

Japan's Nuclear Energy and Hydrogen Alternatives

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Japan's Nuclear Energy and Hydrogen Alternatives

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Noriko Behling

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Japan's Nuclear Energy and Hydrogen Alternatives

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論 文 内 容 の 要 旨

It has been seven years since the Great Tohoku Earthquake and Tsunami. The Fukushima accident costs as estimated by several independent sources are expected to top \$500 billion, while disruptions to the lives of tens of thousands who evacuated contaminated areas can never be truly measured. Fukushima is not the only nuclear accident that has happened in Japan. There have been several, some of them leading to loss of life, putting Japan in the category of having one of the more accident-prone nuclear programs. This thesis conducts a thorough review of the Japanese nuclear history, nuclear programs, successes, failures, and concludes with suggestions as to how safety could be improved and the prospects for supplementing or replacing nuclear energy with a hydrogen alternative.

Japan is now at a crossroads with respect to alternative power sources. The government has yet to address the fundamental question of how Japan can maintain a safe and economically viable nuclear power industry over the long term. Current policy, which is to pursue a step-by-step approach to restart reactors, does not appear to be economically or politically viable. All 54 power reactors were shut down following Fukushima and now must meet new safety criteria before they can restart. So far only nine have met the criteria.

History shows how the interaction of technology, institutions, and human behavior have led to nuclear events and accidents in unexpected ways. Chapter 1 examines Japan's motivation after World War II to increase electricity capacity. It describes how Japan enacted legislation and established regulatory structures to rapidly build nuclear R&D institutions as well as lay the foundation for the commercial nuclear industry. This period was notable for irregularities and lack of transparency with respect to nuclear safety. The chapter examines how bureaucratic entities reacted to nuclear events and accidents and describes how this affected government oversight of the nuclear industry.

The establishment of R&D institutions led to the development of Japan's Four Big National Projects, including uranium enrichment, advanced thermal reactors (ATRs), fast breeder reactors (FBRs), and reprocessing capabilities. These projects evolved over time as Japan's priorities changed and the global nuclear industry matured. Government ministries made efforts to promote these projects and the resulting technology was transferred to the private sector for commercialization. In the end, none of the Big National Projects successfully transitioned to the commercial sector or became commercially successful. Chapter 2 discusses two of the Big National Projects, the ATR and FBR. FBR Monju was the most highly regarded project among the four. Japan saw it as key to the country's energy independence because it would create more fuel than it consumed. If the project was successful, Japan would no longer need to depend on foreign imports of uranium. FBR Monju was not successful. It had two major accidents, operated only for several months, and cost Japan over \$10 billion. The

commercial sector did not see the project as commercially viable. In Chapter 3, we examine Japan's effort to commercialize the other two Big National Projects, enrichment and reprocessing. Japan's R&D institutions, pressured to use indigenous technology for the Rokkasho Reprocessing Plant, ran into technical difficulties by adopting technology that was not yet mature.

Chapter 4 described the rapid growth in worldwide reactors as well as Japan's plans to rapidly expand its nuclear power reactor fleet. In the early 1960s, Japan had a good start in commercializing the US-designed light water reactors. Following the 1973 oil shock, the government accelerated reactor construction by means of the Dengen Sampo (Three Power Laws) to facilitate the acceptance of nuclear reactors in various regions. The law was successful in encouraging reactor construction, but it also had some side effects: It facilitated the building of multiple nuclear reactors at one plant location, which increased the risk that an event such as a major earthquake and tsunami might affect reactors that were clustered at the same location. Chapter 5 discusses how the Fukushima Daiichi nuclear disaster happened and how Japan is coping with the costs of damage compensation, decontamination of land and water, locating melted fuel, and decommissioning of the reactors. Japan's need for a permanent nuclear waste storage site and the challenge of finding an acceptable location for the facility are described in Chapter 6. The scope of the reactor decommissioning program is explained in Chapter 7. Japan currently has 21 reactors slated for decommissioning, which is a three-fold increase compared with the pre-2011 period. These tasks will require skilled talent at the very time that Japan's nuclear industry is having difficulty in attracting new talent. The declining interest of Japan's young engineers and scientists is highlighted in Chapter 8.

How Japan might manage its nuclear reactor fleet in the future is the topic of Chapter 9. Alternative scenarios, including upgrading and hardening existing reactors or constructing a fleet of advanced reactors are assessed in terms of costs and safety implications. The human dimension of safety is also discussed in terms of the need for experienced program managers, the application of lessons learned, and the adaptation of management principles of Admiral Rickover and the findings of the Kemeny Commission's assessment of the accident at Three Mile Island.

As an alternative to the nuclear power scenarios, Chapter 10 considers how Japan could broaden its energy resources by implementing a Basic Hydrogen Strategy. Such a strategy would ensure that all power sources, including nuclear power, renewable energy, and hydrogen-based power are fully integrated in terms of construction, interconnection, and concepts of operation.

Considering the challenges facing Japan's nuclear industry and the limited progress that has been made over the last decades on hydrogen-based technologies, Chapter 11 concludes why progress has been slow and recommends steps that government, industry, and academia could take to accelerate progress in both fields. These steps are similar to those enacted in 2002 by US President Bush to support fuel cell and hydrogen development. A potential goal for Japan's nuclear and hydrogen energy alternatives would be to create and manage a nuclear power infrastructure that is as safe as humanly possible and which is integrated with a hydrogen infrastructure. If the technologies were integrated, for example, nuclear reactors could be used to create hydrogen during periods when electric power was in surplus, such as when renewable energy sources were at peak output. Hydrogen could be converted into forms that are amenable to long-term storage and which minimize carbon release. Hydrogen could be converted back and used to generate power when demand was high. The development of a hydrogen infrastructure would also hold the potential for hydrogen to supplement, or possibly replace nuclear energy. Investments in hydrogen and fuel cell technology could provide "off-ramps" from nuclear if the situation warrants.

Dedication

I dedicate this PhD Dissertation to:

My father, Riichi Hikosaka, a physicist and industrialist from the Imperial Kyoto University who died too soon with his dream and aspirations cut short.

My mother, Chiyo Hikosaka, a teacher and a devout Catholic and Buddhist, who raised three cosmopolitan daughters on her own, Nobuko residing in Japan, Satoko in Germany and me in the United States.

Prof. Hitoshi Yoshioka, who gave me the inspiration to research this study of Japan's nuclear power industry. Dr. Yoshioka was a prominent professor in nuclear and science history and served in government nuclear policymaking forums. He died on 14 January 2018. I miss him for his gentle demeanor and quiet wisdom.

Japan's Nuclear Energy and Hydrogen Alternatives

A Dissertation for the Degree of Doctorate of Environmental Engineering

Noriko Behling

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Chapter 1:

Laying the Foundation for Energy Independence

CHAPTER 1: Laying the Foundation for Energy Independence

Abstract

In December 1953, US President Eisenhower announced his Atoms for Peace policy at the United Nations, which would promote nuclear technology to generate clean, inexpensive electric power. Japan's leaders were receptive to offers by the United States to help build a nuclear power plant in Japan. Japan wanted to acquire technology that spanned the entire nuclear fuel cycle, from uranium enrichment to spent fuel reprocessing. By encouraging indigenous development of much of the technology, Japan's leaders hoped to nurture a robust nuclear industry and achieve energy independence. Japan established laws to promote nuclear power, developed a long term plan, and built major research institutions to study all aspects of the technology. Bureaucratic rivalries, technical mishaps, coupled with lack of transparency, slowed progress and set the stage for serious accidents that plagued the industry years later. Meanwhile major hydrogen and fuel cell research activities did not get started until the 1970s. R&D focused on developing reliable, durable, and inexpensive technologies that were competitive with conventional power generation systems. Over the past 20 years, performance has substantially improved but improvements remain incremental in nature.

Introduction 1.0

This dissertation tells the history of nuclear energy and hydrogen energy alternatives. It considers program histories, successes and failures, contributions and costs, and provides critical perspectives on how these alternatives might one day present an integrated approach to power generation in Japan.

We will trace the origins of Japan's hydrogen energy programs and summarize its current status and future challenges. Japan's nuclear energy programs represent a considerable investment and provide a significant fraction of Japan's total power generation capacity. For this reason we recount the history and scope of the nuclear energy industry in some detail. We consider early developments, explain the legal and bureaucratic underpinnings of programs, and describe the accidents that have led the Japanese people to lose trust in the safety and reliability of nuclear power. We conclude with a discussion of the cost of regaining that trust by striving for a zero-accident culture that addresses all parts of the nuclear fuel cycle, including the need for effective program management to address both technical and human shortfalls with respect to safety.

Recognizing the difficulties in achieving a zero-accident culture, this dissertation considers the pros and cons of using hydrogen in conjunction with fuel cells to supplement or replace nuclear energy. Today Japan depends on overseas fossil fuels for almost all of its primary energy supply and at the same time, the government has mandates to ensure energy security and to reduce greenhouse gas emissions. Japan's government has led the way in energy conservation, the expansion of renewable energy, the utilization of natural gas and the consideration of domestic carbon capture and storage. Hydrogen, however, has the most favorable attributes of all energy sources because its use emits no carbon dioxide and it can be used as an energy carrier to store, carry, and, in effect, to enable the use of renewable energy. As Japan's Ministerial Council on Renewable Energy stated last year, hydrogen could be a trump card in ensuring energy security and preventing further climate change.

The manuscript is divided into eleven chapters:

1. The leadership role played by the nuclear R&D community to lay the foundation and build the infrastructure for nuclear energy, including both government institutions and the private sector.
2. R&D activities that focused on Japan's search for advanced nuclear power technologies that could help realize the dream of energy independence.
3. How Japan attempted to commercialize nuclear technologies and the progress that was made over the last two decades.
4. How Japan came to focus on the practical matter of supporting the construction of a large fleet of nuclear power plants and reactors and the success and problems that the utilities encountered in supplying increasing amounts of electricity to Japan.
5. The scope, consequences, and larger implications of the Fukushima nuclear disaster.
6. The scope and cost of Japan's reactor decommissioning program.
7. The challenges that the government faces in building long-term storage of nuclear waste.
8. The health and status of nuclear programs across the ten major power companies and the shortage of skilled engineers and managers to support suppliers and manufacturers.
9. The tasks that Japan's government and industry leaders must address to get on a path that creates a genuine culture of safety and restores nuclear power to a place of trust and confidence in the minds of the Japanese.
10. Prospects for adopting an alternative energy path that is based on hydrogen and associated fuel cell technologies as a clean energy alternative.
11. Conclusions

1.1 Terminology and Perspectives on Energy Alternatives

Given the complexity of the subject, it is important to have a conceptual and technical framework, as well as an historical perspective for discussing hydrogen and nuclear energy alternatives. We begin with hydrogen and a related technology, fuel cells.

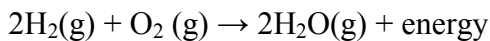
1.1.1 Hydrogen and Fuel Cell Technologies

Hydrogen is the most abundant element in the universe and a promising source of fuel. The pure hydrogen gas is clean with no carbon. On Earth, hydrogen is found in the greatest quantities as water. It is present as a gas in the atmosphere only in tiny amounts – less than 1 part per million by volume. Any hydrogen that does enter the atmosphere quickly escapes the Earth's gravity into outer space ([Royal Society of Chemistry, 2018](#)). Thus, we must produce hydrogen on Earth from hydrocarbons and water.

There are a number of methods to produce hydrogen. The cheapest, most efficient, and most common is natural gas (CH₄) reforming using high-temperature steam. This process also releases carbon in the form of CO₂ carbon and therefore requires carbon sequestration. Other, cleaner methods include electrolysis (an electric current splits H₂O into hydrogen and oxygen), high-temperature water splitting (high temperatures generated by solar concentrators or nuclear reactors drive chemical reactions that split the water molecule to produce hydrogen, fermentation (biomass

that is converted into sugar-rich feedstock can be fermented to produce hydrogen), and photo-electrochemical water splitting (production of hydrogen from water using special semiconductors and energy from sunlight) (AFDC, 2018).

These production methods are costly and need R&D to become economically viable. Nonetheless, hydrogen offers a promising future. For this reason, Japan is promoting the vision of a “Hydrogen Society” to be achieved in the 2040s to 2050s. If the Hydrogen Society becomes a reality, it is possible that hydrogen-based energy sources could supplement or replace nuclear energy. When H_2 is burned in a flame of pure hydrogen gas, it reacts with oxygen (O_2) and forms water (H_2O) and the release of energy:



When used to power fuel cells, hydrogen is directly converted into electrical energy. This efficiency is achieved because fuel cells convert chemical energy contained in H_2 into electrical energy in a single step, extracting more useful energy from the same amount of fuel than any other known device, with very limited impact on the environment. The flow of hydrogen in a fuel cell can be seen in Figure 1.1. The fuel cell itself would be a critical enabling component of the Hydrogen Society. Fuel cells have physical components and characteristics that are similar to those of a battery.

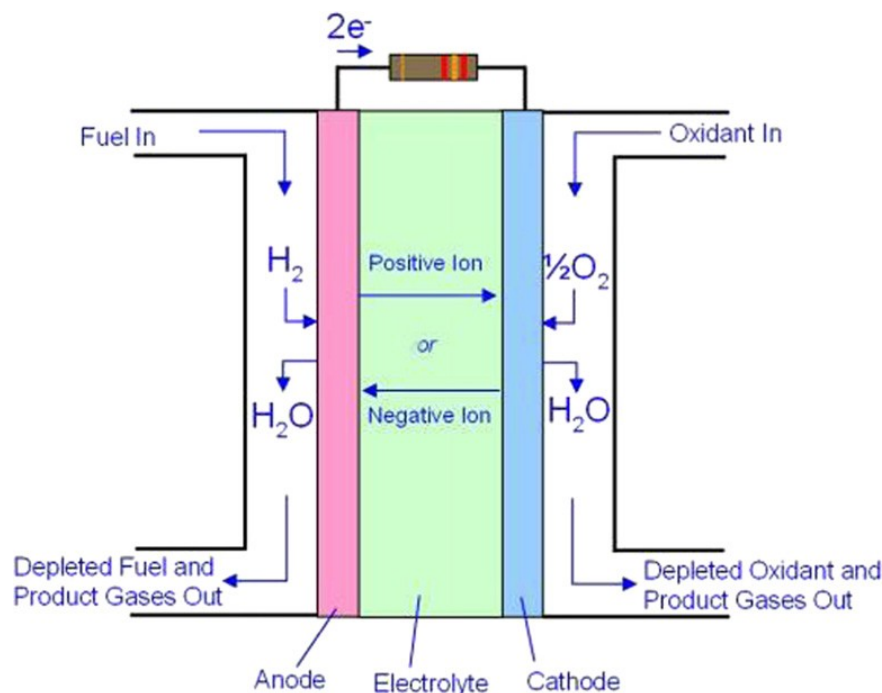


Figure 1.1 Schematic Illustration of a Single Cell. Source: USDOE (US Department of Energy) “Fuel Cell Handbook,” produced by EG&G Technical Services for the USDOE Office of Fossil Energy, National Energy Technology Laboratory, 7th edition, November 2004.

Like a battery the fuel cell is a simple device, consisting of only four basic components that support electrochemical reactions. They are:

- An electrically negative electrode, called the anode with or without a catalyst, to which a fuel (hydrogen) is supplied;
- An electrically positive electrode, called the cathode with or without a catalyst, to which an oxidant (oxygen) is supplied;
- Electrolyte (a substance that allows movement of electrically conductive ions) that separates the electrodes;
- An external electric circuit connecting two electrodes.

Fuel cells differ from batteries in one important respect: fuel cells are theoretically capable of producing electrical energy for as long as fuel and oxidant are supplied to the electrodes. The electrochemical reactions take place at the electrodes, producing or consuming electrons and ions ([Behling, 2013](#)).

Electrons are produced at the anode and are consumed at the cathode. Electrons move from anode to cathode via an external circuit—a process that results in the electric current that the fuel cell produces. Within the fuel cell, ions flow between anode and cathode. Ions are individual atoms that have an uneven number of protons and electrons, and thus possess a net positive charge (ions with a positive charge are called cations and ions with a negative charge are called anions).

A hydrogen atom, which is the simplest case, has a nucleus of one proton that is balanced by a single electron in its surrounding electron shell. A hydrogen cation has no electron, and therefore carries a net positive charge. The cation flows to the cathode where it combines with electrons flowing through the external circuit. Some electrodes require electrocatalysts (commonly precious metal platinum) for the reaction to proceed at the desired rate.

In a fuel cell, ion creation is continuous and enabled by the electrolyte, which allows ions to move between the two electrodes. The electrolyte also serves as a physical barrier to prevent the fuel and oxidant gas streams from directly mixing. The process of consuming electrons and ions at the cathode also creates reaction waste products and heat, which must be transported away.

The working of a fuel cell is nothing if not complex; its various chemical and electrical components and processes are intricate, delicately balanced, and dynamic. The most critical part of a fuel cell is the so-called three-phase boundary or interface, which is the area where the electrodes and the electrolyte meet and the electrochemical reactions take place. For the interface area to be active, it must be exposed to the reactant (fuel or oxidant), be in electrical contact with the electrode, also be in ionic contact with the electrolyte, and contain sufficient amounts of electrocatalyst for the reaction to occur.¹

These requirements lead to complex performance and cost trade-offs. The density or thickness of the electrolyte and the nature of the interface play a critical role in the electrochemical performance of both liquid and solid electrolyte fuel cells. In fuel cells that use liquid electrolytes, the electrolyte could wet the electrodes excessively and flood them, lowering their ability to transport reactants to the electrolyte and causing degradation of cell performance over its life. In solid electrolyte fuel

¹ Fuel cell handbook. 7th ed. US: NETL, the US Department of Energy; November 2004.

cells, the challenge is how to engineer the interface so that the electrodes and the electrolyte remain electrically and ionically well connected and are efficiently exposed to the reactant gases. Also, in fuel cells that operate at low temperatures, rare and precious materials—commonly platinum—are needed at the interface to provide sufficient electrocatalytic activity, making the fuel cells extraordinarily expensive. In high temperature fuel cells, the electrocatalytic activity of the bulk electrode material is often sufficient to support the reaction, but high operating temperatures can cause other problems, including longevity issues.

1.1.2 Brief History of Hydrogen and Fuel Cell Development

The fuel cell was invented in 1839 by William Grove. Grove was a scientist and a lawyer in the courts of Common Law. He became a professor of experimental philosophy at the Royal Institution in London and then its vice-president. He subsequently was knighted and became a Lord Justice of the Queen's Bench.

Grove invented two electrochemical cells, the first in 1839 and the second in 1844. In the days before electrical distribution networks became available, batteries were the only practical source of electricity, and his intent was to invent a robust, practical battery. The first invention, the “gas voltaic battery,” was similar to conventional batteries in its compositions and purpose, but was based on an entirely new concept of electricity generation, and indeed became the forerunner of fuel cells.

Fuel Cell Classification

Fuel cells sometimes are classified by the type of fuel they use. Direct methanol fuel cells (DMFCs), for example, are a subtype of polymer electrolyte membrane fuel cells (PEMFCs). DMFCs use polymers as an electrolyte and methanol as fuel. There are six types of fuel cells currently under development including:

1. Proton exchange membrane fuel cells (PEMFCs) or polymer electrolyte fuel cells (PEFCs)
2. Direct methanol fuel cells (DMFCs)
3. Alkaline fuel cells (AFCs)
4. Phosphoric acid fuel cells (PAFCs)
5. Molten carbonate fuel cells (MCFCs)
6. Solid oxide fuel cells (SOFCs)

Grove probably never expected that his invention would keep the global science and technology community excited as well as exasperated for the next 170 years. Since his invention, scientists, engineers, and businessmen have dreamed that the fuel cell could deliver low cost, clean energy to power factories, homes, cars, appliances—virtually anything that uses electric power. Despite the best of intentions, this dream remains unfulfilled.

In the first 100 years after Grove's invention, many notable European scientists followed his footsteps and attempted to develop a fuel cell with commercial viability. They explored various

electrolytes and electrodes that could produce an electric current reliably and inexpensively. They also experimented with a variety of fuels, including wood, oil, coal, and coal gas. Coal was the major source of fuel in the nineteenth century, readily and easily available for public consumption at that time. Thus, the possibility of using coal in fuel cells drew particular interest among researchers and developers. For example, the direct carbon fuel cell (DCFC) was researched as early as 1896,² but researchers soon realized that an intense research and development was necessary to realize its potential. William Jacques, a US electrical engineer and chemist, described a DCFC in 1896 in a patent for a “Method of converting potential energy of carbon into electrical energy.” Jacques used coke electrodes in a molten NaOH electrolyte.³ Today DCFCs typically operate on carbon particles obtained from a variety of solid fuel feedstocks (Behling, N.H., 2018).

Over time enthusiasm for fuel cells gradually withered away. By the end of the nineteenth century, the internal combustion engine was invented, and the fuel cell was relegated to the status of a scientific curiosity.⁴ By the mid-1900s, however, fuel cell technologies started to make significant progress, and some fuel cells began to serve practical functions.

The first fuel cell used in practical application was the alkaline fuel cell (AFC) developed by British scientist Sir Francis Bacon. Bacon’s AFC technology was licensed by a US company, which developed it as the source of onboard power and drinking water for its Apollo lunar missions in 1962. A number of companies, both in the United States and Europe, sprang into action and began developing terrestrial applications of AFCs. They produced a number of prototype AFC products, but were unable to bring them to the commercial market. They found AFCs intolerant of carbon dioxide, which is omnipresent on Earth, and thus concluded AFCs to be unsuitable for terrestrial applications. Many companies abandoned AFC development by the 1970s.

In the mid-1970s, phosphoric acid fuel cells (PAFCs) came to be recognized as better suited for stationary, terrestrial applications. A number of US companies launched R&D of PAFCs. The US Government and electric and gas utilities started to assist those companies by funding their R&D and demonstrations. Japan followed in the US footsteps and tried to learn the PAFC technology. By the mid-1980s, attention focused on molten carbonate fuel cells (MCFCs) and by the 1990s on solid oxide fuel cells. Also in the mid-1990s, proton exchange membrane fuel cells (PEMFCs) came to be viewed as the most exciting technology; in fact, researchers and developers were able to build an automobile powered by hydrogen fueled PEMFCs.

None of these fuel cells achieved commercial success on any major scale. PAFCs entered the market in the early 1990s as the “first generation” fuel cell technology to be commercialized. A few hundred power plants were installed, but sales of most of them were completed with government and public subsidies. MCFCs also hit the market as “second generation” fuel cells in the early 2000. A small number of stationary power generation systems have been sold, also with subsidies. PEMFCs have been put on the commercial market recently; they are used as a small stationary power plant and the power source for material handling vehicles and emergency backup power

² Zecevic, “Electrochemistry of Direct Carbon Fuel Cell Based on Metal Hydroxide Electrolyte,” presentation at US DOE DCFC Symposium, Pittsburgh, P

³ US Patent number 555511.

⁴ Larminie James, Dicks Andrew. Fuel cell systems explained. 2nd ed. West Sussex, England: Wiley; 2003.

systems. A subtype of PEMFCs, direct methanol fuel cells, is also under development for use in small electronic devices.

Fuel cell researchers and developers are still struggling to develop reliable, durable, and inexpensive fuel cells that are competitive with conventional power generation technologies. Over the past 20 years, the performance of at least some fuel cells has been substantially improved based on improvements in the three-phase boundary interface. The improvements included reductions in the thickness of the electrolyte and the development of improved electrode and electrolyte materials which broaden the temperature range over which the cells can be operated. These improvements, however, are incremental in nature and do not constitute a technical breakthrough.

Major R&D efforts in Japan did not get started until the 1970s. Prior to that time, Japan had not been credited with significant fuel cell accomplishments, nor had it successfully brought fuel cell products to market (Behling, 2013). In reaction to the oil embargos, however, Japan began to invest in two large-scale energy R&D programs: the Sunshine Project (in 1973) and the Moonlight Project (in 1978). The Sunshine Project was to address the problems caused by energy shortages or embargoes and the Moonlight Project was to develop high-efficiency energy conversion technologies to reduce Japan's dependence on oil. These two programs were Japan's first, long-term, large-scale R&D programs, where METI would simultaneously sponsor multiple, multi-year R&D projects. In 1981, the Moonlight Project assumed responsibility for developing fuel cell technology, which was previously managed under the Sunshine Project. Prior to the shift of this responsibility, the Sunshine Project ran only a few minor AFC projects. The Sunshine Project and the Moonlight Project were consolidated into the New Sunshine Program in 1993, which continues to fund fuel cell R&D to the present day. Japan's hydrogen and fuel research efforts have greatly expanded since then and are described in detail in Chapter 10.

1.1.3 Nuclear Energy Terminology

Nuclear power generation has a complex taxonomy that can be understood by referring to the nuclear fuel cycle. The nuclear fuel cycle represents the progression of nuclear fuel from creation to disposal. It describes the various industrial processes by which nuclear material is prepared and used in nuclear reactors. Figure 1.2 shows the general concept of the fuel cycle, which is divided into three parts:

- **The Front End.** The front end of the cycle encompasses exploration for sources of natural uranium, mining, refining, conversion and enrichment. Enrichment is the process of increasing the concentration of fissile uranium (Uranium 235) to a level where it can be used in a reactor. Natural uranium contains only about 0.7 percent Uranium 235 and so must be enriched to a level between 3 and 5 percent. Once enrichment has occurred, the material can be fabricated into ceramic pellets, which are sealed into zirconium alloy tubes for use in reactors (World Nuclear Association (WNA), 2018).
- **The Reactor.** The reactor core contains sufficient radioactive fuel to sustain a fission chain reaction, which produces heat. Specific types of reactors are defined by their purpose, the type of coolant used to keep the reactor from getting too hot and the moderator that is used to control the rate of fission taking place in the nuclear fuel. Power reactors generate heat to

power steam turbines to produce electricity. Typically, these reactors use boiling water (BWR) or pressurized water (PWR) as coolant and moderator. A less common reactor uses heavy water (where the hydrogen atoms have both a proton and a neutron). A second category of reactors are designed to generate heat for power along with more fissile material. Such reactors are often referred to as Fast Breeder Reactors (FBRs). These reactors are designed to maximize the capture of highly energetic neutrons (which move fast) by a non-fissile isotope of uranium, which ultimately becomes a fissile isotope of plutonium. After reprocessing, this isotope can be used as reactor fuel (hence the name breeder). Moderators used in FBRs are selected to maximize this process. The most popular type is liquid sodium.

- **The Back End.** The back end of the fuel cycle is defined by the way in which spent fuel is disposed or reused.
 - In common boiling water or pressurized water reactors, once most uranium 235 has undergone fission or has been “burned,” the fuel needs to be removed from the reactor and stored in cooling pools. After a cooling-off period during which fission continues, the still-hot fuel can be safely transported to a long-term storage repository.
 - An alternative path for spent fuel typically applies to uranium that has been burned in an FBR. Once the spent fuel and fissile products have been removed from the reactor, it can be sent through a complex series of steps (reprocessing steps) to extract fissile plutonium and uranium, which can be blended with additional fissile uranium into Mixed Oxide (MOX) fuel. The fissile MOX can be burned as fresh fuel in a reactor, after which the high-level (highly radioactive) waste would be sent to a long-term storage repository ([USNRC, 2017](#); [WNA, 2017](#)).

The order of ideas in the manuscript follows the flow of this chart, from Front End to Back End. Discussion of historical trends in the nuclear industry can be found in the individual chapters.

One caveat: this dissertation never refers to “zero accidents.” It uses phrases such as “zero accident culture” and “near zero-accident level of safety” to convey that operators, designers, and managers of nuclear power plants should not have a mindset that is accepting of future accidents, however small the likelihood. Disasters are inevitable, but acceptance of them need not be. For this reason a zero accident culture should be understood as an aspirational goal for Japan—a desirable mindset if you will. Accidents will occur, so zero accidents can only be achieved for a finite period of time. But that period should be as long as possible.

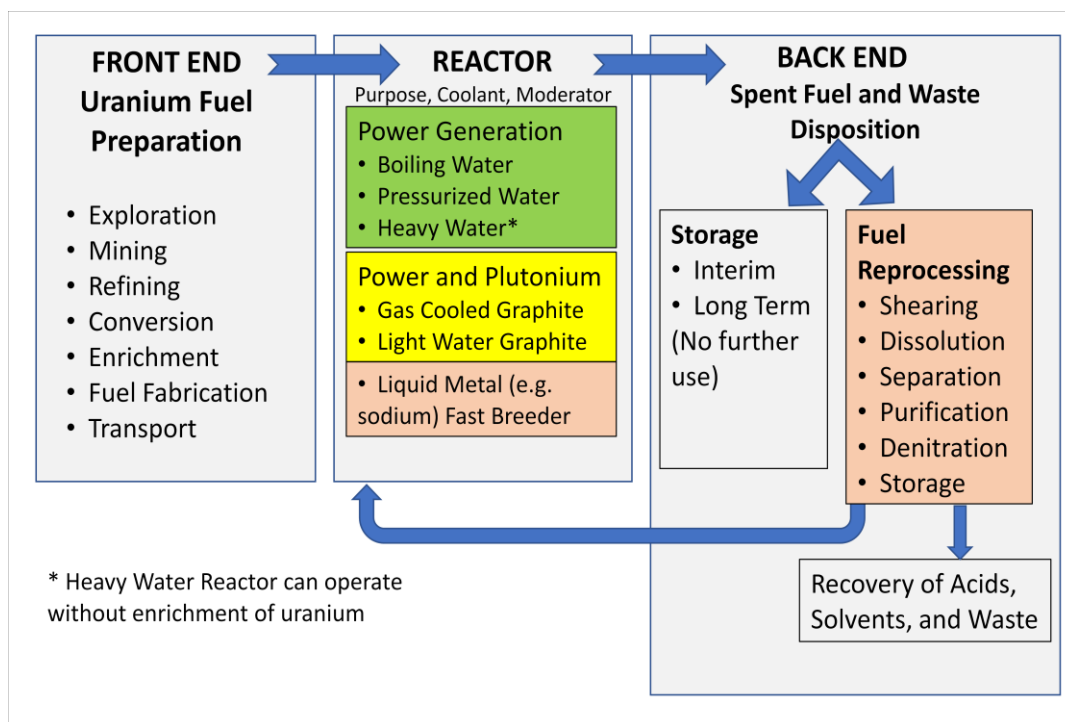


Figure 1.2 The Nuclear Fuel Cycle

Source: Authors

1.2 Japan's Commitment to Energy Independence

In December 1953, US President Eisenhower announced at the United Nations his plan for Atoms for Peace—a plan that would use nuclear technology to generate electric power as a way to better mankind. A year later, the President broke ground for the first nuclear power plant at Shippingport in western Pennsylvania. Admiral Hyman Rickover, the father of the US nuclear Navy, was charged with managing the program. Thirty-two months later, on December 2, 1957, the reactor achieved criticality. The plant began to generate electric power within days.

Japan's political leaders watched the Atoms for Peace program unfold and were receptive to offers by the United States to help build a nuclear power plant in Japan. Nakasone Yasuhiro, a member of the Diet and later Prime Minister, saw nuclear power as an area where Japan could both benefit and contribute to the world. (WNA, 2018).

Japan's leaders were not just interested in nuclear power generation. They also wanted to acquire technology that spanned the full nuclear fuel cycle, including uranium enrichment, spent fuel reprocessing, and development of Advanced Thermal Reactors (ATRs) and FBRs. Japan also wished to develop all the technology indigenously. Only a handful of advanced countries had the resources to embark on such a complex and risky venture. However, Japan's entire policymaking system, including the Diet, the Cabinet, the ministries, the electric and manufacturing industries, the banking industries and academia all embraced the idea that Japan should have both nuclear power and indigenously developed advanced nuclear technologies (Yoshioka, 2013).

Japan faced numerous obstacles to building the needed nuclear infrastructure. The challenge was made even more complicated by the absence of a robust governing structure to oversee nuclear power development and a policy of relying heavily on indigenous development of the technology, even though overseas technologies were less costly, well-tested and proven ([Tolliday, 2012](#)).

1.3 Laying the Foundations for Nuclear Power in the 1950s and 1960s

Throughout the 1950s, electricity was a scarce commodity and absolutely vital for rebuilding Japan's industrial base. Moreover, on order of the Supreme Commander for the Allied Powers (SCAP), Japan had to transform, by May 1951, the Nippon Hassoden Kabushiki Kaisha (Japan Electric Generation and Transmission Company)—the semi-governmental trust company—into nine regional electric companies. The purpose of this change was to end the state monopoly on production of electricity.

The nine companies lacked capital and were financially too weak to build power plants, however. To remedy this, Japan enacted the Degen Kaihatsu Sokushin Ho (The Power Source Promotion Law) in July 1952 and created a semi-governmental Dengen Kaihatsu (Electric Power Development Company) (EPDC) (now J-Power) in September 1952. The Ministry of Finance (MOF) provided 67 percent of the capital, with the rest invested by the nine companies. The EPDC was dynamic and built many hydroelectric dams and power plants. The first major work was the Sakuma dam in Shizuoka Prefecture. Construction was estimated to take 10 years, but EPDC imported US technology and built the dam in three years, completing it in 1956. EPDC continued to build many other dams; it built Okutadami Dam in 1960, Tagokura Dam in 1960, Miboro Dam in 1961, as well as coal and oil thermal power plants. Today, J-Power owns 61 hydroelectric power stations in Japan, with a total capacity of about 8.6 GW, 22 wind farms with a capacity of 443.6 MW, 12 thermal plants at 9 GW and one geothermal plant (15 MW) (J-Power, 2018) ([J-Power, 2018](#)).

While EPDC was doing a fine job, Japan's leaders had become more interested in nuclear power generation. The San Francisco Peace Treaty went into effect in April 1952 and Japan once again became a sovereign nation. Restrictions were lifted on using nuclear energy to generate power. In March 1954, three months after Eisenhower's Atoms for Peace speech, a budget of \$2.6 million⁵ was submitted to the Diet to explore the possibility of nuclear power in Japan. The budget quickly passed and was quickly authorized. The budget represented a significant amount for a first-time budget—over five percent of the then total Japanese budget of \$50 million. The Liberal Democratic Party representative Yasuhiro Nakasone had proposed the budget, along with a group of representatives from multiple parties ([Yoshioka, 2013](#)).

1.4 The Atomic Energy Commission Sets Priorities

Soon after passage of the nuclear budget, Japan enacted the Atomic Energy Basic Law (Law No. 186) in December 1955. The law laid out the basic principle that research, development and industrialization of nuclear power activities in Japan should only be for peaceful purposes. The law

⁵ In this manuscript, the exchange rate of 100 yen to a dollar is used for simplicity sake.

also specified the need for establishing the Atomic Energy Commission of Japan (AEC) and research institutions to promote nuclear R&D.

Days later, the Diet passed the AEC Establishment Law (Law No. 188). The AEC was to be Japan's highest nuclear policymaking body in the Cabinet Office. The law specified that the AEC's policy must be fully respected by the prime minister—meaning that the prime minister largely had to defer to the AEC's recommendations. The law also specified that the chairman of the AEC would have the rank of cabinet minister ([Houko, 2018](#); [Cabinet Office, 2013](#)).

As the highest nuclear policymaking authority in Japan, the AEC could authorize or reject nuclear policy that had been developed by other ministries and could issue directives to ministries through the prime minister. In September 1956, the AEC published its first Long-Term Plan for Development and Utilization of Nuclear Energy (nicknamed the Long-Term Plan).⁶ The Plan specified the need to develop the ATR and FBR as Japan's top priority. The AEC regarded the ATR to be important because it would consume less fuel (and different types of nuclear fuels) and would be less expensive and less challenging to develop than FBRs. In subsequent versions of the Plan, the AEC envisioned that Japan would construct a prototype ATR by 1970 and build a commercial ATR by 1980. The AEC also envisioned that Japan would construct an experimental FBR by 1970, a prototype by 1975 and a demonstration (or commercial) reactor between 1985 and 1990 ([Atomic Energy Commission of Japan \(AEC\), 1967](#)).

1.5 Creation of the Science and Technology Agency (STA)

In March 1956, the Diet passed a law to establish the Science and Technology Agency (STA) (Law No. 49). The STA (now part of the Ministry of Education, Culture, Sports, Science and Technology (MEXT)) was established in May 1956 to promote advanced R&D on nuclear matters. The STA was set up as an external bureau of the Cabinet Office, with the same authority as a ministry. The STA was responsible for nuclear policymaking as well as promoting nuclear R&D. The STA establishment law included a revision of the AEC establishment law, which decreed that the director-general of the STA, a cabinet minister, would be the Chairman of the AEC (this requirement was later dropped when the AEC was downgraded).

The legislation also specified the establishment of two semi-governmental R&D organizations that would assist the STA mission. The STA and its two nuclear R&D institutions were the leading players in Japan's nuclear policy arena for about a decade.

- The Atomic Fuel Corporation (AFC) was responsible for promoting nuclear fuel research, including uranium exploration, mining, enrichment, reprocessing and waste disposal.
- The Japan Atomic Energy Research Institute (JAERI) was responsible for promotion of high energy physics research, nuclear fusion and radiation research and for developing advanced nuclear reactors, including the ATR and FBR.

⁶ The AEC enacted nine Long-Term Plans from 1956 to 2000, one every five to six years. It decided to end legislating Long-Term Plans in 2000 and instead, it enacted a Framework for Nuclear Policy in 2005 with a plan to revise the Framework every ten years. Currently, a second Framework is overdue and has yet to be enacted. The AEC convened a Framework Policy Development Council in November 2010 to deliberate on a second Framework Policy but it was disbanded in October 2012, likely due to the turmoil created by the Fukushima disaster.

The STA and its two affiliated R&D organizations were the primary advocates for nuclear energy's "Big National Projects." These projects included uranium enrichment, spent fuel reprocessing and construction of an ATR and FBR.⁷ In those early years, STA dominated nuclear policy in Japan and served as the secretariat for the AEC and its special committees. The STA R&D policy most likely directly influenced AEC policy and the formulation of its Long-Term Plan. STA consolidated its power and influence when it obtained the go-ahead for its Big National Projects in the mid-1960s.

In parallel with the government activities, the nine electric power companies, acting through the Federation of Electric Power Companies of Japan (FEPC),⁸ established the Japan Atomic Power Company (JAPC) in 1957. The JAPC was to engage in nuclear power generation and help electric utilities in building nuclear reactors.

As its first project, the JAPC imported a copy of the British Magnox reactor, which became Japan's first commercial power reactor (called Tokai). Construction started in 1960 and the reactor started power generation in 1966. As soon as the JAPC started to import nuclear reactors, however, a rival to the STA appeared on the scene: the Ministry of Economy, Trade and Industry (METI), then called the Ministry of International Trade and Industry.⁹ Given its portfolio on trade, the growth of METI's role in promoting nuclear power was inevitable ([Japan Atomic Power Company \(JAPC\), 2018](#)).

Also, in 1957, the Diet enacted the Law for the Regulation of Nuclear Source Material, Nuclear Fuel Material and Reactors (commonly called the Reactor Regulation Law). The law gave the Prime Minister authority to approve licenses for all nuclear businesses. In practical terms, the PM deferred to the STA and the Japan Atomic Energy Agency (as an advisory body) on licensing decisions. At the same time, the former MITI (now METI) was responsible for the development of nuclear power as an energy source for electricity. The issuance of construction permits for commercial nuclear power reactors required the consent of the Minister of METI. However, the AEC and STA exercised considerable influence over nuclear decisions.

1.5.1 The STA's R&D Organizations

The STA's primary mission was to establish the necessary infrastructure for operating a complete nuclear fuel cycle in Japan with indigenous technology. STA's projects evolved as Japan's nuclear development progressed and the situations changed. For example, STA's Big National Projects initially encompassed uranium mining and exploration, enrichment, reprocessing, and development of the ATR and FBR. By the end of 1950s, as uranium mining and exploration expanded globally,

⁷ R&D on radioactive waste disposal and reactor decommissioning would be added as a national project in later years.

⁸ The Federation of Electric Power Companies, or FEPC, is an organization funded by Japan's electric utilities. Its objective is to serve as a lobbyist for electric development. It was established in November 1952 by a group of 9 electric power companies, Hokkaido, Tohoku, Tokyo, Chubu, Hokuriku, Kansai, Chukoku, Kyushu and Okinawa. The Okinawa Electric Power Company joined March 2000.

⁹ We used the name Ministry of Economy, Trade and Industry (METI) throughout. METI was formerly named the Ministry of International Trade and Industry (MITI) and was created in January 2001 by absorbing agencies from other ministries related to economic activities, such as the Economic Planning Agency, at the time of the 2001 Central Government Reform. METI has become a large complex ministry of 80 bureaus and 3 agencies, with 7,963 full-time employees as of March 2015.

Japan was able to reliably import a stable supply of low-cost uranium. The STA, thus, dropped uranium exploration from the Big National Project list. Beginning in the mid-1960s, STA focused on four Big National Projects, including the ATR, FBR, spent fuel reprocessing and uranium enrichment ([Yoshioka, 2013](#)).

1.5.1.1 The Atomic Fuel Corporation (AFC)

The discovery of uranium deposits at Ningyo-toge in Okayama Prefecture prompted the government to establish the AFC in law in April 1956 as a semi-governmental nuclear energy R&D organization. AFC's mission was to support mining uranium ore and to develop refining and fabrication technologies. The AFC established the Tokai Refinery in June 1957 and succeeded in purifying metallic uranium in March 1959 for the first time in Japan. In January 1966, the AFC started operations of the Plutonium Fuel First Development Center. ([Japan Atomic Energy Agency \(JAEA\), \(no date\)a](#)).

1.5.1.2 The Japan Atomic Energy Research Institute (JAERI)

JAERI was a semi-governmental organization that was established in law in April 1956 to assist STA in the advancement of nuclear technology in Japan. JAERI was to engage in advanced nuclear sciences as well as the R&D, construction and operation of advanced nuclear reactors and ships. In 1956, JAERI imported from the United States a water-boiler type research reactor with a thermal output of 50 kWt, nicknamed the JAERI Research Reactor (JRR-1). The reactor achieved criticality in August 1957 and was used for various experiments and for educating and training engineers and students. Also in 1956, JAERI ordered a CP (Chicago pile) type heavy water reactor with the thermal output of 10 MWt from AMF Atomics of the United States. The JRR-2 was a multipurpose high-performance research reactor and attained its first criticality on October 1, 1960. It was used for neutron beam experiments, radioisotope production and medical irradiation.

- The JRR-2 encountered a number of problems, including coping with the design changes made by the manufacturer, construction delays by AMF Atomics and Japanese subcontractors and malfunctions of thermal exchangers. JRR-2 attained criticality in October 1960.

JAERI also began basic research on the Aqueous Homogeneous Reactor and the Semi-Homogenous Reactor. These R&D projects did not go well. The AEC started to have doubts about JAERI's competence project management. JAERI was also developing reprocessing technology, but progress was slow. By the mid-1960s, STA had given up on relying on JAERI for reactor development ([Atomic Energy Commission of Japan \(AEC\), 1957](#)).

In addition to lapses in program management, JAERI had become entangled in serious labor disputes with its labor union. It experienced frequent strikes from June 1959 to 1964. In October 1963, for example, JAERI was preparing to start the operation of the Japan Power Demonstration Reactor (JPDR), a small boiling water reactor and Japan's first nuclear reactor that was acquired from GE and built by GE. Just prior to the start of operations, the workforce staged a walk-out from the reactor site. Later in August 1963, the JPDR reached criticality and JAERI was expecting the

JPDR to generate power for the first time on 26 October 1963. The day was to be celebrated as Japan's first day of nuclear power generation. The workers threatened another walk out on that day, which made JAERI extremely nervous. Although the walk out did not occur, JAERI subsequently retaliated against the workforce by locking them out from the work site for nearly a month. The workforce sued JAERI for unpaid salaries (Kataoka, 1972; Nakai, 2007).

As relationships deteriorated and the ensuing lawsuits became protracted, JAERI largely lost its credibility in terms of personnel management as well as its capability to responsibly execute the development of ATR Fugen and FBRs Joyo and Monju. In January 1964, the House of Representatives' Science and Technology Promotion Measures Special Committee established the Nuclear Policy Subcommittee to investigate the JAERI situation and compiled a plan to reform the JAERI in April 1964. In October 1964, the AEC set up a roundtable committee to discuss concrete plans for the establishment of advanced power reactors. In March 1966, the AEC published a final report that promoted the development of FBR and ATR without relying on JAERI, leading to the establishment of the Power Reactor and Nuclear Fuel Development Corporation (PNC) in October 1967 (Kataoka, 1972, Aida, 2015).

1.6 The Power Reactor and Nuclear Fuel Development Corporation (PNC)

While the responsibilities for the development of advanced nuclear reactors had been taken away, JAERI was not abolished because it still had responsibilities for nuclear science research, including the construction of a commercial class nuclear powered ship (See inset on the Mutsu). JAERI also continued some research activities on nuclear power generation, including uranium enrichment, which unfortunately resulted in an avoidable fire at one of JAERI's facilities.

In July 1967, in the aftermath of JAERI's mounting troubles, the PNC was established by law, absorbing the AFC and all AFC responsibilities as well as JAERI's principal mission of developing the ATR and FBR. The PNC reined over the Japanese nuclear R&D programs for over 30 years (1967-1998). The STA needed the PNC. It represented a new, more dynamic organization for promoting ATR and FBR development and gave STA the flexibility to direct JAERI to perform missions that were focused on advanced nuclear science research, including such things as fusion and synchrotron R&D and development of a nuclear-powered ship.

Given the breadth of STA's big projects (See Table 1.1) the PNC quickly evolved into a research organization with major R&D responsibilities that included virtually the entire nuclear fuel cycle (Yoshioka, 2013). STA managed these projects for nearly three decades, laying the groundwork for the development of advanced nuclear technologies. (Details of individual projects are explained in subsequent chapters). Only nuclear power generation was outside of the PNC's control.

“Mutsu”

The One and Only Nuclear Ship in Japan

The Mutsu was Japan’s failed attempt to build a nuclear-powered ship for commercial purposes. It was built by JAERI. The ship was 130 m (430 ft) long, 19 m (62 ft) wide and 8,240 tons in weight, powered by a 36 MW Mitsubishi PWR and a 10,000 hp (7.5 MW). steam turbine. In November 1968, Ishikawajima-Harima Heavy industries started building the hull, which was launched in June 1969. Construction was completed in July 1969.

The Mutsu sailed to the Ominato harbor, Aomori Prefecture, which was its expected home port, arriving on 19 July. Nuclear fuel loading was completed by 6 June 1972 and the Mutsu departed Ominato to the open sea for testing purposes on 26 August 1974. (Tests could not be conducted pierside because of local protests). On 28 August 1974, the Mutsu achieved initial criticality and on 1 September, the crew raised power levels to 1.4%. At that point, neutrons and gamma rays were detected escaping through the reactor’s shielding.

Westinghouse had reviewed the design and warned of this possibility, but no changes were made to the design. This incident made national headlines and the residents of the Ominato community and the fishing industry refused to let the Mutsu return to the harbor. The ship underwent lengthy repairs from 1978 to 1982 at the port of Sasebo, Nagasaki prefecture. On 6 September 1982, Mutsu sailed once again to Ominato harbor and later to a new home port at Sekinehama, Aomori prefecture. At Sekinehama, the Mutsu’s containment vessel was opened and the ship completely inspected. The Mutsu departed Sekinehama in July 1990 for its first nuclear powered sailing. In October 1990, Mutsu achieved 100 percent of its rated power output. In February 1992, testing was completed. In March 1992, Japan decided to decommission the Mutsu. Japan had no plans to develop additional nuclear power commercial ships because of the lack of commercial viability, unless the ship is larger than hundreds of thousand tons, which would be extremely costly. The Mutsu project cost Japan more than \$1.2 billion over 20 years (Nakao, no date; JAEA, 2018; Adachi, et. Al., 1995).

The Mutsu fiasco did have one lasting impact: it caused the government to revise its bureaucratic oversight of nuclear energy, shifting more responsibility to METI.

Table 1.1 The Power Reactor and Nuclear Fuel Development Corporation (1967-1998): Organizations and Responsibilities

PNC Organizations	
Headquarters	Business management, safety management, advanced reactor development, nuclear fuel cycle technology development, environmental technology development, nuclear fuel facility planning and management, international technology cooperation
Tokai Works	Operation of the spent fuel reprocessing plant, reprocessing technology development, plutonium fuel development, advanced enrichment technology development, high-level radioactive waste disposal technology, FBR fuel recycling technology development
Oarai Engineering Center	Operation of the experimental FBR Joyo, R&D on FBR (plant engineering using full-size scale-models, safety engineering, equipment, material, fuel and material irradiation tests), nuclide annihilation treatment technology, new materials development

Ningyo-toge Environmental Engineering Center	Operation of the uranium enrichment prototype plant, uranium refining and conversion technology development
Tono Geoscience Center	High-level radioactive waste underground disposal technology, uranium exploration and mining technology development, training of overseas engineers
ATR Fugen Power Plant	Operation of the ATR Fugen in Tsuruga, Fukui Prefecture
FBR Monju Facility	Construction of the FBR Monju in Tsuruga, Fukui Prefecture
Tsuruga Facility (Fukui Prefecture)	Operation and management of the ATR Fugen and FBR Monju and environmental safety management. This facility subsequently became the headquarters of the PNC's successor, Japan Nuclear Fuel Cycle Development Institute (JNC).

Source: The table was created by the authors based on the graphics of the Research Institute of Industrial Science and Technology (RIST), 2003.

Serving as STA's principal nuclear R&D organization, however, the PNC eventually became complacent in implementing safety measures across its many activities and became increasingly careless in its handling of fuel systems. By the 1990s, the PNC was "caught out" trying to hide mistakes and failures. It concealed facts, fabricated stories and even disregarded the nuclear regulatory agencies' rulings and directives (See Table 1.2) ([Ministry of Economy, Trade and Industry \(METI\), 2013](#)). Worse, the PNC had become more accident-prone, making it fiscally difficult to sustain. Five accidents occurred under PNC stewardship, starting in 1995. This accident record, coupled with the PNC's attempts in several cases to cover up accident details, eventually led to its demise:

- **(8 December 1995) Prototype FBR Monju Sodium Leak Accident.** On 8 December 1995, the Monju FBR had a major sodium leak. The leak was non-radioactive and did not affect safety systems (reactor shutdown and cooling) but it did lead to a fire. It was rated as INES 1, a breach of operating limits at a nuclear facility and a deficiency of defense-in-depth ([International Atomic Energy Agency \(IAEA\), no date](#); [Federation of Electric Power Companies \(FETC\), no date](#)). Worse, the PNC delayed accident reports, falsified the evidence, imposed gag orders on the workforce and covered up the seriousness of the accident, creating a public uproar ([Sobajima, 1999](#); [Ryall, 2010](#); [Kondo, et al., 2013](#)). Moreover, a mid-level official assigned to conduct an internal investigation of the concealment of evidence of the sodium leak committed suicide. In the evening after he briefed the press, he was found dead, apparently having jumped from his 8th floor hotel room window ([Research Organization for Information, Science and Technology \(RIST\), 2003](#)).
- **(11 March 1997) Tokai Prototype Reprocessing Plant Accident.** On 11 March 1997, a fire and explosion occurred at the PNC's prototype reprocessing plant in Ibaraki Prefecture. The fire began in the radioactive liquid waste bituminization and storage facility at the reprocessing plant. The fire was not properly extinguished and ultimately led to an explosion that smashed windows and the release of radioactive smoke into the environment.

The following day, workers used duct tape to repair windows and doors. At least 37 workers were internally contaminated with radioactive cesium and 10 billion becquerels or more of radio nuclides were released into the environment. Radioactive cesium released during the accident was detected in Tsukuba in the Tokyo suburbs, about 160 km from the Tokai-mura site (RIST, 2000; Wise-Paris, 1998). The plant operators delayed reporting the accident to the authorities, falsified the level of the radioactive leak, and destroyed photographic evidence of the accident. (Dolley, 1999).

- **(14 April 1997) Tritium Leaks at ATR Fugen.** In April 1997, the PNC discovered a tritium leak at ATR Fugen. The PNC delayed reporting the accident for 30 hours. Taking this delayed reporting seriously, the STA Director General ordered Fugen operations to cease the night of 15 April. Following the order, operators began to lower the power output at 10:30 pm. One minute later, the water level at the moisture separator started to rise, the turbine stopped automatically and Fugen shut down. Apparently, there had been a second tritium leak. It was later revealed that 11 similar accidents had occurred in the past, which had long been concealed. Also, at ATR Fugen, on 16 October 1997, about 2 cubic meters of radioactive coolant water leaked from a pressurized pipe during an inspection; on 5 November 1997, a similar accident occurred. It was found that the stainless-steel pipes that had been used since 1979 had cracks in them.

While not under the direct authority of the PNC, JAERI had an accident at a nuclear facility about the same time that other accidents occurred, fueling the public's concern about the lack of adequate safety practices in managing nuclear material.

- **(20 November 1997) Fire at JAERI's atomic steam testing laboratory.** The fire occurred at the Tokai Uranium Enrichment Research Facility, Ibaraki Prefecture. The investigation found that metallic uranium became wet on 19 November while it was being removed from test equipment. The wet metallic uranium was put into two plastic bags and stored in one of 11 metallic cans. The cans were expected to be filled with inert gas the next day. At 1:15 am on 20 November, a fire alarm went off and the fire team found smoke at the stairwell adjacent to the laboratory. The fire was reported to the central security office, which reported the fire to the Tokai Fire Station in Tokai-mura. At the time of fire, the exhaust system in the testing laboratory was operating but soon became disabled due to clogged filters, thus filling the lab with smoke. The exhaust system was shut down and the filters were replaced. At 2:35 am on 20 November, JAERI officers and the Tokai-mura fire fighters entered the atomic steam testing laboratory. They found the fire had spread to 20 boxes that had been stacked and stored along with the 11 metal cans, containing burnable solid waste (wet waste, Tyvek suits, rubber gloves, etc.). The fire fighters used sand to extinguish the fire. It was subsequently reported that flammable gas had been generated from the wet metallic uranium and that the gas had ignited, creating the explosion. The exhaust dust monitor showed no radioactivity contaminants had leaked into the environment and JAERI personnel and fire fighters' radiation exposures were below minimum detection limits (RIST, 1998).

Table 1.2 PNC, JAERI, JNC and JAEA¹⁰ Accidents and Consequences.

Legend:

PNC in charge, listed by location and date		JAERI in charge	
JNC in charge, listed by location and date		JAEA in charge, listed by location and date	
Location	Date	Accident	Misconduct or Error
FBR Monju in Tsuruga, Fukui Prefecture	December 1995	Sodium leak and fire	To conceal the severity of the accident, PNC employees erased some accident scenes from one video tape and concealed the existence of another unabridged video tape, telling employees to hide the tape. Three executives were forced to resign. One employee who was assigned to investigate the tape concealment committed suicide.
	September 2008	Corrosion holes in exhaust ducts	
	26 August 2010	Drop of In-Vessel Fuel Transfer Machine	Lack of robust testing and possible design flaw for the conduct of operations in a liquid sodium environment.
	December 2010	Cracks in cylinder heads of diesel power generator	Not originally reported by operator
	September 2014	50 surveillance cameras out of order	Not originally reported by operator
	2 March 2015	Discovery of deteriorated primary sodium cooling pipe systems	Nuclear Regulation Authority recommends JAEA be removed from operation of Monju FBR.
Tokai-mura reprocessing plant	11 March 1997	Fire and explosion at the bitumen waste facility. At least 37 workers were internally contaminated with cesium. Rated as an INES Level 3 accident.	PNC was the plant operator. Before the explosion, a report sent to the STA falsely stated that the fire had been extinguished. Photos taken by PNC workers were destroyed. PNC waited five hours before informing authorities of the radiation leak. The first figures concerning the release of radioactivity during the accident were underestimated by a factor of ten to twenty.

¹⁰ The Japan Atomic Energy Agency (JAEA) was officially established in 2005.

ATR Fugen in Tsuruga, Fukui Prefecture	14 April 1997	In the morning of 14 April, an alarm warned of a radioactive tritium leak. The PNC found the leak adjacent to a circulation pump. Eleven workers were exposed to low-level doses of radiation.	PNC delayed the accident report by 30 hours.
	15 April 1997	Learning of the delayed report, the STA Director General ordered the reactor to be stopped the night of 15 April. While the PNC was lowering the power level, the reactor shut-down because the moisture separator signaled presence of a high level of moisture, which tripped the turbine, ending plans for a gradual shut down. The PNC then discovered a high level of heavy water in the humidity separator from a second tritium leak.	During the following investigation, it was discovered that there already had been 11 similar incidents. Five managers of the PNC resigned.
	16 October 1997	While inspecting a pressurized pipe, inspectors accidentally caused a leak of 2 cubic meters of radioactive cooling water.	Disconnection of pressurized pipe by inspection team was ill-advised.
	5 November 1997	Stainless steel tube connected to a heavy water drum was cracked, causing a leak.	Repeated flexing of tube caused the crack. Tube had been in use since 1979 and crack not found during inspections.
	8 April 2002	About 200 cubic meters of steam escape from a defective pipe.	ATR Fugen was shut down and decommissioning approved in 2008. During dismantlement, it was discovered that walls with operational controls did not have the required strength at some 25 separate locations,
FBR Joyo, Oarai	October 2001	Fire at the Maintenance Facility.	The fire broke out in a maintenance building, where sodium was removed from equipment and

Engineering Center, Oarai, Ibaraki Prefecture			machinery repaired. There were no injuries or radiation leaks. No inspection since June 2000.
	11 June 2007	The top of the irradiation test subassembly of the material testing rig, named MARICO-2, did not disconnect properly from its handling head; the rig and head were deformed as the rig was moved to its in-vessel storage rack. The deformation created an obstacle, preventing access to part of the reactor fuel.	The damage was discovered six months after it occurred, when the operator tried to replace fuel in November 2007. Moreover, six small pins from the top of the MARICO-2 were missing, which might have dropped to the bottom of the reactor. The sodium liquid in the reactor is not transparent, making it difficult to find the pins.
Tokai Uranium Enrichment Research Facility	20 November 1997	Flammable gas had been generated from the wet metallic uranium, which ignited, creating an explosion and fire.	No cited misconduct.
JCO	30 September 1999	Criticality accident.	Two fatalities occurred due to inadequate training and flawed management of workers.
Plutonium Fuel Research Facility, Oarai R&D Center, Ibaraki Prefecture	8 June 2017	A bag containing plutonium and uranium inside a storage container broke, exposing five men to high levels of radiation.	Incident still under investigation, but preliminary reporting indicates lack of adequate training and safety protocols.

Sources: Table is based on authors' interpretation and analysis of IAEA, no date; RIST, 2000; Iwasaki, S., 2009.

1.7 Japan Nuclear Cycle Development Agency (JNC), a Caretaker Agency

The Japanese bureaucracy, policymakers, utilities, and nuclear manufacturers and the public had clearly lost confidence in the PNC because of its lack of a safety culture and its untrustworthy behavior. Thus, Japan's Diet abolished the PNC and established a new organization, the Japan Nuclear Cycle Development Agency (JNC), in October 1998. While JNC inherited the PNC's staff

and its mission, it is noteworthy that JNC stated in its website that it hoped to differ from its predecessor in the important respect that it would concentrated exclusively on a single well-defined set of development goals. Several other significant changes included a commitment that JNC would improve management and safety and become more responsive to the public's need for greater information disclosure ([Japan Nuclear Cycle Development Agency \(JNC\), no date](#)).¹¹

The JNC clearly hoped to differ from the PNC, but that would be difficult because it inherited the PNC staff and its culture, tradition, and habits. Moreover, the government probably had little confidence in JNC to accomplish its nuclear R&D mission. It already had a plan to create a new and more competent organization. Indeed, the JNC website as early as in December 2001 stated that “the Japanese Government had decided that a new entity will be established to carry on Japan’s nuclear research by merging JNC and JAERI.” It also said that “we are in the preparatory phase of the merger and are discussing the role and management of the new entity in the Task Force established within the MEXT.” Indeed, the new entity—the Japan Atomic Energy Agency (JAEA)—was eventually established in 2005 ([JNC, no date](#)). Even as the JNC was struggling to clean up the PNC’s mistakes, it was nevertheless assigned a new responsibility: to develop nuclear waste disposal technology and decommissioning capabilities, including dismantling, decontamination, volume reduction and recovery of residual uranium from centrifuges ([RIST, 2007](#)).

1.8 Japan Atomic Energy Agency (JAEA)

Japan established JAEA in October 2005, by merging the JNC and JAERI. Since October 1998 when JNC established its “Nuclear Fuel Cycle Development Organization, Tsuruga Head Office,” the work to restart Monju had been underway but was loaded down with many difficulties. JNC had to deal with numerous law suits by local citizens, prepared complicated paper work for the government ministry (METI) and its regulatory authority, the Nuclear and Industrial Safety Agency (NISA), and dealt with local governments to assure them of Monju’s safety. In September 2005, JNC finally started the Monju modification work. During the seven years of its existence the JNC managed to complete all the necessary leg work to give JAEA a head start.

JAEA took over the remodeling and construction work from the JNC in October 2005 and completed it in May 2007. The primary work was to improve sodium safety, including the replacement of temperature sensors in the secondary heat transfer system, modification of sodium leakage countermeasures and improvements in safety characteristics of the steam generator. In August 2007, system function tests were conducted to prepare for regular operations ([JAEA, 2017b](#)).

While JAEA was preoccupied with restarting Monju operations, the string of accidents that began under the PNC’s stewardship continued and indeed, grew worse.

- ***(11 June 2007) The Experimental FBR Joyo In-Vessel Accident.*** On 11 June 2007, the top

¹¹ The JNC website has been deleted and replaced by JAEA.

of the irradiation test subassembly of the material testing rig, named MARICO-2, was deformed as it was moved to its in-vessel storage rack. The deformation occurred because the rig did not fully disconnect from its handling head, which was part of the fuel handling equipment. Both the subassembly and the upper core structure (UCS) were damaged, disabling access to the reactor core fuel in some areas. Fuji Electric was tasked to design and fabricate devices for retrieving the test subassembly and performed retrieval operations at the site, which were successful. Fuji Electric fabricated the devices capable of adjusting the mismatch of the upper core structure removal hole and the central axis of the test subassembly. It performed a simulation test and confirmed the design performance, including procedures for retrieval operations and measures to adjust for any abnormality that might occur. Retrieval of the damaged UCS was completed on 22 May 2014. The MARICO-2 was retrieved on 26 September 2014 (Koga, et al., 2015; Ashida, et al., 2016; Ohira, 2015). The recovery cost was \$35 million and took seven years (JAEA, 2009).

