SAFETY OF BOILING WATER REACTORS

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Keywords: Boiling crisis, Boiling system, Boiling water reactor, Burnout, Cladding failure, Control rod, Critical heat flux, Critical power ratio, Departure from nucleate boiling, Design basis accident, Dryout, Emergency core coolant system, Film boiling, Fission product, Flow regime, Heat transfer regime, Hot channel, Hot spot, Light water reactor, Linear heat generation rate, Loss of coolant accident, Mechanical limit, Minimum critical power ratio, Nuclear power, Nuclear quality, Nuclear reactors, Nuclear safety, Nucleate boiling, Onset of transition boiling, Operation margin, Overheating, Peaking factor, Pressurized water reactor, Safety barrier, Thermal limit, Transition boiling.

Contents

Summary

A brief description of the safety engineered systems and operational procedures of typical commercial nuclear power plants are presented here. Safety design features of light water reactors are also shown. Special attention is given to boiling water reactors. Concepts such as thermal and mechanical limits, power peaking factors, critical power, linear heat generation rate, and their relation to safety of nuclear reactor core design is introduced.

1. Introduction

Because of the high performance operation of current nuclear power plants, high and volatile price of natural gas and oil, and because nuclear energy is the largest energy source without emission of greenhouse gases, nuclear power electricity generation has regained attention from the energy industry. The world nuclear share of electricity generation was about 16% during 2003. The total number of nuclear power plants worldwide generating at least 30 net MWe during this time period was 438. These power plants generated 65,852 net MWe. Compared to 2002, there was a generation increase of 2008 MWe, although there was six nuclear power plants more operating in 2003.

Although the importance of commercial nuclear power is clearly supported by more than 25 nuclear power plants either planned or already under construction (mainly in the Pacific Rim), and safe operation of current nuclear plants is at its highest level of priority, general public opinion still shows clear concerns regarding nuclear reactor safety. In order to provide an understanding of the safety issues during design and operation of commercial nuclear reactors, a short description of the main design and operation parameters related to nuclear reactor safety are presented here.

Before mentioning the technical aspects of nuclear reactor safety, it is important to define *nuclear safety*, and how it is achieved. Nuclear safety is a set of actions taken to protect individuals, society (in general), and the environment against radiation risks. These actions can be divided into three general groups: a) safe normal operation of nuclear facilities; b) prevention of transient events and accidents; and c) mitigation of the consequences of the transient events and accidents that could occur.

For a nuclear power plant, the set of actions related to safe operation imply that normal operation must be performed within specific limits and conditions. Besides normal operation, it also includes maneuvering during reactor startup, power increase and decrease, shutdown, maintenance, test, and reload of nuclear fuel. This group also includes the anticipated operational transients, which are events expected to occur during the life of a nuclear facility. These events must be considered in order to take actions to prevent significant damage to reactor components or to avoid reaching accident conditions.

The prevention of transient events and accident conditions in a nuclear power reactor is accomplished by the use of components, systems and procedures, all related to safety. Accident prevention is the top priority for reactor designers and operators. Operating personnel are required to have strong commitment to the culture of safety. Means of accident prevention include: 1) technical aspects, as emergency systems used to control conditions that could lead to accident scenarios, 2) an *in-depth defense* strategy, which prevents the release of radioactive material by using a series of physical barriers, 3) inspections and tests, which are regularly performed on systems and components to reveal any possible malfunction or degradation, and 4) operator training, which is mainly focused on recognizing conditions leading to accident scenarios, so that the operator response is fast and appropriate.

2. Nuclear Reactor Designs

The main difference between a typical large nuclear power plant and one using fossil fuels is the energy source; the former involves nuclear fission and the latter chemical combustion. The other major components of the power plants are basically the same, as a steam supply system, turbine and condenser, and the electrical generator, as shown in Figure 1. Another major difference between fossil-fueled and nuclear reactor plants is that the latter must have redundant safety systems.

