Pressurized Water Reactor 1600 MWe (EPR)

Nuclear Power Plant Olkiluoto 3, Finland

Functional Description with Poster

AREVA

A Few Words of Introduction

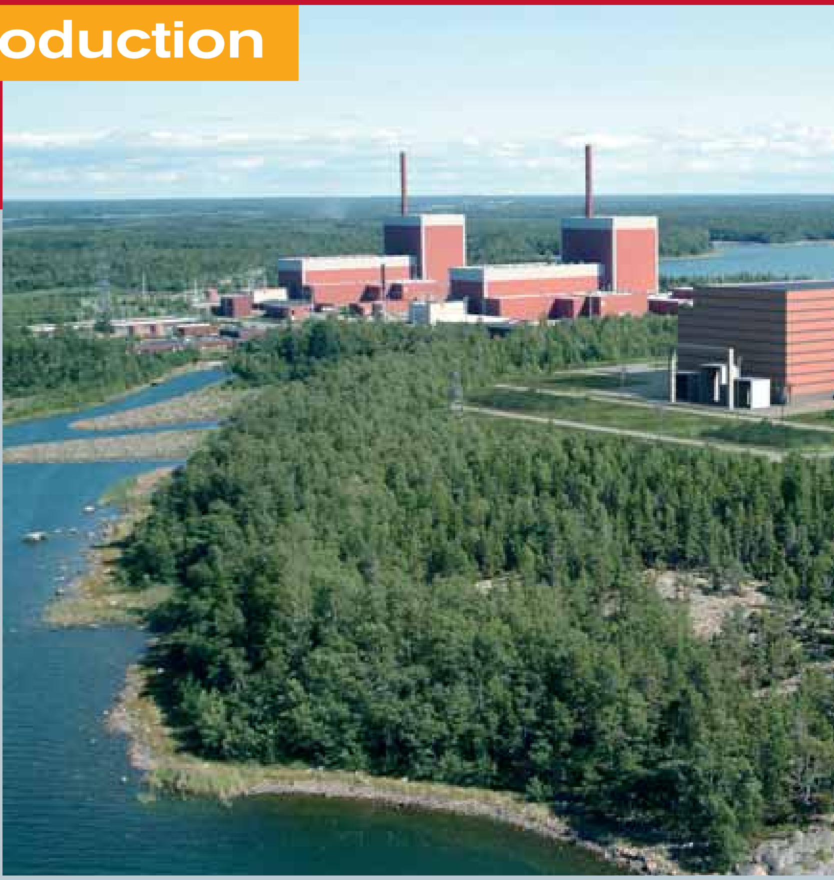
The enclosed poster shows the Finnish nuclear power plant Olkiluoto 3 which will start commercial operation in 2009. The plant is equipped with an EPR, a 1600-MW-class advanced pressurized water reactor*. The poster illustrates the layout and design of the plant buildings and structures as well as the configuration, relative size and locations of the plant systems and components.

However, this kind of illustration can only provide a limited amount of information on how the various components, systems and structures function together.

And that is exactly what this brochure is for: to describe how a pressurized water reactor like this operates so that the poster is easier to understand. The various descriptions given in this brochure are directly referenced to the numbers (X) shown on the poster.

By No Means a Complete Description

But not each and every one of the 85 items shown on the poster is going to be described or even mentioned in this brochure as that would produce a book of enormous proportions! Instead, we will be focusing on those systems and components that are important for understanding how a nuclear power plant of this kind works.



The first EPR (on the right in this photo montage) is being built for the Finnish utility Teollisuuden Voima Oy (TVO) at Olkiluoto in Western Finland. Commercial operation is scheduled to start in 2009.

In October 2004, the French utility Electricité de France (EDF) selected Flamanville in Normandy as the site for the first EPR in France (on the left in this photo montage).

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* This type of reactor is known as a pressurized water reactor because the water inside the reactor pressure vessel and the connected reactor coolant system is kept at such a high pressure that it cannot boil, despite its temperature of approximately 327°C.

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Prospects for Nuclear Power

Today, nuclear power makes a decisive contribution towards ensuring that we have a safe, clean and economical supply of electricity. Since the mid-1980s, the amount of electricity produced by nuclear power plants has doubled, reaching a total of 2525 terawatt-hours* in 2003, equivalent to approximately 16% of the world's power demand. At the end of 2003, 439 reactors were in operation in 30 countries, including all of the major Eastern and Western industrial nations as well as newly industrialized countries such as Brazil, China, India and Korea. Another 33 reactors were under construction in 13 countries (sources: IEA, IAEA).

In order to meet the world's growing demand for electric power while at the same time protecting our climate and environment, nuclear energy will continue to be needed as one of the main sources of power in the coming decades. Consequently, in the course of the last 10 years, nuclear power plant vendors all over the world have greatly enhanced the safety and economic efficiency of their pressurized water reactor (PWR) and boiling water reactor (BWR) product lines to reflect current market requirements and ensure political and social acceptance.

The world's leading nuclear power plant vendor Framatome ANP – an AREVA and Siemens company – has committed itself to further developing nuclear technology. It offers two new designs based on proven light water reactor technology that are now ready for construction: the EPR pressurized water reactor and the SWR 1000 boiling water reactor. These third-generation reactors incorporate more comprehensive safety features than existing nuclear power plants. The first EPR is being built in Finland, and in October 2004 the French utility Electricité de France (EDF) selected Flamanville in Normandy as the site for the first EPR in France.

In addition to the light water reactor designs commercially available today, international research and development programs are also focusing on reactor technologies that might be able to be implemented sometime in the future. These "fourth-generation reactors" could be ready for commercial operation in 20 to 30 years' time but still need further development and testing to verify their safety and cost-effectiveness. In the long term, fourth-generation reactors could be a supplement to existing reactor product lines and could open up new applications for nuclear power such as cogeneration of process heat, production of drinking water through seawater desalination, and hydrogen production. Furthermore, in the second half of the 21st century, nuclear fusion with its enormous energy potential may become a viable source of power, although its general suitability for commercial power generation has yet to be demonstrated.

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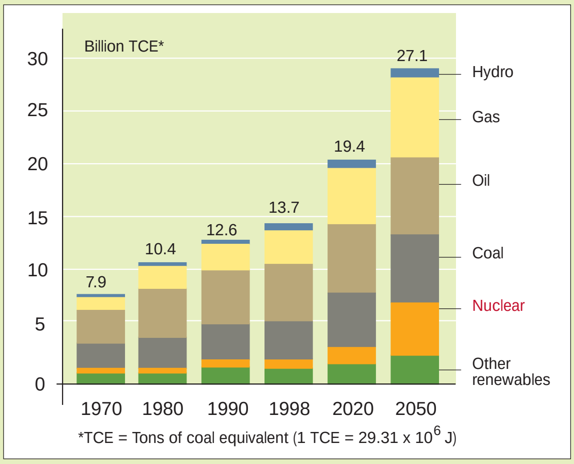
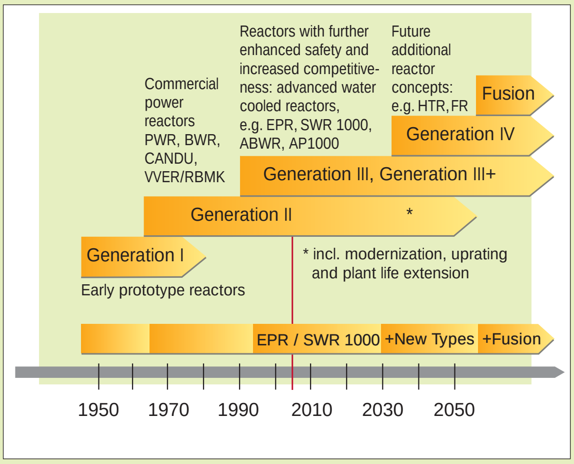
* 2525 billion kilowatt-hours



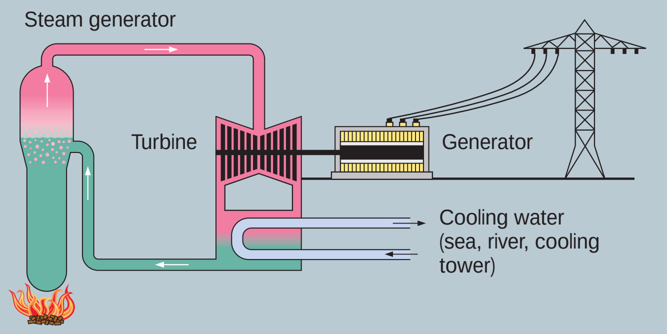
World energy demand and contributions from individual energy sources (source: WEC).



