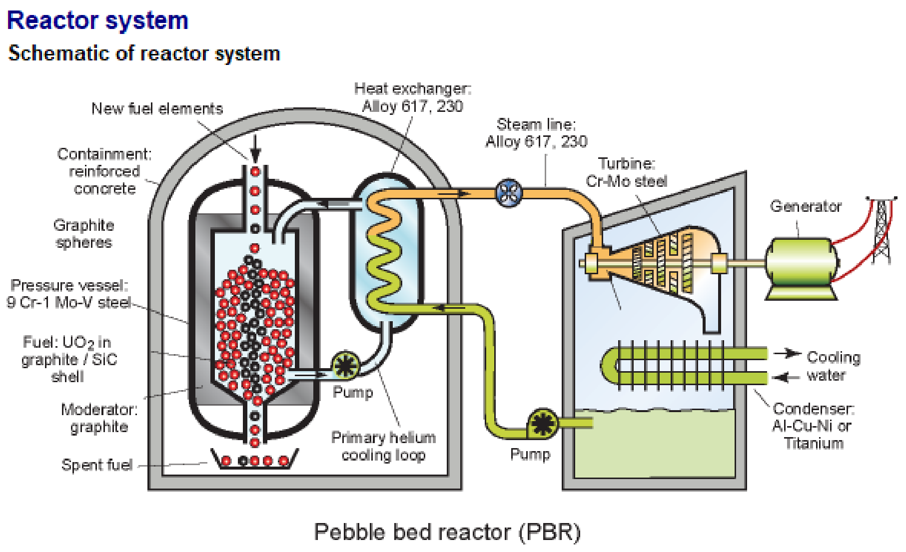
Level 2 Industrial Case Study:
Materials for Nuclear Reactors



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Materials for Nuclear Reactors

Nuclear power remains a real and relevant option for many countries in their search of energy with no fossil greenhouse gas emissions. Given the temperature and radiation characteristics of nuclear processes, materials involved in power generation must meet specific performance needs. These are essential to the efficiency and operational safety of nuclear reactors.

The Pressurized Water Reactor (PWR) is the most common traditional Light-Water reactor. The core of a PWR consists of around 200 fuel assemblies comprised of 264 fuel rods each, containing ceramic fuel pellets, usually made of enriched uranium dioxide (UO_2). The fuel pellets are encased in cladding to avoid excessive reactions and particle debris. This cladding must not interfere with fuel-to-coolant heat transfer, while preventing leakage, containing radioactive fission products, and resisting corrosion. Historically, austenitic stainless steels were used until the 1960s, when zirconium alloys became more widespread due to their lower neutron absorption cross-section.

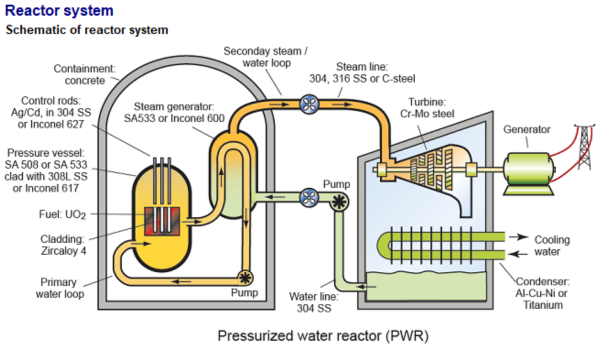

Figure 1: Pressurized water reactor layout

Among the many generations of reactors created since the PWR, one of the most promising Very High Temperature Reactors is the Pebble Bed Reactor (PBR), which has the advantage of allowing the inspection and removal of spent fuel without shutting down the unit.

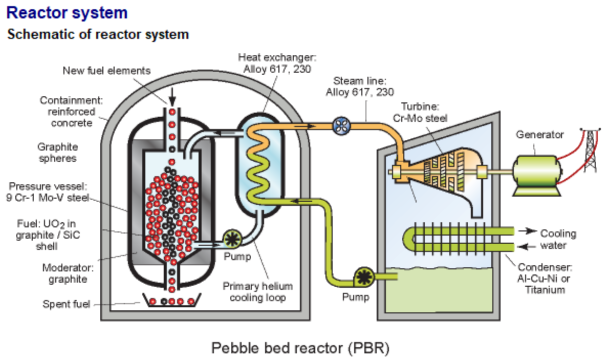

Figure 2: Pebble bed reactor layout

In a PBR, the spheres that encase the fissile material have a 6cm radius, with a 0.5cm graphite outer layer. The inner part of the pebble is composed of a graphite matrix with 10-15 thousand microspheres of tri-structural isotropic particle fuel with 0.9mm in diameter. Each microsphere is made with different material layers, creating a pressure boundary and retention zone around the fissile material. These layers must retain their properties in temperatures above 1500°C. They are usually made of high density and porous pyrolytic carbon as well as silicon carbide.

