The NIS crew of the 3-D activation process

"Monte Carlo" provides an innovation push: New 3-D activation process for decommissioning

by Dirk Bender

The decommissioning of a nuclear power plant presents major challenges to each operator. Just the demolition of the entire area of a typical nuclear power plant to create a "green field" swallows up approximately 1 billion Euro. At the Biblis nuclear power plant in Germany, this task resulted in an innovative idea for more planning reliability in cooperation with the NIS Ingenieurgesellschaft – and a process which has to do with a casino game in name only…

The abrupt stop to power operations at Biblis required a rethink at the power station – having previously been a supplier of electricity, it was now necessary to plan the dismantling. Since the commissioning of the two units A and B in the years 1974 and 1976, the NIS team of physicists had been responsible for the nuclear calculations and core design and therefore made a decisive contribution towards ensuring that the operation of the power plant was both safe and economical. So why not continue the partnership and incorporate the know-how of the system acquired over three decades into the creation of a new activation process and take advantage of it for its decommissioning?

Taking stock: nuclear waste disposal from the two Biblis units is very costly. Because a small portion cannot simply be removed as when a residential building is being demolished. "The operation of a nuclear power plant leaves behind radioactive building structures and installations which first of all have to be dismantled and then disposed of as special waste in containers specifically designed for

The Biblis nuclear power plant is gearing up for dismantling this purpose," explains Dirk Bender, Project Manager for reactor physics calculations.

They include the reactor pressure vessel (RPV), inside which the reactor core is located. This is surrounded by safety barriers such as the biological shield with a concrete shell which is over 2 m thick in places. During operation of the reactor these components have been activated over many years by "neutron" bombardment and are now radioactive.

Precise knowledge of the quantity of radioactive building structures and installations, as well as their degree of activation is essential for two reasons: on the one hand, this knowledge is required for the decommissioning licence. On the other hand it is essential for cost-effective planning of the decommissioning and for minimizing the exposure to radiation of the personnel involved in the decommissioning. Activation calculations carried out in the past overestimated the activity inventory, that is the total quantity of the radioactive reactor components – even seven-fold in the case of unit A in Biblis.

The cost calculations at the time for decommissioning could only be made on the basis of rough assumptions, since for the activation calculation neither the operating history of the plant, which was still in operation at the time, nor the exact switch-off date were known. The degree of activation depends to a large extent on these factors. Moreover, the calculations of the radioactive waste quantities were based on outdated calculation methods. With the methods available at the time it was only possible to take into account the different spatial directions in separate calculations. A direct 3-D method was not feasible – and many components could only be considered as a whole and not in parts, such as the main coolant lines. The consequence of this was that the required number of special containers was overestimated.

3-D potentials: the calculation adds up

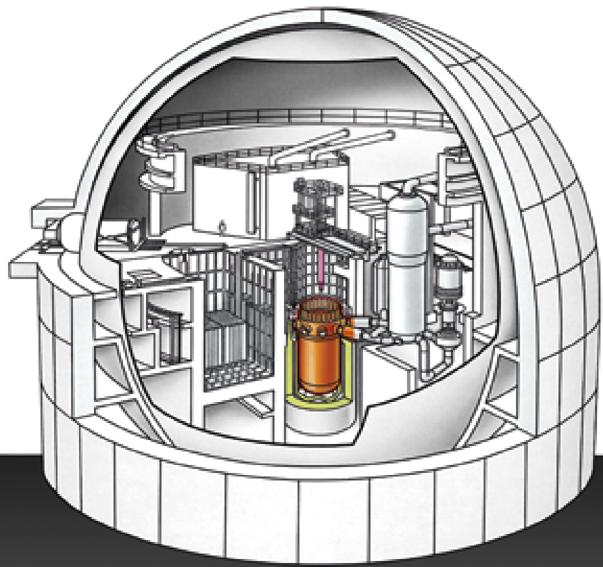
"We assume that thanks to the new 3-D activation process we can achieve savings of up to 10% on cast iron casks in comparison to former planning calculations when planning the decommissioning. The new calculation process guarantees the operators a higher planning reliability for dismantling," explains Reinhold Paul, Project Manager of the NIS department for determining decommissioning costs. This would correspond to a savings potential of 4 million Euro, as a much greater share can be categorized as "moderately activated" or even as conventional waste. "Intermediate" or "low-level" waste is disposed of in containers which are considerably cheaper. So it is worth spending some money in order to save the same amount many times over! NIS is well positioned with this 3-D activation process to assist operators not only in Germany, but also worldwide with planning their decommissioning in a manner which is more cost efficient.

