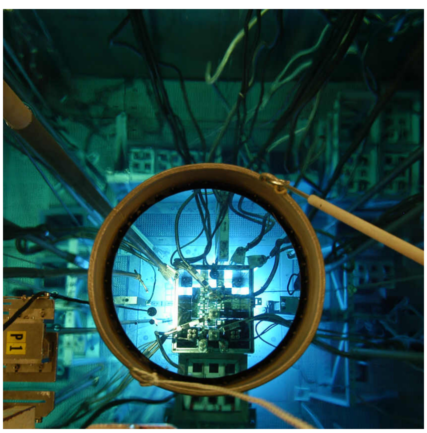
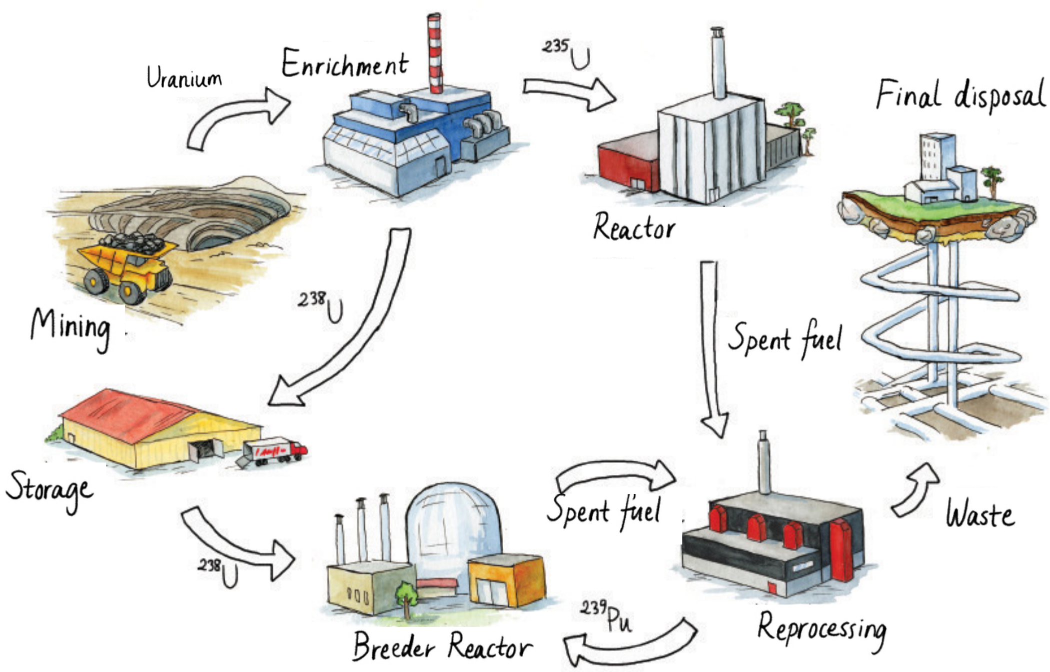
FOURTH GENERATION NUCLEAR POWER



Fourth generation nuclear power



Generation IV

There is a lot of discussion about fourth generation nuclear power and how the new technology may lead to a future energy system where nuclear power plays an important role. Here we address the most important issues concerning the next generation nuclear power – what the technology can achieve, what role it may have, and when it may be in place.

What is Generation IV?

Fourth generation nuclear power, or Generation IV, implies a system of reactors and nuclear fuel cycle facilities – fuel fabrication plants and reprocessing facilities – that together may manage the weaknesses often associated with nuclear power of today.

Quick facts about Generation IV nuclear power:

– It is significantly more fuel-efficient than current nuclear power.
– Does not leave long lived radioactive wastes.
– Designed never to cause accidents with severe consequences. No scenarios are allowed where a malfunction within the facility or an external event leads to release of radioactive material to the surroundings.
–The system as a whole – reactors and fuel cycle facilities – shall be economically competitive as compared to current nuclear power and to other means of power production.
– The fuel cycle is designed so that diversion of fissile material for weapons production is unattractive. This is achieved by assuring that uranium and plutonium are never separated but only ever present mixed together and with other elements. The quality of the nuclear material thus becomes too poor to serve as weapons material, but good enough for fuelling a reactor.

