



The 2011 Fukushima Nuclear Power Plant Accident

How and Why it Happened

Yotaro Hatamura, Seiji Abe, Masao Fuchigami and
Naoto Kasahara

Translated by Kenji Iino

Woodhead Publishing Series in Energy:
Number 73

The 2011 Fukushima Nuclear Power Plant Accident

How and Why it Happened

*Yotaro Hatamura, Seiji Abe, Masao
Fuchigami and Naoto Kasahara*

Translated by Kenji Iino



AMSTERDAM • BOSTON • CAMBRIDGE • HEIDELBERG
LONDON • NEW YORK • OXFORD • PARIS • SAN DIEGO
SAN FRANCISCO • SINGAPORE • SYDNEY • TOKYO

Woodhead Publishing is an imprint of Elsevier



Woodhead Publishing is an imprint of Elsevier
80 High Street, Sawston, Cambridge, CB22 3HJ, UK
225 Wyman Street, Waltham, MA 02451, USA
Langford Lane, Kidlington, OX5 1GB, UK

Copyright © 2015 Elsevier Ltd. All rights reserved.

No part of this publication may be reproduced, stored in a retrieval system or transmitted in any form or by any means electronic, mechanical, photocopying, recording or otherwise without the prior written permission of the publisher.

Permissions may be sought directly from Elsevier's Science & Technology Rights Department in Oxford, UK: phone (+44) (0) 1865 843830; fax (+44) (0) 1865 853333; email: permissions@elsevier.com. Alternatively, you can submit your request online by visiting the Elsevier website at <http://elsevier.com/locate/permissions>, and selecting Obtaining permission to use Elsevier material.

Notice

No responsibility is assumed by the publisher for any injury and/or damage to persons or property as a matter of products liability, negligence or otherwise, or from any use or operation of any methods, products, instructions or ideas contained in the material herein. Because of rapid advances in the medical sciences, in particular, independent verification of diagnoses and drug dosages should be made.

British Library Cataloguing-in-Publication Data

A catalogue record for this book is available from the British Library

Library of Congress Control Number: 2014952343

ISBN 978-0-08-100118-9 (print)

ISBN 978-0-08-100132-5 (online)

For information on all Woodhead Publishing publications visit our website at <http://store.elsevier.com>

Typeset by SPi Global

www.spi-global.com

Printed and bound in the United Kingdom



Working together
to grow libraries in
developing countries

www.elsevier.com • www.bookaid.org

The 2011 Fukushima Nuclear Power Plant Accident

Related titles

Fukushima Accident: Radioactivity Impact on the Environment
(ISBN 978-0-12408-132-1)

Radioactive waste management and contaminated site clean-up: Processes, technologies and international experience
(ISBN 978-0-85709-435-3)

Handbook of small modular nuclear reactors
(ISBN 978-0-85709-851-1)

Managing nuclear projects: A comprehensive management resource
(ISBN 978-0-85709-591-6)

