# Nuclear power and the Second Law

summary

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# Second Law of thermodynamics

## Spontaneous change

A spontaneous change, or spontaneous process, tends to occur without needing to be driven by an external influence. A spontaneous process has a natural tendency to occur; it does not necessarily take place at a significant rate. The key idea that accounts for spontaneous change is that energy and matter tend to become more disordered.

## System

A system in thermodynamics is the part of the world we want to study. The urroundings consist of everything else outside the system. An open system can exchange both matter and energy with the surroundings. A closed system can exchange only energy and an isolated system can exchange nothing.
The biosphere may be considered a closed system: only energy exchange with its surroundings, outer space, is possible. Mass exchange with outer space is negligible. In the thermodynamic assessment of nuclear power of this study the nuclear energy system as a whole is considered the observed system.

## Entropy

Entropy is a measure of dispersal and randomness of matter, of energy and of unidirectional flow of matter and/or energy. A more random distribution of matter and energy in a system means a higher entropy of the system.

The probabilistic character of entropy is based on the quantummechanical concept of quantisation of matter and energy: mass flows and energy flows occur in quanta, smallest units, for example atoms and light quanta. The probabilistic aspects of entropy are important in chemistry, biology and environmental sciences.

Entropy may seem a somewhat elusive notion, but it is a key notion in thermodynamics. In practice only entropy changes of a system can be observed. For understanding some basics of nuclear power and of sustainable energy a semiquantitative approach of entropy changes is satisfactory: we only need to know if the entropy of a system increases or decreases by a given action or phenomenon.
A rise of the entropy of a system means more dispersion of matter, energy and directional movement, or in other words: a loss of quality and usefulness of the observed system. For that reason entropy may be described in non-physical terms as a measure of 'mess and uselessness'.
A decrease of the entropy of a system means less randomness and consequently a gain of quality and usefulness of the system, this is possible by investment of useful energy. An example is the production of iron from iron ore. Metallic iron has a much lower entropy than the same mass of iron in the rock.

## Second Law

Every change in the universe is coupled to an energy conversion and an entropy effect. A basic formulation of the Second Law is:

> With every change the entropy of the universe increases.

The Second Law can be formulated in different ways. Evidently all correct formulations are based on the same principle. In respect of processes of everydays practice and in the context of nuclear power and sustainable energy the following formulation may be useful:

> A spontaneous change is accompanied by an increase in the total entropy of the system and its surroundings.

The Second Law of thermodynamics is one of the most basic laws of nature. No phenomena have been observed in the known universe which would be in conflict with the Second Law, so the law is considered to be valid for all known phenomena in nature.
The following phrase may be a metaphor of an increase of entropy by a spontaneous process:
Any fool can pour a cup of tea into the ocean, but a thousand wise men cannot pull it out again.

Examples of spontaneous processes are: the dispersion of $CO_2$ from burning fuel into the atmosphere, the rusting of steel in the open air, and the dissolving of sugar in a cup of tea.

## Significance of the Second Law for nuclear power

Phenomena governed by the Second Law that are essential in the assessment of nuclear power are:

- ageing
- incompleteness of separation processes
- entropy generation inextricably coupled to energy conversion.

These phenomena determine several important aspects of nuclear power:

- nuclear safety
- dispersion of radioactive materials into the biosphere increasing with time
- energy cliff of uranium resources
- prospects of nuclear power based on thermal-neutron reactors in the once-through mode
- infeasibility of closed-cycle reactors as net energy systems
- limits of the potential of climate change mitigation by nuclear power
- generation of latent entropy and with it the energy debt.

Obviously human behaviour is also an important factor.

### Ageing

Any material and structure inevitably deteriorates with time due to a combination of spontaneous chemical and physical processes, a phenomenon usually called ageing. The rate of ageing of materials and components depends partly on the operating conditions. Presence of nuclear radiation and decaying radionuclides accelerates the degrading processes.
As a consequence of the Second Law spontaneous processes are always degrading the quality of materials and structures. Common examples of such degrading processes are corrosion of metals, wear of moving components, weathering of concrete and quality loss of plastics. The degradation of a material or structure may be retarded by dedicated effort and investments of useful energy and processed materials, but never can be eliminated.