Monte Carlo method: not a game, but complete transparency!

In the year 2009, NIS carried out activation calculations of the Krško nuclear reactor in Slovenia with a 3-D calculation model it had developed itself. As in Krško, the calculations of the new 3-D activation process were performed using the so-called "Monte Carlo method" (see box) in three-dimensional geometry.

The method resembles the computer tomography scan of a human body, which is also carried out in three dimensions. The advantage is self-evident: each location in the model of the reactor is accessible. Depending on the computing power available, it is possible to highlight complex structures such as the shield cooling shafts (meter-long curved shafts embedded in the concrete of the biological shield) or nuclear instrumentation at any desirable resolution. In particular, the neutron scattering – also known as the neutron streaming effect – in remote areas can be made visible. This 3-D computer model is the pre-requisite for an "activity atlas", which represents a type of relief map for the entire reactor.

Cross section of a pressurized water reactor



The reactor building is one of a number of buildings on the power plant site. The reactor is located in the center. During operation, solely the highlighted area is being activated by neutrons from the reactor core, which is inside the reactor pressure vessel. The dismantling of the reactor devours the major part of the decommissioning costs.

Neutron – a small particle with a striking effect

Atoms are the smallest parts of the chemical elements. They are so tiny that 10 million atoms strung together measure approximately 1 mm. Much smaller than that – by a factor of approximately 10,000 – is the central atomic nucleus, which is surrounded by a shell of negatively charged electrons. If an atom corresponded to the size of the Cologne Cathedral, the nucleus of the atom would be the size of a cherry stone. The building blocks of the atomic nucleus are the positively charged protons and the neutrons. The neutron is charge-neutral – therefore its name. In the nuclear reactor, neutrons are produced by the fission of certain uranium atoms in the fuel elements which form the reactor core. On average, the fission of a uranium nucleus produces two to three so-called fission neutrons (as well as two approximately equal-sized pieces of debris and the release of energy).

As almost the entire mass of an atom is united in its nucleus, matter consists primarily of empty space. Because of its speed and type of material, the neutron can pass through matter almost unhindered. For this reason, outside the RPV the shielding is designed in such a way that no neutron from the reactor core can penetrate the biological shield to the outside.

Activation in the nuclear power plant – how does it arise?

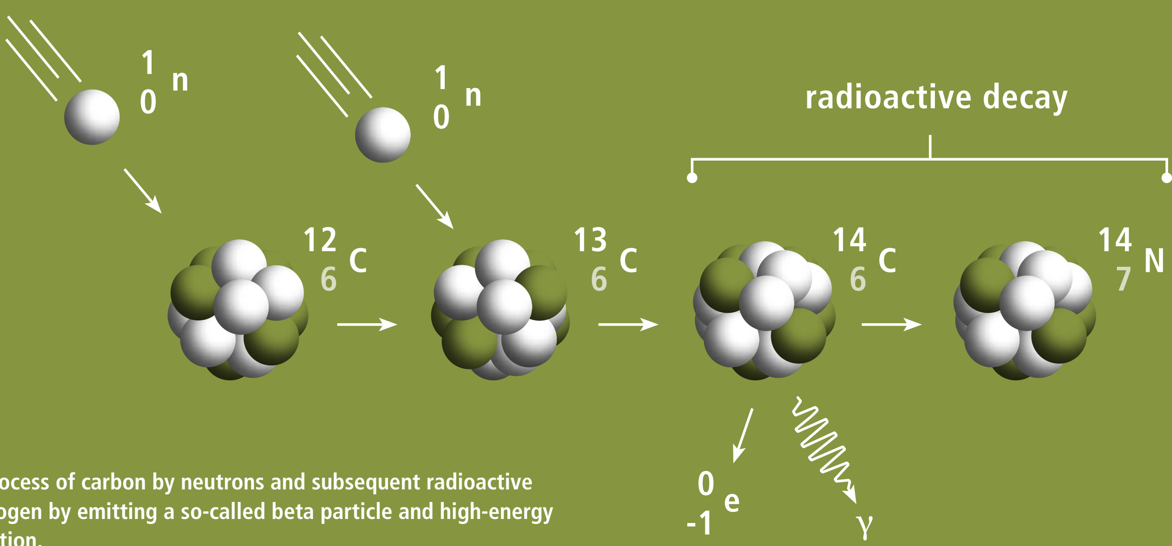
Neutrons are essential for the generation of energy in nuclear power plants. They make use of their neutral charge in order to pass unhindered through the negatively charged shell of the atoms. If a neutron strikes the nucleus of an uranium atom (the fuel in a nuclear reactor), it can split this with the release of energy. In addition, two to three "fission neutrons" are released. After they have been slowed down by collisions with other atomic nuclei, these fast neutrons can split further uranium nuclei in the fuel. This is the wellknown chain reaction which keeps the nuclear reactor going.