List of authors

S. Abe Kansai University, Osaka, Japan

M. Fuchigami Komatsu Ltd, Tokyo, Japan

Y. Hatamura Hatamura Institute for the Advancement of Technology, Tokyo, Japan

N. Kasahara The University of Tokyo, Tokyo, Japan

Woodhead Publishing Series in Energy

- 1 **Generating power at high efficiency: Combined cycle technology for sustainable energy production**
Eric Jeffs
- 2 **Advanced separation techniques for nuclear fuel reprocessing and radioactive waste treatment**
Edited by Kenneth L. Nash and Gregg J. Lumetta
- 3 **Bioalcohol production: Biochemical conversion of lignocellulosic biomass**
Edited by Keith W. Waldron
- 4 **Understanding and mitigating ageing in nuclear power plants: Materials and operational aspects of plant life management (PLiM)**
Edited by Philip G. Tipping
- 5 **Advanced power plant materials, design and technology**
Edited by Dermot Roddy
- 6 **Stand-alone and hybrid wind energy systems: Technology, energy storage and applications**
Edited by John K. Kaldellis
- 7 **Biodiesel science and technology: From soil to oil**
Jan C. J. Bart, Natale Palmeri and Stefano Cavallaro
- 8 **Developments and innovation in carbon dioxide (CO₂) capture and storage technology Volume 1: Carbon dioxide (CO₂) capture, transport and industrial applications**
Edited by M. Mercedes Maroto-Valer
- 9 **Geological repository systems for safe disposal of spent nuclear fuels and radioactive waste**
Edited by Joonhong Ahn and Michael J. Apted
- 10 **Wind energy systems: Optimising design and construction for safe and reliable operation**
Edited by John D. Sørensen and Jens N. Sørensen
- 11 **Solid oxide fuel cell technology: Principles, performance and operations**
Kevin Huang and John Bannister Goodenough
- 12 **Handbook of advanced radioactive waste conditioning technologies**
Edited by Michael I. Ojovan
- 13 **Membranes for clean and renewable power applications**
Edited by Annarosa Gugliuzza and Angelo Basile
- 14 **Materials for energy efficiency and thermal comfort in buildings**
Edited by Matthew R. Hall
- 15 **Handbook of biofuels production: Processes and technologies**
Edited by Rafael Luque, Juan Campelo and James Clark

- 16 **Developments and innovation in carbon dioxide (CO₂) capture and storage technology Volume 2: Carbon dioxide (CO₂) storage and utilisation**
Edited by M. Mercedes Maroto-Valer
- 17 **Oxy-fuel combustion for power generation and carbon dioxide (CO₂) capture**
Edited by Ligang Zheng
- 18 **Small and micro combined heat and power (CHP) systems: Advanced design, performance, materials and applications**
Edited by Robert Beith
- 19 **Advances in clean hydrocarbon fuel processing: Science and technology**
Edited by M. Rashid Khan
- 20 **Modern gas turbine systems: High efficiency, low emission, fuel flexible power generation**
Edited by Peter Jansohn
- 21 **Concentrating solar power technology: Principles, developments and applications**
Edited by Keith Lovegrove and Wes Stein
- 22 **Nuclear corrosion science and engineering**
Edited by Damien Féron
- 23 **Power plant life management and performance improvement**
Edited by John E. Oakey
- 24 **Electrical drives for direct drive renewable energy systems**
Edited by Markus Mueller and Henk Polinder
- 25 **Advanced membrane science and technology for sustainable energy and environmental applications**
Edited by Angelo Basile and Suzana Pereira Nunes
- 26 **Irradiation embrittlement of reactor pressure vessels (RPVs) in nuclear power plants**
Edited by Naoki Soneda
- 27 **High temperature superconductors (HTS) for energy applications**
Edited by Ziad Melhem
- 28 **Infrastructure and methodologies for the justification of nuclear power programmes**
Edited by Agustín Alonso
- 29 **Waste to energy conversion technology**
Edited by Naomi B. Klinghoffer and Marco J. Castaldi
- 30 **Polymer electrolyte membrane and direct methanol fuel cell technology Volume 1: Fundamentals and performance of low temperature fuel cells**
Edited by Christoph Hartnig and Christina Roth
- 31 **Polymer electrolyte membrane and direct methanol fuel cell technology Volume 2: In situ characterization techniques for low temperature fuel cells**
Edited by Christoph Hartnig and Christina Roth
- 32 **Combined cycle systems for near-zero emission power generation**
Edited by Ashok D. Rao
- 33 **Modern earth buildings: Materials, engineering, construction and applications**
Edited by Matthew R. Hall, Rick Lindsay and Meror Krayenhoff
- 34 **Metropolitan sustainability: Understanding and improving the urban environment**
Edited by Frank Zeman
- 35 **Functional materials for sustainable energy applications**
Edited by John A. Kilner, Stephen J. Skinner, Stuart J. C. Irvine and Peter P. Edwards
- 36 **Nuclear decommissioning: Planning, execution and international experience**
Edited by Michele Laraia