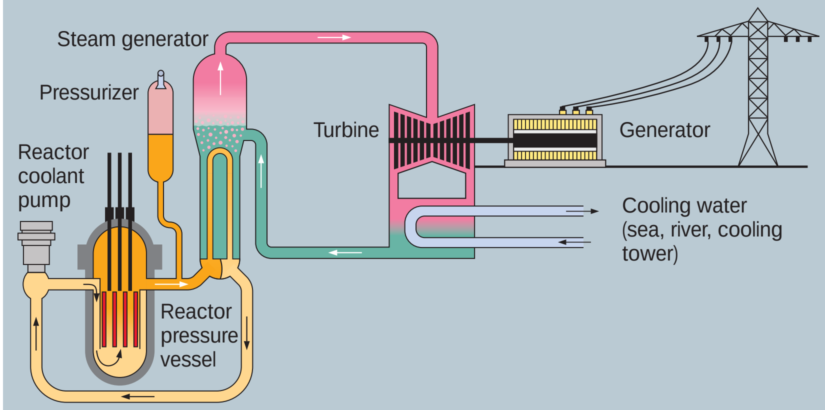
Chronology of generations of nuclear reactors.

What is the Difference between Fossil-Fired and Nuclear Power Plants?

Fossil-fired power plant



Nuclear power plant with pressurized water reactor

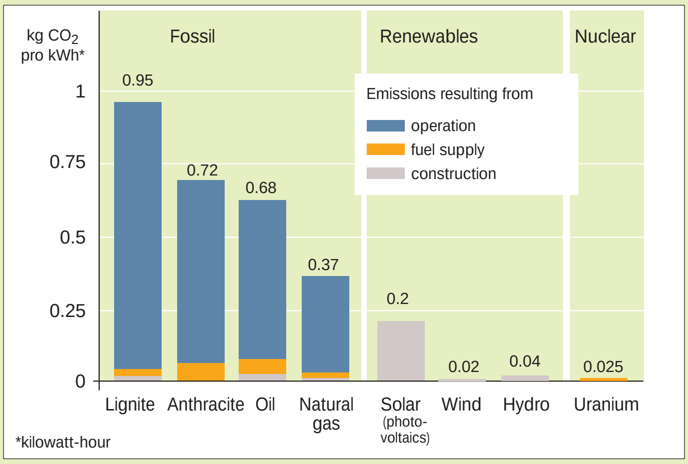


In all thermal power plants, water is made to evaporate inside a "boiler" by applying heat. The resulting steam drives the bladed wheels of a turbine. This turbine is coupled to a generator that produces the electricity. The combined unit formed by the turbine and the generator is called a "turbine generator set".

Basically a nuclear power plant operates in just the same way as a fossil-fired thermal power plant, except that the heat is generated differently: not by burning coal, oil or natural gas (these are called "fossil fuels" because they were formed during early geological eras) but by nuclear fission inside the reactor. All over the world the energy source used in a nuclear power plant is nevertheless also called a "fuel", even though this term is not strictly correct. At a pressurized water reactor plant, water circulating in the reactor coolant system conveys the heat from the reactor to the steam generators which produce the steam to drive the turbine.

Nuclear Energy Helps Protect Our Climate

Every year in Germany, the use of nuclear energy prevents the same amount of carbon dioxide from being emitted into the atmosphere as is produced each year by cars and trucks (around 165 million tons). In exchange for this, small quantities of radioactive waste have to be accommodated. Each year, a modern 1300-MW-class nuclear power plant – such as the Konvoi-series unit Isar 2 – produces approximately 50 cubic meters (m^3) of radioactive process waste with negligible heat generation (NHGW), conditioned and packaged ready for storage in a final repository. The plant's spent fuel assemblies, if directly sent to a repository without prior reprocessing, yield around 45 m^3 of heat-generating waste (HGW). This amount can be substantially reduced by reprocessing, however, to just 10 m^3 of NHGW plus 3 m^3 of HGW, the latter comprising the vitrified, highly radioactive fission products *(source: Kernenergie Basiswissen, January 2004).*



Carbon dioxide (CO_2) emissions from different types of power plants (source: Siemens Power Generation, status: 2002).

Nuclear Energy Comes from the Nucleus of an Atom

The nucleus of an atom consists of two types of elementary particles: protons and neutrons. The proton carries a unit of positive electrical charge, while the neutron is electrically neutral. The number of protons determines the properties of the chemical elements. The neutrons act like a “glue”, binding the protons together as they would otherwise fly apart as a result of electrostatic repulsion. In order for an atomic nucleus to be stable, the ratio of the number of protons to the number of neutrons must lie within a narrow range; if the nucleus contains too many of one or other type of elementary particle, it will become instable and sooner or later disintegrate, or “decay”, while emitting radiation. This process is called “radioactivity”. Very heavy nuclei are capable of splitting either spontaneously or by being given a “hefty knock”. One such heavy nucleus is the heavy metal uranium with its 92 protons.

The fuel used in a pressurized water reactor mainly consists of the non-fissile isotope uranium-238 (it contains 146 neutrons, giving it a total of 238 particles). Only the fissile isotope uranium-235 (with 143 neutrons), which makes up no more than 5 percent of the fuel, is actually responsible for generating power. The fissile uranium nuclei are bombarded with neutrons. When a neutron strikes a uranium-235 nucleus, the nucleus splits into two or three fission fragments, turning the binding energy that is released on fission into kinetic energy. The fission fragments fly apart at high speed. Since they are embedded in a crystal lattice, however, they are not able to move freely but are very quickly brought to a stop. When this happens, the kinetic energy is converted to heat.

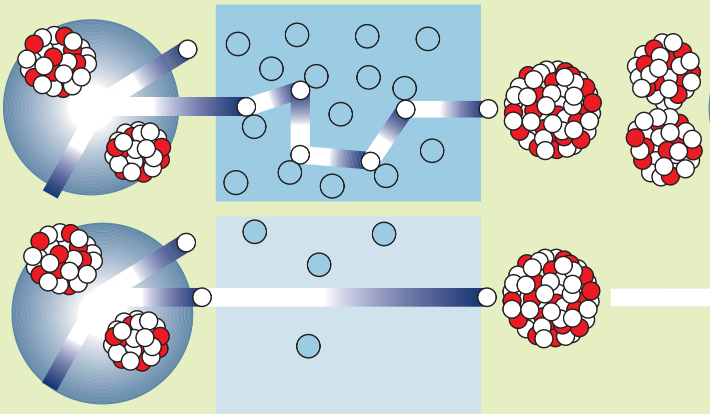
Each time a uranium nucleus splits, two or three neutrons are also emitted. Traveling at an average speed of around 10,000 kilometers per second, these so-called “fast neutrons” are able to move freely within the fuel and the surrounding materials. To ensure that at least one of these fast neutrons strikes another uranium-235 nucleus, thereby causing it to split (and initiating the desired chain reaction), they have to be slowed down before they are lost from the reactor core through leakage or are “captured” (absorbed) by other nuclei without having contributed anything to the fission process.

How water slows down neutrons

The heat produced by fission is conveyed out of the reactor core through the four reactor coolant loops connected to the reactor at the center. The water in

Reactor coolant system comprising four loops connected to the reactor at the center.

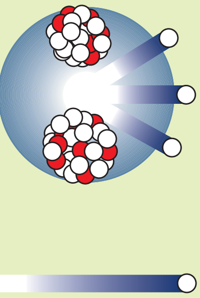
The nuclear fission process



Moderator (e.g. water) slows down fast neutrons.

Fission of a nucleus produces fast neutrons.

Fast neutrons are not slowed down if moderator temperature is too high or there is not enough moderator (loss-of-coolant accident at a light water reactor), meaning no further fission reactions.



Slow neutron collides with another uranium-235 nucleus, causing a new fission reaction.

the loops circulates continuously at a pressure of approximately 160 bar and a temperature of around 327°C. Each loop contains a heat exchanger (steam generator) and a pump.

The reactor water is also called “reactor coolant” as it serves to remove the heat from the reactor and thus cool it. It is ordinary water (H_2O), also known as “light water” to distinguish it from the “heavy water” used in a different, less common type of reactor.

Apart from acting as a coolant, the water also performs another important function inside the reactor: it serves as a “moderator”, which means that it slows down the neutrons. The initially fast neutrons lose their kinetic energy as a result of repeated collisions with the moderator’s atoms, particularly the water’s hydrogen atoms.