A fraction of the neutrons produced escapes from the reactor core – similar to a boiler or car engine, in which thermal energy is lost to the environment. Nevertheless, this fraction is approximately as large as the quantity of raindrops which would rain down on all continents of the earth simultaneously covering the entire surface – and that every second! Some of these neutrons penetrate deep into the 2 meter-thick biological shield and "activate" the reinforced concrete there.

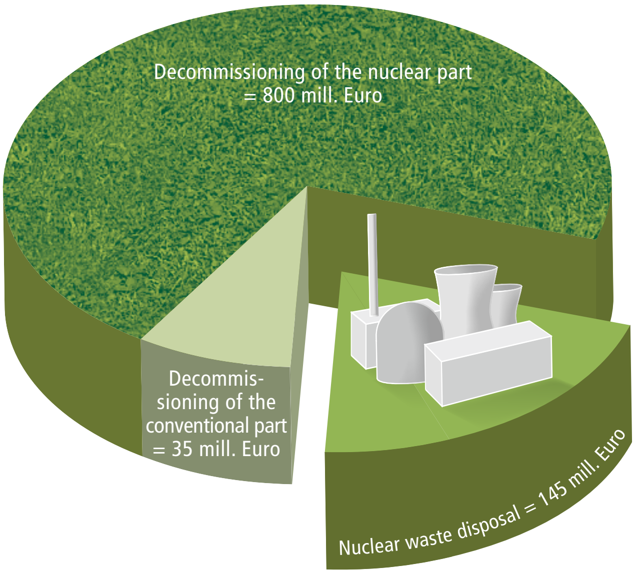
Activation – conventional materials become radioactive

Activation is the process by which materials become radioactive as a result of neutron radiation. Non-radioactive carbon 12 (chem. 12-C) for example, which is added in small quantities to the steel, is converted under neutron bombardment to radioactive carbon 14 (chem. 14-C), which is well known from the C14 dating method.

C14 – with a half-life of 5,730 years – is of no major significance for decommissioning. This is completely contrary to many substances which are easily activated, as their nuclei capture neutrons particularly easily. For example cobalt: although only present in steel in traces, it is activated extremely easily and represents the dominant radioactive material in the steel in spite of its comparatively short half-life of 5.3 years. The half-life represents the period after which the activity of a substance has halved.