- 37 **Nuclear fuel cycle science and engineering**
Edited by Ian Crossland
- 38 **Electricity transmission, distribution and storage systems**
Edited by Ziad Melhem
- 39 **Advances in biodiesel production: Processes and technologies**
Edited by Rafael Luque and Juan A. Melero
- 40 **Biomass combustion science, technology and engineering**
Edited by Lasse Rosendahl
- 41 **Ultra-supercritical coal power plants: Materials, technologies and optimisation**
Edited by Dongke Zhang
- 42 **Radionuclide behaviour in the natural environment: Science, implications and lessons for the nuclear industry**
Edited by Christophe Poinssot and Horst Geckeis
- 43 **Calcium and chemical looping technology for power generation and carbon dioxide (CO₂) capture: Solid oxygen- and CO₂-carriers**
Paul Fennell and E. J. Anthony
- 44 **Materials' ageing and degradation in light water reactors: Mechanisms, and management**
Edited by K. L. Murty
- 45 **Structural alloys for power plants: Operational challenges and high-temperature materials**
Edited by Amir Shirzadi and Susan Jackson
- 46 **Biolubricants: Science and technology**
Jan C. J. Bart, Emanuele Gucciardi and Stefano Cavallaro
- 47 **Advances in wind turbine blade design and materials**
Edited by Povl Brøndsted and Rogier P. L. Nijssen
- 48 **Radioactive waste management and contaminated site clean-up: Processes, technologies and international experience**
Edited by William E. Lee, Michael I. Ojovan, Carol M. Jantzen
- 49 **Probabilistic safety assessment for optimum nuclear power plant life management (PLiM): Theory and application of reliability analysis methods for major power plant components**
Gennadij V. Arkadov, Alexander F. Getman and Andrei N. Rodionov
- 50 **The coal handbook: Towards cleaner production Volume 1: Coal production**
Edited by Dave Osborne
- 51 **The coal handbook: Towards cleaner production Volume 2: Coal utilisation**
Edited by Dave Osborne
- 52 **The biogas handbook: Science, production and applications**
Edited by Arthur Wellinger, Jerry Murphy and David Baxter
- 53 **Advances in biorefineries: Biomass and waste supply chain exploitation**
Edited by Keith Waldron
- 54 **Geological storage of carbon dioxide (CO₂): Geoscience, technologies, environmental aspects and legal frameworks**
Edited by Jon Gluyas and Simon Mathias
- 55 **Handbook of membrane reactors Volume 1: Fundamental materials science, design and optimisation**
Edited by Angelo Basile
- 56 **Handbook of membrane reactors Volume 2: Reactor types and industrial applications**
Edited by Angelo Basile

-
- 57 **Alternative fuels and advanced vehicle technologies for improved environmental performance: Towards zero carbon transportation**
Edited by Richard Folkson
- 58 **Handbook of microalgal bioprocess engineering**
Christopher Lan and Bei Wang
- 59 **Fluidized bed technologies for near-zero emission combustion and gasification**
Edited by Fabrizio Scala
- 60 **Managing nuclear projects: A comprehensive management resource**
Edited by Jas Devgun
- 61 **Handbook of Process Integration (PI): Minimisation of energy and water use, waste and emissions**
Edited by Jiří J. Klemes
- 62 **Coal power plant materials and life assessment**
Edited by Ahmed Shibli
- 63 **Advances in hydrogen production, storage and distribution**
Edited by Ahmed Basile and Adolfo Iulianelli
- 64 **Handbook of small modular nuclear reactors**
Edited by Mario D. Carelli and Dan T. Ingersoll
- 65 **Superconductors in the power grid: Materials and applications**
Edited by Christopher Rey
- 66 **Advances in thermal energy storage systems: Methods and applications**
Edited by Luisa F. Cabeza
- 67 **Advances in batteries for medium and large-scale energy storage**
Edited by Chris Menictas, Maria Skyllas-Kazacos and Lim Tuti Mariana
- 68 **Palladium membrane technology for hydrogen production, carbon capture and other applications**
Edited by Aggelos Doukelis, Kyriakos Panopoulos, Antonios Koumanakos and Emmanouil Kakaras
- 69 **Gasification for synthetic fuel production: Fundamentals, processes and applications**
Edited by Rafael Luque and James G. Speight
- 70 **Renewable heating and cooling: Technologies and applications**
Edited by Gerhard Stryi-Hipp
- 71 **Environmental remediation and restoration of contaminated nuclear and NORM sites**
Edited by Leo van Velzen
- 72 **Eco-friendly innovation in electricity networks**
Edited by Jean-Luc Bessede
- 73 **The 2011 Fukushima nuclear power plant accident: How and why it happened**
Yotaro Hatamura, Seiji Abe, Masao Fuchigami and Naoto Kasahara. Translated by Kenji Iino

