Report of the JSME Research Committee on the Great East Japan Earthquake Disaster

Chapter 9
Crisis Management for Earthquakes, Nuclear Power Plant Accidents and Other Events

Keiji KONDO*, Masayuki NAKAO**, Tsutomu ARAKI*** and Atsushi AKISAWA****
*Fukuda & Kondo
Ginza Madison Bldg. 6F, 5-4 Ginza 8-chome, Chuo-ku, Tokyo 104-0061, Japan
E-mail: kkondo@tokyo.email.ne.jp
**The University of Tokyo, School of Engineering,
Eng. Bldg. #2-71D3, Hongo 7-3-1, Bunkyo-ku, Tokyo 113-8656, Japan
E-mail: nakao@hnl.t.u-tokyo.ac.jp
***Sophia University,
7-1,Kioicho,Chiyoda-ku,Tokyo, 102-8554,Japan
****Tokyo University of Agriculture and Technology,
2-24-16,Nakacho,Koganei,Tokyo, 184-8588 Japan

Abstract

Focusing on the crisis management implemented, the Fukushima Daiichi Nuclear Power Plant disaster, the measures taken by the East Japan Railway Company (JR East), and the shortage of PET-bottled beverages were examined. Regarding the Fukushima Daiichi Nuclear Power Plant, reports published by various bodies have been reviewed to determine the appropriate actions that should be taken after a tsunami strikes. Our study revealed that the disaster could have been prevented if well-structured crisis management procedures were put in place prior to the earthquake. Although the severity of the tsunami was beyond any expectation, the damage caused to the electrical system supplying power to the cooling system should have been predicted, because the nature of the damage was very similar to that addressed in B.5.b. (Code number of Nuclear Regulatory Commission). On the other hand, JR East successfully stopped the Tohoku Shinkansen trains and the trains that were in service did not derail. JR East also successfully evacuated passengers from five trains, which were later washed away by the tsunami after the evacuation. The success of JR East is attributed to its efforts after the Chuetsu Earthquake. Furthermore, our investigation on the shortage of PET-bottled beverages immediately after the earthquake revealed that the standardization and multi-source supply of components are important in business continuity plans.

Keywords: Crisis Management, Fukushima, Shinkansen, Business Continuity Plan (BCP), Supply Chain

1. Introduction

The Japan Society of Mechanical Engineers (JSME) organized a committee to conduct investigations and formulate proposals regarding what lessons mechanical engineers should learn from the 2011 Great East Japan Earthquake. As a result, six working groups that mainly focus on studies based on traditional mechanical engineering were created. However, it was soon recognized that studies based on the viewpoints of the social or human aspects of the disaster should also be made. Accordingly, a seventh working group was created to study the problems with crisis management after the earthquake.

This working group focused on the following three points: (1) to identify the causes of the accidents at the Fukushima Daiichi Nuclear Power Plant (NPP) from the viewpoints of crisis management, (2) to analyze the successful actions taken by the East Japan Railway Company (JR East), and (3) to show the importance of a social system in terms of anti-disaster measures. To achieve these objectives, candidates of various backgrounds were selected as members of the working group. They were not necessarily experts in nuclear engineering, railroads, or designing manufacturing

Received 15 February 2014

ISBN 978-4-88898-244-3

facilities, although they each had some type of engineering background. Therefore, the studies do not fully address specific design problems. It should be noted that the objective of this working group was to identify, from the viewpoint of crisis management, more general conditions that will be accepted as safe by society for various technologies.

2. Viewpoints when Discussing Crisis Management

When translated into Japanese, the distinction between crisis management and risk management is sometimes unclear. Some say that carrying an umbrella in case it rains is risk management, while buying one after it starts raining is crisis management. Following this example, to identify a shop selling umbrellas before going out would be risk management, and actually buying one at that shop is crisis management.

In this chapter, we will first describe how people acted in response to the earthquake and tsunami. Then, we will consider whether other actions would have been more favorable, and for such instances, we explore what prevented such actions from being carried out. In many cases, we have found that not only tangible matters, but also intangible matters such as training, rules and regulations, laws, and political culture have prevented the favorable actions from being carried out. These situations are related to risk management. Accordingly, our studies were initially based on crisis management and are concluded with proposals regarding risk management.

3. Fukushima Daiichi NPP

3.1 Review of the Accident Sequence

(1) Situations Caused by the Accident

When we discuss risk management, we need to first clarify what inconvenient situations were caused by the accident. The process, at the same time, will identify which of these situations should have or could have been prevented with risk management.

The exact causes may differ depending on how the Fukushima Daiichi NPP accident is viewed. From the viewpoint of future safety measures, it should be pointed out that the valuable surrounding land and ocean have been contaminated after the accident. The contamination was the result of our failure to “contain” radioactivity; containing is the most important of the three principles for nuclear power generation, i.e., “stop, cool, and contain”. Our failure to “contain” the radioactivity also led to problems with the evacuation of local residents.

It is clear that the failure to “contain” the radioactivity was the result of the failure to “cool”. Even after successfully attempting to “stop” the reaction by fully inserting the control rods, the decay heat from fission products raised the core temperature. “Cooling” means to release the fission heat to the outside and failure to do so will disable the “containing” function. In the worst case scenario (abandoning the nuclear reactor), the damage would be limited to the reactor core only if the “containing” function was successful. Thus, when managing the risks of NPPs, one should always be aware of the ultimate target of “containing”.

During the Fukushima Daiichi NPP accident, for example, the CV temperature reached 300°C, which melted the resin seals of flanges and electrical wire feedthroughs. Then, hydrogen gas carrying radioactive material was released into the building and exploded in units 1, 3, and 4, which discharged the radioactive material high into the air. Furthermore, in units 1 and 3, some of the radioactive material travelled through the water in the bottom of the suppression chamber of the CV and was vented into the air. Unit 2 released the largest amount of radioactive material, which was speculated by some experts to have leaked through the bellows, but the point of leakage has not yet been confirmed. Regardless, a significant amount of radioactive material leaked into the air from unit 2 without going through water. The fallout was the worst during the morning of 15 March 2011 after the hydrogen explosion of unit 4. A thick contaminated plume was discharged from unit 2, dispersed to the northeast of the Fukushima Daiichi NPP towards Iitate-mura, and the contaminated material of the plume fell to the ground as rain. Significant amounts of radioactive material continued to be released after 15 March 2011 from units 1, 2, and 3, without going through the CV water. The material stopped being released towards the end of March 2011, when the accident was nearly contained. In addition, cooling water leaked out from the CV to the basement of the buildings. Some of the contaminated water made its way to the ocean.

TEPCO announced in May 2012 that the total amount of radioactivity was 900 peta becquerel (PBq; peta is the

ISBN 978-4-88898-244-3

prefix for 10 to the 15th power). This figure was obtained by converting the Cs137 release to the Iodine equivalent, adding the results to the I131 release, and following the International Nuclear Event Scale (INES) method. However, both NISA and JAEA announced that the total amount was 480 PBq. The amount of release due to the Chernobyl accident was 5,200 PBq; thus, the amount of release due to the Fukushima Daiichi NPP accident was 9 to 17% of that of the Chernobyl accident.

The above TEPCO announcement broke down the radioactivity release as follows: about 5 PBq from the hydrogen explosions of the reactor buildings, about 1 PBq due to venting from the CV, and about 900 PBq (i.e., almost 100% of the entire release) escaped from the CVs to the buildings and then to the atmosphere without being transported through water. After watching the hydrogen explosions on television and hearing about the venting, the majority of the public had the impression that the explosions and steam venting released the largest amount of radioactive material; however, the quantitative analysis contradicted this misconception. When the hydrogen explosion occurred at unit 4 at 06:14 JST on 15 March 2011, we thought that the worst was over, since units 1 and 3 had also already exploded. However, after the explosion of unit 4, the largest release of radioactive material was yet to come.

Many on-site workers were exposed to the radiation. The Diet Investigation Committee [12] reported that 167 workers experienced an exposure of more than 100 mSv, and six of them experienced an exposure of 250 mSv or higher. Despite this severe accident, none of the workers or local residents were severely injured. Although some hospital patients passed away during the evacuation for reasons other than exposure to radiation, the respect for life and the emergency evacuation was in a sense a success. However, as of 15th May, 2014. the contamination has not allowed 258,219 evacuees and out-migrants to return to their residential areas, since these areas can still expose a person to an annual dose of 20 mSv. The changes in lifestyle and surroundings, including the loss of friends and family, place a heavy burden on the minds of the evacuees.

(2) Progression of the Accident

a) References

The overall study we are conducting has detail records of the Fukushima NPP accident by a number of workgroups (WG), thus, WG7 will only cover the summary of the accidents. The following is a list of available reports.

