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Review

60th Anniversary of electricity production from light water reactors: Historical review of the contribution of materials science to the safety of the pressure vessel

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ABSTRACT

The first light water nuclear reactor dedicated to electricity production was commissioned in Shippingport, Pennsylvania in the United States in 1957. Sixty years after the event, it is clear that this type of reactor will be a major source of electricity and one of the key solutions to limit climate change in the 21st century. This article pays homage to the teams that contributed to this achievement by their involvement in research and development and their determination to push back the frontiers of knowledge. Via a few examples of scientific or technological milestones, it describes the evolution of ideas, models, and techniques during the last 60 years, and gives the current state-of-the-art in areas related to the safety of the reactor pressure vessel. Among other topics, it focuses on vessel manufacturing, steel fracture mechanics analysis, and understanding of irradiation-induced damage.

Contents

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1. Introduction

The first light water nuclear reactor (LWR) dedicated to electricity production was commissioned in Shippingport, Pennsylvania in the United States in 1957. Sixty years after the event, it is clear that this type of reactor will be a major source of electricity and one of the key solutions to limit climate change during the 21st century. This article pays homage to teams that contributed to this achievement by their involvement in research and development (R&D). It targets materials and nuclear engineers or researchers interested in the historical evolution of ideas and in the current state of the art in areas related to the most important component for LWR safety: the reactor pressure vessel (RPV).

Via a few examples of scientific or technological milestones of the last 60 years, we illustrate what materials science brought to the manufacturing and operation of this component. These examples illustrate the willpower and commitment of teams who tried to open up routes of progress in areas as varied as steel making, fabrication process, mechanics of materials, and understanding of irradiation effects. They also show that the nuclear industry is a sector where technical solutions are systematically backed up by a very deep understanding of the involved phenomena. The article is not a comprehensive review of achievements on RPV (more complete reviews can be found for instance in the following books Refs. [1,2]), but presents a selection of some of the key ones. The authors hope that other articles will take advantage of this 60^{th} anniversary to complement their homage (e.g., on non-destructive evaluation or welding). The next sections successively present a brief history of LWRs, the RPV safety issue, and the authors' selection of examples on what materials science brought to the RPV.

2. The light water reactors of yesterday and of today

LWRs were conceived at Oak Ridge National Laboratory in the US, and the first operational version was developed to power the Nautilus submarine(1), under the leadership of Admiral H. G. Rickover [3]. The first LWR dedicated to electricity production was put into operation on December 2nd, 1957 in Shippingport, Pennsylvania in the US, and supplied 60 MW of electricity to the city of Pittsburgh. It was shut down in 1982. This demonstration reactor was a Pressurized Water Reactor (PWR) developed by Westinghouse Electric Company from a design aimed at the propulsion of aircraft carriers (Fig. 1a).

In parallel, General Electric was developing the Boiling Water Reactor (BWR)-type of LWR. On August 3rd, 1957, a first demonstration BWR with an electrical power of 5 MW was put into operation in Vallecitos, California (Fig. 1b), and was in service until 1963. Due to its small size, this reactor is generally not considered to be the first example of LWR dedicated to electricity production, even though it started operating four months before the Shippingport reactor(2). Shortly after, General Electric came up with the first commercial BWR, with an electric power of 197 MW, which came into operation in 1960 in Morris, Illinois (this reactor is called Dresden).

Many PWRs and BWRs dedicated to electricity production were then constructed across the world by the private sector, in majority by companies from the US (Westinghouse, General Electric, Babcock & Wilcox), Japan (Mitsubishi Heavy Industries, Toshiba, Hitachi), France (Framatome then AREVA), Germany (KWU, Siemens), Korea (KEPCO), Sweden (ABB), and the USSR (Gidropress). A total of 277 PWRs(3) and 80 BWRs are in operation today (out of a total of 438 electricity-generating nuclear reactors) and provide about 11% of the world electricity production. Their electric power output has gradually increased and reaches today 1600 MW with EPR, six units of which are under construction.

For safety, the most important component of LWRs is the pressure vessel (Fig. 2). The integrity of this component must be guaranteed at all times and in any circumstances, in particular to keep control of the nuclear chain reaction. The rise in reactor power output has induced an increase in the size of RPVs. The sizes of those of the Shippingport reactor and EPR are compared in Fig. 3. The transition between these two RPVs was supported by around 50 years of R&D in metallurgy, mechanics of materials, characterization of irradiation effects, and modeling, among others.

3. RPV safety

Pressure vessels of Western type PWRs currently in service (mostly Gen-II reactors) or in construction (e.g., Gen-III reactors) have an inner diameter of about 4–5 m, with a wall thickness in the core region (beltline region) of about 200–250 mm (radius/thickness, $r/t \approx 10$). For a given power, pressure vessels of BWRs are larger than that of PWRs. Typical temperatures of inlet water and pressures in the vessel are about 290 °C and 155 bar for PWRs, and 275 °C and 70 bar for BWRs.

Large efforts have been made to optimize RPV design and define the safety analyses that guarantee the absence of risk of rupture in any nominal or accident conditions. Risks of brittle rupture are the main focus and have to be considered, for instance, during events

[1] The Nautilus came into operation in 1953.

[2] Vallecitos obtained the first license granted in the United States to run a nuclear reactor to produce electricity.

[3] This figure includes PWRs of Western design and PWRs of Soviet design, also known as WWERs (WWER: Water-Water Energetic Reactor).