Introduction

On March 11, 2011, The Great East Japan Earthquake occurred, and the tsunami waves it induced triggered an unprecedented accident at the Tokyo Electric Power Company (TEPCO)-owned Fukushima-1 (Daiichi) Nuclear Power Plant (NPP). Three and a half years have already passed since then. Great efforts by those involved with recovery have placed the reactors in cold shutdown; however, the problems of contaminated water, over 130,000 evacuees (160,000 immediately after the accident) still kept out of their homes, and decontamination still continue.

On May 24, 2011, the Cabinet Council decided to establish the Investigation Committee on the Accident at the Fukushima Nuclear Power Stations. Its assignment was, for Fukushima-1 and Fukushima-2, to “conduct multi-faceted research and verification to identify the cause from a neutral standpoint of the people of Japan and propose policies to stop the damages from escalating and prevent similar accidents from repeating [1].” Naoto Kan, the Prime Minister at the time, appointed one of the authors of this book, Yotaro Hatamura, to chair the committee. Seiji Abe and Masao Fuchigami were appointed by Hatamura to serve as technical consultants to the committee.

After its first meeting on June 7, 2011, the committee visited the sites of Fukushima-1 and -2 NPPs for inspection and interviewed a total of 772 people: the Prime Minister and others from the central government, heads of affected local governments, residents and evacuees of the area, and others. The committee published its Interim Report on December 26, 2011 [1], and the Final Report on July 23, 2012 [2]. After a public presentation in Fukushima prefecture, the Cabinet Council dissolved the committee.

The Interim and Final Reports (English versions available from www.cas.go.jp/jp/seisaku/icanps/eng/) are precise records of the investigation into the facts of the accident. The two-volume reports amount to about 1,500 pages of text and figures and are about 8 cm thick. It will be extremely difficult for the general public to read through the pages to understand what the investigation clarified. The facts in the reports are like potatoes and radishes dug from the ground and piled at the storefront of a grocery store. Potatoes and radishes need to be cooked to taste good. In addition, we will not enjoy their flavors unless we consume them. We cannot understand this situation if we are just given the raw material, and unless we can understand the facts, we will never learn anything from this accident, which caused great sacrifices.

In June of 2011, when the committee started, I made an announcement that, as the chair of the committee, my policy was to explain what happened in the course of the Fukushima NPP accident, and why it happened, so everyone could acquire that information as knowledge. In other words, I set the goal to answer the questions of the people of Japan and of the world. The committee, however, primarily due to time

constraints and limitations of a temporary organization, could not fully meet that goal to my expectations. I felt that leaving the work as such would not be fulfilling the roles I had assigned to myself at the beginning of the project.

Thus, the authors gathered to make available this book, which plainly explains what we can learn from this catastrophic accident based on what the committee published, in addition to the authors' opinions, which were not in the government reports. The book is targeted toward members of the general public who may not have knowledge in nuclear power generation or radiology.

Before publishing this book, in December of 2012 Hatamura and Fuchigami published a book titled *What Happened in Fukushima Nuclear Power Plant?: Breakdown of the Government Investigation Committee Report* (in Japanese, coauthored with Naoto Kasahara, Nikkan Kogyo Shimbun Ltd) [3]. Then in April 2013, Hatamura and Fuchigami joined with Seiji Abe to publish *Why Did the Fukushima Nuclear Power Plant Accident Happen?: Breaking Down the Core of the Government Investigation Committee* (in Japanese, Kodansha) [4].

These two books written in Japanese have not been translated into English. The authors felt an obligation to make the knowledge and lessons learned through their investigation available to those worldwide who are interested in the Fukushima NPP accident.