[1] Cabinet Interim Report, Investigation Committee on the Accident at Fukushima Nuclear Power Stations of Tokyo Electric Power Company, Dec. 26, 2011, http://www.cas.go.jp/jp/seisaku/icanps/eng/interim-report.html

[2] Cabinet Final Report, Investigation Committee on the Accident at Fukushima Nuclear Power Stations of Tokyo Electric Power Company, Jul., 23, 2012, http://www.cas.go.jp/jp/seisaku/icanps/eng/final-report.html

[3] What should we learn from the severe accidents at the Fukushima Dai-ichi Nuclear Power Plant –Final Report, Team H2O Project, Dec. 21, 2011, http://pr.bbt757.com/eng/pdf/finalrepo_111225.pdf

[4] Fukushima Investigation, Research Investigation Report, Rebuild Japan Initiative Foundation, Mar. 11, 2012, Discover 21, Inc. (in Japanese)

[5] TEPCO Interim report of Fukushima Nuclear Accidents Investigation Committee, TEPCO, Dec. 2, 2012, http://www.tepco.co.jp/en/press/corp-com/release/11120205-e.html

[6] Examination of Accident at Tokyo Electric Power Co., Inc.'s Fukushima Daiichi Nuclear Power Station and Proposal of Countermeasures, Oct. 2011, Japan Nuclear Technology Institute, http://www.gengikyo.jp/english/shokai/Tohoku_Jishin/report.pdf

[7] B.5.b Phase 2&3 Submittal Guideline, Revision 2, December 2006, Energy and Research, Inc. http://pbadupws.nrc.gov/docs/ML0700/ML070090060.pdf

[8] Report on initial responses to the accident at Tokyo Electric Power Co.'s Fukushima Daiichi Nuclear Power Plant, Dec. 22, 2011, TEPCO Press Release, http://www.tepco.co.jp/en/press/corp-com/release/betu11_e/images/111222e17.pdf

[9] Measures Taken at Fukushima Daiichi Nuclear Power Station and Fukushima Daini Nuclear Power Station (December 2011 Edition) List of Documents, http://www.tepco.co.jp/en/press/corp-com/release/betu11_e/images/111222e18.pdf

[10] METI, About Technical Knowledge and Findings, Appendix (in Japanese), http://www.meti.go.jp/press/2011/03/20120328009/20120328009-2.pdf

[11] NSCRG: L-DS-I.0 Regulatory Guide for Reviewing Safety Design of Light Water Nuclear Power Reactor

ISBN 978-4-88898-244-3

Facilities, August, 1990, Nuclear Safety Committee of Japan, http://www.nsr.go.jp/archive/nsc/NSCenglish/guides/lwr/L-DS-I_0.pdf

[12] The National Diet of Japan Fukushima Nuclear Accident Independent Investigation Commission, Final Report, http://warp.da.ndl.go.jp/info:ndljp/pid/3856371/naiic.go.jp/en/report/

[13] Lessons Learned from the Nuclear Accident at the Fukushima Daiichi Nuclear Power Station, Nuclear Energy Institute, http://www.nei.org/resourcesandstats/document-library/safetyandsecurity/reports/lessons-learned-from-the-nuclear-accident-at-the-fukushima-daiichi-nuclear-power-station

[14] Special Report on the Nuclear Accident at the Fukushima Daiichi Nuclear Power Station, Nuclear Energy Institute, http://www.nei.org/resourcesandstats/documentlibrary/safetyandsecurity/reports/special-report-on-the-nuclear-accident-at-the-fukushima-daiichi-nuclear-power-station

[15] Estimation of Radioactive Material Released to the Atmosphere during the Fukushima Daiichi NPS Accident, TEPCO, May 2012, http://www.tepco.co.jp/en/press/corp-com/release/betu12_e/images/120524e0205.pdf

[16] The Final Conditions For Restarting Nuclear Power Plants, “Fukushima Daiichi” Accident Investigation Project Final Report, Kenichi Omae, July 2012, Shogakukan (in Japanese).

[17] Technical Report: Fukushima Accident Summary (Aug. 19, 2011), R. Yoshioka, K. Iino, Association for the Study of Failure. http://www.shippai.org/images/html/news559/FukuAccSummary110819Final.pdf

In August 2012, TEPCO released videos of the teleconferences that were held during the accident to the media, and in October 2012, they were made available on TEPCO’s homepage. Although individual names and some portions of the images are censored, they provide viewers with footage showing the high tension on site at the time. In total, they are several hours long, but all that can be seen and heard are reports from the field being transmitted to the headquarters. The headquarters, on the other hand, continued to send inquiries and demands for information. Suggestions and advice were not provided by the headquarters or the design and maintenance manufacturers (Hitachi and Toshiba). Such information could have been provided via a different route; however, decisions were probably being made by the field engineers during the first few days.

These videos revealed that during the accident, engineers collected 12V batteries from cars for reading sensors and operating valves and even announced they were in need of cash to purchase them from hardware stores. It took them as long as 6 hours to assemble the batteries into the electrical circuits. These troubles contributed to the delay in releasing the reactor pressure. The videos also show that when the engineers started to inject cooling water into the RPV from the fire engines, they had to rely on the seawater from the tsunami that was left inside the pits; pumping water from the ocean was not that easy.

In November 2013, TEPCO released images from a boat-mounted camera that showed the water leakage from the suppression chamber of unit 1. We currently cannot access the reactor due to high radiation; however, as we collect more evidence from the remaining reactors we will gain more insight and understanding of the accident. We will not rush to conclusions and will carry out a thorough investigation into what happened with the accident.

b) Outline of the Light-water Units

The progression of the accident can be better understood by first explaining how units 1, 2, and 3 of the Fukushima Daiichi NPP operated. Fig.1 outlines the primary equipment of unit 1 and Fig.2 outlines that of units 2–5.

During normal operation, fuel bundles were placed inside the RPV, which was surrounded with water that was used to moderate the neutrons and cool the fuel. The fuel heated the water, which evaporated into steam that traveled through the main-steam line to reach the main turbine. The steam hit the turbine blades to rotate the turbine rotor, which then turned the electric power generator. The main condenser condensed the steam discharged from the turbine chamber to water to feed it back to the RPV. The condenser was cooled by circulating seawater.

Upon emergency, control rods were inserted from the RPV bottom into the reactor core to stop the nuclear fission reaction. Simultaneously, the RPV was isolated from the main-steam line. Nuclear fission products in the RPV generated decay heat even after the fission reactions were stopped and the fuel temperature would continue to increase. Nuclear reactors have systems to remove this decay heat; an IC was used for unit 1 and an RCIC was used for units 2–5.

ISBN 978-4-88898-244-3

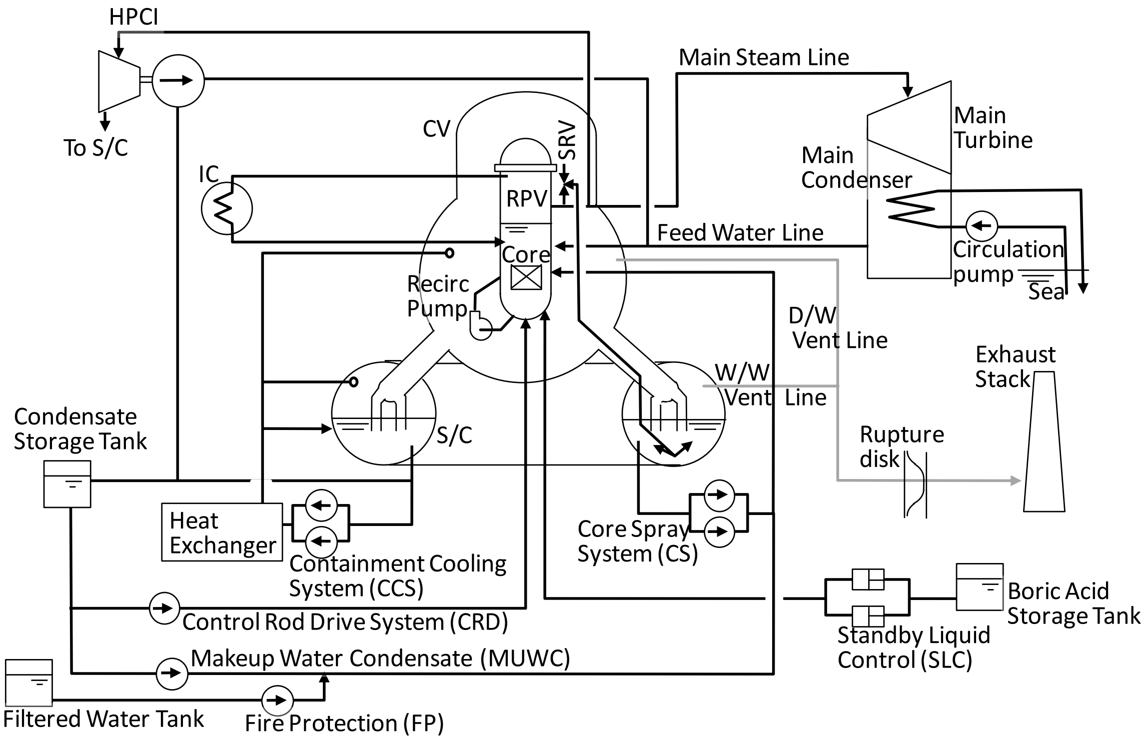


Fig.1 Outline of the primary equipment of unit 1 of the Fukushima Daiichi NPP.

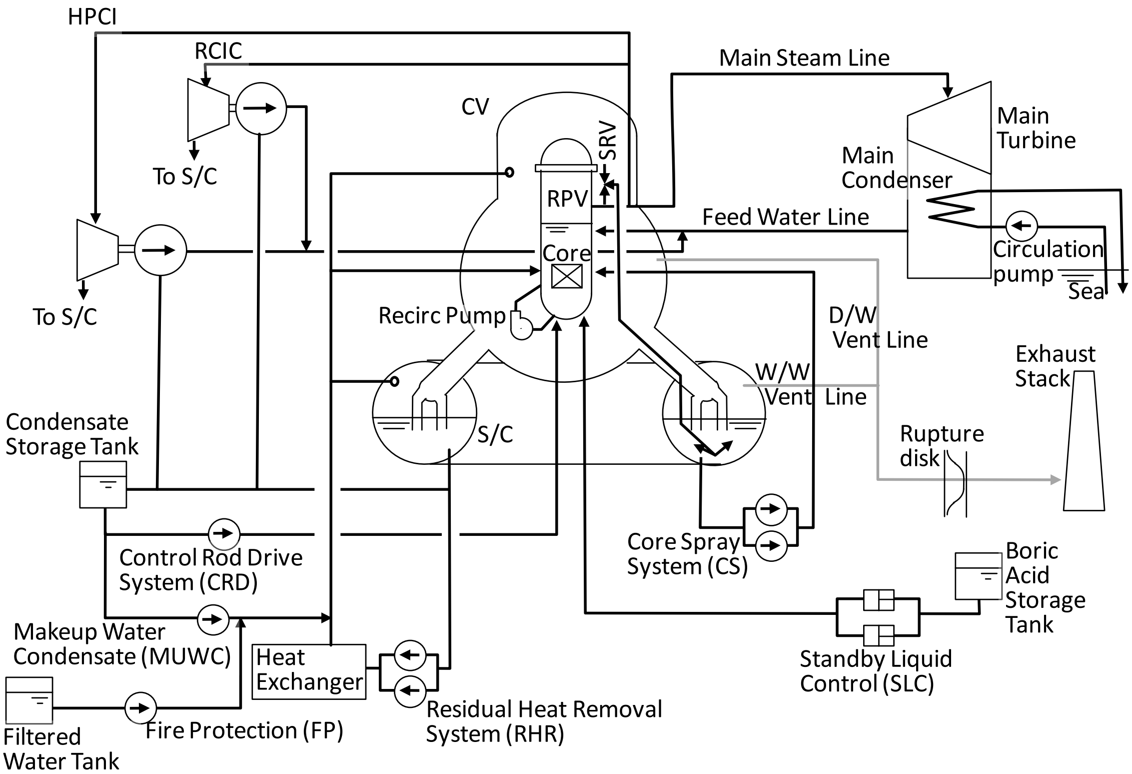


Fig. 2 Outline of the primary equipment of units 2–5 of the Fukushima Daiichi NPP.