- **(26 August 2010) The Prototype FBR Monju Accident—Uncontrolled drop of the In-Vessel Transfer Machine (IVTM) in the Reactor—and other Hardware Troubles.** Monju had been idle since the sodium leak and fire accident in December 1995. After a lengthy lawsuit, submitting much paperwork to METI and the regulatory agency, and remodeling the facility, FBR Monju was finally ready for operation. Plant and performance tests were conducted on 6 May 2010. Monju reached criticality on 8 May 2010. Then, on 22 July 2010, JAEA conducted a core confirmation test and discovered the need to replace some fuel. JAEA used the IVTM, a special device that is inserted into the reactor vessel when fuel replacement is needed. It is a 12-m long, pipe-like structure weighing about 3 tons. Using the IVTM, a spent fuel subassembly was successfully replaced with a fresh fuel assembly. After the work was done, the IVTM was raised through a sleeve structure, but during this operation the IVTM unexpectedly dropped from a height of about 2 m, striking the vessel head plug structure. This drop was caused by the malfunction of the gripping structure of the lifting machine¹² (JAEA, 2011; Deshimaru, 2013; Kondo, et al., 2013).
- Monju had additional hardware troubles. JAEA discovered corrosion holes in the outdoor exhaust ducts in September 2008, which was repaired by May 2009. In December 2010, JAEA discovered cracks in the cylinder liners of a diesel power generator C, which was repaired in June 2011. In July 2015, the cylinder head indicator cock of a diesel power generator B was deformed, which was repaired in October 2015 (JAEA, 2017).

In addition to the Joyo and Monju accidents, JAEA clearly disappointed the newly established Nuclear Regulation Authority (NRA) (established September 2012) for its disregard of safety regulations and deceptive maneuvers. In November 2012, JAEA reported to NRA that it had missed the inspections of about 9,679 items of Monju equipment and machinery (Nuclear Regulation Authority (NRA), 2012). Subsequently, the NRA acknowledged seven instances in which Monju operators violated safety regulations, including equipment malfunctions and failures to properly manage documents.

In February and March 2013, NRA conducted drop-in inspections of the Monju site and discovered 13 additional items that were left uninspected, including emergency power generators. In view of the negligent behavior, NRA decided on 13 May 2013 that JAEA be suspended from operating

¹² For more details on the IVTM accident, please see Section 2.2.2.2.

Monju for an indefinite period and officially directed on 30 May 2013 that the JAEA stop preparations for restarting Monju. During safety inspections conducted by the NRA between 3 and 21 June 2013, it was revealed that the safety inspections on another 2,300 pieces of equipment had been omitted by JAEA ([Wikipedia, 2017](#)).

On 23 March 2015, JAEA filed a report with MEXT, stating that JAEA had rebuilt its organizational structure to ensure it would not miss inspecting various items again. However, when NRA's safety inspectors had been present on 2 March 2015, they discovered that JAEA conducted sloppy and cursory inspections that missed identifying deterioration in the primary sodium cooling pipes and had not identified unacceptable thinning in pipe walls of the auxiliary cooling system. The cooling pipes were the heart of the Monju reactor, classified as Class 1 (most important) safety equipment and in fact were the same ones that had been involved in the sodium leak and fire accident in December 1995. The NRA announced these facts to the press on 25 March 2015 ([NRA, 2015](#); [Wikipedia, 2017](#)).

With all these experiences in mind, the NRA decided that JAEA was not competent enough to restart and operate Monju. In November 2015, the NRA sent the MEXT Minister a recommendation that the MEXT find a specific entity, other than JAEA, that has the competence to operate Monju safely and that, if this were not possible, that Monju be fundamentally reappraised so that Monju's safety risks would be totally mitigated. In May 2016, the MEXT compiled possible qualifications of an entity that would be able to operate Monju but could not name an organization that met the qualifications. On 21 December 2016, the Japanese ministers in charge of nuclear energy in the Cabinet decided to decommission Monju ([Cabinet Secretariat \(CAS\), 2016](#)).

In addition to negligence regarding the safety of Monju, the NRA found other safety lapses within JAEA. One incident was quite serious:

- At 11:15 am on 8 June 2017, five JAEA technicians were taking inventory of a radioactive substance in an old storage container at the Plutonium Fuel Research Facility (PFRF) at JAEA's Oarai Research and Development Center in Ibaraki Prefecture. The container held about 300 grams of uranium oxide and plutonium oxide that had been used in experiments in the past, according to JAEA. The PFRF was constructed in FY 1974 for the research on advanced fuel for fast reactors; the inventory of storage containers was undertaken because of a decision by the NRA to decommission the facility. The inspection process usually involved placing the container in a special machine that adjusts the air pressure to prevent the material inside from being blown into the air. This procedure likely was skipped. The powdery substance that had originally been encased in a plastic container was doubled-wrapped in plastic. It was then placed inside a stainless-steel container sealed with six bolts. The container had not been opened for 26 years ([JAEA, 2017b](#)).
- The stainless-steel container was placed in a protective hood and one of the five workers in protective gear removed the sealing bolts and opened the lid, only to see black power burst forth, exposing the workers to uranium oxide and plutonium oxide powder. The container may have been filled with helium, which can be emitted by plutonium during extended storage and thereby increased the pressure inside the container, according to an expert. JAEA indicated that a "regular safety checklist" was put together for inspection that listed

30 types of radioactive materials held at its R&D centers. One of the check list items requires the workers to determine if there is a risk of fire, or "an explosion, a rupture, or scattering" of powdered materials. However, the workers apparently decided that the checks regarding the risk of "rupture" were "not applicable" because the material had been double-wrapped in plastic bags and they only checked the containers' exteriors. JAEA on 15 June released footage of the radioactive materials container taken by one of the workers just after the accident. The image shows the plastic bags protruding from the top of the stainless steel can.

- At the time of accident, the workers were covering their noses and mouths, but radioactive material was detected inside the noses of three of the five exposed employees. The limbs on all five were also found to be contaminated, even after removing protective gear and taking a shower, which would have washed off most contamination. Up to 22,000 becquerels of plutonium were detected in the lungs of the worker in his 50s who opened the lid of the container. Based on that figure, JAEA estimates his body likely has absorbed 360,000 becquerels of material overall. Under current labor standards, that translates into 1.22 sieverts over a year and perhaps a 12 sieverts over 50 years, according to JAEA ([JAEA, 2017a](#)). The government allows designated nuclear workers to be exposed to a maximum of 0.05 sievert per year, or 0.1 sieverts over five years. The radioactive contamination in one man could mean the effects on his lungs may not be immediately life-threatening but would add up over time and he will need to be regularly monitored, said a doctor at the National Institute of Radiological Sciences, where the workers are being treated. On 19 June 2017, the JAEA revealed at the press conference that the urine from the five workers showed a small amount of plutonium, indicating that they were also internally exposed ([JAEA, 2017b](#)).

The JAEA also submitted an accident report to the Nuclear Regulation Authority (NRA) on 19 June 2017. The cause of the accident has been under investigation, according to JAEA, but a JAEA spokesperson told reporters at a 15 June press conference that the workers' failure to consider the risk of rupture was "inappropriate." It seemed as if JAEA was blaming the workers rather than admitting to its own lapse in safety procedures. The NRA Chairman Shunichi Tanaka criticized the complacency at JAEA regarding routine work safety and cited that as a possible cause of this accident. Regulators have started investigating possible violations of safety standards at the facility. ([Reuters, 2017](#)).

The NRA conducted on-site inspection of the JAEA lab on 21, 23, 28 and 30 June. The storage container that had been in the hood in Room No. 108 was moved to the glove box in Room No. 101. Decontamination and paint fixation of the hood of Room No. 108 started on 28 July and decontamination of the floor of Room No. 108 started on 1 August. The decontamination work was not effective; the JAEA found contamination in Room No. 101 on 8 September. Decontamination work has been suspended since then. The NRA temporarily rated the incident as INES level 2 ([JAEA, 2017a](#)).

Despite and perhaps because of these mishaps, JAEA has announced it is now focusing on nuclear fuel cycle R&D, reprocessing and waste disposal technologies by transferring some of its advanced nuclear science research to other institutions. For example, on 1 April 2016, JAEA turned over nuclear fusion research and some part of quantum beam applied research to the National Institutes

for Quantum and Radiological Science and Technology (QST). QST was established in April 2016 to promote quantum science and technology in a comprehensive and integrated manner. The new organization was formed from the merger of the National Institute of Radiological Sciences (NIRS) with certain operations that were previously undertaken by JAEA. JAEA's gradual decline is clear from the budgetary trends in Figure 1.1 ([JAEA, 2015](#)).

- In 1996, the combined budget of the JNC and JAERI was \$3.61 billion, but in 2016, the JAEA (a combination of JNC and JAERI) budget was only \$1.488 billion, less than half of the budget 20 years ago. At the same time, the number of full-time employees for JNC and JAERI declined from 5,219 in 1996 to 3,683 for JAEA in 2015, a 30 percent drop. Moreover, the JAEA Director is worried about the aging of employees, the lack of a safety culture and the decline of the organizational IQ. He is also deeply aware of its repeated safety violations and the urgent need to fix them ([Kodama, 2016](#)). The problems are overwhelming and perhaps out of control, in part because JAEA inherited many of the unfavorable characteristics of the old PNC.

1.9 Changing Roles of the STA and METI

The AEC and the STA were the two highest nuclear policymaking bodies in Japan in the early days of nuclear energy. The STA Director General chaired the AEC and had a seat on the Cabinet. But both organizations lost status over the years. Ultimately, the STA was placed under MEXT and the AEC became an ordinary council in the Cabinet Office when Japan reorganized the government in January 2001. At the same time, the Ministry of Economy and Trade, and Industry (METI) grew in influence. How did these changes come about?

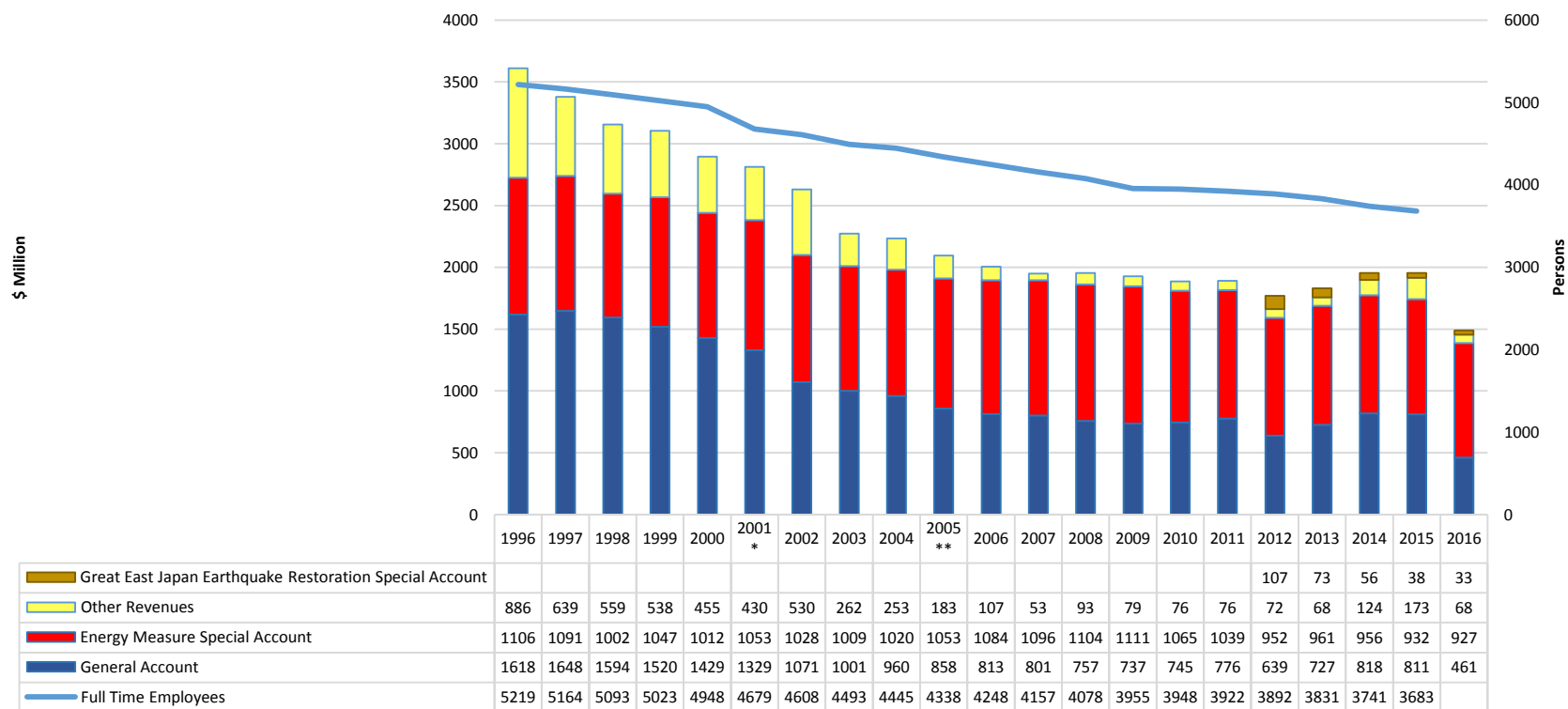


Figure 1.3 Change in the Budget and Number of Employees at the Japan Atomic Energy Agency

Notes: *On 19 December 2001, Japan decided that the Japan Nuclear Cycle Development Institute and the Japan Atomic Energy Research Institute would merge into the Japan Atomic Energy Agency.

**On 1 October 2005, the Japan Atomic Energy Agency was established.

Source: Kodama, 2016.

The AEC establishment law gave AEC the highest nuclear policymaking authority in Japan and, accordingly, the AEC promoted many far-reaching policies, including advancement of the ATR, FBR and a full nuclear fuel cycle. AEC's status, however, gradually diminished. As time passed, there were fewer and fewer major national nuclear projects that AEC could promote. At the same time, the AEC was self-effacing and never made an independent policy decision without first consulting other ministries and the electric utilities ([Yoshioka, 2013](#)). The AEC appeared to be overly yielding to METI's coercive policymaking tactics (See Section 1.8 for details), especially as nuclear priorities in Japan in the 1970s shifted from promoting advanced nuclear technology R&D to building out a fleet of commercial power reactors. The AEC published another nuclear policy document in 2005, but the AEC's recommendations, no longer had the prestige of "having the prime minister's respect," nor did the AEC have the clout it once had.

- The AEC's declining power is apparent in the declining number of AEC's commissioners. It had as many as seven commissioners (including one chairman) between 1960 and 1978, which declined to five commissioners (including one chairman) between 1978 and 2011. The AEC now has a chairman and two commissioners. The chairman is no longer a cabinet minister and the prime minister is not required to respect AEC policy proposals.
- Since 2011, the AEC has fallen directly under METI's control. In November 2012 the National Strategy Office of the Cabinet held a deliberative meeting to review the AEC's future. METI's Agency of Natural Resources and Energy (ANRE) served as the secretariat for the meeting and, in Japan, the secretariat typically controls the outcome. ([CAS National Strategy Office, 2012](#)). This has essentially ended the practice of having three independent semi-competitive nuclear policymaking bodies—the AEC, STA, and METI.

The reasons for the STA's decline perhaps lies in the unprecedented amount of time that the STA ruled the nuclear policy realm—over three decades. Mistakes and errors that any bureaucracy would make over time (and which a government might accept) simply became too numerous to be politically acceptable. The STA also lost clout because its major programs were suffering from lack of achievement and repeated delays.

- ATR Fugen, for example, was bulky and costly due to its use of heavy water and was not economically viable. In 1984, Japan estimated that the construction cost of Fugen was about \$3.96 billion but that increased to \$5.8 billion by 1995, about 1.5 times as much. Fugen's electricity also cost more, three times more than light water reactors. Compounding STA's problem, Yoshioka ([2013](#)) points out that despite Japan's lack of sufficient domestic capabilities to develop viable technologies, STA insisted on indigenous development and refused to accept technology from abroad, although they were tested, proven and less costly. As a result, the STA projects for most part were not technically or economically viable.

Then, there was a costly sodium leak and fire at the Monju FBR in 1995, followed by a fire and explosion at a reprocessing plant in 1997. The final straw was that in the post-accident investigations, STA's leading R&D institution, the PNC, was accused of having a dishonest culture. The Japanese Government needed a scapegoat for the loss of public trust in nuclear power and they found one in the PNC. In 1998 the PNC was abolished and METI was waiting in the wings to pick up the pieces ([AEC, 1996a, 1996b](#)).

1.10 METI's Influence Grows along with the Nuclear Power Industry and Utilities

METI had long wanted a bigger role in the nuclear policy world. Yoshioka (2013) indicates that the center of gravity for nuclear policymaking began to shift almost as soon as the Diet created the STA in 1956. In 1957, a consortium of electric power companies operating under the umbrella of the JAPC funded the first demonstration nuclear power plant (Tokai), which went operational in 1965, and Tsuruga 1, which went online in 1970. While Tokai was classified as a demonstration of a breeder reactor, both it and Tsuruga 1 were intended to generate power to sell and so these reactors fell under the oversight of METI.

METI vigorously promoted the nuclear power industry in close alliance with the eleven electric power companies, the nuclear plant and equipment manufacturing industry, construction industry, banks and like-minded academics. For example, METI successfully managed Japan's response to the 1973 and 1979 oil shocks and embargos. METI created the General Resources and Energy Research Committee (GRERC) to compile reports on the Prospects for Long-Term Energy Supply and Demand, including nuclear power matters. The GRERC's power dramatically increased in the wake of the oil crises. Energy policy had become a vital national security concern and the GRERC's forecasts and recommendations to METI became de facto policy decisions with the approval of the cabinet and prime minister.

METI also attracted like-minded industrialists and academics to its policymaking fora and used them to formulate its own plans and translate them into national policy. At the same time, METI paid little attention to dissenting or opposing views and discouraged substantive debate or deliberation in public. To protect this top-down decision-making practice, METI built close relationships with members of its industry, academics and policy community. This community came to be known as the "nuclear village," whose members had a shared sense of loyalty, camaraderie, responsibility and support—regardless of occasional disagreements and conflicts (Kingston, 2012).

METI's power further increased when it gained responsibility for two agencies that dealt with nuclear energy policy—the ANRE in 1973 and the NISA in 2001. This strengthened METI's ability to promote the nuclear industry and to regulate it as well. A consolidated approach led to rapid expansion of the nuclear reactor fleet but also contributed to a lax safety culture (Kinefuchi, 2015).

Given the need for more reliable sources of energy, METI argued for enactment of the Dengen Sampo law (the Three Laws on Electric Sources) in 1974. The laws were designed to persuade prefectures and local communities to host nuclear power plants by providing incentives, such as subsidies and grants. At the same time, METI actively publicized the notion that "nuclear power is safe, clean and cheap." As anti-nuclear public protests were getting louder, METI had to step up its public relations activities to calm the protests and publicize the safety aspect of nuclear power.

- To publicize the safety aspect of this message, METI even used nuclear-powered cartoon

superheroes and cute images and mascots symbolizing the kind, gentle nature of nuclear power that would endear it to the public (Kinefuchi, 2015).

- METI also worked diligently in public relations to gain the consent and acceptance of nuclear reactors in prefectures and their communities and to make them feel part of the “nuclear village.”

All these efforts paved the way for stable rapid growth of Japan’s nuclear power infrastructure (See Chapter 4). The speed with which nuclear power reactors were constructed was unprecedented and enhanced METI’s standing in establishing policy and funding priorities for nuclear power. Since the oil shocks of the 1970s, the eleven utilities recognized the need to strengthen relationships with METI. The ministry helped them coordinate price movements and reactor site procurement, while the utilities served to promote regional economic development (Tolliday, 2012). (It has been pointed out in post-Fukushima review reports that the utilities “captured” many government institutions that were supposed to oversee or regulate domestic electric power operations, including METI, the STA, and the AEC)¹³ (Kokuritsu Kokkai Toshokan (National Diet Library, 2012).

With METI’s encouragement, expenditures on nuclear energy by the eleven utilities grew in step with expansion of the nuclear reactor fleet. In 2016, spending amounted to \$21 billion, even though nearly all of the power reactors were inactive (See Figure 1.4). In parallel with the growth of the utilities nuclear power programs, the number of nuclear-related suppliers and manufacturers also expanded substantially. In FY2016 there were 240 companies, with revenues of more than \$18 billion (See Figure 1.5).

A side effect of METI’s powerful, top-down policymaking approach, however, was that adverse information tended to get “bottled up” within government and the public was unable to gain much detailed knowledge of nuclear policy. The history of nuclear power in Japan offers few instances where the public has been allowed unrestrained opportunities to learn, discuss and participate in nuclear policy decision-making. As a result, political support for nuclear power in Japan has for decades been limited to a relatively small number of locales and remains, on a nationwide basis, quite shallow. This proved to be a serious problem for the nuclear industry and government in the wake of Fukushima and set the stage for METI’s undoing following that disaster (Yoshioka, 2013; Tolliday, 2012).

¹³ The eleven utilities all have regional monopolies and are among the largest electric utilities in the world. They have concentrated exclusively on the domestic market and have never pursued direct foreign investment. The utilities are closely linked to networks of suppliers drawn primarily from big keiretsu companies, a set of companies with interlocking business relationships and shareholdings and long-term contracts based on “reliability” with little history of competitive bidding. For example, TEPCO buys nearly all its big plant equipment from Toshiba and Hitachi; Kansai purchases from Mitsubishi.

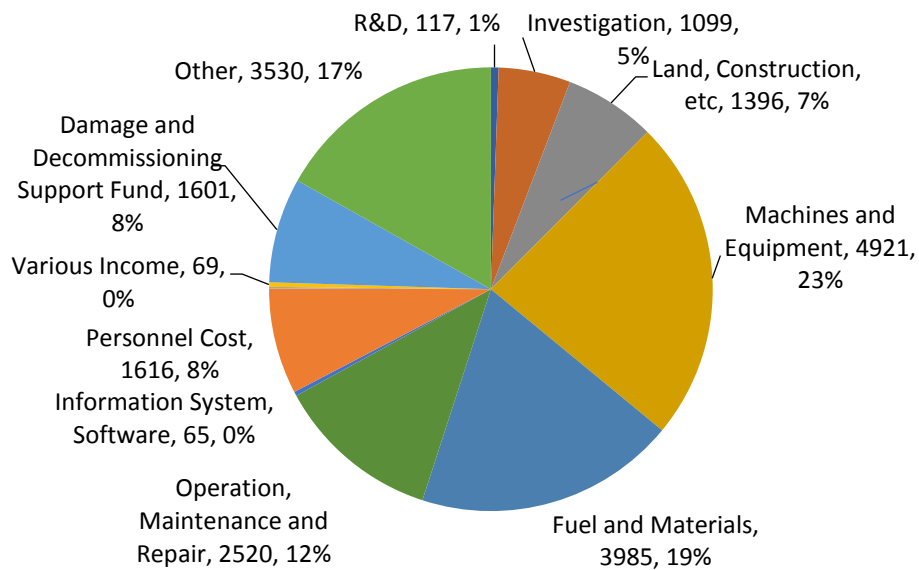


Figure 1.4 Japan's Power Industry: Expenditures (in \$ millions and percent; total \$21 billion as of March 2015)

Source: Japan Atomic Industrial Forum (JAIF), 2016.

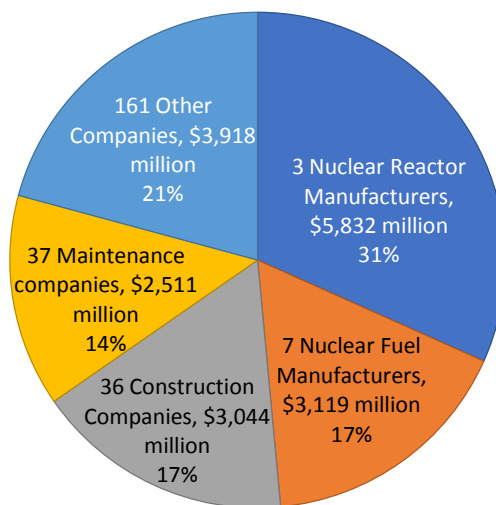


Figure 1.5 Japan's Nuclear Industry: Total Revenues (\$18.4 billion, as of March 2016)

Source: JAIF, 2016.

1.11 Japan's Nuclear Policymaking: Irregularities and Lack of Transparency

When the PNC's was abolished in 1998, STA was left with the JNC as a caretaker organization to oversee its various nuclear programs. Less than 3 years after PNC's downfall, Japan abolished the STA as well and integrated it into the MEXT on 6 January 2001.

METI's power over setting nuclear policy was now at its peak. As discussed earlier, METI had gained more administrative and oversight power by creating policymaking fora of experts well-disposed to nuclear power. To protect this top-down decision-making practice, METI maintained close relationships with and control over the members in its policy track. With this massive power, METI had established a world's third largest nuclear power industry in Japan, after the United States and France. Japan had as many as 54 nuclear reactors operating on the eve of the Fukushima nuclear disaster on 11 March 2011.

Following the Monju sodium leak and the Tokai prototype reprocessing plant fire and explosion, there was a brief period when Japan could have reassessed its goals and priorities for developing components of the nuclear fuel cycle. But this was not to be. METI rolled out what it thought were the best policies for Japan and "bulldozed" the other players in the policymaking apparatus, including the Prime Minister and the AEC. Yoshioka (2013) provides several remarkable stories that reveal how METI contrived to dominate the Japanese nuclear policymaking apparatus and how it became virtually impossible it is to question METI's positions on nuclear power. The following examples were constructed by assembling Yoshioka's recollections in his 2013 book, backed up by supporting materials:

Example 1. On 14 June 1996, the Nuclear Subcommittee of METI's General Resources and Energy Research Committee started a discussion on the nuclear fuel cycle. It was irregular for METI to do this because a highly prestigious Nuclear Energy Policy Roundtable Congress had already been established by the Prime Minister on 15 March 1996 to discuss the same topic. Back on 23 January 1996, the Governors of Fukushima, Niigata and Fukui prefectures requested that the Japanese Government review future Japanese nuclear policy, including the nuclear fuel cycle, the pluthermal plan and the back-end fuel cycle issues. In response, Prime Minister Ryutaro Hashimoto on 12 March 1996 directed the STA Director General and the METI Minister to establish a Nuclear Energy Policy Roundtable Congress to form a national consensus on future nuclear fuel policy. The first Roundtable Congress meeting was held on 25 April 1996 and continued for another 11 meetings until 19 September 1996. The Roundtable Congress had five rules: always have a broad range of invitees, hold meetings at regional locations, require the attendance of all AEC Commissioners at all sessions, hold free and open dialogues among the attendees, and publicly release reports. Despite these rules to ensure transparency, the process of selecting six Roundtable Congress moderators and the more than 100 invitees was kept secret.

On 3 October 1996, the Roundtable Congress submitted its report to the AEC, which included two proposals; one was to set up a new policy discussion forum and the second was to discuss the future FBR policy from a broader point of view. The lack of frank discussion and concrete proposals was not surprising because there were too many invitees and opinions and views were publicized through verbatim transcripts, videotapes and the Internet. The attendees were likely intimidated by the sheer exposure of their views to the public. Meeting moderators seemed to lack the ability to draw conclusions from the discussions. METI undoubtedly saw early on that the Roundtable Congress would not amount to very much and decided to steamroll it. The METI Nuclear Subcommittee compiled its own report on 20 January 1997 after seven discussion sessions of the Subcommittee. It reaffirmed the policy for supporting the nuclear fuel cycle and the pluthermal policy (AEC, 2007).

- Yoshioka (2013) states that this was the beginning of METI's aggressive approach to pushing through its views like "a bulldozer." Consequently, the AEC decided on 31 January 1997 that Japan should promote the plutothermal policy and spent fuel reprocessing commercialization. The AEC abandoned its duty to form a national consensus on nuclear fuel cycle policy as well as its practice of consulting with special subcommittees and discussion meetings. It was as if the AEC had conceded its nuclear policymaking power to METI. Not surprisingly, on 4 February 1997 the Cabinet ruled, at METI's suggestion, to continue promotion of the existing nuclear fuel cycle policy (Yoshioka, 2013).

Example 2. On 18 April 1997, STA established the PNC Reform Study Committee. STA directed the Committee to evaluate the PNC's conduct, reform its internal structure and transfer its mission to a new organization. Yoshioka (2013) points out the narrowness and weaknesses of the agenda: 1) the Committee was totally exempted from discussing the nuclear fuel cycle policy, 2) the Committee lacked third-party objectivity (i.e. an STA committee was deliberating on an STA matter, 3) the Committee did not include even one member who had a neutral or opposing view, 4) it compiled a report totally based on the views of the Liberal Democratic Party (LDP) with no others, 5) it started to compile a report after two meetings, started to draft a report at the third meeting and finalized the report at the sixth meeting on 1 August 1997. The report was entirely written by the STA secretariat. Indeed, the report was compiled within 3 months and closely conformed to the LDP's paper "About Fundamental Reform of the PNC," that was compiled by the LDP Administrative Reform Promotion Headquarters on 2 July 1996.

The STA report recommended that the PNC change its name to the Japan Nuclear Cycle Development Institute (JNC) and undergo some limited internal reform. The report supported the nuclear fuel cycle, plutothermal, and high-level radioactive disposal policies, but puzzlingly it proposed to end the overseas uranium exploration and enrichment research. These activities had not been viable government projects for some time. Overseas uranium exploration had achieved no success over the past 30 years and AEC had ordered in 1981 that uranium enrichment research be transferred to the private sector (AEC, 1998).

Example 3. On 21 February 1997, the AEC established the FBR Discussion Meeting, which was proposed at the Nuclear Policy Roundtable Congress on 3 October 1996. METI's preemptive move had succeeded in steering Japan to endorse the nuclear fuel cycle and, thus, the remaining agenda was to discuss what to do with the FBR. The FBR Discussion Meeting consisted of 16 members; about half of them had been inside the nuclear policymaking apparatus and fully supportive of the FBR, the other half had no nuclear expertise nor had ever expressed views on the nuclear issues. Only Hitoshi Yoshioka had expressed opposition to the FBR.

In Yoshioka's view (2013), the selection of the members for the FBR Discussion Meeting was highly biased. He believed that, to discuss such topic as the FBR that could potentially divide the nation's views into two, the members should all have been experts on nuclear issues and have balanced views: supporting views, neutral views and opposing views. Yet the FBR Discussion Meeting had invited speakers and technical experts who were all supportive of the FBR, except one (Nisaburo Takagi of the Citizen's Nuclear Information Center opposed the concept).

Also, the secretariat was totally biased; it was the Power Reactor Development Branch of STA's Nuclear Energy Bureau that had the responsibility to oversee and promote the FBR development. Moreover, the meeting procedures were highly irregular. The FBR Discussion Meeting had held discussion sessions relatively normally up to the 7th session (30 July 1997). At the 8th session (27 August 1997), the secretariat announced that the FBR Discussion Meeting report must be compiled within the year so that the PNC would be reformed, and a new organization would be formed sooner. At the 9th session (19 September 1997), even before the FBR Discussion Meeting had held discussions on recommendations, the secretariat presented a draft report to the FBR Discussion Meeting. The draft was entirely written by the STA secretariat with some editorial input from the FBR Discussion Meeting chairman. The substance of the draft was to ensure the survival of the FBR and save the PNC core as much as possible. Yoshioka (2013) described the situation "as if a helicopter transported the mountain climbers from the 3rd stop to the 9th stop." Moreover, the FBR Discussion Meeting chairman started to voice openly that he wished the FBR to be restarted soon and accomplish its mission. In the end, the 19 September draft was revised several times and became the draft report on 14 October. Yoshioka (2013) also described how secretive the process of draft revision was. The FBR Discussion Meeting members were limited to sending in their comments in writing and the secretariat had complete editorial liberty as to whether to accept or reject the comments (AEC, 1997a).

In addition, the FBR Discussion Meeting held one public meeting in Tokyo to hear public views on the issue. Only one third of the FBR Discussion Group members attended with no Chairman. There was no opportunity for exchange of views with the public, probably because the secretariat feared that the FBR Discussion Meeting members would not be able to respond to questions, would exhibit lack of expertise, or say something that was not in the report (Yoshioka, 2013). Meanwhile, the public had mailed in more than 1,000 letters. The FBR Discussion Meeting Chair selected four members to hold a 5-hour meeting to decide whether any opinion should be accepted. The meeting was attended by staff of METI's ANRE and the PNC and they had the same authority as the FBR Discussion Meeting members to make decisions. Yoshioka stated that the presence of the PNC staff at the meeting was "as if the defendants served as the judges" (AEC, 1997b).

- The official report of the FBR Discussion Meeting was published on 1 December 1997. The report included the majority views of 15 members and the minority view of one member (Yoshioka) side by side, an unprecedented format as an AEC special committee report. Although the minority view was cut extremely short, the report dramatically changed the Japanese FBR policy.
- First, the FBR was no longer viewed as Japan's mainstay future reactor but viewed as one option among many. Secondly, although R&D for commercial FBRs would continue, no policy was made about the date of FBR commercialization or the type of future commercial FBRs. Indeed, the FBR Discussion Meeting report indefinitely postponed the decision on commercial FBRs. Yoshioka stated that the policy shift is not necessarily due to the FBR Discussion Meeting's initiative. He explained that building a commercial FBR had already been viewed by the utilities as highly difficult even before the Monju accident. The policy shift in the report was simply confirming the tacit understanding of all parties involved (Yoshioka, 2013). Nonetheless, the one opposing view expressed by Yoshioka at the FBR Discussion Meeting suggests that were it not for that one opposing view, the report could have become a full and total endorsement of the commercial FBR after Monju (AEC,

1997a).

Example 4. On 25 September 1996, the AEC published a policy document “On Promotion of the Public Participation in the Nuclear Information Disclosure and Policymaking Process.” The AEC decided to implement the policy in response to a proposal made at the 5th session (24 June 1997) of the Roundtable Congress. The document stated that the AEC would promote public participation in the policymaking process by making available reports and documents created by special subcommittees and soliciting the public’s views. The AEC would incorporate views that are worthy and publish views that were incorporated as well as rejected in the final report. It also stated that the AEC would fully disclose most nuclear information (Yoshioka, 2013). To achieve this, the AEC would open AEC’s special subcommittee meetings to the public, except for those that the subcommittees decided should not be open, including those subcommittees on nuclear non-proliferation, protection of nuclear materials, and diplomatic negotiations. Also, with cooperation from other government agencies, the AEC would create a structure that could swiftly respond to requests for nuclear information. The AEC also would make conference proceedings and discussion materials available through the Internet. For information that could not be disclosed, the AEC would provide explanations as to why documents were held back. The AEC also would carefully monitor and take appropriate action concerning other government agencies’ procedures regarding information disclosure (AEC, 1996a, 1997c).

All these measures were implemented, but with decidedly mixed results. Documents created by AEC’s plenary meetings, the Nuclear Safety Commission (NSC) plenary meetings, special subcommittee meetings, and METI’s nuclear council meetings were made public. On the other hand, there was no substantial progress made in the public’s participation in the policymaking process, except for a few minor word changes to reports. This was because the subcommittees and secretariats had the right to reject public comments and did not engage in two-way conversations with private citizens. Moreover, once the subcommittee and the secretariat had reached a conclusion, the public’s views, no matter how significant, never resulted in any changes. Public opinions that were rejected were returned with non-substantive responses (Yoshioka 2013).

Regarding document disclosure, most proceedings and transcripts of council meetings have been made public since the fall of 1996, but none prior to that time. Also, only documents created by councils have been disclosed, but few others have been released. Some documents were excerpted before they were made public. In 1999, the Information Disclosure Law (the law regarding disclosing information that is in the possession of administration agencies) was passed. It has not improved the situation, however (AEC, 1999).

- In addition, the information on the process of selecting the members for subcommittees and councils is completely hidden from the public. The selection of members would largely determine the content of the final report. If the majority of the committee members were supporters and associates of an agency and agency policies, the report would closely align with agency policy. The selection of council and subcommittee members, even after the Monju accident, showed bias; some councils may have one or two members with opposing views, but most had no opposing views (Yoshioka, 2013).
- Moreover, the process of a report production was mostly secret. In most cases, the

secretariat would write a draft, revise the draft based on council discussions and compile the final report. The committee members and the chairman could express their views on the report, but they would not have specific knowledge of the process by which the draft was written. Public criticism of government councils is on the rise, which could diminish their power. Nonetheless, the secretariat still retains power over the process. All in all, though there have been some progress in openness, there still is no fundamental change in the nuclear policymaking apparatus. People can express their views to some extent and disclosure of information has been encouraged, but public opinion has an insignificant impact on government policy (Yoshioka, 2013).

1.12 Impact of Bureaucratic Rivalries and Accidents on Safety Oversight

An important legacy of the early period of nuclear energy in Japan was the structure of the government's oversight of nuclear activities. As we noted earlier, the Prime Minister was given the authority in law in 1957 to license all nuclear businesses, including R&D and power reactors. The technical complexity of these tasks meant that the PM relied heavily on advice from the AEC and the NSC. These organizations were in turn supported by STA, which provided secretariat staff to both. STA's greater bureaucratic heft meant that the commissions deferred to the judgments of STA staff and for all practical purposes the AEC and the NSC operated as a single entity.

Given the modest beginnings of the nuclear industry in the late 1950s, this oversight process worked well enough. The process came under pressure, however, in the wake of the publicity that surrounded the Mutsu nuclear ship radiation leak. With the ship in dry-dock for repairs, the government established the Advisory Committee on Atomic Energy Administration, chaired by Professor Emeritus Hiromi Arisawa, to examine nuclear related organizations.

The Arisawa Committee urged the government to separate the functions of nuclear safety from the mission of the AEC and establish an independent advisory committee. So, the NSC was re-created as an independent body reporting to the Prime Minister (See Figure 1.6). The NSC still relied on the STA for secretariat support, however, and was largely beholden to its bureaucratic power. The Arisawa Committee also recommended that METI (then MITI) be responsible for the regulation of commercial nuclear power reactors. This represented a dramatic increase in METI's responsibilities, which previously only had authority to grant construction permits for nuclear power plants. Both Committee recommendations were adopted in law in 1978. The upshot was that for the next twenty years METI became the primary government overseer for safety, while responsibilities of the Prime Minister were diminished.

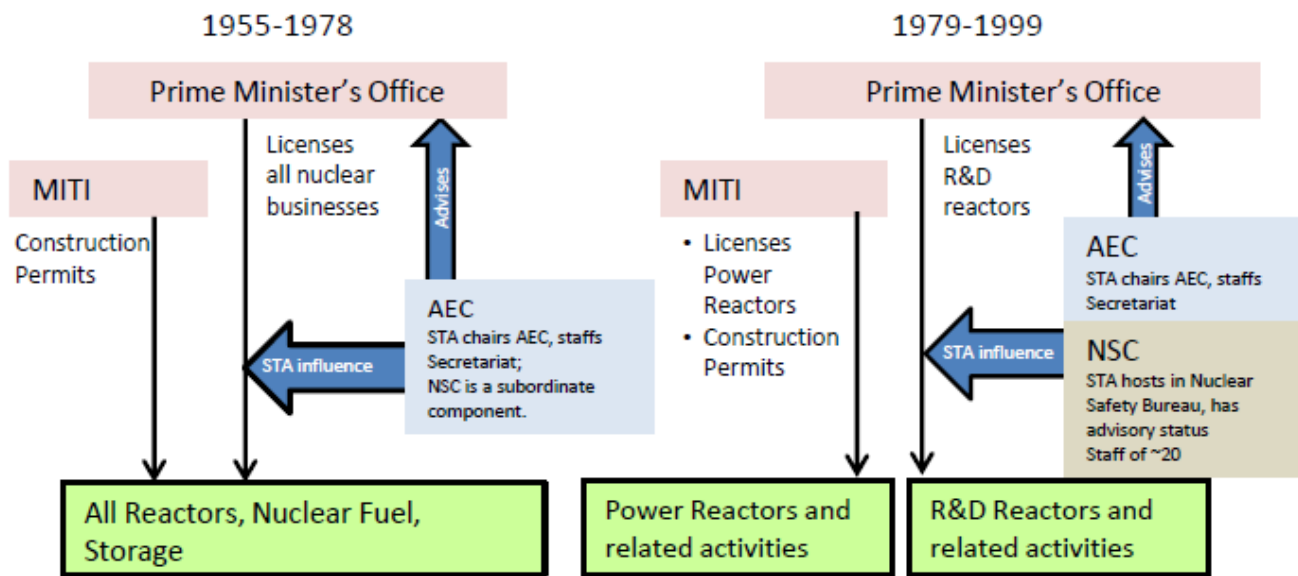


Figure 1.6 Safety Oversight: Changes Pre- and Post-Arisawa Committee
Source: Figure is based on authors' interpretation and analysis of various sources.

As we have seen from the examples given above, METI's priorities dominated government decision-making. Simply put, its goal was to achieve energy independence for Japan by promoting nuclear power and facilitating the construction of new power plants. While it was not the intention of the Arisawa Committee, their recommendations codified a fragmented safety oversight process, distributing it across the government and placing responsibility for safety oversight of power reactors with METI, even though safety was a secondary concern for the Ministry. The NSC, while remaining an independent advisor on safety, had a staff of just 20 and thus was inherently limited in its ability to do meaningful oversight.

Safety oversight remained a back-burner issue for the government until the 1990s, when a series of accidents occurred that raised questions about Japan's ability to manage more complex technologies. The fatal criticality accident was especially disturbing, and so the government revisited the question of nuclear safety oversight. STA was responsible for the organizations that had the major accidents, which left STA in a politically vulnerable position. METI on the other hand had managed to maintain an unblemished record and so was able to benefit from STA's problems. Using its authority to regulate commercial power reactors, METI established the NISA and an inspection staff (called JNES), which together grew to more than 800 (See Figure 1.7). NISA's responsibilities included:

- Regulating nuclear power refining, fabrication, storage, reprocessing and waste disposal businesses and nuclear power generation installations and matters relating to ensuring the safety of these businesses and installations;
- The safety of nuclear power relating to its utilization as an energy source;
- Control of explosives, safety of high-pressure gas, mine safety, and other safety matters under its jurisdiction;
- International cooperation pertaining to affairs under its jurisdiction.

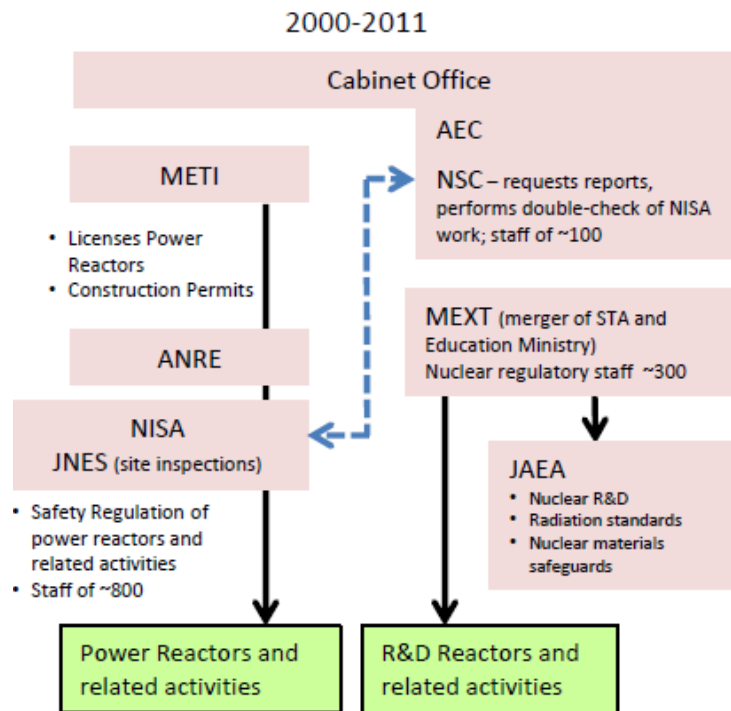


Figure 1.7: Safety Oversight: Post-Criticality Accident

Source: Figure is based on authors' interpretation and analysis of various sources.

The NSC had a modest staff of 100 that was based in the Cabinet Office. While now part of government and no longer just an advisor, the NSC was clearly overtaxed. It had authority to obtain reports from NISA and review (in its double-check role) NISA's work and regulatory decisions for a rapidly expanding fleet of nuclear power plants. The NSC also was responsible for oversight of MEXT's nuclear mission, including JAEO (the re-incarnation of STA) activities, which covered nuclear R&D, nuclear materials safeguards, radioactive dose standards, as well as safety oversight of advanced reactors and reprocessing activities. With all the "here and now" tasks that the NSC had to execute, the staff had little time to consider how to prepare for low probability/high consequence accidents scenarios, such as what happened in 2011.

Figure 1.7 provides a top-level organizational perspective of Japan's safety oversight mechanisms that were in effect in 2011. The government's strongest advocate for safety (NISA), shown on the left side of the Figure, had to distribute its priorities among nuclear and industrial matters. Worse, NISA was positioned within the Agency of Natural Resources and Energy, which focused on a wide range of energy issues, of which nuclear was only one. On the right side of the chart were oversight mechanisms that had largely been discredited because of the rash of accidents in the 1990s; and as we have said, the staff within the Cabinet Office were over-taxed. Thus, safety oversight was hobbled by a combination of divided loyalties and discredited bureaucracies. This set the stage for the Fukushima disaster which was still more than a decade in the future,

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Chapter 2:

Successes and Failures of Big National Projects

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Abstract

Japan began developing nuclear power technologies by establishing Big National Projects. These projects included enrichment, advanced thermal reactors (ATRs), fast breeder reactors (FBRs), and spent fuel reprocessing. The Science and Technology Agency and its research institutions established a pilot enrichment plant, a prototype ATR, and an experimental FBR. These were followed by larger and more costly concepts (FBR Monju, and the Tokai-mura reprocessing plant), but STA was unable to persuade the commercial sector take over these technologies. With the price of natural uranium falling, ATR and FBR technologies were not competitive with simply relying on low-enriched uranium to power reactors. Moreover, the nuclear industry was reeling from a series of accidents at Fugen, Joyo, and Monju, which were made worse by attempts to cover them up. Public outcry led to resignations and in one unfortunate case, suicide.

2.0 Japan's Big National Projects

The goals of the Big National Projects that emerged from Japan's ever-changing nuclear bureaucracy remained constant. They did evolve in emphasis over time as Japan's priorities changed and the global nuclear industry matured. As the reader might surmise from the name "Big National Projects," every agency and ministry in government that the projects touched made every effort to make them economically viable and transfer the resulting technology from the laboratory to the private sector. The Big Projects include:

- Uranium mining and enrichment
- Development of ATRs and FBRs
- Fuel Reprocessing

Moreover, as nuclear reactors aged and spent nuclear fuel was transferred to temporary storage, Japan added waste storage and decommissioning technologies to its list of big national projects.

2.1 Uranium Mining, Exploration and Enrichment

In 1950s and 1960s demand for uranium in the world was dominated by military requirements and the US Government was the biggest buyer. In 1960, uranium production for the western world peaked and then fell back until the mid-1960s. During this period an increasing number of civilian reactors began to come on-line, driving up demand. By 1970, many European countries and Japan feared there would soon be a uranium shortage ([Nuclear Engineering International \(NEI\), 2016](#)).

Uncertainties in uranium supply and demand incentivized a search for uranium deposits within Japan. In November 1955, Japan's National Institute of Advanced Industrial Science and Technology (formerly METI's geological survey office) found a small outcropping of uranium in Ningyo-toge in Okayama Prefecture. Prompted by this discovery, the AFC decided to build the

Ningyo-toge Business Office in August 1957 and launch a concerted R&D effort to process natural uranium¹⁴ ([Japan Atomic Energy Agency \(JAEA\), 2016a](#)). Japan had little knowledge of nuclear fuel technologies and so AFC engaged in both basic research and practical production activities. Progress was slow ([Atomic Energy Commission of Japan \(AEC\), 1956](#)).

- In 1959, AFC produced yellow cake at its Tokai Works in Ibaraki Prefecture and in 1961 succeeded in the development of an advanced refining method, nicknamed the “New Elixir Method.” Eight tons of uranium ingots were produced, which were used to support criticality experiments by Fuji Electric and JAERI.
- In 1964, AFC built another research facility in Ningyo-toge to conduct research on process technology for low-grade uranium ore. Low-grade uranyl chloride produced there was transported to the Tokai Works. By April 1968, the Tokai Works produced 1,998 tons of triuranium octoxide (U₃O₈) ([AEC, 1967a](#)).
- Subsequently in 1974, the PNC (AFC’s successor) developed a one-step refining method to produce uranium tetrafluoride from uranium ore without going through yellow cake production ([Digital Okayama Encyclopedia, 2011](#)).
- By 1987, the Ningyo-toge mine was exhausted. The PNC ended uranium exploration in Japan in March 1988.

Japan continued to actively support exploration and uranium access abroad. By 1998, the PNC and several Japanese companies, such as Idemitsu Kosan and Tokyo Electric Power Company (TEPCO), were participating in uranium equity investment activities in 13 countries, including Australia, Canada and the United States. Through these investments, Japan was able to secure a stable supply of up to 8000 tU per year from Australia, Canada, Kazakhstan and elsewhere ([WNA, 2017a](#)).

In February 1998, the AEC decided that Japan should privatize the uranium exploration activities and JNC (PNC’s successor from 1998 to 2005) transferred all its equities to a Japanese consortium, Japan-Canada Uranium, in November 2000. The consortium consisted of Itochu, Mitsubishi Corporation, and Mitsubishi Material. Other equities that could not be transferred to Japanese companies were sold by 2002.

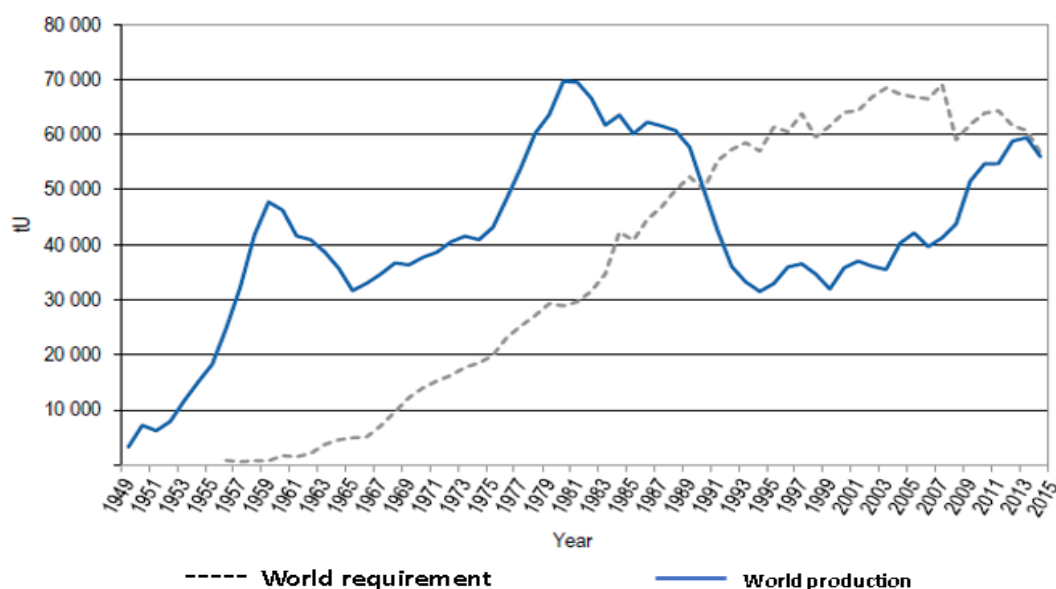
Regardless of the ups and downs of uranium demand the world uranium suppliers have been able to meet demand globally for decades, according to the OECD ([OECD, 2016](#)). After 1990, production fell well below demand, as secondary suppliers fed the market (See Figure 2.1). In addition to existing and likely new mines, nuclear fuel from secondary sources included:

¹⁴ In 1962, Japan discovered a second uranium mine in Tono, Gifu prefecture. The mine, however, was small and of low-grade ore. Japan did not exploit it. The mine was used for geologic research from 1986 to 2004. The closure of the mine has been in progress since 2010 ([Tono Geoscience Center, no date](#). “Tono Kozan (Hei-zan Sochi-chu (Tono Mine (Closing measure in progress),” Japan Atomic Energy Agency, <https://www.jaea.go.jp/04/tono/shisetsu/kouzan/kouzan.html>, (accessed 23 June 2017)).

- Recycled uranium and plutonium from used fuel, such as mixed oxide (MOX) fuel¹⁵
- Re-enriched depleted uranium tails
- Ex-military weapons-grade uranium that was blended down
- Civilian stockpiles
- Ex-military weapons-grade plutonium used in MOX fuel ([WNA, 2017b](#)).

Uranium prices started to go up in 2003, fueling a worldwide uranium acquisition race. In August 2006, METI's ANRE decided to promote its overseas uranium mining again by establishing the Japan Oil, Gas and Metal National Corporation (JOGMEC) in 2007. Starting in 2007, a large number of Japanese companies, including Chubu Electric Power Company, Idemitsu Kosan, Kansai Electric Power Company (KEPCO), Kyushu Electric Power Company, TEPCO, Marubeni, Mitsubishi Corporation, Mitsui & Co., Sumitomo Corporation, Tohoku Electric Power Company, and Toshiba were actively engaging in uranium mining projects in such countries as Australia, Canada, Kazakhstan, Namibia, Niger and Uzbekistan ([Research Organization for Information Science and Technology \(RIST\), 2009](#)).

The shortfall in primary production disappeared in the last five years as mine production increased, and uranium requirements declined ([OECD, 2016](#)). Indeed, Japan has been able to access and import all necessary uranium with few problems ([Yoshioka, 2013](#)). Japan has only nine nuclear reactors generating power today and if this situation continues, there will be no shortage of uranium for some time.



* Data as of 1 January 2015

Figure 2.1 Annual World Uranium Production and Requirements, 1949-2015*

Source: OECD, 2016.

¹⁵ MOX refers to mixed oxide nuclear fuel, which contains more than one oxide of fissile material. MOX usually includes plutonium blended with natural uranium, reprocessed uranium, or depleted uranium. MOX is an alternative to the low-enriched uranium fuel used in light water reactors for nuclear power generation.

2.1.1 Ningyo-toge Pilot Enrichment Plant and Prototype Plant

In the early years of uranium enrichment, many in Europe and Japan feared there would be a shortfall in uranium production. This led European countries to join forces and build uranium enrichment companies. Although Japan held discussions on participating in these enrichment efforts, it never wished to abandon independent development of enrichment technology—even as it relied on foreign enrichment services (Yoshioka, 2013).

One of the first such initiatives undertaken by Japan's AFC was the promotion of R&D on centrifuge technology and construction and operation of pilot enrichment facilities. A basic centrifuge enrichment technology was developed in 1959 by Riken,¹⁶ which was later modified to operate in a small uranium refining and conversion plant at Ningyo-toge (Yoshioka, 2013; RIST, 2007).

In 1972, the AEC designated uranium enrichment to be a Big National Project and so the PNC began to develop a metal-body centrifuge with higher separation capability and better operational safety. In 1976, the AEC felt that centrifuge technology was mature enough to build a pilot plant in Ningyo-toge. Thus, in 1977 the PNC began to install the First Stage of the First Operations Unit (OP-1A) of the Ningyo-toge Pilot Enrichment Plant. Operations commenced in September 1979. The Second Stage of the First Operation Unit (OP-1B) began operations in October 1980 and the Second Operations Unit (OP-2) went operational in March 1982. Its centrifuges were twice as efficient as those in OP-1A (JAEA, (no date)a).

- The separation capacity per year, however, was only 50 tSWU, which was not enough to fuel even one 1 GW nuclear reactor. Yoshioka noted that a 1 GW reactor would need about 30 tons of enriched uranium per year, which would require a separation capacity of 120 tSWU/year. Moreover, production costs at the Ningyo-toge plant were very high.
- The pilot plant did successfully demonstrate Japan's cascade and control technology, uranium hexafluoride (UF₆) analysis technology, and safety inspection technology. Some of the enriched uranium was used in ATR Fugen, which successfully closed the nuclear fuel cycle. But there was no denying that the Ningyo-toge Enrichment Plant technology was not competitive with foreign counterparts—its enriched uranium certainly was far costlier (RIST, 2007).
- It was inevitable that the Ningyo-toge pilot plant would not continue and in March 1990 operations ended. The pilot plant operated for ten years and produced a total of 51 tU of enriched uranium using about 7,000 centrifuges.

Despite the mixed results from the pilot plant, in August 1981, the AEC decided that the Japanese enrichment technology was mature enough for commercialization and ready to transfer to the private sector. In its 1982 Long-Term Plan, the AEC authorized construction of a prototype enrichment plant at Ningyo-toge with a 200 tSWU capacity, to be built jointly by PNC and the

¹⁶ Riken was established as a non-profit research foundation in 1917. It is Japan's only research institution engaged in comprehensive natural science research, including physics, engineering, chemistry, computational science, biology and medicine. It has been a national research institute since 2015.

private sector via a consortium of utility companies. The PNC signed a technology cooperation agreement with the consortium in 1985.¹⁷

The prototype plant incorporated two types of metal-body centrifuges, DOP-1 (the first operation unit), which started operations in April 1988 and DOP-2 (the second operation unit), which started operations in May 1989. These metal-body centrifuges were jointly developed by PNC and private-sector participants. Both plants worked well without accidents for 13 years. DOP-2 ended operations in 1999 and DOP-1 ended operations in 2001. During this period, the plants produced about 350 tU under the contract with the utility companies and yielded about 35 tU of enriched uranium from recycled uranium produced at the Tokai reprocessing plant (RIST, 2007).

On a separate track, in 1986, the AEC decided that the PNC and its private sector partners should jointly develop a high-efficiency centrifuge made with carbon-fiber reinforced plastic resins. The 5-year (1993-1997) project encompassed materials development and testing of a 1,000-unit cascade. The test established a long-term record of operational reliability, but the new centrifuges were still too costly for commercialization (JAEA, (no date)b; Ichimura, T., 2009; RIST, 2007).

In 1993, the private sector and PNC started another 6-year (1993-1998) project to develop a high-function centrifuge in parallel with the carbon-fiber centrifuge project. The high-function centrifuge was expected to be commercialized by 2003 and would have separation efficiencies 1.5 to 2 times better than the carbon-fiber centrifuge. With this new centrifuge, Japan clearly expected to gain international competitiveness. Yoshioka stated that it had been an open secret that the domestic enrichment project was several times as costly as overseas counterparts. The project continued through 2000 but could not solve the material design problems for operations under high temperatures (Yoshioka, 2013; Ichimura, 2009).

In May 1998, JNC took over from the PNC all R&D at the direction of the AEC. It closed the Ningyo-toge Prototype Enrichment Plant in March 2001. Funding for all the STA-sponsored uranium mining, exploration, refining, conversion and enrichment activities ended and results were transferred to the private sector for commercialization. Since then, the Ningyo-toge Environmental Engineering Center (formerly the Ningyo-toge Business Office) has been engaged in decommissioning of both the enrichment plant and the Ningyo-toge mine. (JAEA, (no date)b).

2.2 Advanced Thermal Reactors and Fast Breeder Reactors

In May 1960, Japan started to explore the indigenous development of an FBR and an ATR, which Japan expected would replace light water reactors (LWR) in the future. The FBR was expected to breed more plutonium than it consumed. The ATR was expected to have flexibility in fuel use; it

¹⁷ The consortium was represented by the Japan Nuclear Fuel Limited (JNFL), which was established in 1992 by ten Japanese utilities and 74 major Japanese companies. JNFL was set up to commercialize enrichment, reprocessing and radioactive waste disposal technologies that AFC, PNC, JNC and JAEA had developed. The JNFL was created by the merger of two “forerunner” companies—Japan Nuclear Fuel Service Limited (for reprocessing) and Japan Nuclear Fuel Industry Limited (for enrichment). This arrangement laid the foundation for establishment of the Rokkasho Reprocessing Plant in Aomori Prefecture (JNFL, 2016. “Corporate Profile,” Updated in February 25, 2016, <http://www.jnfl.co.jp/en/about/company/>, (accessed 17 August 2017)).

could use plutonium, spent uranium and natural uranium, thus closing the fuel cycle and using less enriched uranium. At that time, the United States was the only source of enriched uranium supply and Japan's domestic enrichment technology was still under development. To study the issue, AEC established the "Fast Breeder Reactor Roundtable Meeting" in February 1964 and the "Power Reactor Development Roundtable Meeting" in October 1964. This led to the simultaneous development of two reactors in Japan: the prototype ATR Fugen and the experimental FBR Joyo ([RIST, 2005](#)).

- Canada and the UK were already developing ATRs and the information was readily available.
- In addition, the ATR had a similar configuration to BWRs that Japan was becoming familiar with. Thus, AEC decided to develop a prototype ATR Fugen, skipping the experimental stage ([RIST, 2005](#)).

In 1967 JAERI¹⁸ had already built the Oarai Research Center, Ibaraki Prefecture and built many large, full-scale test mockup models that were installed at the Oarai Center. The test equipment that JAERI had built included a deuterium critical assembly to test the reactor core characteristics, a 14-MW heat temperature loop to inspect the core thermal and hydraulic characteristics, a component test loop to verify the safety and reliability of critical reactor parts and equipment and a full-scale safety test facility to assess Fugen's safety ([RIST, 2005](#)).

2.2.1 Advanced Thermal Reactor Fugen

In October 1967, the PNC took over the development of a prototype ATR at Fugen. In 1968, the PNC surveyed the construction site at Tsuruga, Fukui Prefecture and finalized the ATR design a year later. It was to have a power output of 165 MWe and a thermal output of 557 MW. The design was checked and approved by AEC's "ATR Evaluation and Examination Special Committee." Construction permission was granted in December 1970 and construction started in 1972. Builders were Hitachi, Toshiba, MHI, Fuji Electric and Sumitomo (the prime contractor).

Construction of ATR Fugen was completed in 1977. After comprehensive function tests, the fuel was loaded on 20 March 1978 and Fugen reached initial criticality on the same day. Fugen achieved full operations in March 1979. It was a relatively trouble-free development. The reactor was the first in the world to use a full MOX fuel core; it had 772 assemblies, the most in the world. The construction cost of Fugen was \$685 million, half of which was paid by the private sector ([Ministry of Education, Culture, Sport, Science and Technology \(MEXT\), 2017](#); [RIST, 2003](#)).

ATR Fugen boiled ordinary water like a boiling water reactor (BWR) but used heavy water as a moderator. A major milestone was reached in the fall of 1981 with successful operation of Fugen using MOX fuel assemblies fabricated in Japan and containing plutonium recovered from spent

¹⁸ The Japan Atomic Energy Research Institute (JAERI) was assigned to develop advanced nuclear reactors, including an ATR and a FBR. The JAERI had management disputes with its employees' union and was unable to focus on development. Thus, Japan created the Power Reactor and Nuclear Development Corporation (PNC) to take over the task from JAERI.