These collisions and the resulting friction slow the neutrons down to a velocity of around 2000 meters per second. At this velocity they are much more likely to cause further fissions of uranium-235 nuclei. The slowed-down neutrons are called “thermal neutrons” because they are in thermal equilibrium with their surroundings (i.e. moving at approximately the same speed as gas molecules at a temperature of around 300°C).

How do you control a chain reaction?

In order for the thermal output of a reactor to stay at a constant level, an equal number of fission events must occur over a given period of time. For this to happen, exactly one of the two or three neutrons emitted with each fission must go on to split another uranium-235 nucleus. The excess neutrons are captured, for example, by neutron-absorbing materials provided for reactor control (control rods and/or boric acid dissolved in the coolant) or by uranium-238 nuclei. This process of neutron capture results in non-fissile uranium-238 becoming fissile plutonium-239 and plutonium-241, which can also be split through neutron capture, just like uranium-235. The participation by the freshly created plutonium in the fission process increases the energy yield of the fuel by around 50%.

There are two main factors that have to be remembered in this connection:

1. A self-sustaining chain reaction can only occur in the presence of a moderator.
2. The number of fissile uranium-235 nuclei in the nuclear fuel is much too low and the fissile nuclei are too widely distributed among the non-fissile uranium-238 nuclei for an uncontrolled chain reaction to take place.

Radiation and fission products

The fragments produced when a nucleus is split are known as fission products. A large number of different atoms are produced in this way, some of them radioactive (e.g. xenon-133, krypton-85 and iodine-131). These atoms continue to give off radiation for a period of time that depends on their respective “half-lives” – a term denoting the time needed for half of the nuclei to decay. All fission products decay via a number of intermediate stages into stable chemical elements that are no longer radioactive. In the case of many of these, this only lasts a few seconds; with others it may take many years or even decades.

The “decay heat” (or “decay heat power”) that continues to be produced after the reactor has been shut down (bringing the chain reaction to a stop) is generated by the radioactive decay of the fission products. This heat is removed by the residual heat removal systems ⑯ until the decay process comes to a natural end.

In addition to fission products, other radioactive substances known as “activation products” are also generated during reactor operation. These are elements that are not normally radioactive (e.g., alloying elements in fuel cladding and structural materials) but become radioactive as a result of absorbing neutrons.

The radioactive materials in a nuclear power plant are the real source of danger. For that reason all of a plant’s safety systems and equipment are designed to prevent the release of such materials into the environment, or to limit their release to allowable levels.

The most important tasks involved in operating a nuclear power plant are:

1. Production of thermal energy by sustaining a controlled chain reaction of nuclear fission,
2. Removal of this thermal energy and conversion to electrical energy,
3. Prevention of fission product release,
4. Safe and reliable removal of decay heat from the reactor after it has been shut down.

The Reactor Core: the Source of Energy at a Nuclear Power Plant

The reactor core, comprising 241 fuel assemblies, is located inside the reactor pressure vessel ⑩. The fuel assemblies serve to generate the heat inside the reactor core.

Each fuel assembly contains 265 fuel rods arranged in a square-shaped bundle. Each fuel rod comprises a thin-walled tube, 9.5 mm in diameter, made from a special alloy of the metal zirconium and containing a column of sintered uranium dioxide fuel pellets. The length of this fuel column – 4.2 meters – is also called the “active length” of the fuel.

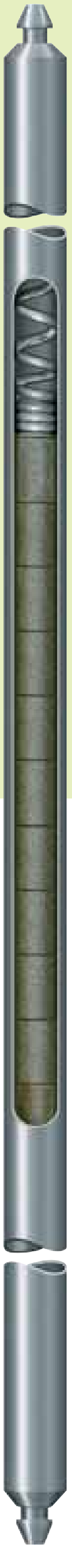
Each fuel bundle is equipped with a number of control rod guide thimbles. The thimbles are empty tubes into which the control rods of the control assemblies are inserted. The material contained inside these control rods absorbs neutrons, making them unavailable for further fissions. The number of neutrons that are absorbed varies, depending on how far the control rods are inserted into the reactor core. If the rods are fully inserted into the core, the chain reaction stops entirely. The EPR has a total of 89 control assemblies, each with 24 control rods.

During normal operation the control assemblies are used to provide a uniform power distribution across the core. To quickly shut down the reactor, they are released to drop under the force of gravity into the core (i.e. solely utilizing laws of nature, without any form of propulsion).

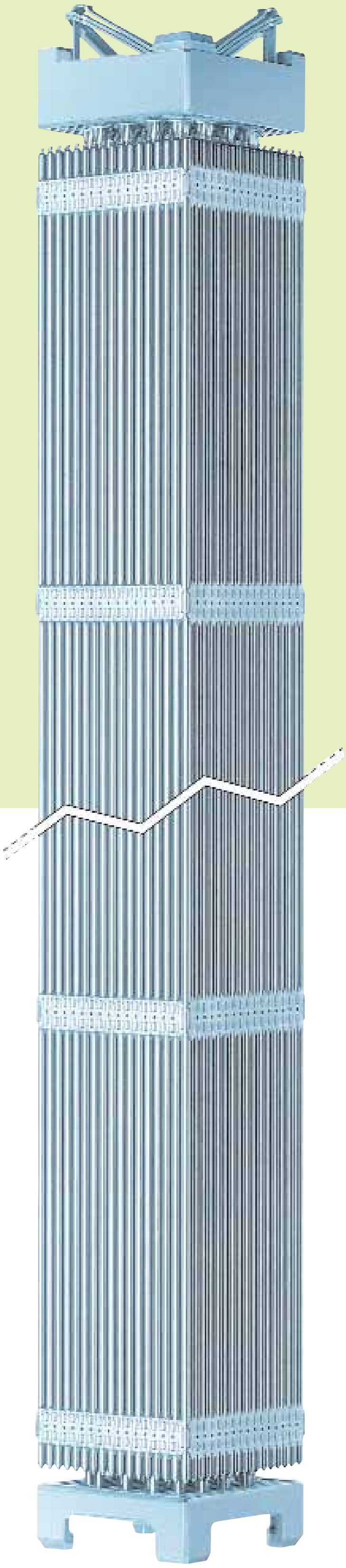
Uranium fuel: “packed full” of energy

The energy content of uranium is far greater than that of oil, natural gas or coal because here use is made of the binding energy of the elementary particles in the atomic nucleus rather than the heat generated by burning carbon. This means that only small stocks of uranium are required to operate a nuclear reactor over many years. In the case of an oil-fired plant, however, even the most gigantic oil storage tanks would run dry after only a few months. Apart from this, oil and coal are not only suitable for generating electricity but also serve as raw materials for other branches of industry (e.g. for making pharmaceutical drugs and plastic).

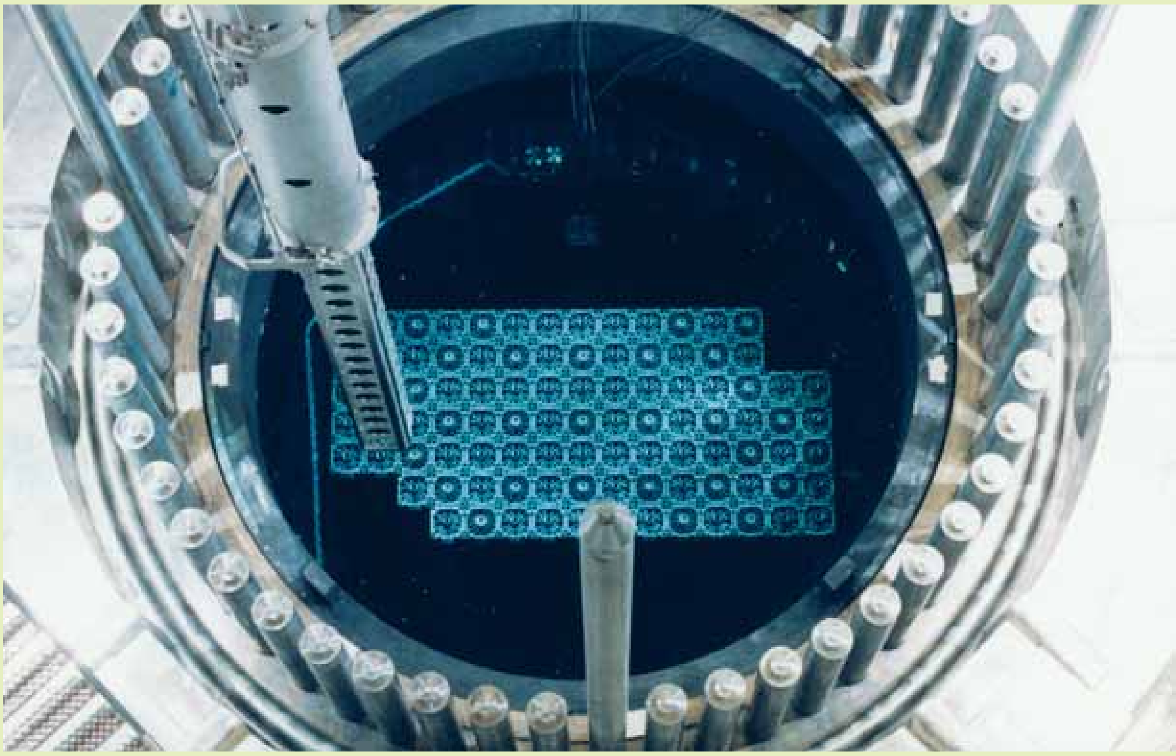
Uranium dioxide fuel pellets – each fuel rod contains a 4.2-meter-long column of these pellets



265 fuel rods make up one fuel assembly.



