO_2 emissions (million tonnes)	Energy use per capita (toe*)
Australia	25	1,574	385	5.2
Austria	9	433	65	3.8
Bangladesh	165	180	78	0.3
Belgium	11	526	90	4.9
Brazil	209	2,279	428	1.4
Bulgaria	7	59	43	2.7
Canada	37	1,873	548	7.9
China	1,386	10,161	9,258	2.2
Colombia	49	374	75	0.8
Congo (DR)	81	33	2	0.4
Croatia	4	63	16	2.1
Czech Republic	11	241	102	4.1
Denmark	6	360	31	3.0
Egypt	98	272	209	1.0
Ethiopia	105	58	13	0.4
Finland	6	262	43	6.0
France	67	2,875	306	3.7
Germany	83	3,884	719	3.8
Hungary	10	154	46	2.7
Iceland	0	18	2	16.0
India	1,339	2,631	2,162	0.7
Indonesia	264	1,091	496	0.9
Iran	81	561	567	3.2
Ireland	5	358	36	2.8
Italy	61	2,121	322	2.5
Japan	127	6,141	1,132	3.4
Lithuania	3	48	11	2.7
Mexico	123	1,285	446	1.5
Myanmar	53	80	30	0.4
Netherlands	17	924	156	4.3
New Zealand	5	181	32	4.3
Nigeria	191	461	86	0.8
North Korea	26	27	20	0.6
Norway	5	483	35	5.7
Pakistan	197	241	183	0.5
Philippines	105	303	127	0.6
Romania	20	216	71	1.7
Russia	145	1,680	1,537	5.1
Saudi Arabia	33	684	532	6.4
Slovakia	5	108	32	3.2
Slovenia	2	53	13	3.3
South Africa	57	427	422	2.3
South Korea	51	1,346	600	5.5
Spain	47	1,510	253	2.7
Sweden	10	569	38	4.9
Switzerland	9	655	37	2.8
Thailand	69	423	244	2.0
Turkey	80	1,206	379	1.8
UAE	9	387	197	7.2
UK	66	2,819	359	2.7
Ukraine	44	127	171	2.0
USA	326	17,349	4,761	6.6
Vietnam	96	175	191	0.8
World	**7,519**	**80,079**	**32,840**	**1.9**

**Tonnes of oil equivalent*

Source: IEA

CO_2 emissions per capita (2017)

Location	tonnes /capita	Location	tonnes /capita	Location	tonnes /capita
Saudi Arabia	16.2	New Zealand	6.7	Mexico	3.6
Australia	15.6	Norway	6.6	Romania	3.6
Canada	15.0	Slovenia	6.5	Thailand	3.5
USA	14.6	Iceland	6.3	Egypt	2.1
Taiwan	12.0	Bulgaria	6.1	Brazil	2.0
South Korea	11.7	Slovakia	5.9	Vietnam	2.0
Russia	10.6	Spain	5.5	Indonesia	1.9
Czech Republic	9.6	UK	5.4	India	1.6
Netherlands	9.1	Denmark	5.4	Colombia	1.5
Japan	8.9	Italy	5.3	Philippines	1.2
Germany	8.7	Turkey	4.7	Pakistan	0.9
Belgium	8.0	Hungary	4.7	North Korea	0.8
Finland	7.7	France	4.6	Myanmar	0.6
Ireland	7.4	Switzerland	4.4	Bangladesh	0.5
Austria	7.4	Croatia	3.9	Nigeria	0.5
South Africa	7.3	Lithuania	3.8	Cote d'Ivoire	0.4
Iran	7.0	Ukraine	3.8	Ethiopia	0.1
China	6.7	Sweden	3.7	Congo (DR)	0.0
World					**4.4**

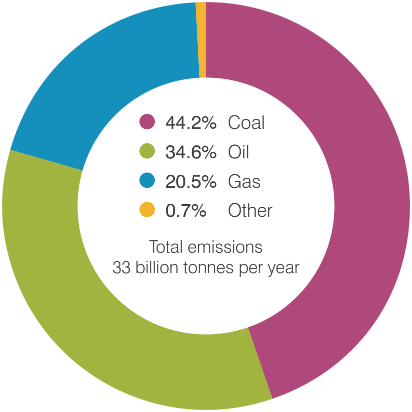
Source: IEA

CO_2 emissions per GDP (2017)

Location	kg/ US$	Location	kg/ US$	Location	kg/ US$
Switzerland	0.06	Germany	0.19	Philippines	0.42
Congo (DR)	0.07	Nigeria	0.19	Bangladesh	0.43
Norway	0.07	Colombia	0.20	South Korea	0.45
Sweden	0.07	Ethiopia	0.23	Indonesia	0.46
Denmark	0.09	Lithuania	0.23	Taiwan	0.51
Ireland	0.10	Australia	0.24	Thailand	0.58
France	0.11	Slovenia	0.25	North Korea	0.71
Iceland	0.12	Cote d'Ivoire	0.26	Bulgaria	0.73
UK	0.13	Croatia	0.26	Pakistan	0.76
Austria	0.15	USA	0.27	Egypt	0.77
Italy	0.15	Canada	0.29	Saudi Arabia	0.78
Finland	0.16	Hungary	0.30	India	0.82
Belgium	0.17	Slovakia	0.30	China	0.91
Netherlands	0.17	Turkey	0.31	Russia	0.91
Spain	0.17	Romania	0.33	South Africa	0.99
Japan	0.18	Mexico	0.35	Iran	1.01
New Zealand	0.18	Myanmar	0.38	Vietnam	1.09
Brazil	0.19	Czech Republic	0.42	Ukraine	1.35
World					**0.41**