LWR fuels from the Tokai-mura fuel reprocessing plant. Thus, Japan was able to claim it had closed the plutonium-uranium fuel cycle—a long-sought dream, albeit limited in scope (JAEA, (no date)c).

Since 1974, AEC had been considering building a demonstration ATR, which would be a successor to the prototype ATR Fugen. In 1979, AEC decided that a 600 MWe demonstration ATR was the best choice. The PNC, STA and METI established an ATR Joint Committee to discuss the practicality and economy of the demonstration ATR. It was decided in 1981 that AEC would study the structure of the demonstration ATR, that J-Power¹⁹ would build and operate the ATR and that the PNC and the utilities would cooperate. AEC published its Long-Term Plan in July 1994, which indicated that the demonstration ATR was to be built and start operation in the early 2000s (RIST, 2003).

The demonstration ATR was expected to be built in Oma, Aomori Prefecture and the expected investors were the Japanese government (30 %), the electric utilities (30 %) and J-Power (40 %). The utilities, however, were reluctant to participate in the demonstration ATR project because of the lack of economic feasibility of the project. As of March 1995, the utilities had estimated that the demonstration ATR would cost \$5.8 billion to build and \$9.57 to generate 1W of electricity, three times as costly as an advanced LWR both in construction and power generation. Moreover, the use of plutonium in LWR was possible in the form of MOX fuel and LWRs could fulfill the role of the ATR in closing the nuclear fuel cycle, meaning the demonstration ATR would be both costly and not necessary. In July 1995, the electric utilities announced their withdrawal from the demonstration ATR project, making it financially impossible for the project to continue. According to Yoshioka (2013), the private sector for the first time used its veto power to halt one of STA's big national projects.

- ATR Fugen stopped operations in March 2003. Since first criticality was achieved in March 1978, Fugen had operated with MOX fuel and natural uranium for more than 25 years (JAEA, (no date)c). A major milestone was reached in the fall of 1981, when ATR Fugen operated using MOX fuel assemblies fabricated at the Tokai Prototype Reprocessing Plant with plutonium recovered from spent LWR fuels. With this, the plutonium-uranium fuel cycle had been successfully closed in Japan and demonstrated the technical feasibility of ATR as the first Japanese-made nuclear power plant (JAEA, (no date)c).
- ATR Fugen used a total of 772 MOX fuel assemblies and 687 natural uranium assemblies by March 1991; Fugen was the world's largest MOX fuel user. MOX fuel manufactured at the PNC's Tokai Prototype Reprocessing Plant had been produced without failures. In addition to closing the nuclear fuel cycle, ATR Fugen demonstrated its ability to conserve enriched uranium. Fugen had generated a total of 21.9 TWh with a facility utilization rate of 62 percent (Furubayashi, et al., 2003; RIST, 2003).
- AEC announced in August 1995 that Japan's ATR program had ended. Since then, the prototype Fugen has operated as a test reactor. Fugen ceased operations on 29 March 2003.

¹⁹ J-power was initially established by law in July 1952 as a special corporation Electric Power Development Company to promote electric power in Japan. Subsequently, it worked to promote nuclear power. In October 2003, the law that established the company was rescinded and the company became a private corporation called J-Power. It listed its stocks on the first section of the Tokyo Stock Exchange in October 2004.

Decommissioning was expected to be completed in 2029 ([Furubayashi, et al., 2003](#)).

ATR Fugen, however, had several accidents that seemed to underscore the PNC's habitual neglect of safety regulations. Details of four separate accidents are summarized in Table 1.2. Two are of greatest concern from a safety perspective because they represent recurring errors or failures:

- On 16 October 1997, operators inspected Fugen's pressurized pipes and accidentally leaked 2 cubic meters of radioactive coolant. On 5 November 1997, a similar accident occurred due to the cracks in a stainless-steel tube. During the following investigation, it was discovered that there already had been 11 similar incidents. Five managers of the PNC resigned.
- On 8 April 2002, about 200 cubic meters of steam escaped from a defective pipe. The reactor was shut down permanently. During dismantling operation, it was discovered that walls with operational controls did not have necessary strength at some 25 of 34 points, clearly showing the operators' lack of a safety culture ([Furubayashi, et al., 2003](#); [Osaka University, no date](#)).

2.2.2 Fast Breeder Reactors (FBR)

A resource-poor Japan had long aspired to establish a nuclear fuel cycle that would include FBRs, thereby reducing Japan's reliance on foreign sources of energy. In May 1966, AEC affirmed its plan to develop an FBR in its "Basic Plan on Advanced Reactor Development ([JAEA, 2007](#)). An FBR could use a variety of nuclear fuels, including natural uranium, depleted uranium and plutonium, and thus enable Japan to economize on natural uranium.²⁰ AEC hoped that FBRs as well as ATRs would replace LWRs in the future as the primary power generating reactors in Japan. Japan's primary goal, however, was to have a FBR, which would create more plutonium than it consumed and thus enable Japan to become more energy independent. Because of the difficulty in dealing with sodium coolant, however, Japan planned to develop the FBR in three or four stages. The stages included building an experimental reactor, a prototype reactor and a demonstration reactor and/or a commercial reactor ([RIST, 2015](#); [AEC, 1967b](#)).

- In 1967, AEC recommended in its Long-Term Plan that Japan should develop the FBR. AEC thought that the FBR initially would use mixed plutonium and uranium fuel (MOX fuel). It envisioned that the FBR would be commercialized in the mid-1980s ([AEC, 1967b](#)).
- AEC also announced in its Long-Term Plan that the FBR (as well as the ATR) would be built with as much domestic content and technology as possible to advance indigenous capabilities. Foreign manufacturers were not included. Contractors for the experimental FBR were Toshiba, Hitachi, MHI and Fuji Electric, and Toshiba (the prime contractor). The non-nuclear facilities and buildings were built by Takenaka Corporation. Contractors for the prototype Monju included Toshiba, Hitachi, Fuji Electric and MHI; they established a joint

²⁰ LWRs use enriched uranium for power generation, leaving spent uranium, plutonium and various other radioactive derivatives. Advanced reactors such as ATR could use plutonium as a fuel, closing the nuclear fuel cycle, enabling Japan to use less uranium. With fast breeder reactors, plutonium could be used as a fuel and also breed more plutonium, enabling Japan to be more energy independent.

company—Fast Reactor Engineering—to coordinate their work.

- The PNC ordered full-size, mockup models to be built for tests, analysis, and design of the prototype ATR and the experimental FBR. In the case of prototype FBR, however, the PNC did not rely on full-scale mockup models in order to save on costs. It assumed models of the experimental FBR would suffice. (Yoshioka, 2013; JAEA, 2016b; AEC, (no date)b; Nomoto, et al, 1977).

Meanwhile, new uranium deposits were being discovered overseas and production rapidly increased. Just as the experimental FBR Joyo project was starting, uranium became abundant and interest in breeder reactors in the world waned. The abundance of natural uranium continues even today: As of 2015, 646,900 tons of reserves are recoverable at \$40 per kilogram of uranium, while 7,641,600 tons of reserves are recoverable at \$260 per kilogram (OECD, 2016).

Despite these economic realities, the AEC continued to have high expectations for the FBR. Yet development was slow. AEC found itself continually delaying the timing of commercialization. Table 2.1 shows how repeated delays in the schedule for FBR commercialization were depicted in AEC's Long-Term Plans. The industry's reluctance to embrace the FBR, plus technical difficulties and the lack of indigenous capabilities likely exacerbated the slow progress in FBR development.

- In the 1960s, the AEC envisioned that the FBR could be commercialized around 1970.
- In the early 1970s, commercialization was expected in 1985-1995.
- In the late 1970s, it was thought possible between 1995-2005.
- In the early 1980s, it was expected in 2010.
- In the mid-1990s, commercialization was expected by 2030 and in 2005, Japan was aiming for commercialization in 2050.

As of today, AEC's target date for commercialization of the FBR, as shown in its nuclear policy framework, is 70 years behind AEC's original schedule (White, Ban, 2010).

Table 2.1 Changes in AEC's Long-Term Plan for Nuclear Development and Commercialization of the FBR

Primary Policy	Date	Changes in Commercialization of Fast Breeder Reactor (FBR)	Other Policies	Estimated year of Commercialization
AEC Long-Term Plan of Nuclear Development and Utilization*	September 1956	Japan's goal is to develop FBRs domestically to effectively use nuclear fuels. Japan should aim at constructing one experimental FBR and JAERI should design and develop it.	Long-Term Plan of Power Generating Reactor (December 1957)	Expected 1970s.
	February 1961	R&D of fast neutron breeder reactors should be promoted at JAERI. A small scale		

		experimental reactor should be built to pursue primarily safety research, while promoting the technology to build a commercial-scale reactor.		
April 1967		FBR would be future Japan's mainstream nuclear power reactor. FBR should be developed independently as a national project. <u>The goal should be to develop a Sodium-cooled FBR for commercial use in late 1980.</u>		Late 1980
June 1972		FBR would be future Japan's mainstream nuclear power reactor. A sodium cooled experimental reactor and prototype reactors should be promoted by PNC. <u>The FBR commercialization is expected to be in the early 1990s</u> and practical ways to construct a demonstration reactor should be actively pursued.		Early 1990s
September 1978		Japan's basic policy is to transition from light water reactors (LWR) to FBR. Demonstration FBR should achieve the criticality in the early 1990s and the <u>commercialization should happen in the early 2000s.</u>		Early 2000s
June 1982		<u>FBR should be commercialized as early as possible or by 2010.</u> The goal should be to start constructing the demonstration FBR in the early 1990s.		2010
June 1987		FBR should be the mainstream power reactor in Japan in the future. Japan should aggressively build the structure for plutonium use by means of FBR. <u>Japan should aim to commercialize FBR in 2020-2030.</u>		2020-2030
June 1994		Japan should use LWR in parallel with FBR for some length of time and develop FBR steadily and strategically to become Japan's mainstream power reactors. The prototype Monju should be steadily tested and start full operation at the end of 1995. Japan should aim to establish its technical structure so that <u>FBR be commercialized by 2030.</u>	Atomic Energy Commission's FBR Roundtable Meeting Report (1997)	2030

	November 2000	The prototype Monju should be placed at the center of Japan's FBR fuel cycle technology R&D and should resume operation at the earliest instance. Japan Nuclear Cycle Development Institute (JNC) should accelerate its "Commercialization Strategy Investigation Research" Program to establish the image of Japan's appropriate FBR fuel cycle technology in commercialization and show the R&D roadmap to get there.		
Framework of Nuclear Policy	October 2005	<u>Japan aims at introducing FBR on the commercial basis in about 2050.</u> The operation of Monju, the core of R&D, should be resumed operation as soon as possible. The verification of FBR reliability as power reactors and the establishment of sodium handling technology though operational experience should be pursued as the priority.		2050

Note: Underlined font shows the scheduling of FBR commercialization.

Source: Table is based on authors' interpretation and analysis of AEC, 2007, 2005; Cabinet Office of Japan, 2013.

2.2.2.1 Experimental FBR Joyo

Although Japan began development of the experimental FBR Joyo with limited knowledge and experience of FBRs, it was determined to make it a success, and to achieve that success by building upon a foundation of indigenously developed technologies. JAERI put together many conceptual designs, many full-scale mockups, prototypes and test equipment to gain knowledge of the technology. Real-size replicas included a reactor vessel, circulation pump and control rod drive mechanism. With these efforts, Japan believed that it would be able to master the technology on its own (Yoshioka, 2013; Nomoto, et al, 1977).

As a first step, JAERI started forming Joyo's preliminary design in 1964. JAERI produced the first conceptual design (1965-1967) and the second conceptual design (1967-1968). Through these processes, JAERI formed the basic specifications of Joyo, including the choice of thermal power generation, the use of oxide fuel and loop type sodium cooling. JAERI installed a full-size mockup and equipment at the Oarai Research Center²¹ to learn the heat transfer characteristics of high

²¹ The Oarai center has changed names many time. It was the Oarai Research Center under AFC, changed the name to the Oarai Engineering Center under PNC and it is the Oarai Research and Development Center under JAEA.

temperature liquid sodium, the compatibility of sodium with other materials, the purity control of sodium and the reaction between sodium and water and air. (Yoshioka, 2013; Nomoto, et al., 1977; AEC, (no date)a; RIST, 1998). It is not clear if JAERI had contracted all the preliminary and conceptual design work to nuclear manufacturers, but the JAERI might have had some preliminary expertise and leadership when the Japanese manufacturers had just begun to learn the technology.

In June 1968, JAERI transferred the second conceptual design to the PNC and the PNC started to prepare the third conceptual design (detailed design). The PNC requested France's CEA (Commissariat à l'énergie atomique et aux énergies alternatives) to check and review the second conceptual design. France had just built its first FBR—Rapsodie—which achieved initial criticality in 1967. Rapsodie was like Joyo; it was a sodium-cooled fast neutron loop-type reactor with a thermal output of 40 MWt and no electric output (Michaille, Rodriguez, 2002). In March 1969, the results of CEA's review and the PNC's third conceptual design were compared. PNC's third design was modified and the thermal output of Joyo, which was designed as 100 MWt originally, was scaled down to 50 MWt. The PNC decided that it would increase the output to 100 MWt in the future after gaining operational experience. The PNC applied for a construction permit on 30 June 1969 and permission for construction was granted in February 1970 (AEC, (no date)a; RIST, 1998).

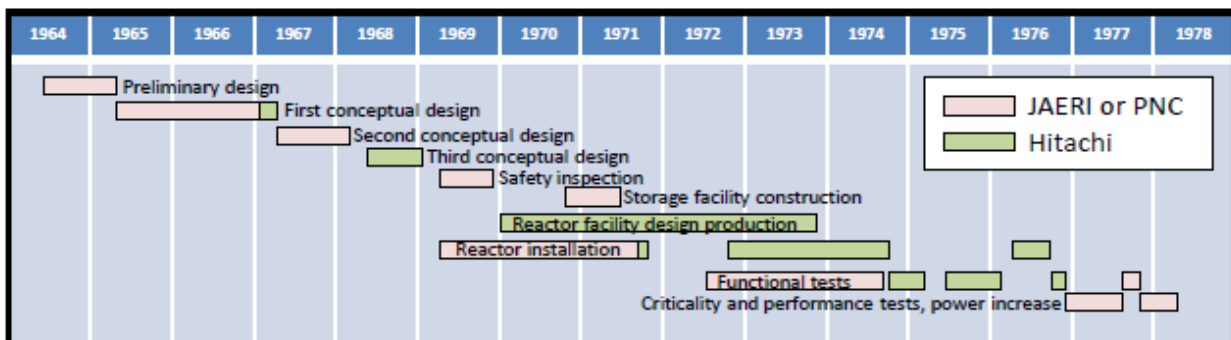


Figure 2.2 Stages of FBR Joyo Development

Source: Nomoto, Aoki, Tachi, Ito, Kai, 1977. The authors provided the translation.

After six years of R&D and four stages of design, the construction of Joyo started in March 1970 at the Oarai Research and Development Center, Ibaraki Prefecture (See Figure 2.2). The PNC conducted a comprehensive functional test of Joyo from January 1975 to March 1977. Joyo received its first breeder core (the MK-I) and reached initial criticality on 24 April 1977. This was Japan's first FBR criticality and the world's 5th. Joyo increased output to 50 MWt in 1978 and then to 75 MWt in 1979. In 1983, Joyo generated 100MWt with an irradiation core (the Mark-II). This core surpassed 50,000 hours of operating time. The Joyo core was upgraded (to the MK-III) in 2004 and generated 140 MWt. Total operating hours from 1977 to 2007 amounted to 71,000. In 1984, plutonium from the reprocessing of spent fuel from Joyo was successfully recycled back into the reactor, thus completing a nuclear fuel cycle (Yoshioka, 2013; Nomoto, et al., 1977; JAEA, 2012a, 2016c, (no date)d; Ohira, Uto, 2013; RIST, 1998).

While Joyo operations were relatively smooth, it did have a serious accident. On 11 June 2007, while the reactor was shut down for periodic inspection, the fuel exchanging device collided with the upper core structure (UCS) irradiation rig. On 28 November 2014, a lengthy repair was completed that extracted the damaged UCS and fuel exchange device. The repair took more than 7 years. (Kobayashi, 2007; Ohira, Uto, 2015; Takamatsu, et al., 2016).

- According to JAEA, Joyo had irradiated around 100 MOX fuel assemblies, which was a significant achievement in Japan's fuel cycle development history. In its 30-year operation between 1977 and 2007, however, Joyo's operational availability was only about 40 percent (Suzuki, 2009; WNA, 2017b).
- The total cost for Joyo was \$1,311 million, including \$289 million for construction and \$1,022 million for operations (Yoshioka, 2013; MEXT, 2015; (World Nuclear News (WNN), 2016).

On 30 March 2017, JAEA applied to the NRA for a conformity assessment of FBR Joyo under the New Regulatory Standards so that Joyo could restart. JAEA hoped to operate Joyo until 2021. The JAEA application estimated that potential earthquakes would reach a maximum of 700 gal and the height of a tsunami would be a maximum of 17 meters. JAEA believed that Joyo would have no safety problems if seismic reinforcements and renovations of outdoor facilities were to be made, which was estimated to cost about \$54 million (Jiji, 2017). According to OECD's Technology Roadmap (2015), Joyo could be employed in various irradiation experiments to develop fast reactor fuel technology. The working group of MEXT also considered that irradiation experiments could be used to support R&D on plutonium and long-lived minor actinides could be conducted (Ohira, Uto, 2015; OECD, 2015).

The NRA, however, directed JAEA to review and amend its application or withdraw it. In the application, JAEA proposed a thermal output of 100 MWt for Joyo although Joyo had been generating a higher output of 140 MWt. JAEA explained to the NRA that if an accident should occur at Joyo, the 140 MWt output would require evacuation of residents within 30 kilometers in radius, but a 100 MWt output would only require the evacuation of residents within 5 kilometers. JAEA also explained that this would make the explanation easier to residents and expedite the restart of Joyo operation. Clearly, this explanation incensed the NRA. The NRA stated that JAEA's understanding of safety is deficient. Thus, the future survival of Joyo is not certain for now (Nihon Keizai Shimbun, 2017).

2.2.2.2 Prototype FBR Monju

FBR Monju has been the cornerstone of Japan's nuclear energy program since the 1960s. Japan's first FBR to generate electric power, it has been the most important goal of the STA among all its big national projects. The FBR has been viewed as a dream machine that will open the door to nuclear power reactors that will breed more fuel than consumed. The spent fuel from power reactors can be reprocessed and made into MOX fuel, which can be fed to the FBR (See Prologue Figure I, The Nuclear Fuel Cycle).

The establishment of the PNC in October 1967 provided a major impetus to develop the FBR. The developmental history of prototype FBR Monju, however, was not a happy one. Progress was constantly hindered by multiple problems, including technical difficulties, lack of domestic technical and R&D capabilities, the government's insistence on indigenous development, lack of a safety culture, declining budgets and serious accidents. As a result, the target date for commercialization of the FBR was delayed numerous times; the PNC initially envisioned commercialization by the late 1980s, but that has now slipped to 2050.

Following the experimental FBR Joyo's relatively smooth launch and operation, the PNC started to develop FBR Monju with great optimism. The PNC decided that Monju, like Joyo, would be a loop-type sodium cooled, MOX-fueled, FBR with three primary coolant loops, designed to produce 280 MWe from 714 MWt. It would have a breeding ratio of approximately 1.2. The plant was to be located on a site that spans 1.08 km² (267 acres), the buildings would occupy 28,678 m² (7 acres) and have 104,680 m² of floor space. It would employ 368 workers ([Wikipedia, 2017](#)).

The PNC started to draw up a design in 1968. The PNC completed the design in March 1977. In December 1980, the PNC submitted a request for the construction of Monju in Tsuruga, Fukui Prefecture. Permission was granted in May 1983. In September 1985, residents filed an administrative lawsuit to invalidate the construction permit and a civil lawsuit to stop construction of the FBR ([JAEA, 2017a](#)).

Nevertheless, the PNC started preparatory construction in October 1985 and full-fledged construction began in October 1986, following settlement of most legal issues. Seven years later, in December 1992, Monju finally began system start-up tests (SST). Fuel assemblies were loaded into the core in October 1993 and reached criticality in April 1994. The PNC's initial plan in March 1968 envisioned that Monju would achieve criticality in 1976, but the delay of 18 years seemed not to matter once Monju went on-line. Yoshioka (2013) explains that most delays were due to the PNC's undue optimism and skimping on funding. The initial plan was aggressive; it stated that Japan would complete each of four phases on five-year timeframes (the experimental FBR, the prototype FBR, the demonstration FBR and the commercial FBR). So, a commercial FBR could be achieved by the late 1980s.

After criticality was achieved, FBR Monju conducted the first test generation of electricity. It was connected to the electric grid in August 1995 and achieved a power output of 40 percent of its design level in October 1995. Monju was expecting to raise power output to the rated power of 280 MWe in June 1996. On 8 December 1995, however, Monju suffered a serious sodium leak and fire.

- At 19:47 on 8 December, an alarm went off, indicating a high sodium temperature at the exit of the intermediate heat exchanger in the C-loop of Monju's secondary coolant system. One minute later, another alarm sounded indicating a sodium leak in Loop C (See Figure 2.3). The leaked sodium reacted with air (oxygen and moisture) in the secondary coolant piping room C, causing a violent spray-fire and filling the room with fumes. It melted the ventilation duct and steel scaffolding and damaged the floor's steel liner to a depth of 3 cm. The sodium became sodium oxide and piled up on the floor, spreading all over the steel liner. According to official reports, the temperature of the steel liner reached 700°C~750°C.

Had the sodium melted through the metal liner and reached the concrete below, the accident would have been even more serious.

- The direct cause of the accident was a broken and detached well tube that contained a thermocouple sensor (See Figure 2.4). The well tube was mounted in a pipe in the secondary cooling system. Once the well tube failed, sodium leaked through the thermocouple sensor assembly near the outlet of the intermediate heat exchanger in the secondary heat transport system Loop C. The well tube broke from its mount because of high-cycle metal fatigue from vibration caused by the sodium flow. The broken sheath was finally recovered four months later 160 m downstream from its original location. The thermocouple well tube, manufactured by Ishikawajima-Harima Heavy Industries (IHI), had a basic design fault combined with the absence of an efficient system to detect such a fault. The angular structure of the thermocouple that penetrated the pipe meant that it was exposed to resonant vibration caused by a symmetrical vortex in the sodium flow. It is suspected that it was already cracked for at least six months and perhaps as long as two years before the accident. The PNC had never inquired about the strength and soundness of the protruding thermocouple tip that was vertically inserted into the sodium pipe, the sodium flow against the tip, or the metal fatigue caused by vibrations. According to Yoshioka, the thermocouple might never have been tested for its soundness and strength (Yoshioka, 2013; Mikami, et al., no date; AEC, (no date)b; White, Ban, 2010; Wise-Paris, no date).
- The conduct of the Monju operator immediately after the accident was viewed as inappropriate (Yoshioka, 2013). The circumstances required the operator to stop the reactor immediately and start the emergency draining of sodium, but he failed to do so. The reactor was tripped manually at 21:20—93 minutes after the first alarm. Draining of sodium out of C-loop started at 22:40—3 hours after the alarm. Draining was completed at 0:15 on 9 December. In addition, the operator should have stopped the ventilation system at an early stage, but he did not. The delay caused 640 kg of sodium to gush out, perhaps several times more than would have occurred if ventilation was stopped earlier. This caused the spread of the sodium aerosol (including radioactive tritium) within the building and likely to the environment. The ventilation system turned off automatically at 23.13, triggered by the low sodium level interlock on the evaporator. Worst of all, the operator did not report the accident to the proper authorities for about 1 hour (White, Ban, 2010; Yoshioka, 2013; Mikami, et al., no date).
- Following the accident, moreover, the PNC concealed and fabricated accident information. It made a videotape recording of the accident scenes twice on 9 December, the first time at 2:05 am (one reel) and the second time at 16:10 pm (2 reels). The PNC tampered with one of the two tapes taken at 16:10 pm and hid the other. In the tampered tape, most of the sodium leak scenes were deleted. The deletion of the sodium leak scenes was discovered in a fourth videotape that was taken by local officials from Tsuruga City and Fukui Prefecture. The officials conducted an on-site inspection at 3:25 am on 11 December. They made a videotape of the scene. The officials found that the PNC tape and their tape were starkly different and demanded an explanation. This led to discovery of the concealment and fabrication. As a result, five top officials were forced to resign. Moreover, on 13 January 1996, the Deputy Administration Manager at the PNC's head office, who had been designated chief investigator, killed himself after stating to the press that the head office had responsibility in the cover-up. The suicide intensified the media scrutiny and the public's anger and distrust of the PNC (Yoshioka, 2013; Diet of Japan, 1998; Wise-Paris, no date).

Yoshioka (2013) also indicated that there were several problems and design errors with Monju that were detected during the construction and testing stage, including the design errors with the secondary cooling tube and inferior fabrication of fuel rods that raised much apprehension and anxiety about safety and reliability. Yoshioka pointed to the PNC's original mistake in cutting the cost of Monju construction and the fact that the PNC did not perform sufficient full-scale model and mock-up tests. Moreover, there were deficiencies in the operating manual for handling of abnormal events and the actions of the operators were not appropriate. Mikami et al (no publication date) listed the following operational procedure problems that were not in the manual:

- The size of the leak should have been recognized early on and the reactor should have been shut down immediately by a manual trip.
- Monitoring of the plant and visual inspections of the leak site had not been carried out appropriately.
- After the second inspection, an emergency shutdown was decided, but the action was delayed.
- A procedure for the draining of sodium at high temperature (i.e. that does not require a cooling period) should have been prepared.
- The ventilation system should have been stopped at an early stage.
- All the operators should have been made proficient in sodium technology with sufficient training.

Fortunately, at least, no injuries were reported, and no radioactive release occurred because the sodium in the secondary loop was not radioactive (Mikami, et al., no date; Suzuki, 2009).

Nonetheless, despite extensive research that has been done over thirty years on safety measures for handling sodium, the complexity of sodium's chemical reactivity and associated risks has not been completely appreciated.

- On 31 March 1994, during the dismantling of the small research FBR, Rapsodie, at Cadarache, France, an unexpected reaction involving about 100 kg of sodium led to an explosion. A technician, a sodium expert, died in this accident and four others were injured (Wise-Paris, no date).

STA's Safety Bureau suspended Monju's operating license at the beginning of August 1997 for a year. A local court also found the PNC and two managers of the plant guilty of giving incomplete information in a report on the accident for the STA. The governor of the Fukui Prefecture, where Monju is located, opposed the restart of Monju, at least in the near future. Without his approval, Monju could not be restarted (Wise-Paris, no date).

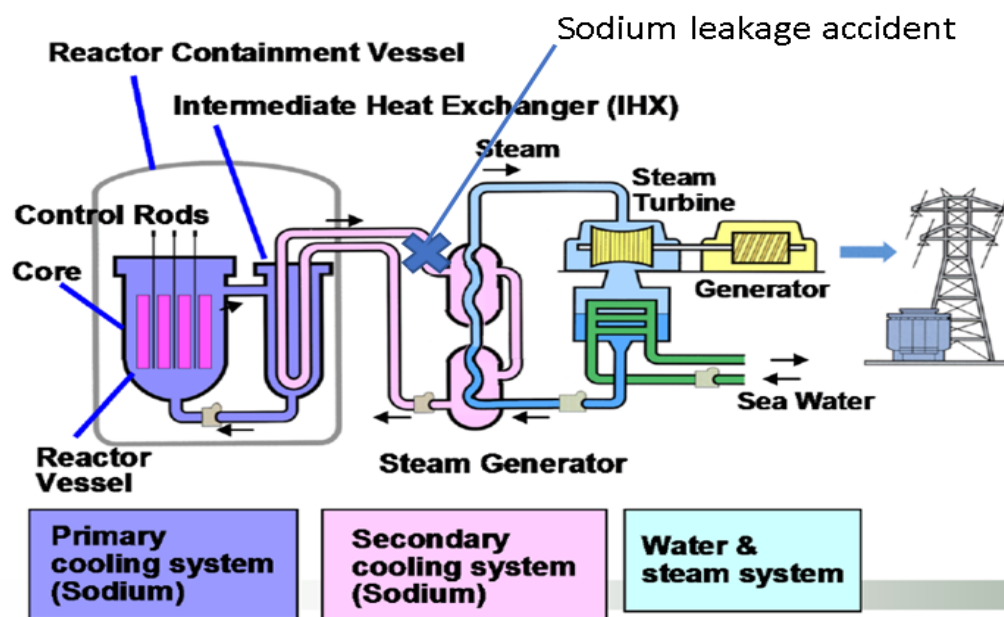


Figure 2.3 Schematic of Monju Sodium Leak

Source: Figure is based on authors' interpretation of Ohira, Uto, 2012; White, Ban, 2010.

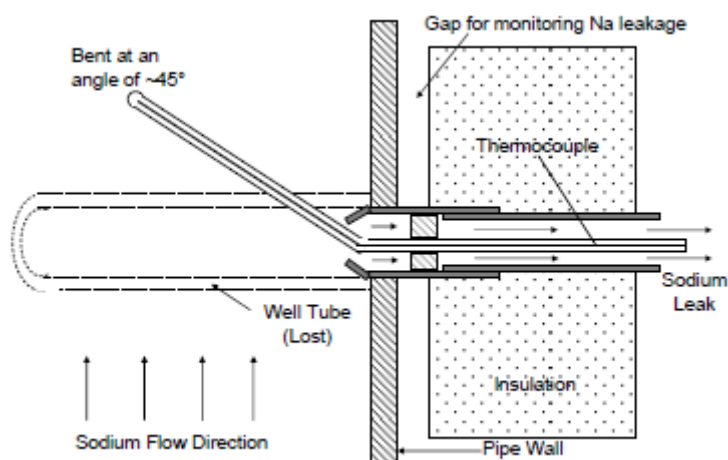


Figure 2.4 Schematic of Damaged Thermocouple Probe That Led to Sodium Leak
(Best picture available)

Source: Oliver, et al. 2007; Mikami, H., Shono, A., Hiroi, H., no date.

Table 2.2 The Life Story of Monju

Point in Time	Incident
1968	Monju design work started
March 1977	Design work completed
December 1980	Permit for installation applied
May 1983	Permit for installation granted
October 1985	Construction started

December 1992	System Start-up Test (SST) began
April 1994	First criticality reached
August 1995	First connection to electrical grid
December 1995	Sodium leak and fire incident
↓ Comprehensive safety review, the abolishment of the PNC and the establishment of the Japan Nuclear Cycle Development Institute (JNC) in October 1998 ↓	
June 2001	Application for modification permit
December 2002	Modification permit granted to JNC
January 2003	The Kanazawa branch of Nagoya's High Court reversed its 1983 approval to build the reactor.
May 2005	Japan's Supreme Court ruled for JNC and cleared all legal barriers for the restart of Monju.
September 2005	Plant modification work started to restart Monju in October 2008,
October 2005	JAEA established by merging JAERI and JNC
December 2006	Modified System Function Tests started
August 2007	Entire System Function Tests started
May 2010	SST, Core Confirmation Test (CCT) started
8 May 2010	Critically achieved and operated for 45 days
July 2010	CCT finished
August 2010	In-Vessel Fuel Transfer Machine (IVTM) dropped
June 2011	IVTM removed from the reactor vessel
November 2012	The Nuclear Regulation Authority (NRA) revealed that more than 9,000 of about 49,000 specifically relevant Monju parts had not received necessary maintenance checks.
February-March 2013	NRA conducted an on-site inspection and found 13 vitally important items, such as emergency generators, had not been maintained properly and falsified the facts.
May 2013	NRA ordered to stop Monju operation until JAEA establish a safe, accident environment.
September 2014	NRA approved JAEA's management reorganization for Monju, with its restart being contingent upon NRA approval of a new maintenance program.
March 2015	In the document to NRA requesting the restart of Monju, JAEA provided assurances that the agency had implemented reforms. NRA, however, found that during the previous two years, the agency had violated safety regulations and committed errors by not conducting thorough checks of multiple pieces of equipment. NRA found 400 additional uninspected pieces of equipment, and 13 of 21 items that NRA specified to be upgraded had been left upgraded.
November 2015	NRA called for a new owner and operator for Monju other than JAEA, claiming that JAEA was "not competent to operate" Monju.
December 2016	Japan announced its decision on decommissioning Monju.

Source: Table is based on authors' interpretation and analysis of Yoshioka, 2013; Ohira, Uto, 2012; World Nuclear Industry Status Report, 2016.

It has been a mystery to many overseas observers why Japan did not change its policy about FBRs and Monju development sooner. From the 1950s to early 1970s, all Western European and US governments with nuclear power had FBRs as significant components of their programs. By the late 1990s, however, nearly all of them had cancelled or suspended their FBRs (See Table 2.3). The US constructed two experimental breeder reactors, neither of which produced power commercially. The Enrico Fermi Nuclear Generating Station in Michigan was the first US FBR but operated only from 1963 until 1972 before engineering problems led to a failed license renewal and subsequent decommissioning. Construction of the only other commercial FBR in the US, the Clinch River plant in Tennessee, was halted in 1983 when Congress cut funding. Elsewhere in the world, only India, Russia and China have operational FBR programs ([Tolliday, 2012](#); [Karam, 2006](#)).

Indeed, in 2010 the International Panel on Fissile Materials (IPFM) said, “After six decades and the expenditure of the equivalent of tens of billions of dollars, the promise of breeder reactors remains largely unfulfilled and efforts to commercialize them have been steadily cut back in most countries” ([IPFM, 2010](#)). A number of scholars have also said that “It's time to give up on breeder reactors” ([Cochran, et al., 2010](#)).

Table 2.3 World Fast Breeder Reactor (FBR) Status (as of 31 December 2016, 3 FBRs are operating).

Reactor	Country	Grid Connection Start	Shutdown
Clementine	US	1946	1952
EBR-1	US	1951	1964
DFR	UK	1962	1977
EBR-2	US	1964	1994
Fermi-1	US	1966	1972
MSRE	US	1965	1969
Rapsodie	France	1967	1983
BOR-60	Russia	1969	2020
BN-350 (KZ-10)	Kazakhstan	1973	1999
Phenix	France	1973	2010
PFR	UK	1975	1994
Shippingport	US	1977 as breeder	1982
KNK II	Germany	1978	1991
BN-600	Russia	1980	Operating
FFTF	US	1982	1993
SNR-300	Germany	1985 (partial operation)	1991
BN-800	Russia	2015	Operating
FBTR	India	1985	Operating
Superphenix	France	1986	1998
PFBR	India	2004 (construction started)	—
CEFR	China	2011	—
Joyo	Japan	1977-2007	2007 (accident); 2015 (repair

			completed); application for restart pending
Monju	Japan	1995	Shut down
BN-1200 (Beloyarsk-5)	Russia	Planned for construction	
BN-1200 (South Urals-1)	Russia	Planned for construction	
BN-1200 (South Urals-2)	Russia	Planned for construction	
BN-800 (Sanming-1)	China	Planned for construction	
BN-800 (Sanming-2)	China	Planned for construction	

Source: IAEA, 2017; JAEA, 2017b.

Despite the difficulties and high cost, however, a move toward restarting Monju started internally in JNC in June 2001. The JNC had applied for the modification of Monju, which was granted in December 2002. Legal challenges against Monju's re-licensing and restart caused further delays and on 27 January 2003, the Kanazawa branch of Nagoya's High Court reversed its 1983 approval to build the Monju reactor. More than two years later, on 30 May 2005, Japan's Supreme Court ruled against the Nagoya High Court decision, thereby clearing all legal barriers for the restart of Monju ([Suzuki, 2009](#)).

In September 2005, having learned lessons from the accident, modification work started. Restart was scheduled for October 2008 by the newly established JAEA but was moved back five months. A restart date of February 2009 was again delayed due to the discovery of holes in the reactor's auxiliary building. In August 2009, it was announced that restart might be in February 2010. A year later, in May 2010, Monju finally restarted, after five years of suspension since the sodium leak and fire. On 8 May 2010, Monju reached criticality. Test runs of increasing the power output were to continue until 2013, at which point the reactor could have started to feed power to the electric grid, beginning "full-fledged" operation. These plans were not to be realized, however. ([Green, 2016](#)).

In July 2010, Monju went through a core confirmation test (CCT) and in late August 2010, it was shut down for fuel change. On 27 July, JAEA installed the In-Vessel Fuel Transfer Machine (IVTM) to prepare to replace some of the depleted fuel assemblies. The IVTM, which is a long and heavy object (about 12-meter long, 46 cm in diameter and 3.3 ton in weight), was inserted through the channeling sleeve inside the reactor vessel. It was suspended by a two-tong gripper that was hung from stainless steel cables from the ceiling of the reactor building. The IVTM completed the task of replacing 33 fuel assemblies from 11 to 17 August and JAEA was removing the tools and equipment for the fuel replacement, including the IVTM. The IVTM was still inside the reactor and was to be lifted and moved to a maintenance building for storage.

- The accident happened at 14:48 on 26 August 2010. When the IVTM was raised about two meters inside the sleeve, the gripper's tongs lost grip and the 3-ton IVTM fell two meters (See Figure 2.5). On October 13, the JAEA tried to lift the IVTM device but failed as it had become deformed inside the sleeve, preventing its retrieval through the upper lid. It was

subsequently found that the Auxiliary Handling Machine (AHM) failed to fully open the gripper tongs due to rotation of the opening and closing rod. The impact from the fall damaged the cylinder liner outer guide tube of the IVTM at a guide tube joint, which opened a crack 8 mm wide. The damaged part of the tube protruded outward as much as 5 mm, preventing the IVTM from being extracted. After several failures to extract the IVTM within the sleeve, the JAEA decided to remove the IVTM and the sleeve as one piece. One year later, on 23 June 2011, JAEA completed the extraction of the IVTM along with the sleeve (JAEA, 2010, 2011; Ohira, Uto, 2015; Onishi, 2016). The repair work was contracted out to Toshiba. The cost of the contract was unclear, which was reported to be \$13 million (Fukui Shimbun), \$17 million (Mainichi Shimbun), or \$21 million (J-Cast). (J-Cast, 2012).

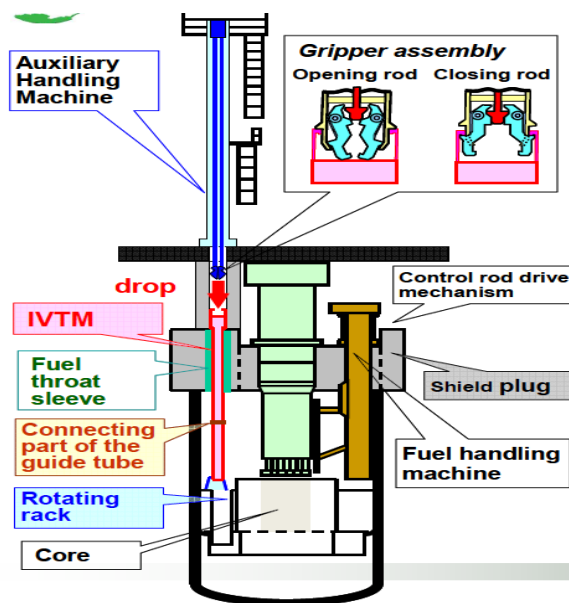


Figure 2.5 Schematic of Uncontrolled Drop of In-Vessel Transfer Machine (IVTM)

Source: JAEA, 2012b. Translation provided by the authors

While the proximate cause of the accident was the failure of the grippers to grip, there were more fundamental causes for the accident—the PNC’s relentless cost cutting measures and lax attitude toward safety.

- According to PNC researchers, in 1975 the PNC re-used Joyo’s mockup models—such as the IVTM mockup, by replacing parts and pipes—for Monju. There were two IVTM mockups made in 1971 for Joyo, one by Mitsubishi Heavy Industries and another by Hitachi. Testing and cleaning facilities were done by Fuji Electric. During the tests, both mockups experienced problems. When the grippers of the IVTM were dipped in sodium liquid, sodium got into the spaces between the grippers and the wire cable, causing malfunctions of the grippers and the wire cable. The PNC made a design change so that the grippers would be always above the surface of the sodium. There is an absence of compelling explanations as to why the grippers did not work in August of 2010. If it was the result of sodium infiltration into the gripper mechanisms, one can conclude that the PNC’s

design change had never solved the problem (JAEA, 1975; Hayakawa, et al., 2003).

- The difficulty in developing IVTMs that would function in a sodium cooled reactor appears to have troubled PNC for a long time. According to PNC researchers in a March 1980 article, the PNC had been conducting full-size mockup tests of an IVTM in sodium for five years and had resolved all problems, except a few, which were not specified. The R&D on the issue, nonetheless, ended in March 1980 when the article was written (Ishii, et al., 1980).

As we noted earlier, in May 2013, the NRA ordered JAEA not to embark on preparations for restart of Monju until a safe, accident-free environment had been established. JAEA ignored that caveat and so in November 2015 the NRA declared the JAEA as unfit for the responsibility for operating Monju. The JAEA responded to the NRA with an assertion that "No entity other than the JAEA can manage Monju" (Burnie, et al., 2016).

Indeed, JAEA's claim was correct, but its assertion ultimately sealed the fate of the Monju FBR. In December 2016, the government had to decide on whether to continue supporting Monju. Inevitably, the Cabinet Ministerial Committee on FBR decided to decommission Monju.

- Used fuel will be removed from Monju over the next five years and the FBR will be fully decommissioned by 2047, according to a ministerial committee on nuclear power.
- The government's draft decommissioning plan is expected to take 30 years and cost more than \$3.75 billion, including \$2.25 billion for maintenance, \$1.35 billion for dismantling the plant and \$150 million for defueling. By way of comparison, FBR Monju's operational costs have averaged about \$200 million a year (See Figure 2.6) (World Nuclear Industry Status Report, 2016; WNN, 2017).

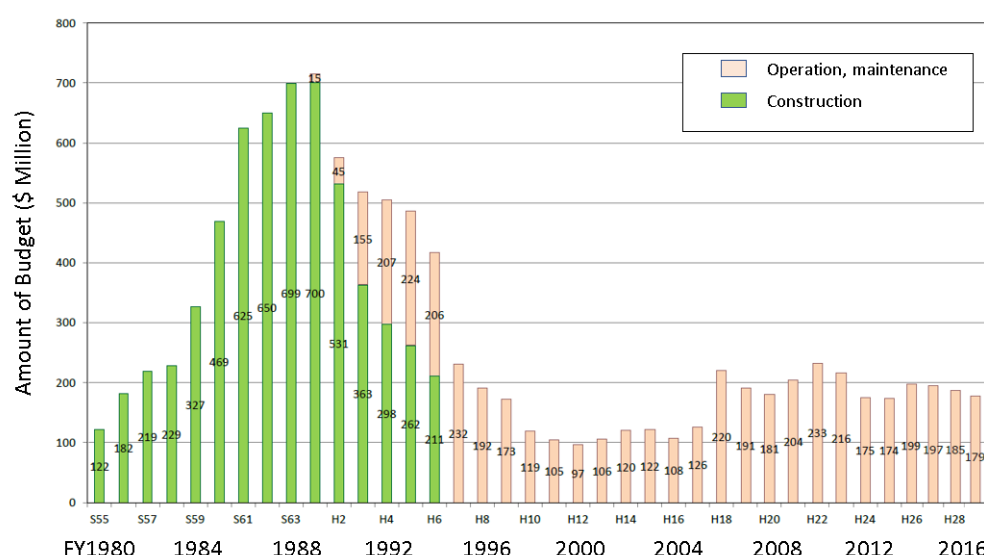


Figure 2.6 Changes in Monju's Budget: Total Cumulative Cost = \$10,593 million*

Source: JAEA, (no date). Translation provided by the authors..

*Japan's Board of Audit has calculated the total Monju cost from 1971 to 2016 to be \$11,314 million (Jbaudit, 2018). The JAEA lists a total of \$1,109 million as costs that fall outside of Monju

direct expenses but are related to Monju. These include \$38 million (1971-1979) for preparation expenses, \$9 million as a carryover of prototype reactor construction preparation fund from 1979, \$590 million in personnel expenses (1974-2016), \$433 million for property tax (1999-2016), and \$29 million for repair expenses.

While MEXT (which houses the former STA) was reportedly in favor of preserving Monju, METI was not, partly because of its bad image and partly because it favored MHI's Sodium-cooled Fast Reactor (JSFR) (WNA, 2017c). The Fukui governor, whose prefecture received major subsidies for hosting Monju, emphasized the importance of Monju and pleaded for its continuation. The Cabinet, however, rejected an FY2016 budget request from MEXT for \$100 million to prepare Monju for restart.

Looking back, PNC managers likely thought that the technical challenges of Monju would primarily involve scaling up the Joyo design. Indeed, the structures of Joyo and Monju are similar, except for scale; Monju is several times larger than Joyo (See tables 2.4 and 2.5), (JAEA, 2017c).

Table 2.4 Cost of Japanese Fast Breeder Reactor Projects

* We used MEXT's operation and maintenance cost, which is \$4,339 million, covering from 1980 to 2015. The cost likely includes the expense of dealing with the 2010 accident involving the uncontrolled drop of equipment inside the reactor. Yoshioka's (2013) operation cost, \$1,022 million, covered up to 1996, which covers the sodium leak accident of 1995 but does not cover the second accident of dropping the IVTM in 2010.

**Yoshioka provides METI's R&D cost of \$145 million and another related R&D cost of \$3,427 million. It might probably be STA and MEXT's R&D cost.

FBR	Item		Cost
Joyo	Construction		\$289 million
	Operation/Maintenance		\$1,022 million
	Decommissioning		TBD
	Sub-Total		\$1,311 million
Monju	Construction	Government	\$4,504 million
		Private Sector	\$1,382 million
	Operation/Maintenance		\$4,339 million*
	Related R&D		\$3,427 million**
	METI R&D		\$145 million
	Decommissioning		\$3,750 million
	Sub-total		\$17,547 million
	Grand Total		\$18,858 million

Source: Figure is based on authors' interpretation and analysis of Yoshioka, 2013; MEXT, 2015; WNN, 2016.

Table 2.5 Major Specifications of Fast Breeder Reactors Joyo and Monju

	Joyo			Monju
	Breeder Core (MK-I)	Irradiation Core (MK-II)	Irradiation Core (MK-III)	
	Sodium cooling fast neutron			Sodium cooling fast neutron
Thermal output	75MWt	100 MWt	140 MWt	714 MWt
Electric output	—	—	—	280 MWe
Thermal efficiency	—	—	—	About 39%
Reactor core				
Height	600 mm	550 mm	500mm	930 mm
Diameter	About 800 mm	About 730 mm	About 800 mm	About 1,800 mm
Volume	About 304 liters	About 230 liters	About 260 liters	About 2,340 liters
Number of cooling loops	2	2	2	3
Coolant temperature (Inlet/Outlet)	370°C/470°C	370°C/470°C	350°C/500°C	397°C/529°C
Fuel				
Number of pins per assembly	91	127	127	169
Number of assemblies	82	67	85	198
Loading amount of U	About 177 kg	About 100 kg	About 110 kg	About 4500 kg (initially)
Loading amount of Pu	About 166 kg	About 220 kg	About 230 kg	About 1400 kg (initially)
PU fissile enrichment (PuO ₂ /(PuO ₂ + UO ₂))	About 18 wt%	About 20 wt%	16 wt% (inner core), 21 wt% (outer core)	Replacement: 16 wt% (inner core), 21 wt% (outer core)
Uranium blanket	About 6.2 ton	—	—	About 17.5 ton
Breeding ratio	1.01	—	—	About 1.2
Burn up degree	About 42,000 MWd/t	About 75,000 MWd/t (highest average)	About 90,000 MWd/t (highest average)	About 80,000 MWd/t (assembly average)

Control rods	6 Safety rods 4 Regulating rods 2	6	6	19 Regulating and safety rods 13 Back-up safety rods 6
Reactor vessel type	Top-supported cylindrical double wall	Top-supported cylindrical double wall	Top-supported cylindrical double wall	Top-supported cylindrical vessel with guard vessel
Containment vessel type	Half double vessel	Half double vessel	Half double vessel	Double vessel
Containment vessel height	54.3 m	54.3 m	54.3 m	79 m
Containment vessel inner diameter	28 m	28 m	28 m	49.5 m
Fuel exchange method	Double rotating system	Double rotating system	Double rotating system	Single rotating fixed arm system
Steam condition	—	—	—	483 °C, 127 kg/cm ² g
Fuel Change Interval	About 3 months			About 6 months

Source: RIST, 1998; Nikkei Business Publications (Nikkei BP), 2017. Translation provided by the authors.

The utilities had long been doubtful of the FBR's commercial value, despite the government's effort to convince them otherwise. According to Tolliday (2012), the electric power companies never accepted the government's argument that national imperatives of energy security should trump costs in relation to technology choices.

- FBR technology was costly and technically challenging as a stand-alone program. When viewed as part of a closed nuclear fuel cycle, moreover, the power companies feared that FBR would lock the industry into supporting a mammoth parallel project: the simultaneous development of costly reprocessing capabilities (Tolliday, 2012).
- To move the FBR project forward, therefore, the government funded almost all the FBR's construction, operations, along with management and research staff. The private sector paid only 13 percent of FBR costs.

During the 22 years of its existence, Monju reached 40 percent of its rated power capacity (280 MWe). It operated for 250 days or 5,300 hours, primarily trying to raise its power output to the rated capacity. It never generated commercial power. While it has been largely inoperative since 2010, Monju will cost Japan more than any other nuclear project. Total cost, including the decommissioning, will be as high as \$15 billion (See Table 2.6). The Japan Board of Audit (Jbaudit, 2018) was critical of the poor maintenance and management practice of Monju operators and the program's poor R&D results. The Board rated Monju's degree of achievement at a scant 16 percent, based on the evaluation method used by MEXT.

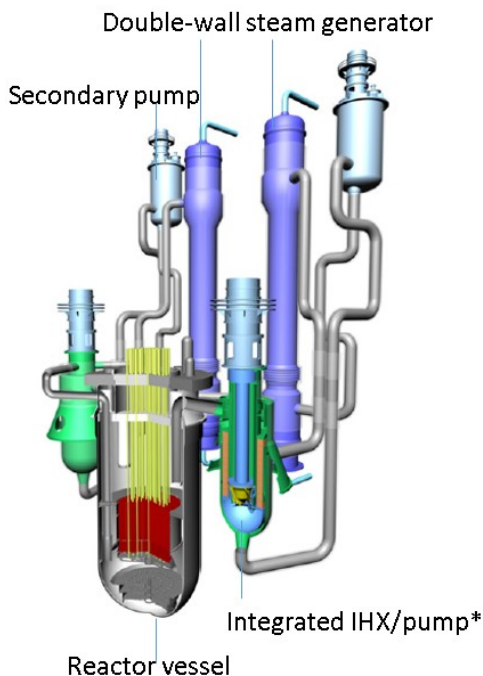


Figure 2.7 Concept for Sodium-Cooled Fast Reactor (JSFR) from Mitsubishi Heavy Industries
Source: Ito, Kunishima, Kobayashi, Mochida, 2009.

Nonetheless, Japan's government remains interested in the development of FBRs in the future. In October 2016, a Council on Fast Reactor Development was established within METI. The

government stated the purpose of the Council is to promote the nuclear fuel cycle from the viewpoint of effective resource utilization, volume reduction of high-level radioactive waste and reduction of the harmfulness of such waste. METI indicated development of fast reactors should be undertaken according to Council policy. The members of the Council included the Minister of METI, the Minister of MEXT, President of JAEA, Chairman of the FEPC,²² and President and CEO, MHI. In view of the selection of the membership, the expected outcome from this Council would likely be to recommend building the fast reactor that MHI has been developing since 2007—called the Japan Sodium-cooled Fast Reactor (JSFR) (See Figure 2.7). It is also likely that JAEA would continue on as operator of the new JSFR reactor (Ito, et al., 2009; Ministry of Economy, Trade and Industry (METI), 2016).

2.3 Reprocessing

In the early 1960s, the STA laid the foundations for development of Japan's reprocessing capability, one of STA's big national projects. Predictably, Japan was hoping to succeed in all these national projects using indigenous technologies. In January 1959, AEC established the Special Subcommittee on Reprocessing to define concrete plans. The subcommittee submitted an interim report in May 1960, recommending that Japan build a pilot reprocessing plant with the capability of 0.35 ton per day (Yoshioka, 2013). AEC, in response, authorized in its Long-Term Plan in February 1961 that a pilot plant be built by the late 1960s.

In April 1961, AEC's Reprocessing Subcommittee dispatched a survey team overseas to assess foreign reprocessing technologies. In April 1962, the study team submitted a report concluding that reprocessing technologies overseas had reached the commercial stage and recommended that Japan build a commercial reprocessing plant with foreign technologies. AEC accepted the subcommittee recommendation and announced in June 1964 that a reprocessing plant with a capacity of 210 ton/year would be built with imported technologies and that operations would start in 1970 (Yoshioka, 2013).

- Meanwhile, JAERI had been engaged in R&D of reprocessing testing equipment as well as other advanced nuclear basic research. JAERI's progress, however, was slow; it managed to have a hot test at its reprocessing test facility in March 1968. By March 1969, JAERI had refined only 208 g of plutonium, however. Despite its status as Japan's pioneer in nuclear research, JAERI remained unreliable as a project manager (Yoshioka, 2013).

At AEC's direction, the AFC sought assistance from two foreign companies to build Japan's prototype reprocessing plant. First, in October 1963, AFC asked the UK's Nuclear Chemical Plant (NCP) to draw up a preliminary design, which was completed at the end of 1964. Then, in August 1964, AFC asked for bids for preparing a detailed design of the reprocessing plant. Two companies submitted bids; NCP of UK and Saint-Gobain Nucléaire (SGN) of France. The AFC chose SGN and signed a contract in February 1966 to draw up the detailed design. Meanwhile, in September

²² The Federation of Electric Power Companies (FETC) is an industry lobbying organization of electric utilities in Japan. Its objective is to promote the policies for electric companies in Japan.

1964, the AFC requested permission from Ibaraki Prefecture to construct a reprocessing plant in Tokai-mura. The prefectural assembly, the fishery union and some cities opposed plant construction. In August 1969, the PNC (AFC's successor) again requested permission to build a reprocessing facility. In January 1970, permission was granted. In May 1970, the Governor of Ibaraki Prefecture and the STA came to agreement on plant construction. The construction of the Tokai Prototype Reprocessing Plant was started in June 1971 by the Japanese subcontractor Nikki. However, disputes with the fishery union were not settled until November 1974 ([Yoshioka, 2013](#)).

2.3.1 Tokai Prototype Reprocessing Plant

While the Tokai Prototype Reprocessing Plant began trial operations in 1977, it met a series of setbacks. The plant completed its cold test in March 1977, but the hot test was suspended. US President Carter, shocked by the 1974 Indian Nuclear Test, announced in April 1977 that the US would indefinitely suspend US commercial reprocessing and plutonium recycling to reduce risks of the further spread of sensitive technologies. The US decided to dispose of spent fuel in a deep underground geologic repository where it would remain isolated from the environment for at least tens of thousands of years ([University of California, Santa Barbara, 1977](#)). The US also requested Japan to reassess the Tokai Prototype Reprocessing Plant hot test. Under the US-Japan Nuclear Energy Treaty,²³ Japan is required to have US consent to operate a reprocessing plant because Japan was purchasing enriched uranium from the US that required US approval to reprocess. After three rounds of intense negotiations from April to September 1977, the US tentatively approved that the Tokai plant could operate on the condition that Japan would reprocess only up to 99 tU per year and that Japan develop the uranium-plutonium co-process and co-conversion process to make MOX fuel.

The hot test started in September 1977. It used the spent fuel from JAERI's JPDR and the boiling water reactors (BWR) and pressurized water reactors (PWR) operated by the Japanese utilities. The hot test, however, was disrupted due to damaged equipment. A heat transfer tube from the acid recovery evaporator canister had corrosion damage and needed to be replaced. The hot test was finally completed in February 1980 and the plant passed pre-commissioning inspection in December 1980 ([RIST, 2010](#)). After the inspection, however, the plant was unable to achieve full operations for two more years. The plant had sustained damage to the acid recovery evaporator and two dissolving tanks as well as corrosion damage to equipment and machinery. The plant used a new remote-control repair technology to repair the dissolving tanks and install a third tank. After the repairs were made, the plant maintained stable operations for 12 years from 1985 to 1996 ([Yoshioka, 2013](#)).

Unfortunately, at 10:06 am on 11 March 1997, the Tokai Prototype Reprocessing Plant suffered a major fire and explosion. A fire broke out in its asphalt solidification demonstration plant. The asphalt solidification plant mixed and solidified asphalt and low-level radioactive liquid waste generated from the reprocessing plant. After the mixture was filled into several drums, the drums were placed in a storage room. Twenty hours later, one drum caught on fire, which ignited the other

²³ The Agreement for Cooperation Between the Government of the United States of America and the Government of Japan Concerning Peaceful Uses of Nuclear Energy, was originally signed in 1955 and revised in 1968 and 1973.

drums in the room. A contract worker saw the fire and asked a PNC employee for instruction, who discussed the matter with his superior and directed the contractor to spray water over the drums. Six minutes after the start of the fire, water was sprayed over the drums from a sprinkler for one minute. By that time, radioactive smoke filled not only the drum room but also the entire facility. All personnel in the facility were evacuated for 30 minutes. At 8:04 pm, about 10 hours after the fire started, an explosion occurred near the drum room, blowing out virtually all the windows and doors of the asphalt solidification plant. The fire lasted for three hours. Of 129 employees, 37 were exposed to radiation. The accident was rated as an INES Level 3. Due to this accident, the asphalt solidification plant at Tokai was shut down ([Yoshioka, 2013](#); [Hatamura Institute for the Advancement of Technology and Science, no date](#)).

- According to the December 1999 accident investigatory study report drafted by the Japan Nuclear Cycle Development Institute (JNC), the main cause of the fire was the high temperature of the mixture of radioactive liquid waste and asphalt. The temperature rose to an unusually high level because of physical heating inside the extruder, which was caused by a reduction in the feed rate of liquid waste. A moderate chemical reaction in the mixed product continued in the drums and consequently the mixture overheated and ignited. The cause of the explosion was the accumulation of flammable gases generated from insufficiently mixed product in the filling room—where the ventilation system had been switched off. The flammable gas was ignited by another mixed product that overheated to the flash point temperature ([JNC, 1999](#)).
- Japan's 1998 Nuclear Energy White Paper stated that the STA reprimanded the PNC and disciplined three PNC officials for the lack of a safety culture and lack of ethical integrity before the accident and behavior after the accident. The White Paper indicated that the PNC knew that such a fire would require about 8 minutes to be extinguished but did not spend enough time to put it out. Moreover, the PNC issued a report after the accident, claiming that "the fire was judged to be extinguished by sight," which turned out to be false. The PNC had never inspected whether the fire had been completely extinguished. According to the White Paper, the PNC ordered the employees to support the story, but one employee refused to obey the order, leading to its exposure in the press ([Yoshioka, 2013](#)). Furthermore, the White Paper reiterated that the PNC never learned a lesson from the Monju sodium leak accident, where improper behavior triggered a public furor ([AEC, 1998](#)).

The fate of PNC was sealed in the aftermath of the two accidents under its purview (the 8 December 1995 sodium leak and fire and the 11 March 1997 Tokai asphalt fire). The government and the public saw in those accidents the PNC's lack of technical competence, the absence of an effective safety culture, and poor management. The PNC had not even conducted a fire drill prior to these accidents. Moreover, the PNC had cut corners by choosing asphalt instead of cement to mix with radioactive wastes. Asphalt is more easily flammable and, if ignited, would spread radioactive matter into the environment. Cement was globally preferred to asphalt but was more expensive.²⁴ ([Yoshioka, 2013](#)).

²⁴ STA had the idea of disposing the low- to medium-level radioactive waste into the ocean until the 1983 London Treaty that prohibited the disposal of radioactive wastes into the ocean.

Thus, on 1 October 1998, PNC was abolished and the Japan Nuclear Fuel Development Institute (JNC) was established. The JNC hoped to re-start the Tokai Prototype Reprocessing Plant in the fall of 1999. This plan was delayed by a criticality accident at JCO,²⁵ however, at a commercial nuclear fuel fabrication plant in Tokai-mura. JNC eventually re-started Tokai and operated it briefly in 2000 and 2001. The plant had a capacity of 0.7 tU a day—reprocessed spent fuel from LWRs and BWRs. The plant, however, has stood idle since 2006—the contracts for reprocessing fuel from commercial power plants having ended that year. The plant also processed MOX fuel from the ATR Fugen from 1985, but Fugen ceased operations in 2003. The cumulative spent fuel that the Tokai Prototype Reprocessing Plant amounted to a total of 1,069.2 tU, including 8.9 tU from the Japan Power Demonstration Reactor (JPDR), 600.9 tU from BWRs, 360.1 tU from PWRs and 99.3 tU from the ATR Fugen (RIST, 2002; JAEA, (no date)f).

According to the annual plutonium report in September 2013, JAEA kept a total of 668 kg in plutonium nitrate solution at the Tokai-mura plant and a total of 83 kg of separated plutonium oxide. An additional 120 tons of spent fuel, including MOX fuel from Fugen, currently in storage at the site, is likely to be shipped overseas for reprocessing, according to JAEA. No details were provided (Burnie, Schneider, 2014).

JAEA decided to scrap the Tokai Prototype Reprocessing Plant in 2014. A JAEA spokesman told the Kyodo News Agency that it would cost too much to upgrade the plant to meet the new safety rules that came into effect after the March 2011 Fukushima accident. He said more than \$1 billion would be needed to upgrade and enhance safety for the Tokai Plant. According to an estimate made in 2003, the nation's first reprocessing facility would cost an estimated \$8 billion to be decommissioned, more than ten times that of a “standard” nuclear power reactor. JAEA intends to submit a detailed plan for decommissioning and associated cost during FY 2017.

- JAEA has said that the decommissioning work would take 70 years to complete. The reprocessing process at the Tokai plant will be ready for decommissioning, but the pre-processing part of the plant, called the Recycle Equipment Test Facility (RETF), will continue operations for the next 20 years. The JAEA has indicated that the RETF will be used to insert vitrified radioactive waste into canisters for transport to yet undetermined disposal sites.
- JAEA's decision to decommission the Tokai Reprocessing Plant likely was driven by the agency's tight budget. According to a 2016 presentation by JAEA Director Kodama, the agency was seriously concerned about its rapidly declining budget.