If all criteria are fulfilled, the nuclear system can be called fourth generation. Note that it may take various forms as there are several different reactor types that may fulfil the criteria, and there is also a range of fuels and different options for the chemical reprocessing of spent fuel. In practice, it is sufficient that the system has the ability to meet all criteria for us to refer to it as a Generation IV system. For example, it would be hard to show that a system would be cheaper than the current power production before it has been industrialised.

The generations of nuclear power

The denotation Generation IV is derived from the early commercial reactors constituting the first generation, the larger models being the second generation, and the modern reactors being built around the world today belonging to the third generation. The continued development thus becomes the fourth generation.

Originally, the denotation stems from an American research programme that should develop the new nuclear systems. This is also where the list of Generation IV criteria was developed.

Creating more fuel than is consumed

The requirements imposed on Generation IV imply that the reactors should produce more fuel than is consumed, while also destroying the long-lived elements created in the reactor during operation.

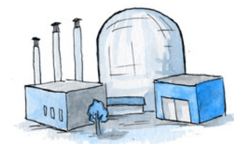
GENERATIONS OF NUCLEAR POWER

The first commercial reactors were small and it was common for a reactor to be the only one of its kind. The technology was continuously improved.

The reactors were eventually standardised and became much larger. Most reactors from the 1970s and 80s belong to the second generation.

Modern reactor designs belong to the third generation. They represent developments of the earlier standardised designs. Forsmark 3 and Oskarshamn 3, from the mid-80s, have a lot in common with the reactors built today and are thus often referred to as generation three reactors.

For fourth generation nuclear power there is a set of requirements including sustainability and a requirement not to leave long-lived waste behind. To fulfil these, a system of reactors and fuel cycle facilities is needed.

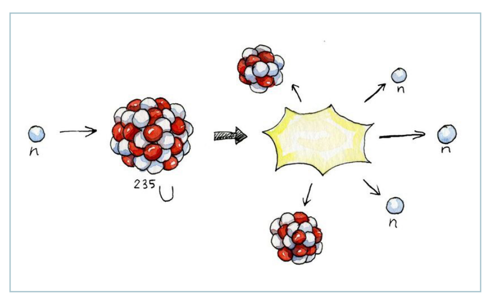


Uranium

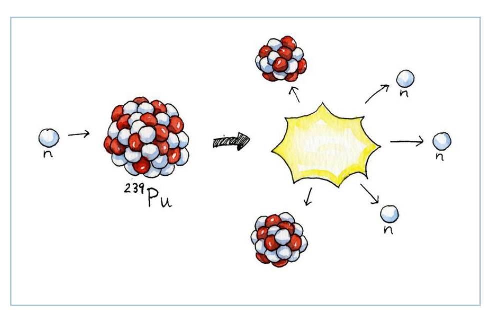
Uranium in nature consists of two isotopes. One of them, uranium-235, may be used as fuel for reactors. The other, uranium-238, constituting 99.3 % of natural uranium, must be converted to plutonium before it may be used as fuel. Plutonium is formed as neutrons from nuclear fission reactions are captured in uranium-238. A reactor that in this manner creates more fuel than it consumes is known as a breeder reactor. The reactors we have in Sweden and Finland do form some plutonium during operation, but the amounts are not sufficient to produce enough new fuel to reload the reactor. Therefore, the reactors must be fed uranium-235 from nature regardless of whether the fuel is reprocessed or not. Fourth generation reactors only need to be fed small amounts of uranium-238 to work. Already today, there are huge stores of that isotope available, having been put aside over the years as a by-product of the process where uranium-235 was enriched to the concentration required for the current reactors.