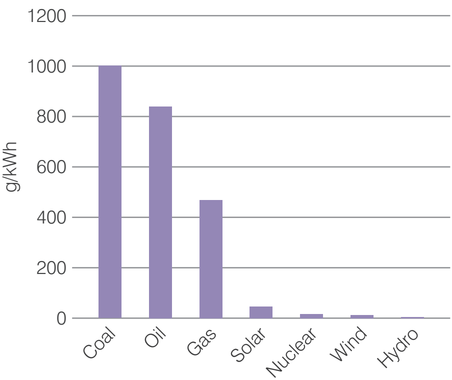
Source: IEA

Global CO_2 emissions (2017)



Source: IEA

Emissions intensity by energy source



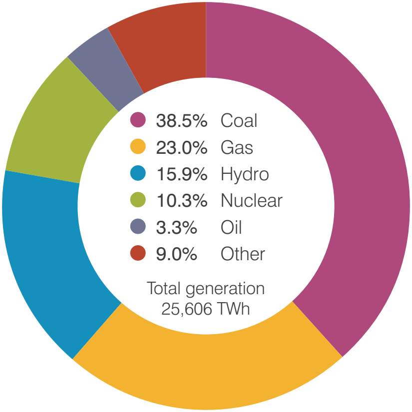
Source: IPCC

Countries with nuclear electricity

Location	Nuclear capacity MWe	% share of electricity, 2019
USA	96,772	20
France	62,250	71
China	45,498	5
Japan	31,679	8
Russia	29,203	20
South Korea	23,231	26
Canada	13,553	15
Ukraine	13,107	54
Germany	8052	12
UK	8883	16
Sweden	7738	34
Spain	7121	21
India	6255	3
Belgium	5930	48
Czech Republic	3932	35
Switzerland	2960	24
Finland	2764	35
Bulgaria	1926	38
Brazil	1884	3
Hungary	1902	49
South Africa	1830	7
Slovakia	1816	54
Argentina	1641	6
Mexico	1600	5
Pakistan	1355	7
Romania	1310	19
Iran	915	2
Slovenia	696	37
Netherlands	485	3
Armenia	375	28
Total*	390,382	10.2

* Includes four reactors on Taiwan with total of 3844 MWe.
Sources: World Nuclear Association, IAEA
as of 07.07.2020

Electricity generation by fuel (2017)



Source: IEA

Nuclear and climate change

The production of electricity from nuclear power plants generates significantly lower emissions of carbon dioxide (CO_2) compared with fossil fuel plants.

A study by the International Atomic Energy Agency (IAEA) puts greenhouse gas emissions from nuclear generation at between 9 and 21 tonnes CO_2-equivalent per GWh of electricity produced. This compares with between 385 and 1343 tonnes for fossil fuel and between 9 and 279 tonnes for renewable energy sources.

Nuclear power accounted for about 10.2% of global electricity production in 2019. The current use of nuclear energy avoids the emission of about 2.1 billion tonnes of CO_2-equivalent every year.

According to the International Energy Agency (IEA), nuclear energy has avoided the emission of some 56 gigatonnes of CO_2, the equivalent of two years' global emissions at today's rate. It is estimated that, at current nuclear usage and CO_2 emission levels, almost four years' worth of CO_2 emissions will be avoided by 2040.

Under IEA scenarios, global electricity demand will increase by between 80% and 130% by 2050. Studies show that significant reductions in carbon emissions, while also meeting this growing demand, cannot happen without nuclear as a major component of the energy mix.

At least 80% of the world's electricity must be low-carbon by 2050 if the world is to keep global warming within 2°C, according to the Intergovernmental Panel on Climate Change (IPPC).

Harmony

The nuclear industry believes a diverse mix of low-carbon generating technologies is needed in order for the 2°C goal to be met. Its target for nuclear energy is to provide 25% of electricity in 2050, requiring some 1000 GWe of new nuclear capacity to be constructed. The build rate required to meet this goal is: 10 GWe per year between 2016 and 2020; 25 GWe per year between 2021 and 2025; and 33 GWe per year between 2026 and 2050.

To realise the Harmony goal, the global nuclear industry should seek: a level playing field for all low-carbon technologies; harmonized regulatory processes; and an effective safety paradigm.

Achieving 1000 GWe of new nuclear build by 2050 will require a cooperative effort by the whole nuclear community — from industry to research, governments and regulators — to focus on removing the real barriers to growth. Harmony provides the framework for the nuclear industry to deliver its potential.

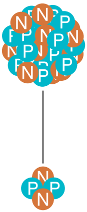
Radiation

What is radiation?

Radiation is energy being transmitted through space. Visible light, ultra-violet light and transmission signals for TV and radio communications are all forms of radiation that are common in our daily lives. There are two types of radiation: 'ionizing' and 'non-ionizing'. Ionizing radiation is electromagnetic radiation with sufficient energy to remove tightly bound electrons from atoms, thereby creating ions capable of breaking chemical bonds, and thus causing ionization of the matter through which it passes. Non-ionizing radiation has sufficient energy to move atoms but not create ions.

Types of ionizing radiation

Alpha (α) particles

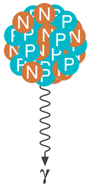


- Particles (helium nuclei) consisting of two protons and two neutrons.
- Emitted from naturally-occurring heavy elements such as uranium and radium, as well as from some man-made unstable elements (formed artificially by neutron capture and possibly subsequent beta decay).
- Densely ionizing but can be readily stopped by a few centimetres of air, a sheet of paper, or human skin.
- Only dangerous if alpha-emitter is inhaled or ingested and released inside the body at high exposures.
- Alpha-emitters can be safely stored in a sealed container.
- Measurement of exposures from alpha particles requires special detector systems.

Beta (β) particles

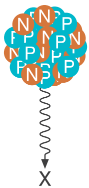
- Either electrons or positrons emitted by many radioactive elements.
- Can be stopped by wood, aluminium or glass a few millimetres thick.
- Can penetrate into human skin but generally less so than gamma radiation.
- High exposure produces an effect like sunburn, but which is slower to heal.
- Can be safely stored in appropriate sealed containers.
- Measurement of exposures from beta particles requires special detector systems.

