NUCLEAR ELECTRIC POWER

Safety, Operation, and Control Aspects

J. BRIAN KNOWLES

WILEY
Nuclear Electric Power
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J. Brian Knowles

WILEY
To Lesley Martin
A good neighbor to everyone and our dear friend.
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If the industries and lifestyles of economically developed nations are to be preserved, then their aging, high-capacity power stations will soon need replacing. Those industrialized nations with intentions to lower their carbon emissions are proposing nuclear and renewable energy sources to fill the gap. As well as UK nuclear plant proposals, China plans an impressive 40% new-build capacity, with India, Brazil, and South Korea also having construction policies. Even with centuries of coal and shale-gas reserves, the United States has recently granted a construction license for a pressurized water reactor (PWR) near Augusta, Georgia. Nuclear power is again on the global agenda.

Initially renewable sources, especially wind, were greeted with enthusiastic public support because of their perceived potential to decelerate global climate change. Now however, the media and an often vociferous public are challenging the green credentials of all renewables as well as their ability to provide reliable electricity supplies. Experienced engineering assessments are first given herein for the commercial use of geothermal, hydro, solar, tidal and wind power sources in terms of costs per installed MW, capacity factors, hectares per installed MW and their other environmental impacts. These factors, and a frequent lack of compatibility with national power demands, militate against these power sources making reliable major contributions in some well-developed economies. Though recent global discoveries of significant shale and conventional gas deposits suggest prolonging the UK investment in reliable and high thermal efficiency combined cycle gas turbine (CCGT) plants, ratified emission targets would be contravened and there are also political uncertainties. Accordingly, a nuclear component is argued as necessary in the UK Grid system. Reactor physics, reliability and civil engineering costs reveal that water reactors are the most cost-effective. By virtue of higher linear fuel ratings and the emergency cooling option provided by separate steam generators, PWRs are globally more widely favored.
Power station and grid operations require the control of a number of system variables, but this cannot be engineered directly from their full nonlinear dynamics. A linearization technique is briefly described and then applied to successfully establish the stability of reactor power, steam drum-water level, flow in boiling reactor channels and of a Grid network as a whole. The reduction of these multivariable problems to single input-single output (SISO) analyses illustrates the importance of specific engineering insight, which is further confirmed by the subsequently presented nonlinear control strategy for a station blackout accident.

Public apprehensions over nuclear power arise from a perceived concomitant production of weapons material, the long-term storage of waste and its operational safety. Reactor physics and economics are shown herein to completely separate the activities of nuclear power and weapons. Because fission products from a natural fission reactor some 1800 million years ago are still incarcerated in local igneous rock strata, the additional barriers now proposed appear more than sufficient for safe and secure long-term storage. Spokespersons for various non-nuclear organizations frequently seek to reassure us with “Lessons have been learned”: yet the same misadventures still reoccur. Readers find here that the global nuclear industry has indeed learned and reacted constructively to the Three Mile Island and Chernobyl incidents with the provision of safety enhancements and operational legislation. With regard to legislation, the number of cancers induced by highly unlikely releases of fission products over a nuclear plant’s lifetime must be demonstrably less than the natural incidence by orders of magnitude. Also the most exposed person must not be exposed to an unreasonable radiological hazard. Furthermore, a prerequisite for operation is a hierarchical management structure based on professional expertise, plant experience and mandatory simulator training. Finally, a well-conceived local evacuation plan must pre-exist and the aggregate probability of all fuel-melting incidents must be typically less than 1 in 10 million operating years.

Faulty plant siting is argued as the reason for fuel melting at Fukushima and not the nuclear technology itself. If these reactors like others had been built on the sheltered West Coast, their emergency power supplies would not have been swamped by the tsunami and safe neutronic shut-downs after the Richter-scale 9 quake would have been sustained.
To quantify the expectation of thyroid cancers from fission product releases, international research following TMI-2 switched from intact plant performance to the phenomenology and consequences of fuel melting (i.e., Severe Accidents) after the unlikely failure of the multiple emergency core cooling systems. This book examines in detail the physics, likelihood and plant consequences of thermally driven explosive interactions between molten core debris and reactor coolant (MFCIs). Because such events or disintegrating plant items, or an aircraft crash are potential threats to a reactor vessel and its containment building, the described "replica scale" experiments and finite element calculations were undertaken at Winfrith. Finally, the operation and simulation of containment sprays in preventing an over-pressurization are outlined in relation to the TOSQAN experiments.