There are 241 fuel assemblies in the reactor core.



View inside the reactor pressure vessel of a nuclear power plant (German Konvoi-series Isar 2 with rated electric output of 1300 megawatts) during core loading.

One kilogram of nuclear fuel enriched to 4.3% in uranium-235 (in the form of a cube having sides that are 45 millimeters long) produces the same amount of electricity as 102 tons of oil (six trucks carrying 17 tons each) or 140 tons of hard coal (five railroad cars of 28 tons each).

Fuel operating cycles of up to 24 months

Depending on the length of the fuel cycle on which the nuclear power plant is operating, one-quarter to one-third of the "spent" fuel assemblies have to be replaced every 12 to 24 months with fresh fuel using a specially designed refueling machine ⑤. The fresh fuel assemblies as well as the fuel assemblies remaining in the reactor are positioned according to a carefully calculated "core loading plan" in order to ensure optimum utilization of the nuclear fuel within the specified design limits.

This periodic refueling outage is also used for inspections and maintenance work.

Fuel storage

The spent fuel assemblies removed from the reactor during refueling as well as the fresh fuel assemblies are stored in a separate "fuel building" Ⓕ.

The fresh fuel assemblies to be loaded into the reactor are stored in a special dry storage facility called the "new fuel store". Before they are placed in the core, the fuel assemblies are subjected to a detailed examination using special inspection equipment.

The spent fuel assemblies are stored in the spent fuel pool (37). Here they are kept in storage racks under water (for shielding and cooling purposes) until their radioactivity and heat generation levels have dropped sufficiently to allow them to be placed in special shipping casks for transfer to a reprocessing plant or an interim storage facility. The fuel pool can accommodate six to seven years' worth of spent fuel from the reactor.

How Much Power Does a Nuclear Plant Generate?

A large city like Frankfurt am Main (Germany) has an average electricity demand of 365 megawatts (MW). Thus an advanced nuclear power plant with an EPR-type pressurized water reactor rated for an electric output of around 1600 MW can continuously supply all of the power needed by four such cities. (Photo: Tourismus+Congress GmbH Frankfurt am Main)

Power is described using a standard unit of measurement called the watt (abbreviated to "W"). Power is the ability to do a certain amount of work in a given unit of time. When these values are very large or very small, other more suitable units of measurement are used instead: 1000 W are called a kilowatt (kW), while 1000 kW are a megawatt (MW). By way of comparison: a domestic fan heater consumes around 2 kW and a washing machine around 1 kW, while a medium-sized automobile engine has a power rating of approximately 100 kW. The energy that a washing machine needs to wash one load of laundry is calculated from the electricity it consumes and the duration of the washing cycle: if the latter is 1 hour (h), then the washing machine needs 1 kW times 1 h = 1 kWh (kilowatt-hour). An EPR with an electric output of 1600 MW produces each hour 1,600,000 kWh (1600 MW times 1 h); that is enough to run 1.6 million washing machines at the same time!

Thermal power output

The EPR shown in the poster has a "thermal" output of 4300 MW. This represents the total heat output of the reactor; in other words, all of the thermal energy produced by the nuclear fission process occurring in the fuel.

Electric power output

Just like in any thermal power plant, only about a third of the reactor's thermal output can actually be converted to electric power due to the laws of physics. The other two-thirds are unavoidably "lost" to the environment via the power plant's cooling systems (e.g. cooling tower and river water).

Around 100 MW of the gross electric output produced by the generator is directly tapped off to cover the "auxiliary power" requirements of the power plant itself (e.g. to operate pump motors, electronic equipment and lighting).

The remaining amount is termed the "net electric output" and is what is actually fed into the high-voltage offsite power grid. In the case of Finland's nuclear power plant unit Olkiluoto 3 shown in the poster the net electric output is approximately 1600 MW.

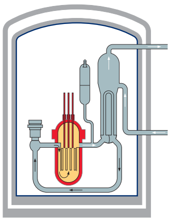
The Reactor Building

Contains the Reactor Pressure Vessel...

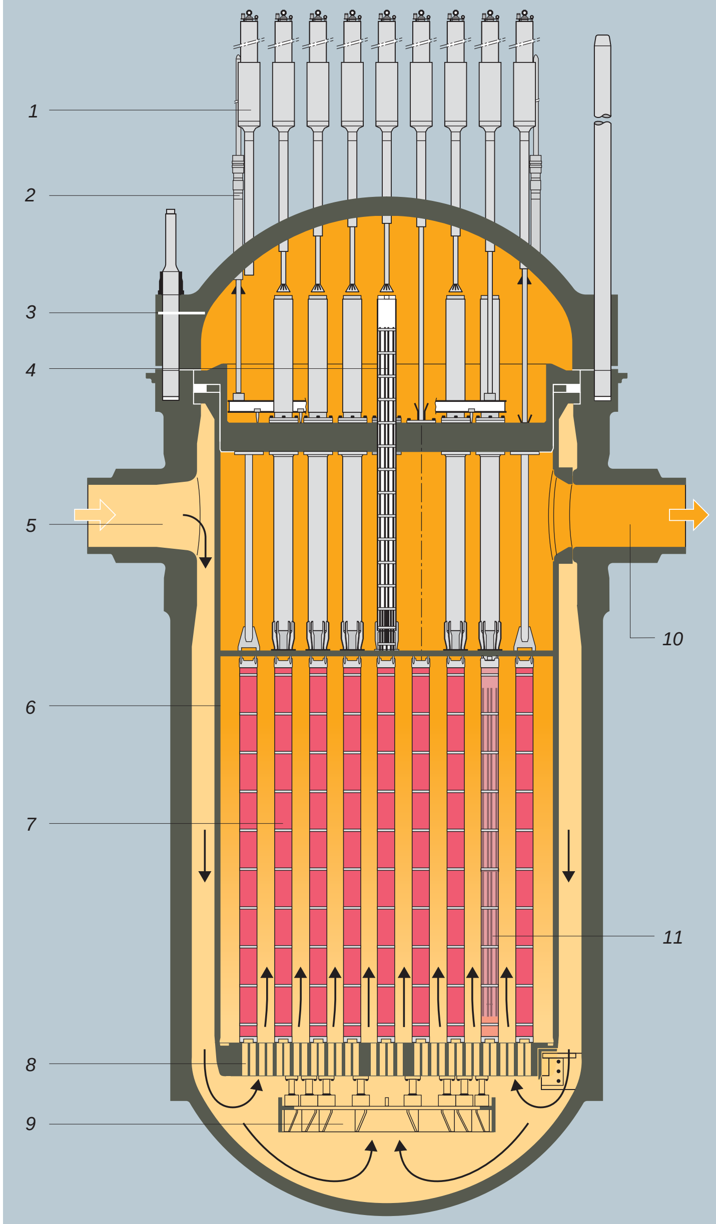
The reactor building Ⓐ of the EPR – in the shape of a cylinder with ellipsoidal dome – is a double-shell structure with internal steel liner. The outer concrete shell protects the entire building against damage from natural and external man-made hazards. It is designed, for example, to withstand the impact of an airplane (military jet or large civilian aircraft) on the reactor building dome, as well as the pressure wave resulting from the explosion of a liquefied gas tanker on a nearby river. The inner concrete shell can withstand a buildup in pressure such as that occurring in the (highly unlikely) event of a double-ended reactor coolant pipe break. The gastight steel liner on the inside prevents the release of radioactive materials to the outside environment.