Gamma (γ) rays



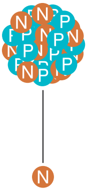
- High-energy beams similar to X-rays.
- A form of electromagnetic radiation.
- Emitted during radioactive alpha and beta decays.
- Very penetrating so need dense materials such as water, glass, lead, steel or concrete to shield them.
- Poses the main hazard to people when a container holding radioactive materials becomes unsealed.
- Gamma activity can be measured with a scintillation detector or Geiger counter.
- Doses can be assessed by the small badges worn by workers handling radioactive materials.

X-rays



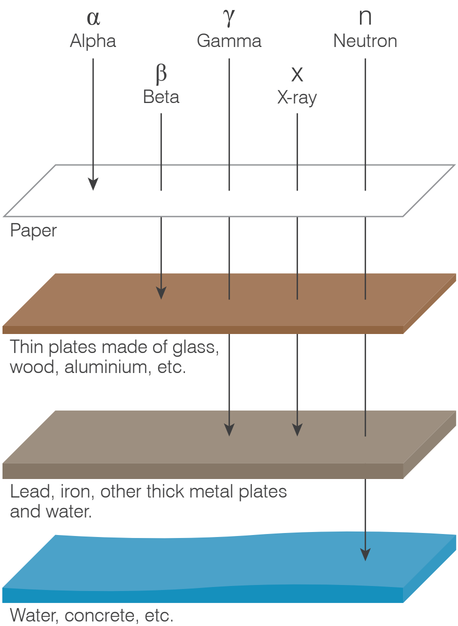
- Similar to gamma rays, but originate from the electron cloud.
- A form of electromagnetic radiation.
- X-ray photons carry enough energy to ionize atoms and disrupt molecular bonds.
- Higher energy X-rays can traverse relatively thick objects without being absorbed or scattered much.

Neutrons



- A free neutron usually emitted as a result of spontaneous or induced nuclear fission.
- Can be shielded by light atoms, particularly those containing hydrogen.
- Indirectly ionizing and hence can be destructive to human tissue.
- Can be slowed down (or 'moderated') by graphite or water.
- Measurement of exposures from neutrons requires special detector systems.

Types of radiation and penetration



Measuring radiation

The becquerel (Bq) is the SI derived unit of radioactivity. One becquerel is defined as the activity of a quantity of radioactive material in which one nucleus decays per second. A kilogram of granite might have 1000 Bq of activity.

The amount of ionizing radiation absorbed in tissue can be expressed in grays (Gy): 1 Gy = 1 joule per kilogram. Since neutrons and alpha particles cause more damage per gray than gamma or beta radiation, another unit, the sievert (Sv), is used in setting radiological protection standards. Total dose is measured in sieverts: as this unit is so large, millisieverts (mSv) and microsieverts (μSv) are often used. One gray of beta or gamma radiation has one sievert of biological effect; one gray of alpha particles has a 20 Sv effect; and one gray of neutrons is equivalent to around 10 Sv (depending on their energy).

Background radiation

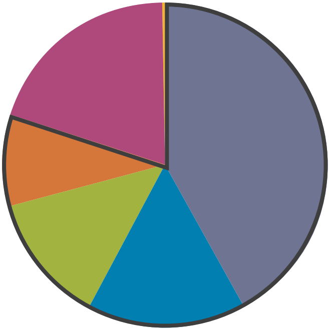
Everyone is exposed to low levels of ionizing radiation. Naturally-occurring background radiation resulting from radioactive materials in the ground (mainly radon gas), cosmic rays and natural radioactivity in our bodies are the main sources of exposure for most people. Annual doses typically received range from about 1.5 to 3.5 mSv, but can be more than 50 mSv.

Natural radiation contributes about 80% of the annual dose to the population. The remaining 20% come from a range of medical, commercial and industrial activities. The most familiar of these sources of exposure is medical X-rays. The nuclear power industry accounts for less than 0.1% of background radiation. A 2012 UNSCEAR report confirmed that radiation from the normal operation of nuclear power plants poses no increase in risk to public health.

Key points

- Radiation exists naturally everywhere at widely varying levels. In some places, due to radioactive materials in the ground, natural background radiation is 10 times higher-than-average.
- Humankind exists and thrives in a world with strongly differing background radiation, while experiencing no detrimental effects to human health.
- Radiation has always been around, and has been used and studied for more than 100 years.
- Radiation resulting from the use of nuclear energy accounts for only a minute fraction of background radiation.
- Scientific advancements demonstrate that there is no increased health risk from exposure to low-dose radiation.

Sources of exposure to radiation

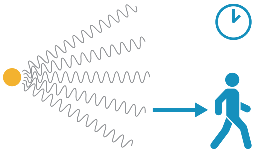


●	20%	Medicine
●	<0.1%	Nuclear Industry
●	42%	Radon
●	16%	Soil
●	13%	Cosmic
●	9%	Food and Drinking Water
○	80%	Natural Radiation

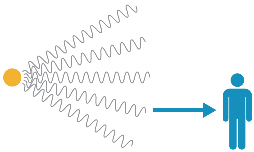
Source: UNSCEAR

Protection against radiation

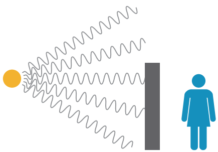
Radiation has always been present in the environment and in our bodies. However, we can and should minimise unnecessary exposure to significant levels of man-made radiation. Radiation can be very easily detected. There are a range of simple, sensitive instruments capable of detecting minute amounts of radiation from natural and anthropogenic sources. There are three ways in which people can be protected from identified radiation sources:



Time: Dose is reduced by limiting exposure time.



Distance: The intensity of radiation decreases with distance from its source.



Shielding: Barriers of lead, concrete or water give good protection from penetrating radiation such as gamma rays.

The International Commission for Radiological Protection has developed a system for protection with three basic principles:

Justification: No practice involving exposure to radiation should be adopted unless it produces a net benefit to those exposed or to society generally.