ISBN 978-4-88898-244-3

The IC operated without the help of a pump to condense steam from the RPV to water, which gravity carried back to the RPV. The coolant that condensed steam in the IC heat exchanger was stored separately as water. The cooling water evaporated into steam and was discharged to the outside of the reactor building; thus, when in use, the IC required its cooling water to be refilled in order to maintain its cooling capacity. When cooling water was filled to its maximum storage level, the IC was able to condense steam from the RPV for 8 hours. In contrast, the RCIC and HPCI pumps were driven by turbines that were turned by steam from the RPV. The IC and RCIC did not require electrical power sources; however, if the RPV steam pressure dropped, the IC and RCIC would stop operating

In addition to the above cooling systems, each reactor comprised a water condensation system (MUWC) and a residual heat removal system (RHR), which were driven by electrical pumps. The fire protection systems (FC) were driven either electrically or by diesel. The pressure within the RPV reached about 70 atm; however, the CV maximum allowable pressure was about 5 atm. The diesel pump driven by the FP pressure reached about 6 to 7 atm, and that of the fire engine reached about 8 atm.

c) Progression of the Accident towards a Cold Shutdown State

The equipment of both the Fukushima Daiichi and Daini NPPs suffered a number of tsunami damages. The DC power at the Fukushima Daini NPP was maintained throughout the tsunami and the plant managed to restore its AC power within 2 days. Restoration efforts were carried out under harsh conditions; however, thanks to the preparations and training that were followed in accordance with the accident management (AM) plans, severe accidents were avoided at the Fukushima Daini NPP.

The Fukushima Daiichi NPP, on the other hand, lost all its electrical power sources except for the DC power at unit 3, which was eventually lost after 2 days. At the Fukushima Daiini NPP, the valves were controllable from within the central control room, whereas the operators of the Fukushima Daiichi NPP had to climb to the physical locations of the valves or switchboards to supply the compressed air or direct the electrical power. These delays in valve operation led to the release of radioactive material from the Fukushima Daiichi NPP.

At both plants, engineers attempted to reach a cold shutdown state by following scenarios (i) through (vi); however, different procedures were followed at the Fukushima Daiichi NPP.

(i) Start the emergency diesel generators after an earthquake

Both the Fukushima Daiichi and Daini NPPs were able to fully insert their control rods within 1.6 seconds after the earthquake occurred, which was before the tremors from the earthquake ceased. Offsite power sources were lost immediately after the earthquake; however, the emergency diesel generators (D/G) began operating. The IC and RCIC systems began operating to cool the fuel rods in the RPVs.

The Diet Report [12] speculated that the earthquake caused damages to the reactor or piping before the tsunami struck, whereas the Cabinet Report [1] [2] concluded from their actual temperature, pressure, and radioactivity measurements that the damages did not take place until after the tsunami struck.

(ii) Use the emergency D/G, DC power, and switchboards after a tsunami

Seawater from the tsunami poured into the Fukushima Daiichi NPP through the doors and windows of the turbine buildings. The emergency D/G, DC battery, and switchboard functions were lost, except for the DC power at unit 3. Units 5 and 6 of the Fukushima Daiichi NPP and units 1–4 of the Fukushima Daini NPP had at minimum an emergency D/G, DC battery, or a switchboard to operate the valves and pumps. Units 5 and 6 of the Fukushima Daiichi NPP had an air-cooled emergency D/G and were luckily shut down for maintenance. Simply increasing the number of emergency subsystems is insufficient for the large systems comprising a power plant unit; they require a number of diversified safety subsystems that operate under different principles.

Eventually, the Fukushima Daini NPP recovered from the severe damage; however, at the time, all of its seawater pumps were lost due to the tsunami. It took two days of hard work to connect temporary power cables directly to the pumps. The Fukushima Daiichi NPP took similar efforts to make use of the switchboards that were repaired; however, the repeated hydrogen explosions did not allow any progress to be retained. The accident, which reached a level of catastrophic severity, was partly due to the multiplicity of simultaneous accidents with multiple reactors.

(iii) Initiate cooling with high pressure steam from the RPV after a tsunami

Units 4, 5, and 6 of the Fukushima Daiichi NPP were shut down for maintenance and did not have an urgent need for cooling. After the earthquake, the IC of unit 1 of the Fukushima Daiichi NPP was started, and the RCICs of units 2 and 3 were started. The RCICs of units 1–4 of the Fukushima Daini NPP were started after the tsunami struck. If the

ISBN 978-4-88898-244-3

plant had lost all of its AC power as the Fukushima Daiichi NPP did, a meltdown would have occurred within 3 hours, since the units were unable to start their high pressure cooling systems.

An IC works by forcing high pressure steam into water cooled pipes in order to condense the steam to water and by then letting the water flow back into the RPV under gravity. A RCIC turns a turbine with the high pressure steam to drive a pump that forces water inside the CV or from outside tanks into the RPV at high pressure. Both the IC and RCIC do not require AC power. The concept is to allow cooling whether emergency electrical power is available or not. These systems, however, have valves on their piping, and the valves on the IC of unit 1 were designed to close upon power failure (fail-close), whereas those on the RCICs of the other units were designed to fail-as-is. After the earthquake, operators started the RCICs of units 2 and 3 of the Fukushima Daiichi NPP and thus their valves remained opened to cool the reactor core after the tsunami had struck.

In contrast, unit 1, without its IC after the tsunami, experienced a severe accident. Within three hours, the RPV water level decreased enough to expose the fuel rods, and the inner and outer surfaces of the Zircaloy cladding (tube that houses the stacks of fuel pellets) were oxidized. The oxidized films had high melting points and the cladding melted from the inside. As the tubes deformed, the oxidized surface films could no longer hold their shape and broke. The fuel pellets inside the rods cracked into fragments [17] and the radioactive material fell to the RPV bottom and further down into the CV. As the fuel rods disintegrated, zirconium reacted with oxygen in the surrounding water and produced about 1 ton (nearly 10,000 cubic meters) of hydrogen gas. Half a day later, the hydrogen gas exploded.

(iv) Arrange piping to inject low pressure cooling water into the RPV and start cooling

The type of IC and RCIC described above can inject cooling water into the reactor even when the pressure is 70 atm; however, they are driven by high-pressure steam and will stop running when the reactor pressure drops. The RCIC in unit 2 ran for 3 days and that in unit 3 ran for a day, followed by the HPCI that worked in a similar manner for another half a day.

While the high-pressure cooling systems were operating, methods of injecting cooling water without the use of AC power were required for the Fukushima Daiichi NPP. At the plant, the engineers injected cooling water at several atmospheres into the RPV by using fire engines and diesel driven pumps from the outside through piping for the fire protection system (FP). These procedures were not planned in advance; thus, the workers in the field had to connect the pipes on the spot. The work proved to be difficult; for example, for unit 2, the workers built a cooling water route from the FP to the RPV via the RHR. This route had an AC-powered motor operated valve (MOV) with a diameter of 24 inches. The valve could have been opened within 24 seconds if the AC power was available, however, without it, 10 workers took turns in turning the heavy valve manually and this labor took an entire hour to complete.

The plant manager at the Fukushima Daiichi NPP decided to rely on fire engines at 17:12 JST, an hour after the tsunami, as an alternate method of water injection. The AM of TEPCO, however, did not have such plans, and the search for water inlets and the layout of hoses for the first time further delayed the cooling of the reactors.

(v) Open the SRVs to reduce the RPV pressure and vent valves to reduce the CV pressure

In order for the low pressure cooling systems in (iv) to operate, the high pressure steam in the RPV has to be released into the CV and then released into the atmosphere to lower the RPV pressure. Fig..3 shows the structure of the main steam safety relief valve (SRV). When the main-steam line pressure rises to an abnormally high level, the pressure on the valve lifts it from the seat and the steam is released into the SC. Manual activation requires energizing the solenoid valve to bring nitrogen gas into the cylinder to push the piston up and the lever mechanism lifts the valve off its seat. This solenoid valve is activated by DC 125V.

The air operated (A/O) vent valve from the SC to the vent line is structured similarly to the SRV, except instead of a cylinder/piston and lever action, compressed air pushes a diaphragm up to lift the valve. Manual activation of this vent valve also requires DC-powered solenoid activation.