The reactor building is also designed to withstand earthquakes so that none of the equipment inside can be damaged, let alone destroyed, by such vibrations. In the highly improbable event of a core melt accident, the molten core material would be collected and cooled in a specially designed “corium spreading area” ⑭ situated at the lowest point in the reactor building but still inside the containment. The extremely robust double-walled containment ① would reliably keep any radioactivity confined inside the building.

Reactor pressure vessel



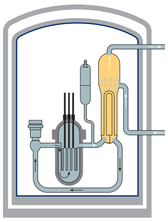
The reactor pressure vessel (RPV) ⑩ can rightly be called the “heart” of the nuclear plant. It contains the reactor core with its 241 fuel assemblies as well as various internals such as control rod guide assemblies, measuring instruments and devices for coolant flow distribution. Above the reactor coolant inlet and outlet nozzles, the RPV is closed off by a cover – the RPV closure head – on which the control rod drive mechanisms ⑨ are mounted. The RPV designed for the EPR, complete with its closure head, will weigh 526 tons. It will be 12.7 meters (m) high, will have an inside diameter of around 4.9 m and shell walls that are 0.25 m thick.



Section through reactor pressure vessel of EPR showing RPV internals

1	*Control rod drive mechanism*
2	*Liquid level probe*
3	*RPV closure head*
4	*Control rod guide assembly*
5	*Coolant inlet nozzle*
6	*Core barrel*
7	*Fuel assembly*
8	*Lower core support grid*
9	*Flow distribution plate*
10	*Coolant outlet nozzle*
11	*Fuel assembly with inserted control rod*

...and All Other Components of the Nuclear Steam Supply System

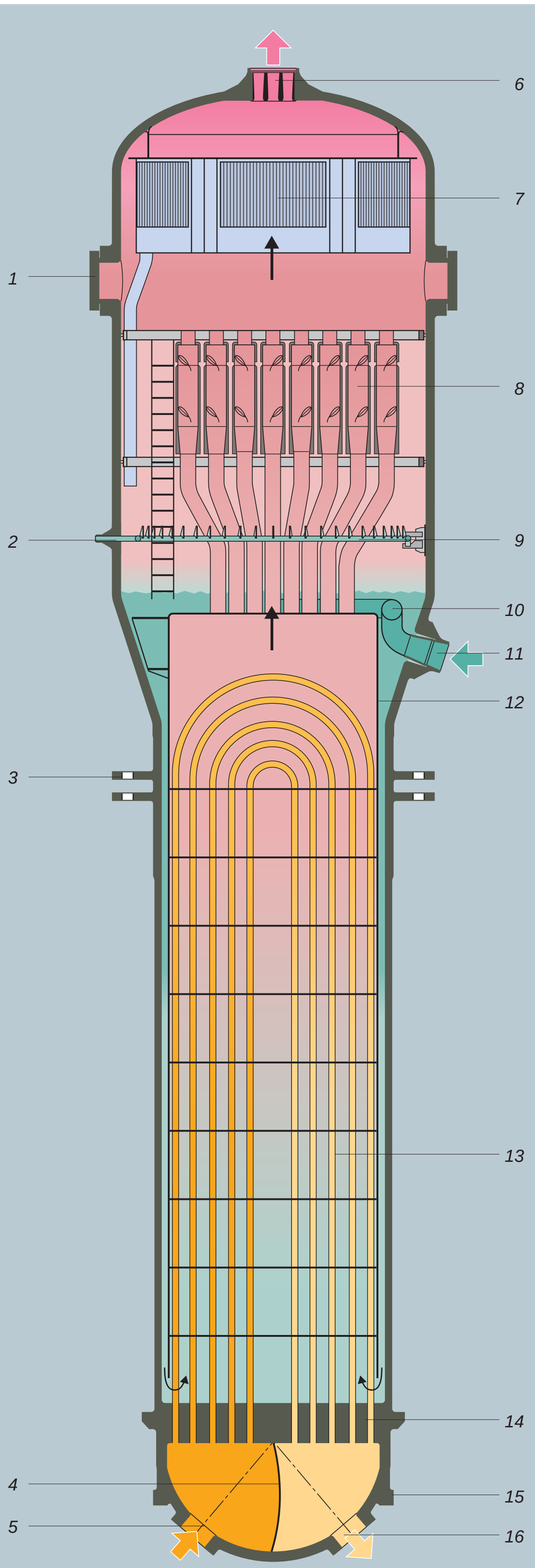


Steam generators

The four steam generators ⑥ are large heat exchangers which serve as the interface between the four reactor coolant loops (the primary system) and the non-radioactive steam, condensate and feedwater cycle (secondary system). They produce the steam used to drive the turbine (51) (52), which in turn drives the generator (55).

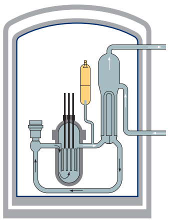
Inside each steam generator are thousands of U-shaped tubes. The hot reactor coolant flows at a temperature of around 327°C through these tubes. It gives up its heat to the colder feedwater from the secondary system that is passing over the outside of the tubes. This causes the feedwater to gradually heat up and eventually evaporate. The resulting steam exits the steam generator and is conveyed to the turbine via the main steam piping ⑦.

Steam generator on its way to the Chinese nuclear power plant unit Ling Ao 2



On the right: section through steam generator. Each of the steam generators designed for the EPR has a heat-transfer surface of 7960 square meters and a height of around 23 meters.

1 Secondary manway
2 Emergency feedwater nozzle
3 Horizontal supports
4 Divider plate
5 Coolant inlet nozzle
6 Steam outlet nozzle
7 Steam dryer
8 Steam separator
9 Emergency feedwater sparger
10 Feedwater sparger
11 Feedwater nozzle
12 Tube bundle shroud
13 Tube bundle
14 Tubesheet
15 Vertical supports
16 Coolant outlet nozzle

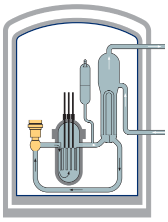


Pressurizer

Just like the expansion tank of a central heating system, the task of the pressurizer ⑱ is to compensate for fluctuations in reactor coolant volume caused by temperature changes, and thus keep the operating pressure of the coolant circulating through the reactor coolant system at a relatively constant level. This is necessary, for example, to prevent steam bubbles from forming inside the system which would impede coolant flow as well as heat transfer from the fuel rods to the water.

The pressurizer is a vertical pressure vessel filled with water in its lower section and steam above this. It is connected to the reactor coolant system by a pipe known as the surge line. Pressure is increased using electrical heaters installed in the lower (water-filled) section to evaporate some of the water (to produce additional steam), and reduced by spraying water through nozzles into the upper (steam-filled) section (to condense steam). Valves directly mounted on the top of the pressurizer provide overpressure protection by blowing down steam to a separate relief tank.

Pressurizer being rigged into place at the French nuclear power plant unit Golfech 2. The pressurizer for the EPR will be 14.4 meters high and will weigh around 150 tons when empty.



Reactor coolant pumps

The four reactor coolant pumps ⑪ keep the coolant in continuous circulation by pumping it back to the reactor pressure vessel after it has given up some of its heat in the steam generators. They are vertical single-stage centrifugal pumps. Each of the four pumps requires approximately 9 megawatts of electricity to operate (this roughly corresponds to the power needed to drive 100 mid-size automobiles) and delivers a volumetric flow of around 28,000 cubic meters per hour.