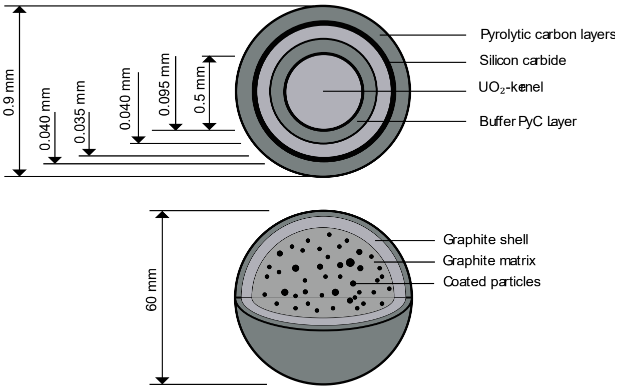

Figure 3: Pebble structure and composition

What is the Problem?

The main failure mechanism for PWRs is known as grid-to-rod fretting, caused by the turbulent flow of cooling fluid. This generates structural vibrations that lead to wear and to the formation of a gap, which can ultimately damage the material and result in the failure of the fuel rod.

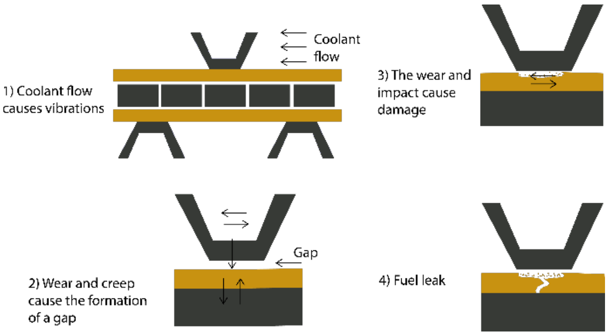

Figure 4: Grid-to-rod fretting mechanism

In PBRs, the fissile reaction temperature and its products generate internal compressive and tensile stresses that may lead to the failure of the silicon carbide barrier. This occurs due to cracks on the porous carbon layer that propagate to the subsequent layers, concentrating stress on the silicon carbide layer.

The critical structural parts of each nuclear fuel are: providing adequate heat transfer, fuel integrity and fuel protection from the coolant (in the case of the PWR), and acting as a pressure vessel while retaining the fissile products (in the PBR). Nuclear reactor materials must, therefore, present very specific properties, such as: hardness; thermal expansion coefficient and conductivity; coolant, fissile material and product durability; creep resistance and yield strength; neutron absorption cross-section; corrosion resistance and resistance to irradiation creep. These requirements are essential to achieve the two main objectives in this application: operation safety and maximum process efficiency.

What can EduPack do?

Achieving the objectives discussed so far requires that the design requirements be translated into adequate performance indices. Process efficiency for both reactors is proportional to the *thermal conductivity* of the fuel enclosure material and its *maximum service temperature,* given the objective of maximum heat transfer. We introduce here a *performance indicator* to reflect those measures in a simplified way.

Regarding operational safety, PWRs and PBRs have different indices. In PWRs, the cladding needs to resist grid-to-rod fretting, which involves *hardness*. Also, in terms of mechanical properties, it must present sufficient *yield strength* and *fracture toughness*. And, in the event of overheating, it must also have a high *melting temperature* — all of which are included in a second performance indicator. The limit and tree stages applied were:

- Low neutron absorption elements (C, Si, Zr and carbides)
- Excellent durability in water
- Low thermal expansion (0-8 microns)
- Melting point > 1850°C

Figure 5 shows the performance indicators for PWRs:

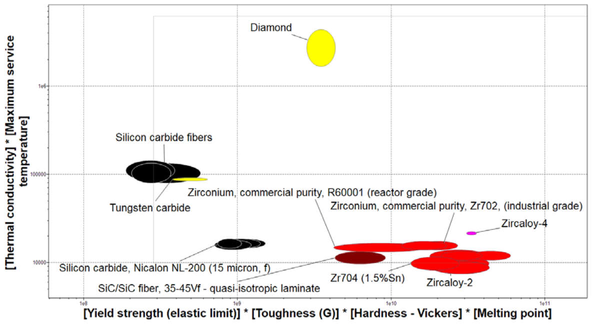

Figure 5: Candidate materials for PWRs

Zirconium alloys, silicon carbide fibers, diamond, tungsten carbide and SiC/SiC composites have the best performance.