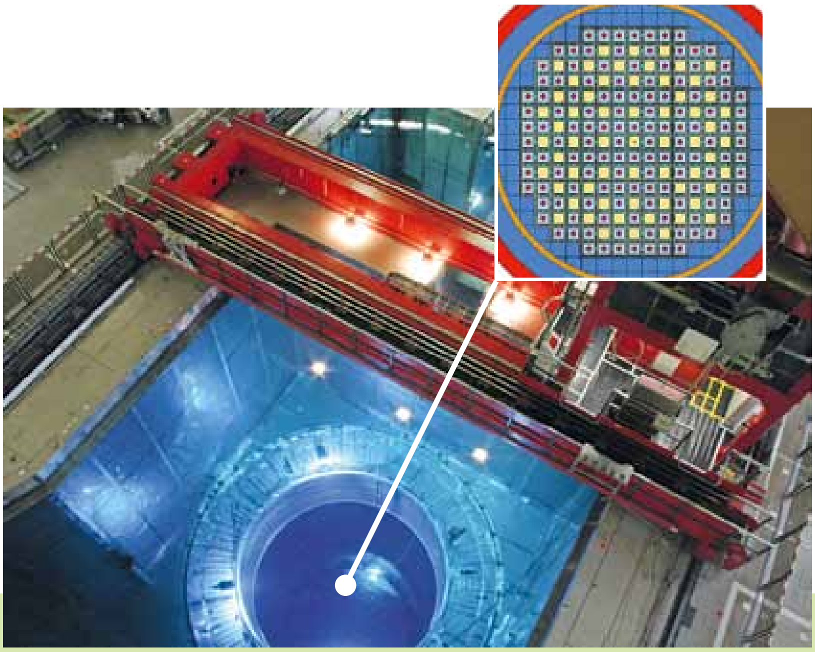
Activation process of carbon by neutrons and subsequent radioactive decay to nitrogen by emitting a so-called beta particle and high-energy gamma radiation.



Dismantling costs of a pressurized-water reactor in Germany:

Total costs for the decommissioning back to the "green field" about 1 billion Euro

About 680 cast iron containers are planned for the "highly activated" components. Savings of approx. 50 cast iron containers are possible in the decommissioning planning thanks to the use of the new 3-D activation process.



Opened reactor pressure vessel with a view to the fuel elements of the reactor core – next to it the cut-out of the 3-D activation model: the core is the source of the neutrons that leave the reactor core during operation and activate parts of the reactor building.

The innovation of the 3-D activation process

The new aspect is the inclusion of the nuclear calculation which maps the lifetime of the reactor, so to speak – in the case of Biblis NPP in Germany since its commissioning 39 years ago. "With the successful connection of the operational side to the decommissioning side in the activation calculation we are breaking new ground," says Dr. Stefan Jaag, one of the project participants who succeeded in doing this, proudly. "Nobody has done this before us!"

For this to work, Jaag had to intervene in the Monte Carlo program and reprogram part of the computational code. Why the integration of the calculations of reactor operations is of such importance can be most easily explained using the metaphor of rain. With this it is possible to symbolize the stream of neutrons escaping from the reactor core: in reality it does not rain everywhere or permanently. It is therefore important to take into account the downtimes (in which hardly any fission neutrons are produced in the reactor core and therefore do not escape), as well as other important parameters from the past operations of the power station.

One of the eight main coolant pipes at the Biblis NPP with a diameter greater than 1 m: The pipes of the hot leg lead the water with a temperature of almost 300 °C and a pressure of 155 bar from the reactor to the steam generators. They were partially activated by the neutron radiation from the reactor core.

In the computer model each reactor block is covered with more than 100,000 "detector cells" in each case. The flow of neutrons emerging from the reactor core over the 39 years of operation is simulated and the number of incoming neutrons in the detector cells registered over time. With this information, the activity in each detector cell is calculated. The RPV alone possesses more than 3,000 such cells!

The models of the two Biblis reactors were developed in close consultation with the decommissioning experts at NIS. They were able to incorporate all of the experience they had acquired during the decommissioning project in Stade, Germany, in the modeling phase of the 3-D activation process. For example, in the case of the RPV, the grid arrangement of the detector cells was harmonized with the dismantling and packaging strategy. As a result, the number of containers required is optimized. Finally, the results of the activation calculations are stored in an "activity database". By means of a simple input routine, the activity values can be shown for any location and cutout section within the reactor. As the next development step, the database is coupled to a 3-D activity visualization tool, with which it is possible to zoom in on cutouts directly on the screen or view them from another perspective.

Parallel processing saves time

The computational effort of the Monte Carlo calculation is immense: a single standard desktop PC would have had to calculate for an entire year (and that for one reactor block). Thanks to parallel processing, it was possible to reduce the computing time to a few days. This processing power was necessary in order to obtain a high spatial resolution of the degree of activation. The reason for this is that only in this way is it possible to identify "hot spots" (areas with particularly high levels of radioactivity). Precise knowledge of the distribution of the activation within the reactor helps to effectively reduce the radiation exposure of the personnel carrying out the decommissioning to a minimum. The team knows where the hot spots are located when they enter the reactor building and can therefore avoid them.