Accumulators

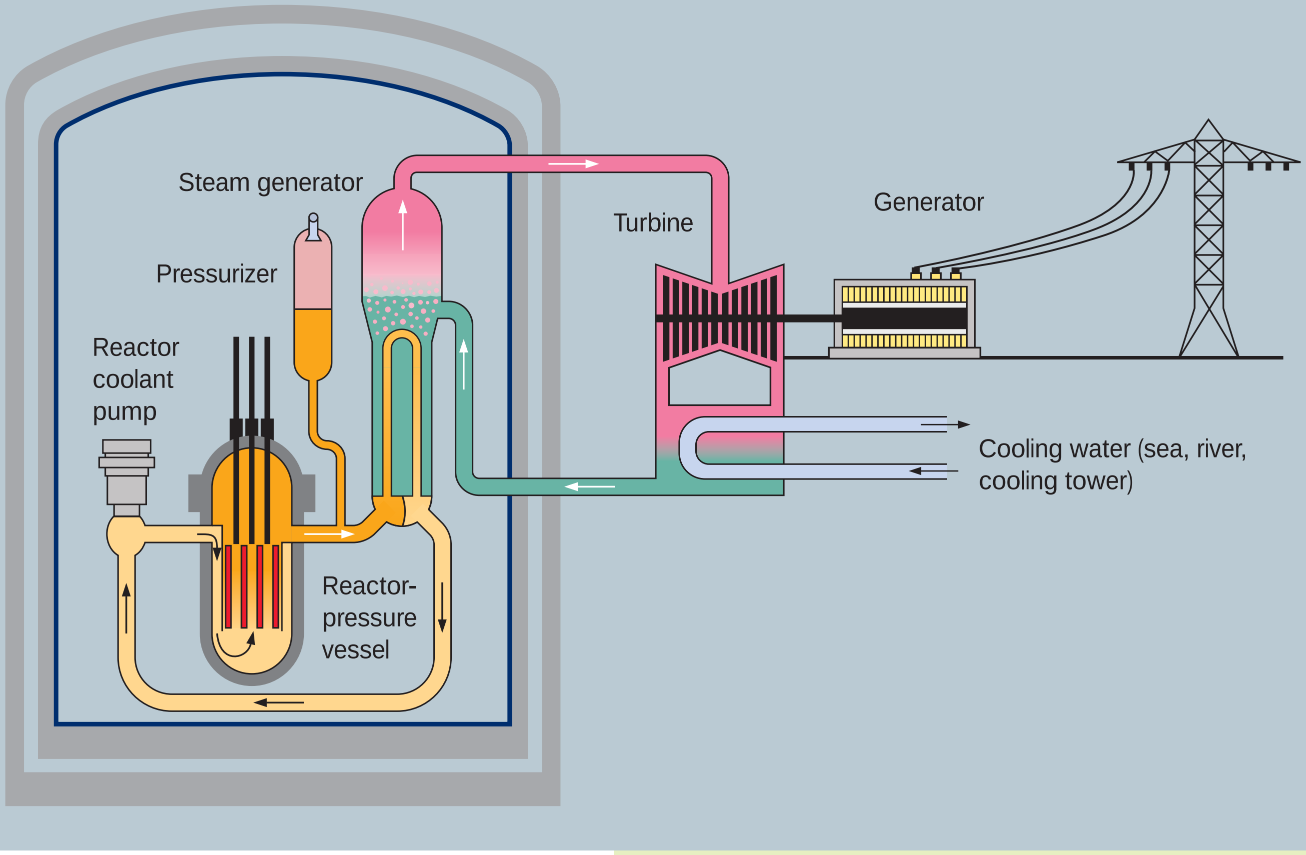
The four accumulators ⑰ are engineered safety features for emergency core cooling (one is provided for each reactor coolant loop) that are located inside the containment in the immediate vicinity of the coolant loops. They contain borated water which is kept under pressure by means of a nitrogen cushion so that the water inventory can be automatically injected into the coolant loops for emergency core cooling in the (highly unlikely) event of a double-ended reactor coolant pipe break resulting in a large drop in reactor pressure. The boric acid contained in the water absorbs neutrons and thus reliably prevents the chain reaction from resuming, even at low temperatures.

Controlled area

The four safeguard buildings Ⓑ Ⓒ Ⓓ Ⓔ, the fuel building Ⓕ and the nuclear auxiliary building Ⓖ are directly adjacent to the reactor building Ⓐ. Together they form the “controlled area” that houses all of the plant components and piping systems containing radioactivity. The reactor building, safeguard buildings 2 and 3, and the fuel building are protected by double concrete walls against the effects of the natural and external man-made hazards described on Page 11. Physical separation of safeguard buildings 1 and 4 ensures that if, for example, an aircraft should crash onto one of the buildings, the other will not be damaged. Access to this area is strictly controlled and is only possible through the access building Ⓙ.

The Two Cycles of a Pressurized Water Reactor Plant

The two cycles of a pressurized water reactor nuclear power plant



One of the distinguishing features of a pressurized water reactor is its dual-cycle configuration consisting of the radioactive reactor coolant system (primary system) and the non-radioactive steam, condensate and feedwater cycle (secondary system). These are supplemented by a cooling system that discharges the remaining heat to the sea or river.

The reactor coolant system carries the heat to the steam generators

Four symmetrically arranged coolant loops, each consisting of a steam generator 6, a reactor coolant pump 11 and the connecting reactor coolant piping 12, are joined to nozzles on the reactor pressure vessel 10. Together with the pressurizer 18, connected via its surge line, they form the reactor coolant system.

From the reactor pressure vessel the hot reactor coolant is conveyed through the reactor coolant piping to the steam generators where it flows through the U-tubes, giving up part of its heat (energy) to the feedwater from the steam, condensate and feedwater cycle flowing along the outside of the tubes. The reactor coolant pumps then pump the coolant – now around 30 degrees cooler after passing through the steam generators – back to the reactor pressure vessel and into the reactor core.

Fluctuations in reactor coolant volume caused by temperature changes are compensated for in the short term by the pressurizer and in the long term by the chemical and volume control system 13.

A low-pressure turbine rotor at Isar 2. At Olkiluoto 3 the last turbine stage will have a diameter of around 7 meters (m) and a blade length of 1.8 m.

The steam, condensate and feedwater cycle supplies the turbine with steam

The steam, condensate and feedwater cycle is also called the "conventional" part of the nuclear power plant since its components are also found in traditional coal-, oil- and gas-fired power plants.

The main components of the steam, condensate and feedwater cycle, all housed inside the turbine building L, are the turbine 51 52, generator 55, condenser 53, main condensate pumps (not shown in the poster), feedwater pumps 60, feedwater heaters 50 59 61 and feedwater tank 57.

The "main steam" produced in the steam generators 6 at a pressure of 78 bar and temperature of 293°C exits the reactor building through the four main steam lines 7 and is first conveyed to the main steam valve compartments 19. These house the isolation valves provided to prevent steam generator dryout through uncontrolled steam blowdown in the event of a pipe break downstream of the valve compartments. Safety and relief valves, also installed here, reliably protect the secondary system against overpressure.

From the valve compartments the main steam lines enter the turbine building L where they are first routed to the high-pressure (HP) section of the steam turbine 51. The steam is admitted at the center of the turbine casing and then flows outwards to both sides*, striking the rows of turbine blades that increase in size from one stage to the next and are rigidly attached to the turbine shaft. The high-pressure, high-temperature steam expands and the energy released in this process causes the turbine shaft to rotate. Approximately one-third of the turbine's total output is produced in this HP section.

The steam – now much cooler (178°C) and wetter and at a considerably lower pressure (10 bar) than on admission – flows out of the two ends of the "double-flow" HP section of the turbine into the crossover lines 54 on its way to three (or two) double-flow low-pressure (LP) turbine sections 52. Before entering the LP sections, however, the steam is routed through a component called a moisture separator/reheater (MSR) 49. Here the steam coming from the HP turbine section is first dried and then reheated (to increase its energy content again) using steam extracted from the main steam line. This prevents the last-stage blading of the LP turbine sections from being damaged by the impingement of condensate water droplets in the steam.

Once around one-third of the energy contained in the steam has been converted to work (mechanical energy) at the turbine blades, causing the turbine shaft

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* Hence the term "double-flow" for this type of turbine

to rotate, the steam – which has now expanded down to a pressure of around 0.03 bar* – enters the condensers ㊳ installed underneath the turbine. The condensers are heat exchangers in which circulating water (from the cooling tower, river or sea) flows through thousands of titanium tubes approximately 2 centimeters in diameter. The task of the condensers is to condense the steam exiting the turbine, thereby turning it back into water (known as "condensate"). When it comes into contact with the cold condenser tubes, the steam – now at a temperature of only around 30°C – condenses to form water droplets.

The remaining heat is discharged via the turbine condenser to the plant environs

Before we look at the next stage in the steam, condensate and feedwater cycle, we should first explain that, because of the steam condensation process described above, a considerable proportion (over 60%) of the heat contained in the steam is lost. This is the latent heat of condensation, which is discharged to the cooling tower, river water or seawater via the condenser. This happens at all thermal power plants; i.e. also at those firing coal, oil or gas. The cooler the circulating water, the lower the steam pressure which, at temperatures below 100°C, is in the vacuum range. And the lower the steam pressure in the condenser, the higher the energy gradient that can be utilized to produce electric power – and thus the higher the efficiency.

