Book Review

The Thermal-Hydraulics of a Boiling Water Nuclear Reactor. By R. T. Lahey, Jr. and F. J. Moody. American Nuclear Society, La Grange Park, Illinois (1977). 433 pp. $41.95.

As pointed out by the authors, the purpose of this book "is to present an overview of the various important thermal-hydraulic mechanisms in boiling water nuclear reactor (BWR) technology." In writing the book, the authors have presented a wealth of information, including very detailed mathematical descriptions of the various thermal-hydraulic models and mechanisms in use today. There are less detailed chapters on general descriptive material, which are placed in the earlier part of the text and which serve to balance the presentation. The material on evaluation of BWRs and hardware descriptions set the proper framework for the reader to dig into the more complex portions of the book.

In general, the text is well organized and clearly written. It contains an up-to-date discussion of the various analytical tools available to the reactor designer for thermal-hydraulic design and safety analysis. The chapters on boiling heat transfer and two-phase flow, for example, provide sufficient detail to be very useful as text material for a graduate-level course in heat transfer. There are a few example problems in the text, but in most chapters the reader is given the technical base from which he should be able to apply the material. The authors have presented a balanced view of the many analytical models involved in two-phase flow and heat transfer. Recommendations are given where the authors feel that their suggestions are helpful. Engineering uncertainties and special mathematical difficulties encountered (such as convergence in code calculations) are pointed out to the reader.

The book is divided into four parts:

1. a description of BWR systems
2. basic thermal-hydraulic analyses
3. performance of the nuclear steam supply system
4. performance of BWR safety systems.

Chapter 1 lists the evolution of BWRs. The discussions of reactor configurations are limited to General Electric (GE) designs. The authors provide a brief description of Dresden 1, the first commercial BWR plant, and give a listing of the various GE BWR series of products. Some discussion is included of the various design changes and improvements made during the evolution of the BWR plants. Also given is a table listing the 12 "Turnkey" plants built by GE during the period from 1962 to 1966.

Chapter 2 deals with the nuclear parts of a BWR, i.e. the reactor vessel, the recirculating system, main steam lines, control rod drive system, and nuclear fuel and instrumentation. Each of these subject areas is, of course, difficult to summarize in capsule form. The authors at this point, however, do provide a fairly good picture for the reader of the GE nuclear boiler assembly and of how the system is mechanically assembled. Some design features noted include jet pumps for recirculating water, steam dryers, typical fuel assembly, etc. The material is meant to introduce the reader to the mechanical interplay of hardware and to the general manner in which a controlled amount of steam power is generated.

Chapter 3 covers applied thermodynamics with respect to a BWR plant. While space limitations prevent more than a brief summary, the authors show a simple BWR system heat balance and list some of the thermodynamic relationships that are useful in analyzing steam power systems. Some discussion is also provided on the available power loss from both frictional dissipation and heat exchange. The authors point out that the available power at the reactor vessel is typically around 44% of core thermal power and that overall BWR plant efficiencies are near 34%.

Chapter 4 summarizes the latest available information on boiling heat transfer as it is applied to nuclear fuel. An introduction to boiling is given first with discussions of "micro convection." The authors then lead into a discussion of the important physical properties of water relating to the boiling process, such as surface tension, contact angle for wetting, and Gibbs free-energy function. A fairly detailed discussion follows on the nature of two-phase equilibrium, the existence of meta-stable states, and the processes involved in cavity nucleation. This brief discussion of fundamentals is followed by applications to multirod pool boiling and counter-current flow limiting (or flooding) conditions. Flooding criteria are covered in some detail since, as the authors note, global and local void fractions must be known during power transients to analyze the consequences of an accident. Boiling transition [burnout, dryout, critical heat flux (CHF), etc.] is discussed in terms of film dryout as governed by flow rate and entrainment. The interpretation of CHF or "boiling transition" data is covered in some detail. The effect of nonuniform heat flux on CHF as accounted for by various researchers is discussed and compared. Finally, the problem of providing subchannel analysis by the use of large digital computer codes is covered, including some of the mathematical bases involved in these calculations. As a finale, the difficult area of post-boiling-transition convective heat transfer is treated. Thermal nonequilibrium effects are discussed in enough detail to give the reader an appreciation of what can be analyzed. An extensive list of references is provided for the reader.

Chapter 5 deals with the physical and mathematical complexities of two-phase flow. The authors start gently by introducing the concepts of void fraction, phase velocity, volumetric flux and flow fraction, slip ratio, quality, etc., through to densities and drift flux, and then define in detail the relationship of these quantities to each other in the conservation equations of mass, energy, and momentum for both homogeneous and separated flow. This discussion is followed by the development of the relation between voids and quality for the cases of equilibrium bulk boiling and nonequilibrium subcooled boiling. The calculation of two-phase pressure drop including entrance and exit losses is covered by design equations. A comparison of typical correlations is graphically shown for the reader.

Chapter 6 is devoted to the thermal-hydraulic performance of a boiling reactor core. Fuel element heat transfer covers both steady-state and transient conduction analyses with sections handling thermal properties of UO_2 and Zircoloy-2, expressions for gap conductance, and the fundamental numerical equations for generalized heat conduction in cylindrical coordinates. Core hydraulics is touched upon, but not in the same detail as core heat transfer.

Chapter 7 in dealing with stability analysis provides a basis for further study by the reader. The authors discuss various types of flow instability such as Ledinegg instability, flow regime instability, and geysering. Analyses of both Ledinegg instability and density-wave oscillations are provided. The void-reactivity feedback mechanism is discussed, and the results of analysis with a computer code (NUFREO) are demonstrated. Results are shown as Nyquist plots and a typical stability map for a BWR/4 hot channel.

Chapter 8 provides a good summary of postulated abnormal operating conditions, postulated accidents [such as design basis loss-of-coolant accident (LOCA)], and engineering safeguards of BWR reactors. The chapter presents a listing of safety concerns. Chapter 9 covers the details of a few of these concerns. In particular, some analytical techniques dealing with single-operator error or equipment malfunction are discussed, and some analysis is given for the design basis LOCA. While it is noted that nonequilibrium effects in heat transfer were covered earlier in the text, the authors here also include detailed discussions on nonequilibrium effects in critical flow. Considerable space is also devoted to pipe thrust and jet loads (reactive force model for surface loading by jet impingement). Under the topic of core heatup, the authors cover radiation heat transfer between elements, falling film rewetting, and heat generation effects.

In conclusion, it should be noted that the authors have written about a very complex subject and have managed, in this reviewer's opinion, to present an unbiased view of the subject. Some obvious preferences are recognized by the authors, but these are most likely due to the authors' own contributions to science and most likely reflect their own engineering judgment. This reader was left with a general impression that the manuscript is a compilation of current technology, well organized and presented. The book could serve either as a text for a graduate-level course or as a library reference book for reactor designers.

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About the Reviewer: Paul Lottes completed his graduate work at Purdue University in 1950. The early years of his career were spent in the development of thermal-hydraulic analysis techniques for boiling water reactors (BWRs). He was involved in the early Borax experiments as well as the development of the EBWR at Argonne National Laboratory (ANL). He spent several years in liquid-metal fast breeder reactor heat transfer and most recently has been involved in light water reactor safety at ANL. He has taught reactor heat transfer at Kjeller, Norway (1959) and the University of Illinois (1961). Dr. Lottes has been a lecturer at a number of American universities and is a fellow of the American Nuclear Society and the American Society of Mechanical Engineers.