Optimization: Radiation doses and risks should be kept "as low as reasonably achievable" (ALARA), whilst taking into account economic and social factors.

Limitation: The exposure of individuals should be subject to dose or risk limits, above which the radiation risk would be deemed unacceptable.

These principles apply to normal exposures. A similar system applies for accidental exposures but where it is not possible to limit doses, a target 'reference' level is suggested instead.

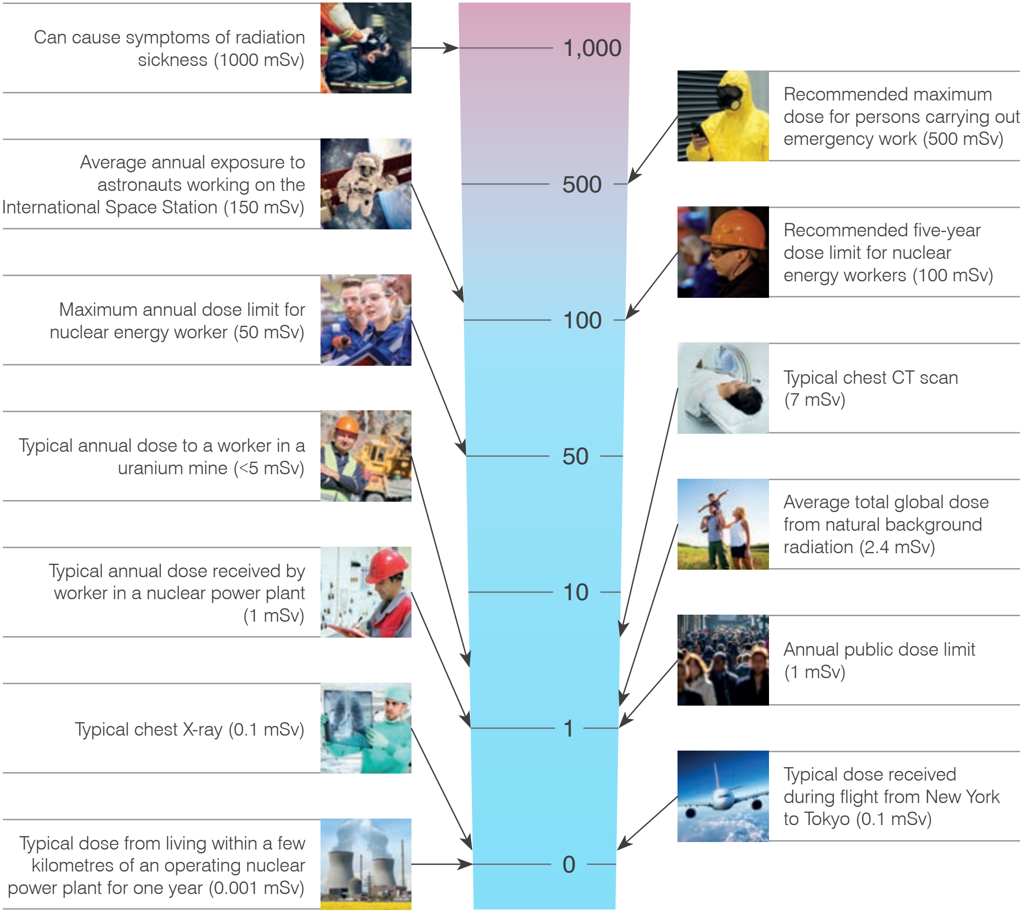
Underlying these principles is the application of the 'linear hypothesis' based on the idea that any level of radiation dose, no matter how low, involves the possibility of risk to human health. However, the weight of scientific evidence has never established any cancer risk or other health effects at doses below 50 mSv over a short period or at about 100 mSv/yr.