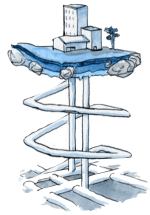
There is no need for mining uranium for the fourth generation reactors until after a very long time even if the nuclear power production is significantly expanded. Would nuclear power production remain at the current level, the already mined uranium would be sufficient to operate the reactors for several thousand years.

Uranium fission



Plutonium fission





Long-lived waste is managed

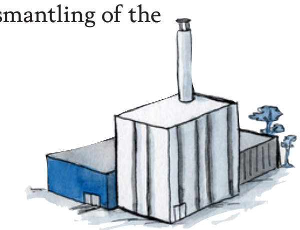
Inside the reactor core, neutrons from nuclear reactions are sometimes captured by plutonium atoms to form even heavier elements. These feature long half-lives which make the spent fuel radioactive for a long time.

It is also possible to design reactors so that the reactions inside actually destroy more of the long-lived elements than are formed during their operation. The heavy elements remaining in the fuel when the reactor is refuelled may be extracted and returned to the next batch of fuel, thereby not ending up in the waste stream. As long as the reactor destroys more of these elements in every operational cycle than is produced, the total amount of long lived material decreases.

This requires a reprocessing method that can completely extract the heavy elements from the spent fuel. Unless the separation is sufficiently good, some of the long-lived wastes will end up in the waste stream as losses. It is mandatory that the fuel manufacturing process is adjusted so that radioactive material may be managed there. Both these steps become more complex if the heavy elements are to be retrieved rather than being passed to the waste. That is an important reason why the focus has previously been on the ability of the reactors to form new fuel with only a weak interest in recycling the long-lived elements. To create a Generation IV system, the cycle needs to be closed. The heavy elements need to be taken care of, despite this complicating the fuel management and making the reactor physics more demanding.

Final storage

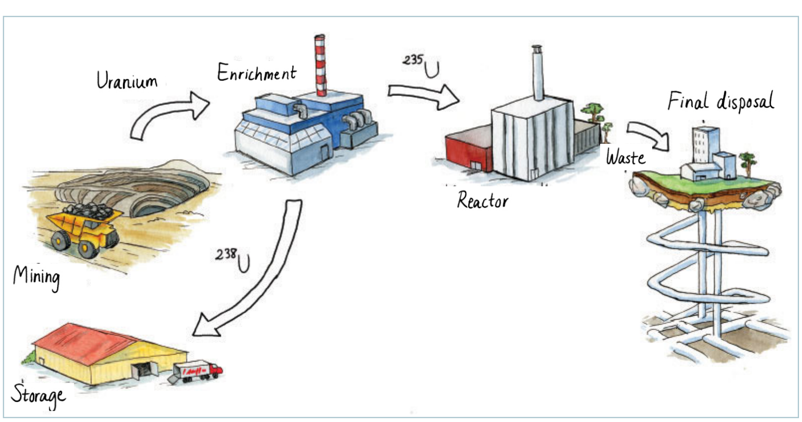
A final repository is required also in a Generation IV system. This is to permanently store the elements created in the reactor – fission products – which may not be reused in the fuel. The fission products need to be stored with the same precaution as fuel from the current reactors. There will also, just as today, be a need for disposing of the wastes that arise during the operation and the dismantling of the reactors and the fuel cycle facilities.



Current reactors

Today, water cooled reactors are the most common. They are designed so that the neutrons released in the fission reactions are slowed down and lose their energy. Slow neutrons, with low energy, give the reactors favourable features. However, with slow neutrons it is not possible to breed new fuel – produce more than is consumed – or destroy the heavy elements that build up in the reactor core.

The longer a light water reactor is operated, the more long-lived material is accumulated. The way of managing this today is by disposing this material in a repository, where it is kept separated from society and from the biosphere. The material needs to remain contained until it has been transformed into stable elements through radioactive decay.



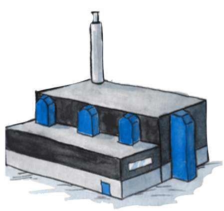
Today, nuclear fuel in Sweden and Finland is used only once. As the fuel is sent for final disposal only a small amount of the uranium has come to use.