This book has been written with two objectives in mind. The first is to show that the safety of nuclear power plants has been thoroughly researched, so that the computed numbers of induced cancers from plant operations are indeed orders of magnitude less than the natural statistical incidence, and still far less than deaths from road traffic accidents or tobacco smoking. With secure waste storage also assured, voiced opposition to nuclear power on health grounds appears irrational. After 1993 the manpower in the UK nuclear industry contracted markedly leaving a younger minority to focus on decommissioning and waste classification. The presented information with other material was then placed in the United Kingdom Atomic Energy Authority (UKAEA) archives so it is now difficult to access. Accordingly this compilation under one cover is the second objective. Its value as part of a comprehensive series of texts remains as strong as when originally conceived by the UKAEA. Specifically, an appreciation helps foster a productive interface between diversely educated new entrants and their experienced in situ industrial colleagues.

Though the author contributed to the original research work herein, it was only as a member of various international teams. This friendly collaboration with UKAEA, French, German and Russian colleagues greatly enriched his life with humor and scientific understanding. Gratitude is also extended to the Nuclear Decommissioning Authority of the United Kingdom for their permission to reproduce, within this book alone, copyrighted UKAEA research material. In addition thanks are due to Alan Neilson, Paula Miller, and Professor Derek Wilson, who have particularly helped to “hatch” this book. Finally, please note that
the opinions expressed are the author’s own which might not concur with those of the now-disbanded UKAEA or its successors in title.

BRIAN KNOWLES

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## Glossary

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>AEC</td>
<td>Atomic Energy Commission (US)</td>
</tr>
<tr>
<td>AEEW</td>
<td>Atomic Energy Establishment Winfrith</td>
</tr>
<tr>
<td>AERE</td>
<td>Atomic Energy Research Establishment (Harwell)</td>
</tr>
<tr>
<td>AGR</td>
<td>Advanced Gas Cooled Reactor</td>
</tr>
<tr>
<td>ALARP</td>
<td>As Low as Reasonably Practicable</td>
</tr>
<tr>
<td>ANL</td>
<td>Argonne National Laboratory (US)</td>
</tr>
<tr>
<td>ASME</td>
<td>American Society of Mechanical Engineers</td>
</tr>
<tr>
<td>AWRE</td>
<td>Atomic Weapons Research Establishment (Aldermaston)</td>
</tr>
<tr>
<td>BNES</td>
<td>British Nuclear Energy Society</td>
</tr>
<tr>
<td>BRL</td>
<td>Ballistics Research Laboratory (US)</td>
</tr>
<tr>
<td>BWR</td>
<td>Boiling Water Reactor</td>
</tr>
<tr>
<td>CEGB</td>
<td>Central Electricity Generating Board (now disbanded)</td>
</tr>
<tr>
<td>CEN</td>
<td>Centre d’Etude Nucléaires (Grenoble)</td>
</tr>
<tr>
<td>CFR (EFR)</td>
<td>Proposed Commercial (European) Fast Reactor</td>
</tr>
<tr>
<td>Corium</td>
<td>A mixture of fuel, clad and steelwork formed after core-melting in a Severe Accident</td>
</tr>
<tr>
<td>DBA</td>
<td>Design Base Accident(s)</td>
</tr>
<tr>
<td>EC</td>
<td>European Commission</td>
</tr>
<tr>
<td>ECCS</td>
<td>Emergency Core-Cooling Systems</td>
</tr>
<tr>
<td>EWEF</td>
<td>Each Way-Each Face (for steel reinforcement of concrete)</td>
</tr>
<tr>
<td>HCDA</td>
<td>Hypothetical Core Disruptive Accident (↔ Severe Accident)</td>
</tr>
<tr>
<td>HMSO</td>
<td>Her Majesty’s Stationary Office (London)</td>
</tr>
<tr>
<td>IAEA</td>
<td>International Atomic Energy Agency</td>
</tr>
<tr>
<td>IEE</td>
<td>Institute of Electrical Engineers (now IET)</td>
</tr>
<tr>
<td>IEEE</td>
<td>Institute of Electrical and Electronic Engineers (US)</td>
</tr>
<tr>
<td>JRC</td>
<td>(European) Joint Research Centre (Ispra)</td>
</tr>
<tr>
<td>KfA</td>
<td>Kernforschungsanlage (Jülich)</td>
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