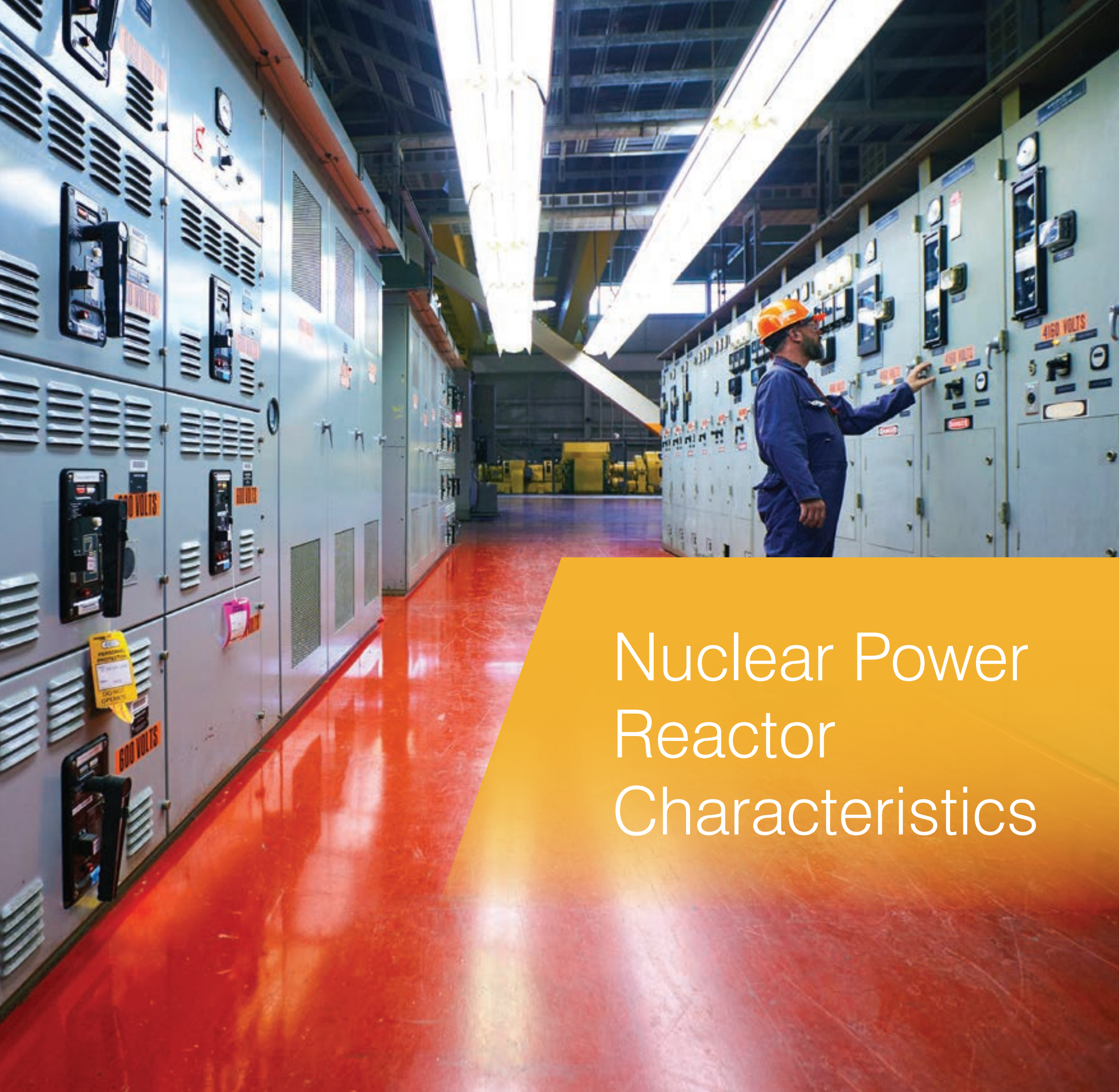
Nuclear accidents and radiation release

The exposure levels during normal operation of civil nuclear facilities are very low. However, there have been some serious accidents, which received extensive public attention and whose consequences have been reviewed by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR).

- A 2017 report from UNSCEAR concluded that the majority of cases in an observed increase of thyroid cancer in adults — who were under the age of 18 — in the exposed area at the time of the April 1986 Chernobyl accident in Ukraine cannot be "attributable to radiation exposure". Thyroid cancer is usually not fatal if diagnosed and treated early.
- A May 2013 UNSCEAR report observed that radiation exposure following the March 2011 accident at the Fukushima Daiichi plant in Japan "did not cause any immediate health effects" nor would it be likely "to be able to attribute any health effects in the future among the general public and the vast majority of workers" to the accident. A White Paper published by UNSCEAR in 2017 reaffirmed the earlier report's conclusions.

Some comparative whole-body radiation doses





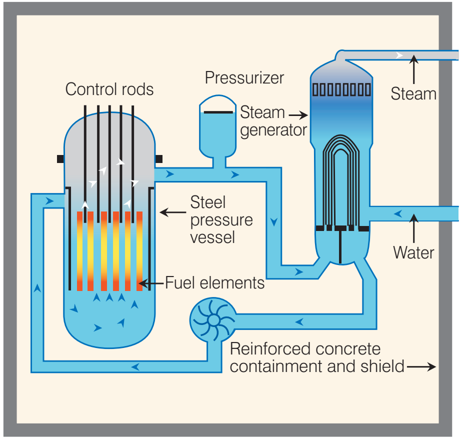
Nuclear Power Reactor Characteristics

Nuclear power & reactors worldwide

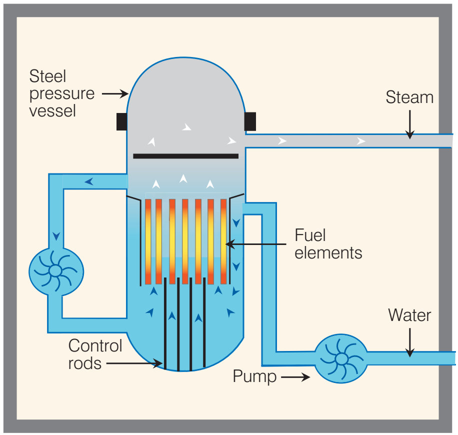
Location	Nuclear electricity generation, 2019 (billion kWh)	Share of total electricity production, 2019 (%)	Number of operable reactors*	Nuclear generating capacity* (MWe)
Argentina	7.9	5.9	3	1641
Armenia	2.0	27.8	1	375
Belgium	41.3	47.6	7	5943
Brazil	16.1	2.7	2	1884
Bulgaria	16.6	37.5	2	1926
Canada	95.5	14.9	19	13,553
China	348.4	4.9	47	45,498
Czech Rep	28.6	35.2	6	3932
Finland	22.9	34.7	4	2764
France	379.5	70.6	57	62,250
Germany	71.0	12.4	6	8052
Hungary	15.4	49.2	4	1902
India	40.7	3.2	22	6255
Iran	5.9	1.8	1	915
Japan	65.6	7.5	33	31,679
Mexico	10.9	4.5	2	1600
Netherlands	3.7	3.2	1	485
Pakistan	9.0	6.6	5	1355
Romania	10.3	18.5	2	1310
Russia	208.8	19.7	38	29,203
Slovakia	15.4	53.9	4	1816
Slovenia	5.5	37.0	1	696
South Africa	13.6	6.7	2	1830
South Korea	138.6	26.2	24	23,231
Spain	55.9	21.4	7	7121
Sweden	55.9	34.0	7	7738
Switzerland	16.6	23.9	4	2960
Ukraine	83.0	53.9	15	13,107
UK	51.0	15.6	15	8883
USA	809.4	19.7	95	96,772
Total**	**2676**	**10.2**	**440**	**390,382**

*as of 07.07.2020 *Sources: World Nuclear Association, IAEA*

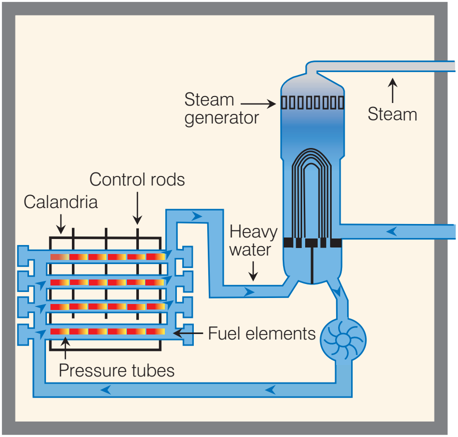
**The world total includes four reactors on Taiwan with a combined capacity of 3844 MWe, which generated a total of 31.1 billion kWh in 2019, accounting for 13.4% of its electricity generation.