Ageing processes are often difficult to detect because they occur on the microscopic level of the inner structure of materials. They frequently become apparent only after a component failure has occurred. Not always leakages or other signals can be detected before a component catastrophically fails.

*Figure 1*
Rusting of a steel pole is a result of spontaneous processes, in accordance with the Second Law. When left unattended long enough, the steel pole will end up as a pile of rust grains. The entropy of the steel of the pole, the system in this case, has increased by the spontaneous process: the mess and uselessness of the original amount of steel have increased. The amount of iron in the observed system has not changed: the iron atoms of the original tube are still present in the pile of rust grains.

## Nuclear safety

In nuclear technology exceedingly high quality specifications and high degrees of predictability of the behaviour of materials and equipment are required. Deterioration of the materials by, often unseen, ageing processes affects the reliability of a nuclear reactor at an increasing rate with time. A design may be perfect on paper, in practice inherent fail-safe technical systems are impossible.
Nuclear reactors are part of an intricate system of industrial processes and activities, so even with inherently safe reactors nuclear power is not necessarily safe.
Inherently safe means that on no condition an accident or unwanted event could occur in a technical system and would imply the availability of fail-safe materials, fail-safe design, fail-safe construction and maintenance and fail-safe human behaviour. Inherently safe nuclear reactors exist only on paper, because this concept would imply the availability of 100% perfect materials and 100% perfect separation processes, in addition to the absence of ageing processes. These desirable conditions are in conflict with the Second Law.
Human behaviour, terrorism, natural disasters are evidently not predictable. The conclusion is that inherently safe nuclear reactors are inherently impossible, let alone the an inherent safe nuclear energy system as a whole.

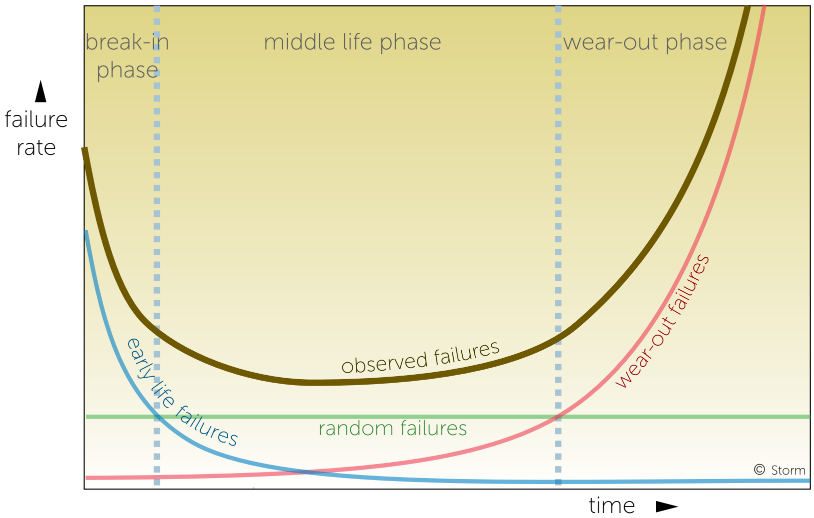


*Figure 2*

The bathtub hazard curve is the sum of three types of failures rates: the early life failures, decreasing with time, the random failures, constant over time, and the wear out failures, increasing over time. The wear-out failures are typical Second Law phenomena. The bathtub curve is valid for technical devices, including nuclear installations, and for living organisms.

## Increasing dispersion of radioactive materials into the human environment

The human-made radioactive materials are stored in containers at temporary storage facilities. By ageing of the materials of the containers, accelerated by nuclear radiation, the containers go leaking in the long term, at an increasing rate with time. For the same reasons the chance of severe accidents with storage facilities, such as cooling pools of spent fuel and storage tanks at reprocessing plants, increase with time.