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²⁵ The JCO plant was owned and operated by the Sumitomo Mining Company and located in the same Tokai-mura, Ibaraki Prefecture. The JCO plant will be discussed later in Chapter 3.

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Chapter 3:

Commercialization of the Nuclear Fuel Cycle

Chapter 3: Commercialization of the Nuclear Fuel Cycle

Abstract

Since the mid-1950s, Japan's Science and Technology Agency (STA) aspired to develop indigenous capabilities that would span all phases of the nuclear fuel cycle, while the Ministry of Economy, Trade and Industry (METI) was interested in promoting power generation. STA's desire to promote advanced technology for the back-end nuclear fuel cycle put the government and private sector relationships under considerable strain. Eventually, the nuclear industry supported enrichment and waste disposal projects, but withdrew their support for the Advanced Thermal Reactor and the Fast Breeder Reactor. They reluctantly agreed to undertake construction of a reprocessing plant. This chapter considers projects that span all phases of the nuclear fuel cycle, including the industry's fuel fabrication activities, the Rokkasho reprocessing and mixed oxide fuel (MOX) plant, as well as serious accidents that caused the public to question whether the industry could safely operate its nuclear facilities.

3.0 Struggling Over Priorities, Technical Challenges, and Plant Construction

Since the mid-1950s, Japan has aspired to have operational capabilities that would span all phases of the nuclear fuel cycle. It has made massive investments to build major nuclear facilities over the past 60 years. As mentioned earlier, Japan had two distinctive nuclear policy tracks, one track pursued by METI and the other by STA. METI was interested in increasing power generation through the construction of nuclear reactors, relying on technology developed overseas. STA, aspired to develop domestic nuclear technologies and encouraged the utilities to build an indigenous, advanced nuclear industry. STA had pursued several big national projects, including enrichment, ATR, FBR, reprocessing and waste disposal. The utilities favored enrichment and waste disposal—the simplest components of the nuclear cycle. Enrichment is an essential phase at the front-end of the fuel cycle and is less costly than the other projects. Waste disposal is also indispensable, considering the ever-mounting nuclear waste and the increasing number of reactors that were about to be decommissioned. The utilities remained wary, however, of projects that entailed complex components that were part of the back-end of the nuclear cycle. Moreover, the Japanese utilities were nervous about adopting indigenously-developed nuclear technology, such as reprocessing.

The government and the private sector have always been mutually inter-dependent, but the government's desire to promote advanced technology for the back-end of the nuclear cycle put the government/private sector relationship under considerable strain. Faced with contradictory signals from STA and METI, the utilities supported enrichment and waste disposal projects, withdrew their support for the ATR and FBR projects and only reluctantly chose to undertake the development of reprocessing capabilities.

Slow-Rolling the Government on Proceeding with a Demonstration FBR. In the case of the Monju FBR, the utilities initially went along with the government's goals by carrying a minor share (about 13 percent) of the project's costs ([Japan Atomic Energy Agency \(JAEA\), no date](#)). The utilities concluded, however, that any FBR would have very high costs and many technical difficulties.

- Since the mid-1970s, the private sector had been slow to meet the government's request to prepare for the demonstration FBR, the successor to the prototype FBR Monju. When the prototype Monju was in the design stage in the mid-1970s, Japan expected the private sector to start designing a demonstration FBR. Even when the Atomic Energy Commission (AEC) agreed that the government and the private sector would jointly promote the development of a demonstration FBR, the private sector made little progress in development.
- Finally, in 1992, the private sector came up with a design. The demonstration FBR was to be a small reactor (67 MWe) and use a technology—the top-entry loop type reactor—that had few precedents and would need much R&D (Yoshioka, 2013). The government did not embrace the concept and decided instead in December 2016 that FBR Monju would be decommissioned.

Backing Away from the Next Demonstration ATR. Since the mid-1960s, the private sector had believed that the ATR was more expensive than LWRs and yet the merits of the ATR were ambiguous. On 11 July 1995, the FEPC publicly announced that it would withdraw from investing in the demonstration ATR (RIST, 1996). The demonstration ATR had been planned to be built in Oma, Aomori Prefecture, and the Japanese Government was to invest 30 %, the electric utilities, 30 % and J-Power (formerly the Electric Power Development Corporation), 40 %. Without the 30 %-share from the utilities, the project was ended.

Reluctant Agreement on Reprocessing. Eventually, the Japanese government resorted to more coercive tactics to force the private sector to accept commercialization of reprocessing. Following the worldwide trend in electricity deregulation in the 1980s, the US Energy Policy Act of 1992 eliminated obstacles for wholesale electricity competition, which led to the introduction of electricity deregulation in many US states. Japan also started to address deregulation and a small fraction of METI officers started to advocate for change (Kim, 2013). METI's senior leadership, however, pushed back against deregulation—a move sought by the private sector. Clearly in return, the private sector began to get behind the construction of a reprocessing plant in Rokkasho-mura, Aomori Prefecture.

The power companies' commitment in reprocessing, however, was reluctant and so the government created a set of requirements that would make it onerous for the private sector to use overseas reprocessing services, leaving them with no choice but to establish a domestic reprocessing plant:

- According to Yoshioka (2013), Tatsuro Ihara, a nuclear journal editor and reporter, found that the government had put in place financial requirements that would force the private sector to build a reprocessing plant. First, the government affirmed that the Tokai Prototype Reprocessing Plant would have insufficient capacity to reprocess fuel for future industry needs. At the same time, METI made it clear it would not approve loans from the Export-Import Bank of Japan if the utilities wanted to use overseas reprocessing services. Finally, the government used its authority to disapprove construction of new nuclear reactors based on the absence of sufficient domestic reprocessing capacity. Given that the power companies were deep into planning and construction of nuclear power plants and that it had already undermined two of Japan's prized big national projects—ATR and FBR—it was inevitable that they ultimately would endorse the Rokkasho Reprocessing Plant (Ihara, 1984).

In the early 1980s, Japan's electric utilities finally started to move toward commercializing enrichment, reprocessing and waste disposal. The utilities established two small companies: Japan Nuclear Fuel Service Limited (JNFS) on 1 March 1980 for reprocessing and Japan Nuclear Fuel Industry Limited (JNFI) on 1 March 1985 for enrichment, waste storage and disposal. These two forerunner companies merged and became the Japan Nuclear Fuel Limited (JNFL)²⁶ in 1 July 1992. The merged company represented 10 electric utilities and 74 major Japanese companies. Table 3.1 shows the speed and scale of the projects started by these companies, from filing license applications, start of plant construction, and commencement of business operations

On 20 April 1984, the FEPC announced that the electric utility industry had plans to establish a large cluster of nuclear fuel cycle facilities in Rokkasho-mura, Aomori Prefecture, and requested cooperation from the Aomori Governor. The plan was to establish several facilities, including uranium enrichment facilities, low-level radioactive nuclear waste storage facilities and reprocessing facilities. Three months later, the FEPC presented concrete plans to the Aomori Governor and the Village Head of Rokkasho-mura and asked their approval and cooperation. The plans indicated that the reprocessing plant would process a total of 800 tons/year and the construction cost of the plant would be \$7.6 billion. Moreover, the JNFS disclosed that the technology, machinery and equipment for the reprocessing plant would be imported from France, which was a major blow to the Japanese government. The company planned to import a copy of the La Hague Reprocessing Plant (the UP3 Plant was under construction at the time) owned by Areva NC, formerly COGEMA (JNFL, 2016a, 2017a).²⁷

3.1 Commercialization of the Front-End Nuclear Fuel Cycle

Japan's success in commercialization of the front-end of nuclear fuel cycle using indigenous technology has been limited. Japan had no viable domestic mines and thus had few accomplishments in domestic exploration and mining ventures. Japan engaged in some overseas explorations and mining investments, but AEC support for these ventures was rather indecisive for any success to be achieved. Moreover, in view of the widespread availability of uranium supplies internationally, Japan's growing nuclear industry looked elsewhere for business opportunities in the front end nuclear fuel cycle. Fuel fabrication, storage, and handling presented such an opportunity, and Japan's industry actively pursued business ventures in this area starting in the 1970s (See Table 3.2) (World Nuclear Association (WNA), 2017a).

²⁶ JNFL is a conglomerate of 10 electric power companies and 74 other companies. With a capital stock of \$4 billion, it owns facilities in Rokkasho, Aomori Prefecture and is focused on back-end nuclear fuel cycle businesses.

²⁷ COGEMA (Compagnie générale des matières nucléaires) was created in 1976 as part of the State Commissariat à l'énergie atomique (CEA). It merged with Framatome and FCI to form the New Areva Group.

Table 3.1 Japan Nuclear Fuel Limited (JNFL): Businesses, Facility Construction, and Costs (As of October 2014)

Plant	Location	Scale	Date of License: Applied/Granted	Construction: Start/Complete	Construction Cost	Operations Start
Uranium Enrichment Plant	Rokkasho- mura, Aomori Prefecture	Operations started with 150 tSWU/year; Eventually, 1,500 tSWU/year	26 May 1987 / 10 August 1988	October 1988	\$2.5 billion	27 March 1992
Reprocessing Plant	Rokkasho- mura, Aomori Prefecture	Reprocessing capacity: 800 tU/ year; Spent fuel storage capacity: 3,000 tU	30 Mar 1989 / 24 Dec 1992	April 1993 / first half of FY2018	\$21.93 billion	First half of FY2018
MOX Fuel Fabrication Plant	Rokkasho- mura, Aomori Prefecture	Maximum fabrication ability: 130 tHM/year*; MOX fuel assemblies for domestic BWR and PWR	20 April 2005 / 28 October 2010	Oct 2010 / first half of FY2019	\$2.1 billion	First half of FY2019
Vitrified Waste Storage Center	Rokkasho- mura, Aomori Prefecture	Returned waste storage capacity from Europe: Vitrified waste 2,880	27 April 1988 / 15 Nov 1990	May 1992	\$1.25 billion	December 1992
Low-Level Radioactive Waste Disposal Center	Rokkasho- mura, Aomori Prefecture	Authorized capacity: 80,000 m ³ (400,000 of 200-liter waste drums) planned expansion to 600,000 m ³ (equivalent to 3 million 200-liter waste drums)	30 Mar 1989 / 3 April 1992	Nov 1990 / December 1992	\$1.6 billion, based on 200,000 cubic meters	26 April 1995

Source: Table is based on authors' interpretation and analysis of Yoshioka, 2013 and JNFL, 2015a, 2016a.

Table 3.2 Japanese Companies Involved in the Front-End Nuclear Fuel Cycle* (As of December 1998)

*The table excludes those government-owned R&D facilities engaged in fuel fabrication under contracts, such as the Ningyo-toge Environment Technology Center that enriched uranium. It was licensed in October 1985 and had a production capacity of 300 tSWU/year of enriched uranium (up to 5%).

Company Name	Location	Date of Licensing	Enrichment %	Annual Production (tU)	Fabrication Method
Japan Nuclear Fuel	Yokosuka, Kanagawa	August 1969	Less than 5%	750 tU	Fuel rods (for BWR)
Mitsubishi Nuclear Fuel (MNF)	Tokai-mura, Ibaraki	January 1972	Less than 5%	440 tU 475 tU	Fuel rods (for PWR) Conversion (to PWR)
Nuclear Fuel Industries (NFI) Tokai Plant Kumatori Plant	Tokaimura, Ibaraki Kumatori, Osaka	Sept 1978 August 1975 Sept 1972	Less than 5% Less than 5% Above 90%	200 tU 284 tU 475 kgU	Fuel rods (BWR) Fuel rods (PWR) Plate fabrication (test reactors)
JCO Tokai Plant	Tokai-mura, Ibaraki	August 1969	Less than 5% Less than 20%	715 tU 3 tU	Conversion (for BWR and PWR) Conversion (for test reactors)
Japan Nuclear Fuel Ltd (JNFL) Rokkasho Enrichment Plant	Rokkasho-mura, Aomori	August 1988	Less than 5%	1,050 tSWU (plan)	Uranium enrichment

Source: AEC, 1998; Nuclear Safety Commission (NSC), 1999.

3.1.1 Tragedy Strikes the JCO Fuel Preparation Plant

JCO was a major player in the fuel fabrication business and it unfortunately became notorious for a major safety accident that occurred at one of its facilities. At about 10.35 on 30 September 1999, JCO experienced Japan's first criticality accident with fatalities. According to post-accident investigations, despite the company's many years of experience with nuclear fuel preparation, this type of accident was predestined to happen (Takai, 2002). As we shall see, its origins go back many years.

Sumitomo Metal Mining (SMM) first became interested in the nuclear fuel processing business in the 1960s and obtained permission in August 1969 to build a nuclear fuel plant in Tokai-mura, Ibaraki Prefecture. The plant started operations in March 1973. In October 1979, SMM established the Japan Nuclear Fuel Conversion (JNF) company and provided JNF with its production facilities, employees and fuel conversion technologies. It was a 100 percent-owned subsidiary of SMM. In August 1998, it changed its name to JCO.

JCO was unique in the world's fuel industry in that its principal involvement was based solely on UF₆- to-UF₄ re-conversion, a service which was provided to both domestic and foreign companies. The company converted low-enriched UF₆ into UF₄ powder (re-conversion) for commercial LWRs (both BWRs and PWRs). It also prepared uranium enriched up to 20 percent U-235—a much higher level of enrichment than required for ordinary power reactors—for use in research and experimental reactors.

JCO had an annual production capacity of 715 tons of uranium for LWRs and 3 tons of uranium for FBRs. While JCO shared a large part of the market for reconversion in Japan with Mitsubishi Nuclear Fuel Co. (MFC), it had been steadily losing sales due to increasingly severe competition and immense pressure from the utility companies to lower prices. In 1991, JCO produced 552 tU with sales of \$32.5 million, while in 1998, these metrics declined by 55.4 and 66 percent, respectively. The decline in business prompted rationalization and downsizing, including the lay-offs of about one-third of its work force (See Table 3.3 and Figure 3.1) (Takai, 2002).

Table 3.3 JCO's Business Data

Year	1991	1995	1998
Staff	162	145	110
Engineers with college degree	34	33	20
Output (t)	552	495	365
Sales (\$ millions)	32.5	28.06	18

Source: NSC, 1999.

JCO had an exclusive relationship with the PNC in re-conversion of uranium into MOX fuels for power reactors and the fabrication of uranium oxide fuels for experimental and test reactors. The reactors Fugen, Joyo, and Monju all had different fuel demands and different enrichment levels, and these demands would change subject to the progress and events in the nuclear fuel cycle R&D program operated by PNC. The program consisted of the reprocessing project, the MOX fuel fabrication project and the three reactor projects, all running in parallel. The JCO, thus, needed to

accommodate different demands for uranium and plutonium from these reactors, concurrent with a non-straightforward change in the plutonium supply (IAEA, 1999).

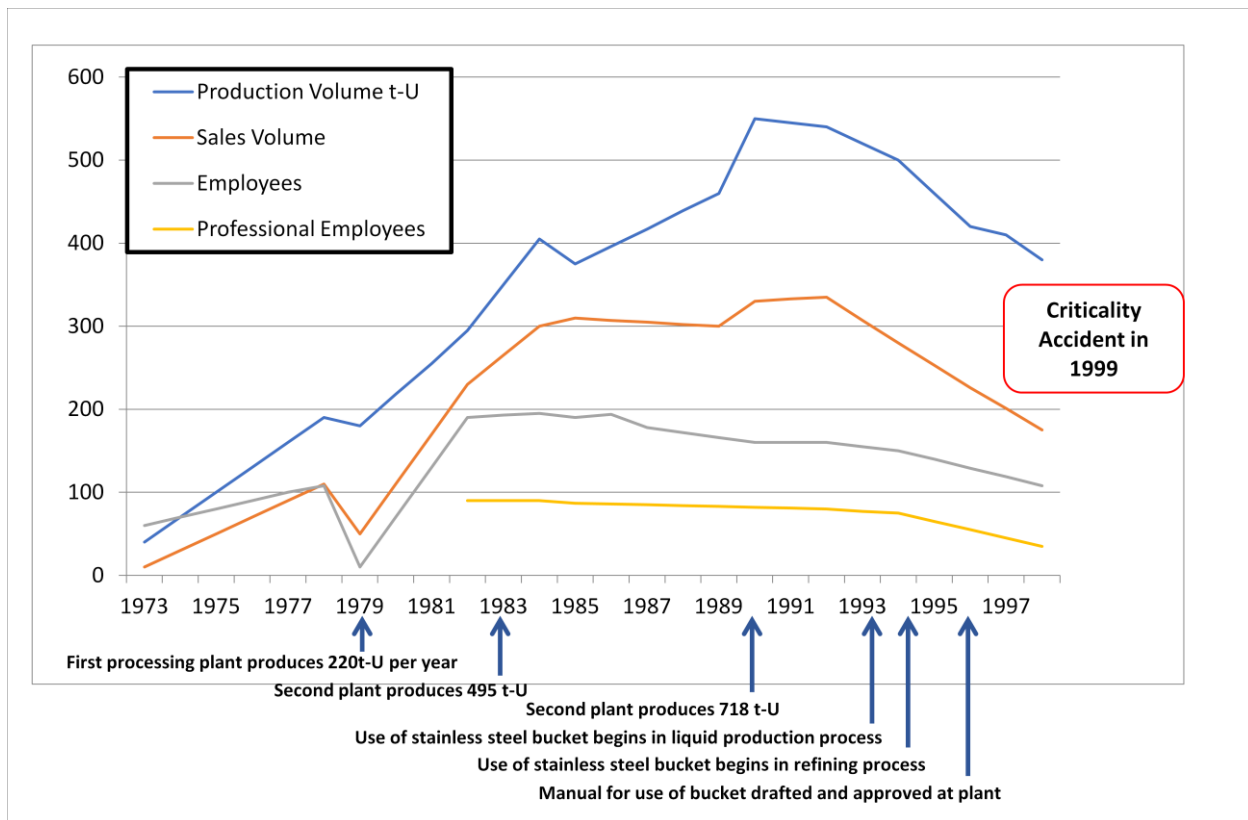


Figure 3.1 Declining JCO Corporate Performance in Run-up to Criticality Accident

Source: From a figure published in Takai, 2002 that was created by H. Kohama, TEPCO, Nuclear Research Institute. Translated by the authors.

The company used a “wet” re-conversion technique developed by SMM, which consisted of solvent extraction utilizing precipitation for collecting solids. The approved nuclear fuel preparation procedure involved dissolving triuranium octoxide (U_3O_8) powder in nitric acid in a dissolution tank, then its transfer as pure uranyl nitrate solution to a storage column for mixing, followed by transfer to a precipitation tank. This tank was surrounded by a water cooling jacket to remove excess heat generated by the exothermic chemical reaction. Prevention of criticality was based upon the general licensing requirements for mass and volume limitation, as well as the design of the process. A key part of the design was the use of a storage column with a criticality-safe geometry and careful control of the amount of material transferred to the precipitation tank (Nuclear Safety Commission (NSC), 1999; JCO, no date; WNA, 2013; IAEA, 1999).

In November 1992, JCO’s major customer, the PNC, began changing the volume of products and the timing of delivery more frequently to accommodate the operation of the experimental FBR Joyo (Takai, 2002). In 1996, the company’s work procedure was altered, without permission from the regulatory authorities, to allow uranium oxide to be dissolved in stainless-steel buckets rather than in a dissolution tank. It was then further modified by the operators to speed things up by pouring the solution directly into the precipitation tank. The mixing that originally was designed to occur in the storage column was instead undertaken by mechanical stirring in the precipitation tank, thus

bypassing the criticality controls. There were no proper controls on the amount poured into the hundred-liter precipitation tank or the shape taken by the liquid in the tank. In 1999, JCO was preparing to introduce a “dry” re-conversion technique that would be more competitive in the LWR fuel material processing market, and thus this operation was expected to be one of the last (IAEA, 1999; Ban, 2002; WNA, 2013).

On the day of the accident, three workers were in a lab conducting fuel preparation. Two were preparing a small batch of fuel in one room for the Joyo experimental FBR, using uranium enriched to 18.8% U-235 (See Figure 3.2). A third worker was the chief of the crew, working at his desk in the next room, separated by a thin wall and open doors from the fuel processing work room. The task that his crew was performing was not a routine manufacturing operation where operators might know their jobs reasonably well. It was JCO's first batch of fuel for Joyo in three years and no proper qualification and training requirements had been established to prepare those workers for the job.

The crew had previously used this procedure many times with much lower-enriched uranium—less than 5% and had no understanding of the criticality implications of 18.8% enrichment. At around 10:35, when the seventh bucket was poured into the precipitation tank and the volume of solution in the tank reached 16.6 kgU, criticality was reached, accompanied by a loud noise and a blue flash. Criticality continued intermittently for 20 hours (McLaughlin, et al., 2000; WNN, 2014a; Yaginuma, 2013).

The Nuclear Safety Commission (NSC) advised that the cooling water be drained from the precipitation tank to stop the criticality. Work started at 02:30 on 1 October to drain the cooling water that was flowing through the jacket around the sedimentation tank. The criticality reaction stopped at 06:15. The water acted as a neutron reflector that perpetuated the criticality. At 08:50 boric acid solution (a neutron absorber) was added to the tank to finally ensure that the contents remained subcritical. These operations exposed 27 workers to some level of radiation. The next task was to install shielding to protect people outside the building from gamma radiation from the fission products in the tank. Neutron radiation had ceased (Yaginuma, 2013; IAEA, 1999; NSC, 1999; WNA, 2013).

The criticality accident at JCO was the first of its kind in Japan at a commercial nuclear facility. The three workers' radiation doses were above permissible limits, which were more than 16-20 gray equivalent (GyEq) (about 17,000 times the maximum annual permissible exposure level set by the government), 6.0-10 GyEq and 1-4.5 GyEq, respectively. Two of the doses proved fatal.

According to the doctors who treated Mr. Hisashi Ouchi, the patient who was most severely exposed, “Mr. Ouchi's chromosomes were severely damaged, dissected and unidentifiable (See Figure 3.3). The chromosomes are the blueprint that contains the specific instructions to recreate each cell in a human body. Without the instructions, nothing can be recreated in the body.” Mr. Ouchi saw a blue flash, a sign of criticality and indicator of neutron radiation. The

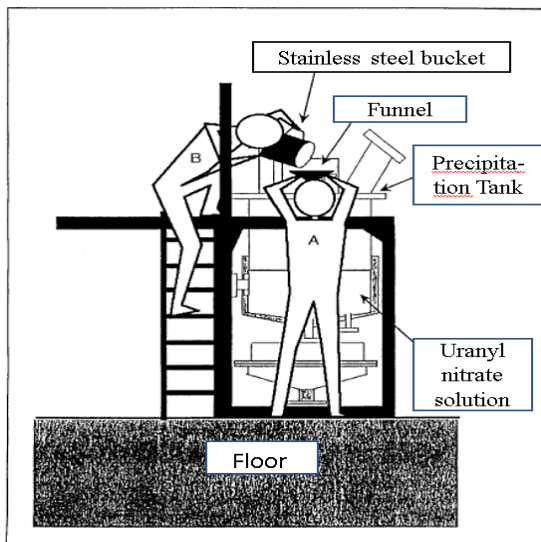


Figure 3.2 Crew Work Situation at the JCO Fuel Fabrication Plant*

*Notes: At the time of the accident, three workers were in the vicinity. Two workers (A&B) were at the precipitation tank and exposed to high level of radiation. Person A is Mr. Hisashi Ouchi, who was holding the funnel with his right hand and received the highest dose that severely damaged his chromosomes. He died on 21 December 1999, 83 days after the radiation exposure. Person B is Mr. Masato Shinohara who suffered severe damage to his chromosomes. He died on 27 April 2000, 211 days after the accident. A third person, Mr. Yutaka Yokakawa, the crew chief, was in the next room and had less radiation exposures. At the time of the accident, he heard a loud noise and saw a blue light through the open door. Although his white blood cell level fell to zero, he recovered after a bone marrow transplant.

Source: NSC, 1999.

radiation effectively destroyed Ouchi's immune system by sending his white blood cell count plummeting to near zero, according to the doctors. He died of multiple organ failure on 21 December 1999, 83 days after the accident. The co-worker, Mr. Masato Shinohara, also suffered severe damage to his chromosomes. Although transfusions of white blood cells helped him recover temporarily, his condition progressively deteriorated. He died of multiple organ failure on 27 April 2000, 211 days after the accident. The third worker was Mr. Yutaka Yokokawa, who was in the room next to the fuel mixing crew. He too suffered serious symptoms; his white blood count fell to zero at one point. He recovered after a bone marrow transplant. He was arrested along with six JCO employees for various safety violations and was sentenced to two years in prison (suspended) (Wikipedia, 2017; NSC, 1999).

The JCO accident was rated at INES Level 4, indicating an event without significant off-site risk. Nonetheless, many people were exposed to radiation; 24 JCO personnel engaged in the operations to stop criticality were subject to planned exposure, 145 JCO employees, 60 government officials and 207 local residents also received radiation doses of varying levels. Five hours after the start of criticality, evacuation commenced of some 161 people from 39 households within a 350-metre radius from the conversion building. They were allowed to come home two days later after sandbags and other shielding ensured no hazard from residual gamma radiation. Twelve hours after the start of the incident, some 310,000 people were advised by the governor of Ibaraki Prefecture to stay indoors for about 18 hours as a precautionary measure. This restriction was lifted the following afternoon (Clayton, 1965; WNA, 2013; Nuclear Safety Commission (NSC), 1999; IAEA, 1999).



Figure 3.3 Microscopic Photo of Mr. Ouchi's Chromosomes

Taken from Bone Marrow Cell from the Ilium, 3 October 1999 (4th day after radiation exposure) (the Best Picture Available). Source: YouTube, 2014.

On 2 October 1999, the Japanese government investigated and discovered that JCO committed many questionable actions; including use of unauthorized work manuals and the use of buckets for mixing uranium solution. The government concluded that there were three general root causes involved with the JCO criticality accident: 1) Inadequate regulatory oversight, 2) the lack of a proper safety culture at the JCO facility and 3) inadequate worker training and qualification. For example, the regulatory oversight program for the JCO plant failed to establish and maintain adequate safety margins. The licensing review incorrectly concluded that there was “no possibility of a criticality accident due to malfunction and other failures,” Consequently, no criticality accident alarm was required or installed, and the facility was not included in the National Plan for the Prevention of Nuclear Disasters. Neither did the regulator conduct periodic inspections of the process to confirm that it was being operated safely and in accordance with the regulations. Furthermore, because of the infrequent use of this special process and the recent lay-offs, there were no experienced operators available to operate the system. Management had no verification and validation procedures and operators had no training and qualification checks prior to restart of a process that had not been performed for about 3 years. In total, these company actions indicated a significant lack of a safety culture and negligence. Because of the accident, the regulator revoked JCO's business license ([IAEA, 1999](#)).

- JCO conceded that it violated both normal safety standards and legal requirements and criminal charges were made. On 11 October 2000, six executive persons in JCO were arrested. If the operators had been given fundamental knowledge that certain actions could result in criticality, this fatal accident might not have occurred. Indeed, Mr. Yokokawa, one of the three workers and the crew leader, stated in an interview that ignorance was the fundamental cause of the accident and that he had absolutely no idea that criticality would

occur from mixing uranium in a liquid form. The US National Regulatory Commission (NRC) reviewed the available information and agreed with the conclusion of the Japanese government (IAEA, 1999; NRC, 2000; Suda, 2005).

The JCO accident also became Japan's first case that dealt with compensation for nuclear damages. JCO first drafted its idea of compensation and standard for payment. It, however, was viewed as inequitable and strained negotiations. The STA, thus, established a Nuclear Damage Investigation and Study Committee consisting of a panel of specialists. The committee compiled the "Report on Interim Checklist: Way of Approach" in December 1999 and released a final report in March 2000. The two reports laid out the basis for limitations on damages and the compensation calculation formula. Based on the reports, STA established, on 26 May 2000, the guidelines to determine what damage caused by the JCO accident would be qualified as "nuclear damage" for compensation. Ultimately, about 7,000 claims were filed and \$154 million paid. JCO's nuclear damage insurance amounted to \$10 million at that time. SMM paid the remaining \$144 million to make the settlement (See Table 3.4). According to STA, almost all compensation with respect to the accident had been awarded by 30 September 2000. Direct damages, for example, included the forced closure of businesses and suspension of agricultural activities and fisheries (See Table 3.5). Perceived damage was not included in what was called "direct damage." In addition, real estate prices were not evaluated although they were falling as were the prices of agricultural products. No compensation was made to those who complained that their health had deteriorated (Yaginuma, 2013; Citizens' Nuclear Information Center in Japan (CNIC), 2002; World Nuclear Association (WNA), 1999).

Table 3.4 JCO Accident: Status of Damage Compensation and Settlement (as of 13 May 2010)

Total Number of Damage Declarations (1)	About 8,018
Number of Exclusions (Withdrawal, No Claim Intention) (2)	About 1035
Number of Claims for Compensation (1) – (2)	About 6983
Number of Settlements	About 6983 (100% in Agreed Settlement)
Agreed Amount	\$154 million

Source: Yaginuma, 2013; MEXT, 2011.

Table 3.5 Industries that Suffered JCO Radiation Damage and Received Compensation (at the end of October 2000)

Category of Industry	Amount of Damages (\$ Million)
Commercial Industry	95.96
Agriculture, Livestock, Fishing Industry	25.04
Tourist Industry	14.72
Transportation Industry	2.11
Other Industries	7.5
Reduction of Tax Revenue (expected)	7.69
Total	153.02

Source: Citizens' Nuclear Information Center (CNIC), 2002.

Following the 30 September 1999 criticality accident, the JCO uranium conversion activities ended. On April 18, 2003, SMM announced its fuel-processing subsidiary, JCO, would end its fuel conversion operations, but would not be dissolved. It would continue to compensate victims of the accident and store low-level radioactive waste that remained at the facility. On 11 May 2005, JCO said it obtained approval from the government to dismantle its nuclear fuel-processing facility. The company started dismantling operations in June 2005. As of 17 July 2017, JCO is still safekeeping the radioactive materials and disposing of the remaining liquid solvents (JCO, 2017; Dudzinski, 2017).

3.1.2 Mitsubishi Nuclear Fuel Co Ltd (MNF) Fuel Fabrication Plant

Mitsubishi Nuclear Fuel Co Ltd (MNF) in Tokai-mura, Ibaraki Prefecture, operates a 440 tU/yr fuel fabrication facility. MNF started its business in December 1971 with the majority shareholding by Mitsubishi Materials Corporation (MMC). In January 1972, MNF acquired a license for nuclear fuel fabrication at the Tokai Plant. In December 1996, the company received the ISO 9002 certification and in October 2001, MNF received a Total Productive Maintenance (TPM) Award, an award for contributing to the creation of a beautiful environment and a healthy society. In April 2009, it was restructured as a comprehensive nuclear fuel fabrication company to supply Japanese customers with uranium fuel assemblies for PWRs, BWRs, as well as MOX fuel assemblies. In October 2009, it was announced that the company would build a new 600 t/yr plant using Areva's dry process technology. MNF also has a plant at Okegawa, Saitama Prefecture, to make zirconium alloy tubing for fuel rods, with a capacity of 800 tU/yr. In 2010, MHI and Areva announced a 50-50 joint venture to manufacture advanced pressure water reactor (APWR) fuel at Areva's Richland plant in Washington state, but it did not materialize. On 31 January 2014, MNF met Japan's new nuclear safety requirements. Also, in 2014, the company started providing uranium reconversion services with new shareholders. The new shareholders are MHI (95%) and Areva NP (5%) with a total capital of \$188.5 million. No major accidents have been reported at the plant since the start of the company in 1971 (Mitsubishi Nuclear Fuel Company (MNF), 2017; WNA, 2017a).

3.1.3 Nuclear Fuel Industries (NFI) Fuel Fabrication Plants

Nuclear Fuel Industries (NFI) was established in July 1972 by obtaining the production facility and fuel fabrication technology from Sumitomo Electric and Furukawa Electric. It produces fuel for both BWRs and PWRs, designs the basic structure of BWR and PWR fuel components and manufactures parts of FBRs. It also produces fuel for the high temperature gas-cooled test reactor (HTTR)²⁸ and provides reactor core management services. The company is owned by Westinghouse Electric UK Holdings (52%), Sumitomo Electric (24%) and Furukawa Electric (24%) and is capitalized at \$10 million. It has two plants; the Kuramori Plant in Kumatori, Osaka Prefecture, which was established in 1972 and the Tokai Plant in Tokai-mura, Ibaraki Prefecture, which was established in 1980. The Kumatori Plant has an annual capacity of 284 tU/year (PWR

²⁸ The high temperature gas-cooled test reactor (HTTR) was developed by the Japan Atomic Energy Research Institute (now JAEA) in 1998. It has been safely operating since then. There have been six other reactors similar to Japan's HTTR. The United States had two, Germany had two and UK had one; all of them have ceased operation. Only one HTTR in China and one in Japan have been operating since 1998 (IAEA, No date. "General Atomics' Prismatic Modular High Temperature Gas Cooled Reactor," <https://aris.iaea.org/PDF/PrismaticHTR.pdf>>(accessed 22 September 2017).

fuel). It had shipped a total of 8,674 fuel assemblies as of March 2017. The Tokai Plant has a capacity of 250 tU/year (BWR fuel) and 400 kgU/year for the High Temperature Gas Reactor (HTGR).²⁹ The plant had shipped a total of 18,551 assemblies for BWRs and 300 assemblies for HTGR as of March 2017 and a total of 687 assemblies for the ATR, until the ATR ceased operation in 1999. No major accidents have been reported. In 2009, Westinghouse bought the 52% share of NFI owned by Furukawa and Sumitomo for \$100 million (IAEA, 2003; NFI, 2017; WNA, 2017a).

3.1.4 Global Nuclear Fuel – Japan (GNF-J) Fuel Fabrication Plant

Global Nuclear Fuel – Japan (GNF-J), formerly Japan Nuclear Fuel Co., Ltd. (JNF), was established in May 1967 as part of the GE-led Global Nuclear Fuel joint venture with Hitachi and Toshiba. The company designs and manufactures fuel for BWRs. It completed a 750 tU/yr plant at Kurihama, Yokosuka, Kanagawa Prefecture in September 1970. The company had produced a cumulative total of 10,000 assemblies by December 1980, 30,000 by May 1989, 50,000 by February 1996, 70,000 by June 2004 and 80,000 by June 2010. The company is proud of its high-quality management standards; it has received ISO 9002 certification in March 1998, ISO 14001 certification in March 1999, and ISO 9001 certification in April 2000. The company had a capitalization of \$4 billion in April 2000. In January of that year, Toshiba, Hitachi and GE transferred all design, development and sales operations related to fuel fabrication to GNF-J. In March 2017, the NRA approved the plant as meeting the 2013 safety standards and METI approved the plant to restart. A sister company, Global Nuclear Fuel – Americas, LLC (GNF-A), is in North Carolina. It supplies BWR fuels and provides related technology in the United States and around the globe. No major accidents have been reported (Global Nuclear Fuel-Japan Company, Ltd (GNF-J), 2008; WNA, 2017b).

3.1.5 Rokkasho Enrichment Plant (REP)

In the 1970s, STA and PNC made major strides in developing indigenous enrichment technology. The PNC built two uranium enrichment plants using domestic centrifuge technology, a pilot plant and a prototype plant, in Ningyo-toge, Okayama Prefecture. In 1981, AEC decided that the PNC should transfer the enrichment technology to the private sector so that the domestic enrichment commercialization could start. A large-scale technology transfer effort began as a result. The PNC sent over a hundred personnel to the Japan Nuclear Fuel Industry Limited (JNFI), a forerunner of JNFL, educated and trained more than 160 JNFI personnel, and provided the JNFI documents on technology knowhow (MEXT, 2009).

In October 1988, the JNFI started construction of the Rokkasho Enrichment Plant (REP). The plant was expected to have an ultimate enrichment capacity of 1,500 tSWU/year. In March 1992, the REP went on-line with its first centrifuge cascade, RE-1A (150 tSWU/year). Further cascades of 150 tSWU/year were added to reach a capacity in 1998 of 1,050 tSWU/year (150 tSWU/year × 7 operational units).

²⁹ The high temperature gas-cooled reactor (HTGR) has inherent safety features and can be used for a wide range of heat applications. The international cooperation for R&D on HTGR was espoused in the Strategic Energy Plan and approved by the Cabinet on 11 April 2014 (JAEA, no date. “HTGR Hydrogen and Heat Application Center,” https://www.jaea.go.jp/04/o-arai/nhc/en/_top/top.htm)>(accessed 11 January 2018).

- In June 2008, JNFL began construction of the Uranium Enrichment Machinery Manufacturing Plant for mass production of centrifuges. In October 2009, the plant was completed and in April 2010, the plant started manufacturing the new centrifuges. (JNFL, (no date)a; Ichimura, 2009).

In early 2000, the REP decided to completely replace its older centrifuges with new types starting in 2010. In April 2000, the REP began to gradually phase out older centrifuge cascades and completed the phase-out of all 1,050 tSWU/year centrifuge systems (that had been installed in two phases) by 15 December 2010 (See Table 3.6) (Morikami, 2013). The REP stated in a press release that the suspension of centrifuge operations was to ensure that renovation work would proceed in the safest possible way (JNFL, 2010). Following the suspension, however, the REP updated only a small number of centrifuges during the next two years, amounting to a capacity of just 75 tSWU/year.

The operation of these updated centrifuges was suspended on 12 September 2017 and the entire upgrade plan has been delayed. The REP stated that it now plans to update the remaining RE-2 centrifuges (375 tSWU) by 2024 and that eventually a total of 1,500 tSWU would be installed (JNFL, 2018a).

- Yoshioka (2013) suggests that the reason behind the inactivity might be the lack of cost competitiveness of the Japanese enrichment technology and that it would be far cheaper to buy enriched uranium from overseas.
- At the government's urging, Japanese nuclear manufacturers have been working to develop newer types of centrifuges, but progress has been slow. JNFL and the REP apparently have been reluctant to introduce new centrifuges (Yoshioka, 2013).

The JNFL said that the plant needed to undergo further renovations to meet new regulatory safety requirements. The REP has neither restarted its operations as of March 2018 nor has it issued any more press releases on the matter. The JNFL website indicates that no product shipments have occurred since 2013. Between 1993 and 2017 the REP had shipped a total of 1,698 tUF (JNFL, 2017b, 2017g).

Table 3.6 Installation and Operational Status of Centrifuges at Rokkasho Uranium Enrichment Plant

Date	Installation Activity	Date Suspended
26 May 1987	Requested permission to enter nuclear material manufacturing business	
10 August 1988	Permission granted	
14 October 1988	Construction of the Rokkasho Uranium Enrichment Plant started	
27 March 1992	RE-1A 150 tSWU/year	3 April 2000
18 December 1992	RE-1B 150 tSWU/year	19 December 2002
27 May 1993	RE-1C 150 tSWU/year	30 November 2005
21 September	RE-1D 150 tSWU/year	30 June 2003

1994		
3 July 1992	Requested permission to alter plans for a second phase installation of 450 tSWU	
12 July 1993	Permission granted	
17 October 1997	RE-2A 150 tSWU/year	30 November 2006
1 April 1998	RE-2B 150 tSWU/year	15 December 2010
6 October 1998	RE-2C 150 tSWU/year	12 February 2008
16 December 2008	Requested permission to alter installation plan for new RE-2A (150 tSWU/year); installation to be done in two phases (75 tSWU/year each phase)	
21 January 2010	Permission granted	
9 March 2012	New RE-2A 37.5 tSWU	12 September 2017
21 May 2013	New RE-2A 37.5 tSWU	12 September 2017

Source: Table is based on authors' interpretation and analysis of JNFL, (no date)a.

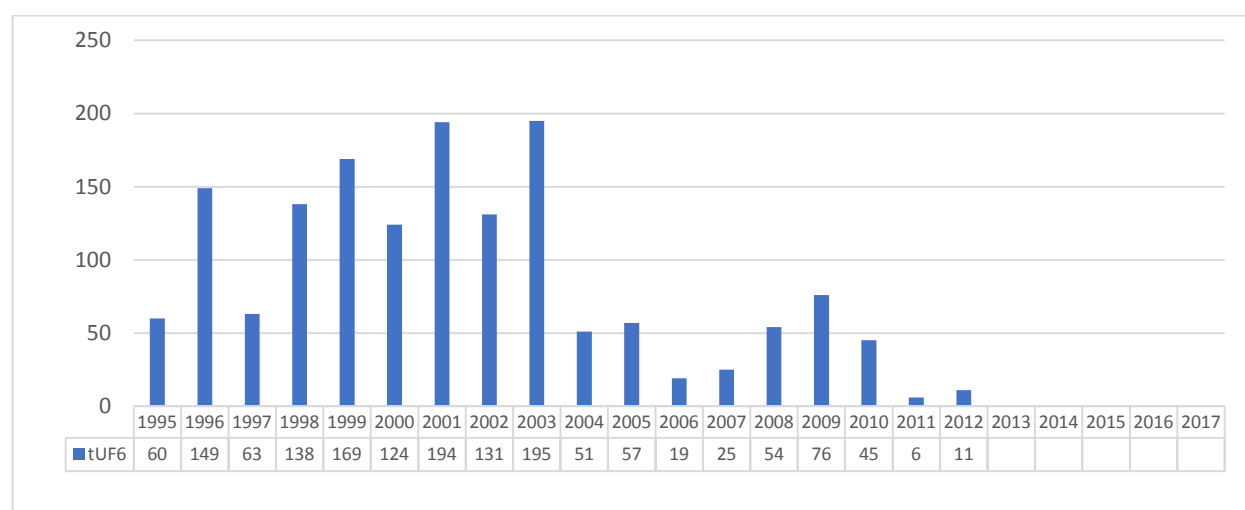


Figure 3.4 Rokkasho Enrichment Plant Shipments of Enriched Uranium

Total shipments = 1,567 tUF₆. (JNFL indicates that it has enriched a total of 1,698 tons, but its website indicates it has enriched a total of 1567 tons).

Source: JNFL, 2017c.

Table 3.7 World Enrichment Capacity – Operational and Planned (thousand SWU/yr)

Country	Company and plant	2013	2015	2020
France	Areva, Georges Besse I & II	5500	7000	7500
Germany-Netherlands-UK	Urenco: Gronau, Germany; Almelo, Netherlands; Capenhurst, UK.	14,200	14,400	14,900
Japan	JNFL, Rokkasho	75	75	75
USA	USEC, Piketon	0*	0	0
USA	Urenco, New Mexico	3500	4700	4700
USA	Areva, Idaho Falls	0	0	0
USA	Global Laser Enrichment,	0	0	0

	Paducah			
Russia	Tenex: Angarsk, Novouralsk, Zelenogorsk, Seversk	26,000	26,578	28,663
China	CNNC, Hanzhun & Lanzhou	2200	5760	10,700+
Other	Various: Argentina, Brazil, India, Pakistan, Iran	75	100	170
Worldwide	Total SWU/yr approx.	51,550	58,600	66,700
	Requirements (WNA reference scenario)	49,154	47,285	57,456

Source: Table is based on authors' interpretation and analysis of WNA, 2017c, World Nuclear Association Nuclear Fuel Report 2013 and 2015, information paper on China's Nuclear Fuel Cycle, and Areva 2014 Reference Document (for most 2013 figures).

3.2 Commercialization of the Back-End Nuclear Fuel Cycle

For more than 30 years STA had been pursuing the dream of completing four big national projects, three of which were technologies that would enable Japan to close the back-end of the nuclear fuel cycle, whereby spent fuel is reprocessed into fresh fuel to generate more energy. The big projects were the ATR, the FBR and reprocessing (including MOX fuel fabrication). STA's dream of an ATR, however, ended in October 1992 when FEPC, after dragging its feet for decades, proposed an untested technology that would require much additional research. This proposal served as a show stopper and set the stage FEPC's withdrawal of all support for building the demonstration ATR, the successor to the prototype ATR Fugen. In July 1995, the FEPC put the final nail in the coffin when it announced it would not fund its share of the project ([Yoshioka, 2013](#)). While the STA's disappointment was great, it feared more what might happen next: that the private sector might veto construction of a new reprocessing facility because of the plant's high cost and because the output of MOX fuel would cost much more than imported enriched uranium.

3.2.1 The Fight for the Rokkasho Reprocessing Plant (RRP)

In the 1980s, Japan had only one government-owned reprocessing plant, the Tokai Prototype Reprocessing Plant, which had limited capacity to recycle spent nuclear fuel. Tokai had provided Japan with sufficient experience and expertise to begin commercialization of reprocessing, however. To that end in 1982, at AEC's instruction, the PNC established a long-term, large-scale plan to transfer of expertise and technology to the private sector.

- As of April 2009, the PNC and its successor organizations had dispatched a total of 342 personnel on rotational assignments to the JNFL and trained 666 personnel.
- Technologies that were transferred included uranium de-nitrification, plutonium uranium mixed conversion (MOX fuel fabrication) and vitrification ([MEXT, 2009](#)).

The AEC and METI pulled every string to gain approval of the massive demonstration reprocessing plant at Rokkasho. According to Tolliday, METI carried out one of its longest, most lavish and most strenuous public acceptance campaigns to ensure that construction of the Rokkasho Reprocessing Plant (RRP) would proceed ([Tolliday, 2012](#)). Despite the government's enthusiasm,

there were numerous people opposed to the commercialization of reprocessing and urged caution (Yoshioka, 2013). They were:

- Anti-nuclear activists
- Electric power industry insiders who were concerned about business risks
- Electric power industry insiders who wished to revise unsound practices of the nuclear industry
- Policymakers and government bureaucrats who wished to break up deeply rooted interest groups
- Neoliberal economists who advocated electricity deregulation
- Administrative reformers who were weary of wasteful government projects

Except for the anti-nuclear activists and abolitionists, the majority were supportive or accepting of nuclear power generation. Even among the majority of supporters, however, were those who opposed reprocessing because of the high risks involved. To quell the widespread apprehension, the AEC established a 32-member New Plan-Making Committee to discuss the choice between the reprocessing path and the direct disposal path, where spent fuel is sent directly into disposal without reprocessing.

The Committee first set up a technical subcommittee that was assigned to compare the costs of the two paths. The subcommittee concluded that the direct disposal was less costly than reprocessing. The subcommittee assessed that the cost of reprocessing all spent fuel in Japan would be 0.16 ¢/kWh. In comparison, direct disposal with no reprocessing would cost 0.11 ¢-0.12 ¢/kWh (Yoshioka, 2013). The New Plan-Making Committee, however, also introduced a new evaluation criterion that argued for reprocessing. The Committee claimed that reprocessing would reduce the volume of radioactive waste that requires deep burial by about 95 percent and that direct disposal of (unprocessed) nuclear waste would have no place to go and might lead to the cessation of nuclear power generation.

- Most of the Committee members were persuaded that the advantage of reduced storage requirements justified the higher cost of reprocessing.
- Only two of the 32 committee members opposed the conclusion: Hitoshi Yoshioka and Hideyuki Ban of the NPO.

On 12 November 2004, the committee compiled a report that gave the “go” sign to the reprocessing policy and the Rokkasho Reprocessing plant proceeded to start the uranium test in December 2004. The Committee, at the same time, recommended banning direct disposal of spent fuel in Japan. These recommendations served as the basis for joint industry-government nuclear policy for the next decade (Yoshioka, 2013).

In March 2005, Yoshioka formed and chaired an 8-man International Critical Review Committee Panel (ICRC) to reassess AEC’s New Plan-Making Committee report. The ICRC panel consisted of leading international nuclear scholars and analysts, including Frank von Hippel (US), Fred Barker (UK), Christian Kuppers (Germany), Mycle Schneider (France), and Tetsuya Iida, Yuichi Kaido, Takeo Kikkawa and Yo Fujimura (Japan). After a 6-month study, the Panel compiled its report in September 2005. The ICRC report found that the New Plan-Making Committee’s report to be flawed.

- According to the ICRC report, AEC’s Committee report lacked a proper methodology; it

used unbalanced logic, lacked standards in weighing options and focused only on the advantages of reprocessing and not its dangers.

- The ICRC Panel pointed out that AEC's Committee report failed to consider "What if" scenarios, including situations where some unexpected event or accident occurred.

In contrast to the Committee report, the ICRC Panel concluded that there is virtually no meaningful difference between direct disposal storage and glass vitrification disposal after reprocessing. But the Panel concluded that reprocessing is disadvantaged in terms of economy, proliferation risk, and environmental safety. Moreover, the Panel pointed out that the production of plutonium via reprocessing would be meaningless without also having FBRs, which have been largely abandoned globally ([International Critical Review Committee of Long Term Nuclear Program Panel \(ICRC\), 2005](#)).

Finally, the ICRC Panel stated that it makes little sense to produce more plutonium through reprocessing when Japan already had more than 40 tons of plutonium, which would be sufficient to satisfy Japan's MOX fuel needs for several decades. By the end of 2015, the amount of Japanese plutonium had increased to 47.9 tons, including 10.8 tons in Japan, 20.9 tons in UK and 16.2 tons in France ([WNA, 2017d](#)).

In conclusion, the ICRC report recommended that AEC withdraw the New Plan-Making Committee report, mandate an indefinite freeze on Rokkasho reprocessing plant operation and conduct a fresh debate to formulate the best policy for the back-end nuclear fuel cycle. If AEC were to conduct such a review, the ICRC Panel advised that the committee chairman and the secretariat be neutral with respect to the current policy and select new committee members whose views are evenly balanced between pro and con on the issue ([ICRC, 2005](#)).

- Yoshioka handed the ICRC Panel report to each of the members of the New Plan-Making Committee at one of its meetings ([Yoshioka, 2013](#)).

AEC ignored the ICRC Panel report, which was not a surprise. It is a characteristic of Japan's governing culture that policymaking mechanisms work to protect pre-determined government views and policies and are not intended to be receptive to hearing outside views, however valid and legitimate, unless they are fully supportive of government views.

The ICRC report also volunteered that if AEC was unable or unwilling to establish an appropriate policy-making forum, the government should establish a new organization other than AEC that could take responsibility for delivering policy options regarding the back-end nuclear fuel cycle. This recommendation also was not embraced, of course ([ICRC, 2005](#)).

It is noteworthy that the ICRC Panel provided assessments both pro and con with respect to reprocessing economics, proliferation risk, and environmental safety. AEC's New Plan-Making Committee's argument ignored those issues and focused narrowly on reprocessing's advantage in terms of waste volume reduction and saving space for waste disposal. Even that argument has been proven false. According to Nosenzo (1977), the area required in an underground repository for highly radioactive waste is determined not by the volume of the waste but by its heat output. The waste must be spread out in a repository to limit the temperature increase of the surrounding buffer clay and rock. One ton of spent MOX light water reactor fuel and high-level waste generate about 1.2 times as much radioactive decay heat as eight tons of spent low enriched uranium. Reprocessing and one recycle of plutonium in MOX therefore do not result in a significant benefit

in reducing the area of a geological repository ([International Panel on Fissile Materials \(IPFM\), 2015](#)).

Key points of the ICRC Panel report on reprocessing and MOX fuel fabrication, vis-à-vis direct disposal included the following:

- **Economics.** Tabuchi and von Hippel (2017) state that many studies have confirmed that the separation of plutonium from spent fuel and its use in MOX fuel is not economically competitive compared to simply disposing the spent fuel until its radioactive heat has declined in deep underground depositories (See Table 3.8) ([Takubo, von Hippel, 2017](#)). Yoshioka (2013) testified that one uranium fuel assembly for a pressurized water reactor (PWR) costs about \$1 million but one MOX fuel assembly, without counting the reprocessing costs, amounts to \$5 -\$10 million ([Yoshioka, 2013](#)). Also, according to a 2011 estimate by Japan's AEC, MOX fuel made with plutonium separated at the Rokkasho Reprocessing Plant will cost Japan twelve times as much to produce compared to an equivalent amount of low-enriched uranium fuel, including the cost of reprocessing ([IPFM, 2015](#)).

Table 3.8 Cost of Direct Disposal and Reprocessing and MOX Fuel Fabrication in Selected Studies

Reprocessing Premium (C) = (B – A) ÷ A	Study					
	MIT 2011	Harvard 2003	Rothwell 2011	Nuclear Energy Agency, OECD		
				1994	2006	2013
A: Direct disposal (\$/MWh)	8.2	6.5	7.5	9.4	5.6	6.7
B: Reprocessing and MOX fuel fabrication	10.3-11.3	8.1	12.4	10.4	6.4	7.3
C: Reprocessing Premium (in Percent)	26-37	25	65	11	14	20

Source: Takubo and von Hippel, 2017. Original data was published in OECD, 2013.

- The latest estimate of the total project cost for Japan's Rokkasho Reprocessing Plant, including construction, operation for 40 years and decommissioning, is now \$139 billion, with the construction cost alone reaching \$29.5 billion, including \$7.5 billion for upgrades due to the new safety regulations introduced after the Fukushima nuclear disaster. The total project cost of the MOX fuel fabrication facility alone, including some 42 years of operation and expected decommissioning costs, is now estimated at \$23 billion ([Nuclear Reprocessing Organization of Japan \(NuRO\), 2017](#)).
- At present, Japan that has only a few operating nuclear plants, so reprocessing spent fuel and MOX fuel fabrication will become even more costly. This was the reason for the UK's 2012 decision to close the Thermal Oxide Reprocessing Plant (THORP, formerly BNFL) at Sellafield. It would have taken billions of pounds to upgrade THORP and its support plants to continue reprocessing operations beyond 2018 ([Leafe, 2017](#)).

- **Proliferation Risk.** Direct disposal of spent fuel in a disposal site is superior to reprocessing in terms of nonproliferation. In the direct disposal fuel cycle, the plutonium remains mixed with the radioactive fission products in the intact spent fuel and therefore is relatively inaccessible for use in weapons (Takubo, von Hippel, 2017). On the other hand, it would be difficult to prevent theft or diversion of plutonium from a reprocessing plant or a MOX fuel fabrication plant. At a reprocessing plant, plutonium flows through pipe galleries in large quantities and in different forms such that making an accurate inventory is almost impossible. There would be inevitable measurement errors that could not be resolved by advanced accounting management—a circumstance that could be exploited for purposes of making a bomb (WNA, 2017d; ICRC, 2005).
- **Environment.** A reprocessing plant would create 10,000 times more radioactive material than a power generation reactor; a MOX fuel fabrication plant would create 100 times more harmful radioactive material than a uranium fuel enrichment and fabrication plant. Thus, if an accident were to occur, a reprocessing or MOX fabrication plant could release more heat and radioactive contamination than uranium, exposing plant workers, the public and the environment to greater harm (Yoshioka, 2013; ICRC, 2005). Moreover, MOX fuel is a mixture of plutonium, natural uranium, reprocessed uranium, or depleted uranium. Different reactivity coefficients of the ingredients make it difficult to control in a nuclear reactor, thereby increasing the potential for accidents. The same diversity of ingredients makes MOX fuel disposal difficult; spent MOX fuel would need to be cooled in pools virtually semi-permanently (Yoshioka, 2013).

It must have been a great relief to STA when the JNFL announced in 1993 that it would proceed with building a Rokkasho Reprocessing Plant (RRP). JNFL was Japan’s most powerful “nuclear village” member, representing nearly all of Japan’s electric utilities and most corporations in the nuclear industry. When finished, the reprocessing plant consisted of more than three dozen buildings spread over 740 hectares (1,829 acres). The plant will have an annual capacity of 800 tons of uranium or 8 tons of plutonium, enough to reprocess spent fuel produced from about forty 1,000 MW-class power plant reactors, or about 80 percent of the reactors that were in operation at the time of the Fukushima nuclear disaster (See Figure 3.5) (JNFL, 2017d).



Figure 3.5 Japan Nuclear Fuel Limited (JNFL) Facility in Rokkasho, Aomori Prefecture
Source: JNFL, (no date)b.

The Rokkasho Reprocessing Plant (RRP) is a copy of Areva's La Hague UP3 reprocessing plant developed by COGEMA that was tested and proven for its effectiveness at the UP2 and UP3 plants (Emim, et al, 2003). JNFL, however, added several new technologies to the RRP to improve the efficiency of the plant as well as to placate the PNC's desire to rely on indigenous technology. For example, the RRP introduced glass vitrification technology developed by the PNC and Ishikawajima Harima Heavy Industries; uranium/plutonium de-nitrification technology developed by the PNC, Mitsubishi Material, and Toshiba; and acid recovery and high-level liquid concentration technology developed by BNFL of the UK. These capabilities are integrated with shearing/dissolving and separation and purification technologies developed by COGEMA's subsidiary SGN (See Figure 3.6), (JNFL, 2009).

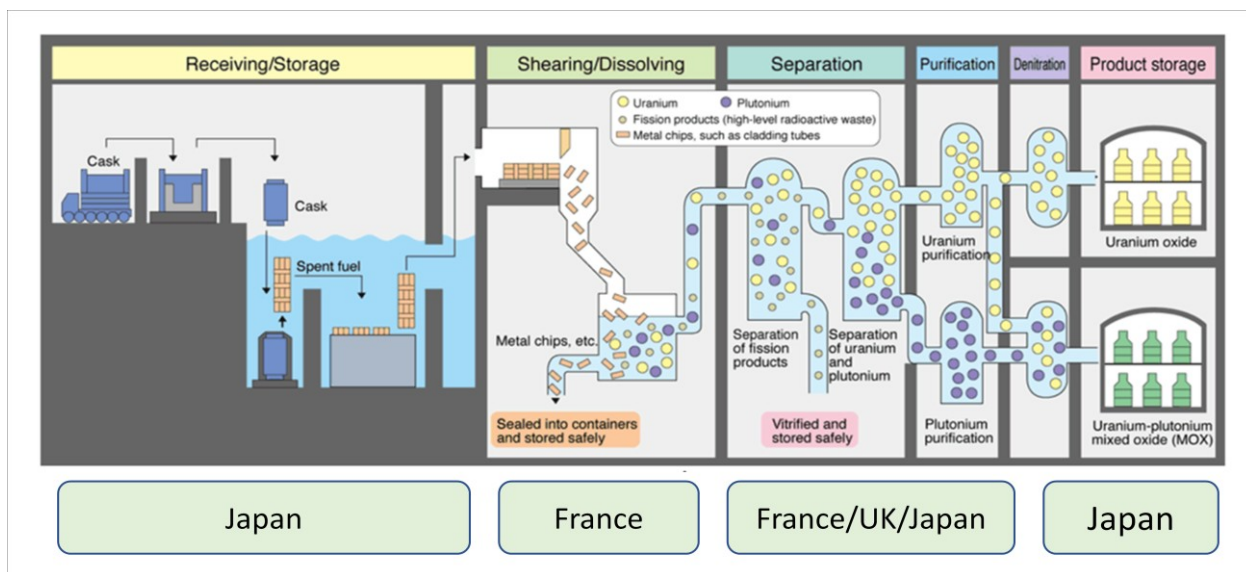


Figure 3.6 Reprocessing Steps and Country Technologies at Rokkasho Reprocessing Plant*

* The reprocessing plant is a copy of Areva's La Hague UP3 reprocessing plant, but other technologies were added to the French plant. The origin of the technologies and where the foreign technologies were introduced are shown below in the diagram of the plant.

Source: JNFL, 2015b, 2016b. The authors added country descriptions.

In a surprising move, METI announced on 20 January 1997 that Japan would promote a so-called "Pluthermal" policy.³⁰ The policy endorsed 1) the creation of mixed oxide fuels of plutonium and uranium made by reprocessing spent fuel and 2) that such fuel would be used in LWRs in Japan. Apparently in response to this policy statement, JNFL later announced that it would be the main party to support MOX fuel fabrication and would set up a fabrication plant in Rokkasho.

METI aggressively pushed for adoption of the policy by announcing it in an interim report of the Nuclear Subcommittee of METI's Comprehensive Energy Investigation Committee. The subcommittee had had little debate on the subject and so METI's interim report became something of a *fait accompli*; the policy was adopted without public participation or input. Almost at the same time, AEC on 31 January 1997 declared that Japan would promote the Pluthermal plan for reprocessing, without customary discussion or input from special committees or deliberative committees. On 2 February 1997, the Japanese cabinet held a meeting to decide that Japan should

³⁰ The "Pluthermal" plan, a word made in Japan, means a plan to make mixed oxide fuel of plutonium and uranium and use it in Japanese power reactors. One of the primary goals was to dispose of plutonium and save uranium.

promote the nuclear fuel cycle, with no other inputs. This decision effectively “locked in” Japan’s policy to rely on FBRs and reprocessing as critical elements of its nuclear infrastructure ([Yoshioka, 2013](#)).

3.2.1.1 Use of Immature Technology Causes Major Delays at the RRP

In November 2007, the Rokkasho Reprocessing Plant (RRP) encountered several difficulties in combining liquid high-level waste (HLW) with borosilicate glass. HLW is waste that remains after uranium and plutonium are recovered from used fuel. Operators had difficulty in controlling the vitrification furnace temperature, problems with accumulation of platinum group elements that impact glass pourability, bricks falling to the bottom of the furnace and clogging of nozzles that prevented the waste liquid from flowing into the vitrification canister below (See Figure 3.7).³¹ The problems were like those which had been encountered at the Tokai Reprocessing Plant. Joule heating of the furnace could not uniformly heat and liquefy the wastes ([Yoshioka, 2013](#); [Okubo](#)).

- In January 2004, the R&D Problem Evaluation Committee of the Japan Nuclear Cycle Development Institute (JNC), the PNC’s successor, reported that the committee had learnt for the first time that the PNC’s glass melting furnace was an immature technology that had not been fully developed. There were many problems that needed to be resolved. The furnace was too small for the RRP’s AREVA plant and needed to be scaled up to function at the RRP. More surprisingly to the committee, the vitrification furnace design did not address any of the problems that had occurred earlier. The committee judged that the technology would be mature in five years at the latest ([JNC, 2004](#); [JCA, 2017](#)).

³¹ The vitrification process occurs at the separation stage. The separated highly radioactive fission materials travel downward into the glass melting furnace. The fission materials are melted and flow down into a canister that will store the vitrified waste (See Figure 3.7).