"With our high-resolution 3-D computational model we were even able to gain experience for the construction of new nuclear power plants," explains project manager Dirk Bender. "We were able to identify which remote areas within the reactor building were activated by neutron bombardment and we can therefore make recommendations for better shielding." For example, it would be possible to use alternative materials in these areas

The Monte Carlo method – cleverly analyzed!

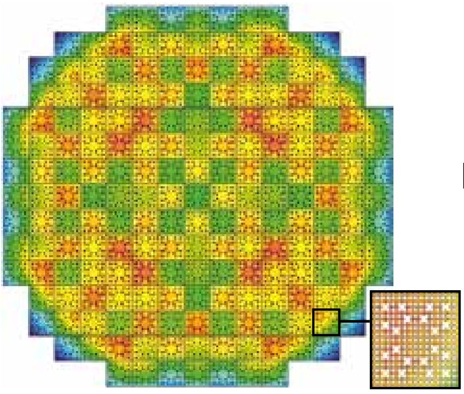
Monte Carlo simulations are used if analytical formulas for the evaluation of processes in nature fail or their solutions are too complex. Questions from the world of finance and many other fields can also be answered relatively simply with Monte Carlo approaches.

In this method from stochastics (a branch of mathematics), random experiments performed very frequently play an important role. With the help of probability theory, problems are solved numerically. Here, use is made of the law of large numbers (in our case a large number of neutrons). The random experiments are carried out with the generation of random numbers (i.e. playing dice with numbers – in line with the casino in Monte Carlo).

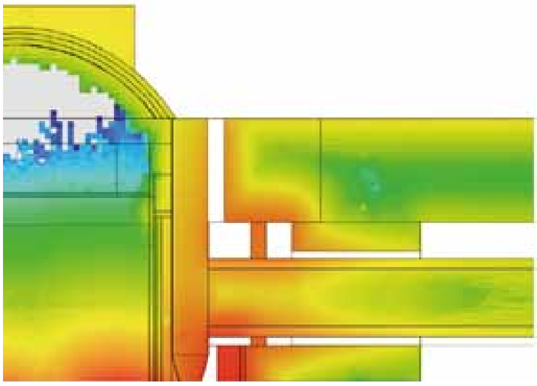
Specifically, in the 3-D activation process the Monte Carlo method is used to simulate the path that a neutron takes – from its generation somewhere in the reactor core to its destruction by nuclear capture. Theoretically it would be possible to simulate the path taken by each individual neutron generated in the reactor. Through the use of sophisticated tools from statistics it is possible to reduce the number of neutrons to be simulated to a manageable level which desktop PCs that are currently commercially available and can cope with within a reasonable time. The results obtained from the Monte Carlo calculation satisfy the accuracy requirements which are usually demanded for such problems.

Past meets with future:

The linking of the reactor's power operation and its decommissioning



New 3-D activation process



Typical power distribution in an operating nuclear power plant: representation of a reactor core with its 193 fuel elements. Red areas generate greater thermal output and more neutrons than the areas marked in blue.

Presentation of the reactor neutron intensity distribution in a cut-out of the 3-D model of the upper reactor pressure vessel and the loop pipe: red = higher neutron intensity and thus higher activity.

which can only be activated to a small degree by neutron bombardment.

As the Biblis site will soon begin with the decommissioning process, the next step on the agenda is sampling measurements of the reactor pressure vessel, the biological shield and other activated components. The comparison of the measurements with the calculation is considered to be the litmus test for the 3-D activation process. We are very curious to see the results and will report these to you!

Neutron intensity distribution in a vertical cut of the 3-D activation model of the Biblis NPP, reactor B: Embedded by the reactor pressure vessel is the reactor core (black). Increased activation (red) dominates near the core. The activation decreases from green to blue. Areas of the reactor cavity floor or below the lid of the RPV floor underneath the head do not show any reactor neutrons (white). Parts of these components can be disposed of cost-effectively as conventional waste, as they have not been activated.