Excluding graphite-moderated light water-cooled nuclear reactors, 423 of the current (2003) operating reactors are cooled either by gas or water. If heavy water is used as coolant, this type of nuclear reactor is referred as to Heavy Water Reactor (HWR), whereas the term Light Water Reactor (LWR) is applied to a nuclear reactor cooled by ordinary water. Two types of LWR exist: Pressurized Water Reactor (PWR) and Boiling Water Reactor (BWR). By 2003, about 81% of all nuclear reactors (those generating at least 30 net MWe) in the world are LWR type and they produced about 87% of the total nuclear power. herein this chapter, the discussion of safety aspects will be focused on LWR nuclear power plants, and more specifically in BWR plants.

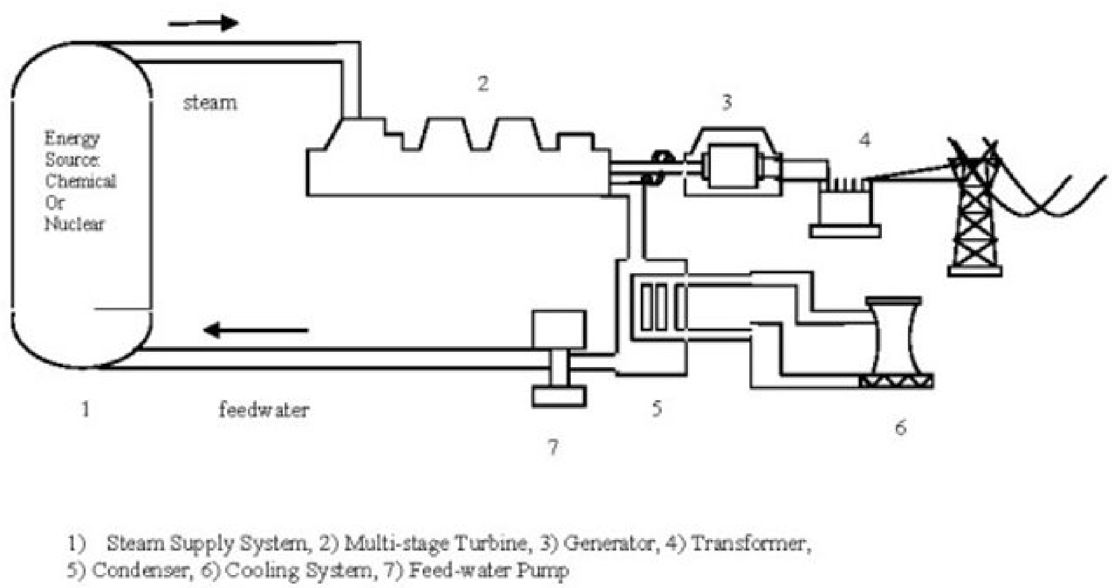

Figure 1: Typical main components of power plants

3. Nuclear Reactor Safety Design

The nuclear aspects of the design of a nuclear reactor core are highly dependent on other areas of design of the power plant, as thermal hydraulics, structural analysis, economic performance, etc. Thus, the overall design of a large commercial nuclear power plant is an enormously complex task that involves coordination among several diverse disciplines. The design is not at all a one-time, static process, but an iterative one, since the design is refined through several steps to identify and satisfy constraints, safety issues, and economic performance.

The major safety concern for a commercial nuclear power plant is to avoid the release to the environment of the large inventory of radioactive fission products accumulated in the nuclear fuel, for any foreseeable accident. To avoid such fission product escape, several safety engineering barriers exist: first, the fuel pellet itself keeps the solid and some of the gaseous fission products in the fuel matrix. Then, the next barrier is the fuel rod cladding, which keeps those fission products accumulated in the fuel rod gap from reaching the core coolant. Figure 2 shows the schematic of a typical BWR fuel element.