## Separation processes

Processes to separate mixtures into fractions containing a single components and to purify materials involve dynamic equilibria that are governed by the basic laws of nature, among other the Second Law of thermodynamics. One of the consequences of these laws is that separation processes never go to completion. As a consequence it is impossible to separate a mixture of different chemical species into 100% pure fractions without losses. A part of the desired species gets lost in the waste streams and each fraction is more ore less contaminated with other species. Separation becomes more difficult, requires more energy, and goes less completely as:

- more different kinds of species are present in the mixture,
- the concentration of the wanted for species in the mixture are lower,
- constituting species are chemically more alike.

In addition radioactivity seriously hampers chemical separation processes, due to breakdown of the separating chemicals by nuclear radiation. Radioactive and non-radioactive isotopes of the same element cannot be separated.

Separation processes play a vital role in the recovery of uranium from the earth's crust and in reprocessing of spent fuel.

### Extraction of uranium from natural sources: the energy cliff

The nuclear process chain starts with the extraction of uranium from its ore, by means of a sequence of physical and chemical separation processes.
Uranium-bearing rocks are present in the earth's crust in different appearances and at widely different properties. Rocks with the highest content of uranium are the rarest, rocks with lower contents are much more widespread. This common geologic phenomenon, valid for almost all metals in the crust, results in a well-known distribution of the uranium resources: more uranium is present the lower its content in geologic formations.

From the Second Law follows that the energy investment per mass unit of extracted uranium increases with declining ore grade of the deposits from which the uranium is extracted. When uranium is extracted from ore at a grade below about 100 grams uranium per ton rock, no net energy can be delivered by the nuclear energy system as a whole: the energy cliff.
This observation implies that only a fraction of the uranium occurencies in the earth's crust qualify for exploitation as energy source.
Depletion of uranium resources is a matter of quality, not of quantity.

Probably the nuclear industry has also advanced concepts of uranium recovery in mind, expecting that advanced technology will make it possible to recover uranium at an affordable price from unconventional sources, for example from seawater. However, the energy cliff is based on natural laws, not on economic notions.

### Uranium-plutonium breeder and thorium-uranium breeder systems

Reprocessing of spent nuclear fuel is a pivotal process in a number of advanced nuclear concepts. Separation of highly radioactive mixtures, containing dozens of radionuclides, into 100% pure fractions is impossible, as explained in a previous section. For the same reason the production of materials and machines with 100% predictable properties and behaviour during decades is not possible. A far-reaching consequence is that advanced closed-cycle nuclear concepts relying on a perfect separation efficiency are infeasible, that are: the uranium-plutonium breeder system, the thorium-uranium breeder system and the partitioning & transmutation of long-lived radionuclides.

## Entropy generation of energy conversions

From the Second Law follows that the conversion of the potential energy embodied in a mineral energy source into useful energy inextricably is coupled to the generation of more entropy than theoretically could be compensated for by investment of the generated amount of useful energy.

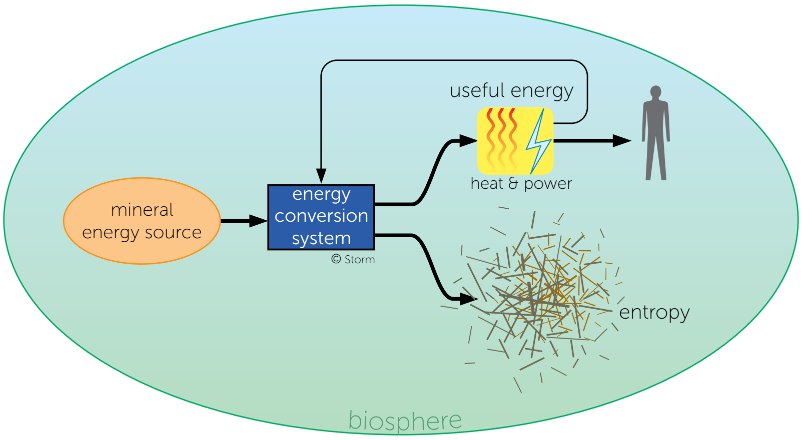


Figure 3
Conversion of potential energy embodied in mineral energy sources into useful energy is inextricably coupled to the generation of more entropy than theoretically could be compensated for by the generated amount of useful energy. A part of the produced useful energy is required to build, operate and maintain the energy system and to manage its waste.