When the compressed air and DC power were lost due to the tsunami, the field workers had to prepare high pressure gas and somehow apply DC power to the solenoids to bring the gas under the piston or diaphragm to activate these valves. During the accident, workers collected compressed gas bottles and portable compressors, and for DC power, 12V automobile batteries and small 2V batteries stacked in series were used. When the gas or battery power was drained, the valves would close and the field workers had to repeatedly assemble their temporary valve activators. Thus, the process of relieving pressure was slow and the extra time that the high pressure systems provided was wasted. Then, the hydrogen explosion at unit 1 set back the pressure relief efforts at unit 3, and when the top floor of the reactor

ISBN 978-4-88898-244-3

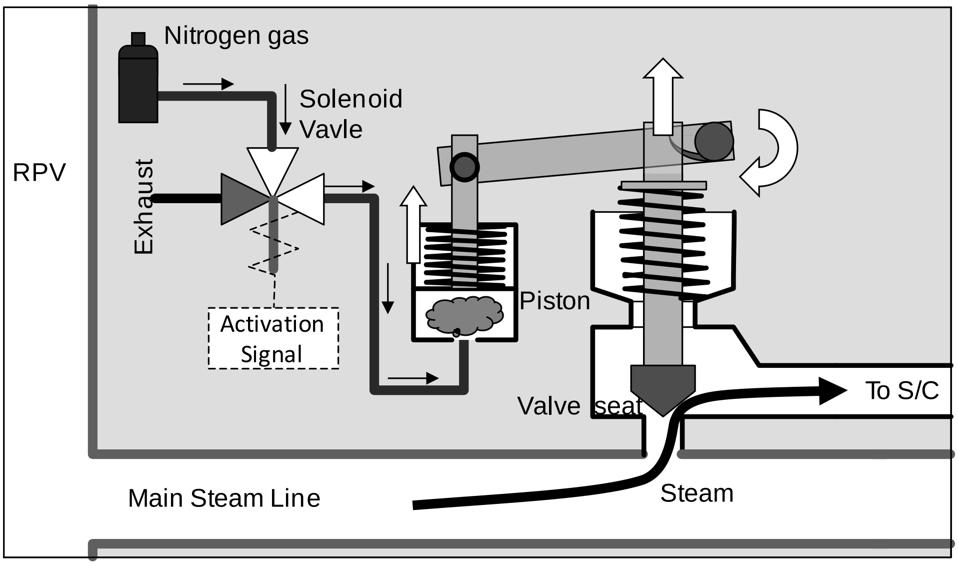


Fig..3 Safety relief valve.

building at unit 3 exploded, the recovery efforts for unit 2 were set back.

(vi) Circulate cooling water through the heat exchangers to release the heat into the sea

Injecting water from a low pressure system into the reactor would have prevented the meltdown; however, to reach a cold shutdown state, high-temperature steam and water had to run through the heat exchangers to release the heat into the sea. Contaminated water accumulated in the reactor buildings of units 1–3, probably due to cracks in the RPV or CV. To cool and filter the contaminated water, recirculation systems were built on outside of the reactors to reach a cold shutdown state. The contaminated water, unlike cooling water under normal conditions, had directly contacted the fuel and contained a large amount of radioactive material. The water had to go through a zeolite-filled filter tank to capture the cesium and other radioactive materials. The filter tanks are not reusable and the used tanks continue to accumulate in Fukushima.

3.2 Scenario of avoiding an accident

(1) The severe accidents were avoidable

Units 5 and 6 of the Fukushima Daiichi NPP and units 1–4 of the Fukushima Daini NPP successfully reached a cold shutdown state; in other words, they followed the scenarios to avoid severe accidents and succeeded. Fig. 4 shows this scenario, i.e., to run the high pressure cooling systems for about 1 day and to gain some extra time, open the SRVs and vent valves to reduce the reactor pressure to run the low pressure cooling systems, then while the low pressure systems are running, continuously remove the heat with the prepared heat exchangers and circulation routes.

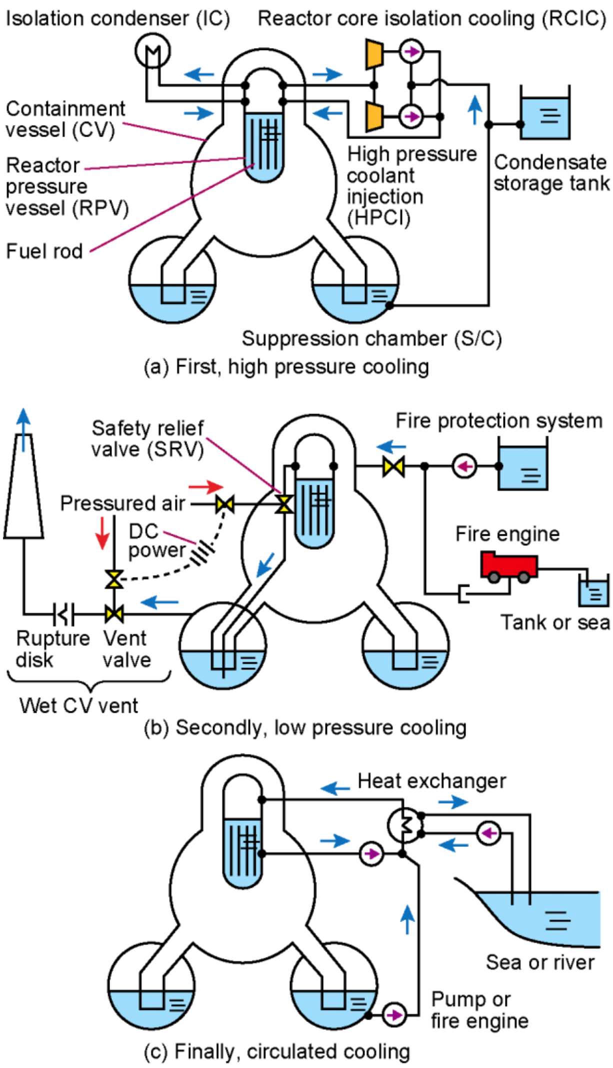


Fig..4 Scenario of a successful cold shutdown.

ISBN 978-4-88898-244-3

Unit 1, however, failed to operate its high pressure cooling system (IC) and did not succeed. Units 2 and 3 did not succeed when they failed to open their SRVs and vent valves. The Fukushima Daiichi NPP manager gave orders to prepare to initiate low pressure cooling with fire engines 1.5 hours after the tsunami; however, the high pressure cooling system of unit 1 had already stopped and the core had already been exposed.

(2) Would there have been less loss if all the right decisions were made?

Although the operations that were being carried out at the Fukushima Daiichi NPP were similar to those at the Fukushima Daini NPP, the media speculated that human errors were made by the operators during the critical points of the accident. We do not intend to blame individuals, and would rather like to discuss why the engineering team, which included off-site engineers, failed and did not cooperate with one another. When Apollo 13 lost one of its oxygen tanks and was in danger of not returning to Earth, ground-based engineering was used to create mock-up trials with the same elements and conditions to devise ways to ensure survival and to send instructions to the spaceship. This is the type of teamwork that is needed for NPPs.

a) Could the IC at Unit 1 have been restarted?

The IC of the Fukushima Daiichi NPP had the capability of cooling the RPV without a pump. Its capacity was sufficient because after the earthquake and before the tsunami, operators ran them with partial capacity to avoid a sudden cooling of 55°C per hour or faster. Such rapid cooling could cause RPV damage due to thermal stress.

Unit 1 had two IC systems (A and B). Each system had two lines: the upper line where the RPV steam traveled to the IC and the lower line that passed the IC condensed water back to the RPV. Each line had a 125V DC operated valve on the exterior of the CV and a 480V AC operated valve in the interior of the CV. The valve on the exterior of the CV had a manual handle, but the one on the inside did not.

Just before the tsunami hit, both systems had only the DC-operated valves on the exterior of the CV on the lower line closed and all of the other six valves were open. When the tsunami caused an SBO, the IC system safety sensors lost their “safe” signal and all eight IC valves closed. The reasoning for this closure is to keep the IC offline, because if a signal is lost, an accident is likely to be the case, and without identifying the accident, it is safer to keep the RPV isolated from any external system that may have been damaged. The engineers called this “fail close” behavior “fail safe”. A later investigation, however, revealed that all four valves in the CV were not fully closed.

The problem in terms of accident management was that none of the field engineers or the off-site engineers realized that the IC systems both stopped after the SBO. We later learned that the Fukushima Daiichi NPP simulator that was used to train the operators did not include an IC (it was only installed at unit 1), and the standard process at the Fukushima Daiichi NPP to counter high RPV pressure was to only activate the SRVs. The two IC systems at unit 1 of the Fukushima Daiichi NPP were never operated since the reactor began operating in 1971.

A later investigation revealed that the “fail close” logic upon SBO closed all eight IC valves; however, the AC 480 V valves inside the CV did not fully close, because the AC driving power was lost before they were fully shut. The on-site engineers were confused, because they tried opening the DC powered valves on the exterior of the CV and saw some steam escape from the IC discharge lines that vented to the outside of the reactor building; however, they were worried about high temperature damage to the IC piping, and closed the valves.

It is understandable that the on-site engineers misinterpreted the IC valve status while in the chaotic control room, but what about the off-site engineers or manufacturers of the plant? No one remembered the “fail close” logic that should be implemented with the IC valve system to warn the operators on site. If they had received such advice, the on-site engineers could have scrambled to collect DC batteries or even manually turned the handles to open the IC valves located on the exterior of the CV.

b) Could the HPCI of Unit 1 have been restarted?

Unit 1 also had an HPCI system, which would have been able to turn a turbine with high pressure steam to drive a pump to inject cooling water into the RPV. After the tsunami, however, the unit was out of DC power to control the HPCI turbine and its lubrication pump for the bearing was inoperable as well.

c) Why was the HPCI of Unit 3 stopped without confirming a reduction in pressure?

The RCIC of unit 3 stopped on 13 March 2011, the day after the tsunami, at 11:36 JST. The RPV water level decreased and the HPCI started automatically. The HPCI ran for about 14 hours before it was manually stopped at 02:42 JST on 13 March 2011. The plan was to relieve the high RPV pressure with SRVs while the HPCI was running;

ISBN 978-4-88898-244-3

however, the chief operator stopped the HPCI without confirming the action with top level management. When the operators later tried to pop the SRVs, the DC power was exhausted and the valves did not open. The stopped HPCI could not be restarted either and this was when the unit started its way towards core exposure and meltdown.