In the case of PBRs, since the cladding acts as a sort of small pressure vessel, the following material performance index should be maximized in order to maximize operation safety:

$$M = {K_{IC}}^2/\sigma_y$$

The limit and tree stages applied were:

- Low neutron absorption elements (C, Si, Zr and carbides)
- Thermal shock resistance > 300°C
- Low thermal expansion (0-6 microns)
- Melting point > 2000°C

Most results involve SiC, whether in pure or composite form, as well as zirconium carbide. Diamond also has excellent properties but would not be practical from a processing and cost point of view. Figure 6 shows the relation between the first performance indicator mentioned above and the safety performance index for PBRs.

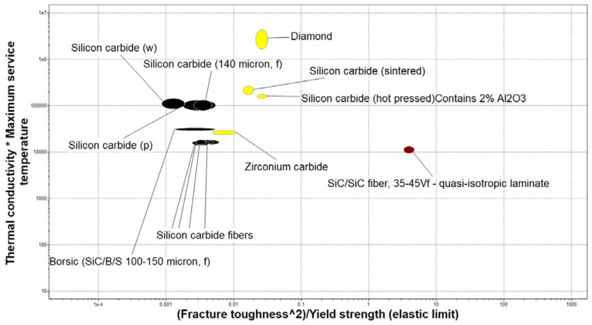

Figure 6: Candidate materials for PBRs

Sustainability Database

The Sustainability Level 3 database has additional data sets that can be used to investigate other aspects of nuclear power generation. The Elements data table provides nuclear properties such as *neutron absorption cross-section*, which can be plotted against *melting temperature* to verify the elements that can withstand the temperature requirements and do not disturb the neutrons in the reactor. Using the *Limit stage*, a 0.5 Barns maximum can be applied to the neutron absorption and a 500°C minimum for the melting temperature, resulting in Figure 7, confirming that carbon, silicon and zirconium are indeed sensible options.

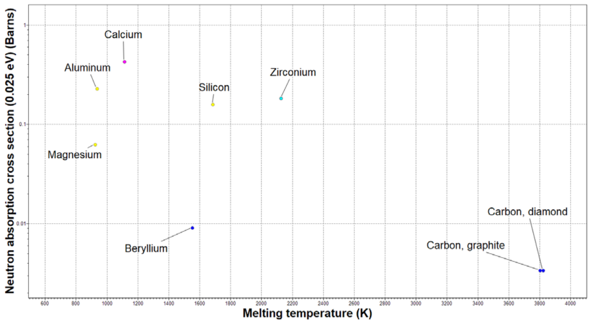

Figure 7: Candidate elements for nuclear applications

There are also other examples of nuclear reactors in the Power System – Nuclear data table, with further descriptions of the reactors and details on their fuel, cladding, coolant, and outlet temperature. In the PWR record, Zircaloy-4 is reassuringly given as the current material in use for its cladding, confirming our previous results.

The Power System – Low carbon data table can be explored to compare different energy plants and discuss their potential impacts and advantages in composing a country's energy mix.

Reality check and conclusions

This case study is derived from Camila Nogueira's work at the University of São Paulo Materials and Metallurgical Engineering Department. It has allowed exploration of nuclear-related materials and properties, as well as the application of material selection methodology to a function and loading not covered by the regular *Performance Index Finder* tool or the embedded *Performance Index Tables*. Given the confidentiality of developments in this field, little information on new materials is available. Even so, we are confident that the results of this case study are coherent with current industrial practices.

Document Information

This case study is part of a set of teaching resources to help introduce students to materials, processes and rational selections.

Accuracy

The author(s) try hard to make sure that these resources are of a high quality. If you have any suggestions for improvements, please contact the author(s) by email. You may also write to the Ansys Granta Education Team with your suggestions at granta-education-team@ansys.com.

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