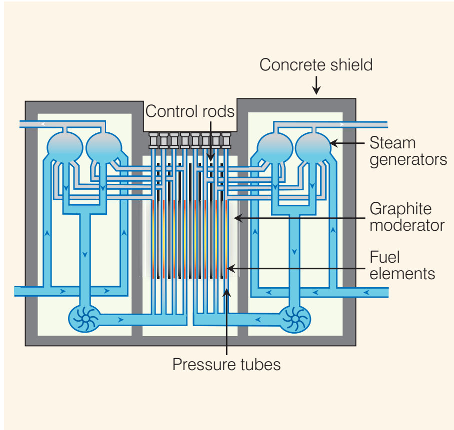
Pressurized water reactor (PWR)



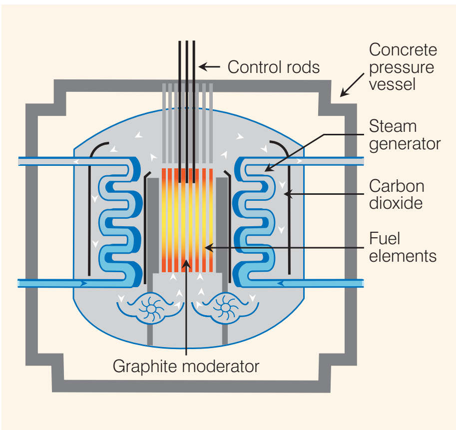
Boiling water reactor (BWR)



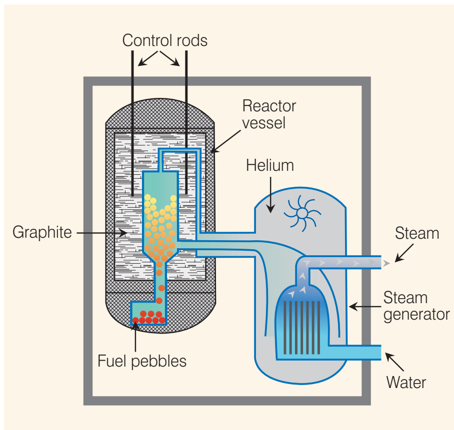
Pressurized heavy water reactor (PHWR/Candu)



Light water graphite-moderated reactor (LWGR/RBMK)



Advanced gas-cooled reactor (AGR)



High-temperature reactor (HTR)

Nuclear fission and types of nuclear reactor

- Like all other thermal power plants, nuclear reactors work by generating heat, which boils water to produce steam to drive the turbogenerators. In a nuclear reactor, the heat is the product of nuclear fission.
- Uranium and plutonium nuclei in the fuel are bombarded by neutrons and split usually into two smaller fragments, releasing energy in the form of heat, as well as more neutrons. Some of these released neutrons then cause further fissions, thereby setting up a chain reaction.
- The neutrons released are 'fast' neutrons, with high energy. These neutrons need to be slowed down by a moderator for the chain reaction to occur.
- In BWRs (boiling water reactors) and PWRs (pressurized water reactors), collectively known as LWRs (light water reactors), the light water (H_2O) coolant is also the moderator.
- PHWRs (pressurized heavy water reactors) use heavy water (deuterium oxide, D_2O) as moderator. Unlike LWRs, they have separate coolant and moderator circuits. Coolant may be light or heavy water.
- The chain reaction is controlled by the use of control rods, which are inserted into the reactor core either to slow or stop the reaction by absorbing neutrons.
- In the Candu PHWR, fuel bundles are arranged in pressure tubes, which are individually cooled. These pressure tubes are situated within a large tank called a calandria containing the heavy water moderator. Unlike LWRs, which use low enriched uranium, PHWRs use natural uranium fuel, or it may be slightly enriched. Candu reactors can be refuelled whilst on-line.
- A PWR generates steam indirectly: heat is transferred from the primary reactor coolant, which is kept liquid at high pressure, into a secondary circuit where steam is produced for the turbine.
- A BWR produces steam directly by boiling the water coolant. The steam is separated from the remaining water in steam separators positioned above the core, and passed to the turbines, then condensed and recycled.
- In GCRs (gas-cooled reactors) and AGRs (advanced gas-cooled reactors) carbon dioxide is used as the coolant and graphite as the moderator. Like heavy water, a graphite moderator allows natural uranium (in GCRs) or very low-enriched uranium (in AGRs) fuel to be used.
- The LWGR (light water graphite reactor) has enriched fuel in pressure tubes with the light water coolant. These are surrounded by the graphite moderator. More often referred to as the RBMK.
- In FBR (fast breeder reactor) types, the fuel is a mix of oxides of plutonium and uranium; no moderator is used. The core is usually surrounded by a 'fertile blanket' of uranium-238. Neutrons escaping the core are absorbed by the blanket, producing further plutonium, which is separated out during subsequent reprocessing for use as fuel. FBRs normally use liquid metal, such as sodium, as the coolant at low pressure.
- High temperature gas-cooled reactors (HTGRs), not yet in commercial operation, offer an alternative to conventional designs. They use graphite as the moderator and helium as the coolant. HTGRs have ceramic-coated fuel capable of handling temperatures exceeding 1600°C and gain their efficiency by operating at temperatures of 700-950°C. The helium can drive a gas turbine directly or be used to make steam.
- While the size of individual reactors is increasing to well over 1200 MWe, there is growing interest in small units down to about 10 MWe.