Later at 09:36 JST on 13 March 2011, the SRVs and vent valves finally opened and the fire engines succeeded in injecting water into the RPV with lower pressure; however, the core had already been damaged.

d) Why did the cooling water source for the RCIC of Unit 2 change?

The RCIC of unit 2 was operating at the time of the SBO and it kept running without being controlled. At about 12:30 JST on the 14 March 2011, however, it lost its water injection function, probably due to the high water temperature in the SC. When the water temperature increased on the pump suction side, cavitations in the water lowered the water injection capability.

The RCIC was first running with water from the condensate storage tank; however, the water source switched to the SC between 04:00 to 05:00 JST on 12 March 2011. At this time, the condensate storage tank was still about 30% full. Without the RHR to remove heat in the SC, relying on SC water to cool the core would raise the internal temperature and pressure. When the RCIC ceased to operate, the SC reached 149°C and 0.49 MPa.

This question should also have been addressed by the off-site engineers and manufacturers. However, low pressure coolant injected from the fire engine made it in time for unit 2; thus, the switched water source had no direct affect on the fuel damage. However, the progression of the accident could have been different if there were any further delays in the water injection from the fire engine.

e) Was the fire engine running out of gas while cooling Unit 2 an oversight?

When unit 3 exploded at 11:01 JST on 14 March 2011, the RCIC for unit 2 stopped and the top of the core of unit 2 began to be exposed above the water level at 17:17 JST. Immediately after this event, the news reported that the pressure of the RPV of unit 2 decreased and was followed by the injection of low pressure water via a fire engine. Later news, however, reported that the water level dropped at 18:22 JST, exposing the full length of all the fuel bundles. This news was then followed by a surprising fact that the fire engine that was used to inject the seawater was inoperable due to an insufficient supply of gas.

f) Did reinforcing the blowout panel fixture lead to the hydrogen explosion?

While units 1, 3, and 4 experienced hydrogen explosions, unit 2 did not experience a hydrogen explosion. The blowout panel on the reactor building of unit 2 popped open at 15:36 JST on the 12 March 2011 when unit 1 experienced its hydrogen explosion. The 5 m^2 opening allowed the hydrogen gas to escape and the gas never accumulated to a level that would have caused an explosion.

The Cabinet Interim Report (pg. 214 of [1]) stated that TEPCO, following the case in which the blowout panel popped open at the Kashiwazaki-Kariwa plant and efforts failed to contain the air inside the reactor building during the 2007 Chuetsu Offshore Earthquake, made design changes to strengthen this panel on its Fukushima NPPs.

As we mentioned earlier, the release of radioactive material due to the hydrogen explosion was small; however, the explosion affected other works underway to control the plant. Similar to the following problem associated with a rupture disk, the efforts to “contain” a small amount of radioactivity led to explosions that delayed the work efforts.

g) Why were the rupture disks in place?

The venting line had two vent valves in series and a rupture disk before the line reached the exhaust stack. A rupture disk is commonly used in chemical plants to completely shut off the flow inside a pipe. The disk, however, ruptures when the pressure difference on its two sides exceeds its set point. Its completeness overcomes the limitation with regular valves with valve seats that always have the possibility of allowing small leakage. The original GE design called for either a double valve configuration or one with a rupture disk. The Japanese plant adopted both to have two regular valves and a rupture disk. The set point, however, was at twice the CV pressure limit, causing great difficulty in venting the CV. The rupture disks, after all, were not needed.

(3) What was the cause of the accident?

a) Tsunami

In a sense, it is true to say that the accident would not have happened if the tsunami did not hit the NPP. It is also true that TEPCO failed to take precautions against such a great tsunami despite the studies that have been conducted in the past 10 years and results obtained regarding the 869 Jyogan tsunami. At the same time, if the other events with

ISBN 978-4-88898-244-3

similar chances of occurrence are taken into consideration, we would have to plan against volcano eruptions, fires, airplane crashes, meteor strikes, terrorist attacks, war, mud slides, and so on. The fact is NPPs have to take precautions against events that are extremely unlikely to occur.

b) SBO

During this accident, the Fukushima Daiichi NPP succeeded in “stopping” the reaction, but failed to “cool” the reactor, and as a result it also failed to “contain” the radioactivity. The cause of this failure is considered to be the SBO.

What we should learn from this accident, however, is the fact that there always will be events that are Beyond Design Basis (BDB). In preparation, we needed to prepare multiple layers of protection and to determine what countermeasures to take for any possible sequence of events.

In contrast, the nuclear industry and regulation denied the need to prepare measures against an extended (30 minutes or longer) SBO. The real cause was not the SBO, but the failure to plan for an extended SBO.

c) Lack of preparation and training for an emergency

TEPCO and the Government of Japan are to blame for this accident, since their preparations and training against severe accidents were poor. They should have invested more in preparing and training for an accident to lower the risk of such a disaster. However, training was conducted on how to share electricity between adjacent units and alternate water injections through FP; however, this training was certainly not sufficient. Foreign countries such as the US and Switzerland have 125 V batteries and nitrogen gas bottles on hand-pulled carts that can be easily transported.

NRC’s B.5.b. [11] requires preparations that include having hand operable valves, transportable alternate pumps, alternate water level and pressure sensors, and a way of filling the fuel pool using gravity. Such preparations would have made a great difference in this accident. The government report pointed out that NISA received explanations about the B.5.b from the NRC, but ignored the information stating that terrorist attacks will not take place in Japan.

The most critical type of preparation and training needed for this accident was to “relieve the reactor pressure within 1 hour and inject low pressure cooling water into the RPV”. The units could have reached a cold shutdown state if only this process was conducted successfully. Unit 1 with its IC stopped, however, would not have had enough time to relieve the reactor pressure, and its core would have been partially damaged even if preparations were made.

(4) Design interference of the “cooling” and “containing” functions

Decay heat is like a smoldering fire in that a significant amount of heat is released. The generation of heat immediately after a shutdown is about 7% of the reactor thermal output, which drops to about 0.6% in one day and to 0.2% in one year. If we take unit 1 as an example, and assume a value of 460 MWe and a power generation efficiency of 30%, the thermal power would be 1,530 MWth, and the decrease to 0.6% after 1 day would be 9,200 kW. If we were to remove this decay heat with the vaporization heat (540 cal/g) and sensible heat (80 cal/g to heat water from 20°C to 100°C) of water, 12.7 tons of water would need to be poured every hour into the RPV. This would be possible since a regular fire engine can discharge 2 tons of water every minute at about 10 atm. The only problem is that the RPV pressure would be as high as 70 atm.

This is why the RPV pressure needs to be lowered. A nuclear reactor has a double shell structure with the RPV and CV and the RPV pressure needs to be released into the CV. However, this increases the CV pressure and temperature, and the CV pressure has to be released into the atmosphere. This process cools the fuel rods through vaporization of the cooling water, and ultimately uses the atmosphere as a heat sink. Since contaminated steam is released into the air, this process fails to meet the function of “containing” the radioactivity, even though the amount of material that would be released would be small. Thus, such a process can only be allowed for emergency situations such as the Fukushima accident.

The Fukushima Daiichi NPP, however, failed to follow the above emergency scenario, because it first failed to “cool” the reactor. This failure caused the fuel cladding to melt and the cooling water came into direct contact with the fuel pellets. Then, when the highly contaminated steam and water escaped the CV, they contaminated the land, sea, and air.

The above discussion showed that the functional requirement of “cooling” interferes with that of “containing”. During the Kashiwazaki-Kariwa NPP accident in 2007, a small amount of radioactive material was released from the condenser of unit 7 through the exhaust stack. The release of radiation made the news and caused turmoil among the public. The media also exaggerated the effects of water splashing out of the fuel pool of unit 6; however, the

ISBN 978-4-88898-244-3

radioactivity spill was equivalent to 9 liters of water from the Miasa hot springs (known for its radium rich springs). The Fukushima Daiichi NPP accident was so severe that venting the CVs finally spreading the radioactive debris, was considered to be reluctant. The delays in venting were caused by the technical difficulties that were discussed above. We must, however, recognize that the "fail close" design of the IC valves for unit 1 and the rupture disks on the vent lines interfered with the efforts to quickly reduce the pressure to ensure low pressure cooling was applied to the reactor cores. We are not particularly opposed to the idea of filtered venting. However, the coverage by the media confuses the idea of containing radioactivity under normal circumstances with what actions to take during serious emergencies. During a serious emergency, the design function of "cooling" must have priority over the function of "containing" and we may have to review the designs to confirm if the systems are designed in such a way. This severe accident should not be repeated and the knowledge gained from its consequences should be implemented in an effective manner.

3.3 Proposals Concerning Crisis Management at NPPs

(1) Departure from Absolute Safety

The internationally accepted definition of safety is "freedom from unacceptable risk". However, a widespread opinion in Japan is that we should seek absolute safety when NPPs are involved. It is true that Japanese people fear the use of nuclear energy. As Japan is currently the only country to have been attacked with atomic bombs, the people have specific emotions related to the use of nuclear energy. In addition, television programs aired shocking scenes of the hydrogen explosions during the Fukushima NPP accident, which caused people to fear atomic energy more.

However, such technology cannot be utilized if absolute safety is a requirement. In addition, as the Fukushima NPP accident demonstrated, once "absolute safety" is mentioned as a method to persuade people, no true measures for realistic safety can be taken, because taking such measures would prove that those who mention "absolute safety" are stretching the truth. Regardless of whether they are for or against the utilization of nuclear energy, anyone should accept the internationally accepted definition of safety, and discuss whether the remaining risks are acceptable after all efforts have been made to reduce the risks accompanying the use of nuclear energy. Therefore, we propose that "absolute safety" should not be the sought after standard when considering the safety of NPPs.

(2) Distinction between "Beyond the Design Basis" and "Beyond Conceivability"

Immediately after the accident, the phrase "beyond conceivability" became very popular. The phrase was used to state that TEPCO should not be held liable because the accident was "beyond conceivability". However, the phrase "beyond conceivability" does not literally mean that no one was able to conceive such a situation. In fact, TEPCO was aware of information pertaining to the Jogan Earthquake, which caused a disastrous tsunami. Nevertheless, TEPCO decided not to take any action, because the information about the earthquake was not certain.