High energy neutrons

The key both to efficient breeding and to destroying long-lived elements is the utilisation of high energy neutrons. These have good breeding ability and may also fission heavy elements to destroy them and release useful heat at the same time.

Energy may not be added to the neutrons. The energy that neutrons carry when they are born in the fission reactions should therefore be preserved as far as possible. As large a fraction of the energy as possible needs to remain when the neutron starts the next fission reaction. Fuel, coolant, and reactor materials therefore have to be chosen with care to slow down the neutrons as little as possible. There are essentially three suitable coolants: sodium and lead as liquid metals, and helium gas. A reactor utilising liquid fuel in the form of molten salt may also be an option in which case the fuel is also the coolant.

Out of the possible technologies, sodium cooled reactors may be considered proven. Full scale facilities have been operated in several countries and the experience gathered both from operation and maintenance is extensive.



Reprocessing

Through reprocessing, elements in spent fuel are chemically separated from each other. Historically, retrieving uranium and plutonium for recycling in fresh fuel has been the prime interest. All other elements were left in the material stream considered waste. With Generation IV, all elements heavier than uranium are returned to the reactor in order to avoid creating long-lived waste.

Two methods

There are two fundamental methods for reprocessing spent fuel; aqueous or pyrochemically.

Aqueous method

The aqueous methods are based on dissolution of the fuel in a strong acid where tailored molecules attach to the metals to be retrieved. The method is very efficient and may extract uranium and plutonium more or less completely. The weakness is that the molecules used for the separation are complex and easily destroyed by radiation. It is necessary to wait for the radioactivity to decay before the fuel is reprocessed. A few years need to pass between the removal of the fuel from the reactor and the reprocessing. This means that in a fuel cycle where the fuel is to be recycled by aqueous means more fuel needs to be in circulation as compared to if the reprocessing could have been performed without delay. The amount of fuel waiting for reprocessing is approximately as large as the amount of fuel in the reactors.

Pyrochemical method

The pyrochemical method is insensitive to radiation and may therefore be applied directly. The method is based on dissolution of the fuel in liquid salt where it is separated electrochemically by varying the voltage between an anode and a cathode. Since metals feature different electro-negativity, they will be disposed at the cathode one at a time as the voltage is changed. Unfortunately, the method is far from as efficient as aqueous methods. It gives losses of the metals to be retrieved as well as large amounts of wastes. The waste primarily consists of the liquid salt. So far, there is no efficient means of cleaning and recycling the salt and hence large volumes of highly active salt arise which have to be dealt with.

REPROCESSING METHODS

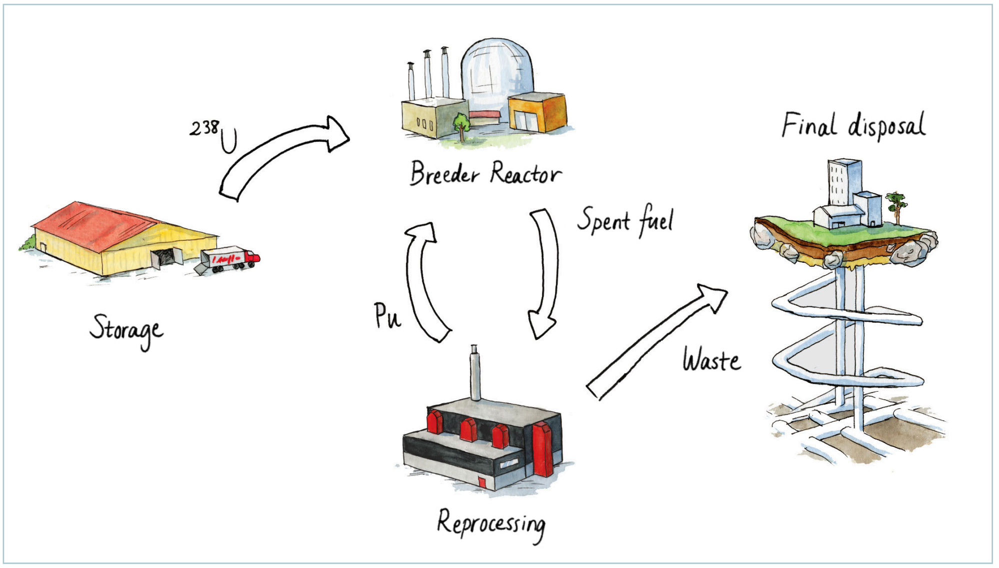
Aqueous method:

Fuel is dissolved in a strong acid and special molecules bind the metals to be retrieved. An efficient method, extracting close to all uranium and plutonium. Reprocessing is performed after a few years as the radioactivity of the fuel has decayed.

Pyrochemical method:

Fuel is dissolved in liquid salt where it is separated in an electrochemical process. The method is insensitive to radiation and may therefore be used directly, but it implies losses of material and large amounts of secondary waste.

In the pure Generation IV fuel cycle, all conventional reactors have been closed. Uranium mining is not required as long as there is still uranium-238 in stock. At the current capacity installed, there is enough uranium in stock for thousands of years of nuclear production. The waste consists of fission products. The long-lived elements are separated from the wastes for recycling in the reactors, where they are fissioned into fission products.



Separation of heavy elements

In order for a nuclear infrastructure to be considered a Generation IV system, all elements heavier than uranium need to be taken care of. They may not end up in the waste stream, which would in that case become long-lived. The reprocessing methods so far used at large scale were designed to separate uranium and plutonium from the fuel and not for extraction of these heavier elements. Therefore, reprocessing methods need to be adjusted to also separate the other heavy elements before fourth generation nuclear power may become a reality. It also needs to be scaled up to an industrial scale.

Generation IV today

A number of countries have put considerable effort both into developing the reactors needed for the fourth generation and into developing feasible means of reprocessing. The historical driving force for this has been to improve fuel utilisation in the context of 1970s forecasts which indicated that fuel efficient nuclear power would be the only way of meeting growing global energy needs. Research programmes for developing breeder reactors and reprocessing techniques were thus fundamental.

But, in the West, the growth in energy demand slowed and uranium has so far not become scarce. This made it less urgent to develop the new reactors, and in the West the breeder reactor development was halted. In Russia, Japan, China, and India the work continued. France has since then picked up development work again. This renewed effort has a somewhat different direction than before: Now, the goal is to design reactors that are able to destroy long-lived elements in the spent fuel in addition to the ability of breeding new fuel.

There are no systems of reactors and fuel cycle facilities in operation today that could be called Generation IV systems, but the programmes for developing breeder reactors continue and new full scale prototypes are on their way. At the same time, work of improving the reprocessing methods is progressing.

The fourth generation at large scale

Additional work is required before the required methods for reprocessing will work at industrial scale, but in principle all components required for a Generation IV system are available. At this point, what is missing before the system may emerge are strong driving forces.

Generation IV promises a sustainable way of producing energy which may be scaled infinitely. The reactors may be designed to solve other tasks than to produce electricity, such as propelling ships, producing hydrogen, delivering hot steam to industry, or to serve as a completely independent sources of energy for decades. The main strength though is the ability of delivering unlimited amounts of energy sustainably in a planned manner more or less without interruption.

Apart from this, the other requirements posed on Generation IV systems are essentially about managing weaknesses associated with existing nuclear power. A very extensive expansion of nuclear power demands a system with no possibility of severe accidents and from which the wastes are easily managed. There must also be no way of misusing the new technology to manufacture nuclear weapons. Unless these requirements are met, Generation IV will not gain acceptance. The implementation of the system will occur stepwise. To start with, a few reactors will be commissioned and the fuel cycle facilities will have low capacity. It is not certain that the first reactors will fulfil all the requirements e.g. the recycling of the heavy elements.