Reactor facts and performance

- Electricity was first generated by a nuclear reactor on 20 December 1951 when the EBR-I test reactor in the USA lit up four light bulbs.

- The 5 MWe Obninsk LWGR in Russia, which commenced power generation in 1954, was the first to supply electricity to a grid system. It was shut down on 30 April 2002.
- Calder Hall, at Sellafield, UK, was the world's first industrial-scale nuclear power station, becoming operational in 1956. The plant finally shut down on 31 March 2003.
- Grohnde, a 1360 MWe German PWR which first produced power in 1984, has generated over 387 billion kWh of electricity, more than any other reactor.
- With a cumulative load factor of 93.6% since first power in 2007, the Cernavoda 2 PHWR in Romania leads the way on lifetime performance, followed by Germany's Emsland, a PWR.
- On 31 December 2018, unit 1 of the Kaiga plant in India - a 220 MWe PHWR - set a new world record of 962 days continuous power production, breaking the previous record of 940 days set in 2016 by unit 2 of the Heysham II AGR plant in the UK.
- In 2019, 66 nuclear power reactors achieved load factors of more than 95%, compared with 40 the previous year.
- Over 18,550 reactor-years of operating experience have so far been accumulated.
- Nuclear electricity supplied worldwide in 2019 was 2676 billion kWh, about 10.2% of the total.

Nuclear fuel performance

- The amount of electricity generated from a given amount of fuel is referred to as burn-up, expressed in megawatt days per tonne of fuel (MWd/t).
- Typically, PWRs now operate at around 40,000 MWd/t, with an enrichment level of about 4% uranium-235.
- Advances in fuel assembly design and fuel management techniques, combined with slightly higher enrichment levels of up to 5%, now make burn-ups of up to 50,000 to 60,000 MWd/t achievable.
- With a typical burn-up of 45,000 MWd/t, one tonne of natural uranium made into fuel will produce as much electricity as 17,000 to 20,000 tonnes of black coal.

Nuclear power reactor types: typical characteristics

Characteristic	PWR	BWR	AGR	PHWR (Candu)	LWGR (RBMK)	FBR
Active core height, m	4.2	3.7	8.3	5.9	7.0	1.0
Active core diameter, m	3.4	4.7	9.3	6.0	11.8	3.7
Fuel inventory, tonnes	104	134	110	90	192	32
Vessel type	Cylinder	Cylinder	Cylinder	Tubes	Tubes	Cylinder
Fuel	UO_2	UO_2	UO_2	UO_2	UO_2	PuO_2/UO_2
Form	Enriched	Enriched	Enriched	Natural	Enriched	-
Coolant	H_2O	H_2O	CO_2	D_2O	H_2O	Sodium
Steam generation	Indirect	Direct	Indirect	Indirect	Direct	Indirect
Moderator	H_2O	H_2O	Graphite	D_2O	Graphite	None
Number operable*	298	73	14	49	14	3

*as of 31.12.18

Source: IAEA

Uranium, from Mine to Mill

Mineralogy and ore grade

- **Uraninite** is the most common primary uranium mineral; others of economic interest include coffinite and brannerite. The most common form of uraninite is **pitchblende**, which is sometimes associated with colourful secondary uranium minerals derived from weathering.
- The average abundance of uranium in the Earth's crust is 2.7 parts per million, making it more common than tin.
- The concentration of uranium needed to form an economic mineral deposit varies widely depending on its geological setting and physical location. Average ore grades at operating uranium mines range from 0.03% U to as high as 24% U, but are most frequently less than 1% U. Lower uranium grades are viable as by-product.

Mining methods

- **Open pit:** used to mine relatively shallow deposits. Economics depend on the ratio of ore to waste, higher grade ores having lower ratios.
- **Underground:** used to mine deposits too deep for open pit mining. For mining to be viable, these deposits must be comparatively high grade.
- **In-situ leach:** this method is applicable only to sandstone-hosted uranium deposits located below the water table in a confined aquifer. The uranium is dissolved in acid or alkali injected into and recovered from the aquifer by means of wells. The geology remains undisturbed.
- **By-product:** uranium often occurs in association with other minerals such as gold (South Africa), phosphates (USA and elsewhere) and copper (Australia).

Top uranium mines in 2018-2019

Mine	Country	Main owner	Mine type	Production (tU)		% of world production	
				2018	2019	2018	2019
Cigar Lake	Canada	Cameco/Orano	Underground	6924	6924	13	13
Husab	Namibia	Swakop Uranium (CGN)	Open pit	3028	3400	6	6
Olympic Dam	Australia	BHP Billiton	By-product/underground	3159	3364	6	6
Moinkum & Tortkuduk	Kazakhstan	Orano/Kazatomprom	ISL	1900	3252	4	6
Inkai, sites 1-3	Kazakhstan	Kazaktomprom/Cameco	ISL	2643	3209	5	6
Budenovskoye 2	Kazakhstan	Uranium One/Kazatomprom	ISL	2081	2600	4	5
Rössing	Namibia	Rio Tinto	Open pit	2102	2076	4	4
Somair	Niger	Orano	Open pit	1783	1912	3	4
Central Mynkuduk	Kazakhstan	Kazatomprom	ISL	1600	1694	3	3
South Inkai (Block 4)	Kazakhstan	Uranium One/Kazatomprom	ISL	1635	1601	3	3
Top 10 total				**26,855**	**30,032**	**50**	**56**

Uranium output by producer*

Company	2019 production	
	Actual (tU)	World share (%)
Kazatomprom	13,291	25
Orano	5809	11
Cameco	4754	9
Uranium One	4624	9
CNNC	3961	7
CGN	3871	7
BHP	3364	6
ARMZ	2904	5
Navoi Mining	2404	4
Energy Asia	2122	4
General Atomics/Quasar	1764	3
Sopamin	1032	2
Rio Tinto	1016	2
VostGok	801	1
Other	**3001**	**6**
Total**	**53,656**	**100**