Hatamura, Fuchigami, and Abe, who served as members and technical consultants in the government investigation team, with Kasahara, an expert in nuclear engineering, gathered to edit this English version. This book extracts important contents from the two aforementioned Japanese books, rearranges the significant information coherently, reworks the text into plainer language, and with additional analyses, further clarifies the overall picture of the Fukushima NPP accident. Kenji Iino, a former GE Nuclear engineer, translated our Japanese manuscripts.

The book begins with Chapter 1, which outlines the accident and the operation of the nuclear power industry, including how the government and TEPCO prepared for nuclear safety and disaster prevention. Chapter 2 explains the accident progress inside the plant; Chapter 3 shows where and how the central and local governments made mistakes; and, Chapter 4 outlines problems with TEPCO's response. Chapter 5 discusses the events outside the plant, including how radiation was released and how people evacuated the area. The chapter also discusses how to tackle the problem of decontamination. Chapter 6 reviews the accident from the viewpoint of the "Study of Failure" and reveals my opinions after serving as the committee chair, and finally, Chapter 7 concludes with suggestions on how we should approach (or depart from) nuclear power.

Chapters 1, 3, and 4 were primarily written by Abe; Chapter 2 was written by Fuchigami and Kasahara; and Chapters 5–7 were mainly produced by Hatamura. Position titles and affiliations of people mentioned in the book are all from the time of the accident.

It is the authors' hope that this book will serve to provide the information, clarified as of today, of what happened in Fukushima NPP and how the events progressed. It is intended for those who desire to learn the background and causes of the accident so the information can offer a foundation for those who are at the turning point of whether to

push for nuclear power generation or to abandon it. We also hope that the book will provide the lessons we learned from the Fukushima NPP accident to those that are working to reduce accidents and disasters anywhere in the world. It will be our great pleasure if this book can reduce at least some of the anxiety in those who are still not allowed into their homes.

*August, 2014
Representing the authors,
Yotaro Hatamura*

References

- [1] Investigation committee on the accident at the Fukushima Nuclear Power Stations of Tokyo Electric Power Company, Interim report. <http://www.cas.go.jp/jp/seisaku/icanps/eng/interim-report.html>, 2011 (accessed 20.08.13).
- [2] Investigation committee on the accident at the Fukushima Nuclear Power Stations of Tokyo Electric Power Company, Final report. <http://www.cas.go.jp/jp/seisaku/icanps/eng/final-report.html>, 2012 (accessed 20.08.13).
- [3] What Happened in Fukushima Nuclear Power Plant?: Breakdown of the Government Investigation Committee Report (in Japanese), M. Fuchigami, N. Kasahara, Y. Hatamura, and Nikkan Kogyo Shimbun Ltd., December, 2012.
- [4] Why did the Fukushima Nuclear Power Plant Accident Happen?: Breaking Down the Core of the Government Investigation Committee (in Japanese), Y. Hatamura, S. Abe, M. Fuchigami, and Kodansha, April, 2013.

Contents

List of authors	ix
Woodhead Publishing Series in Energy	xi
Introduction	xv
1 The Fukushima-1 nuclear power plant accident	1
<i>S. Abe</i>	
1.1 Introduction	1
1.2 Energy production in Japan	1
1.3 The Fukushima-1 nuclear power plant	5
1.4 The Tohoku Area Pacific Offshore Earthquake and tsunami	9
1.5 Nuclear power safety and disaster prevention systems in Japan	12
1.6 Conclusions	19
References	19
2 The Fukushima nuclear power plant accident: the main sequence of events	21
<i>M. Fuchigami, N. Kasahara</i>	
2.1 Introduction	21
2.2 Outline of primary facilities at the Fukushima plant	21
2.3 The sequence of events from earthquake and tsunami to station blackout (SBO)	27
2.4 Possible damage caused by the earthquake	32
2.5 The condition of Unit 1 after SBO	36
2.6 The condition of Unit 3 after SBO	54
2.7 The condition of Unit 2 after SBO	65
2.8 Sequence of events leading to hydrogen explosions in Units 1, 3, and 4	75
2.9 The process of water injection into the spent fuel pools	80
2.10 How the accident might have been avoided	83
2.11 Background to nuclear power generation	87
2.12 Conclusions	95
References	95
3 The response of central and local government agencies to the Fukushima nuclear power plant accident	97
<i>S. Abe</i>	
3.1 Introduction	97
3.2 Central government: key responsibilities and preparatory measures	98