Uranium is a mineral energy source recovered from the upper layers of the earth's crust. Recovery and use occur within biosphere. As a consequence the entropy generation inevitably coupled to the generation of useful energy by fissioning uranium, occurs within the biosphere. Effects of increasing entropy within the biosphere always mean loss of quality of the human environment. A major part of the nuclear entropy is the generation and dispersion of radioactivity. Inevitably people are exposed to radioactivity, inflicting serious harm.

From the Second Law follows that the generated amount of useful energy from any mineral energy source is insufficient to compensate for its coupled entropy generation, even if all useful energy would applied to that purpose. As a result, by using uranium the entropy of the biosphere increases constantly, which means increasing damage and deterioration. For that reason fission power is not sustainable, nor is any other mineral energy source: fossil fuel systems but also fusion of deuterium and tritium.

Sustainable energy generation is only possible if based on solar energy, because the entropy coupled to the energy conversion in the sum stays outside the biosphere.

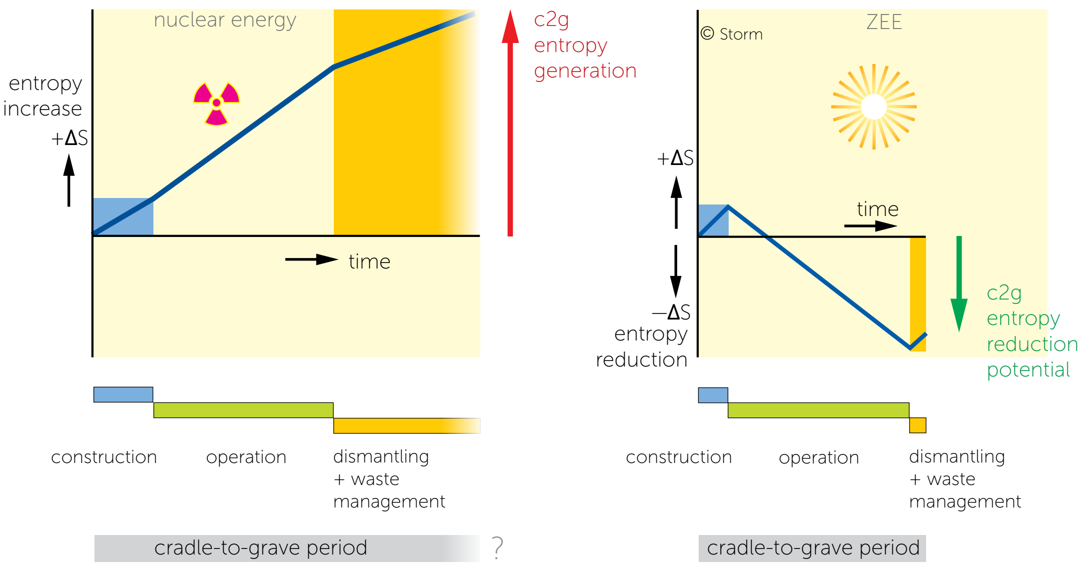


*Figure 4*

Entropy generation and/or reduction of two energy systems: nuclear energy and a renewable system system, based on solar energy. The diagrams are not to scale. The cradle-to-grave period of nuclear power is long: 100-150 years. A renewable system, except hydropower, has a much shorter period: something like 40-50 years. The downstream processes of the nuclear system are systematically postponed to the future, so its duration is unknown.

## Latent entropy: the energy debt

An important difference between fossil fuels and nuclear power as regards this observation is the way the entropy generation becomes observable. A part of the entropy generation associated with the extraction of mineral energy carriers is instantly visible as disturbances of ecosystems in the mining areas, dispersal of dust, contamination of groundwater and soil by chemicals, etcetera.