When a person adopts a design basis, they usually know that the probability that an accident could occur beyond any expectation is not zero. In that sense, they conceive an event or occurrence beyond the design basis. However, if one assumes that nothing will happen beyond the design basis, actions will not be taken against any situation that could occur. Even after the Fukushima NPP accident, people still expect that accidents will not occur beyond the design basis. Therefore, pressure is exerted on regulatory bodies so that the regulatory standards will be raised. If a report says that a tsunami with a height of 15 m is expected, regulations will be made to ensure that it is mandatory to build a wall higher than 15 m.

However, what should be taken from the Fukushima NPP accident is that we should be prepared for anything beyond the design basis. Even if a tsunami with a height of 18 m is expected, a wall could be as low as 15 m if countermeasures are taken for a tsunami that comes beyond the wall. Therefore, we propose that the design basis should not be correlated with conceivability. When a design basis is adopted, the possibilities of what could happen beyond it should be taken into consideration.

(3) Scenario for the Remaining Risks

If one accepts that an accident could occur beyond the design basis, then they should assess the remaining risks of the design basis. For this purpose, a scenario is necessary. The Fukushima NPP accident has provided sufficient material for such scenarios.

Using the reactor of unit 1 as an example, an investigation revealed that its HPCI system became unusable immediately after the tsunami struck. The cause was that the direct current power supply failed, which further caused the electric valves and lubrication pumps to be inoperable. Even under the conditions of an SBO, the direct current power supply would not automatically fail. However, the water of the tsunami soaked the direct current elements,

ISBN 978-4-88898-244-3

which caused them to be unusable. In such a scenario, if an element fails, another element will back it up. If that element fails, another element will back it up. In short, failures that occur one after the other should be taken into consideration. By repeating this process, one will reach a point where there is no longer an unacceptable risk. Therefore, we propose that a method to create such a scenario should be developed.

(4) Learn from the Past

After the Chuetsu-oki Earthquake, JSME formed a committee to study regulatory actions to determine whether the successful survival of the Kashiwazaki-Kariwa NPP was a result of implementing effective regulations. However, the committee reached no meaningful conclusion, because most of the experts were only willing to state that the "Stop, Cool, and Containment" procedure was successfully completed.

Nevertheless, experts have pointed out certain areas that need improvement. Some of the examples are as follows:

- Prevent office lockers, ceiling lights, etc., from falling;
- Provide an emergency power supply for necessary locations;
- Improve the condition of emergency vehicle access roads; and
- Use flexible joints for the buried pipes of the fire protection system and other emergency systems.

Unfortunately, however, the safety measures taken after the earthquake are mostly focused on the anti-earthquake strength of various structures. In addition, there were many cases where existing structures were found to be safe, because the improved calculation of a stress-strength analysis determined the safety margins to be sufficient, and no actual structural changes were made.

The Chuetsu-oki Earthquake occurred on 16 July 2007, which was well after the September 11 attacks. Therefore, the government should have known the importance of crisis management for NPPs, because they received the B.5.b from the US. Nevertheless, the Kashiwazaki-Kariwa NPP accident did not enhance efforts in crisis management. Conversely, many experts used the accident as evidence to persuade the public that the NPPs of Japan were absolutely safe. It also seems that the Fukushima NPP accident did not change this view. Experts, including those from regulatory organizations, still focus on the strength of the structures. Their efforts are to enforce rules that require protective walls to be constructed higher than any tsunami that may come in a thousand years. Therefore, we propose that the shortcomings of the disaster relief efforts that were made after the Chuetsu-oki Earthquake be taken into consideration.

(5) Role of Legal Framework

The Act for the Regulation of Nuclear Power Plants and Related Facilities empowers the Minister of the Economy, Trade, and Industry to issue orders to entities operating NPPs. To the best of our knowledge, two orders were issued during the Fukushima NPP accident. One order said, "Regarding the reactor of unit 1 of the Fukushima Daiichi NPP, appropriate measures, such as filling the reactor vessel with sea water, should be studied, and the soundness of the reactor should be secured." Another order required that water should be promptly poured into the used fuel pool of the reactor of unit 4.

We can only simply wonder whether these orders had any effect. Usually, administrative orders are issued when those that need to be regulated do not voluntarily take measures that are necessary for public safety, since there are some disincentives against taking such measures. However, the measures that TEPCO were instructed to carry out were not completed due to technical difficulties; there was no lack of willingness on their part.

Administrative orders are necessary when the operating body of a NPP is hesitant to perform a task that is technically possible but politically difficult to conduct. In the political culture of Japan, early venting is one such example. During the Fukushima NPP accident, early venting would have prevented the meltdown of the nuclear fuel. However, early venting could have been a target of criticism, because it intentionally discharges small amounts of radioactive materials. In such a situation, an administrative order should make it easy for the operating body of the plant to take the necessary measures. Therefore, we propose that an effective legal framework should be created to improve the administrative regulations of NPPs.

(6) Contamination of Radioactive Materials

Due to the Fukushima NPP accident, the areas of land around the NPPs are contaminated with radioactive material. People were evacuated from these areas and many still live in temporary housings far from their homes.

The land needs to be cleared from this radioactive material before the evacuees can return to their homes, but there is a disagreement to what extent this process should be taken. Scientists suggest that the LNT model and the principles of ALARP or ALARA should be adopted. For laymen, however, this suggestion is somewhat misleading. The phrase

ISBN 978-4-88898-244-3

"as low as reasonably practicable (or achievable)" is often interpreted as "as low as possible", and environmentalists suggest that the contaminated soil should be removed as much as possible. However, such a viewpoint leads to a more difficult question: after the contaminated soil is removed, where should it be disposed to? No area is willing to accept such soil. It seems that the effects of low radioactivity are overestimated and the effects of stress caused by the evacuation are underestimated. Although the LNT model should make it possible to conduct a risk-benefit analysis, it is very difficult to allow people to accept its true meaning. Therefore, we propose that a better method of balancing the risk of low radioactivity and the benefit of early soil removal should be developed.

4. Reponses of JR East to the Earthquake and Tsunami

4.1 Tohoku Shinkansen, Commuting Railways around the Tokyo Metropolitan Area, and Local Lines along the Sanriku Coastal Line

(1) Tohoku Shinkansen

When the earthquake occurred, 18 trains were in service, and one train was operating at a speed of 270 km/h. The early detection system for earthquake motions successfully responded to the occurrence of the earthquake and all trains came to an emergency stop. Derail prevention rails successfully prevented all the trains that were in service from derailing. There were no passenger injuries that were reported.

The successful management of these trains is mostly attributed to the well-prepared countermeasures of JR East; however, we would like to point out some of the fortunate conditions. One is that the Tohoku Shinkansen line runs parallel to but at some distance from the coast, and because the seismic center was in the Pacific Ocean, the train was far enough for the early detection system to work in a timely manner. Another is that only a few people were on the platform of Sendai station, since the earthquake occurred soon after the train departed. We should take these fortunate conditions into consideration.

(2) Commuting Railways around the Tokyo Metropolitan Area

(a) Overview

The Yamanote Line of JR East provides some examples of the problems that are likely to arise after an earthquake. The following three problems can cause railway services to be suspended:

- An upheaval of the railway tracks;
- Displacement of the insulators for the overhead wires; and
- Detachment of the overhead wires.

(b) Timeline of the Decision not to Resume Operations

The earthquake occurred at 14:46 JST. Inspection teams were organized immediately and 12 parties (24 members) were allocated to inspect the railway tracks and related facilities. The Yamanote Line has a circular route that is 34.5 km in length and its inspection started at 15:40 JST. An upheaval of the railway track was discovered at 18:05 JST, and an announcement was made to the public and mass media at 18:20 JST that all JR lines would not resume service that day.

Some criticized the decision and timing of the announcement, but we consider that it was unavoidable. The upheaval of the railway track could have caused serious accidents, and the restoration process for such damages is lengthy. In addition, many commuting lines run radially from or across the Yamanote Line. Therefore, the decision not to resume all commuting train services was reasonable. Although the unavailability of the JR commuting train services caused many people to spend the entire night at their offices, a better decision could not have been made under such circumstances.

(c) Resumption of Service

Many workers were needed to repair the damaged railway track, but transporting them to the site was very difficult because many of the roadways were congested. It took more than 2.5 hours to transport the workers and materials. The restoration efforts commenced early the next morning and finished at 06:58 JST. Preparations were then made to resume service. The Yamanote Line resumed service at 08:36 JST. Considering the amount of traffic and the continuous efforts throughout the night, we consider that the best efforts were made.

(3) Local Lines along the Sanriku Coast

Following the occurrence of the earthquake, the trains came to an emergency stop and passengers were evacuated to places of refuge. In addition, 27 trains were located between stations. Five of those trains along the Sanriku coast

ISBN 978-4-88898-244-3

were swept away thereafter by the tsunami. However, since the employees of the railway company successfully guided the passengers to the places of refuge, none of the passengers were injured or became missing. Some of the employees, at their own judgment, followed the advice from older passengers who knew the nature of a tsunami. Such examples demonstrate the importance of training and the use of independent judgment.

The area along the Sanriku coastline has been struck by tsunamis many times in the past. The elderly passengers proved that the lessons learned from the previous tsunamis were beneficial. The successful evacuation from the trains demonstrated the importance relaying such experiences from generation to generation.

4.2 Proposals Concerning Countermeasures against Future Great Earthquakes

(1) Lessons from the Successful Examples

The success of JR East should of course be appreciated. However, it is very likely that another earthquake will hit the Tokaido area. Many conditions that existed with the 2011 Great East Japan Earthquake will not exist in that area. The Tokaido Shinkansen mostly runs along the coast where the amount of time between trains is much shorter. Thus, there are many passengers on the platforms at all times. These conditions would make it more difficult to stop the trains safely without any accidents. Therefore, studies should be conducted carefully to gain insight and knowledge from the success of JR East.