As more reactors are constructed and the current reactors approach decommissioning, the system slowly moves towards working as a Generation IV system. In countries that already use nuclear power, the existing reactors will coexist with the emerging system for decades. It may be stated that this development is already under way in Russia and in India, where reactors are in operation and more are under construction. But neither the Russian, nor the Indian fuel cycles fulfil all of the criteria today. So far these are not Generation IV systems.

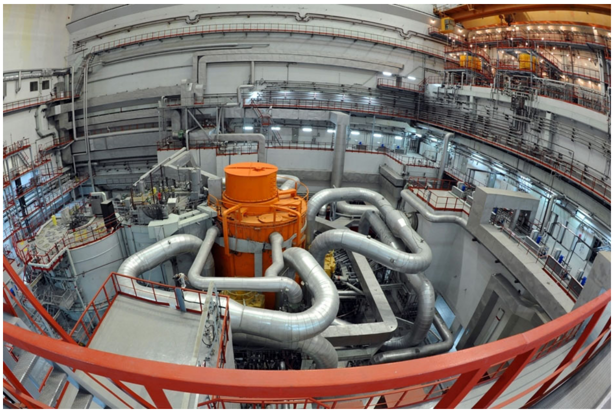
What might possibly lead directly to a Generation IV system without the coexistence with conventional reactors would be in the case where a country without nuclear power today would pursue direct development of Generation IV. Such a system could be fully operational, with all components interacting as planned, within 20 years. Specific parts of the system could come into place earlier. Such an undertaking would require strong political support for decades. The need for political support and the magnitude of the commitment also implies that one or several states need to take the overall responsibility of implementing the project.

Nuclear power in Sweden and Finland

The six Swedish reactors that went into operation after the 1980 referendum have just been modernised and will be able to operate for at least 30 more years. The electricity they produce together with hydropower and wind power is likely to be able to meet the Swedish demand for many years. There is no urgency for Sweden to choose the Generation IV path.

Several of the Finnish reactors will be in operation for many more years and there are new reactors on their way. Even if the expansion of Finnish nuclear power would continue with more reactors in coming decades, a transition to Generation IV would require that other countries also started the construction of fast reactors and reprocessing facilities. Finland has a too small a fleet of reactors to choose a Generation IV strategy on its own.

The most interesting perspective on Generation IV from a Swedish and Finnish perspective is rather the promise of the technology to significantly contribute to the reduction of climate gas emissions. What is important is that there are ambitious nuclear power programmes, and dedicated efforts to develop Generation IV, in the countries that are currently dependent on fossil fuels for their energy supply.



The sodium cooled fast reactor Beloyarsk 4 entered commercial operation 31 October 2016. Even though it does not fulfil all of the Generation IV criteria, it demonstrates that technology for large breeder reactors is in place.
Photo credit Rosatom

Future nuclear power

In a future where nuclear power around the world has expanded and the price of uranium has increased, there may be economic incentives for a Nordic Generation IV venture. In such a case, it is probable that the some of the fuel cycle facilities would be shared between countries, for example facilities for large scale aqueous reprocessing and also fuel manufacturing.

Fourth generation nuclear power is most of all a way of managing the climate issue. Neither Sweden, nor Finland has any urgent need for the technology, but both countries will indirectly benefit when fossil fuels are phased out and more people get access to plentiful energy.

FOURTH GENERATION NUCLEAR

Fourth generation nuclear power is discussed in different contexts. It is no longer just a discussion for scientists and engineers, but has become relevant for politicians, journalists and the general public. This publication answers some of the most common questions regarding fourth generation nuclear power systems – what the technology can achieve, what role it may have, and when it may be in place.

Daniel Westlén, who has his doctorate in reactor physics, is the author of the text and is responsible for the content. Carl Hellesen, Uppsala University, and Carl Berglöf, Vattenfall, have both provided their comments in the compilation of the text. Illustrations are made by Lova Delfin. The initiative to publish this text was taken by the Energiforsk steering group for nuclear power research.

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