The difference concerns the entropy generation associated with the conversion of the potential energy embodied in the mineral energy carriers into useful energy. When fossil fuels are burned, the combustion products and waste heat are instantly released: matter and energy are dispersed into the environment and the entropy coupled to the energy conversion increases the entropy of the biosphere, meaning loss of its quality.

When uranium is fissioned the dozens of different kinds of fission products and radionuclides stay localised inside the spent fuel elements. A part of the fission entropy becomes manifest outside of the nuclear system, for example as waste heat, discharges of radionuclides into the environment and as radiation damage to materials and living organisms in the vicinity of the reactor.

The fission products confined in the spent fuel elements inevitably will spread into the environment when nothing is done to prevent that. Then the fission entropy becomes manifest in its full size: dispersal of tens of different kinds of radionuclides, the spread of nuclear radiation and the damage to materials and living organisms in the biosphere caused by radiation. In every respect that would mean a rise of disorder, a degradation of the human environment.

Only by dedicated effort and energy investments it possible to prevent the dispersal of the main part of the fission products and radioactivity generated in the nuclear reactor: by appropiate packing the radioactive wastes and by isolating it from the biosphere as best as possible. At the moment of its generation, the main part of the fission entropy may be considered latent entropy. The longer we postpone adequate treatment of the nuclear waste, the more latent entropy will turn into  actual entropy of the human environment.

The dedicated effort to prevent this disastrous scenario will require massive investments of ordered materials, useful energy and human skill: this is the energy debt.

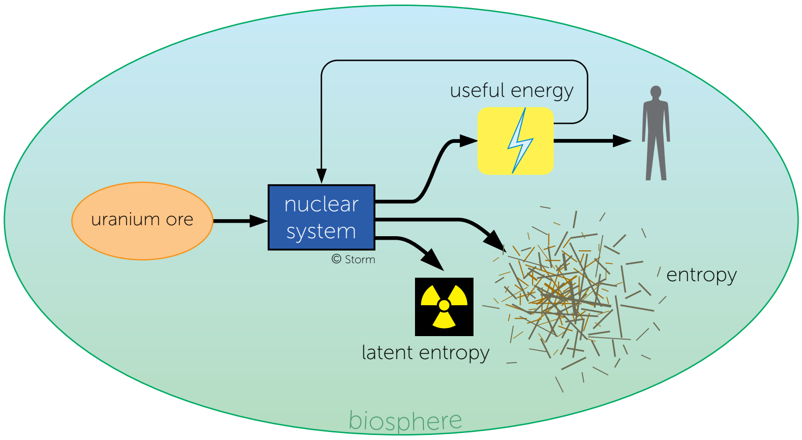


*Figure 5*

Nuclear power is generated by an energy system, based on uranium, a mineral energy source. An important difference of the nuclear energy system with other mineral energy systems is the generation of latent entropy. Without investments of useful energy and human effort the latent entropy will develop into a huge and irreversible increase of the entropy of the biosphere.

## Delayed entropy

After the fission process stops in spent fuel elements the entropy production goes on. By radioactive decay of the fission products new nuclides come into being, and radiation and heat is generated. This decay heat generation, called residual heat, is intense enough to melt the nuclear fuel if it would not be cooled during decades after the nuclear fuel is removed from the reactor. Obviously the decay process of radionuclides occur in exactly the same way when the radionuclides are dispersed in the environment.

This kind of on-going spontaneous entropy generation, inextricably bound up with the fission entropy generation, is called the delayed entropy generated by nuclear power.

Delayed entropy effects may become seriously damaging in living organisms.

## Reports

More details on the Second Law and nuclear power are addressed in report:

m38 *Nuclear power and the Second Law.*

See also reports:

m01 *Uranium-plutonium breeders*
m07 *Energy debt, latent CO2 emissions, latent entropy*
m20 *Reprocessing of spent fuel*
m21 *Nuclear safety*
m26 *Uranium mining + milling*
m29 *Uranium-for-energy resources*
m35 *Energy cliff and CO2 trap*