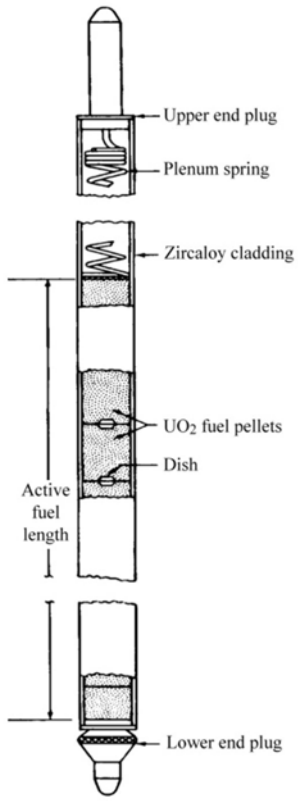

Figure 2: Typical BWR fuel element, which also serves as the first safety barrier.

If some fission products could leak out through the fuel rod cladding into the coolant system, the next barrier is the reactor primary system, that is, the coolant piping system and the pressure vessel. If a catastrophic situation is considered, the pressure vessel could fail, and then the containment structure, that is the reactor building, is the last barrier that the fission products need to leak out through to, finally, reach out to the power plant surrounding environment. Figure 3 shows all the typical safety barriers and their features of a modern BWR design.

The design of the above mentioned safety engineering barriers involves choosing the correct construction materials for each of the barriers, except, clearly, the fuel pellet, since the environment in a nuclear reactor is characterized by very high pressures, large thermal gradients, and an intense nuclear radiation field. Therefore, those materials employed for the safety barriers are required to have *nuclear quality*, since nuclear radiations alter the properties of such materials, besides the demanding thermo-mechanical stresses.

Although the engineered safety barriers are intended to physically contain the fission products, there are additional operational measures and systems designed to take preventive action, in the event of abnormal behavior of the nuclear reactor. Separate safety systems have primarily to keep the reactor core cooled, and fully covered at all times, in case of accident. Even when the reactor is shut down, the remaining decay heat needs to be removed from the core to avoid core meltdown. These safety systems include control rods and an Emergency Core Cooling System (ECCS). The ECCS mainly includes high and low pressure coolant injection systems to keep the core fully covered.

Control rods are not only designed for abnormal or emergency situations but are also an important aspect of fuel management (economics of the nuclear power plant) because they are normally employed to keep the reactor core critical, that is, the total number of neutrons produced by fission reactions throughout the core is, approximately, the same as those neutrons lost by absorption (to produce more fissions) or escape from the core. Control rods, therefore, are needed to compensate the excess reactivity of fresh and low-burnup fuels, so they are used during normal operation to achieve the desired power output and profile. For abnormal situations, control rods are designed to diminish or kill the neutron chain reaction in the core, by absorbing more neutrons than those produced during the fission reactions. In BWR, the control device is not an array of rods, as in PWRs, but a cruciform blade containing stainless steel tubes with the reactivity control material. This is compacted boron carbide powder. There is a cruciform control rod for each of the four fuel assemblies, as it can be seen in figure 4.