Due to the low seawater temperatures in Finland the thermal efficiency of Olkiluoto 3 will be around 37%.

Back to the steam generator – and it all starts over again

The condensate collecting in the condenser is pumped through LP feedwater heaters (59) (61) to the feedwater tank (57). This is basically a large buffer tank capable of absorbing short-term inventory fluctuations in the steam, condensate and feedwater cycle.

The feedwater pumps (60) then pump the water from the feedwater tank via HP feedwater heaters ㊿ and the feedwater valves ⑳ back into the steam generators where it is heated and evaporated all over again.

Turbine generator set at Isar 2:
the exciter and the generator are in the foreground

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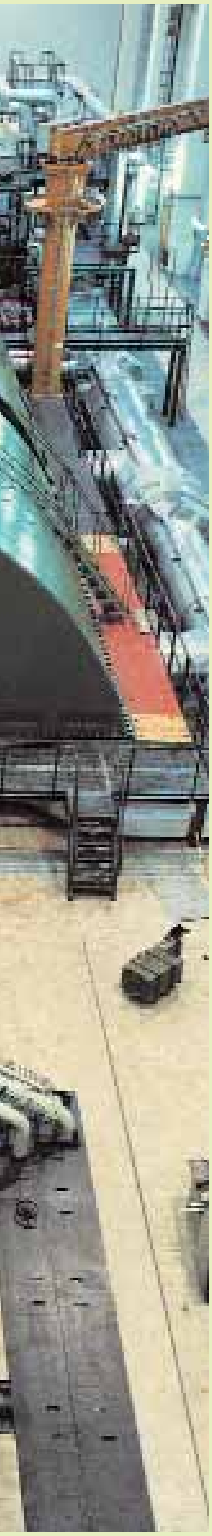
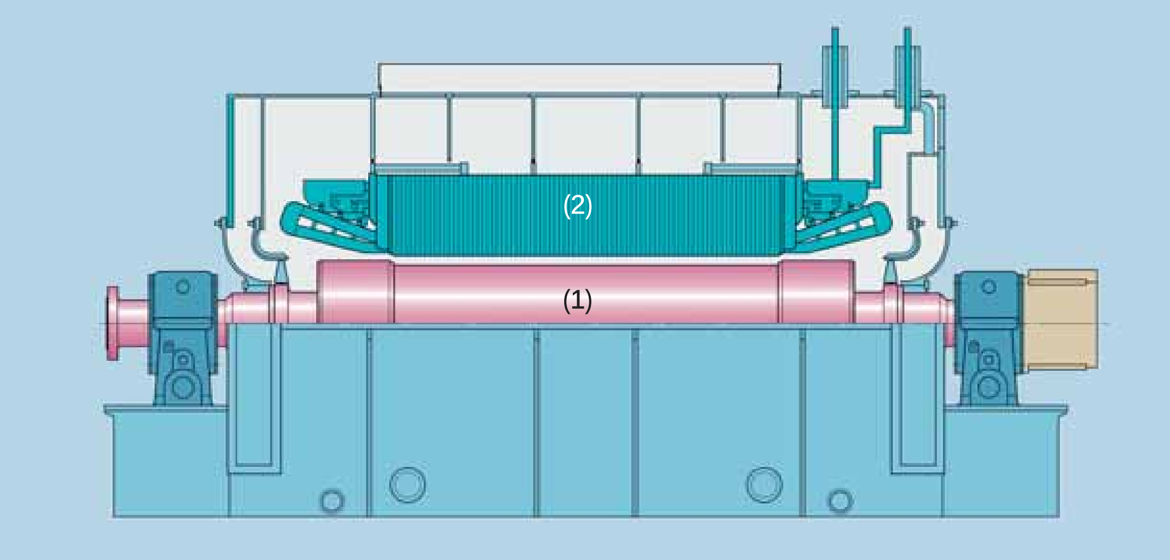
* Corresponds to the pressure of air at an altitude of around 24 kilometers

How is Electricity Generated?





Three-phase alternating current generator with generator rotor (1) and generator stator (2)

The steam turbine drives the generator which finally converts the rotational energy of the turbine shaft to electrical energy.

The principle underlying this is that of “electromagnetic induction”: when a magnetic field moves past a conducting coil, an electrical voltage is produced in the coil, causing a current to flow in a connected conductor circuit.

The three-phase alternating current generator used to generate electricity in power plants has the generator rotor at the center with its rotating magnetic field and three coils spaced 120° apart in the generator stator. The rotor, caused to rotate by the turbine shaft, induces an alternating voltage in each coil, one after the other.

However, in order that a magnetic field can build up in the generator rotor, an electrical current has to flow through its windings. The direct current needed for this is supplied by the exciter ⑤⑥ (a kind of auxiliary generator) connected to the main generator.

The electricity generated by the turbine generator set is stepped up from 27 kilovolts (kV) to 400 kV in three generator transformers ⑥② and fed into the offsite power grid ⑥⑧ via high-voltage switchgear ⑥⑦.

A Brief Look at the EPR's Safety Concept

A large number of safety features are incorporated into the design of a nuclear power plant to protect people living in the vicinity of the plant and the plant personnel against the hazards of radiation. These safety features ensure that there will be no unacceptable releases of radioactivity into the reactor containment or the plant environs either during normal plant operation or in the event of an accident.

Safety systems are also deployed to ensure that the reactor can be safely and reliably shut down at any time, and subsequently maintained in a safe condition (i.e. with adequate cooling) by continuously removing the decay heat generated in the core after shutdown, thus preventing the reactor from overheating.

The “self-regulating” reactor

By “self-regulating” we mean the inherent (built-in) safety of a nuclear reactor deriving from the physical properties of water and uranium: when the temperature inside the reactor core rises, more fission neutrons are captured by uranium-238 or are able to “escape” through the moderator without being slowed down.

As a result, the number of fissions per unit time, and hence the level of heat generation, drops again. This self-regulating capability ensures that the reactor cannot get out of control even in the event of failure of the reactor control systems (neutron-absorbing control rods and boric acid injection).

A sudden, uncontrolled increase in fissions – resulting in a “runaway” reactor – is physically impossible. For economic reasons and to avoid unnecessary stressing of plant components and their materials, however, this self-regulating capability is backed up by fast-acting control equipment.

Safety systems and equipment

Despite the vast number of safety precautions taken to prevent abnormal conditions from arising during plant operation, the nuclear power plant systems are nevertheless designed to withstand the effects of highly improbable accidents. These accidents could include the following:

- Large breaks in system piping (reactor coolant pipe, main steam line, feedwater line, etc.)
- Loss of reactor control systems (control rods fail to drop into the reactor core, or boric acid injection fails to operate)
- Natural phenomena or external man-made hazards (e.g. earthquake, aircraft crash, explosion pressure wave, etc.).

To ensure that radioactivity remains safely and reliably confined inside the reactor containment under normal and accident conditions, numerous engineered safeguards are incorporated into the plant design.

The passive safety features do not require an operating signal or electric power to perform their safety functions. They function solely by virtue of their presence, like the many protective barriers made of concrete and steel.