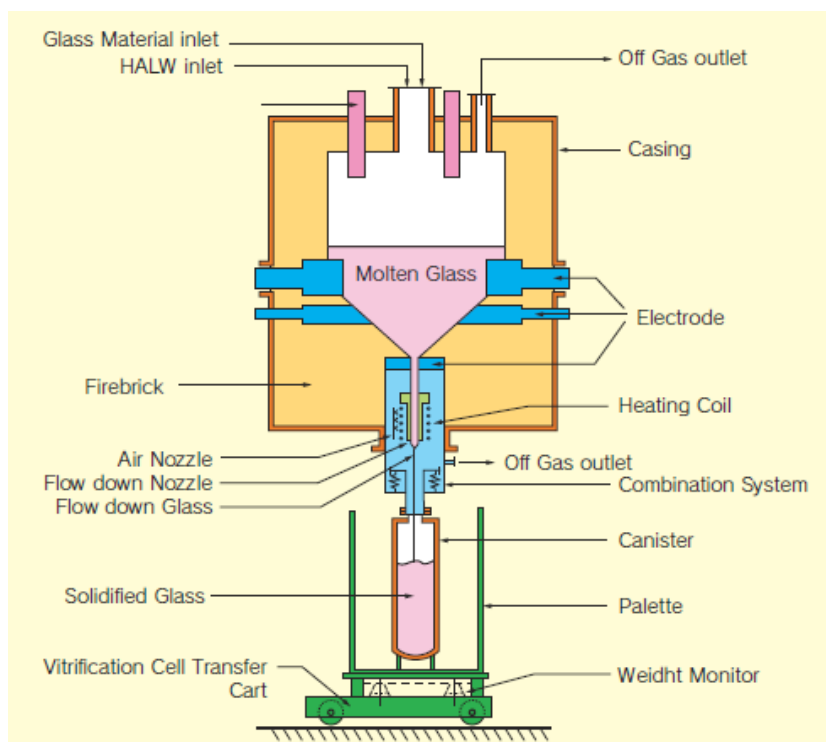


Figure 3.7 Glass Melting Furnace

Note: 1) HALW is highly radioactive liquid waste. 2) In the glass melting furnace, electric current passes directly through the glass by means of electrodes installed in the furnace. Joule heating melts the glass. The molten glass combines with HALW and is poured into the canister by heating the flow-down nozzle located at the lower part of the casing.

Source: JNFL, 2014.

The problems with the vitrification process were finally resolved in 2013, apparently by replacing it with La Hague's furnace. The JNFL described its experience with the glass solidification problem at a meeting of METI's Nuclear Energy Business Environment Preparation Study Special Working Group as follows:

- The RRP acquired the main segment of its reprocessing machinery from AVEVA (except for the PNC's glass vitrification segment). The RRP imported the main segment after the La Hague UP2-400, UP2-800 and UP3 plants had successfully tested and proven the validity and operational soundness of the segment. UP2-400 conducted the test operation in 1986 and completed the rated operation in 1987, the UP2-800 conducted the same test from 1994 to 1995 and UP3 from 1989 to 1993
- In 1988, the glass vitrification technology was still under development at both PNC and AREVA and both were immature. But the RRP introduced the PNC's glass vitrification technology first because it was indigenously developed.
- The RRP started the final, pre-operative test of the entire process in March 2006 and completed the test successfully in February 2008, except for the glass vitrification section. It processed 425 tons of spent fuel, as planned.
- The RRP did not validate the glass vitrification technology. The RRP conducted an active test without going through an orderly development process, from concept design, mockup test, basic design and detail design. It immediately conducted an active test. The RRP

started to install the device without waiting for the findings of the operational test at the Tokai Reprocessing Plant and without obtaining sufficient validation from its own real-size mockup test.

- The now-defunct PNC had no obligation to guarantee the performance of the technology and it is ambiguous who is responsible for technology verification after the technology transfer. Moreover, the RRP depended on the PNC and its affiliated manufacturers for the operation of glass vitrification and scarcely involved itself in the management of the process. Furthermore, there were few full-time RRP employees at the work site and the reprocessing work was basically run by loaned-out contract workers who had little experience in reprocessing ([Kamata, Saito, 2011](#)).

In addition to the glass vitrification problem, the RRP had problems with high-level waste concentration technology that was imported from UK's BNFL. The liquid concentration technology entails the collection and concentration of waste liquid from various sources into a can, from which the liquid is separated from solids and would be siphoned into the glass vitrification device. On 30 July 2010, the RRP discovered a leak from the can for the first time, followed by two more similar incidents. The RRP investigation found that the bottom of the can had corroded due to buildup of solid waste at the can's bottom ([Mihama no Kai, 2011](#)). The reprocessing plants in France and UK reportedly had similar problems with their glass vitrification facilities ([ICRC, 2005](#)).

These problems of course delayed commissioning of the RRP. The reason these problems emerged stemmed partly from Japan's determination to rely on indigenously-designed technologies for the RRP and partly on management's over-confidence that it could improve upon imported foreign technologies. In 2010, the JNFL finally decided to remodel the glass vitrification unit to better control temperature of the molten glass by using the segment supplied by AREVA. Also, in June 2013, AREVA signed a new strategic agreement with JNFL to bring the RRP into commercial operation, including active testing, the start-up itself, capacity ramp-up and plant optimization. This means that the RRP now is virtually an AREVA plant ([WNN, 2013, 2014b](#)). In October 2013, the RRP completed the vitrification technology development facility, "Rokkasho Vitrification Laboratory (RVL)," and was ready to start-up operation.

However, new regulations from the Nuclear Regulation Authority (NRA) came into effect in December 2013, including a requirement that facilities have a seismic design basis of 600 Gal (up from 375 Gal). This meant that the RRP plant had to withstand earthquakes five times bigger than it was built for (magnitude 9.0 instead of magnitude 8.3) and oceanic earthquakes 1.5 times bigger (magnitude 7.4 instead of 7.2). Under the new regulations, any building would be required to be anchored to bedrock, an existing water storage tank built before the new regulations must be retrofitted with anchors to secure it to the bedrock and a large amount of piping must be upgraded to higher seismic standards ([WNN, 2017a](#)). JNFL filed requests in January 2014 for safety reviews of the RRP. It had hoped to get an operating license by September 2018. But a false report was found in relation to a safety rule violation, which came to light in 2015, leading to a delay in the NRA's screening. As of 22 December 2017, JNFL announced at its extraordinary press conference that to comply with additional regulatory requirements of the NRA, the schedule for the expected completion of the RRP had been changed from the first half of Japan's fiscal year 2018 to the first half of FY 2021 and the completion of the MOX Fuel Fabrication Plant (J-MOX) had been changed from the first half of FY 2019 to the first half of FY 2022 (See Figure 3.8) ([JNFL, 2017e](#)).

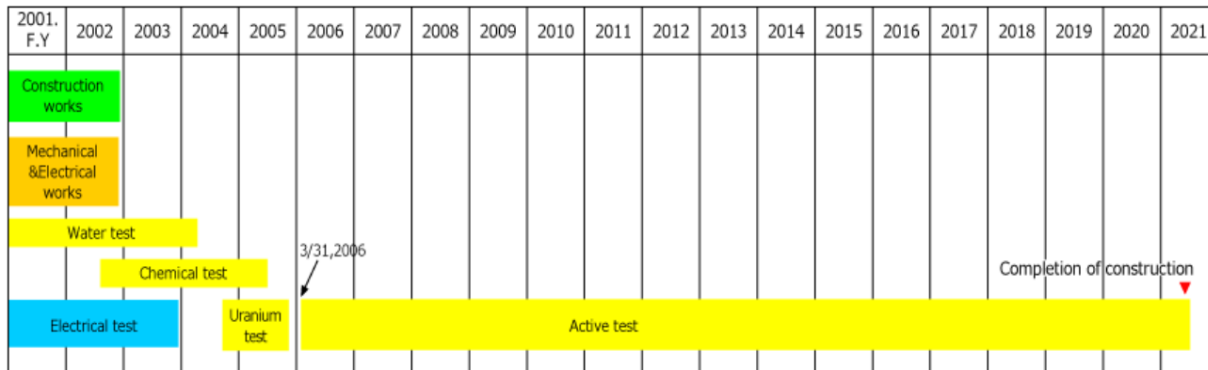


Figure 3.8 History of Rokkasho Reprocessing Plant (RRP) Construction and the Expected Date for Start of Operation *

* The chart shows the construction timeline of RRP as indicated on the RRP website. It implies that plant construction started in FY2001. Actually, RRP construction started on 28 April 1993 and the effort to complete the construction has continued for 26 years. Currently, the RRP has reached the stage of “Final Commissioning Test” to meet new regulatory safety standards and hopes to complete its construction in the first half of FY 2018.

Source: JNFL, 2018b

Japan remains the only non-weapon state that has not abandoned reprocessing. The RRP is large and the operations and maintenance are costly. Data presented by Japan’s AEC in 2012 break down the annual projected costs of reprocessing and associated activities for each year from 2012 through the plant’s eventual decommissioning. Japan’s AEC estimates that the total cost of the Rokkasho reprocessing plant over its life, including capital, operating, and decommissioning costs, along with some allowance for interest during construction, will be \$108 billion for reprocessing 32,000 tons of spent fuel.

Meeting the new safety regulations will certainly add to the cost of reprocessed fuel. Moreover, once the plant starts operation, it will be far costlier to decommission than if the plant had never gone into operation. Plants that have operated will have widespread high-level radioactive contamination. Once started, it will be almost impossible to turn back. Thus, the JNFL could be tempted to not start up the RRP and decommission it before it is used. The decommissioning cost would theoretically be the responsibility of the JNFL and FEPC.

Even if the RRP successfully begins its reprocessing operations, the outlook for business does not look positive. The RRP no longer has Monju FBR as its primary source of plutonium, which had been the major reason for the establishment of the RRP in the first place. Also, the growth in the amount of spent fuel on-hand (spent fuel received, as shown in Figure 3.9) has not increased because so few nuclear power plants are in operation in Japan. Unless this situation changes and the RRP has access to more feed material, it will have little work to do.

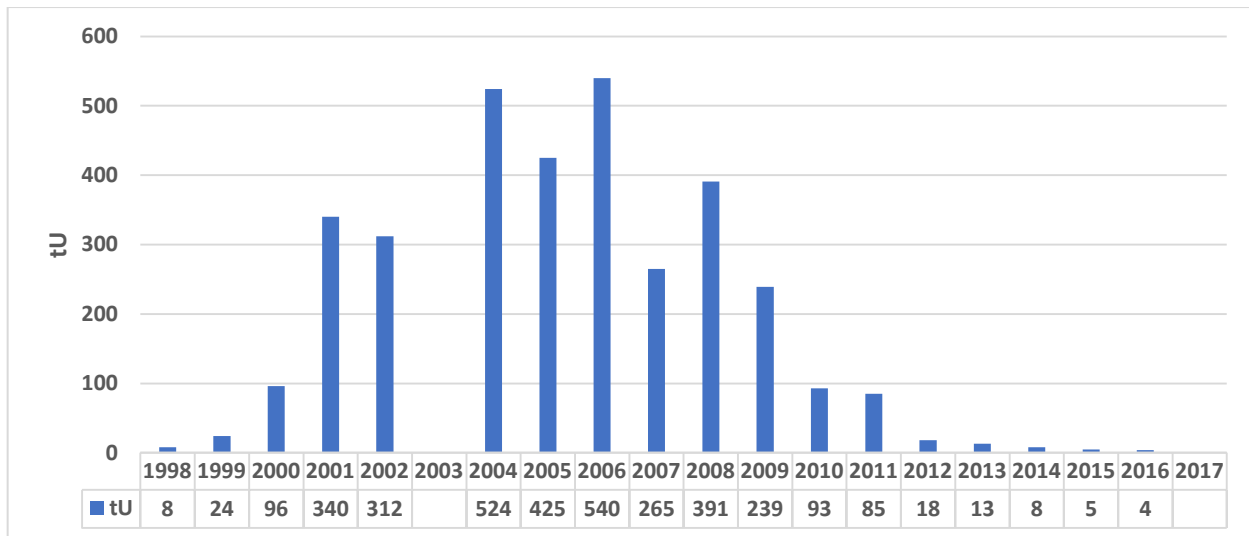


Figure 3.9 Trends in Japan's Spent Fuel Received for Reprocessing; Total = 3,390 tU
Source: JNFL, 2017f.

By comparison, Japan has relatively less spent fuel in its inventory compared to states such as Canada and the United States (See Table 3.9). Given the number of power reactors that have been in operation (prior to the Fukushima disaster), Japan's experience is most comparable to France. At the end of 2007, for example, Japan had 54 reactors operating and about 19,000 tons of spent fuel on hand, whereas France had 58 reactors and about 13,500 tons of spent fuel. The reason France has a relatively small inventory of spent fuel is that it reprocesses its own spent fuel. Canada and the United States do not and therefore they have several times more spent fuel in their inventories—considering the size of their reactor fleets. Their experience with direct disposal of spent fuel, without reprocessing, would indicate that this is a viable strategy for the long term. Japan's government has long resisted the economic arguments that have been made against reprocessing, however.

At this point, Japan still has a choice with respect its nuclear policy: it could continue the present course, depending upon expensive reprocessed fuels and accepting the greater risk that is associated with more complex nuclear technology, or it could shift to reliance on enriched uranium and long-term direct disposal of spent fuel.

Table 3.9 Spent Fuel Management Programs of Selected Countries

Country	Began Commercial Operations	Number Operating Reactors	Spent Fuel Inventory (as of 2007 in Tons Heavy Metal)	Spent Fuel Management Program	Commercial Reprocessing Capacity (Tons Per Year)
Canada	1968	18	38,400	Does not process spent nuclear fuel	
India	1957	22	Not transparent about its fissile material stocks	Reprocesses its own spent nuclear fuel as well as spent fuel from other countries	India (PHWR, 4 plants) 360
Japan	1966	54	19,000	Reprocesses spent nuclear fuel; Historically, Japan has shipped its spent nuclear fuel to France and the UK	Japan (Rokkasho) 800*
Russia	1963	33	17,895	Reprocesses some spent nuclear fuel as well as spent fuel from other countries	Russia, Ozersk (Mayak) 400
France	1964	58	13,500	Reprocesses its own spent nuclear fuel as well as spent fuel from other countries	France, La Hague 1700
South Korea	1978	23	10,900	Does not reprocess spent nuclear fuel	
Germany	1969	9	5,850	Shipped most of its spent nuclear fuel to France and United Kingdom for reprocessing, until 2005	
United Kingdom	1956	18	5,850	Reprocesses its own spent nuclear fuel as well as spent fuel from other countries	UK, Sellafield (THORP) 600 UK, Sellafield (Magnox) 1500
Sweden	1972	10	5,400	Does not reprocess spent nuclear fuel	
Finland	1972	4	1,600	Does not reprocess spent nuclear fuel	
United States	1977	100	70,000	Does not reprocess spent nuclear fuel	

* Now expected to start operation in the first half of FY 2021.

Source: Table is based on authors' interpretation and analysis of data from the United States General Accounting Office, 2012; the European Nuclear Society, no date; Business Standard, 2011; Nuclear Power Corporation of India, 2015; Albright and Kelleher-Vergantini, 2015); Nuclear Energy Institute (NEI), 2017).

3.2.2 Rokkasho MOX Fuel Fabrication Plant (J-MOX)

For more than two decades (1969-1990) Japan had shipped spent nuclear fuel to Europe for reprocessing, which was returned to Japan in the form of mixed oxide fuel assemblies for use in power and research reactors, as well as high level radioactive waste. More than 160 shipments occurred during this period, returning more than 7,000 tons. In the late 1990s, Japan's utility companies decided to link MOX fuel fabrication contracts with reprocessing contracts. Since then, nearly 200 MOX fuel assemblies, including more than 5000 kg of plutonium, have been returned to Japan (See Table 3.10). Japan obtained the fuel assemblies from France's AREVA's Melox, the UK's BNFL and Belgium's Belgonucleaire (BN) (WNA, 2017e).

Table 3.10 MOX Shipments to Japan

MOX Shipments to Japan			
Year of Shipment	Number of MOX fuel assemblies	Net kg of Plutonium	Designated Recipient Reactors
1999	30	210	TEPCO Fukushima 1-3, Kashiwazaki-Kariwa 3, and Kansai Electric Takahama 4
2001	30	205	
2009	68	1721	Shikoku Electric Ikata 3, Chubu Electric Hamaoka, Kyushu Electric Genkai 3
2010	32	1353	Kansai Electric Takahama 4, Kyushu Electric Genkai 3
2013	20	901	Kansai Electric Takahama 3
2017	16	700	Kansai Electric Takahama 4
Totals	196	5090	

Source: WNA, 2017e.

Japan's nuclear industry saw the prospect of further shipments for reprocessing and MOX fuel fabrication as a business opportunity. JNFL declared its intention to start its own MOX fuel fabrication business and approached Aomori Prefecture and Rokkasho village in August 2000 for permission to locate a fabrication facility in their region. In 2010 JNFL received a license for MOX fabrication and started construction of the facility in the same year.

The business case seemed straight forward enough: Japan's electric power companies had announced in September 2010 a plan to run 16-18 reactors with MOX fuel by 2015 (JNFL, 2017g). The Rokkasho MOX Fuel Fabrication Plant was sized to satisfy a substantial part of the expected demand for MOX, with a planned maximum production capacity of 130 t-HM/year.³² JNFL estimated construction cost would be about \$2.1 billion. The MOX plant and the Rokkasho Reprocessing Plant (RRP) would store spent fuel from nuclear power plants before separating it into uranium and plutonium that would be fabricated into new MOX fuel assemblies. Unfortunately, a series of problems emerged which has called into question the viability of MOX fuel (Yoneda, no date; WNN, 2017b).

To begin with, construction for the MOX plant in Rokkasho—nicknamed J-MOX—has been slow. JNFL had planned to start construction of the J-MOX in 2007 but was delayed by the need to meet

³² HM is heavy metal.

new seismic requirements following the powerful Niigata-Chuetsu-Oki earthquake of 2007. Also, the March 2011 accident at Fukushima Daiichi led to new safety standards for power plants that also applied to the fuel fabrication plants, reprocessing facilities, radioactive waste storage and disposal facilities, research reactors and nuclear fuel research centers. In November 2015, JNFL announced completion of the Rokkasho reprocessing plant but noted that the J-MOX plant had been postponed by two years. At the end of December 2017, JNFL again announced that completion of the MOX plant had been pushed back to the first-half of FY2022 (WNN, 2017b; Rokkasho, 2012; JNFL, 2018b).

Japan expected that once MOX fuel was in routine use in Japan, its stockpile of separated plutonium in Europe would be used up in about 15 years. Demand was projected at about 5-6 tons per year of fissile plutonium, with the output from Rokkasho covering about 4 tons of that demand (WNA, 2017f). The suspension of reactor operations following the Fukushima disaster, however, drove down demand for fissile plutonium dramatically. In fact, Japan's plutonium stocks have been increasing, with separated reactor-grade plutonium stored and awaiting use as MOX fuel. At the end of 2015, as mentioned earlier, Japan owned a total of 47.9 tons of unirradiated plutonium, including 10.8 tons in Japan, 16.2 tons in France and 20.9 tons in the UK (See Figure 3.10). At the end of 2016, total plutonium in Japan was reduced to 9.8 tons, due to fuel loading at Takahama reactors 3 and 4 and the return of plutonium to the US (WNA, 2017g).

- About 40 percent of plutonium in Japan is held at JAEA's RRP and another 37 percent is held at JNFL's fabrication facilities. Most of the remainder is in the form of new fuel stored at commercial power plants (See Figure 3.11)
- On 18 March 2016, Japan shipped back to the US about 300 kg of plutonium on armed British transport vessels. The plutonium was originally bought from the US in the 1960s for civilian research purposes. In 2014, President Obama and Prime Minister Abe agreed that Japan would return the plutonium (AEC, 2017).

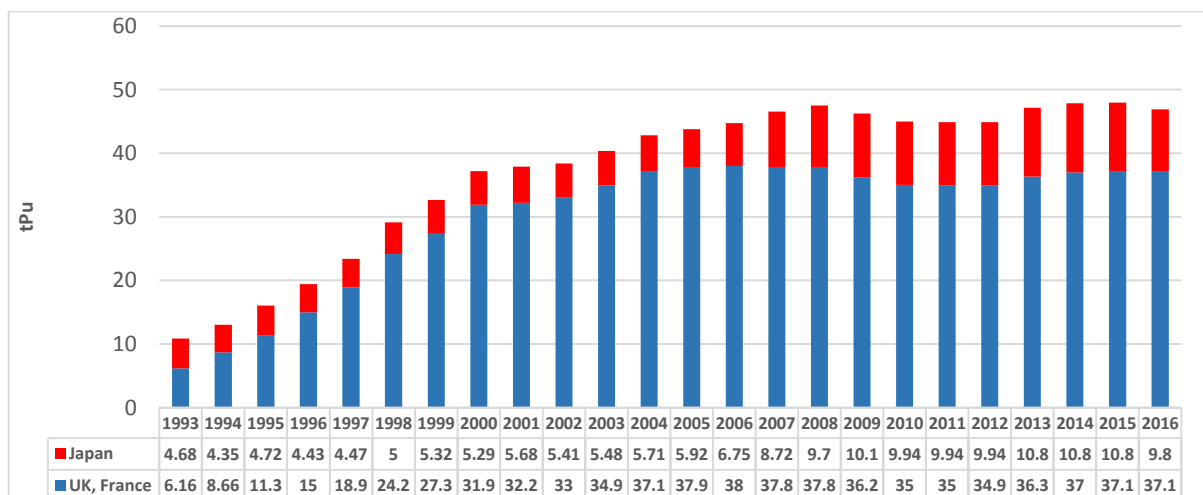


Figure 3.10 Status of Japan's Plutonium Stockpile, as of end 2016

(Some plutonium is kept in the UK and France).

Source: AEC, 2013-2017; Kakujoho, 2017.

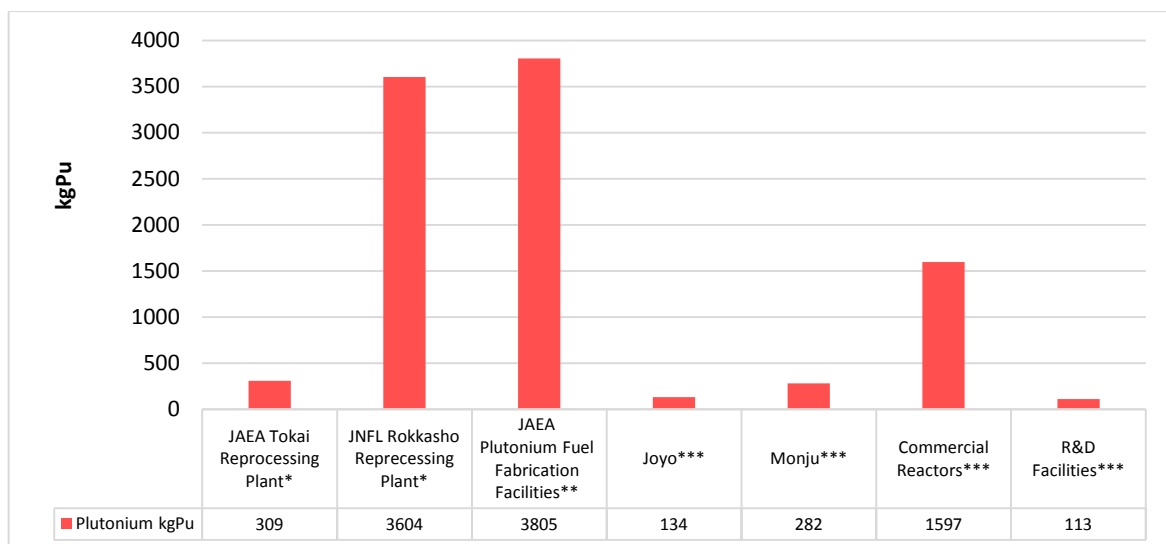


Figure 3.11 Locations of Plutonium Stockpiles in Japan, as of end 2016

Notes: *Plutonium nitrate (dissolved into nitric acid for reprocessing or kept as mixed oxide);

**Plutonium oxide (held in plutonium oxide containers), plutonium in the stage of testing or

fabrication, or new fuel (held as finished fuel assemblies); ***Unirradiated new fuel held at nuclear reactor sites Source: Cabinet Office of Japan, 2017.

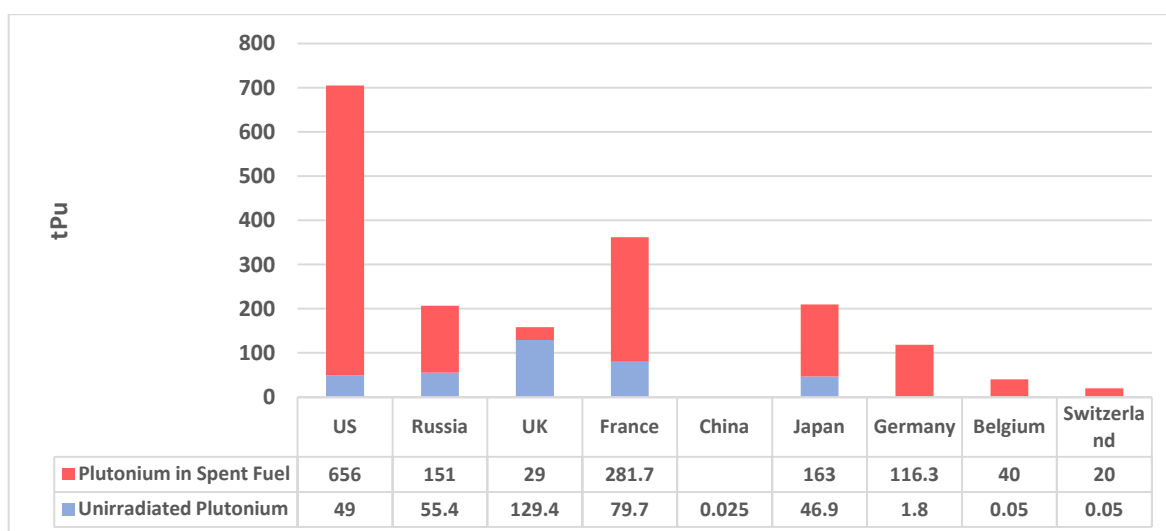


Figure 3.12 Amount of Plutonium Held by Various Countries

Notes: Numbers are rounded to 100 kg; China does not announce the amount of unirradiated plutonium; the Japanese number includes the plutonium held domestically as well as overseas.

Source: Authors created based on AEC, 2017.

While the Japanese government, the AEC and the utilities continue to strongly support MOX fuel fabrication, the business case for fabrication in Japan has fallen apart. First, MOX fuel is costly. As discussed earlier, the AEC stated in its 2011 estimate that MOX fuel made with plutonium separated at the Rokkasho Reprocessing Plant will cost Japan twelve times as much to produce

compared to an equivalent amount of low-enriched uranium fuel, including the cost of reprocessing (IPFM, 2015).

At present Japan has about 12 percent of worldwide plutonium that is locked up in spent fuel, which could be reprocessed. Only the United States and France have more (See Figure 3.12). However, the output of reprocessing plants exceeds the global rate of plutonium usage for MOX. Once Japan's MOX plant comes on line, the glut of MOX fabrication capacity will become that much worse, driving down the price of MOX fuel below actual production costs (See Table 3.11) (WNA, 2017h).

Table 3.11 Commercial MOX Fuel Fabrication Facilities in Japan and Abroad

Abbreviations in Table					
BNFL: British Nuclear Fuels Ltd			MCC: Mining & Chemical Combine (MCC)		
ERC: Experimental Research Complex (Dimitrovgrad)			MDF: MOX Demonstration Facility		
FBFC: Franco-Belgian Fuel Fabrication			MFFF: MOX Fuel Fabrication Facility		
JAEA: Japan Atomic Energy Agency			NDA: Nuclear Decommissioning Authority		
JNFL: Japan Nuclear Fuel Limited			SMP: Sellafield MOX Plant		
Country	Owner	Location	Plant	Capacity (tHM/year)	Period of Operation
France	AREVA	Cadarache	Cadarache	40	1962-2005*
		Marcoule	Melox	195	1995
Belgium	Belgonucleaire	Dessel	FBFC International	40	1973*
UK	NDA BNFL	Sellafield	MDF	8	1993*
	BNFL		SMP	40	December 2001*
US	SAMS LLC	Savannah River	MFFF	70	Cancelled
Japan	JAEA	Tokai-mura	The 2 nd Laboratory	8.8	1972*
			The 3 rd Laboratory	4.4	1988*
	JNFL	Rokkasho	Rokkasho MOX Fuel Fabrication Plant (J-MOX)	130	The first half of FY 2022
Russia	MCC	Zheleznogorsk	MFFF	60	September 2015
TOTAL			2 plants operating	255	

*No longer operating or in suspension

Source: The authors created the table based on IPFM, 2017; WNA, 2017h; RIST, 2011.

In terms of risk, plutonium would need to be separated from spent fuel, stored and transported to a plant for MOX production. During the process, it could be hijacked or diverted to weapon production. Furthermore, if an accident were to happen, the consequences of contamination would be substantial. Plutonium-239 has a half-life of 24,000 years, which would make clean-up and disposal difficult; spent MOX fuel would need to be cooled in the pool virtually semi-permanently (Yoshioka, 2013).

- Japan has not thought through what to do with Japan's spent MOX fuel. AEC's 2005 "Framework" stated that the "study on the measures to be taken for spent fuel stored at interim storage facilities and spent MOX fuel from light water reactors (LWRs) will start around 2010" (Katsuta, Takubo, 2011).

Some MOX fuel fabricators have experienced business failures. In 1997, Sellafield British Nuclear Fuels Limited (BNFL) completed construction of its MOX Plant (SMP) but did not commence operation until 2001. The plant produced its first MOX fuel assembly suitable for export in 2005 but was then scaled down to 40 t/yr from its 120 t/yr-design capacity. In August 2009, it was reported that the SMP had produced only 8 tons of fuel (24 assemblies) in eight years, after costing £637 million to build and £626 million to operate. However, technical and commercial endeavors continued and, in May 2010, the UK's Nuclear Decommissioning Authority (NDA) announced that agreement had been reached with Japan's utilities on "an overall framework for future fabrication of MOX fuel in SMP (WNA, 2016).

- In light of the uneconomical nature of the business, BNFL was restructured and divested. In the process, the NDA took over 49% of BNFL's Spent Fuel Services in 2006 and renamed it the International Nuclear Services (INS) in 2007. In April 2008, the NDA acquired the remaining 51% of INS. INS has been responsible for fulfilling the spent fuel reprocessing and MOX fuel fabrication contracts for Japan. Transportation of the materials associated with these contracts is carried out by its Pacific Nuclear Transport Limited (PNTL) a subsidiary that is owned by INS (62.5%), Areva subsidiary TN International (12.5%) and the Overseas Reprocessing Committee (25%), an organization that belongs to the FEPC (WNA, 2016).

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Chapter 4:

**The Build-Out of
Japan's Nuclear Power Plants**

CHAPTER 4: The Build-Out of Japan's Nuclear Power Plants

Abstract

Japan initially relied on American technology to build its reactors but by the end of the 1970s, Japanese companies had largely mastered nuclear power plant technologies and could proceed on their own. In 1973, Japan was hit by sudden and severe oil shortages. Fearful of continuing to rely on foreign states for energy supplies, government leaders resolved to step up nuclear power generation. Japan enacted the Dengen Sampo (the Three Power Source Laws) in June 1974, which relied on energy taxes to pay for subsidies to local governments, encouraging them to agree to host nuclear power plants. The plan was effective, but it also created local dependence on continuing subsidies indefinitely and incentivized plant construction strategies that effected reactor safety.

4.0 The Worldwide Power Reactor Boom

Despite Japan's relentless support for advanced nuclear reactor and fuel reprocessing technologies, the heart of its nuclear industry—its bread and butter product—were commercial light water reactors (LWRs) to produce electric power. With the success of the Shippingport nuclear power plant, the US became the clear leader in LWR design. Westinghouse, in cooperation with the Division of Naval Reactors of the US Atomic Energy Commission, had designed the Shippingport reactor as a pressurized water reactor (PWR). PWRs were thought to have safety advantages over boiling water reactors (BWRs), but over time those advantages became less significant. Nevertheless, Westinghouse got a head-start with its reactor design and eventually PWRs became the most popular type of reactor worldwide.

The first commercial boiling water reactor (BWR) was the Dresden Nuclear Plant (180 MW) in Illinois. It was developed by the Argonne National Laboratory and designed by General Electric (GE). The reactor started operations in June 1960 and based on this accomplishment, GE won a bid to build the Oyster Creek Nuclear Plant (650 MW). Oyster Creek was publicized as being economically competitive with a coal power plant. To make the technology more attractive, GE marketed its BWR by promising a fixed price and strict observance to a delivery date. The offer proved irresistible and soon GE (and Westinghouse) had created a worldwide boom in nuclear reactors ([WNA, 2018a](#); [Research Institute of Industrial Science & Technology \(RIST\), 1998](#)).

- By the end of the 1960s, orders were being placed for PWR and BWR reactor units that could deliver power outputs of 1,000 MWe or more. Around the world, many countries selected light-water designs for their nuclear power programs. Today 60 percent of the world's nuclear capacity is in PWRs and 21 percent is in BWRs ([WNA, 2018a](#)).

4.1 Japan Chooses Light Water Reactors (LWRs) for Power Generation

In the early 1960s, Japan decided to experiment with different reactor designs before deciding which reactor type would be the best for Japan. JAERI, one of the STA R&D institutions, sponsored construction of Japan's first nuclear reactor in 1963, which was a 12.5 MWe boiling water reactor designed by GE. Named the Japan Power Demonstration Reactor (JPDR), it was commissioned on 26 October 1963—the day was named “Nuclear Power Day” to commemorate

the event. The JPDR was a major success and helped prepare Japan for the introduction of commercial nuclear reactors, according to JAERI researchers ([Tanaka, et al., 1999](#)).

- Over its lifetime the JPDR operated for a total of 17,000 hours and produced about 140 GWh of electricity. It shut down in 1976 due to problems with cracks in monitor tubes and failure of a control rod drive mechanism ([Tanaka, et al., 1997](#)).

Following the JPDR, Japan's utility companies established the Japan Atomic Power Company (JAPC) to build two commercial nuclear reactors. The first was a 12 MW graphite-moderated, gas-cooled reactor designed by GE in the UK, which was called Magnox. The Magnox reactor was originally designed and built for the dual purpose of producing electrical power and plutonium 239 for the nuclear weapons program in Britain. The Japanese version of the reactor, called Tokai, began operations in July 1966 and was shut down in March 1998. The design suffered from modest generation capacity and low efficiency and so the utility companies judged it to be less than satisfactory ([Japan Atomic Power Company \(JAPC\), 2018](#)).

JAPC's second reactor was Tsuruga 1, a 357 MW BWR, designed by GE. Commissioned in 1969, the reactor was much liked and became Japan's most popular nuclear reactor type. Of the total of 54 nuclear reactors that were in operation in Japan on 11 March 2011 (the date of the Fukushima Daiichi Nuclear disaster), 30 were BWR types and 24 were PWRs ([JAPC, 2018](#); [Japan Atomic Industrial Forum \(JAIF\), 2014](#)).

While Tsuruga 1 was a great success, it also suffered from haphazard safety practices and maintenance problems. For example,

- On 24 October 1997, Tsuruga 1 had a malfunction of a control rod and the operation of the reactor was manually halted. The operators claimed that the failure of the control rod was due to a manufacturing error. The incident was rated an INES level 1 ([Shippai Gakkai, 1997](#)).
- On 21 July 2010, JAPC announced that it had never conducted inspections of the welded sections of reactor parts, such as the reactor circulation pumps and drainage valves from the reactor pressure vessel ([JAPC, 2010](#)).
- On 24 January 2011, METI's NISA discovered that Tsuruga 1 had operated for about one month while one of the reactor's multiple emergency cooling systems was malfunctioning. NISA reprimanded JAPC for the safety violation. ([Titibu, 2015](#)).

Tsuruga 1 was scheduled to be decommissioned in December 2009 at the end of its 40-year design life but was granted permission in August 2009 to operate until 2016. While it was undergoing renovation and upgrading, the Fukushima nuclear disaster happened, which led to the establishment of more stringent safety regulations. Under the new regulations, JAPC could apply to extend the life of Tsuruga 1 to 60 years, but the owners decided to decommission it instead.

After the operation of three different reactors (JPDR, Tokai and Tsuruga 1) by the semi-governmental R&D institution JAERI and the industry consortium JAPC, the Japanese utilities decided to begin the rapid expansion of nuclear power reactor fleet. KEPCO started first. It selected the PWR designed by Westinghouse for its Mihama power plant (See Table 4.1). Westinghouse had a long-standing licensing agreement with MHI and MHI had already received power

generation and nuclear power technologies from Westinghouse, including the design and manufacture of combustion turbines and nuclear steam supply systems (MHI, 2012). Thus, MHI served as a lead subcontractor for Westinghouse on the nuclear reactor project, called Mihama 1. MHI's learning curve was steep; according to Yoshioka (2013), the domestic content of the Mihama plant was initially about 62 percent and eventually increased to 99 percent after MHI became the prime contractor under a licensing agreement.

Table 4.1 Summary of the Mihama Nuclear Plant

Reactor Unit	Type	Year Commissioned	Generation Capacity (MW)	Prime Contractor		Construction Cost (\$ Million)	Domestic Content (%)
Mihama 1	PWR	1970	340	WH	MHI	312	62
2	PWR	1972	500	MHI		363	
3	PWR	1976	826	Mitsubishi Corporation		786	99

Source: Wikipedia, 2018a.

Just months after KEPCO started construction of Mihama, TEPCO launched its own nuclear power plant project, which was ironically the Fukushima Daiichi Nuclear Plant. TEPCO chose BWRs for the plant and contracted with GE for all the major components of the first reactor (See Table 4.2). Toshiba and Hitachi served as subcontractors to GE for the project. Construction of Unit 1 started in 1967 and it was successfully commissioned in 1971.

- TEPCO continued to build five more reactors at the Fukushima Daiichi Plant during the 1970s. According to the company's Fukushima Daiichi construction records, Toshiba and Hitachi had licensed the technology from GE, learned the tradecraft fast and served as contractors for all three major components of the first reactor Unit 1, including the reactor vessel, the turbine generator and the auxiliary equipment. As a result, the domestic content of the plant rapidly increased with each project. The domestic content of Fukushima Daiichi Unit 1 was initially about 56 percent and eventually became more than 99 percent (Yoshioka, 2013).
- The Fukushima Daiichi Nuclear Power Plant undoubtedly was a major milestone in Japan's nuclear history. The plant became a 6-reactor plant with a combined power generation capacity of 4.7 GW, one of the 15 largest nuclear reactor complexes in the world (Wikipedia, 2018b, 2018c). TEPCO was planning to construct Reactor 7 and 8 at the Fukushima Daiichi but cancelled the plan in May 2011 (Tokyo Electric Power Company (TEPCO), 2011).
- Fukushima Daiichi Unit 6 was a BWR with a different type of containment vessel and larger generation capacity. In this case, GE took the lead in building the reactor and turbine generator while Toshiba worked on the auxiliary equipment. Relying on foreign companies as the prime contractor was more the exception than the rule, however. (Yoshioka, 2013)

By the end of the 1970s, the Japanese companies, Toshiba, Hitachi and MHI, had largely mastered all nuclear power plant component technologies. Today, they export to other east Asian countries under licensing agreements and are involved in the development of new reactor designs on a global basis. After the early plant construction projects by KEPCO and TEPCO, all the other Japanese electric utilities started to launch their own nuclear power plants. These fell into two groups in terms of the reactor type and the contractors. METI probably influenced this de facto division of labor to have a competitive, healthy industrial base for nuclear technologies (See Table 4.3) (WNA, 2018b).

Table 4.2 Summary of the Fukushima Daiichi Nuclear Plant

Reactor Unit Number	Type	Year of Commissioning	Capacity (MW)	Prime Contractor			Construction Cost \$ Million *	Domestic Content (%)
				Reactor	Turbine Generator	Auxiliary Equipment		
Fukushima Daiichi 1	BWR	1971	460	GE	GE	GE	390	56
2	BWR	1974	784	GE	GE	Toshiba	560	**
3	BWR	1976	784	Toshiba	Toshiba	Toshiba	620	**
4	BWR	1978	784	Hitachi	Hitachi	Hitachi	800	**
5	BWR	1978	784	Toshiba	Toshiba	Toshiba	900	99
6	BWR	1979	1,100	GE	GE	Toshiba	1750	**

* The original document shows the construction cost in Japanese yen. It is converted to US dollar at an exchange rate of 100 yen to a dollar. ** Unspecified.

Source: Denryoku Shimpō, 1979; Wikipedia, 2016

Table 4.3 Two Japanese Nuclear Industry Groups

Type of Reactor	Boiling Water Reactor (BWR)	Pressurized Water Reactor (PWR)
Industry Group	The Tokyo Electric Power Company (TEPCO)- Toshiba/Hitachi-General Electric (GE) Group	The Kansai Electric Power Company (KEPCO)-MHI-Westinghouse (WH) Group
Electric Power Companies	Tohoku Electric Power Company Chubu Electric Power Company Hokuriku Electric Power Company Chugoku Electric Power Company	Hokkaido Electric Power Company Shikoku Electric Power Company Kyushu Electric Power Company

Table was created by the authors.

4.2 Coping with the Global Oil Crisis and Marketing Expansion of Nuclear Power

In 1973, Japan suddenly was hit with severe oil shortages, high oil prices and the loss of much of the power that was generated by oil-based thermal power plants. Fearful of continuing to rely on other states for vital energy supplies, government leaders resolved to step up nuclear power generation. Since the mid-1960s, however, the anti-nuclear movement had gained strength and every proposed nuclear power plant encountered major demonstrations and protests. To accelerate nuclear plant construction in the face of the anti-nuclear protests, Japan enacted the Dengen Sampo (the Three Power Source Laws) in June 1974 (Law No. 80) ([Houko, 2018](#)).

METI had the administrative jurisdiction over the electric power industry and was largely responsible for the legislation. The Dengen Sampo consisted of three laws:

- The Regional Maintenance Surrounding Power Source Facilities Law,
- The Power Source Development Acceleration Tax Law (the PSDAT Law)
- The Power Source Development Acceleration Special Account Law (the PSDA Special Account Law)

All three of these laws were aimed at increasing nuclear power quickly. The PSDAT Law allowed the government to collect a tax from the electric power utilities for subsidizing various initiatives that would accelerate construction of nuclear power. The tax was based on the amount of electricity the utilities sold (the tax was initially set at 0.85¢ per 1,000 kWh). The utilities, in turn, collected the tax from their ratepayers. Tax revenues were deposited in the PSDA Account (PSDAA) within the government's Energy Measures Special Account (EMSA). The EMSA served as an umbrella accounting mechanism for taxes collected from various energy sources and for disbursing them through government ministries (See Table 4.4). Typically, a nuclear power plant received twice as much in subsidies compared to a thermal or a hydropower plant ([Yoshioka, 2013](#)).

Table 4.4 Three Major Energy Special Accounts Supported by the Oil and Coal Tax and the Power Source Development Acceleration Tax (PSDAT) (FY 2016 Preliminary Budget)³³

Millions of \$	Revenue Sources for Japan's General Account					
	Oil and Coal Tax \$6,880		Power Source Development Acceleration Tax (PSDAT) \$3,200			Government bonds purchased by private sector
(Subtractions) and Additions to General Account	(\$913) held in reserve ↓ \$5,967 plus \$2,095 surplus from earlier years ↓ \$8,062		(\$287) held in reserve ↓ \$2,913 plus \$230 for local preparation plus \$313 surplus from earlier years ↓ \$3,456			(\$132) Nuclear Accident Damage Compensation Support Fund plus \$3 in surplus ↓ \$135
	Funds Transferred to Energy Measures Special Account (EMSA)					
Special Account Name	\$8,062 Energy Supply and Demand Account (ESDA)		\$3,456 Power Source Development Acceleration Account (PSDAA)			\$135 Nuclear Accident Damage Compensation Support Account (NADCSA)*
Stated Purpose, Measure	Fuel Stable Supply	Energy Supply and Demand Structure Improvement	Power Source Location Measure (PSLM)	Power Source Utilization Measure (PSUM)	Nuclear Safety Regulation Measure**	Nuclear Accident Damage Compensation Support
Recipient Ministry for Funds	\$2,821 to METI	\$3,677 to METI \$1,564 to Ministry of Environment (MOE)	\$1,593 to METI \$148 to MEXT	\$159 to METI \$948 to MEXT \$11 to MOE	\$456 to MOE	\$135 to METI

* Japan created the Nuclear Accident Damage Compensation Support Account (NADCSA) in 2012 after the Fukushima nuclear disaster. This account pays interest on cumulative debt undertaken by the government to pay for damage compensation from the accident.

** Japan created the Nuclear Safety Regulation Measure in 2012 after the Fukushima disaster.

Source: Ministry of Finance (MOF), no date. Translated by the authors.

In 1974, Japan started providing subsidies to municipal governments under the Power Source Location Measure (PSLM), drawing funds from the PSDAA for building nuclear reactors in their region. The initial subsidy measures and budget were modest but increased rapidly as

³³ Japan's fiscal year (FY) starts in 1 April of the year and ends in March of the following year. The preliminary budget reflects initial plans for expenditures. In the final budget for FY 2016, PSDAA expenditures were \$3,682 million and PSLM expenditures were \$1,566 million, about 42 percent of the total PSDAA budget.

many new subsidy measures were established under the PSLM. Initially, there were three subsidy measures: the Power Source Location Acceleration Measure Subsidy, the Warm Waste Water Effect Survey Subsidy and the Public Relation Measure Subsidy. The budget in the first year was \$14 million. In 1975, the Radiation Surveillance Subsidy was added under the PSLM. In 1980, three more measures were added: the Power Source Location Region Warm Waste Water Measure Subsidy, the Power Source Location Region Warm Water Wide Area Measure Subsidy and the Nuclear Energy Generation Facility Emergency Safety Measure Subsidy ([Athome, 2008](#)).

In 1982, five more subsidy measures were added under the PSLM: the Nuclear Power Generation Facility Surrounding Region Subsidy, the Electric Exporting Prefecture Subsidy, the Nuclear Energy Public Relations Training Facility Maintenance Subsidy, the Maintenance Plan-Making Subsidy and the Subsidy Management Subsidy. By 2003, there were 28 different subsidy measures under the PSLM. ([Athome, 2008](#)).

The PSDAA initially provided funds only to the PSLM and all of its many attendant subsidy measures, but in 1980 a second separate measure was added under the PSDAA—the Power Source Diversification Measure (PSDM). The new measure aimed to promote R&D on advanced nuclear technology, including uranium enrichment, FBRs, advanced thermal reactors and reprocessing, as well as alternative new energy. This measure came with new subsidy recipients, including STA's R&D institutions, such as the PNC and JAERI, as well as private-sector corporations that assisted STA on advanced nuclear R&D. As a result of the expansion in subsidy measures, within just three years the PSDAT tax rate increased more than five-fold to \$4.45 per 1,000 kWh. Tax revenue was largely managed by two agencies, STA (that managed the R&D of nuclear technology and new energy technology) and METI (that promoted the acceleration of nuclear plant construction).

In 1991 when Japan's asset price bubble burst and the two decade-long recession began, reactor construction dramatically slowed in Japan. There were many cancellations and withdrawals of planned reactors, likely owing to the reduced need for power and stronger anti-nuclear protests. By October 2003, METI revised the Dengen Sampo subsidy system to the one that exists today. The revision included consolidating various subsidies and renaming the PSDM to the Power Source Utilization Measure (PSUM), as some of the advanced nuclear technologies, such as reprocessing and enrichment, were approaching the commercialization stage and warranted removal from the subsidy list. The new PSUM also discontinued some energy R&D projects, such as solar, geothermal, coal and natural gas and retained funding only for nuclear and hydropower R&D.

Subsidies under the PSLM were consolidated into one measure—the Power Source Location Region Measure Subsidies (PSLRM)—with five sub-measures (See Figure 4.1). Three of the five were for municipal governments and two were for prefectural governments. The subsidies for prefectures include the Subsidy for Exporting Nuclear Power to the Neighboring Prefectures and the Nuclear Power Generation Facilities Location Region Long-Term Development Measure subsidies.

One new measure was added in 2004 that was separately funded directly via the PSLM—the Nuclear Power Generation Facility Location Region Co-Existence subsidy. The new subsidy was provided to prefectural governments for five years if the reactor in the prefecture was older than 30 years (Yamaguchi, 2016; METI, 2010; METI, 2016).

In addition to receiving these subsidies, the prefecture and municipal governments that hosted a nuclear plant had the privilege of levying taxes on nuclear plant owners. This included property tax, nuclear fuel tax, spent fuel storage tax and a municipal tax (METI, 2010).

At the same time, the PSLRM subsidies could be spent more flexibly. Earlier, the subsidies were designated to be spent for specific purposes only, such as construction of public facilities (schools, city halls, libraries, gymnasium, sport centers and culture centers, etc.), but were not allowed to be spent on the maintenance or management of the facilities. The new PSLRM subsidies can be spent on any activities that apply to any of the five sub-measures. (Japan Board of Audit (Jbaudit), 2004).

The consolidation and revision of subsidies allowed for reduction in taxes for funding the PSDAA. The tax was initially lowered to \$4.25 per 1,000 kWh in 2003 and reduced again to \$3.75 in 2007 (See Table 4.5). The tax rate today is four times more than the initial tax rate that was established in 1974. Over time, the taxes have added up. Since the Dengen Sampo Laws were enacted, approximately \$110 billion has been collected from the ratepayers to pay for the various measures to accelerate reactor construction and subsidize regional governments (See Figure 4.1 for Dengen Sampo subsidy rates).

Table 4.5 Changes in Tax Rate in the Power Source Development Acceleration Tax (\$ per 1,000 kWh)

1974~	1980~	1 April 1983~30 September 2003	1 October 2003~	1 April 2005~	1 April 2007
0.85	3.00	4.45	4.25	4.00	3.75

Source: Yoshioka, 2013; METI, no date.

After the Fukushima nuclear disaster on 11 March 2011, Japan added a third measure under the Power Source Development Acceleration Account (PSDAA)—the Nuclear Safety Regulation Measure (See Table 4.4). The new measure was to fund the new regulatory institutions, such as the Japan Nuclear Energy Safety Organization (JNES). The tax rate, however, remained the same (METI, 2002). Also, in 2012, Japan established a third major account under the EMSA—the Nuclear Accident Damage Compensation Support Account (NADCSA). The establishment of the NADCSA was not accompanied by a tax rate hike; Japan planned to finance the budget by issuing 322s, in effect, getting loans from the private financial sector (See Chapter 5 discussion on damage compensation) (METI, 2010; METI, 2016; MOF, 2014).

Measures and Sub-Measures Under the Power Source Location Development Acceleration Account FY2016		Recipients of Subsidy	Year of Implementation	Duration of Subsidy (years)	Total Amount of Subsidies (\$ millions)
Power Source Location Regional Measure Subsidies (PSLRM)			1974	54	1,340
A 	Power Source Location Early Measure Subsidies	Municipal Governments	2001	12	56
B 	Power Source Location Acceleration Measure Subsidies		1974	5	170
C 	Nuclear Power Generation Facilities Surrounding Region Subsidies		1981	29	657
D 	Electricity Exporting Prefecture Subsidies	Prefectural Government	1981	48	273
E 	Nuclear Power Generation Facilities Region Long-Term Development Measures Subsidies		1997	40	184
F 	Nuclear Generation Facility Location Region Co-Existence Subsidy	Prefectural Government	2004	5	25
Total				54	1,365

Figure 4.1 FY 2016 Subsidy Structure for a Typical 1350 MW Nuclear Reactor Plant

Notes: Subsidies are under the Power Source Location Measures (PSLM) and the Power Source Development Acceleration Account (FY 2016). Figures 4.1 and 4.2 should be read together. Figure 4.1 provides a legend (color codes) that identifies the category of subsidy that is shown over a 54 year time period in Figure 4.2.

Source: Figure is based on authors' interpretation and analysis of METI, 2016; Satumasendai City, no date.

Subsidies under the PSLM have grown over time, though the payment period has been stretched out. For example, in 2016, PSLM subsidies for a typical 1,350 MW nuclear power reactor amounted to \$1,365 million, which were distributed to the prefecture and its municipal governments over 54 years (See Figures 4.1 and 4.2). This was a 10 percent increase over subsidies for an equivalent nuclear reactor under the PSLM in 2010. The total subsidy for a typical 1,350 MW nuclear reactor then was \$1,240 million, which was paid out to the prefecture and its municipal governments over 45 years. (MOF, 2018a).

As mentioned earlier, the government manages all energy taxes and subsidies (as well as the power source development acceleration tax—the nuclear power promotion tax) through the EMSA umbrella account. This practice is enabled by the Administrative Reform Promotion Law legislated on 2 June 2006 and enacted in 2007. Under the law, the government receives all taxes on oil, oil products, liquefied petroleum gas (LPG) and coal, appropriates a proper amount and distributes it through EMSA to the Energy Supply and Demand Account. The funds flow into two separate funds (or measures), referred to as the Fuel Stable Supply Measure and the Energy Supply and Demand Structure Improvement Measure.

Back in July 2003, Japan broadened the Oil Tax Law (Law No. 25, 1978) to cover both oil and coal. The government soon began taxing coal (See Table 4.6). At the same time, Japan increased taxes on oil, oil products and LNG. The Oil and Coal Tax Law was revised again in 2012 to add a “Special Tax to Counter Global Warming.” The tax rate is based on the amount of CO₂ that each of these fuels would generate. Not surprisingly, tax revenue from fossil fuel sources has grown rapidly and surpassed the Power Source Development Acceleration Tax (PSDAT) in 2005.

Table 4.6 Tax Rate Hikes on Crude Oil · Petroleum Products, LNG·LPG and Coal

	Crude Oil · Petroleum Products	LNG · LPG	Coal
1 October 2012~	\$2.50/kl	\$2.60/t	\$2.20/t
1 April 2014~	\$5.00/kl	\$5.20/t	\$4.40/t
1 April 2016~	\$7.60/kl	\$7.80/t	\$6.70/t
Current	\$20.40/kl	\$10.80/t	\$7.00/t

Source: METI, 2018.

By 2017, tax revenues had more than doubled (See Figure 4.3). The structure of the EMSA provided the government with a great deal of flexibility in how to allocate surplus funds from the Energy Supply Demand Account (ESDA) to other accounts under EMSA, such as the Power Source Development Acceleration Account (PSDAA) and the Nuclear Accident Damage Compensation Support Account (NADCSA). In the FY 2016 budget, the ESDA account had a surplus of \$5.3 billion (See Table 4.7).

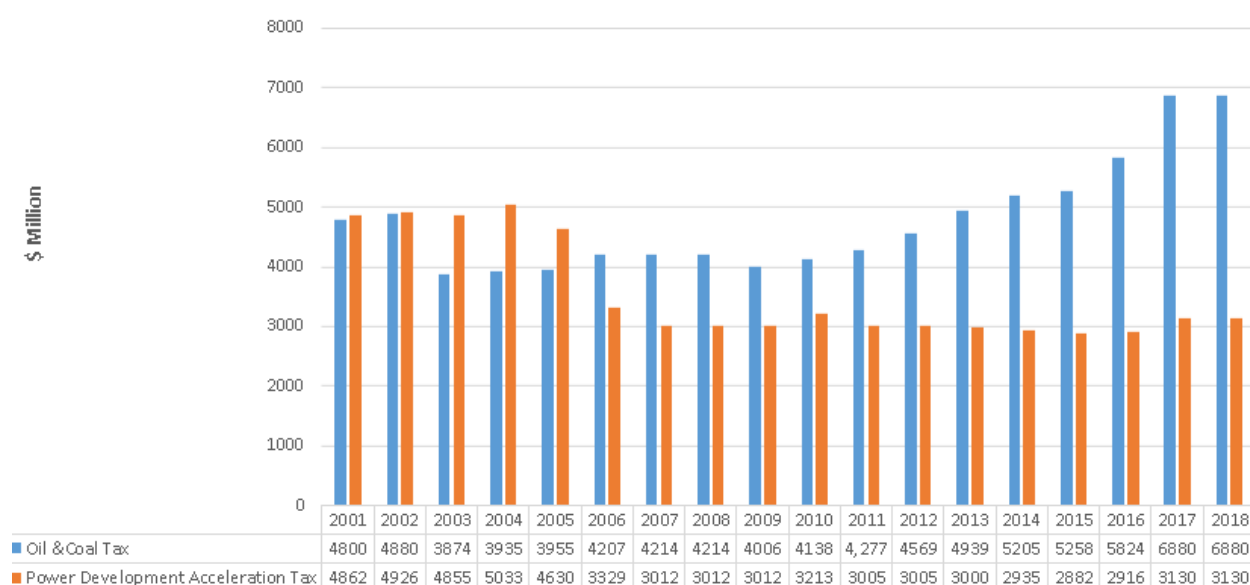


Figure 4.3 Revenues from the Oil and Coal Tax and the Power Source Development Acceleration Tax, FY 2001-2019

Source: The authors created the figure based on MOF, 2018b.

Table 4.7 FY 2016 Year-End Settlement of the Energy Supply Demand Account (ESDA) under the Energy Measure Special Account (EMSA)

Special Account (in \$ millions, rounded up)	Income	Expenditure	Surplus	Transfer to Next Year's Budget	Transfer to General Account
Energy Supply and Demand Account	25,601	21,870	3,730	3,727	3
Power Source Development Acceleration Account	3,682	3,167	514	514	
Nuclear Damage Compensation Support Account	66,798	65,779	1,019	1,019	
Account Total	96,082	90,817	5,264	5,261	3

Source: MOF, 2016.

4.3 Effects of the Dengen Sampo on Nuclear Reactor Construction

The Dengen Sampo that was enacted in June 1974 appeared to have had little impact on the rate of nuclear reactor construction. In the 17 years from 1974 to 1991, 30 reactors were constructed or

1.76 reactors a year. In the 13 years prior to implementation of the Dengen Sampo, from 1961 to 1973, 23 reactors were constructed, or 1.77 reactors a year (See Figures 4.4 to 4.7 and Appendix A). For reactors starting operations the conclusion is much the same. Assuming about a five year lag in Dengen Sampo's impact due to time needed for construction and testing, 20 reactors started operations from 1980 to 1992, compared to 21 from 1966 to 1979.

There is a case to be made, however, that in the 1990s the Dengen Sampo prevented a bad situation from getting worse. This conclusion can be seen by considering trends in the cancellation rate of planned reactors. Since the 1974 Dengen Sampo was enacted, nuclear reactor construction remained very active until 1991, when the two-decade long recession began. The cancellation rate prior to the recession was 22 percent. Thirty-two reactors were built and nine were cancelled. Given the growing anti-nuclear movement during this period, it is possible that the cancellation rate would have been higher. Without the Dengen Sampo's subsidies, local and prefectural governments might not have been as willing to consider hosting new nuclear power plants. After 1991, however, harsh economic conditions became a driving factor that substantially slowed the rate of reactor construction. From 1992 to 2018, only 5 reactors were built and 14 were cancelled, a 74 percent cancellation rate.

4.4 Management of the Dengen Sampo

In the early years the Diet and the Japan Board of Audit (Jbaudit) criticized METI's financial management of the Dengen Sampo taxes and subsidies. For example, Jbaudit claimed the Power Source Development Acceleration Account (PSDAA) was unwieldy and not functioning as intended. Actual subsidy expenditures exceeded an accumulating surplus (See Figure 4.8). In 1974, which was the first year of budget allocation for the PSDAA, actual expenditures were \$13 million while the surplus and unspent funds amounted to \$88 million. Those funds were forwarded to the following year's budget, where they continued to accumulate.

Jbaudit stated that reasons for the surplus were due to delays in nuclear plant construction caused by difficult negotiations with local governments. According to Jbaudit, surplus and unspent funds also accumulated because the ministries' administrators expected that there would be more applications for subsidized projects and more contractors applying for projects, which did not happen. For example, one new subsidy measure that was created in 2003 was the Surrounding Area Development Fund (SADF). The SADF was intended to fund any "soft" projects to help revitalize areas where newly built reactors had begun operations. But since the SADF has come into existence, only four new reactors have begun operations, and none have started operations since 2011. So budget surpluses have continued to grow. (Jbaudit, 1985, 2004; Oshima, 2010). In 2005, the Diet again criticized the management of the Power Source Development Acceleration Account (PSDAA) for routinely planning budgets far greater than what could possibly be spent. The Diet called the PSDAA "wasted money" and questioned the value of some measures. It advocated that in view of the country's critical need for fiscal restructuring, under-spending of the PSDAA should not continue (Fukazawa, 2006).

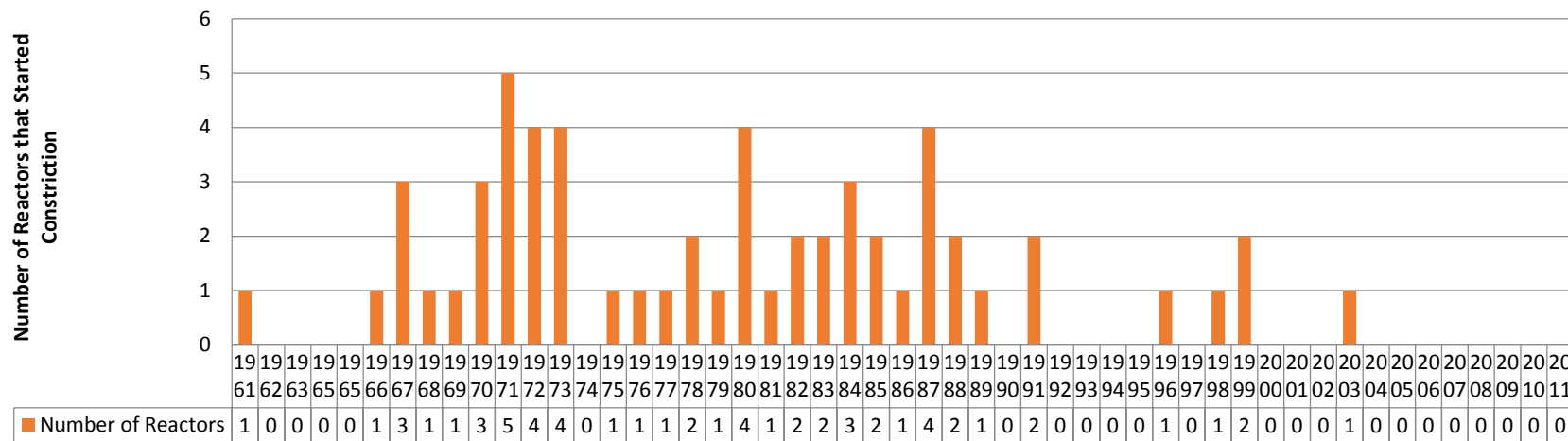


Figure 4.4 Nuclear Reactors in Japan: Number of Construction Starts, 1966-2011. (57 reactors, including 3 being decommissioned)
Source: Compiled by the authors. Figure is based on interpretation and analysis of based on JAIF data, Various Dates.

