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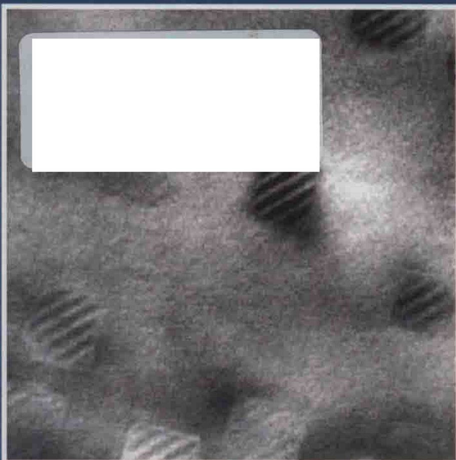

Structural Materials for Generation IV Nuclear Reactors

Edited by Pascal Yvon

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Operating at a high level of fuel efficiency, safety, proliferation resistance, sustainability, and cost, generation IV nuclear reactors promise enhanced features to an energy resource that is already seen as an outstanding source of reliable base load power. The performance and reliability of materials when subjected to the higher neutron doses and extremely corrosive higher-temperature environments that will be found in generation IV nuclear reactors are essential areas of study. Key considerations for the successful development of generation IV reactors are suitable structural materials for both in-core and out-of-core applications. *Structural Materials for Generation IV Nuclear Reactors* explores the current state of the art in these areas.

Part One reviews the materials, requirements, and challenges in generation IV systems. Part Two presents the core materials with chapters on irradiation-resistant austenitic steels, ODS/FM steels, and refractory metals among others. Part Three looks at out-of-core materials.

Structural Materials for Generation IV Nuclear Reactors is an essential reference text for professional scientists, engineers, and postgraduate researchers involved in the development of generation IV nuclear reactors.

Dr. Pascal Yvon is head of the Department of Materials for Nuclear Applications of the Nuclear Energy Division of CEA. He holds a PhD in Applied Physics from the California Institute of Technology (Caltech). After working as a research assistant at the Center for Material Science at the Los Alamos National Laboratory (USA), he worked at the Institute for Advanced Materials in Petten (the Netherlands), before joining CEA in 1996, where he was in charge of studies on the behavior under irradiation of zirconium alloys. Then he held several management positions in the Department of Materials for Nuclear Applications before becoming in 2006 program manager for high-temperature reactors, hydrogen production, and nonelectric applications. Since 2009 he has been the head of the Department of Materials for Nuclear Applications of the Nuclear Energy Division of CEA. Pascal Yvon also teaches at Centrale Supelec and at PHELMA Grenoble.

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Introduction

At a time when energy demands are increasing, concerns are growing about global warming associated with greenhouse gas emissions, the focus is on producing a larger part of carbon-free electricity. While renewable energies are part of the solution, nuclear energy is bound to play a role, as the intermittent renewable energies have to be complemented by a steady source of energy. However, between the worldwide development of light water reactors, and the assumed uranium reserves, fission nuclear energy is not sustainable: even with a once-through recycling of spent fuel and the use of mixed plutonium-uranium fuel, only about 1% of the energetic power of uranium is used. This drives the research for reactors which will make a better use of uranium (and also thorium) resources. Also, fission reactors generate long-life radioactive waste, and even if long-term storage solutions are available, transmutation of the long-life minor actinides in advanced reactor systems could prove an attractive alternative. These reactors need to offer a level of safety at least as good as that of the current generation of reactors and also need to generate electricity at a competitive cost. Finally, attention has to be paid to the development of proliferation resistant technologies.

In the early 2000s an international expert panel selected six families of reactors to meet these expectations. All of these reactors will have higher outlet temperatures than light water reactors in order to increase the power conversion efficiency and some of them can also provide heat at a temperature suitable for cogeneration applications. Three of the six reactors have a fast neutron spectrum, the sodium-cooled fast reactor (SFR), the lead-cooled fast reactor (LFR) and the gas-cooled fast reactor (GFR), and will be able to operate as breeders as well as burners of minor actinides. One system, the very-high-temperature reactor (VHTR), cooled by helium, has a thermal neutron spectrum with a graphite moderator and has the advantage of providing heat at a temperature compatible with hydrogen production processes and other industrial processes. The last two reactors, the supercritical water-cooled reactor (SCWR) and the molten salt-cooled reactor (MSR) can have either a thermal or fast neutron spectrum.

Some precursors of these reactors were built in the past, like, for instance, the SFR and the VHTR, but some of the Generation IV requirements were not met. For others, such as the GFR, the technological feasibility still has to be demonstrated. For all these reactors, there is a need for suitable materials to change from the status of "paper" reactors to become operating reactors. Depending on the concept, the core materials will have to withstand high irradiation doses, up to 200 displacements per atom (dpa): they will have to retain adequate mechanical properties and show dimensional stability under and after irradiation. They will also have to operate at high temperatures, close to 1000°C for the VHTR in normal conditions. In case of accidents, the materials will have to retain adequate properties at even higher temperatures, up to 2000°C for the GFR for instance. As well as higher temperatures and higher irradiation doses, the materials will also have to operate in different environments: liquid metals, helium, molten salts, supercritical water for the coolant, corrosive atmospheres for the energy conversion system such as nitrogen or supercritical carbon dioxide, or sulfuric acid for the sulfur iodine hydrogen production process. Reprocessing also has to be taken into account and cladding materials have to be able to resist corrosion in nitric acid environments. The cost and availability of the materials will also be an important factor to ensure the economic competitiveness of these reactors. Joining techniques will need to be developed as well as innovative techniques for in-service inspections in media such as liquid metals. Another requirement imposed on the materials is the demonstration of a design 60-year lifetime: codes and standards will have to be able to meet this expectation as well as accommodate new materials. Secondly, deconstruction aspects have to be taken into account in the design, and waste treatment has to be optimized.

To meet these requirements, in most cases, new materials have to be designed, as those used today in light water reactors will show their limitations. For some materials, experience has been gained in early experimental reactors or demonstrators such as Phenix or AVR. Industrial materials such as those used in the power conversion systems of fossil plants can be considered for intermediate levels of temperature. Other materials used in the aerospace industry, such as ceramic matrix composites, might be needed for the higher levels of temperature. As for irradiation resistance, new classes of materials such as oxide dispersion-strengthened steels have to be developed. To speed up the design and qualification of these new materials, simulation will play an essential role, whether it be experimental simulation with charged particle irradiation or numerical modeling.

This book will introduce the materials considered for the different structural components of the Generation IV systems, under high doses of irradiation such as fuel cladding, wrapper tubes, internal structures, lower doses such as pressure vessel, or no irradiation such as the power conversion systems. It will deal with the behavior in the different environments encountered, liquid metals, molten salts, supercritical water, and gas, as well as the behavior under mechanical stress and irradiation. Subsequently, the different classes of materials for in-core and out-of-core applications will be discussed.

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