(2) Prevention of Social Disorders

When the safety of a railway is considered, the passengers in the trains are usually the main priority. However, the 2011 Great East Japan Earthquake revealed the importance of the safety of railway stations. When commuting trains are suspended, people tend to stay in or around the stations. However, a great earthquake is often followed by aftershocks, and once a station is hit by an earthquake, cracks may form in the walls and an aftershock may cause broken pieces to fall. Taking such possibilities into account, JR East ordered people to keep away from the station buildings. Although using a station as refuge building is not realistic, it is important to provide passengers with reasonable safety when they are in or around stations and waiting for services to resume.

The 2011 Great East Japan Earthquake has taught us that stopping trains to avoid accidents is not the goal for the crisis management of railway services. As the principal mode of public transportation in Japan, railways should provide reasonable safety measures for passengers that have come to the stations and have been told that all trains are out of service.

5. Necessity of a BCP as Shown by the Shortage of Beverages Bottled in PET Containers

5.1 Facts about PET Containers

Many buildings such as marine produce processing plants and the distribution centers of the pacific coast, retail stores like shopping centers and specialist stores, a group of food wholesale distribution centers in the Iwanuma industrial park adjacent to the Sendai airport, a group of factories near the Sendai port, the Fukushima NPPs, and a group of factories at the Kashima Industrial Complex were covered with water as a result of the tsunami. Buildings disappeared without leaving any trace of evidence and many of the other buildings were devastated by the force of the tsunami. For example, an ironworks in Iwate was covered with water and mud, and port facilities were badly damaged. A beer factory near Sendai port was directly damaged by the tsunami; four storage tanks collapsed and the production line was badly damaged. At the distribution center in the Iwanuma industrial park, the warehouses were washed away by the tsunami and the frozen food from the storage containers was scattered throughout the area.

Moreover, in many factories, ceilings collapsed and facilities were either completely destroyed or rendered unserviceable by the seismic motion. The physical distribution center stopped functioning because the products and raw materials on the shelves and the automatic warehouse collapsed. A significant amount of time was needed to shutdown and repair the machines, which made many factories and the physical distribution center unsure when their lines would resume normal services.

After the Fukushima Daiichi NPP accident, the head of water purification for the Tokyo Water Department announced that iodine 131 was detected in the water samples at the water supply plant in Kanamachi on 23 March 2011, and the levels of which were twice the levels that are considered safe for babies and infants. Although Kanamachi is roughly 200 km south of Fukushima Prefecture, where the Fukushima Daiichi NPP is located, the water from the Line River to the Edo River flew into the water purification plant.

After the government sent out an alert that households, hospitals, and daycare centers should not allow babies and infants to drink tap water, people began to panic and bought bottled water at supermarkets and convenience stores. The

ISBN 978-4-88898-244-3

metropolitan area had a water shortage and there were many people who asked their friends in the Chukyo or Kansai areas to buy and send them bottled water. The large beverage manufacturers ran at full capacity to meet the consumer demands, but their limit was reached. This had a negative effect on companies' turnovers because bottled water is a less profitable item than soft drinks; pricing became more competitive as a result. Moreover, the demand for PET bottles (plastic bottles) and their caps exceeded the supply. In particular, colored caps and caps with logos were not able to be produced.

The annual production of bottle caps was about 24 billion, and 90% of them were produced by three major companies. The manufacturing facilities at the Ishioka and Utsunomiya factories, which produce 40% of the bottle caps, had to stop production because of the earthquake and they could not keep up with the demand for mineral water. Usually, the color of the cap and the logo is different for different brands or product images. Thus, the setup at each facility has to change (e.g., the production line has to change every time the color is changed in accordance with the request of the customer) and production efficiency is low. Therefore, the manufacturer proposed to unify all the PET bottles with plain white caps. The Japan Soft Drink Association accepted the proposal, which then eliminated the shortage of bottle caps.

In a general supply chain, tier two companies supply tier one companies, tier three supplies tier two, and so on. In the context of this study, the companies are supplying parts and materials to the factories. The structure of a supply chain can be seen as a tributary that gives off branches to upstream sectors in a wide river. For example, an automobile consists of 2000 to 3000 parts. It begins with the material processing of thousands of small to medium sized components by various enterprises, which are eventually assembled into a car by the car company. However, recently, products such as semiconductors, which need dedicated facilities and clean rooms for the fabrication of their materials, require a production structure in which particular companies assume specialist roles. This type of structure is called a barrel or diamond structure and improves productivity and reduces costs.

When the 2011 Great East Japan Earthquake occurred, the Ibaraki plant in Hitachinaka City, Ibaraki Prefecture, which manufactured microcomputers for automobiles, suffered damages. The machines were severely damaged and the building with the clean room was damaged, which caused the plant to shutdown, since cleaning operations could not be carried out. The company that produced this microcomputer had a global share of 45%, and 25% of this was manufactured in that factory. Many other automobile parts were manufactured in the plants in the Tohoku region and parts became out of stock due to the damages sustained. Therefore, automobile assembly plants in Japan, including those in Hiroshima and Kyushu that were not directly damaged, had to stop operations and automotive factories in Europe were also subsequently forced into lengthy shutdowns. This led to a disruption in supply chains across the world.

5.2 Recommendations regarding the BCP

(1) Risk avoidance via decentralization and standardization

The 2011 Great East Japan Earthquake showed the importance of the plants in the Tohoku region and their ability to affect global economic activity. Automobile parts are not always manufactured in the Tohoku region, and it was beyond any prediction that the plants that were shutdown would affect the automobile factories across the world. Many people criticized this incident even though the 15 m tsunami that destroyed the back-up generators at the Fukushima Daiichi NPP was unexpected.

The companies in the global manufacturing industry did not have any stocks, because they were actively introducing new Toyota production systems. After this disaster, people were troubled by the low stock values; furthermore, during times of competitive pricing, the stock interest rate is a large financial burden on companies. Companies are expected to continue using the just-in-time system, which is likely to advance the decentralization of business operations, such as production, supply, and distribution, to avoid risks. For example, the plants that pursued higher efficiency by gathering distribution bases stopped functioning and they could not produce or sell items, because the raw materials and products fell from the racks of the automatic warehouses. Therefore, some companies considered distributing their physical distribution base to several places and having a simple rack warehouse where damages can be overcome manually. Furthermore, some companies distributed databases by introducing cloud computing and moved their suppliers to the western regions of Japan or to a location outside of Japan. Movements are being made to distribute the production bases to different locations, but the danger of

ISBN 978-4-88898-244-3

technology leaks needs to be taken into consideration.

On the other hand, they promote the standardization and communalization of the operation systems for vehicular control systems in the automobile industry and the Ministry of the Economy, Trade, and Industry plans to promote the communalization of automobile parts following this disaster. They will focus on the cases in which vehicle factories stopped operation not just in Japan but worldwide, which disrupted the supply chain for vehicle parts. They have also already begun the standardization and communization of specific parts. There is increasing interest in such collaboration even though there is a risk of decreasing the motivation to improve the quality of parts and reduce costs, because the element of competition between the parts manufacturing companies would be removed.

(2) Reconsidering the performance of the BCP

In 2008, each company created a BCP in case they experienced an emergency. Some companies authenticated the standards of the global BCP management (BS 25999-2007). A plant that produces laptops in Date City, Fukushima, suffered damages because of the disaster. There is a company that can transfer operations to a factory in Shimane Prefecture in accordance with its BCP. Many companies confirmed the safety of their employees when the 2011 Great East Japan Earthquake occurred; however, it was impossible to continue operations due to the damages to the facilities and supply chain disruptions. The BCP was supposed to work on specification of priority business, a consultation of service level, alternatives of global business center, agreement for the employee and education, but the BCP did not work because tsunami waves that were higher than expected hit the coastal zones, surpassed the embankments, and caused devastating damage.

(3) Reducing the Risk of Power Outages in Supply Chains via Decentralized Power Generation

During the Great East Japan Earthquake Disaster, the destroyed supply chains caused setbacks when attempting to deliver products to the markets. Generally it can be said that industrial processes deal with supply chains that consist of many companies. Even if a company is not directly affected by electrical power outages, operations may become impossible if other companies upstream in the supply chain are without electricity. As a result, the final product cannot be manufactured.

From this point of view, this study investigates the possibility of sustaining the operation of supply chains through the inclusion of decentralized power plants. Factories in a supply chain are sometimes located in a single power supply system or in multiple power supply systems. Simplified mathematical models were employed in this study to evaluate the probability of a sustainable power supply throughout the entire supply chain.

(a) A Supply Chain within One Power Supply System

The supply chain consists of one assembling factory to which parts and materials are supplied by N additional factories. In this section, one power supply system provides electricity for all the factories of the supply chain as shown in Fig. 5(a). Each factory has its own distributed power plant, which has a certain capacity to maintain the power supply in case the power supply system stops working. It is assumed that the probability of a power supply outage is P_0, where the suspending probability of the distributed power plants is P. When the supply chain relies on only the power supply system, which is regarded as a reference, the probability of malfunction of the supply chain is equal to P_0.