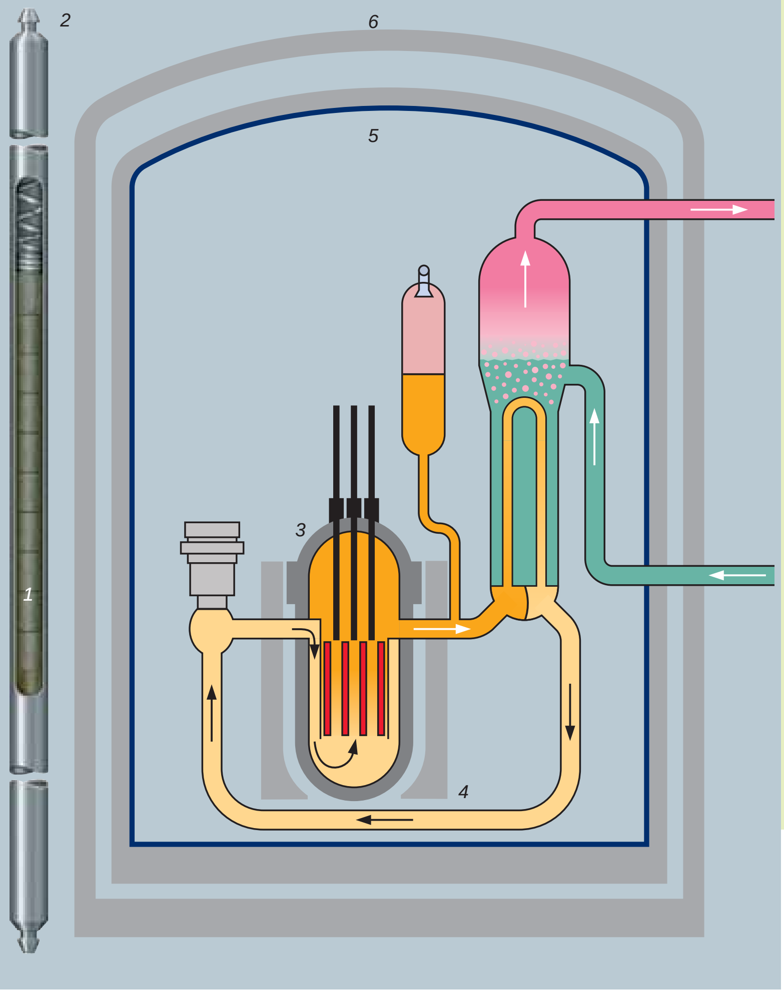
Several passive barriers (see diagram on Page 19) reliably prevent unacceptable releases of radioactive substances and direct radiation from the nuclear power plant. The active safety systems maintain the operating parameters of the plant within the design limits so as to protect these barriers. The safety systems are controlled by an electronic “brain”, the reactor protection system ㉘. It performs all of the switching operations required to guarantee reactor safety automatically, without human intervention. This means that safety does not depend on prompt and correct actions taken by plant operating personnel.

The reactor protection system monitors all key plant operating parameters and initiates certain actions to activate safety systems, if required, as soon as the plant approaches certain specified safety limits. These active safety systems include:

- The reactor scram system, which drops neutron-absorbing control rods into the core by gravity.
- The containment isolation system: if there is a risk that radioactivity might be released into the reactor building Ⓐ during an accident, this system enables the reactor building to be isolated from the outside atmosphere by automatically closing isolation valves installed in all of the pipes passing through the reactor building wall.

Barriers to prevent release of radioactive substances and direct radiation

1. *Except for a few percent, the vast majority of the fission products arising from nuclear fission are retained in the crystal lattice of the uranium pellets.*
2. *Cladding tubes made of Zircaloy that are seal-welded to make them gas- and pressure-tight enclose the fuel pellets and hold back the fission products.*
3. *The reactor pressure vessel is like a strong suit of armor designed to withstand all loads induced by pressure, temperature and radiation.*
4. *The concrete shield, a thick-walled cylinder made of reinforced concrete, surrounds the reactor pressure vessel and is nearly impenetrable for the radiation emanating from the reactor pressure vessel.*
5. *The inner reinforced-concrete shell of the reactor building that surrounds the Nuclear Island of the plant is completely leak-tight thanks to its steel liner, the only means of access to the interior being via airlocks.*
6. *The outer reinforced-concrete shell of the reactor building is primarily there to provide protection against natural phenomena and external man-made hazards. Together with the inner concrete shell it acts as a final shield, reducing the radiation leaving the plant to levels far below the permitted limits.*



– The emergency core cooling system: this system cools the reactor core in the event of pipe breaks in the reactor coolant system leading to a loss of coolant. The four safety injection pumps ㉘ are able to inject enough coolant to make up for small pipe breaks. The four low head safety injection pumps ㉜ can make up for larger losses of coolant and are also used for long-term removal of decay heat from the reactor following shutdown. Furthermore, the accumulators ⑰ already mentioned above are also there to automatically discharge their inventory of borated (neutron-absorbing) water into the core in the event of a large break in the reactor coolant system resulting in a large drop in reactor pressure.

– In the event of failures in the steam, condensate and feedwater cycle, heat removal from the reactor coolant loops via the steam generators can be maintained by the four main steam relief valves and by the emergency feedwater system ㉔ ㉕ ㉚.

– The emergency power supply system ㊽ takes over supplying power to the safety-related systems using diesel generators that are automatically started up if, in the event of an accident, the generator should no longer be able to meet the plant's auxiliary power requirements and offsite power supplies have also been lost.

As a backup for the emergency diesel generators, supplementary diesels of diverse design as well as batteries are available to supply power to electrical equipment needed for safe plant shutdown.

Most of the active safety systems are configured with quadruple redundancy, with no more than two of these redundant subsystems being needed to control an accident. If an accident should occur, the plant operating personnel have plenty of time to think and react calmly because, within the first 30 minutes, the safety systems automatically carry out all switching operations necessary to bring the plant into a stable and safe condition.

Control of beyond-design-basis events

The probability of incidents or accidents developing into beyond-design-basis events has been minimized thanks to the safety concept implemented in the plant design.

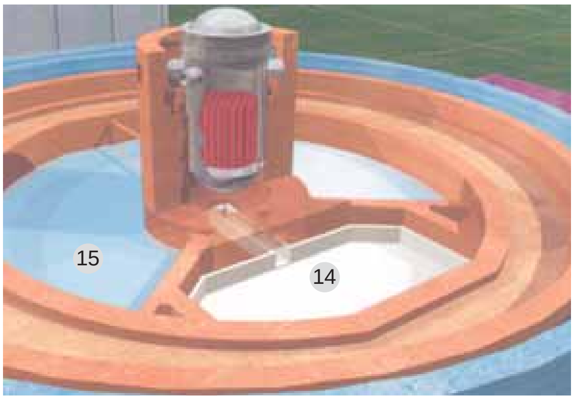
Plant systems are always designed with a certain safety margin so that even an event that exceeds design limits can be controlled either by virtue of these margins or by means of additional "accident management" measures.

In addition, further precautions have been incorporated into the design of the EPR to ensure that there can be no impact on the environment even if beyond-design-basis events should occur. These include, for example, special design features to ensure that, in the event of a postulated core melt accident, the molten core material (corium) can be kept inside the containment by the corium spreading area ⑭ and reliably cooled.

Maximum Safety through Redundancy and

As there is no technology in which the failure of individual components or systems can be completely ruled out, all safety systems in a nuclear power plant such as the EPR are designed with multiple redundancy; i.e. with multiple trains and subsystems of identical design. Depending on the specific design, at least two more trains or subsystems are provided than would normally be needed to perform a designated (safety) function (this is called the "n+2" principle); i.e. one of the trains/subsystems may be under repair and another one may be inoperable due to a single failure. Most of the safety systems of the EPR are designed with quadruple redundancy; i.e. each has four identical trains or subsystems. In order to prevent more than one of these trains/subsystems from being damaged by one and the

Emergency diesel generator at Konvoi-series plant Isar 2



If a core melt accident were to occur despite all the accident prevention measures deployed, the molten core material (corium) would be collected in a specially designed corium spreading area ⑭ underneath the reactor pressure vessel inside the containment and would be cooled by the water in the in-containment refueling water storage tank ⑮ .

Diversity

same event, they are physically separated from one another; e.g. installed in the four safeguard buildings.

However, as redundant safety systems of identical design could also fail due to a common cause (e.g. a component design deficiency or manufacturing defect), components of different designs are additionally provided for performing certain safety functions as an added safety precaution (e.g. equipment made by different manufacturers, or hydraulic vs. electric actuators). This is known as the principle of diversity.

Application of all of these design principles together – redundancy, physical separation and diversity – makes the likelihood that a safety system could fail very, very small.

The nerve center of the power plant

The nerve center of the nuclear power plant is the control room ㉒ that contains all control and monitoring equipment needed for plant operation. From here the entire power plant can be monitored and operated by just five people. Three other people are also on duty, standing by to perform any maintenance work that might be necessary outside the control room.

All major plant parameters are displayed on large wall screens and there are a number of control desks at which all active components of the nuclear power plant (control rods, pumps and valves, etc.) can be manually operated.

If, although this is very unlikely, the control room should not be available for use, there is also a remote shutdown station from which the power plant can be safely shut down at any time.

Computer study of state-of-the-art nuclear power plant control room

Want to Find Out More?

As was said at the start, in a brief description like this we have only been able to touch on the most important plant systems and components and how they interrelate. If you would like to receive more information, just send an e-mail to:

DEinfo@framatome-anp.com

EPR Cardboard Model Kit

Want to build your own reactor? Then just purchase our EPR cardmodel kit. With the kit's 32 size-A3 sheets containing more than 3000 parts you can put together an extremely detailed model of the EPR (the one being built at Olkiluoto 3) in around 320 hours.

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