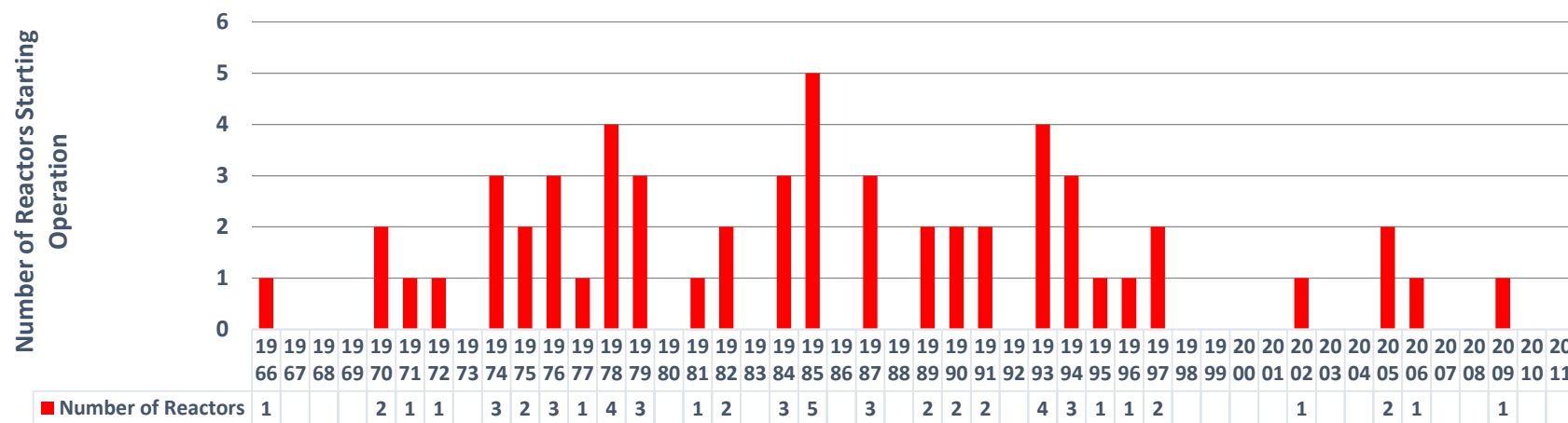


Figure 4.5 Nuclear Reactors in Japan: Number that Started Operations, 1966-2011. (57 reactors, including 3 being decommissioned)
Source: Compiled by the authors. Figure is based on interpretation and analysis of on JAIF data, Various Dates.

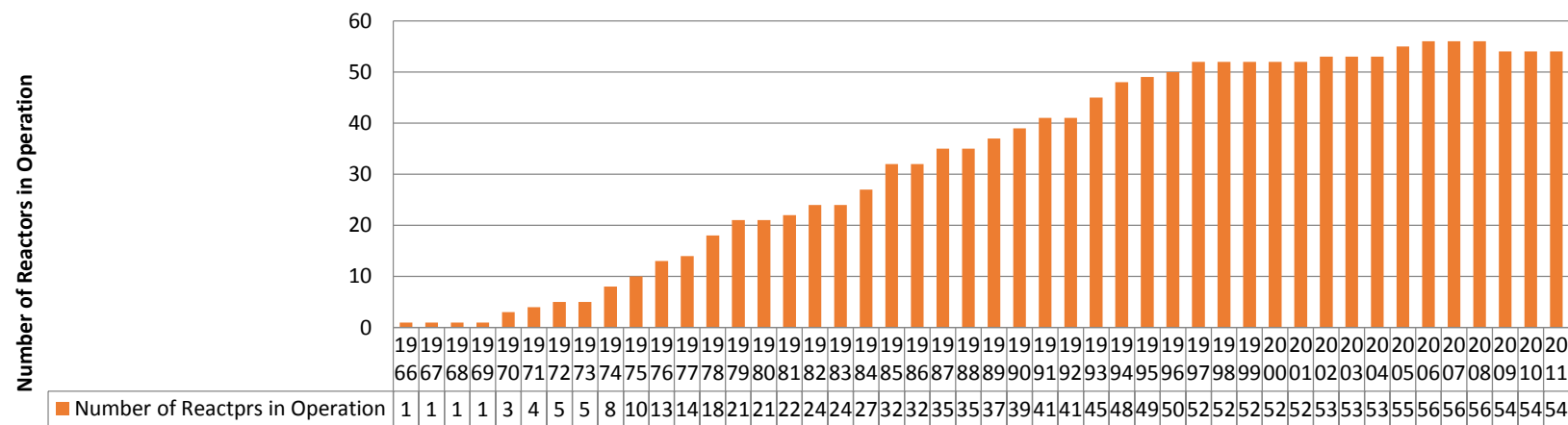


Figure 4.6 Cumulative Numbers of Nuclear Reactors in Japan, 1966-2011
Source: Figure is based on interpretation and analysis of on JAIF data, Various Dates.

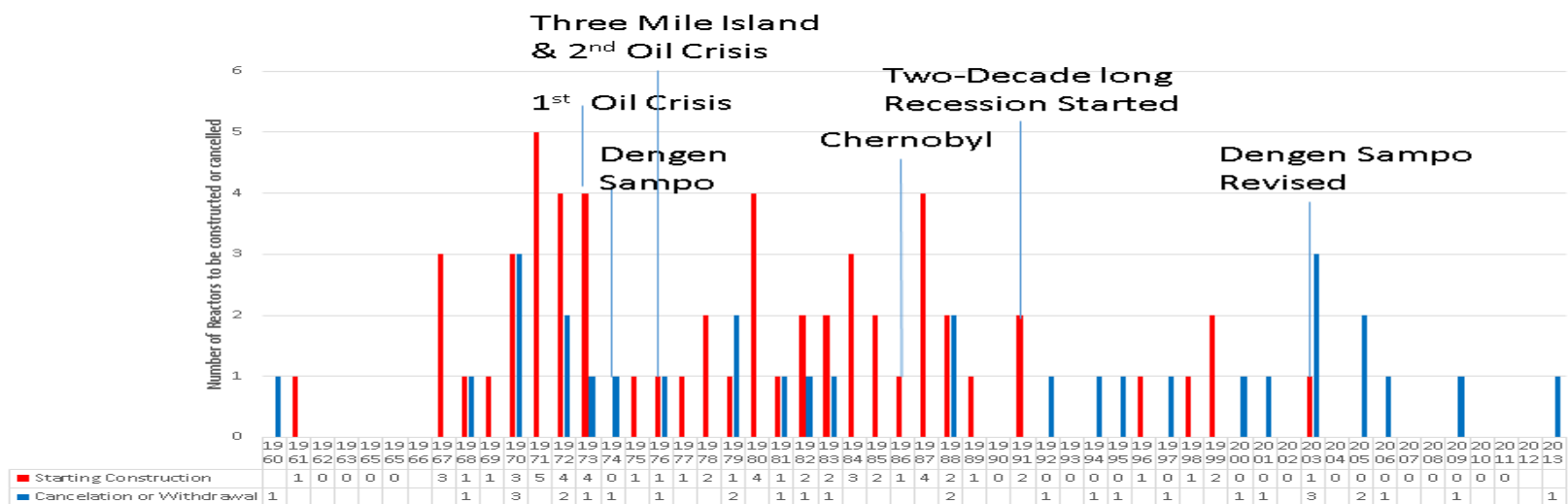


Figure 4.7 Number of Nuclear Power Reactors in Japan, Constructed or Cancelled
Source: Figure was created by the authors based on interpretation and analysis of Cho, 2014 and JAIF, 2018.

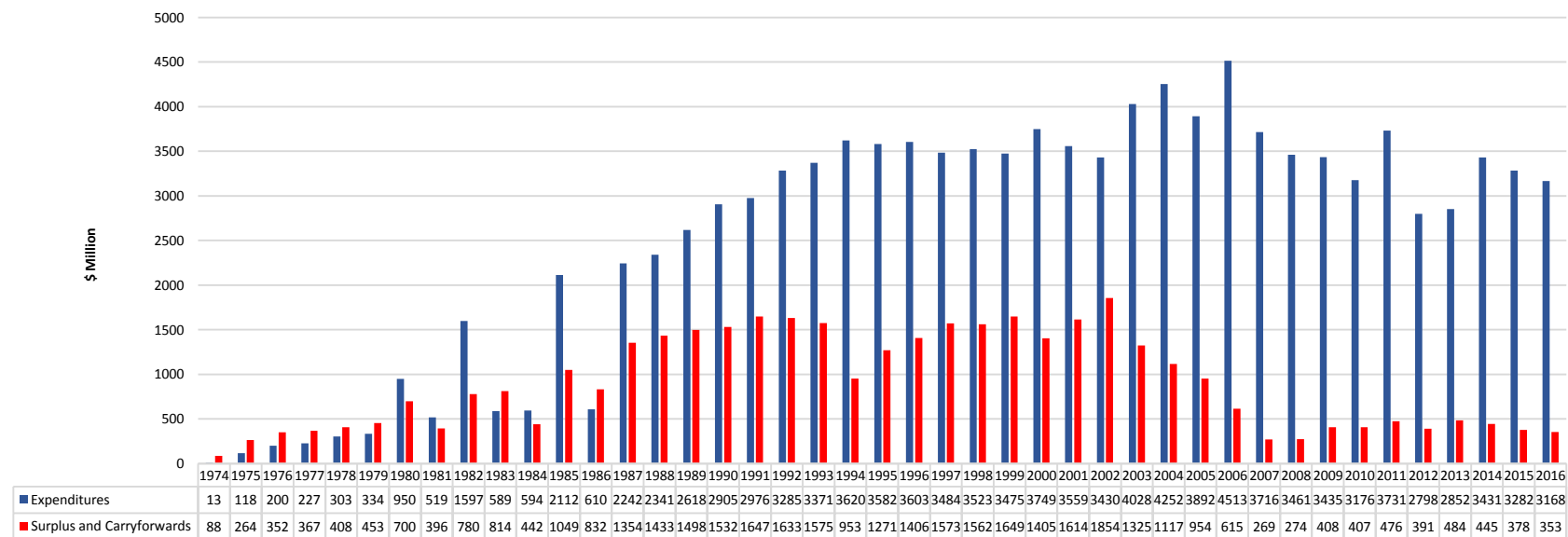


Figure 4.8 Trends in the Power Source Development Acceleration Account: Actual Expenditures and Unspent Funds, 1974-2016
Notes: Unspent and surplus funds are carried forward in the MOF's End-of-Year Settlement; Total Expenditures = \$109,664 million
Source: Figure created by the authors based on year-end MOF settlement data (MOF, 2018d; Oshima, 2010).

According to Fukazawa (2006), since the 1980s there had been a strong correlation between the increase in the budget surplus and unspent funds and an increase in the number of “soft” projects, particularly under the Power Source Location Measure (PSLM) of the PSDAA. While those projects were implemented in the hope that it would help the local economy, no statistical difference could be discerned between those regions hosting a nuclear reactor and those that did not, according to Fukazawa. He stated that in view of the growing amount of unspent funds in the PSLM, ministry administrators might have felt compelled to spend money on unneeded projects.

- By 2003, the surplus declined from about half of total expenditures to about a third. The ratio continued to decline to under seven percent by 2007, the lowest on record, but this level of surplus was still seen as a significant problem of over-budgeting (MOF, 2018c; Cho, 2014). Finally, in March 2007, the Diet enacted the Law Concerning the Special Account (2007, Law No. 23), which ruled that when a major surplus occurred at end-of-year settlement, the funds should be saved as a reserve and if the surplus continued, it should be transferred back to the General Account as revenue to be spent for general purposes in the following year. The law generally has prevented unspent funds from increasing, but the ratio of unspent to spent funds in the PSDAA continues to hover at around ten percent.

4.5 Effects of Dengen Sampo Subsidies on One Local Economy

The town of Mihama was created in 1954 by combining four small villages. The new town included the scenic Wakasa Bay, which had a pleasant shoreline to the north and mountains to the south. Primary industries were fishery, agriculture and sightseeing. Mihama’s combined population was 10,566, but after its creation the town suffered from depopulation and local governments needed a stimulus to revitalize the town’s economy. (Kobe University, 1999). The town found that stimulus in nuclear power plants. In October 1961, KEPCO was inspecting the town of Mihama and Tsuruga City for suitability. KEPCO picked Mihama because of its convenient shoreline and started to build Mihama 1 (340 MW) in August 1967. Mihama 1 reached criticality in July 1970.

The Dengen Sampo subsidies were not implemented until 1974, but the town of Mihama started to receive property tax revenues from Mihama 1 after it commenced operations. KEPCO soon built two more reactors: Mihama 2 (500 MW) in 1972 and Mihama 3 (825 MW) in 1976. Moreover, the PNC began construction of FBR Monju in 1983 and the JAPC built Tsuruga 2 (1160 MW) in 1987. Following passage of the Dengen Sampo, Mihama began to benefit from all this construction. It received both subsidies and various tax revenues, including the nuclear property tax and the nuclear fuel tax. According to Miyoshi (2012), Dengen Sampo subsidies for the Mihama nuclear plants amount to \$184.72 million from 1974 to 2009; most of these revenues were received after 2001 (See Figure 4.9).

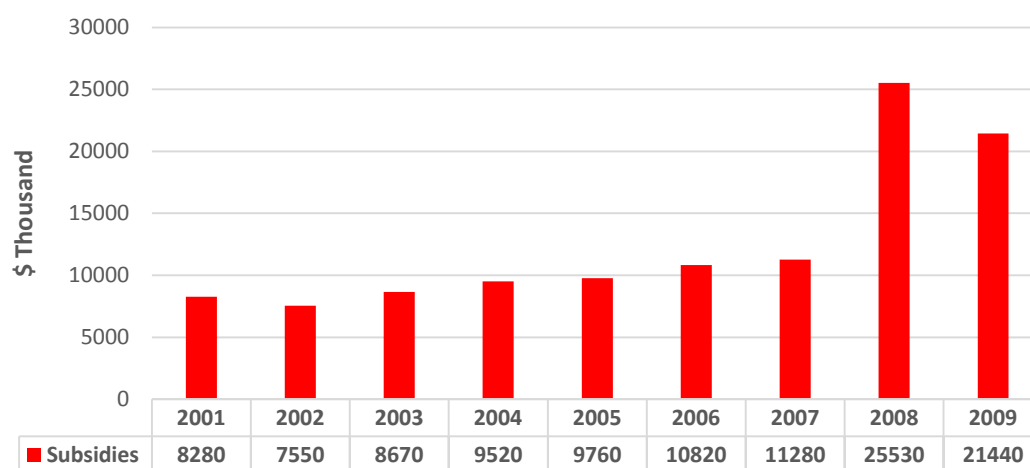


Figure 4.9 Dengen Sampo Subsidies provided to the Town of Mihama, 2001-2009

Notes: Miyoshi (2012) states that total subsidies for 2001-2009 amounted to \$184.72 million, but the table presented totals of \$113 million, a discrepancy of \$71.72 million. The difference can be accounted for by including subsidies provided prior to 2001.

Source: Figure created by authors based on data from Miyoshi, 2012.

The Dengen Sampo subsidies provided to Mihama were primarily spent for building public facilities, including elementary schools, a middle school, kindergartens, water supply systems and town roads. Mihama spent a total of about \$50 million in Dengen Sampo subsidies to build a range of public facilities from 1974 to 1993 (See Table 4.8). It is unfortunate that the subsidies were not invested in establishing infrastructure that could create future industries and associated businesses, however (Kobe University, 1999).

Table 4.8 Dengen Sampo Subsidies for Mihama and the Mihama Public Work Projects

Note: Costs are rounded up to the nearest thousand

(\$ Thousands)

\$ Thousands)					
Year	Reactor	Projects	Total Project Costs	Subsidies	Ratio of Subsidies to Total Project Cost (%)
1974	Mihama 3	Town road Mihama Middle School line	14	14	98.6
		Mihama Middle School indoor gymnasium	2392	2,391	100
1975		Town road Yamagami line	203	203	100
		Mihama Middle School wrestling gymnasium	237	237	100
		Takenami city hall	340	200	58.8
		Farm road Shioiri	26	26	100

		line			
	Fugen	Town road Sakajiri Ota line	766	766	100
		Agricultural drain (Miyakawa)	44	44	100
		Farm road Ochiai lone	100	100	100
1976	Mihama 3	Town road Sakajiri Ota line	129	126	98
		Town road Kanayasu line	86	86	100
		Water supply system expansion	511	505	98.8
		Central city hall	3,299	2,489	75.4
		Town pool	308	295	95.9
1982	Tsuruga 2	Fishing boat Hyuga hoisting facility	77	77	100
1983		Sugahama simple water service	300	260	86.7
		Yahazu Kindergarten	557	470	84.5
		Higashi Elementary School Survey Design	47	45	94.9
1984	Tsuruga 2	Higashi Elementary School building	4,247	4,000	94.2
1985		Higashi Elementary School gymnasium	1,520	1,460	96.1
	Monju	Sugahama Elementary School land acquisition	1,184	1,060	89.5
1986	Tsuruga 2	Nyu simple water service	493	396	80.3
		Trash collection vehicles	26	25	96.1
		Nyu fishing boat landing	180	130	72.2
		Sugahama ice crusher	77	67	86.6
	Monju	Sugahama Elementary School building	2,972	2,800	94.2
		Sugahama Elementary School indoor playground	1,198	1,150	96
1988		Town baseball ground site preparation	3,147	2,850	94.2
		Shinsho Elementary	761	700	92

		School site preparation			
1989		Town baseball ground night lighting construction	2,713	13,350	492
		Shinsho Elementary School building	5,076	4,900	96.5
		Tobu Medical Clinic	1,407	1,340	95.2
		Sugahama Nursery School	774	460	59.4
	Tsuruga Coal Thermal Power Plant	Crematorium ground preparation	159	153	95
1990	Monju	Shinsho Nursery School	789	540	69.4
	Tsuruga Coal Thermal Power Plant	Crematorium building	1,828	1,400	76.6
1992	Monju	Wired radio station equipment	537	414	77.1
		Water supply system intake facility	41	37	89.8
		Nyu Elementary School building	2,683	2,625	97.8
		Nyu Nursery School	898	861	95.9
		Nishi Nursery School	545	540	99.2
	Tsuruga Coal Thermal Power Plant	Wired radio station equipment	537	71	13.2
1993	Monju	Water supply system intake facility	742	673	90.7
Total			43,970	50,337	87

Source: Kobe University, 1999.

Mihama also received property tax and nuclear fuel tax revenues from the nuclear power plants. For example, 60 to 70 percent of Mihama's tax revenues came from property taxes paid by nuclear plant owners (See Figure 4.10). In 2001, the property tax paid by nuclear plants was about \$21.4 million, which represented 74.4 percent of Mihama's entire tax revenue base ($6.34 + 21.38 + 1.02 = \$28.74$ million tax revenue base) (Miyoshi, 2012). Mihama is overwhelmingly dependent on the nuclear property tax for its revenue. If there are fewer or no nuclear plants, Mihama would have great difficulty sustaining its economy.

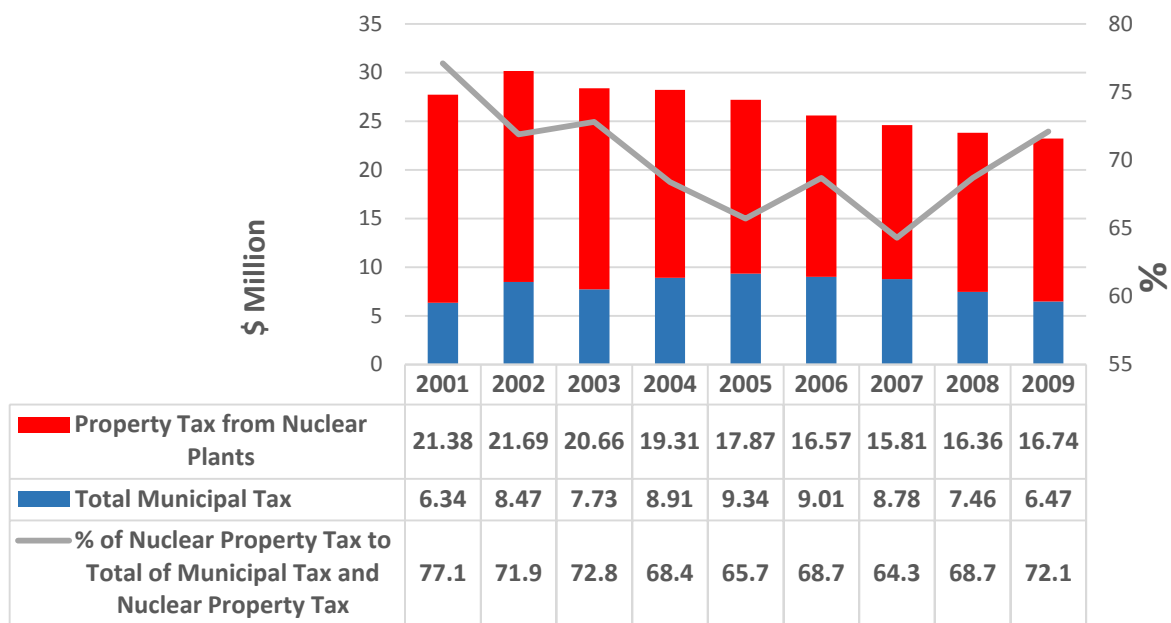


Figure 4.10 Nuclear Plant Property Tax, Municipal Tax, and Ratio of Nuclear Property Tax to Total Tax, 2001-2009

Notes: Total Municipal Tax, 2001-2009 = \$72.51 million; Total Nuclear Property Tax, 2001-2009 = \$166 million; no other taxes are incorporated in the calculation because they are of insignificant value.

Source: Figure created by the authors based on data from Miyoshi (2012).

In addition to the Dengen Sampo subsidies, the town of Mihama received substantial benefits from KEPCO. From 1991 to 2010, the gifts amounted to about \$55.3 million (Miyoshi, 2012). During that time, Mihama reactors had two serious accidents. On 9 February 1991, a break in a heat transfer tube at the Mihama 2 steam generator triggered a SCRAM with full activation of the Emergency Core Cooling System. The operators had failed to install a bracing bracket to the heat transfer tube as designed. Eventually, a small amount of radiation was released to the environment. The accident was rated as INES 2.

On 9 August 2004, a fatal accident occurred at Mihama 3. Four workers were scalded to death by superheated steam, a fifth died on August 25th. The accident was caused by a break in a steam pipe in the non-radioactive part of the reactor. In 27 years of operation the 56 cm diameter pipe had never been checked for corrosion. The walls of the pipe had worn down from an initial 10 mm of carbon steel to 1.4 mm (Wein, 2013; Citizen's Nuclear Information Center (CNIC), 2004). Despite the seriousness of these accidents and the plant management's apparent lax attitude toward safety, Mihama residents did not register any strong complaints. Residents may have become inured to the risks of living next to nuclear power plants. Moreover, as population and indigenous industries continued to decline, residents likely felt a greater dependence on nuclear power plants for their livelihood.

With a population of about 5,500 in 2006 (half what it was in the 1950s), only 58 residents (1 percent) were engaged in fishery and 15 (0.3 percent) were employed in agriculture. The largest

numbers of people, about 2,000, were in the service sector and 700 people (12 percent) were engaged in the retail or wholesale business (See Figure 4.11). Moreover,

- About 1,000 people (20 percent) were engaged in construction work related to the nuclear plants;
- About 800 people (15 percent) were engaged in electricity, gas, heating and plumbing trades that were also linked to the nuclear plants.

Thus, if the nuclear industry were not in Mihama about a third of the town would have few ways to earn a living (Miyoshi, 2012).

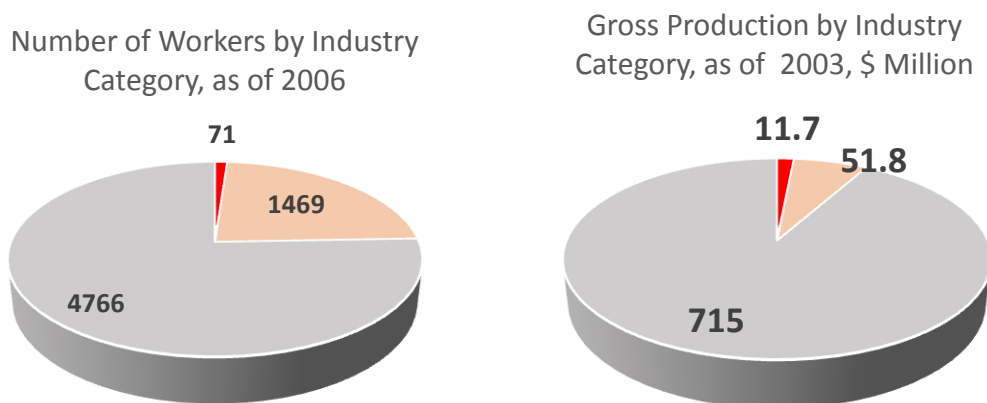


Figure 4.11 Economic Snapshot of the Town of Mihama

Category of Industry Shown:

- Primary—Agriculture, Forestry, Fishery
- Secondary—Mining, Construction, Manufacturing
- Tertiary—Electric, Gas, Heating Supply, Water Supply, Transportation, Information and Communication, Retail, Wholesale, Finance, Insurance, Real Estate, Service, Public Service.

Source: Miyoshi, 2012.

Despite the revenues that the town of Mihama receives from the Dengen Sampo subsidies and the property taxes from the nuclear power plants, Mihama's financial strength index³⁴ has remained below 1.0 (See Figure 4.12). This suggests that the town is unable to function on its own and continues to require government subsidies.

³⁴ The financial strength index is an index used to measure the financial strength of local communities and is a value obtained by dividing the standard fiscal revenue by the standard fiscal expenditure. It usually is the average of the past three years. If the financial power index falls below 1.0, the community is regarded as unable to perform administrative functions with the tax revenues from its local community and would become a recipient of the central government tax subsidies.

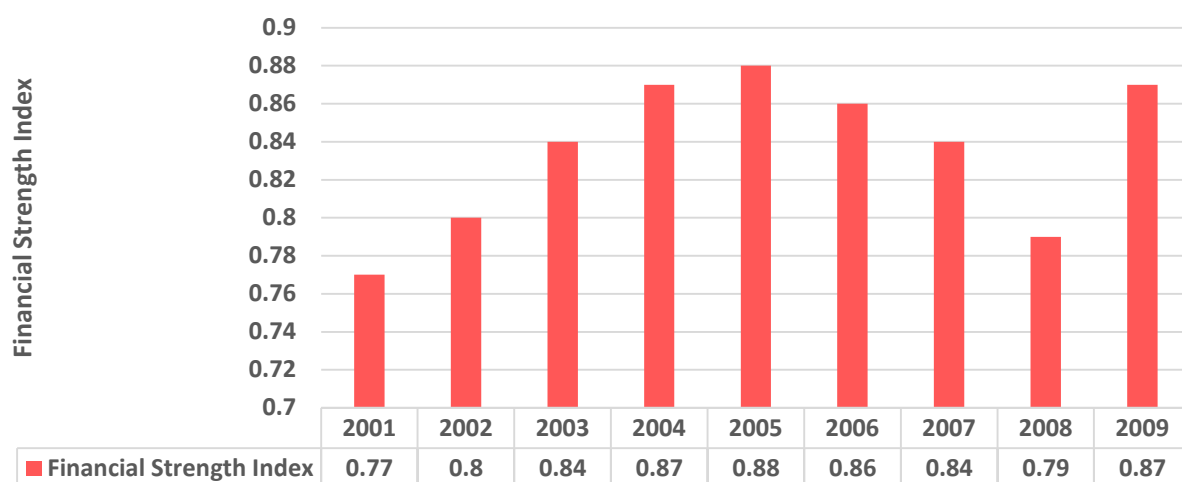


Figure 4.12 Trend in the Financial Strength Index of the Town of Mihama, 2001-2009

Source: Figure created by authors based on the data from Miyoshi (2012).

The financial vulnerability of the town of Mihama became apparent on 17 March 2015. That was the day Mihama residents learned that KEPCO and JAPC had decided to decommission Mihama 1 and 2 and Tsuruga 1. Since the Fukushima nuclear disaster and the implementation of new safety regulations, the owners of the old reactors had to face a tough business decision. Given the high cost of updating and modernizing older reactors, which generally had small generation capacities, the owners decided it was more economical to decommission them. Two years later the town learned that FBR Monju was to be decommissioned. Worse still, the Nuclear Regulation Authority (NRA) had discovered that an active fault ran underneath the Tsuruga Nuclear plant site, which meant that JAPC's plans to build Tsuruga 3 and 4 had to be abandoned.

There have been side effects from the Dengen Sampo subsidies. Local governments such as Mihama became accustomed to and dependent on revenues generated by the continuing operation of the nuclear power plants. When a nuclear reactor approaches end of the life, for example, the prefecture and the municipality often would lobby for the construction of another reactor to keep the flow of subsidies going. These requests brought other problems to the surface. Anti-nuclear sentiment drove plant owners to add reactors to existing plant sites, thereby increasing the complexity of those sites and the risks associated with managing and recovering from a reactor accident.

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Chapter 5:

The Fukushima Daiichi Nuclear Disaster

CHAPTER 5: The Fukushima Daiichi Nuclear Disaster

Abstract

On 11 March 2011, the Great East Japan Earthquake and Tsunami struck Fukushima Daiichi Nuclear Plant, triggering a total station blackout and a disastrous nuclear accident. Radioactive cores of three reactors (Unit 1, 2 and 3) lost cooling. The hot fuel fell melted its way through the primary pressure vessels and breached the container vessels. Specific locations of all the melted fuel have yet to be identified, and technology to retrieve the fuel has yet to be invented. Several studies indicate the cost of the accident and damage compensation is approaching \$500 billion and climbing. Put in a larger historical context, Japan has had more serious accidents than other states with comparable nuclear infrastructures. Various investigatory reports have catalogued a multitude of reasons for Japan's track record, including locating reactors on active geologic faults, a mindset that ignores or plays down precursors to accidents, simple negligence, lack of a safety culture among senior managers, and regulatory capture.

5.0 Scope of the Disaster

On 11 March 2011 at 2:46 p.m. local time, a catastrophic Magnitude 9.0 earthquake ruptured the mega thrust fault offshore of Miyagi and Fukushima prefectures in northeastern Honshu, generating strong shaking and a large tsunami. The tsunami reached run-up heights as high as 38 meters, causing tremendous local devastation ([Lay, et al., 2011](#)). A total of 15,894 people lost their lives and over 2,558 are still officially reported as missing, while a further 6,152 suffered injuries. The devastating natural events caused extensive damage to infrastructure in Iwate, Miyagi and Fukushima prefectures. Some 121,806 buildings were destroyed, 278,575 buildings suffered severe damage, and 736,176 buildings were partially damaged ([Reconstruction Agency, 2016](#)).

According to information from the Cabinet Office, the direct financial damage from the disaster was estimated to be approximately \$169 billion, including \$104 billion in building damage, \$13 billion for lifeline utilities,³⁵ \$22 billion in social infrastructure and \$30 billion in other costs as of June 2011. The World Bank estimates that the economic cost could reach up to \$235 billion, making it the costliest natural disaster in world history ([Cabinet Office, 2011](#); [World Bank, 2012](#)).

The 3.11 earthquake was the most devastating earthquake to occur in Japan since the 1995 Kobe earthquake. That Kobe earthquake was a magnitude 7 and caused more than 5,500 deaths. Prior to Fukushima, the worst tsunami in modern Japan occurred in 1993 in Hokkaido and was responsible for over 200 deaths ([Starr, 2012](#); [Cabinet Office, 2014](#); [National Geophysical, 2018](#); [Toyama, Sagara, no date](#)).

The 3.11 earthquake and tsunami triggered one of the worst nuclear accidents on record. Following the earthquake, a 15-meter tsunami struck the Fukushima Daiichi Nuclear Plant, located near the coastal town of Futaba in Fukushima Prefecture, about 60 miles south of Miyagi ([WNA, 2016a](#)).

³⁵ Lifeline utilities are basic necessities for everyday life, such as electricity, gas, water supply, wastewater, transport, energy and telecommunications.

The nuclear plant, owned and operated by TEPCO, had six boiling water reactors (BWR). On that day, three of the six (Fukushima Daiichi 1, 2 and 3) were operating while the other three (Fukushima Daiichi 4, 5 and 6) were off line in preparation for re-fueling.

The tsunami waves overwhelmed the plant's 5.7-meter sea wall and inundated the nuclear plant complex, which had been built 10 meters above sea level. Both the reactor buildings and the turbine buildings were built on bed rock with lower levels located below sea level. The diesel generators used for emergency power were in the basement of the turbine buildings. These areas were totally flooded by the tsunami preventing the generators from operating ([National Diet, 2012](#)) (See Figure 5.1).

The tsunami also destroyed significant pieces of reactor control and support hardware, washed away much of the equipment needed to get matters back under control and left a large amount of wreckage that blocked access to critical places on the site. Worst of all, the earthquake and tsunami had devastated the area surrounding the nuclear plant, taking the local power grid off-line. With the emergency generators flooded and no access to outside power, the station was in total blackout conditions. Cooling pumps could not operate. As time passed with no access to power, the cores of three reactors (Units 1, 2 and 3) began to overheat and then melt. A fourth reactor (Unit 4), which was off-line, was also damaged.

Extremely high temperatures reached by the fuel rods caused its zirconium cladding to interact with steam, stripping out the hydrogen, which led to several hydrogen-air chemical explosions between 12 March and 15 March. The explosions released massive amounts of radioactive material into the atmosphere and ocean. TEPCO estimated that about 940 PBq (10^{15} Bq) (iodine-131 equivalent) of radioactivity was released during the three days, about one-fifth of the 5200 PBq released in the Chernobyl accident ([WNA, 2017](#)). In 2014, the UN Scientific Committee on the Effects of Atomic Radiation released its final report on the radiological consequences of the accident, which concluded that radioactive releases from the Fukushima accident were between 10 to 20 percent of the releases of the Chernobyl accident ([United Nations Scientific Committee on the Effects of Atomic Radiation \(UNSCEAR\), 2014](#); [OECD, 2015](#)).

The Fukushima accident was rated 7 on the INES scale, its highest rating. The rating signifies that the accident caused widespread contamination with serious health and environmental effects (See Figure 5.2). Three of the most severe nuclear accidents in world history are the Fukushima accident rated as level 7, the Chernobyl disaster rated as level 7 and the Three Mile Island accident rated as level 5.

- According to former Nuclear Regulatory Commission Chairman Gregory Jaczko, Japan was lucky that the wind was blowing out to sea during the first three days of the accident, or things would have been much worse. In comparison, during the Chernobyl accident the wind was blowing toward Scandinavia during the worst days of the nuclear disaster, spreading radioactive materials throughout Europe. ([Broekhoven, 2011](#)).

Height of Fukushima Daiichi Nuclear Power Station grounds and tsunami (illustration)

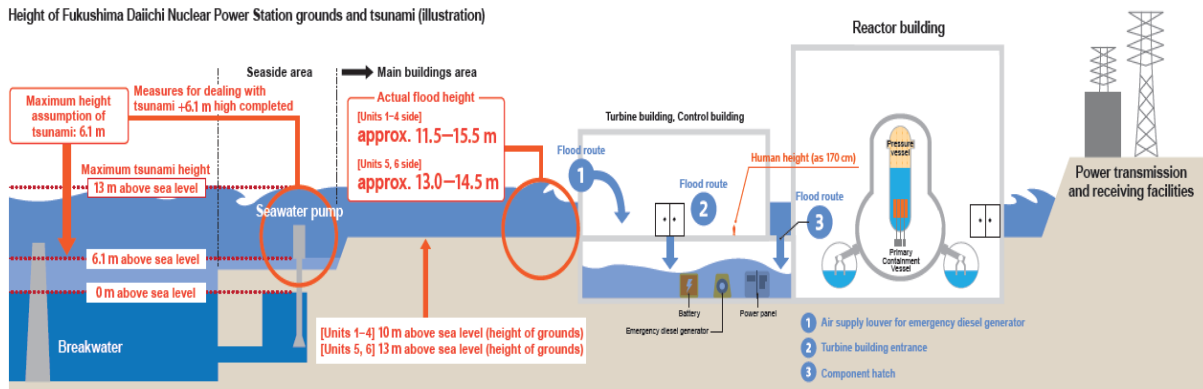


Figure 5.1 Schematic of Fukushima Daiichi Nuclear Plant: Actual Cliff Elevation, Height of Nuclear Plant, and Tsunami Run-up

Source: Tokyo Electric Power Company (TEPCO), 2013.

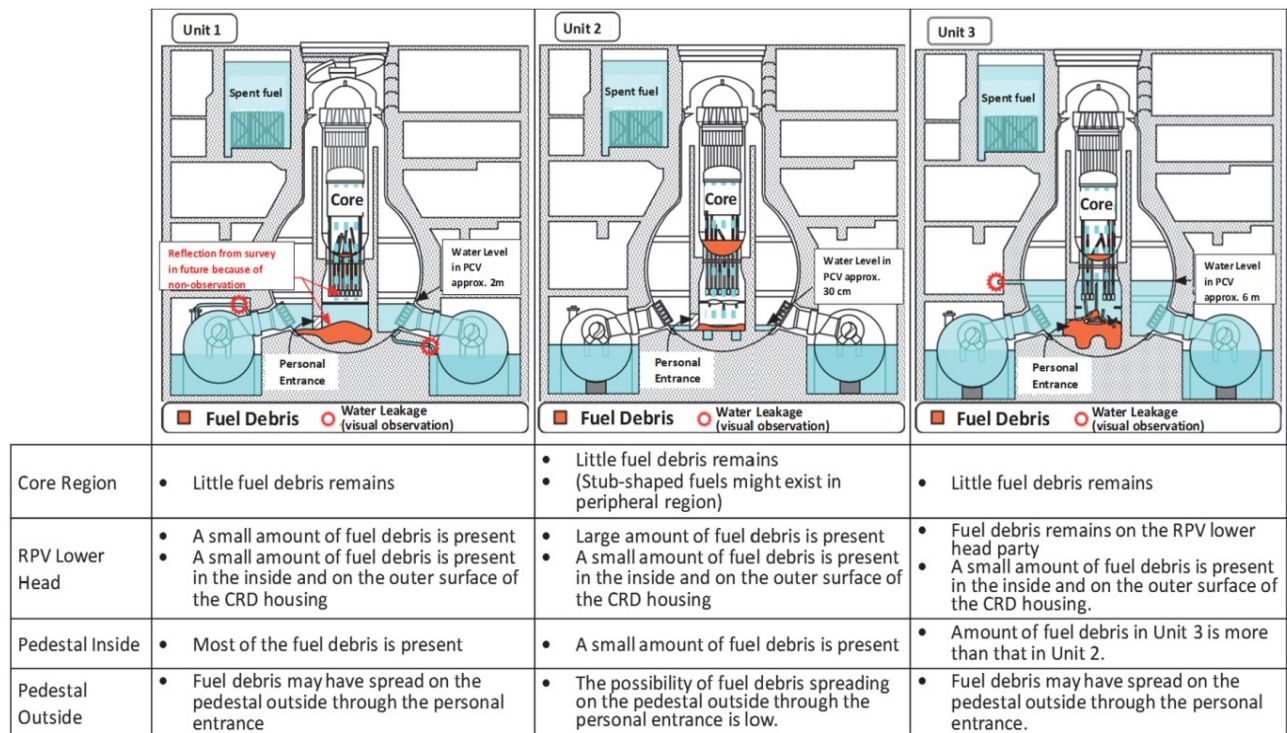


Figure 5.2 Fukushima Daiichi Status of Damaged Reactors and Core Meltdowns at Units 1, 2 and 3

Source: NDF, 2018

To locate the melted fuel, TEPCO has been sending remotely operated robotic cameras into the reactor halls. On 6 February 2017, an image revealed that a steel grating underneath the pressure vessel at Unit 2, heavily encrusted with brownish-black deposits, had melted away entirely, leaving a large hole about one-meter in diameter (See Figure 5.3). Based on electronic noise on the image, operators estimated radiation levels were extremely high—530 sieverts per hour near the pressure vessel. The previous high in Unit 2 was 73 sieverts recorded in 2012. ([Takahashi, 2017](#); [Daley, 2017](#)). It is believed that the fuel melted through the pressure vessel and then through the grating and is now located at a lower level. On 18 January 2018, TEPCO captured more images inside the containment vessel of Fukushima Reactor Unit 2 through a long telescopic probe ([Yamaguchi, 2018](#)). One image shows part of what is believed to be a fuel assembly lifting handle and a tie plate, which are components from the top of a fuel assembly that hold a fuel rod bundle together (See Figure 5.4). Along with the handle and a tie plate, the image shows small lumps of what appear to be fuel debris scattered on a structure below the reactor core, signifying that the rods melted and breached the bottom of the core ([Yamaguchi, 2018](#)). Also, new readings taken inside Unit 2 using the TEPCO probe have revealed lethal levels of radiation. Near the containment vessel, radiation levels were 8 Sv/hour, which would be lethal to a human after an hour of exposure.

- Many experts say that all three reactors—Units 1, 2 and 3—suffered serious damage to both the reactor pressure vessels (RPVs) and the primary containment vessels (PCVs) ([Hatamura, et al., 2014](#)). They have stated that the damage occurred within a few days of the Fukushima disaster on 11 March 2011 and that further damage will be possible in the future (See Table 5.1). The Fukushima Prefectural Government also affirms that the pressure vessels and containment vessels of Units 1, 2 and 3 were damaged and that cooling water is leaking from cracks in the vessels ([Fukushima Prefecture, 2017](#)). Experts speculate that the melted fuel may be supported by a partition inside the containment vessel and that another earthquake could further damage the PCV, triggering radioactive release ([Research Institute for Environmental Finance \(RIEF\), 2017](#)).



Figure 5.3 Meter-wide Hole in Grate Below Pressure Vessel in Reactor 2, Possibly Caused by Melted Nuclear Fuel (As of 6 February 2017)

Source: TEPCO, 2017. Photo taken 30 January 2017 by IRID.

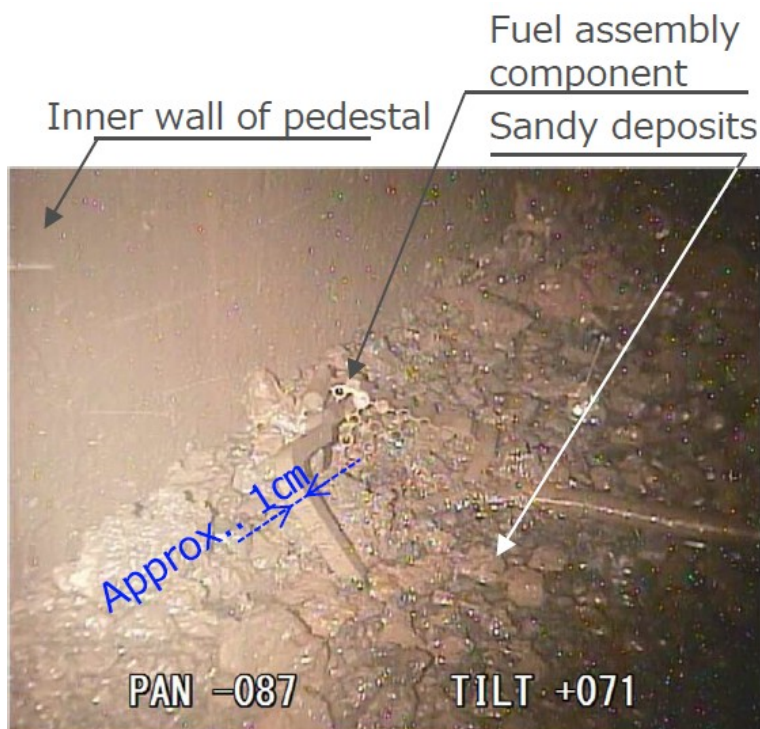


Photo location C Bottom of pedestal

Figure 5.4 Image Inside Primary Containment Vessel of Unit 2, Showing Fuel Assembly Lifting Handle and a Tie Plate (as of 18 January 2018)

Source: TEPCO, 2018a. Photo taken on 19 January 2018, by IRID

Table 5.1 Chronology of Damage to Fukushima Daiichi Units 1, 2 and 3

RPV: Reactor Pressure Vessel

PCV: Primary Containment Vessel

	Confirmed damage to Unit 1	Confirmed damage to Unit 2	Confirmed damage to Unit 3
RPV	Damage occurred from 20:07 on 11 Mar. to 2:45 on 12 Mar. Further damage may have occurred later.	Damage is likely to have occurred by 21:18 on 14 Mar. High possibility of severe damage later.	High possibility of damage about 6:30 and about 9:10 on 13 Mar. High possibility of further damage by 5:00 14 Mar. Later, further severe damage probable.
PCV	Possible damage by 21:51 on 11 Mar.. Further damage may have taken place afterwards.	Plenty of evidence that damage occurred between about 13:45 and 18:10 on 14 Mar. Possibility of further damage is very high. High possibility of severe damage leading to release of a large amount of radiation from 7:38 on 15 Mar. to about 4:00 on 16 Mar.	Possibility of damage between 2:42 on 13 Mar. and 2:20 on 14 Mar. cannot be denied. Evidence of severe damage between about 7:00 to about 21:35 on 14 Mar.. There is a possibility of further severe damage that followed.

Source: [Hatamura, et al., 2014.](#)

5.1 Consequences and Costs

The Fukushima Daiichi nuclear disaster has brought long-lasting, severe damage to the Japanese people. As of November 2011, more than 8,900 km² (3,436 square miles) of land had been contaminated with radioactive cesium (Cesium-137 and Cesium-134), extending over eight prefectures.³⁶ On 12 March 2011, about 81,000 residents living within a radius of 20 km of the Fukushima nuclear plant (covering an area of 1,150 km²) were ordered to evacuate. As many as 470,000 people ultimately evacuated, including those who voluntarily left the areas outside the 20-km radius. As of April 2017, after more than 6 years, areas totaling 780 km² have been cleaned up enough that radiation readings are now less than 20 mSv/year. Evacuation orders were lifted in those areas and the residents can return home. Of the remaining 370 km², some 337 km² have radiation readings higher than 50 mSv/year and residents are not permitted to return home. The remaining area of 33 km² is either designated as “permitted daytime visit only” or “evacuation orders are soon to be lifted” (See Figure 5.5) (Nakayama, 2014; Cabinet Office, 2017; Reconstruction Agency, 2018).

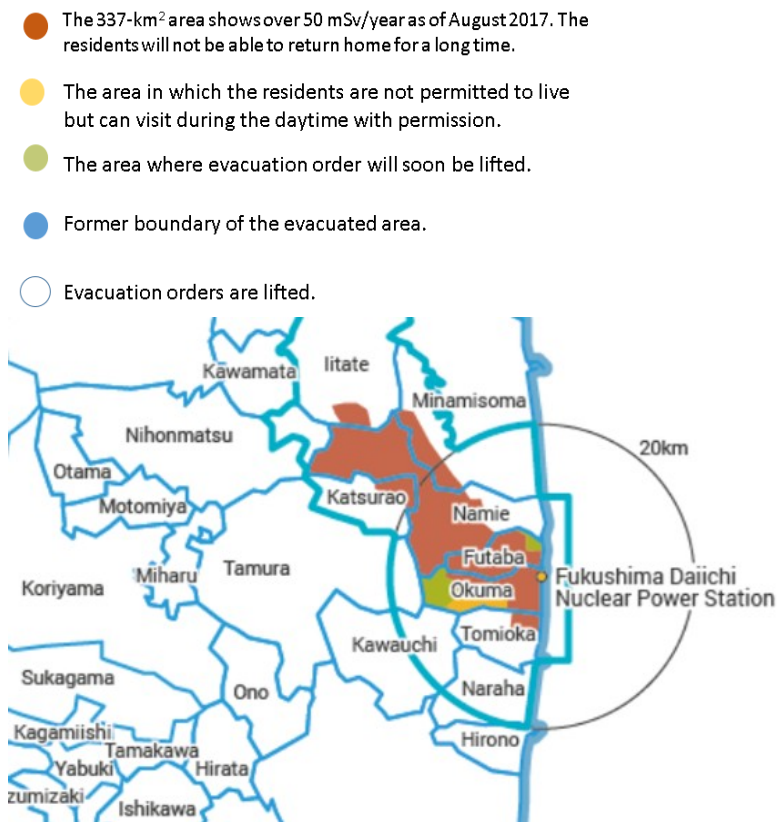


Figure 5.5 Areas Contaminated with Cesium-137 in Fukushima

Source: World Nuclear Association, 2017; Cabinet Office, 2018.

³⁶ Cesium-137 (Cs-137) and Cs-134 are produced by nuclear fission and have a half-life of about 30.2 years and 2.06 years, respectively. The objects and regions contaminated by Cs-137 could remain dangerous to humans for up to 300 years. Cs-137 constitutes most of the radioactivity still left from the Chernobyl accident and is a major health concern for decontaminating land near the Fukushima nuclear power plant (Colin Wessells, 2012. “Cesium-137: A Deadly Hazard,” Stanford University, Winter 2012).

The most contaminated area (337 km²) which is marked by the brown areas in Figure 5.5) has been declared to be a permanent “exclusion” zone because it is heavily contaminated with Cesium-137. This area represents almost one percent of Japan’s scarce arable land (which is about 17,274 square miles (44,739 km²)) and is equivalent to the combined land area of the boroughs of Manhattan, the Bronx and Brooklyn in New York City. Cesium-137 has a half-life of 30 years and thus it will take several generations before humans can continuously (and safely) inhabit these areas again. (Starr, no date; World Nuclear News (WNN), 2012).

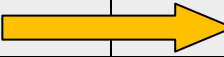
According to the Brookings Institution, the economic, political and social consequences of the 3.11 earthquake, tsunami and nuclear disaster have uprooted entire communities and created large infrastructural losses, causing substantial declines in industrial production. This has imposed a toll on Japan’s economy and it also has impacted many other countries linked through production networks (Ferris, Solis, 2013).

At present, the final costs for the disaster remain open-ended. The accident is not “over” because much of the melted fuel has not been located and radioactive material continues to leak into the environment. No technology exists to identify the precise whereabouts of the melted fuel debris and safely retrieve it. It could take years before this task is completed. (METI, 2015).

Estimating future costs of any nuclear accident is a difficult and inexact art, but it is important to make the attempt. Cost estimates, along with who bears the burden for them, are critical for developing strategies for coping with future disasters and are also necessary for incentivizing businesses to take remedial action with respect to safety.

This is particularly true for the Fukushima nuclear disaster. A November 2016 report by the Ministry of Economy, Trade and Industry (METI) indicates that the Fukushima disaster cost had doubled from previous estimates and could amount to more than \$220 billion (See Table 5.2). Of this amount, METI estimates that decommissioning and decontamination would amount to \$140 billion, to be paid mostly by TEPCO (METI, 2015).

Table 5.2 METI’s Revised Fukushima Accident Cost Estimates

Fukushima Daiichi Nuclear Accident Costs Expected to Grow Larger								
Type of Expense	Estimate Mar 2014	Who will be Responsible to Pay		Estimate Dec 2016	Who Will be Responsible to Pay			
Decommissioning	\$20 billion	TEPCO		\$80 billion	TEPCO			
Damage Compensation	\$50 billion	TEPCO	Other major utilities	\$80 billion	TEPCO \$40 billion	Other major utilities, \$40 billion	New power companies \$2.4 billion	
Decontamination	\$40 billion	TEPCO stock sale		\$60 billion	TEPCO \$40 billion			Japanese government \$20 billion
Total	\$110 billion			\$220 billion	\$160 billion	\$40 million	\$2.4 billion	\$20 billion

Source: Table created by authors based on METI, 2015; Ando, Momose, 2017.

A separate estimate comes from Japan's Ministry of Finance. The MOF reports that government expenditures for damage compensation support related to the nuclear accident is rapidly approaching \$500 billion (Figure 5.6) (MOF, 2018a). This estimate did not include decommissioning costs or decontamination costs, mentioned above.

Another source for damage compensation costs is the Nuclear Damage Compensation and Decommissioning Facilitation Corporation (NDF). According to annual financial reports, from 2011 to 2016 the Corporation paid out a total of about \$204 billion for damage compensation (See Figure 5.7). The NDF stopped publishing financial reports in 2017, however. Now it only reports on decommissioning costs.³⁷ Without NDF data from 2017 to 2018, it is difficult to estimate cumulative damage compensation costs, but the total might be close to the MOF data.

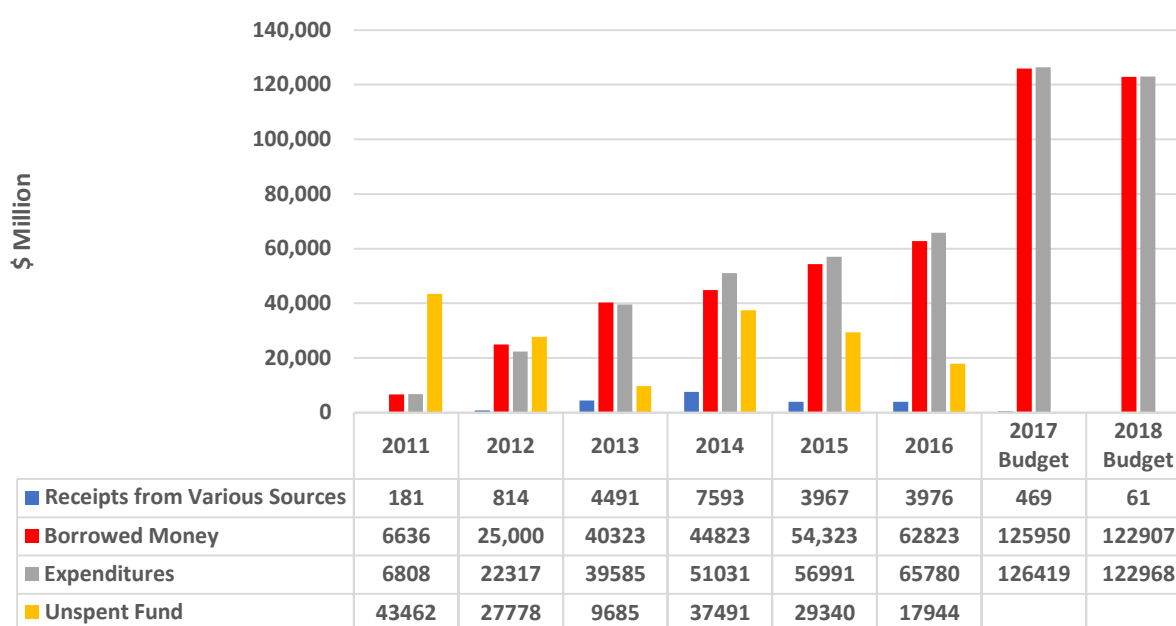


Figure 5.6 Nuclear Damage Compensation Support Account

Notes: Total Accumulated Debt (FY2011-2018) under the Nuclear Compensation Support Account is \$483 billion. The figures for FY2011-2016 are from the year-end budget settlement (*Kessan*) and the figures for FY 2017-2018 are from the initial budget (*Tosho Yosan*). The Settlement Account for any year is compiled 24 months after the year's accounts are closed.

Source: MOF, 2018b.

Independent estimates suggest the final cost for retrieving the melted cores, plant clean-up, restoration of land areas in the exclusion zones, compensation for economic losses and the

³⁷ The NDF law was partially revised and the revised law was enacted on 1 October 2017. The NDF was given the responsibility to deal with decommissioning.

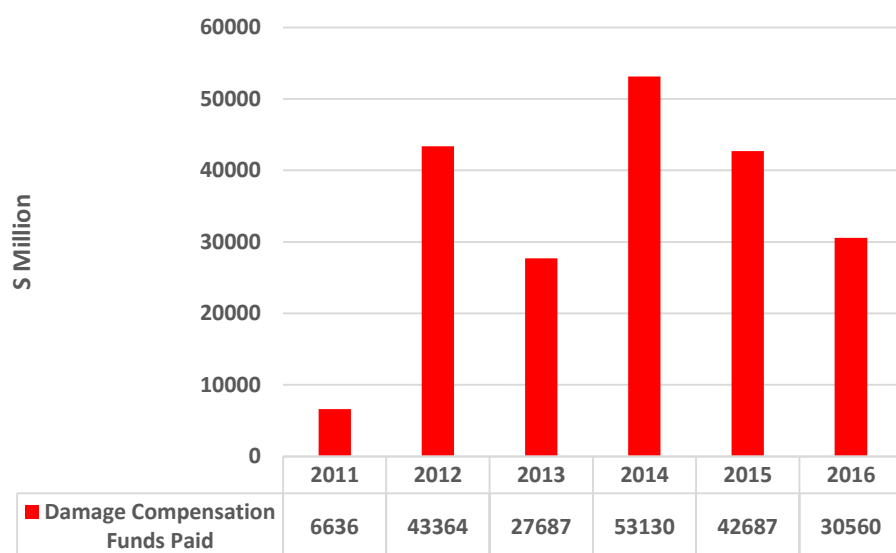


Figure 5.7 NDF Financial Reports on Damage Compensation Payments

Cumulative payments total \$264 billion from 2011-2016

Source: NDF, 2018a.

immense pain and suffering of victims who have lost their homes, will be at least \$500 billion:

- According to the Brookings Institution, the disaster could result in \$360 billion in economic losses in Japan. This estimate does not cover recovery and decontamination costs ([Ferris, Solis, 2013](#)).
- A French study estimates that if a generic major accident similar to a Fukushima-level event occurred at a French nuclear reactor the cost could reach \$515 billion, including \$15 billion for on-site decommissioning and clean-up³⁸ ([Institut de Radioprotection et de Surete Nucleaire \(IRSN\), 2014](#)).
- A special task force sponsored by the American Society of Mechanical Engineers (ASME) assessed a rough estimate of the total cost to Japan from the Fukushima Daiichi accident would be about \$500 billion. The task force went on to say that these costs will substantially increase because of the need for additional imported LNG to replace the power from shuttered nuclear power plants and from other losses of commerce ([ASME, 2012](#)).
- According to the Japan Center of Economic Research (JCER), total cost for the Fukushima clean-up would be as much as \$700 billion. The JCER estimate consists of the cost for reactor decommissioning and water decontamination (\$320 billion), clean-up of contaminated land (\$300 billion) and damage compensation (\$80 billion) ([Kobayashi, et al., 2017](#)).

³⁸ The French IRSN cost estimate of \$515 billion was based on the median costs for a range of major accident scenarios that involved uncontrolled releases of radionuclides—but did not include the worst possible cases (IRSN, 2014), which drove cost estimates much higher. The IRSN study also postulated a much smaller cost for decommissioning and clean-up than did METI, which would drive cost estimates down.

Cost estimates could grow over time as the recovery process progresses because unexpected problems often crop up. This happened with respect to both direct and indirect costs for Chernobyl (1986) and Three Mile Island (1979) ([Chernobyl Gallery, no date](#)). Based on Japan's MOF cumulative expenditures for damage compensation and METI's estimates of decommissioning and decontamination costs, a cost of \$700 billion would not be unreasonable.

If the MOF continues to borrow funds at the current rate to cover damage compensation, estimates of total accident costs could rise above a trillion dollars by 2020. To put this into perspective, in a few years, the disaster could represent ten percent of Japan's total national debt, which currently stands at about \$11 trillion (See Figure 5.8) ([MOF, 2017a, 2017b](#)). Japan's current national debt is about 15 times Japan's annual tax receipts and almost double Japan's GDP, a ratio which is the highest in the world (See Figure 5.9). The Japanese Government admits that the debts will be inevitably passed onto the next generations ([MOF, 2018c; IMF, 2018](#)). This estimate, moreover, does not take into account human suffering of those who had to evacuate contaminated areas. No doubt their pain is immense and immeasurable; yet we tend to ignore this in cost estimates because it is difficult to quantify in monetary terms.

5.2 Underlying Causes of the Fukushima Disaster

Many investigatory reports and studies have been published in the aftermath of the Fukushima nuclear accident and virtually all have criticized the Japanese administrative and

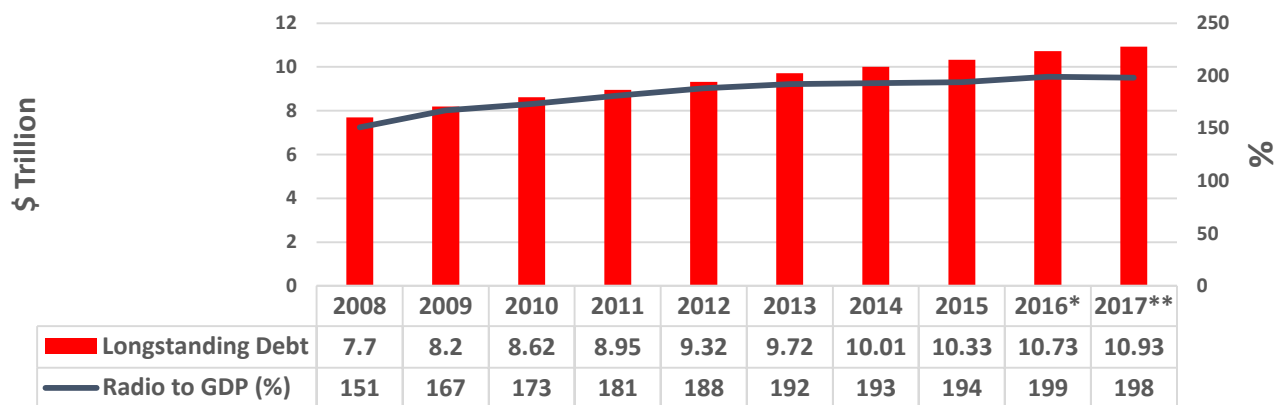


Figure 5.8 Japan's Long-Term Outstanding Debt, Ratio to GDP

Notes: Cumulative debt for 2017 is \$10.9 trillion, or 200 % of GDP.

* The 2016 debt figure is an estimate.

**The 2017 debt figure is an estimate in FY2017 budget.

Source: MOF, 2017a; IMF, 2017.