Here, P_1 represents the malfunction probability when the factories have distributed power plants. There are two cases where the supply chain is sustainable: one is that the power supply system is working, and the other is that the distributed power plants are all operating when the power supply system stops. This probability is expressed as follows:

$$P_1' = 1-P_0+P_0(1-P)^{N+1}$$

Then, the malfunction probability can be described as follows:

$$P_1 = 1-P_1' = P_0[1-(1-P)^{N+1}] \qquad \text{eq. 1}$$

The ratio of this probability to the probability of the reference case is defined for an index as follows:

$$R_1 = P_1/P_0 = 1-(1-P)^{N+1} \qquad \text{eq. 2}$$

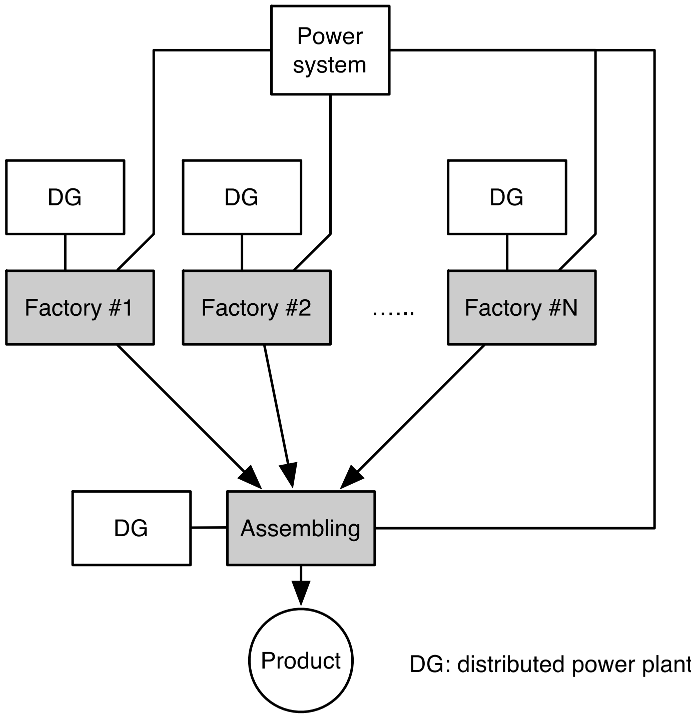
This index indicates that the ratio does not depend on the reliability of the power supply system.

Fig. 6 shows a numerical example where P_0 is assumed to be 0.1% and P is considered to be larger than P_0, i.e., P=0.1–1.0%. The following can be derived from the results.

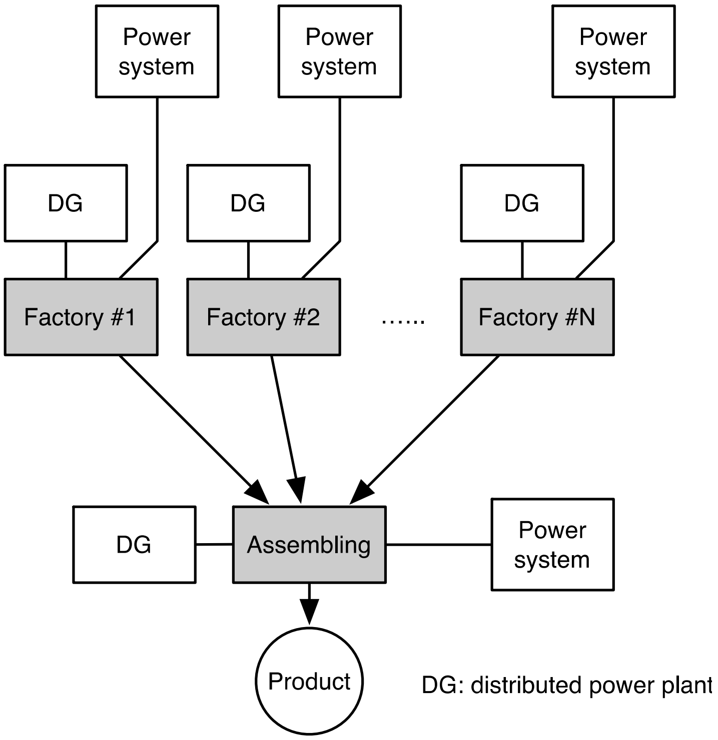
- When all factories are equipped with distributed power plants, the malfunction probability of the supply chain is

ISBN 978-4-88898-244-3

significantly reduced compared with that of the reference case.
- The malfunction probability increases as the number of factories increases.



(a) The case of one power supply system.



(b) The case of multiple individual power supply systems.
Fig. 5 Schematic of the power supply flow in the supply chain.

ISBN 978-4-88898-244-3

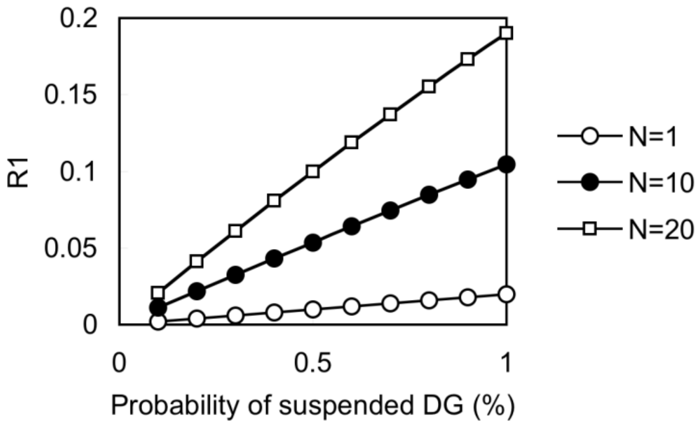


Fig. 6 Malfunction probability when using one power supply system.

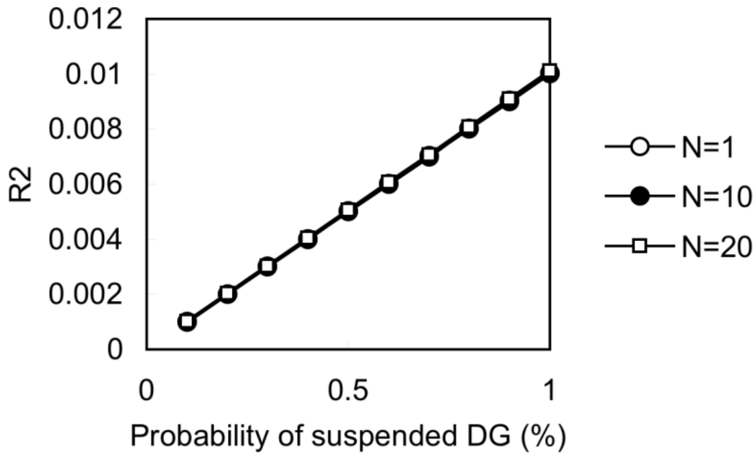


Fig. 7 Malfunction probability when using multiple power supply systems.

(b) A Supply Chain with Multiple Power Supply Systems

In this section, it is assumed that each of the factories in the supply chain is located in different power supply systems. Fig. 5(b) illustrates the schematic flow of electricity for this case.

As a reference, the probability that the supply chain is sustained without distributed power plants is considered, which implies that all of the power supply systems are in operation. The probability can be expressed as follows:

$P_2' = (1-P_0)^{N+1}$

Hence, the malfunction probability can be represented as follows:

$P_2 = 1-P_2' = 1-(1-P_0)^{N+1}$ eq. 3

When either the power supply system or the distributed power plant for each factory is available, the supply chain can operate. The following expression describes the probability that all factories are operating:

$P_3' = (1-P_0P)^{N+1}$

The malfunction probability is denoted as follows:

$P_3 = 1-P_3' = 1-(1-P_0P)^{N+1}$ eq. 4

An index is defined as the ratio of this probability to that of the reference case as follows:

$R_2 = P_3/P_2 = [1-(1-P_0P)^{N+1}]/[1-(1-P_0)^{N+1}]$ eq. 5

Fig. 7 depicts a numerical example with the outage probability of power supply systems, P_0, which is

ISBN 978-4-88898-244-3

commonly assumed to be 0.1%. The results consequently imply the following.
- Incorporating distributed power plants in the supply chain is very effective to reduce the malfunction probability, i.e., less than 0.01 in terms of the R_2 index in the example.
- The malfunction probability does not depend on the number of factories in the supply chain.

The analyses suggest that when distributed power plants are installed in the supply chain, the malfunction probability can be decreased quite effectively regardless of the conditions of external power supply systems; that is, one power supplier or multiple power suppliers provide electricity for each factory of the supply chain. In other words, it is not enough for only a portion of the supply chain to be equipped with BCP measures when attempting to ensure the sustainability of the entire supply chain. In order to reduce the risk of malfunction, in terms of a continuous power supply, it is important to have backup power plants in all factories in the supply chain.

6. Proposals from the Viewpoint of Crisis Management with regard to Safety Measures

6.1 Safety Measures and Crisis Management

When designing machines, three steps are usually taken to ensure that they are safe. First, they are designed to be inherently safe. Second, safety guards, alarm buzzers, or other measures are used to avoid accidents. Finally, information regarding residual risk is provided to users.

These three steps may be useful for designing large-scale systems such as NPPs. However, placing too much emphasis on the first step is not appropriate, especially when the causes of the accidents can only be predicted based on probability. For example, the height of the largest tsunami that could possibly reach a NPP during its lifetime cannot be precisely predicted. Therefore, no NPP can be inherently safe, regardless of the height of its protection wall. Even in such a situation, the design basis should be reasonably chosen, but one should always be aware that an event beyond the design basis could occur.

Accordingly, when a design basis is chosen, one should first consider what kind of accident an event beyond the design basis could bring about. Then, a chain, or a cascade, of prevention measures should be put in place. Such measures should include well-structured crisis management procedures. In this sense, designing crisis management procedures should be conducted when designing a large-scale system. The safety of a large-scale system cannot be achieved only by implementing the design basis.

6.2 Definition of Safety and Risk Communication

The internationally accepted definition of safety is the “freedom from unacceptable risk”. Under this definition, whether a large-scale system is regarded as safe or not depends on the recognition of an acceptable risk by the public.

As mentioned above, after a design basis is chosen and a chain of accident-prevention measures are taken, there will be one remaining risk. If that risk is acceptable, the system is safe. However, if the public does not regard that risk to be acceptable, the system would not be regarded as safe. In this regard, it should be noted that people tend to regard a risk as unacceptable if it is unfamiliar. Therefore, once a system is designed and the designer determines it as safe, they should persuade the public that the remaining risk is acceptable. This is why risk communication is important in developing new technologies. Without appropriate risk communication, no new technology can be accepted by the public. Therefore, engineers should incorporate the basic concepts and techniques required for risk communication into their skill set.

ISBN 978-4-88898-244-3