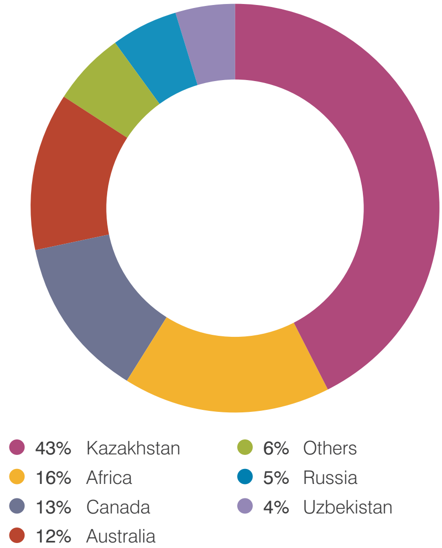
** based on ownership share*

*** Kazatomprom owns 50% share of Energy Asia, as a result, some quantity is double counted. Percentage figures do not add up to 100% due to rounding.*

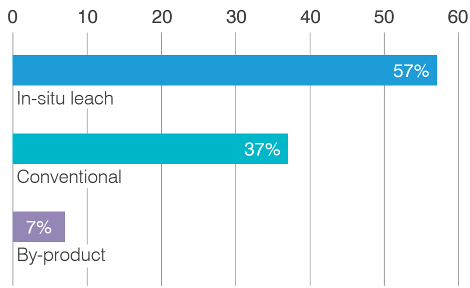
Processing and extraction

- Crushing and grinding: breaks down the ore to fine particles.
- Leaching: acid or alkali dissolves the uranium, and the uranium-bearing solution is separated from the leached solids.
- Extraction: ion exchange or solvent extraction methods are used to separate the dissolved uranium.
- Precipitation and drying: uranium is precipitated from solution using one of several chemicals. Dewatering, filtration and drying complete the process. The final product is sometimes known as yellowcake, although it is typically khaki in colour.

World uranium production (2019)



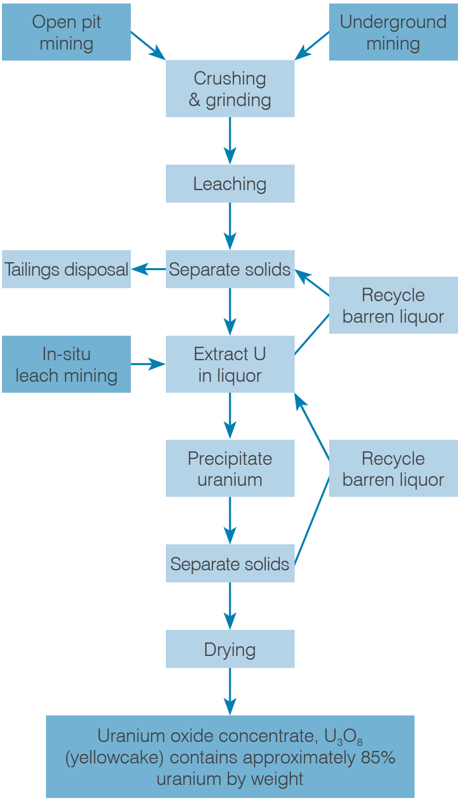
Mining method (2019)



** Percentage figures do not add up to 100% due to rounding.*

Milling

Simplified flow chart of uranium ore processing from mining to the production of concentrate. These processes are commonly known as milling and the product – uranium oxide concentrate – is the raw material for making nuclear fuel.



Uranium production and resources

Country	2019 production (tU)	Uranium resources (tU)* <US$260/kg
Australia	6613	2,055,000
Canada	6938	846,000
China	1885	290,000
India	308	157,000
Kazakhstan	22,808	905,000
Namibia	5476	541,000
Niger	2983	426,000
Russia	2911	657,000
South Africa	346	449,000
Ukraine	801	219,000
USA	67	101,000
Uzbekistan	2404	139,000
Other	116	1,203,000
Total	**53,656**	**7,988,000**

*OECD/NEA Reasonably Assured Resources category

Sources: World Nuclear Association & OECD/NEA

Uranium history

- In 1789, Martin Klaproth, a German chemist, isolated an oxide of uranium while analyzing pitchblende samples from silver mines in Bohemia.
- For over 100 years uranium was mainly used as a colorant for ceramic glazes and for tinting in early photography. Uranium was produced in Bohemia, Cornwall (UK), Portugal and Colorado and total production amounted to about 300-400 tonnes.
- The discovery of radium in 1898 by Marie Curie led to the construction of a number of radium extraction plants processing uranium ore (radium is a decay product of uranium).
- Prized for its use in cancer therapy, radium reached a price of 750,000 gold francs per gram in 1906 (US$10 million). It is estimated that 754 grams were produced worldwide between 1898 and 1928. Uranium itself was treated simply as a waste material.
- With the discovery of nuclear fission in 1938, the uranium industry entered a new era. On 2 December 1942, the first controlled nuclear chain reaction was achieved in Chicago. Although nuclear fission was first used for military purposes, the emergence of civil nuclear power reactors in the 1950s demonstrated the enormous potential of nuclear fission for supplying electricity.
- From a small beginning in 1951, when four lightbulbs were lit with nuclear electricity, the nuclear power industry now supplies about 10.2% of world electricity.
- Between the mid-1940s and the late-1980s, uranium supply exceeded reactor requirements. However, the gap between requirements and production since 1990 has been filled by secondary supplies, mostly from stockpiles including military inventory. Going forward, the gap will increasingly be filled by higher primary production, as secondary supplies diminish.

Front cover image: Ontario Power Generation

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This pocket guide covers:

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Nuclear Power Reactor Characteristics

How do nuclear power plants work? What are the different types of reactors in use? Which countries have chosen nuclear to meet their electricity needs?

Uranium, Mine to Mill

Where does uranium come from? Which countries are the largest producers? How is uranium extracted and processed to produce nuclear fuel?

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