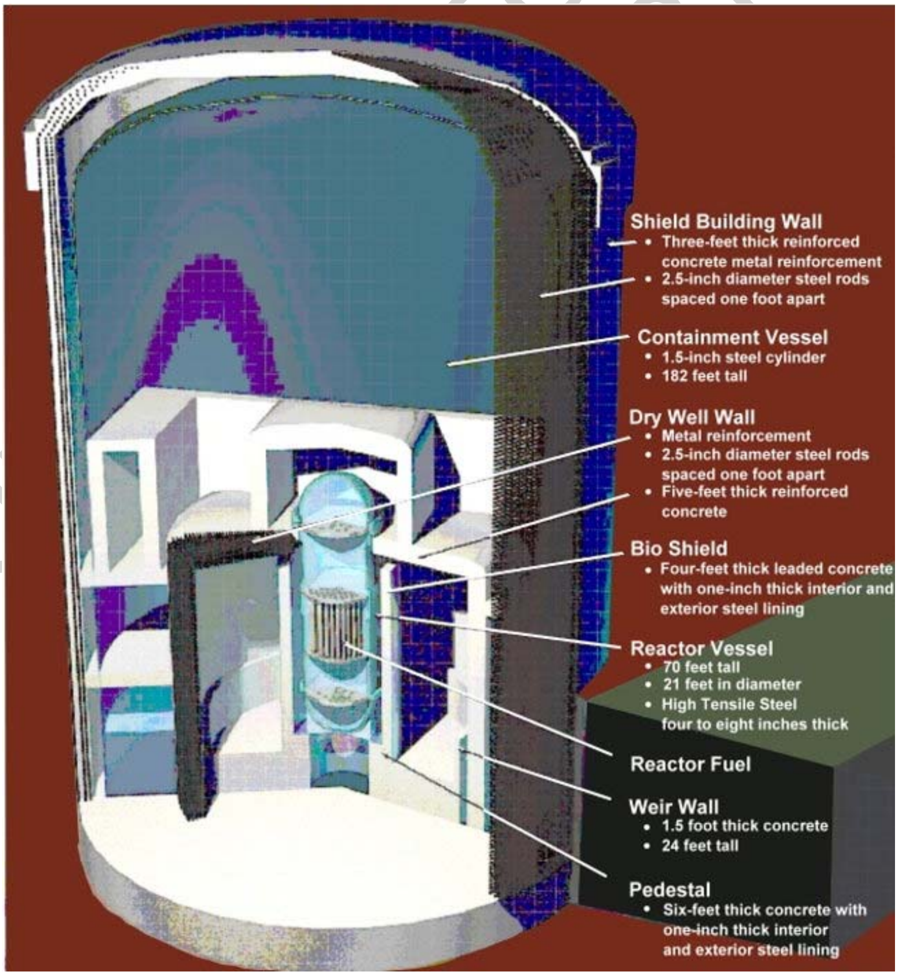

Figure 3: Multiple layers of Safety of a Modern BWR.

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Biographical Sketches

Javier Ortiz-Villafuerte was born in Moroleon, Guanajuato, Mexico on October 11, 1967. He was granted his BSc in Physics and Mathematics in 1992 and his MSc in Nuclear Engineering in 1994 by the National Polytechnic Institute of Mexico. His Ph.D. in Nuclear Engineering was granted by Texas A&M University in 1999. Currently, he works as Researcher at the Department of Nuclear Systems of the National Institute for Nuclear Research of Mexico. He also is an Invited Professor at the Department of Nuclear Engineering of the National Polytechnic Institute, lecturing on Nuclear Reactor Engineering. He is member of the National System of Researchers of Mexico. His main research interests include Nuclear Reactor Safety and Thermalhydraulics, Thermomechanical Analysis of fuel pins, Power Reactor Signal Analysis for early detection of equipment malfunction, Turbulent Multiphase Flow Modeling and Experimentation. His work experience also includes serving as Technical Consultant for the National

Commission of Nuclear Safety and Safeguards of Mexico during 1994, and as Research Associate and later as Assistant Research Engineer at the Department of Nuclear Engineering of Texas A&M University from 2000 to 2002.

Yassin A. Hassan has been at Texas A&M University, College Station, since 1986. He is a professor in the Department of Nuclear Engineering and the Department of Mechanical Engineering. He received his Ph.D. and MS in nuclear engineering from University of Illinois, and MS in mechanical engineering from University of Virginia. Prior to his academic career, he was principal engineer (1980-1986) at Babcock & Wilcox Company's Nuclear Power Division in Virginia. Hassan has authored/co-authored over 100 refereed papers in various journals and several chapters in books. Hassan is a registered professional engineer in Texas and a Fellow of the American Society of Mechanical Engineers (ASME) and the American Nuclear Society (ANS). He is also a member of several other societies, and chair of Nuclear Engineering of ASME. Hassan was the recipient of Arthur Holly Compton Award and Thermal Hydraulics Achievement Award of ANS. He has given invited lectures and short courses in the United States, Italy, Japan, Korea, Netherlands, Belgium and Mexico. He lectured at the recent "Industrial Two-Phase Flow CFD" short course, May 23-2005 at von Karman Institute, Brussels. Hassan's research interest is in the areas of computational and experimental fluid mechanics and turbulence, two-phase flow, laser-based flow visualization and diagnostic imaging techniques, and system modeling.