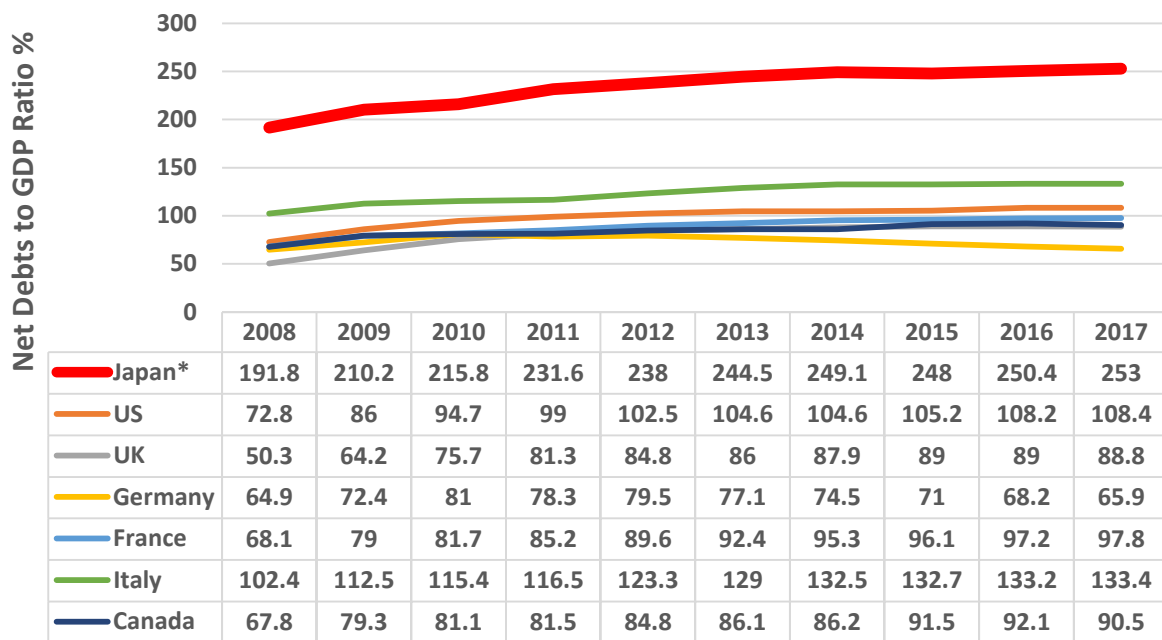


Figure 5.9 Comparison of National Debt in Terms of Ratio to GDP (in percent)
Source: IMF, 2017.

regulatory authorities and the Japanese nuclear industry for regulatory capture, negligence, lack of a safety culture, and the presence of moral hazards. The most cogent summary of the root causes of the accident can be found in a report prepared by the Examination Committee of the National Diet of Japan (WNA 2016a; National Diet, 2012).

The Commission Chair, Professor Emeritus of Tokyo University Kiyoshi Kurokawa said:

“Our report catalogues a multitude of errors and willful negligence that left the Fukushima plant unprepared for the events of March 11. And it examines serious deficiencies in the response to the accident by TEPCO, regulators and the government. For all the extensive detail it provides, **what this report cannot fully convey— especially to a global audience—is the mindset that supported the negligence behind this disaster** (emphasis added). What must be admitted—very painfully—is that this was a disaster “Made in Japan.” Its fundamental causes are to be found in the ingrained conventions of Japanese culture: our reflexive obedience; our reluctance to question authority; our devotion to ‘sticking with the program’; our groupism; and our insularity” (National Diet, 2012).

In retrospect, TEPCO and its safety oversight authority³⁹ were aware of the possibility that a tsunami might overwhelm the 5.7-meter seawall. TEPCO had been warned about such possibilities many times. Some 18 years before the 2011 disaster, new data had emerged about the likelihood of a large earthquake and resulting major tsunami of some 15.7 meters at the Fukushima Daiichi Nuclear Power Plant site (WNA, 2016a). But despite these warnings TEPCO did not fund a higher

³⁹ At the time of the Fukushima disaster, NISA fell under the Agency of National Resources and Energy (ANRE), which was a component of the Ministry of Economy, Trade and Industry (METI). METI was a key promoter of the nuclear power industry for many decades.

seawall, nor did it move back-up generators to a more protected location. In 2005, IAEA advised Japan to review the Japanese tsunami safety standards in view of the catastrophic earthquake and tsunami that struck the Indian Ocean in 2004 (IAEA, 2005). The WNA (2017) states that the tsunami countermeasures had been reviewed in accordance with IAEA guidelines, but NISA continued to allow the Fukushima plant to operate without sufficient countermeasures.

TEPCO's behavior exemplifies a widespread mindset among nuclear plant owners to downplay the importance of those safety measures that address infrequent but inevitably high consequence events. As a former Nuclear Safety Commission (NSC)⁴⁰ chairman remarked at a court hearing in 2007, "worrying about such possibilities would "make it impossible to ever build anything" (Kingston, 2012). Indeed, there is a systemic reluctance among government leaders to consider worst-case scenarios because discussing a worst-case scenario might panic the citizens, and so these contingencies were omitted from regulatory discussions (Knowledge@Wharton, 2013). Moreover, TEPCO's management apparently did not see value from a business perspective to fund safety improvements.

- The Diet Final Report on the Fukushima nuclear disaster asserted that "worrying about such possibilities and worst-case scenarios is obligatory for nuclear reactor operators and assuming them away is an inexcusable dereliction of duty (Diet, 2012).

According to Kingston (2012), the increased costs of meeting tougher safety standards poses a threat to the nuclear industry, which is why the nuclear operators have minimized the consequences of nuclear accidents and have fought to contain costs at the expense of operational safety.

Even though the disaster was predictable, no one, including TEPCO and METI, was prepared to cope with it. According to Kunreuther (Knowledge@Wharton, 2013), for example, even though experts were knowledgeable about the historical inevitability of an earthquake and tsunami and the consequences for a nuclear accident, responsible leaders tended to diminish the likelihood of such events by reasoning that earlier natural disasters happened long ago. In another post-Fukushima report made by the Cabinet of Japan, distinguished Tokyo University professor Yotaro Hatamura, who served as Chairman of the investigatory committee,⁴¹ philosophically remarked, "We must take this accident as a lesson from nature that **there are flaws in human thought and analysis**" (emphasis added) (Cabinet Office, 2012).

Particularly harsh criticisms were directed at the deficiencies in Japan's nuclear regulatory institutions, including the lack of independence and effectiveness, which the National Diet Investigatory Committee called "regulatory capture." The Committee report pointed out NISA's failure or willful negligence to enforce its regulatory duties and its failure to exercise due diligence

⁴⁰ The Nuclear Safety Commission (NSC) was an independent nuclear regulatory commission in the Cabinet of Japan that oversees and reviews safety inspections conducted by the Nuclear and Industrial Safety Agency (NISA). The government merged NSC and NISA to create a new nuclear safety agency, the Nuclear Regulation Authority (NRA), under the environment ministry, on September 19, 2012.

⁴¹ Prof. Hatamura with his coauthors published a book on the Fukushima accident in 2004. He served as the Chairman of the investigatory committee on the Fukushima Accident for the Cabinet, which published a report in 2012. Prof. Hitoshi Yoshioka, also a committee member of the investigatory committee, had told the authors that the Cabinet secretariat would not allow the committee members' opinion into the report. The committee members are only allowed to write the preface of the report.

(Čavoški, 2013; National Diet, 2012). In addition to regulatory capture, the report pointed to the lack of a meaningful safety culture at TEPCO (Cabinet Office, 2012). Decision-making practices seemed to border on sacrificing safety for the sake of cost-savings.

An example of this tendency can be found in TEPCO's cost-benefit analysis and risk assessments for the siting of reactors at Fukushima. In 1967 during the height of Fukushima plant construction, TEPCO had to deal with the terrain at the selected construction site, which was located atop a 35-meter cliff overlooking the sea. TEPCO's primary goal concerning the site was to reduce the height of the cliff to make it easier and cheaper to conduct sea-based delivery of nuclear reactors, machinery and equipment to the plant site. All nuclear construction material was transported to the site by sea because the area was remote at that time with no good access roads. Constructing new roads for transport of material was deemed too costly for TEPCO. Moreover, the plant would need seawater to keep the reactors cool. Pump capabilities then were of inferior quality and the closer the plant was to sea level, the more easily water would be pumped up to the plant. At the same time, the cost of electricity for pumping water would be less if the pumping distance was reduced (Wikipedia, 2016). TEPCO calculated that the cost would be about \$14-\$15 million to build the plant at a height of 11 meters above sea level and about \$15-\$16 million if it were built at 15 meters. TEPCO thus reduced the cliff height by 25-meters to just 10 meters to save \$1 million (See Figure 5.10). The effect of this decision was to place the nuclear plant five meters below the level of the 15-meter tsunami on March 11.

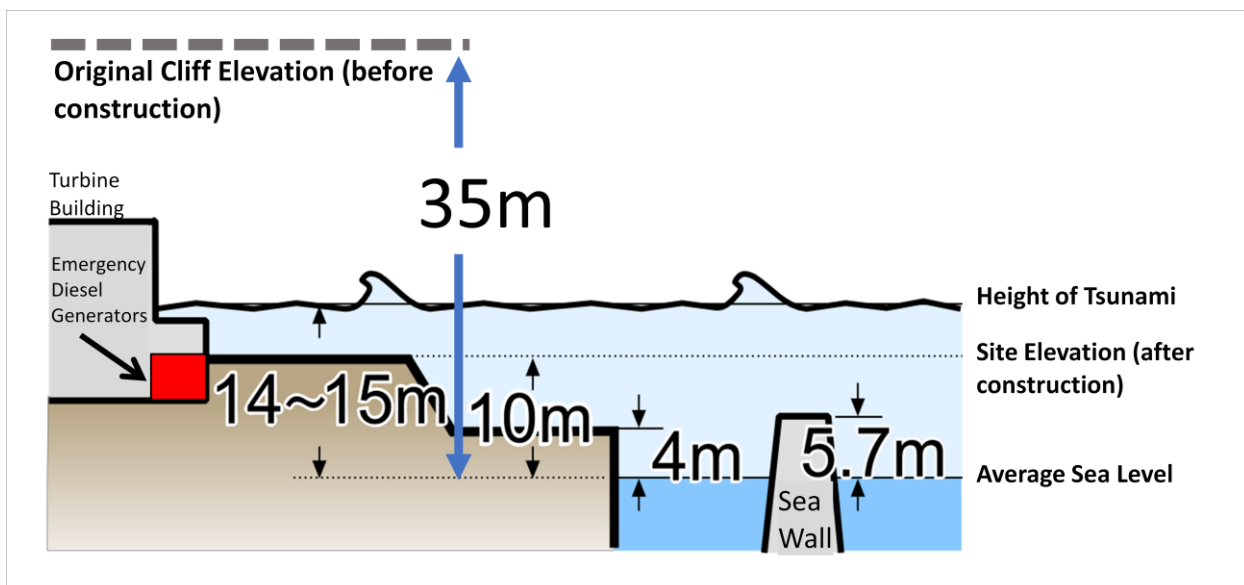


Figure 5.10 Schematic of Fukushima Daiichi Nuclear Plant Construction Site

Source: Created by authors based on data from National Diet, 2012

Other studies make the case that TEPCO was subject to “moral hazard” because the company had limited liability for any nuclear accident. Ramseyer suggests that, having limited exposure to accident costs, TEPCO thus could discount safety risks to save on acquisition and operating costs, according to (Ramseyer, 2012). Under the “Genshiryoku songai no baisho ni kansuru horitsu (Law

regulating the Compensation for Nuclear Damage),” Law No. 147 of 1961, a nuclear plant owner would be liable for damage, limited to its assets; beyond that amount any losses would fall on its victims. The law required the operators to buy insurance from a private insurer and obtain separate insurance from the government. Both would cover liabilities up to \$1.2 billion per reactor. The private insurer would cover most accidents except natural disasters, while the government would cover disasters caused by natural events, like earthquakes and tsunamis, which private insurers typically exclude. Should all this prove insufficient, the statute authorizes the government to help.

In retrospect, TEPCO was certainly aware of the possibility of a tsunami that might overwhelm the 5.7-meter seawall and the nuclear facilities on the 10-meter high site because it was warned about such possibilities many times. Certainly, if TEPCO wanted to raise the sea wall, it could have done so with a modest investment. According to Schwarz and Cochran (Schwarz, Cochran, 2012), such an accident as the 3.11 disaster could have been avoided or alleviated if certain technological safeguard measures had been taken when the plant was originally under construction. Their study points to four measures (See Table 5.3): relocating the plant 10 km inland, building a 15-meter sea wall, using a lead acid battery backup system and relocating the diesel generators to a higher site. Schwarz and Cochran suggested that if TEPCO had implemented at least one of the four safeguards before the Fukushima disaster, it would have greatly reduced the probability of a catastrophic nuclear reactor meltdown. They argue these measures would have added \$62 million to the cost of constructing a nuclear plant. This would have been a mere fraction of the cost of the Fukushima disaster.

Table 5.3 Cost of Safeguards That Could Have Alleviated the Fukushima Disaster

Safeguard	Effective Total Cost Of the Safeguard (\$)
Alternative site	30 million
Fifteen-meter tsunami wall	30 million
Lead acid batteries	1 million
Alternative emergency generator site	1 million
Total	62 million

Source: Schwarz and Cochran, 2012.

5.3 Japan’s Response to Fukushima

Many post-Fukushima accident reviews have argued that the government’s desire to protect “the nuclear village” and its lax safety supervision of the nuclear industry were major reasons why the disaster occurred. These views triggered several regulatory reforms in the post-Fukushima government and the establishment of stricter safety regulations, notably measures that would apply

in case of accidents that went beyond “design basis” ([Kingston, 2013](#); [Tolliday, 2012](#)). In addition, the Diet instituted major changes to organizations with safety oversight authorities:

- Based on what was seen to be collusion between NISA and METI, the Diet took away METI’s responsibility for nuclear safety and established a new regulation authority focused on safety (Law 47, 27 June 2012). The law combined NISA with the Nuclear Safety Commission, which had been based in the Cabinet Office, and established the Nuclear Regulation Authority (NRA) reporting to the Ministry of Environment (Law 47, 27 June 2012).
- A related law on Regulation of Nuclear Source Material, Nuclear Fuel Material and Reactors (Law 82, 22 November 2013) gave the NRA authority over refining activities, fabricating and enrichment activities, interim storage activities, reprocessing activities and waste disposal activities, as well as on the installation, operation, maintenance and, significantly, dismantlement (abolition) of reactors.
- Under the new authority, the NRA established stricter safety standards, which were enacted on 8 July 2013. The new standards reinforced the protective measures against large scale, natural and man-made disasters, such as earthquakes, tsunamis and terrorist attacks, and promoted defense-in-depth preparedness to prevent multiple failures, multiple core damage, containment failures, and radioactive material releases. The new standards applied retroactively to all the existing nuclear facilities. The former regulations lacked robust measures against natural disasters and terrorist attacks and did not have the power to retroactively impose the new standards on existing facilities. These additional requirements are illustrated in Figure 5.11 ([NRA, no date](#)).
- The National Diet also established the NDF in September 2011 (Law No. 94) to ensure that compensation payouts were promptly and appropriately provided and that a stable supply of electricity could be secured. This was to be accomplished by giving the NDF the authority to grant compensation funds to nuclear plant operators if they were faced with a large-scale nuclear damage scenario. The NDF also created a Business Transformation Plan (or Special Business Plan) for TEPCO to ensure that the corporation paid compensation to those affected by the accident.
- In August 2014, the Diet gave the NDF additional responsibilities to oversee decommissioning of the Fukushima reactors.⁴² The NDF Act was revised yet again in May 2017, giving the NDF still more authority—this time to direct TEPCO to reserve specified funds with the NDF and “to be further involved in the project management as an administrator/supervisor of the decommissioning.” The various responsibilities of the NDF are depicted on the left side of Figure 5.11.

⁴² The formal name for the NDF is now the Nuclear Damage Compensation and Decommissioning Facilitation Corporation. Decommissioning was added to the name in 2014.

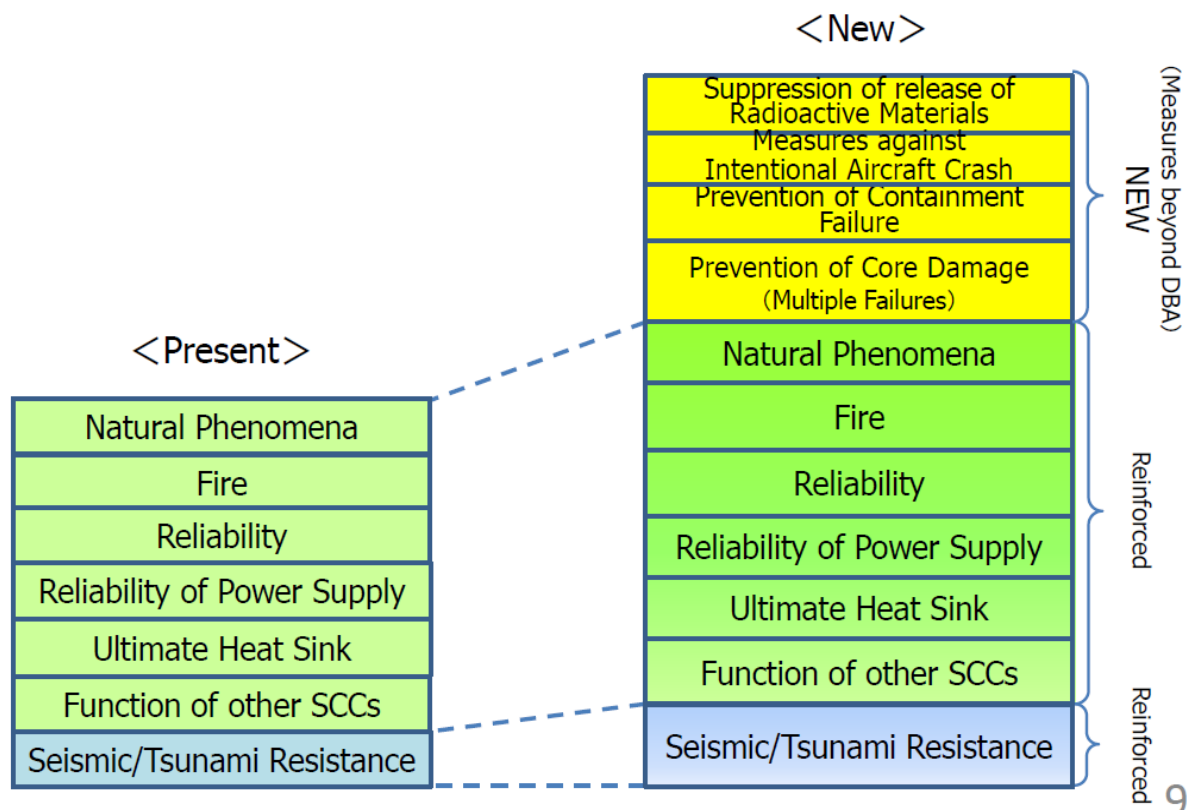


Figure 5.11 Regulatory Changes for Nuclear Power Plants in Japan
Source: Yamada, 2013.

Under its statutory obligations the NDF prepares an annual “Technical Strategic Plan” that provides detailed technical guidance for dealing with decommissioning challenges, conducting R&D, and disseminating information regarding decommissioning efforts. Specific duties of the NDF now include:

- Determining the amount of funds to be reserved by TEPCO (with the approval of the METI minister) and held by the NDF in each fiscal year.
- Working with TEPCO and the competent minister to create a withdrawal plan by which TEPCO will spend reserved funds for decommissioning the Fukushima reactors.
- Determining R&D policy and managing R&D activities performed by the International Research Institute for Nuclear Decommissioning.
- As indicated in its Technical Strategic Plan, acting as project manager and supervising the decommissioning project.

Given its greater responsibilities, the NDF states in its Technical Strategy Plan that it will supervise an appropriate system for executing the decommissioning project and will provide support for steady work management. This includes such activities as conducting assessments of project execution by TEPCO and proposing tasks that should be included in the funding withdrawal schedule.

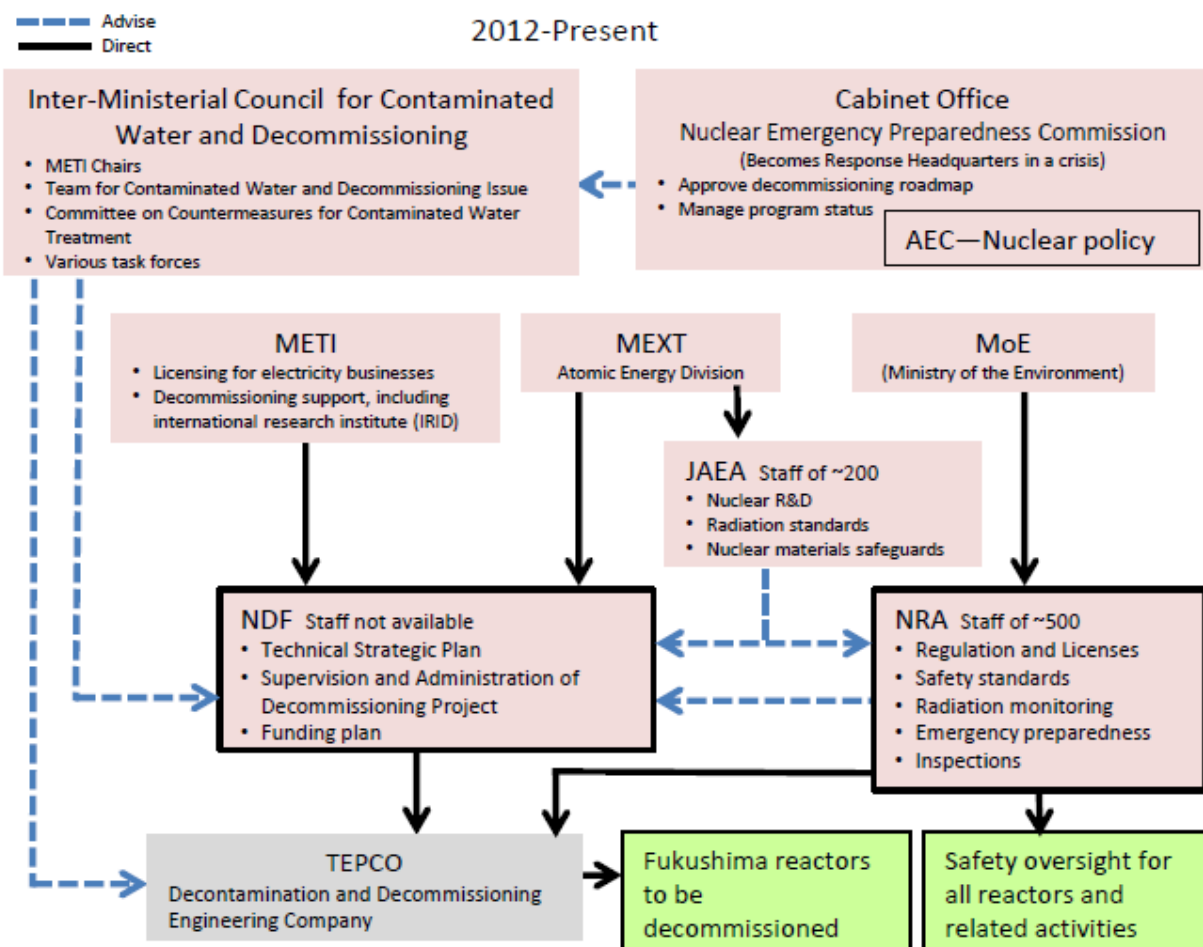


Figure 5.12 Post-Fukushima Oversight: Overlapping Responsibilities of Bureaucracy
 Source: Created by the authors based on analysis of organizational information from the NDF, 2017a; Oshima, 2013; IMC, 2017; NRA, no date (webpage).

While the NDF has taken on a comprehensive set of tasks to manage, this has not stopped other government entities from providing more help. At the Ministry level, for example, concern was growing in 2012-2013 that problems of contaminated water leakage around the damaged Fukushima reactors were not getting solved. The Prime Minister activated his Nuclear Emergency Response Headquarters (NERH) and directed it to convene an Inter-Ministerial Council (IMC) to tackle water and other decommissioning issues. The IMC set up a Team for Contaminated Water and Decommissioning, which led to the formulation of a plan to implement “a multi-layered set of countermeasures,” including managing contaminated water by such measures as freezing soil walls around the site to create a barrier to the flow of ground water. Many other measures were proposed in the plan, which duplicated in many ways the Technical Strategic Plan for Decommissioning put forward by the NDF.

The duties of the NDF, the NRA, and the various Inter-Ministerial teams clearly overlap in law and executive control. Both the NDF and the NRA have oversight responsibilities for decommissioning. The NDF creates the plan for decommissioning and supervises TEPCO’s work, while the NRA has

the legal authority to review and approve the decommissioning plan from a safety perspective and can withdraw that approval if it doesn't like what it sees. The IMC teams have substantial influence and control of the decommissioning plans as well because their members come from government Ministries that control the NDF and the NRA.

Figure 5.12 illustrates this tension. The Figure is a composite of selected organizational charts that have been issued by the NDF, NRA, and other oversight components of the Japanese government. TEPCO clearly is responsible for executing decommissioning tasks, but legally it must take direction from at least three authorities: from the NDF for executing decommissioning tasks, from the NRA for maintaining appropriate safety standards, and from the Nuclear Emergency Response Headquarters at the ministerial level for any issue it might identify. Ideally, TEPCO should be responsible only to a single authority. The current arrangement is almost guaranteed to result in conflicting guidance to TEPCO, giving TEPCO the opportunity to follow the guidance that it finds most congenial. There is real ambiguity with respect to who is actually in charge of the Fukushima decommissioning project, but one thing is certain: complex technical projects that lack a clear chain of command are rarely successful.

5.4 Confronting the Larger Problem: A History of Accidents

According to the Japan Nuclear Energy Safety Organization (JNES)⁴³ and the Nuclear Regulatory Authority (NRA), Japan has had a total of 772 nuclear incidents and accidents at nuclear power reactors from 1966 through December 2015, or about 13 per year (JNES, 2012a; NRA, 2016). This seems to be a startlingly large number.⁴⁴ Whether it is actually high or low we cannot tell because we were unable to make comparisons due to the lack of comparable, reliable world-wide databases. Nonetheless, three data sources stand out:

- The UK's Office of Nuclear Regulation published a comprehensive list of 3,857 safety events, both minor (representing the vast majority,) and a few that were of safety significance (nine events). The report covered the period from 1 April 2001 thru 31 March 2015 and an average of 22 operating reactors, representing about 12 reportable events per reactor per year.
- France's IRSN (2016) reviewed 711 safety and radiation protection events for 2015, of which 73 were rated on the INES scale (nearly all Level 1—only one event was classified Level 2). The report covered 58 reactors, representing about 12 events per reactor for 2015.
- The US Government Accounting Office (GAO, 2006) conducted a survey of more than 4,000 events assessed by the Nuclear Regulatory Commission, of which 13 were of increased safety significance. The report covered 103 reactors for the period from 2001 to 2005, representing about 8 events per reactor per year.

⁴³ The Japan Nuclear Energy Safety Organization (JNES) was integrated into the Nuclear Regulation Authority (NRA) on 1 March 2014. The NRA continues to issue accident reports every year. The website for the FY2016 issue is <http://www.nsr.go.jp/data/000187560.pdf>.

⁴⁴ The authors have searched for global nuclear incidents and accidents statistics but have been unable to find comprehensive and credible ones. It would be valuable to all nuclear power researchers if such a database were to be created and offered to the public.

Looking at the numbers in the Japan Nuclear Energy Safety Organization (JNES) database, it is possible to make only very gross comparisons (See Figure 5.13). Japan's event rate per reactor was notably high in the 1960s, but gradually dropped to a few per reactor in the 1970s, stabilized at less than one accident per reactor per year in the mid-1980s, and remained at that level throughout the 1990s and 2000s. We note that in 2014, five events were reported when there were no reactors generating power at the time. While the overall trend in the number of incidents and accidents has been mostly favorable, compared to the UK, France, and the US, Japan's record has not been outstanding. Adjusting for differing reporting standards, Japan's record might even be significantly worse.

Japan's most serious accidents have been unprecedented in scope and complexity. The Fukushima Daiichi accident did not happen in isolation; it was accompanied by a series of accidents at the neighboring Fukushima Daini power plant, located 12 km (7.5 mi) south of Fukushima Daiichi. Fukushima Daiichi has six reactors and Fukushima Daini four reactors. According to the JNES database, these two plants had a total of eight accidents during the 3.11 disaster, including one Level 7 (that applies to the entire Daiichi plant site), three Level 5s (that apply to the three Daiichi reactors that suffered core meltdowns) and four Level 3s (that apply to the four Daini reactors) (See Table 5.4). We suggest that the accidents involving three melted cores and the breach of containment vessels should each be separately rated as Level 7 accidents (vice Level 5). We show both ratings in Table 5.4.

Table 5.4 The Nuclear Accidents at Fukushima Daiichi and Fukushima Daini
The JNES database reports that Japan had 8 INES Level accidents at Fukushima Daiichi and Fukushima Daini Nuclear Plants on 11 March 2011. Our is also shown on table.

Accident Period	Plant/Reactor Name	Date	JNES Report	Authors View
On 11 March 2011 or soon afterwards	Fukushima Daiichi Nuclear Plant	11 March 2011	Level 7	3 Level 7 because of damage to 3 cores and 3 explosions
	Fukushima Daiichi 1	11 March 2011	Level 5	
	Fukushima Daiichi 2	11 March 2011	Level 5	
	Fukushima Daiichi 3	11 March 2011	Level 5	
	Fukushima Daiichi 4	11 March 2011	Level 3	Level 3
	Fukushima Daini 1	11 March 2011	Level 3	Level 3
	Fukushima Daini 2	11 March 2011	Level 3	Level 3
	Fukushima Daini 4	11 March 2011	Level 3	Level 3
Total			1 Level 7 3 Level 5 4 Level 4	3 Level 7 4 Level 3

Source: Table created by authors based on interpretation of data from

Source: JNES, 2014.

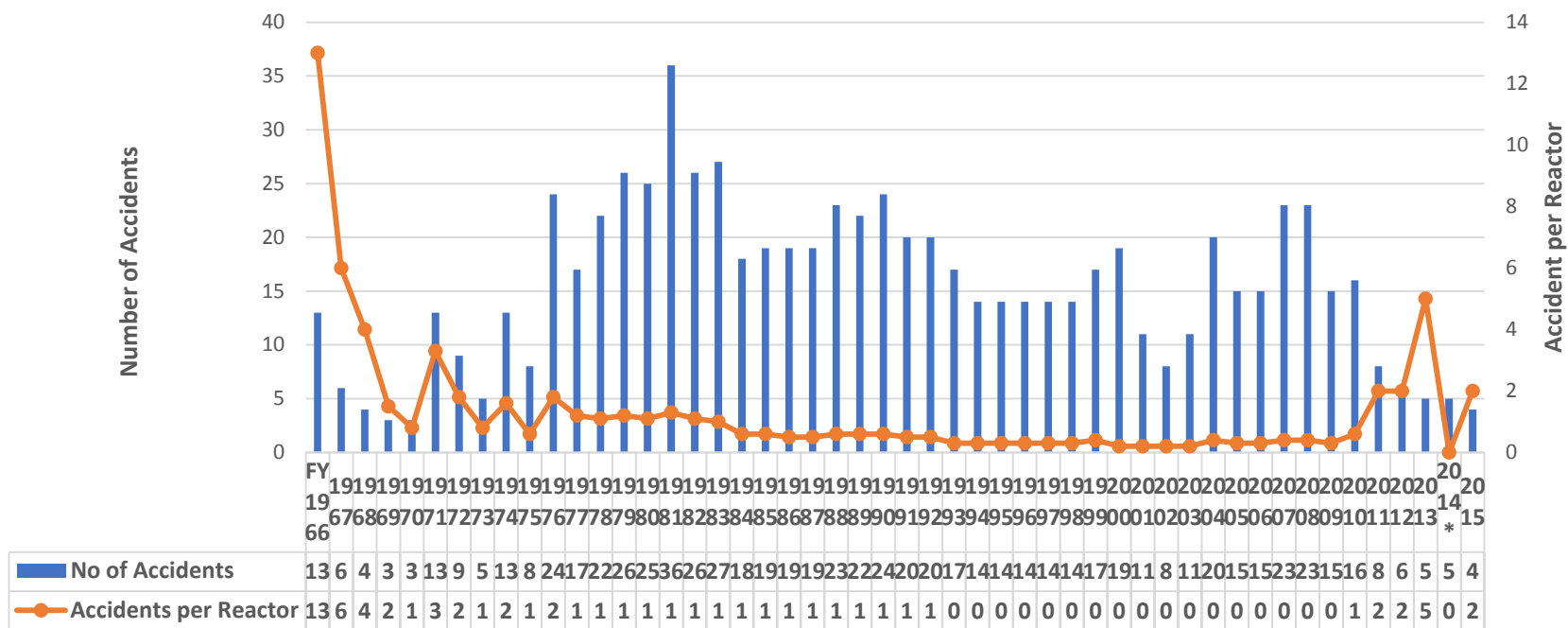


Figure 5.13 Trends in Nuclear Accidents and Accidents per Reactor, Fiscal Year 1966-2015

Note: Total Number of Accidents = 772. Accidents per reactor is calculated based on the number of accidents divided by the number of operating reactors in the particular fiscal year. In FY2014, although there were 54 dormant reactors and no operating reactors, there were 5 accidents. Because it is not possible to divide 5 accidents by 0 reactors, the chart shows no accident.

Source: Created by the authors based on analysis of data from Japan Nuclear Energy Safety Organization (JNES), 2014; Japan Atomic Industry Forum (JAIF), 2014a, 2016; Nuclear Regulation Authority (NRA), 2016.

We have rated the Fukushima accident ourselves because there have been disputes over the authoritativeness of the INES rating system as it has been applied to Fukushima.. For example, the Fukushima Daiichi nuclear accident was originally rated as INES 5, but then upgraded to INES 7 when the events of Units 1, 2 and 3 were combined into a single accident. Considering that change, we judge that the INES rating for the Fukushima accident is very likely to be revisited. Others say that the INES scale is inconsistent, that the scores provided by the IAEA are incomplete, and that many significant events have not been given an INES rating ([Minh, Journé, 2014](#); [Wikipedia, 2018c](#)).

Taking into account the limitations of the INES rating system it is nevertheless apparent that Japan has had a greater number of more serious accidents than any other country in the world (See Table 5.5). Of a total of 25 serious accidents worldwide rated INES 3 or higher, Japan had 7 of them, or 28 percent of the world total.

- Japan's share of serious accidents is disproportionately large for a country that had 54 nuclear reactors, which is 12 percent of the 450 power reactors that were in service worldwide as of March 2011. (A comparison of the respective sizes of the current worldwide nuclear power reactor fleets can be found at Appendix B).

INES ratings of 3 or higher should be considered as the tip of an iceberg. Many accidents have occurred on a worldwide basis at lower levels of severity and still more have been recorded as incidents that could be construed as a kind of "near miss." Thus, it is possible to conclude that Japan not only has had the highest number of nuclear events per reactor but also has had more accidents of a serious nature than any other country. Looking across all accidents with an INES rating of 3 or more, Japan has had twice as many serious accidents as the United States and more than three times as many as France ([JAIF, 2014b](#)).⁴⁵

5.5 Vulnerability to Natural Disasters

Since the Fukushima disaster on 11 March 2011, the public has become skeptical of the Government of Japan's assertions of nuclear safety, especially those that would argue Japan's reactors have the capability to withstand frequent earthquakes, tsunamis and related hazards. Indeed, prior to Fukushima, the government had played down the dangers posed by geologic faults near Japan's nuclear power plants as well as the inherent risks associated with handling and protecting radioactive fuel in the midst of a natural disaster.

- For example, Atsuyuki Sassa, first Director General of the Japanese Cabinet Security Affairs Office (1986–89) stated that when the Great Hanshin-Awaji Earthquake (Kobe Earthquake) of Magnitude 7.3 struck in the southern part of Hyogo Prefecture in January 1995, then director general of the STA Makiko Tanaka questioned whether Japan's nuclear plants really were prepared to withstand earthquakes and suggested that geologic surveys be conducted near nuclear plant locations ([Sassa, 2015](#)).

⁴⁵ On the eve of 3.11, Japan had 54 nuclear reactors in operation, the United States had 100 reactors and France had 58 reactors.

Table 5.5: Global Nuclear Power Plant Serious Accidents (Author's rating for Japan)

Country	INES 3	INES 4	INES 5	INES 6	INES 7	Total
Canada	Pickering A, 1994 (est.)					1
Czechoslovakia	Jaslovske Bounce A-1, 1976 ⁴⁶	Jaslovske Bounce A-1, 1977				2
France		Saint-Laurent-de-Eaux, 1969; Loir-et-Cher, 1980				2
Germany	Greifswald, 1975					1
Hungary	Paks, 2003					1
India	Rajasthan 2, 1993					1
Japan	Fukushima Daiichi 4, 2011; Fukushima Daini Units 1, 2 & 4, 2011				Fukushima Daiichi Units 1, 2 & 3, 2011	7 ⁴⁷
Russia		Leningrad, 1974	Beloyarsk, 1977			2
Spain	Vandellos, 1989					1
Switzerland			Lucens, Vaud, 1969			1
Ukraine			Chernobyl 1, 1982 ⁴⁸		Chernobyl 4, 1986	2
UK	Chapel Cross, 1967, est.					1
USA	Browns Ferry, 1975, est.	Davis-Besse, 2002	TMI, 1979			3
Total	12	5	4	0	4	25

Sources: Table created by authors based on interpretation of data from Baranowsky, 2004; HM Nuclear Installations Inspectorate, 2002; JNES, 2014; Kuruc, 2007; Lochbaum, 2016; Minh, Journ'e, 2014; Sovacool, 2010; Taylor, Spivak, 2001; Wikipedia, 2018a; Wikipedia, 2018b; Wikipedia, 2018c; Wikipedia, 2018d; Wikipedia, 2018e; Wikipedia, 2018f.

⁴⁶ Accident not formally rated. Description by J. Kuruc, Comenius University, 2007, indicates refueling accident with two fatalities; Kuruc suggests INES 3.

⁴⁷ IAEA rated the Fukushima accident as a tentative INES 7. The authors tentatively rated the Fukushima disaster as three Level 7s and four Level 3s.

⁴⁸ A partial core meltdown occurred at reactor No. 1. The accident was not made public until 1985. IAEA rated the accident as INES 5.

- All local government leaders voiced their opposition to her idea, however. They thought that such surveys might invite unwanted scrutiny or start rumors that their nuclear plants were vulnerable to earthquakes. They argued that “there was no chance of threat from earthquakes” ([Sassa, 2015](#)).
- The Cabinet of Japan supported the position and no geologic surveys were conducted. Sassa indicated in 2015 that if the surveys had been performed, the disaster at the Fukushima Daiichi Nuclear Power Plant might have been avoided ([Sassa, 2015](#)). Considering how past accidents have been triggered directly or indirectly by seismic events, Sassa’s assessment could be applied to a number of other nuclear power plants which are located near active geologic faults, as the discussion below will show.

5.5.1 The Breadth of Japan’s Seismic Geology

Japan’s vulnerability to earthquakes is a consequence of complex movements of tectonic plates that led to the creation of the Islands of Japan over hundreds of millions of years. These movements were driven in part by the subduction of the Philippine Sea Plate beneath the continental Eurasian Plate to the south and the subduction of the Pacific Plate under the North American Plate to the north. What are now the Islands of Japan originally were attached to the East coast of the Eurasian continent. As the plates shifted, the islands moved eastward, opening the Sea of Japan some 15 million years ago. As a result, Japan today is located atop four tectonic plates whose boundaries are defined by deep sea trenches, many hundreds of geologic faults that transit both land and sea and nearly-continuous seismic and volcanic activity (See Figure 5.14). This zone of intense geologic activity is part of what is called the Pacific Ring of Fire or the circum-Pacific belt. The circum-Pacific belt encompasses 452 volcanoes and more than 75 percent of the world's active and dormant volcanoes. About 90 percent of the world's earthquakes and 81 percent of the world's largest earthquakes occur along the Ring of Fire. Low intensity earth tremors are felt throughout the Japan Islands almost daily and about 1500 earthquakes strike Japan every year, accompanied by occasional destructive earthquakes which result in tsunamis several times a century. Japan accounts for about 20 percent of the world's earthquakes of Magnitude 6 or greater ([Obayashi, Lies, 2016](#); [USGS, no date](#)), (See Table 5.6).

Map of Epicenters and Nuclear Power Plants in Japan

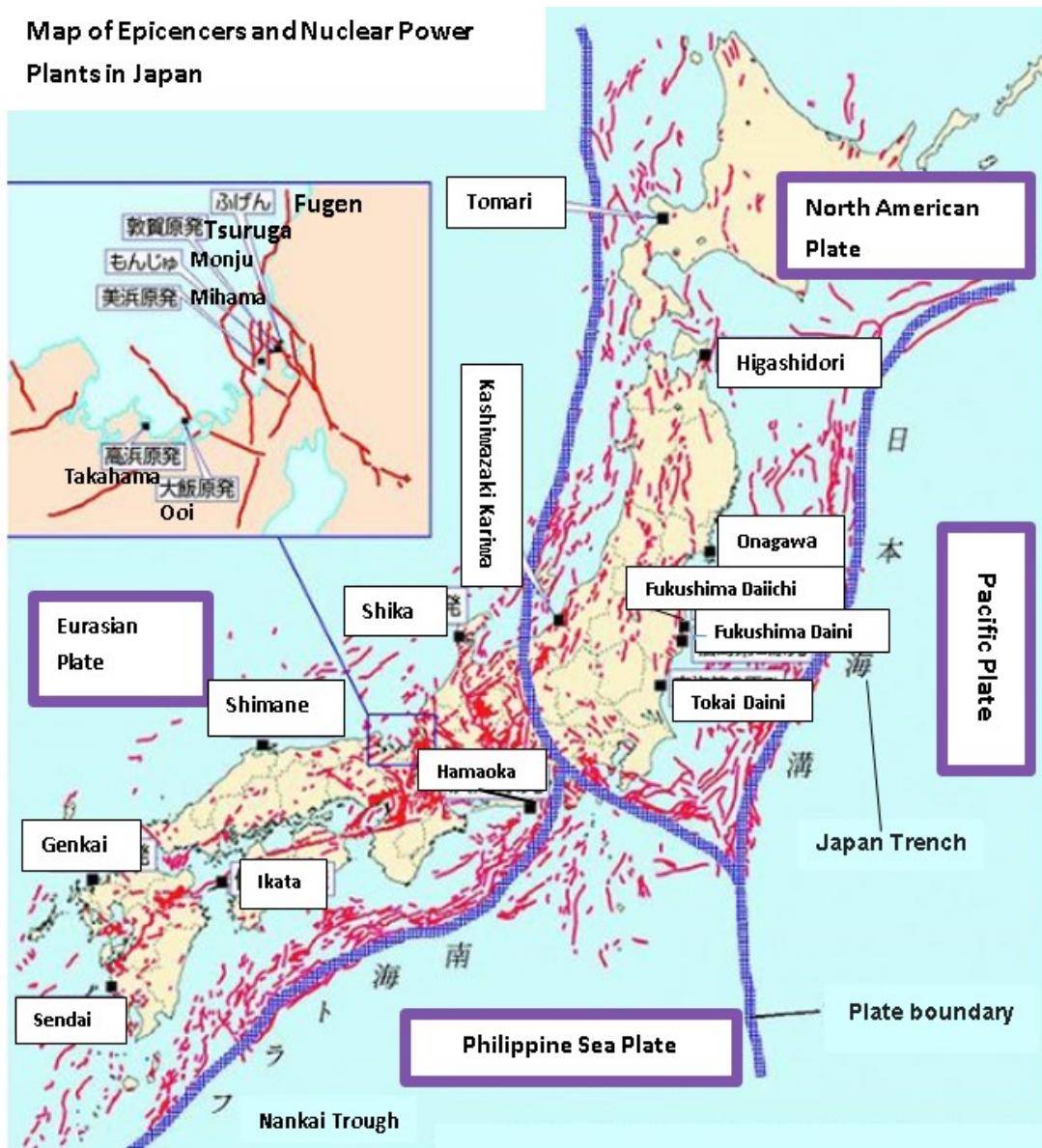


Figure 5.14 Japan Sits Atop Four Plates of the Earth's Crust: Map of Plates, Active Faults and Nuclear Power Plants in Japan

— Purple Links shows the boundaries of four tectonic plates

— Red lines are active faults

Source: From Geological Survey Research Center of the Agency of Industrial Science and Technology, 2016. Originally published in “Shin-hen, Nihon no Katsu-danso (New Edition, Japanese Active Faults)” by Tokyo University Press, 2016. <http://imart.co.jp/katu-dansou-japan.html> (accessed 17.01.26).

Table 5.6 Recent Earthquakes on or near the Islands of Japan Greater than Magnitude 7

Date	Magnitude (<u>moment magnitude scale Mw</u>)	Name of Earthquake
January 17, 1995	7.3 Mw	Great Hanshin earthquake (Kobe earthquake)
May 4, 1998	7.5 Mw	<u>1998 Ryukyu Islands earthquake</u>
Sept 25, 2003	8.3 Mw	Hokkaido earthquake
October 23, 2004	6.9 Mw	<u>2004 Chuetsu earthquake</u>
March 20, 2005	7.0 Mw	<u>2005 Fukuoka earthquake</u>
August 16, 2005	7.2 Mw	<u>2005 Miyagi earthquake</u>
November 15, 2006	8.3 Mw	<u>2006 Kuril Islands earthquake</u>
January 13, 2007	8.1 Mw	<u>2007 Kuril Islands earthquake</u>
August 9, 2009	7.0 Mw	<u>2009 Izu Islands earthquake</u>
February 26, 2010	7.0 Mw	Ryukyu Islands earthquake
December 21, 2010	7.4 Mw	<u>Bonin Islands earthquake</u>
March 9, 2011	7.2 Mw	<u>2011 Tohoku earthquake</u> (or Great East Japan earthquake) foreshock
March 11, 2011 (14:46 JST)	9.1 Mw	<u>2011 Tohoku earthquake</u>
March 11, 2011 (15:25 JST)	7.1 Mw	<u>2011 Tohoku earthquake</u> aftershock
April 7, 2011 (23:30 JST)	7.1 Mw	<u>2011 Miyagi earthquake</u> aftershock
April 11, 2011 (17:16 JST)	7.1 Mw	<u>2011 Fukushima earthquake</u> aftershock
July 10, 2011 (10:57 JST)	7.0 Mw	<u>2011 Fukushima earthquake</u> aftershock
December 7, 2012	7.3 Mw	<u>2012 Kamaishi earthquake</u>
May 30, 2015	7.8 Mw	<u>Bonin Islands</u>
April 16, 2016	7.0 Mw	<u>2016 Kumamoto earthquakes</u>

Source: Wikipedia, 2017a.

5.5.2 Vulnerability of Japan's Nuclear Plants to Earthquakes

Given the geologic deck of cards that Japan has been dealt, it is natural for the public to have concerns about the vulnerability of Japan's nuclear plants to earthquakes. This concern was succinctly summarized in a National Diet report on the Fukushima Disaster, which revealed that Japan had no seismic standards for withstanding earthquakes in the early years of plant construction and that plant safety was entirely left to the operators' discretion. Even after earthquake-resistant standards were established in later years, older reactors were not required to meet these standards. Instead, decisions about meeting new standards were left to the operators of the plants (National Diet, 2012). It is, therefore, not surprising that some reactors still do not meet current seismic safety standards (Ishibashi, 2007). Evidence of this has been pointed out by Kobe University seismologist professor Katsuhiko Ishibashi. According to Ishibashi, between 2005 and 2007, three nuclear power plants were struck by three major earthquakes, with seismic readings at the reactor sites

exceeding the plant's seismic design⁴⁹ (Takada, 2012; Ishibashi, 2007). Those plants, thus, should have been built to a higher seismic standard, certainly higher than the level of the earthquakes that had just struck them.

- Ishibashi (2007) has warned that Japanese nuclear plants will be faced with more frequent and greater earthquakes in the future. He indicated that during the 40 years when Japan was building its nuclear plants, seismic activities were relatively quiet and not a single nuclear facility was struck by a major earthquake during that time. The government, along with the power industry and the academic community developed overconfidence in plant engineering, which led to underestimating the potential risks posed by major earthquakes. Ishibashi points out that since the time of the Great Hanshin Earthquake that devastated Kobe in 1995, almost all of the Japan archipelago has entered a period of increased seismic activity. Indeed, Japan has experienced many large earthquakes since then, including the 2011 Great East Japan Earthquake at a Magnitude 9.0, which was the most violent earthquake ever recorded in Japan.

It is noteworthy that Ishibashi was a member of the 2006 Japanese government subcommittee that was charged with revising the national guidelines for earthquake-resistant nuclear power plants, the final report of which was published in September 2006. Ishibashi's recommendations that the subcommittee establish more robust seismic guidelines and that the government review the standards for surveying active faults were rejected. He resigned in protest at the subcommittee's final meeting, claiming that the review process was "unscientific" and the outcome rigged to suit the interests of the Japan Electric Association (JEA)—an association of Japanese power utilities and the owners of Japanese nuclear plants. Indeed, 11 of the 19 members on the subcommittee were JEA representatives. Ishibashi also alleged that the government guidelines were "seriously flawed" because the guidelines underestimated the design basis for earthquake ground motion (Ishibashi, 2006).

- Five years later, Japan experienced the catastrophic Fukushima disaster. On 15 March 2011, Ishibashi said: "If Japan had faced up to the dangers earlier, we could have prevented Fukushima" (Ishibashi, 2011). Atsuyuki Sassa, first Director General of the Japanese Cabinet Security Affairs Office, had made a similar remark.

5.5.3 Increased Scrutiny of Power Plant Seismic Hardening

In recent years, the Japanese government has become much more cognizant of the threat posed by earthquakes to nuclear plants. The Nuclear and Industrial Safety Agency (NISA), the former nuclear regulatory overseer that was abolished after the 3.11 disaster, had directed that geological surveys be conducted at six nuclear plants and facilities, Higashidori, Mihama, Monju (FBR), Oi,

⁴⁹ The plants were the Onagawa Plant in Miyagi Prefecture struck by the August 2005 Miyagi earthquake, the Shika Plant in Ishikawa Prefecture struck by the March 2007 Noto earthquake, and the Kashiwazaki Kariwa plant in Niigata Prefecture struck by the July 2007 Chuetsuoki earthquake. In each case, the maximum ground motion caused by the earthquake was greater than the seismic design criteria for the nuclear power plants. This implies that these plants lacked adequate earthquake design standards.

Shika and Tsuruga.⁵⁰ The surveys, however, were entrusted to the plant operators. NISA had often delegated oversight duties to the operators, including periodic inspections of the plants. In many instances, the operators conducted self-inspections with no government supervision. Reports on the Fukushima disaster including the Diet report indicate that at times operators falsified records or made no record of abnormalities. Even when government officials were present at some inspections, minor misconduct apparently was condoned ([National Diet, 2012](#)).

Since the Nuclear Regulation Authority (NRA) took over oversight responsibility in September 2012, six panels of experts have been formed to investigate the geologic faults at the six aforementioned nuclear facilities. They have concluded so far that faults at Oi and Shika were inactive but faults at Tsuruga and Mihama were active. The owners of Tsuruga and Mihama announced in April 2015 that they plan to decommission three reactors at their plants, Tsuruga 1, Mihama 1 and Mihama 2 (See Figure 5.15). In December 2016, Cabinet ministers directed that Monju FBR be decommissioned. The JAEA submitted its decommissioning plan on 13 June 2017 to MEXT ([JAEA, 2017](#)). Higashidori was found to be located on an active fault but the operator has challenged the NRA assessment and a final assessment is not available ([NRA, 2018](#)).

- It is noteworthy that JNES, which merged with the Nuclear Regulation Authority (NRA) in March 2014, likely was concerned about the links between the earthquakes and nuclear accidents. In its 2012 accident assessment report, JNES mentioned that accidents common to Japanese boiling water reactors (BWRs) and pressurized water reactors (PWRs) during the past 50 years were due to cracking of small pipes and nozzles from earthquake vibration and shocks, such as the 2007 July Niigata Earthquake. JNES, nonetheless, made no mention of direct links between nuclear accidents and earthquakes ([JNES, 2012b](#)).

As a result of the Fukushima nuclear accident, NRA-sponsored geologic studies, and other economic reasons, the TEPCO CEO told the Fukushima Governor on 14 June 2018 that the company was working toward a decision to decommission all four units of the Fukushima Daini power plant (4 BWRs, 4400 MWe total) ([JAIF, 2018a, 2018b](#)). He provided no other details. Therefore we have not yet included the four reactors in the decommissioning program (See Chapter 8).

In addition to the six nuclear plants that have been reviewed by NRA's geologic studies, there are a number of other nuclear plants that are widely viewed as vulnerable to earthquake damage. They include Hamaoka 3, 4 and 5, which are believed to be located directly above the epicenter of the Tokai earthquake, Ikata 3, which is located on the median tectonic line in Shikoku, and all or some of the seven Kashiwazaki Kariwa reactors, which are close to various active faults.

⁵⁰ The Nuclear and Industrial Safety Agency (NISA) was abolished on June 20, 2012 and was replaced by a new agency, the Nuclear Regulation Authority (NRA), under the Ministry of the Environment, in September 2012. On March 1, 2014, the Japan Nuclear Energy Safety (JNES) was integrated into the NRA.

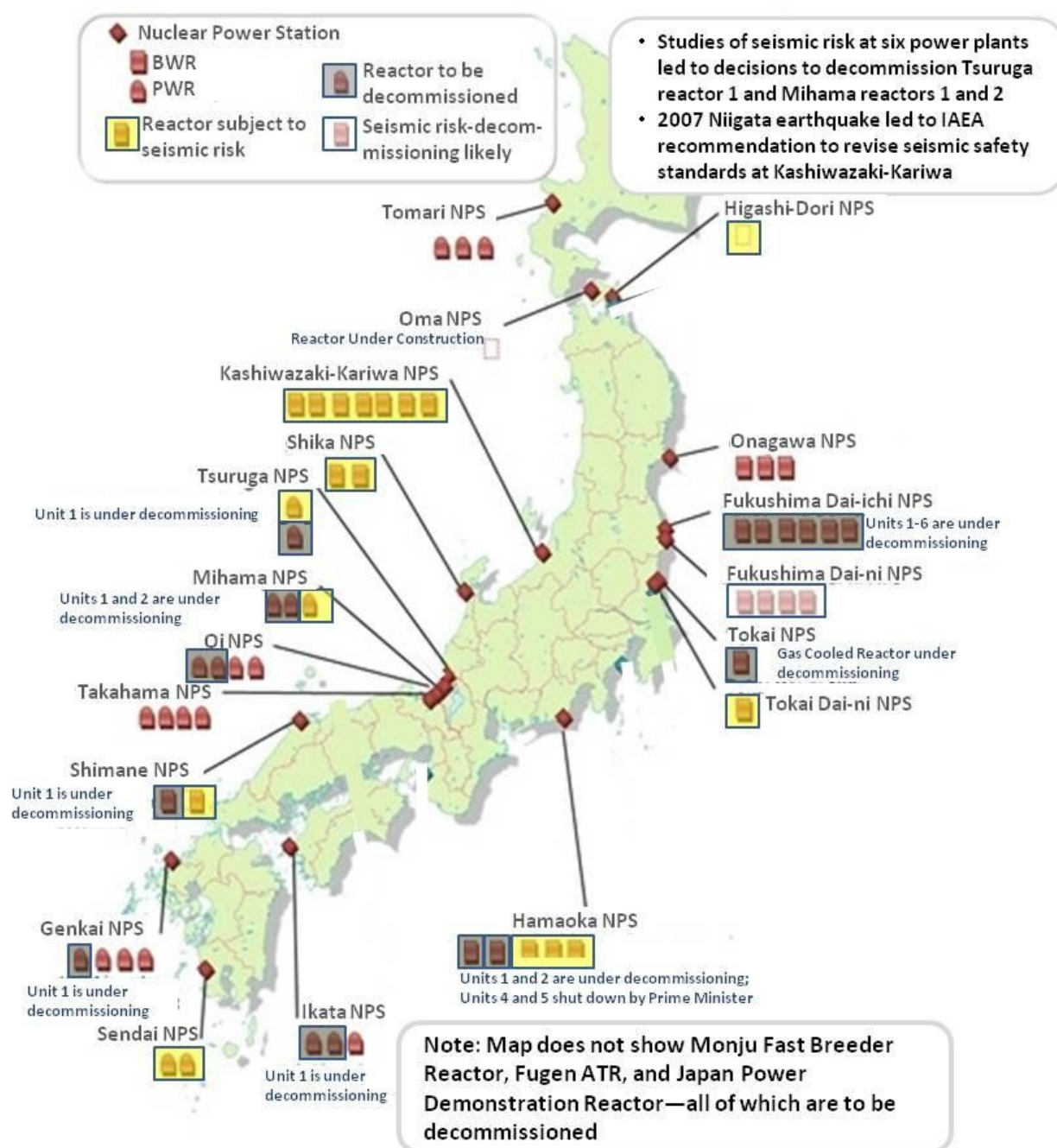


Figure 5.15 Seismic Risk to Japan's Nuclear Power Reactor Fleet (best graphic available)
 Of 57 reactors originally built, 18 are to be decommissioned; 23 are subject to seismic risk.
 Source: Created by the authors based on the data provided by the Government of Japan to the OECD. Notes are added by the authors.

Hamaoka 1 and 2 have been scheduled for decommissioning since 2009. In the aftermath of the 3.11 Fukushima disaster, Prime Minister Naoto Kan on May 6, 2011, also ordered the closure of Hamaoka 4 and 5 because of earthquake risk (Figure 5.16). Hamaoka 3 was closed for regular inspection in November 2010 has not operated since then (JAIF, 2018b).

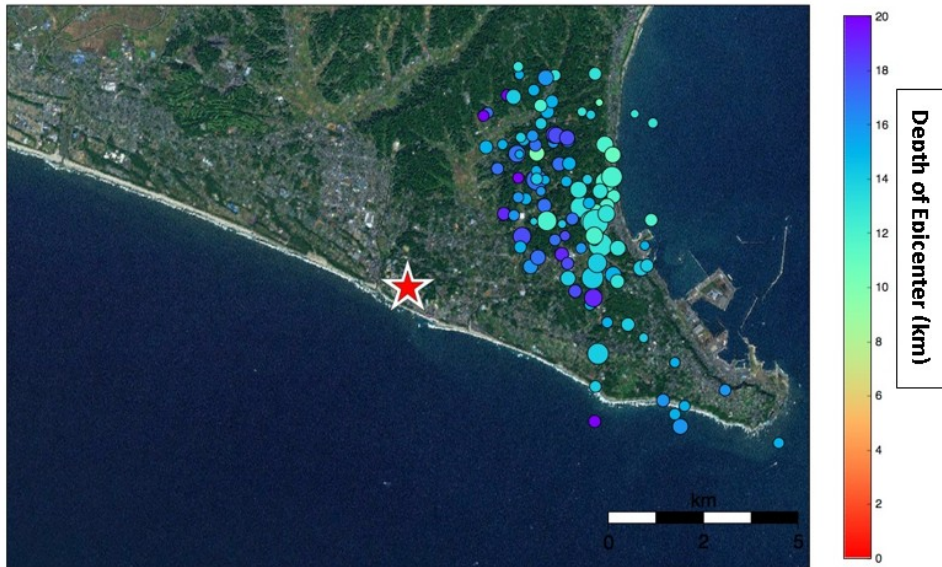


Figure 5.16 Epicenters of Swarm Earthquakes that Occurred Near the Hamaoka Nuclear Power Plant, August 29, 2015 to September 1, 2015

Note: The asterisk shows where the Hamaoka nuclear plant is located. The dots indicate epicenters of more than 100 earthquakes that occurred near the Hamaoka Nuclear Power Plant from August 29, 2015 to September 1, 2015. The shortest surface distance from the epicenter to the Hamaoka Plant is 2.6 km. The depth of the epicenter is shown by the color of the scale.

Source: Gtogg, 2015.

The Ikata Plant in Shikoku is located in the southern part of the Sadamisaki Peninsula in close proximity to the median tectonic line, which is one of the most prominent in Japan (See Figure 5.17). If an earthquake strikes the area causing the collapse of roads and ports and triggering a nuclear accident, about 5,000 residents living to the west of the plant could become isolated. In Ehime and Yamaguchi prefectures, more than 120,000 people reside within a 30-km radius of the Ikata plant. The operator of Ikata, Shikoku Electric, recently decided to decommission one of the three reactors at the plant. Ikata 1 is a small 566 MW reactor and is almost 40 years old (it was commissioned in 1976). It would require approximately \$2 billion to upgrade the reactor to meet new regulations, according to the operator. The decision reverses Shikoku's earlier position of planning for the restart of Ikata 1 (World Nuclear Industry Status Report, 2016).

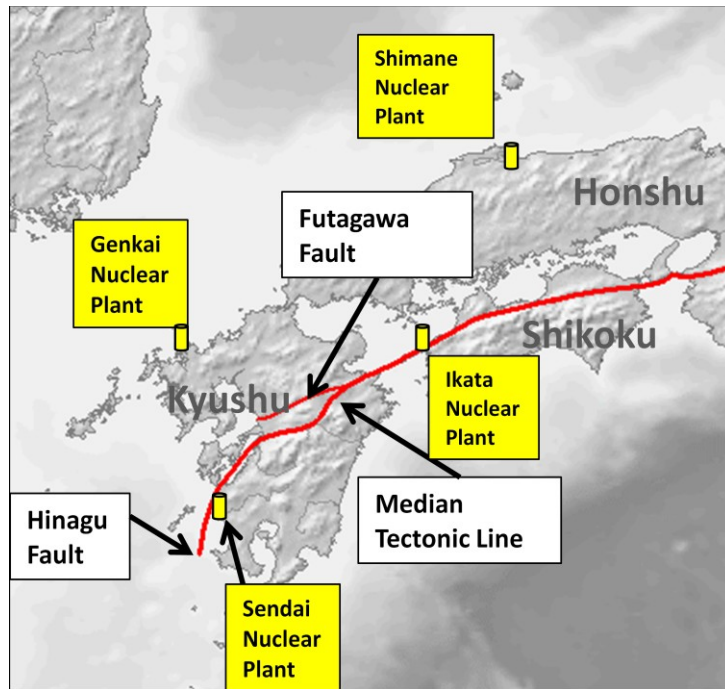


Figure 5.17 Locations of Nuclear Power Plants and Major Fault Lines in Western Japan Sources: Base map obtained from “Japan Median Tectonic Line,” Wikipedia, 2017b. Notations provided by the authors.

The Kashiwazaki Kariwa plant is also exposed to high seismic risks. As discussed earlier, Professor Ishibashi pointed out that the plant registered abnormally high seismic readings at the time of the Chuetsuoki offshore earthquake on July 16, 2007. Kashiwazaki Kariwa was 19 km away from the epicenter of the magnitude 6.6 Chuetsuoki earthquake. Shaking of 6.8 m/s^2 (0.69 g) was recorded at the plant in the east-west direction, exceeding the design specification for safe shutdown (4.5 m/s^2) and well above the rapid restart specification for key equipment in the plant (2.73 m/s^2). An IAEA team was invited for a four-day inspection in August 2007 and it provided two recommendations, which included a re-evaluation of the seismic safety standard and detailed geophysical investigations (IAEA, 2007). The Japanese government acknowledged that it was responsible for approving construction of the first Kashiwazaki Kariwa units in the 1970s very close to what is now known to be a geological fault line (See Figure 5.18). The report was presented to the IAEA Senior Regulators' Meeting in September 2007 (WNA, 2016b).