3.3	The response and preparedness of the central government	105
3.4	Local government: key responsibilities	110
3.5	Conclusions: key lessons and improvements needed	113
	References	114
	Appendix: Government offices and organizations	115
4	The response of the plant owner/operator (TEPCO) to the Fukushima nuclear power plant accident	119
	<i>S. Abe</i>	
4.1	Introduction	119
4.2	Accident management by Fukushima's nuclear plant owner and operator, TEPCO	119
4.3	TEPCO's risk assessment and safety planning documentation at the Fukushima plant	122
4.4	Assessing the postaccident responses of TEPCO	124
4.5	Why procedures were inadequate: organizational problems within TEPCO	129
4.6	Conclusions	133
	References	134
5	Evacuation and decontamination in response to the Fukushima nuclear power plant accident	135
	<i>Y. Hatamura</i>	
5.1	Introduction	135
5.2	Evacuation of local residents	136
5.3	Predicting and monitoring the leak of radioactive material after the Fukushima accident	138
5.4	The impact of nuclear radiation on the human body	141
5.5	Assessing the evacuation process in response to the Fukushima nuclear power plant accident	147
5.6	Radioactivity, radioactive material, and radiation	150
5.7	Benefits and challenges of evacuation	151
5.8	Effectiveness of methods to decontaminate the site and local area	151
5.9	Conclusions: key lessons learned in the evacuation, return, and decontamination at Fukushima's nuclear power plant	157
	References	158
6	Learning from the Fukushima nuclear power plant accident	159
	<i>Y. Hatamura</i>	
6.1	Introduction	159
6.2	Learning from accidents: key findings from the official investigation	159
6.3	Recommendations for improving the safe design and operation of NPPs	162

6.4	Comparing the Fukushima accident with other nuclear incidents	175
6.5	Reflections from the Chairman of the official Investigation Committee on the accident at the Fukushima NPP	180
6.6	Conclusions	188
	Reference	188
7	The future of nuclear power generation after the Fukushima accident	189
	<i>Y. Hatamura</i>	
7.1	Introduction	189
7.2	Restarting the Fukushima plant	189
7.3	Conclusions: the future of nuclear power in Japan	193
	Postscript	195
	Index	197

The Fukushima-1 nuclear power plant accident

1

S. Abe

Kansai University, Osaka, Japan

1.1 Introduction

This chapter provides background information about nuclear power generation in Japan, including how the Japanese nuclear power industry is structured and the position of the owner of the plant where the accident occurred. The accident was triggered by an earthquake and tsunami that crippled the plant. This chapter also covers the earthquake and tsunami data as background for understanding the accident. Although no direct fatalities were caused by radiation from the plant accident, there were related deaths. Some, however, are hard to categorize into those caused by natural disaster or those that were a consequence of forced evacuation from radiation release by the power plant. The total fatality counts are provided.

The specific troubled plant is outlined here, as well as how Japan was prepared, or at least how it thought it was prepared, for disasters of this kind.

1.2 Energy production in Japan

1.2.1 The energy situation in Japan

Japan consists of 6852 small to large islands with an area of 378,000 km². The four main islands are Honshu, Hokkaido, Shikoku, and Kyushu. About 70% of the lands are forests and rivers, and the inhabitable area is only about 30% of the land. As of July 2013, the population was just over 127 million.

Located in the warm region of East Asia, Japan enjoys variations of the four seasons. The temperature in the capital area of Tokyo reaches an average of 27.4 °C in August, and in January it is as low as 6.1 °C (1981–2010). Electricity consumption in Japan thus reaches its peak from July to September followed by a second peak from December to January. The month of lowest electricity consumption is October, when the load is about 60% of the peak value.

The private sector of Japan is responsible for the electricity business. Deregulation in the 1990s invited independent power producers (IPPs) that sell bulk electricity to power companies and some specific corporations that sell electricity to large commercial entities; however, the primary electricity supply is managed by 10 electric power companies, each monopolizing its assigned area (Figure 1.1). These 10 companies