Nonetheless, at the end of September 2013, TEPCO filed an application for safety inspections of Units 6 and 7 at its Kashiwazaki-Kariwa with the NRA, seeking restart of the two reactors. TEPCO argued that reactivation of the two advanced boiling water reactors (ABWRs), with an output of 1,356 MW each, would greatly contribute to the financial rehabilitation of the power company (Citizens' Nuclear Information Center (CNIC), 2013). On 27 December 2017, the NRA announced that Units 6 and 7 met the new regulatory standards (NEI, 2017). Local oppositions to restart of the plants, however, has remained strong. Niigata Prefecture Governor Ryuichi Yoneyama has said he will not discuss restart of the units until TEPCO develops a clear plan for the disposition of Fukushima Daiichi, which is expected to take several years. The mayor of Kashiwazaki, Masahiro Sakurai, has also called for at least one of the plant's seven reactors to be decommissioned as a precondition to restart of Kashiwazaki-Kariwa Units 6 and 7 (Iiyama, Fukumoto, 2018).

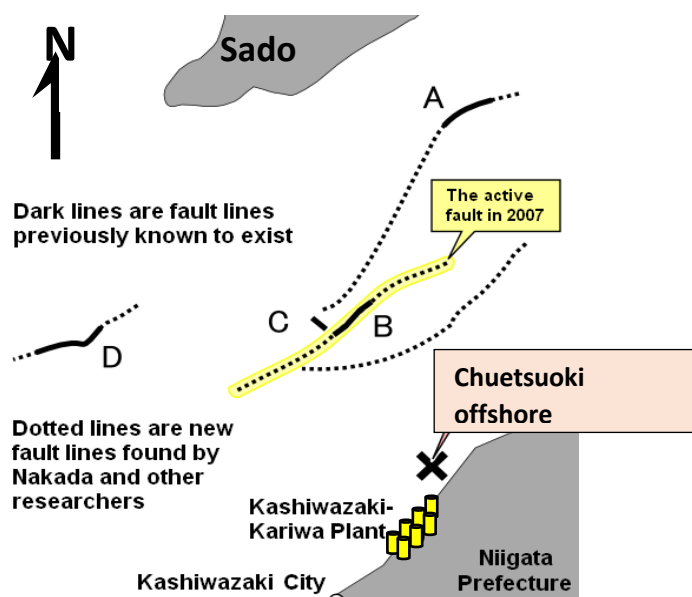


Figure 5.18 Kashiwazaki Kariwa Plant and its Newly Discovered Fault Lines

Note: Lines A, B, C, and D represent active faults.

Source: Wikipedia, 2017c.

Besides seismic risk, the Nuclear Regulatory Authority (NRA) in 2013 initiated a study regarding the monitoring of volcanoes near nuclear facilities and the need for rapid and complete nuclear reactor shutdown capabilities in case of volcanic activities. Based on the study recommendation, NRA set up in March 2016 a Nuclear Reactor Volcano Subcommittee to assess potential earthquake eruptions and the NRA's authority to shut down nuclear plants. (Ministry of Environment (MOE), 2017). Professor Ishibashi points out that earthquakes are caused not only by geologic faults, tectonic plate movements and the movements of slabs, but also by other unknown reasons and causes. He stated that earthquakes could occur even when there are no apparent causes. Thus, it is prudent for the NRA to monitor volcanic activity and strengthen its regulatory authority over plant safety with respect to these types of indicators. (Ishibashi, 2002).

5.6 More Reasons Why Japan Has So Many Nuclear Accidents

The location of many of Japan's reactors near seismically active geologic faults is an important factor influencing the number and severity of nuclear incidents and accidents. But a complete answer to the question of why Japan has nuclear accidents is more complicated. The high seismic activity in Japan, the frequency of tsunamis, the co-location of multiple reactors at a single site, the absence of truly robust and redundant back-up power, the inherent vulnerabilities of reactor designs and the on-site storage of radioactive material—these are but some of the factors in a complex causal chain—an accident chain that begins with decisions made by governments, corporations and individuals.

To gain insight into the human component of why Japan has had so many nuclear accidents, we need to understand the “sociology” of how system failures occur. One of the most authoritative experts in this field is Charles Perrow. In one of his more recent publications, he stated that modern society has created conditions that have led to vulnerable concentrations of humans, economic power and hazardous materials and that the most fearful concentrations of hazardous materials are nuclear power plants. (Perrow, 2011). He notes that nuclear experts ignore or underestimate major risks at nuclear plants, as has been demonstrated by the Fukushima nuclear disaster, even though those risks have long been evident. For example, referring to the 3.11 earthquake and tsunami, Tsuneo Futami, a nuclear engineer who was the director of Fukushima Daiichi in the late 1990s, stated that he could only work on precedent and there was no precedent for what happened on 3.11. Professor Perrow refers to this approach as a “probabilistic” approach. He contends that risk assessments should be made on the basis of a “possibilistic” approach, as defined by Rutgers University sociologist Lee Clarke (Clarke, 2006). Perrow advises that nothing that we build—except nuclear bombs—has as much catastrophic potential as nuclear power plants and that since we have them, the least we can do is change our attitude toward risks and do much more to prevent failures. He goes on to argue that few nations have the institutional capacity to contain the catastrophic potential of nuclear energy and that we now know that Japan is not one of them.

With this perspective in mind, we consider and evaluate the direct and indirect causes of nuclear accidents in Japan, using the Fukushima disaster as a “lesson learned” and conclude with observations on the role of management and policy in preventing future nuclear accidents.

More Frequent Large Earthquakes. Almost all of Japan’s nuclear plants are built on or near geologic faults. In fact, there are few safe zones in terms of seismic threats, due to the geology of the Islands of Japan and the higher level of seismic activity that has been apparent over the past two decades. Although the 9.0 magnitude of the March 11 earthquake was a rare event, (described by the USGS as an “infrequent catastrophe” for the area), a proper risk analysis should anticipate that large earthquakes are common in Japan, according to Perrow (USGS, 2011).

Indeed, Katsuhiko Ishibashi, the renowned Japanese seismologist, had been warning of such events. In view of the geologic location and high seismic activity near Japan’s nuclear plants, Ishibashi has long argued that nuclear plants should be built more robustly and regulated more tightly. However, instead of increasing robustness of plants to withstand earthquake shocks, Japanese engineers have focused on building nuclear plants with greater capacity to shut down safely when ground acceleration exceeds seismic design limits. (WNA, 2016b). This reasoning is that if a reactor shuts down safely during an earthquake, a major disaster could be avoided. While this approach is perhaps less costly and might achieve the same effect of avoiding a severe accident, the effectiveness of this strategy has not been proven. The 3.11 earthquake and tsunami not only damaged Fukushima Daiichi plant buildings, reactors, control systems and spent fuel storage pools, the earthquake and tsunami disasters damaged the regional electrical grid, leaving the plant operators without power and no provisions to save the plant from a nuclear disaster. If the plant and its systems had been built with more resilience, the effect of the earthquake and tsunami could have been less severe (Hatamura, et al., 2014).

- In contrast, the US and French nuclear reactors have been built with greater seismic resilience to possible large earthquakes. French nuclear reactors have been designed to

withstand an earthquake twice as strong as the 1000-year event calculated for each site and the standard was adopted on that basis, even though there are far fewer such seismic events in France than in Japan. In the United States, where there also are far fewer earthquakes than Japan, US seismic standards for nuclear plants are higher than those in Japan ([United States Nuclear Regulatory Commission \(USNRC\), 2017](#)). American regulators mandate that all U.S. reactors be built not only to withstand the most powerful earthquake ever recorded for their respective sites, but also to withstand the strongest earthquake that geologists think are possible for each site.

Continuous Tremors and Vibrations. In addition to major earthquakes, Japan's nuclear power plants are exposed to small tremors and vibrations daily. Such daily abuse from shaking would over a long period of time weaken pipes, valves, actuators, sensors and other equipment and could result in unexpected incidents and failures—appearing suddenly during a major natural disaster such as an earthquake. As discussed earlier, JNES was aware of the connection between frequent vibrations and tremors and the wear and tear on equipment at nuclear reactors and plants. ([JNES, 2012](#)). Despite these issues, the Japanese government is contemplating extending the life of reactors from 30 years to 60 years, without consideration of how the effect of frequent vibrations and tremors, combined with the normal aging of systems, might create new failure modes for reactors.

Major Tsunamis. There was ample evidence that Fukushima was at risk of experiencing major tsunamis. Four of the five "megaquakes" in the past century have generated tsunamis in the area. Moreover, an earthquake does not have to be gigantic to create a tsunami: Japan had a 30-foot-high (9.1 meter) tsunami from a 7.8 earthquake on the west coast in 1993. Nonetheless, the Nuclear Safety Commission,⁵¹ the Japanese equivalent of the US Nuclear Regulatory Commission, had never officially recognized the tsunamis as a risk to nuclear reactor safety. In 2002, a Japanese engineering group concerned with tsunami risks to nuclear reactors issued a warning that this vulnerability needed to be addressed. The word "tsunami" did not appear in government safety guidelines until 2006, however ([Perrow 2011](#)). The initial plant designs for Fukushima Daiichi did take tsunamis into account or factor in past historical events in the region with scientific analysis. When guidelines were established for protection against tsunamis, they proved to be insufficient. Tsunamis heights greater than 10 meters seemed so unlikely as to be impossible to occur. But unlikely does not mean impossible and the 15-meter tsunami did occur. ([Wikipedia, 2017d](#)).

Power Outages. The Fukushima Daiichi Plant had a serious design flaw that remained unaddressed since the plant was originally built in the 1960s. The emergency power source—diesel generators to be used if offsite power failed—were in a basement vulnerable to flooding ([Perrow 2011](#)). To TEPCO, flooding should not have come as a surprise. Most of the area subject to earthquakes lies beneath the sea level and underwater earthquakes can be expected to cause tsunamis that are capable of flooding buildings on shore. Diesel emergency generators should be as reliable as possible and should not be in areas subject to flooding. Emergency generators should have their own back-up power sources, moreover.

⁵¹The Nuclear Safety Commission (NSC) was a commission established within the Cabinet of Japan as an agency to play the role of double-checking whether the Nuclear and Industrial Safety Agency (NISA) of METI has been enforcing nuclear safety. The NSC merged with the Nuclear and Industrial Safety Agency (NISA) of METI and became a new nuclear safety agency, the Nuclear Regulation Authority (NRA), under the Ministry of Environment, on September 19, 2012.

Failure to Implement Corrective Measures. The boiling water reactor (BWR) design at Fukushima, called the Mark 1, was the subject of much controversy when it was first developed in the 1960s by GE. Compared with pressurized water reactors (PWRs), the BWR was cheaper and easier to build because of the thinner and smaller containment shell surrounding the reactor vessel (Perrow 2011). When in the 1970s some critics warned that the BWR containment vessel was inferior to the PWR design, the chairman of what was to become the US NRC agreed that the BWR was more dangerous than the PWR but said that banning the design "could well be the end of nuclear power," because the Mark 1 was already in wide use. According to the Heritage Foundation, after Federal regulators identified several shortcomings with the original design that posed potential safety problems, the industry addressed and resolved the shortcomings. This included procedures to supply off-site power and water to reactors and a hardened containment venting system to ensure that pressure could be safely released from the reactor should there be a system breakdown. Similar modifications probably were made to Mark 1 reactors in Japan. (Spencer, 2011).

TEPCO apparently did not make all the required modifications, however. On 5 July 1989, the U.S. Nuclear Regulatory Commission (NRC) issued a notice on the failure of emergency electricity generators at plants in seismically active areas, which could cause the subsequent failure of cooling systems. Two days later, TEPCO responded to the NRC that it had already taken ample measures and therefore did not make any modifications (Fukushima Mimpo, 1989). The Japanese Nuclear and Industrial Safety Agency (NISA) cited this report in 2004 to TEPCO. According to Jun Tateno, a former NISA scientist, TEPCO did not respond to these warnings and did not take any action to implement corrective measures (Wikipedia, 2017d).

Multiple Reactors Collocated. Japan's reactor construction program in the 1960s and 1970s was very rapid and led to collocation of multiple reactors at one construction site. This reactor "crowding" was partly due to the inability to find politically acceptable green-field locations for new nuclear power plants due to anti-nuclear protests. For example, Kashiwazaki Kariwa in Niigata has seven reactors with a total power capacity of 8,000MW, the largest nuclear power plant in the world by net electrical power capacity. Fukushima Daiichi had six reactors and its owners had planned to build two more at the same location. The Fukushima Daini, with four reactors, is located nearby. Multiple reactors at a plant increase the chance that all reactors could be vulnerable to a "common mode" failure. A common mode failure is one that affects all reactors at once, such as a station-wide power loss and insufficient personnel to deal with a site-wide emergency. Common mode failures could be caused by internal or external events. For example, the release of radiation into the environment from one reactor could prevent the safe monitoring of all other reactors at a facility (Perrow, 2011; Wikipedia, 2017c).

Moreover, if reactors were built on geologically unstable ground, it would be very nearly impossible to deal with an accident involving multiple reactors under conditions of a severe natural disaster. As shown by events at Fukushima Daiichi, a chain of fateful events, including total loss of station power, lack of situational awareness, limited ability of decision makers to communicate with skilled engineers, lack of access to tools and needed parts and cables, utterly overwhelmed the operators (Yoshioka, 2013).

Professor Ishibashi recently hypothesized an accident at Hamaoka if a major Tokai Earthquake occurred. Hamaoka has three reactors and has been of a concern because the plant is in the middle of the predicted focal region of a future Tokai Earthquake. A Tokai Earthquake is expected to occur every 100 to 150 years. The last Tokai Earthquake happened in 1854, 163 years ago. The Japan Meteorological Agency has warned that another Tokai earthquake of Magnitude 8 is overdue. ([Japan Meteorological Agency \(JMA\)](#), no date). Professor Ishibashi described in 2002 a possible scenario if the Hamaoka plant were struck by a major earthquake:

- The plant would experience an instantaneous and simultaneous failure of all systems, equipment and piping, affecting all three reactors.
- The plant would suffer failure of multiple safety devices, control rod insertion failure, loss of power supply, rupture of piping, coolant loss, failure of emergency core cooling systems, leading to nuclear runaway and core meltdown accompanied by steam explosions, hydrogen explosions and the uncontrolled spread of radiation.
- Severe earthquake shocks will have a major physical and psychological impact on plant operators, creating conditions for operator error. The main earthquake would also be followed by major aftershocks, which would further damage the plants and equipment.

Ishibashi indicated that what would really happen could not be known until a real earthquake occurs, but he forecast that there would be a release of huge amounts of radioactive material that would contaminate a wide area, depending on weather conditions. ([Ishibashi, 2002](#)).

- Fortunately Ishibashi's 2002 scenario would unlikely happen today. All three Hamaoka reactors are not operating at present. One reactor has been closed since November 2010 for regular inspection and the other two have been shut down since May 2011 at the request of the Prime Minister, who was concerned about earthquake risks. Although inactive, they would still pose a danger if there were a local power loss, because reactors still have nuclear fuel in their cores and spent fuel remains in the cooling pools.

Perrow ([2011](#)) suggests that if the utility had been required to disperse its plants—at some economic penalty—earthquake and tsunami risks and the risk of collateral damage to adjacent plants from an industrial accident, would be greatly reduced. Under these circumstances, the fearsome consequences outlined in the scenario above could be greatly reduced.

Warnings Ignored by Government and Industry. Japan has a relatively weak central government, which has difficulty in monitoring technological threats and regulating hazardous activities. For example, the nuclear industry has a history of falsifying data and hiding accidents. The Japanese government typically is unaware of these events and may even overlook them. For example, one engineer, Mr. Mitsuhiro Tanaka, acknowledged in a public symposium in 1988 that he falsified documents when casting a containment vessel for the Fukushima complex—Fukushima Daiichi—and received a large bonus for saving the company the expense of making a new one. ([Tanaka, 1990](#)). TEPCO responded with ritual apologies and resignations only after the engineer's acknowledgement appeared in the press.

Also, in 1990, the US NRC conveyed warnings of unsafe practices to the Japanese government. A representative in the Japanese national parliament became concerned that the six reactors at the

Fukushima Daiichi facility only were required to withstand a 19-foot (6 meter) tsunami. He discussed his concerns at least 20 times with TEPCO in 2003 and sent a warning to its president. Both demarches were ignored. A seismology professor at Kobe University resigned in protest from a government nuclear safety board in 2006 because of a lack of attention to earthquake and tsunami risks. His action had no effect (Perrow, 2011).

Perrow states: “The nuclear industry is highly centralized, giving it political clout in all countries. Toshiba bought Westinghouse; the French company Areva dominates in Europe and is now participating in joint projects in the United States; Exelon and Entergy run most of the plants in the United States; TEPCO accounts for 30 to 33 percent of the generating capacity in Japan and is the fourth largest utility in the world. Vast amounts of capital and potential profits are concentrated in nuclear plants. They could supply a third of Japan's electric power and a fifth of the US market; which gives them substantial influence over their governments” (Perrow, 2011)

Policy, Decision-Making and Management. The frequency and occurrence of nuclear reactor accidents are powerfully influenced by Japan’s design, construction and operations policies and how this complex endeavor is managed. According to Perrow, a lengthy decision-making process would generally make it easier to avoid the rare but inevitable "normal" accident. The interests of shareholders are very short term, however, impacting nuclear decision making. Legally obedient to them, managers must maximize quarterly profits, and this could lead to riskier designs, less-vigilant maintenance, operating shortcuts and lobbying to prevent expensive regulatory rules. Yet private ownership does not appear to encourage safety and long-range hazard analysis. Government ownership, as in Sweden and France, seems to do better but will not necessarily guarantee no accidents, according to Perrow (2011).

Even in China where nuclear plants are state-owned, the importance of safety is tempered by competing priorities of the central government, such as the promotion of rapid growth, funding requirements of other state enterprises and the need to placate the provincial governments. King and Ramana (2015) state that in China safety falls down the hierarchy of priorities in shaping nuclear decision-making. King, moreover, states that in the State Council's Medium and Long-Term Nuclear Power Development Plan (2011-2020) from October 2012, China declared that since the Fukushima Daiichi nuclear disaster in 2011, China has launched comprehensive safety inspections at all nuclear power plants and announced that “the inspection results show that nuclear security is guaranteed in China.” Considering this evident overconfidence in being able to guarantee nuclear safety, it is not surprising that when faced with conflicts between safety and other priorities, decision makers would elevate competing priorities while persuading themselves and others that China's nuclear power sector is safe.

In a multi-layered hierarchical society, such as Japan, leaders especially tend to refuse to delegate decision-making and the underlings tend not to express disagreements or alternative opinions. In the National Diet’s Fukushima accident report (2012) that was introduced earlier, Chairman Kurokawa of the Diet Report attributed this failing to Japanese culture. He stated that fundamental causes were to be found in the ingrained mindset of obedience to authority that hindered the free flow of ideas and information. In another post-Fukushima investigatory report made by the Cabinet of Japan, distinguished Tokyo University professor Yotaro Hatakeyama, who served as Chairman of the investigatory committee, philosophically remarked, “We must take this accident as a lesson

from nature that there are flaws in human thought and analysis” (Yoshioka, 2013; Hatamura Institute for the Advancement of Technology and Science, no date).

5.7 What Happened to TEPCO

In the aftermath of Fukushima, the Japanese government worked aggressively to amend laws to help TEPCO. All involved likely knew that the amount of the nuclear damage compensation and accident clean-up costs would far exceed \$1.2 billion, which was the maximum amount of accident damage insurance TEPCO was required to hold. The question was how to pay for claims beyond this amount. One key step was to turn matters over to the NDF.

To manage damage compensation matters, Law No. 94 was amended to establish the NDF in September 2011. In July 2012, the NDF borrowed \$10 billion from commercial banks to buy a controlling interest in TEPCO (50.1% of the voting rights). With the NDF’s corporate control and its enhanced statutory authorities, TEPCO was dealt out of the management chain with respect to handling the Fukushima clean-up and decommissioning (NDF, 2017b).

The government created a complex scheme to secure funds by using the NDF as the centerpiece for rescue efforts. It established the Nuclear Damage Compensation Support Account under the Energy Measure Special Account in 2011 to help facilitate financing. The government would issue \$90 billion-worth of “Kofu Kokusai (grand bonds) (an equivalent of grant-in-aid or federal aid) and provide these funds to TEPCO through the NDF. TEPCO would ask the NDF to cash the bonds incrementally, as needed. The government secured the funds through loans from financial institutions. The government initially issued \$50 billion-worth of bonds to TEPCO prior to 2013 but increased the issuance amount to \$90 billion in 2014 in view of rapidly increasing damage compensation expenditures (MOF, 2018d).

- As of December 2014, TEPCO had drawn a total of \$45.337 billion in government bonds in 35 separate transactions from 8 November 2011 to 24 December 2014 (See Figure 5.19)
- In addition, on 3 October 2014, TEPCO asked the government to pay \$1.2 billion as a liability insurance payment that TEPCO signed with the government in November 1980 on the Fukushima Daiichi Plant. The government paid TEPCO about \$689 million out of the \$1.2 billion on 4 March 2015.

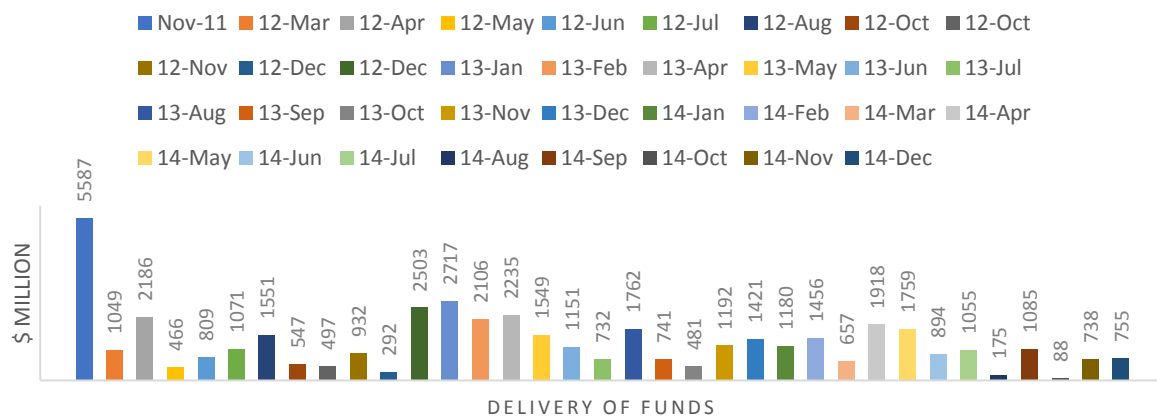


Figure 5.19 Status of Government Bond Sales for TEPCO, November 2011 to December 2014
Source: Jbaudit, 2014a.

As of February 2018, according to TEPCO's website, the company had paid a total of \$81 billion for damage compensation (including \$79 billion from the government fund and \$2 billion from government-backed insurance (TEPCO, 2018b; Jbaudit, 2014a).

The government is expecting that the \$90 billion will be paid back in full by various payers, including rate payers, as shown in Figure 5.20. The government expects \$54 billion will be reimbursed from TEPCO, other utility companies and new renewable energy companies (from the surcharges imposed on their rate payers). Another \$11 billion will come from the Energy Measures Special Account (from the Coal and Oil Tax and the Power Source Development and Acceleration Tax). Another \$25 billion will be raised by selling TEPCO stock that the NDF is holding.

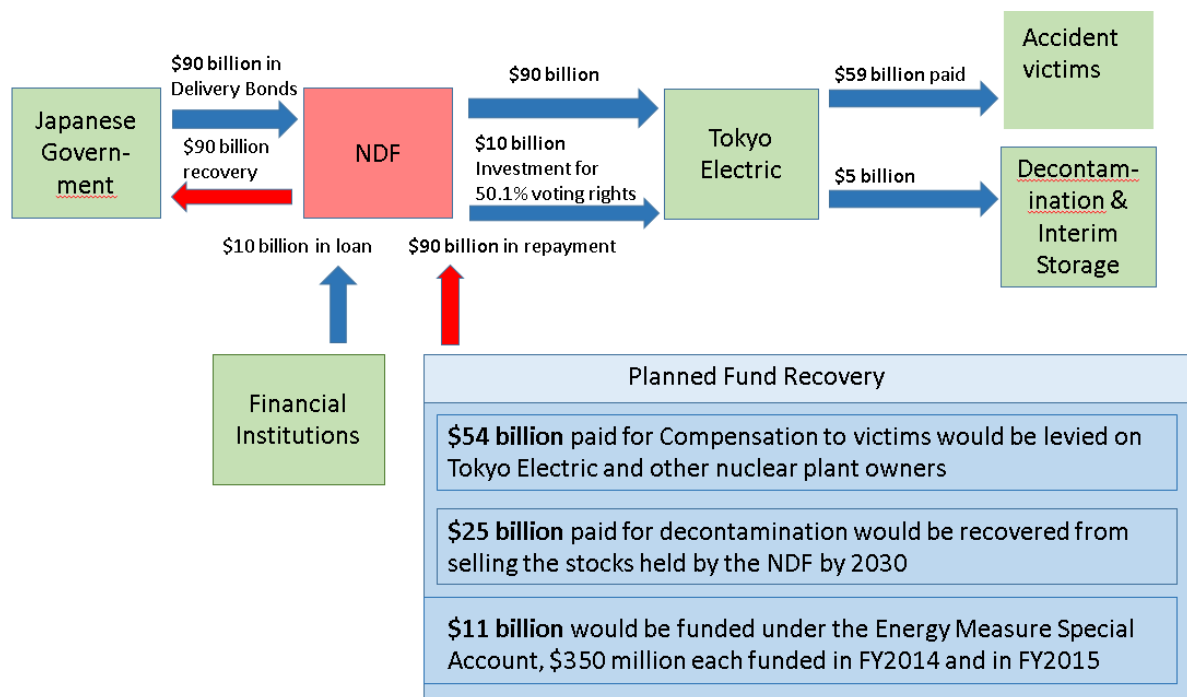


Figure 5.20 Payment Plan of the Nuclear Damage Compensation and Decommissioning Facilitation Corporation (NDF) and the Flow of Funds, as of October 2016

Source: METI, 2016.

While the NDF paid TEPCO \$10 billion to acquire the majority (50.1%) of the company's voting rights, the arrangement is temporary, according to TEPCO. Under the current arrangement, the government controls TEPCO and supports it while it is in bankruptcy, but when the time comes, the government will reduce its voting rights and the company will be an independent company again, with no liability from the nuclear accident. The situation is described by Ramseyer, who indicates that "Tokyo Electric wildly underplayed the risk of a large earthquake and tsunami, but it did not underplay it carelessly or negligently. It underplayed it rationally — wildly, but rationally" (Knowledge@Wharton, 2013; Ramseyer, 2012; TEPCO, 2016).

Indeed, the accident liability lies fully with the government and TEPCO and if the amount of damage compensation increases and TEPCO is unable to pay, the liability would be on the shoulders of the government, or more specifically the taxpayers. Expenditures have been increasing rapidly, cumulative debts increasing, and any reserve has been depleting fast. As discussed in Chapter 5. The total Japanese debt that has accrued for damage compensation by the end of FY2018 (March 2019) is now \$483 billion, according to the MOF.

- The taxpayers' responsibility for the Fukushima accident will likely remain even after TEPCO becomes an independent company and free from any liability. Thus, the taxpaying citizens will be liable for all the damages without explicit knowledge of any of the particulars. The full extent of the accident damage and its clean-up cost are yet unknown, and the mounting costs will likely burden future generations of Japanese.

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Chapter 6:

Nuclear Waste Storage and Disposal

CHAPTER 6: Nuclear Waste Storage and Disposal

Abstract

In the mid-1970s, Japan began to ponder how to store and dispose of radioactive waste that was accumulating at utility-owned nuclear power plants. On 8 October 1976, the AEC issued a policy paper “On Measures for Radioactive Waste,” which noted that Japan was not yet ready to face the issue and that it needed to conduct surveys and R&D on waste disposal and hope to arrive at a policy by 2000. That did not happen. Instead, METI has developed a map of candidate areas suitable for deep underground storage. A down-select of candidate areas is expected to take 20 years. Some progress is being made in developing vitrified waste storage technology and there is commercial interest in construction of low level waste storage sites, but in the meantime the waste continues to pile up. Fukushima substantially adds to the problem. Onsite storage at nuclear plants is now almost 70 percent full.

6.0 False Starts

In the mid-1970s, Japan began to ponder how to safely store and dispose all of the radioactive nuclear waste that was accumulating as the utilities expanded their power reactor fleets. On 8 October 1976, the AEC issued a policy paper, “On Measures for Radioactive Waste.” The paper noted that Japan was not yet ready to face the issue and that it needed to conduct surveys and research and development of waste disposal with the hope that it can arrive at a policy by 2000.

The paper showed interest in ocean dumping of radioactive waste. Indeed, in 1978 STA started to plan for an ocean dumping test. The Japanese fishermen’s union strongly objected and stopped the planned test. Subsequently, on 12 October 1979, the AEC planned to dump drums of radioactive waste to the seabed at the depth of 5,000 meters, some 900 km south off the coast of Tokyo Bay. Many South Pacific nations strongly objected to the plan and took the case to the London Convention.⁵² In 1983, the 7th meeting of the treaty countries of the London Convention passed a resolution that no ocean dumping of radioactive wastes would be allowed. Thus, Japan’s plans for ocean dumping of radioactive wastes was terminated ([Yoshioka, 2013](#); [Sjoblom, Linsley, 1994](#)).

Since ocean disposal was off the table, Japan started considering the establishment of waste disposal facilities within Japan. In December 1980, the AEC’s Radioactive Disposal Measures Special Subcommittee compiled a report that endorsed the development of vitrification technology and deep ground disposal. The Subcommittee later suggested in 1984 that Japan select a disposal site by the mid-1990s and start disposal operations by 2000. The PNC took charge of the matter, located a candidate site in Horonobe, Hokkaido and started to talk to the Mayor of Horonobe ([Yoshioka, 2013](#)).

⁵² The London Convention (the 1972 Prevention of Marine Pollution by Dumping of Wastes and Other Matter) protects the marine environment from pollution caused by the dumping of wastes and other matter into the ocean. The Convention was called for by the [United Nations Conference on the Human Environment](#) (June 1972, Stockholm) and the treaty was drafted at the [Intergovernmental Conference on the Convention on the Dumping of Wastes at Sea](#) (13 November 1972, London); it was opened for signature on 29 December 1972.

On 21 April 1984, the PNC's plan to build a high-level radioactive storage facility in Horonobe was leaked to the press. The mayor of Horonobe immediately expressed his support for the plan. The Hokkaido prefectural governor (the Socialist Party), however, opposed it and the prefectural assembly (the Liberal Democratic Party was in the majority) supported the mayor's plan. The plan, thus, did not progress, but also did not die. Then in the spring of 1987 the Hokkaido LDP suffered a major defeat in national elections and the opposition party took control of the Hokkaido Assembly. Inevitably, the PNC's plan to build the Horonobe waste facility was terminated ([Yoshioka, 2013](#)). Nonetheless, in October 2000, the Hokkaido government established regulations concerning the handling of radioactive waste and granted permission to the prefecture to host a Horonobe Underground Research Center (Horonobe URC). Approval had one important string attached: no radioactive materials could be brought to the site. The Horonobe URC would only conduct research and development of geological disposal technology for high-level radioactive waste and pursue scientific research on the deep geological environment for the next 20 years, which could be extended as needed ([JAEA, 2005](#)).

6.1 Near-Term Waste Management

While Japan's progress in establishing a permanent geological disposal facility proceeded ever so slowly, the volume of spent fuel inexorably grew at individual nuclear plant storage sites. The ten power companies in Japan that owned nuclear power plants began to improvise measures to increase their storage capacities. Most of them opted for the least costly and politically difficult means, such as re-racking (modifying the spent fuel pool grid and fuel assembly consolidation in the pool) or sharing one pool to store spent fuel from multiple reactors (See Table 6.1). Three electric companies decided to use dry casket storage facilities and only one company built an additional cooling pool. In addition, Tokyo Electric Power Company and JAPC jointly established a dry storage facility in Mutsu, Aomori Prefecture ([FEPC, 2015](#)).

The problem has not gone away, however. As of September 2016, a total of 14,830 tons of spent fuel were being stored at the cooling pools at the individual nuclear plant sites, which are almost 70 percent full (See Figure 6.1). There is less than 6,000 tons of spare capacity in Japan ([FEPC, 2016](#)).

In addition to the large volume of spent fuel stored at the individual reactor sites, the RRP has a large amount of spent fuel that the customers had sent for reprocessing. As of 31 August 2017, the RRP has received a total of 3,393 tons of spent fuel, which is beyond its spent fuel storage capacity of 3,000 tU. Spent fuel that exceeded the RRP's storage capacity was sent to the Mutsu storage facility ([JNFL, 2017a](#)).

The government has not been helpful in assisting the power companies with their storage problems:

- On 3 February 2016, NRC Commissioner Shunichi Tanaka stated at the 54th extraordinary NRC meeting that the dry cask storage was safer than re-racking spent fuel assemblies and that the power companies should choose the dry casket storage over re-racking. According

to Kyushu Electric, it had tried to use dry caskets and met with local resistance. Commissioner Tanaka suggested that the company should explain to the local community that the dry caskets are safer than relying on cooling pool storage (NRA, 2015).

Table 6.1 Japan Power Company Effort to Increase Storage Capacity for Spent Nuclear Fuel

	Onsite Facilities			
	Power Plant	Spent Fuel on Site (tU)	Storage Capacity (tU)	Recent Efforts
Hokkaido Electric	Tomari	400	1,020	Sharing a pool (reactor 1, 2 and reactor 3)
Tohoku Electric	Onagawa	420	790	Sharing a pool (reactor 1 and reactor 2, 3)
	Higashidori	100	440	-
TEPCO	Fukushima Daiichi	2,130	2,260	Re-racking (Reactor 1,2, 3, 4, 5, 6) Sharing a pool Building dry cask storage (reactor 4, 5, 6)
	Fukushima Daini	1,120	1,360	Re-racking (reactor 1,2, 3, 4) Sharing a pool (reactor 1,2, 3, 4)
	Kashiwazaki Kariwa	2,370	2,920	Building new racks (reactor 1, 3, 4, 6, 7) Re-racking (reactor 2, 5) Sharing a pool (reactor 1, 2, 5 and reactor 3, 4, 6, 7)
Chubu Electric	Hamaoka	1,130	1,700	Re-racking (reactor 1, 2, 3) Building more racks (reactor 4) Sharing a pool (reactor 1, 2, 3 and reactor 4; reactor 1,2, 3, 4 and reactor 5)
Hokuriku Electric	Shika	150	690	Re-racking (reactor 1)
Kansai Electric	Mihama	470	620	Sharing a pool (reactor 1, 3 and reactor 2, 3) Re-racking (reactor 2, 3)
	Takahama	1,220	1,730	Sharing a pool (reactor 1 and 3, 4; reactor 2 and reactor 3, 4; reactor 3 and 4) Expanding a pool (Area B for reactor 3, 4) Re-racking (Area A for reactor 3, 4)
	Oi	1,420	2,020	Sharing a pool (reactor 1, 2 and 3; reactor 1, 2 and 4) Expanding a pool (Area B for reactor 3, 4)
Chugoku Electric	Shimane	460	680	Sharing a pool (reactor 1, 2) Building racks and re-racking (reactor 1) Re-racking (reactor 2)
Shikoku	Ikata	640	1,020	Sharing a pool (reactor 1, 2, 3)

Electric				Re-racking (reactor 3)
Kyushu Electric	Genkai	900	1,600	Sharing a pool and re-racking (Reactors 1, 2 and 4; Reactor 1, 2, 4 and Reactor 3) Re-racking (Reactor 3)
	Sendai	890	1,290	Re-racking (Reactors 1, 2)
Japan Atomic Power Company	Tsuruga	630	920	Building more racks (Reactor 1) Sharing a pool (Reactor 1, 2) Re-racking (Reactors 1, 2)
	Tokai Daini	370	510	Re-racking Building a dry cask storage facility
Off-Site Facilities				
TEPCO, Japan Atomic Power Company	Recyclable-Fuel Storage Company	• In June 2000, the Nuclear Reactor and Other Nuclear Facilities Regulation Law amended to permit off-site nuclear waste storage. • In November 2000, the Mayor of Mutsu, Aomori Prefecture, requested a survey to assess the suitability of Mutsu to locate the Recyclable Fuel Storage Center. • On 21 November 2005, TEPCO and JAPC established the Recyclable-Fuel Storage Company in Mutsu. • On 13 May 2010, license granted for spent fuel storage. On 31 August 2010, construction of the storage facility started. • On 29 August 2013, the first storage building with a capacity of 3,000 ton completed. • Since 5 November 2013, the Recyclable-Fuel Storage Center has been working with the Atomic Regulatory Authority to meet new regulatory standards and obtain a business license.		

Source: The authors compiled the table based on AEC, 2012; FEPC, 2016.

6.2 Nuclear Waste Classification and Disposal System

Japan has had more success in establishing a nuclear waste classification system that categorizes nuclear waste by radioactivity, source and type of disposal required. The classification system generally follows the international standards but has uniquely Japanese categories for high-level and low-level waste. The high-level waste, such as what would remain after the recovery of uranium and plutonium from spent fuel reprocessing, would require deep underground geologic disposal. Other high-level waste would require sub-surface or near-surface disposal. Three kinds of low-level waste are defined based on different sources and a “below clearance level” category is defined to cover other types of waste.

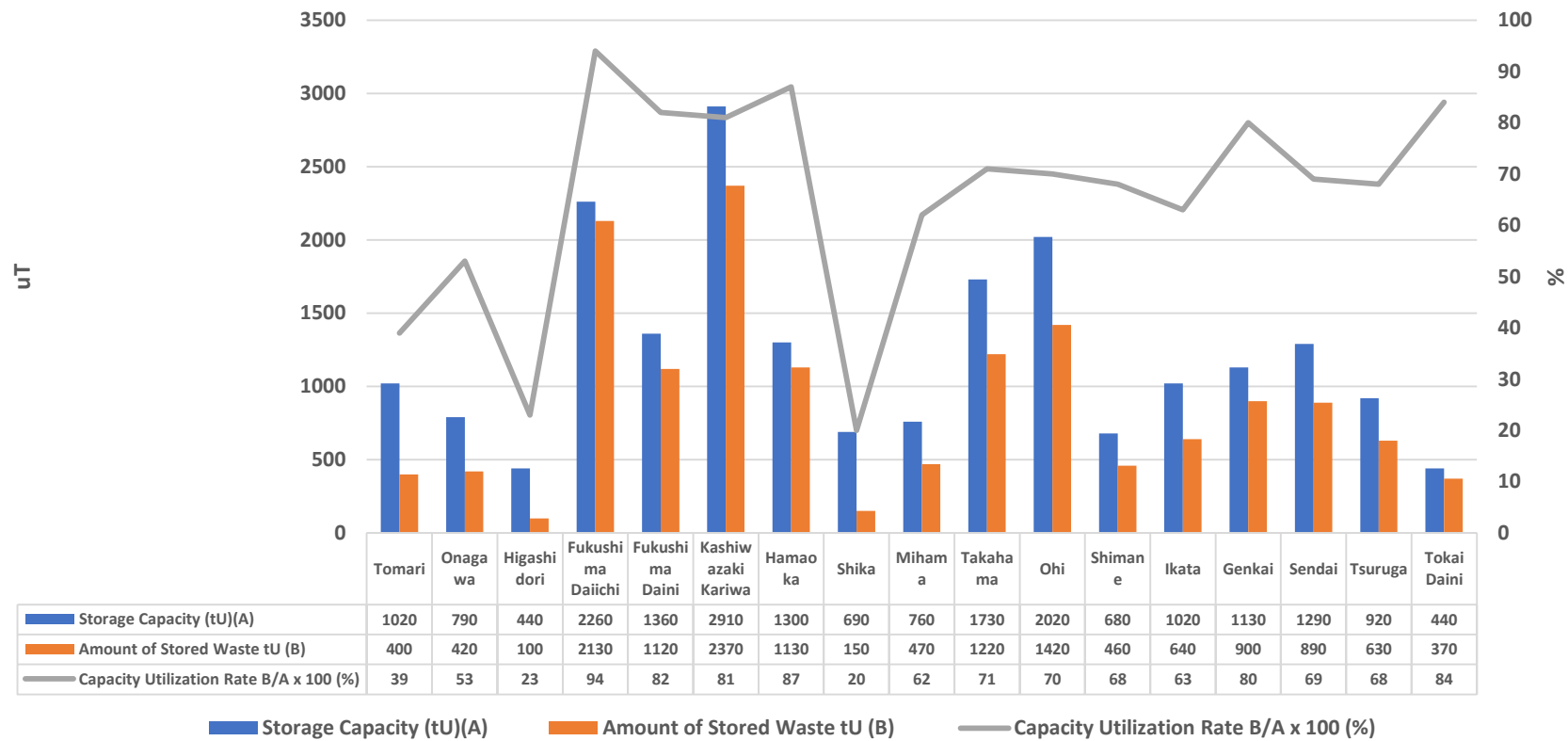


Figure 6.1 Spent Nuclear Waste Stored at Power Plants in Japan
 Cumulative Volume, Maximum Storage Capacity and Capacity Utilization Rate (As of September 2016)
 (A) total capacity = 20,760 tU; (B) total of volume = 14,820 tU; Average capacity utilization rate = 71%
 Source: The authors created the table based on the compound data table that was presented in FEPC, 2016.

Table 6.2 Classification of Radioactive Waste

Classification			Example	Origin of Waste	Disposal Method (Example)
High-Level Radioactive Waste (L1)			Vitrified Waste	Reprocessing Facilities	Geologic Disposal (more than 300 meters deep)
Low-Level Radioactive Waste	High ↑ Radio-active Level ↓ Low	Relatively High Radioactive Waste (L1)	Control Rods Core Internals	Power Reactors	Sub-Surface (less than 100 meters deep)
		Relatively Low Radio-active Waste (L2)	Liquid Waste Filters Used Equipment Expendables		Near-Surface (Concrete Pit Type) (less than 25 meters deep)
		Very Low-Level Radioactive Waste (L3)	Concrete Metals		Near-Surface (Trench Type) (less than 25 meters deep)
	Waste Containing Transuranic Nuclides (TRU Waste)		Parts of Fuel Rods Liquid Waste Filters	Reprocessing Facilities, MOX Fuel Manufacturing Facilities	Geologic Disposal
					Sub-Surface Disposal
					Near-Surface (Concrete Pit Type)
	Uranium Waste		Expendables Sludge Used Equipment	Enrichment and Fuel Manufacturing Facilities	Sub-Surface
					Near-Surface (Concrete Pit Type)
					Near-Surface (Trench Type)
					Geologic Disposal when appropriate
Waste That is Below Clearance Level			Most Waste from Dismantling	All Sources Shown Above	Reuse/Recycling for General Waste

Source: The table is a composite of data based on METI, 2013 and JAEA, 2017a, 2017b.

Four types of disposal systems are part of the waste classification system. Their use depends on the type of waste and the level of radioactivity (See Figure 6.2):

- Near-Surface Disposal (Trench Type). Very low-level radioactive wastes are placed in shallow, unlined trenches and then covered with soil.

- Near-Surface Disposal (Concrete Pit Type). After low-level radioactive wastes are placed in concrete pits, mortar is poured into the spaces between the wastes. The pits are enclosed with low water permeability soil to prevent groundwater from flowing into the pits.
- Sub-Surface Disposal. Relatively high-level radioactive wastes are disposed of at a depth of 50–100 meters below the surface of the ground, while maintaining enough distance from general underground use.
- Geologic Disposal. High-level radioactive wastes are disposed of in concrete constructs at least 300 m below the surface of the ground.

According to this system, radioactive waste disposal would be performed in phases by entities responsible for each category of waste. Japan applied this waste classification scheme to the waste generated by the Tokai Reprocessing Plant. High-Level Waste (HLW) will fill some 30,000 drums and will be buried more than 300 meters underground. Low-Level Waste (LLW), which will fill about 24,000 drums, is expected to be buried several dozens of meters underground. Less radioactive low-level waste, involving another 81,000 drums, will be buried close to the surface, according to the JAEA. The decommissioning of Tokai Reprocessing plant would take 70 years and \$8 billion. Another big problem is that no one has stepped forward to offer a location that could accommodate the burial of drums (Kyodo, 2017; Tokyo Shimbun, 2017; Burnie, Schneider, 2014).

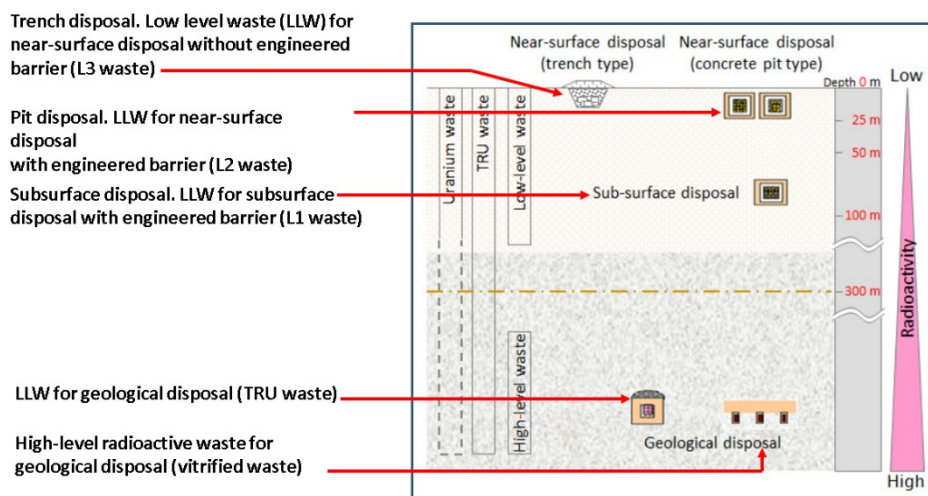


Figure 6.2 Radioactive Waste Disposal Methods in Japan

Source: JAEA, 2017c.

6.3 Efforts to Establish Deep Underground Disposal Repository

In May 2000, the Japanese Diet finally passed the Law on Final Disposal of Specified Radioactive Waste (the “Final Disposal Act”). The Law mandated deep geologic disposal of high-level waste (defined as only vitrified waste from reprocessing spent reactor fuel) and the establishment of the Nuclear Waste Management Organization of Japan (NUMO) that would manage high-level radioactive nuclear waste, manage the funding system and proceed with the selection of a disposal site. The law was amended in June 2007 to extend the definition of “specified waste” to include

waste containing long-lived transuranic waste (TRU waste)⁵³ that is appropriate for geologic disposal (Umeki, 2010).

These laws stipulated that NUMO would promote the investigations, selection of repository site(s), construction, operation and closure of the repository, giving priority to assuring safety. NUMO was to commence solicitations in December 2002 for candidate sites from municipalities throughout Japan, using literature surveys as the first step in the assessment process.

- Based on the May 2000 law, Japan also established the Radioactive Waste Management Funding and Research Center (RWMC) to manage NUMO's finances.
- The law directed NUMO to select five candidate sites for waste disposal by 2003, conduct comprehensive surveys and choose a final site by about 2020. Disposal operations are expected to start by about 2040 (Yoshioka, 2013; NUMO, 2017a; Radioactive Waste Management Funding and Research Center (RWMC), 2014).
- The construction of the NUMO repository is expected to cost \$35 billion, which is to be paid with funds that would be accumulated at 0.2 ¢/kWh from electric utilities' nuclear power generation (and hence their customers). This tax would be paid to RWMC. By 2015, \$10 billion had been collected. This sum excludes any financial compensation paid by the government to local communities (METI, 2015).
- NUMO might not be able to collect all the remaining \$25 billion required for the repository during the remaining 19 years of the plan, because few nuclear reactors are operating today and there is no clarity on how many reactors would actually be generating power over the next two decades.
- Japan also raised incentive money for those municipalities that showed interest in the literature survey. The amount of money offered to incentivize applications for the literature-survey stage was raised in 2007 to a maximum of \$2 billion per site. Up to \$7 billion would be provided during the preliminary investigation stage (Katsuta, Takubo, 2011).

Regardless of much preparatory work is undertaken, NUMO has made little progress in finding potential sites. The METI minister said in October 2013 that “the government will play an active role in choosing a permanent place, abandoning the current approach of waiting for volunteers to raise their hands.” In April 2014, METI's new Basic Energy Plan included facilitating construction and use of new intermediate and dry storage facilities. In May 2015, the cabinet endorsed the proactive approach.

Since 2000, the Geological Disposal Working Group of METI's Advisory Committee for the ANRE had been assessing geologic disposal technology and reported in April 2014 that potential repository sites were available throughout Japan. In May 2015, METI decided to identify several suitable candidate sites and present them to the public and a final site would be decided with certainty and without delay for operations to commence in the 2033-2038 period (Agency of Natural Resources and Energy (ANRE), no date).

⁵³ Transuranic (TRU) waste is material contaminated with transuranic elements—artificially made radioactive elements, such as neptunium, plutonium, americium and others—that have atomic numbers higher than uranium in the periodic table of elements. Transuranic waste is primarily produced from recycling spent fuel or using plutonium to fabricate nuclear weapons.

Once possible locations are short-listed with the AEC, the government will seek the local government's consent to pursue plans for a deep geologic repository. In January 2016, the ANRE invited opinions from experts for an interim report concerning specific requirements and standards for "scientifically promising sites" for final disposal of HLW. Based on two calls for public comment in August 2016 and March 2017, the Geological Disposal Working Group presented a report in April 2017 titled Summary of Requirements and Criteria for a Nationwide Map of Scientific Features for Geological Disposal (See Figure 6.3) ([WNA, 2017a](#)).

- On 28 July 2017, METI presented the map to the public and announced that there are about 800 municipalities out of about 1750 in Japan that are suitable for locating a permanent nuclear disposal site, which comprises about 30 percent of Japan's land area. METI plans to talk to the municipalities and start the site selection process, which would take about 20 years, including drilling surveys.
- Two prefectures were exempted from the selection process: Aomori Prefecture that already has a heavy burden by hosting several major nuclear facilities and Fukushima Prefecture that is recovering from the 2011 Fukushima Daiichi nuclear disaster.
- Nuclear waste would be buried 300 meters underground and require tens of thousands of years to become harmless. The cost of the construction of the disposal site is estimated at \$37 billion ([Nihon Keizai Shimbun, 2017](#)).
- The selection process is to go through three stages (See Figure 6.4):
 1. Literature survey: review of available information on the geology and other information relevant to the suitability of the site (about 2 years),
 2. Preliminary investigation: borehole survey, geophysical prospecting, etc. (about 3 years) and
 3. Detailed investigation: for selection of a repository site (about 15 years) ([Katsuta, Takubo, 2011](#)).

Current plans call for the underground waste disposal facility to be 6-10 km² in area with galleries more than 300 meters long. The facility is intended to store more than 40,000 vitrified canisters for hundreds of thousands of years. Plans call for facility construction and entombment of the canisters to take about 100 years, including site selection, safety inspections and burying and closing the galleries ([Mainichi Shimbun, 2017](#)).

Some 40,000 canisters of vitrified HLW are envisaged to exist by 2020, which will require disposal. All the waste would originate from Japan's nuclear plants ([NUMO, 2017b](#)). Of course, there are no certainties about how many reactors would be generating power and for how long.

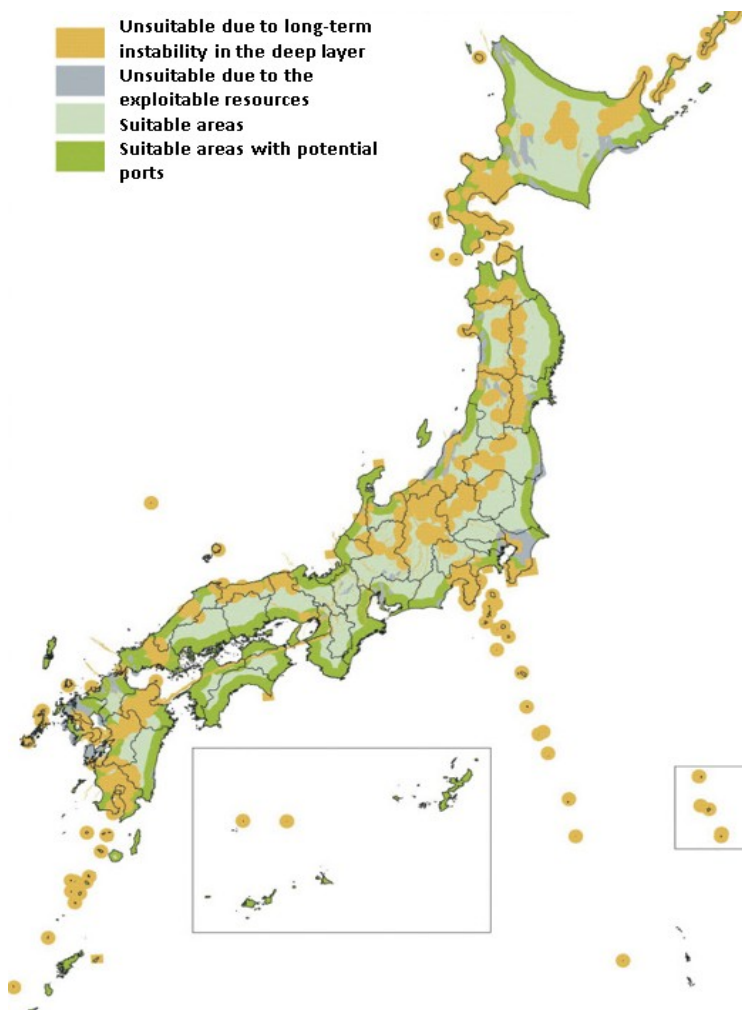


Figure 6.3 Map of Scientific Characteristics of Regions in terms of Suitability for Nuclear Waste Disposal

Source: Nihon Keizai Shimbun, 2017. Translation was provided by the authors.

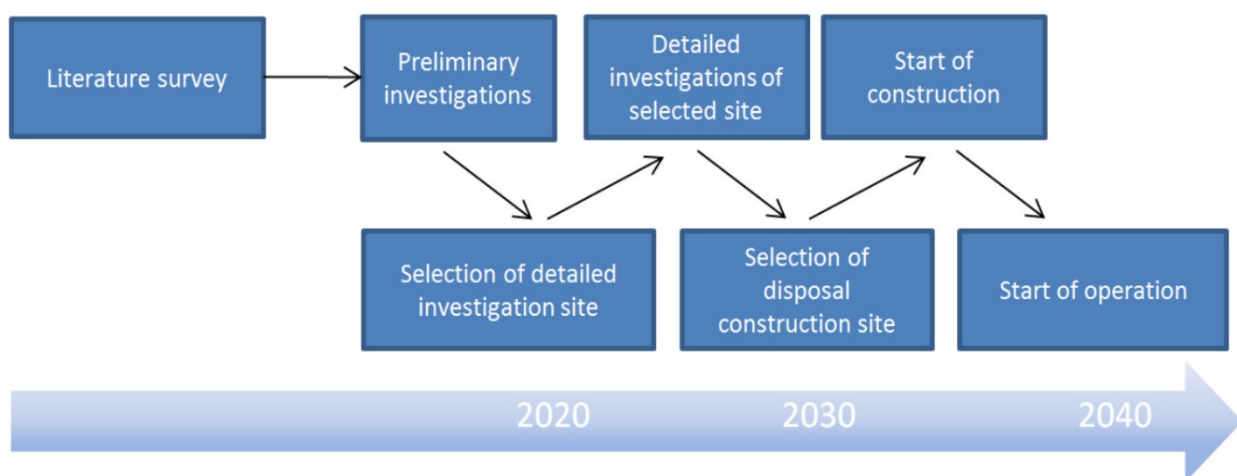


Figure 6.4 Nuclear Waste Management Organization's Process for Establishment of Final Nuclear Waste Disposal Facility

Source: JNFL, 2017b.

Current plans call for the underground waste disposal facility to be 6-10 km² in area with galleries more than 300 meters long. The facility is intended to store more than 40,000 vitrified canisters for hundreds of thousands of years. Plans call for facility construction and entombment of the canisters to take about 100 years, including site selection, safety inspections and burying and closing the galleries ([Mainichi Shimbun, 2017](#)).

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The Japanese radioactive waste disposal concept is founded on a few decades' research work conducted at two underground research laboratories by JAEA (formerly JNC). The research and experience at the two geologic centers would be used to prepare NUMO's final waste storage concept ([WNA, 2017a](#)).

- The Mizunami Underground Research Laboratory in Tono, Gifu Prefecture, has been investigating the crystalline rock environment since 1996. Two 1,000-meter deep shafts and several drifts (horizontal tunnels) have been excavated in igneous rock, as of 22 December 2017 ([JAEA, 2002, 2017d](#)).
- The Horonobe Underground Research Laboratory, Hokkaido, has been investigating the sedimentary rock environment since 2000. It has excavated the sedimentary rocks about 500 m deep and constructed underground shafts and a 760-metre gallery in November 2005. This is a seismically stable area of Japan ([Ota, et al., 2007](#)).

Like Japan, the efforts to establish a radioactive waste disposal site have met with difficulty in many countries overseas. Only Finland and Sweden have been able to select their sites. Finland started construction in December 2016 and hopes to begin operating in the 2020s. The US decided on a site in 2002, but the residents objected to it and President Obama terminated the plan in 2009. President Trump announced in March 2017 that the plan would resume but the residents continue their opposition. Germany had a candidate site, but the plan is back to a blank sheet of paper because of residents' opposition ([Mainichi Shimbun, 2017](#)).

6.4 Private Sector Interest in Waste Storage and Disposal Facilities

The private sector started to establish a few low-level radioactive waste storage facilities, high-level storage facilities and disposal facilities. The government has encouraged them to do so, no doubt motivated by their own slow progress in preparing a deep geologic disposal facility.

6.4.1 Recyclable-Fuel Storage Company (RFS)

The Recyclable-Fuel Storage Company (RFS) located in Mutsu, Aomori Prefecture, is Japan's first commercial off-site interim nuclear waste storage facility. Capitalized at \$30-million, the private company was established in November 2005 by TEPCO (80 percent) and JAPC (20 percent). The RFS facility temporarily stores recyclable spent fuel from (TEPCO and JAPC until it can be reprocessed. The spent fuel is to be stored for a maximum of 50 years. The storage capacity of the first building is 3,000 tU or 288 dry metal casks. Final storage capacity is planned to be expanded to 5,000 tons after 10-15 years (See Figure 6.5) (Takahashi, et al., 2015). Of the 5,000 tons, 4,000 tons will belong to TEPCO and 1,000 tons to JAPC. Construction will cost at about \$1 billion (METI, 2014).

RFS applied to METI for a permit to operate its storage facility in March 2007. The permit was issued in May 2010. RFS submitted plans for design and construction of the facility in June 2010 and approval was given in August 2010. The construction work started in August 2010 but was suspended in March 2011 for a year in the aftermath of the Fukushima nuclear disaster. Construction resumed in March 2012 and was completed in August 2013. Metal casks and necessary equipment are being fabricated at RFS factories. About 70% of the \$1-billion cost is reported to be associated with the casks, according to World Nuclear Association. In December 2013, post-Fukushima new regulatory standards came into force.

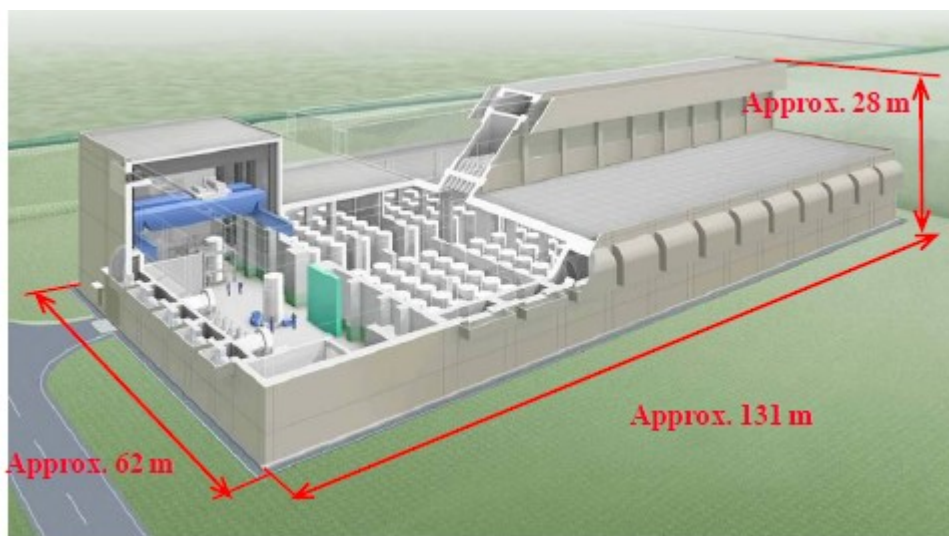


Figure 6.5 Overview of the Recyclable-Fuel Storage Facility
Source: Takahashi, et al., 2015.

The new NRA regulations specified that interim storage of spent fuel should be in dry storage with convection cooling, which applies principally to the RFS. RFS submitted the application for renewal of its permit to operate the facility in January 2014. Since then, RFS submitted revised applications for facility design. In August 2017, the NRA approved a seismic level of 620 Gal for RFS. The RFS application awaits full NRA review. So far, the RFS is expected to come into service late in 2018 (Takahashi, et.al, 2015; Ishikawa, 2014; WNA, 2017a).

- According to a calculation by the Central Research Institute of Electric Power Industry (CRIEPI), the cost of the transportation/storage cask system at RFS is about 60 percent less than that of pool storage and this will result in more than \$1 billion in cost reduction for storing 3,000 tons of spent fuel for 50 years ([Katsuta, Takubo, 2011](#)).

RFS clearly gives impetus to Japan's plans for reprocessing. On 9 October 2005, the Aomori Prefecture governor stated that one of his reasons for giving consent to RFS was the assurance given him by responsible ministries that "the facility would be there temporarily and that a second reprocessing plant would be built in addition to the Rokkasho reprocessing plant to facilitate reprocessing." He noted that, "It is vitally important that the reprocessing of all the spent fuel be the premise for the interim storage program. The spent fuel should not be kept in Mutsu city forever" ([Katsuta, Takubo, 2011](#)).

- In addition to Tokyo Electric, other utilities are also thinking about developing off-site storage facilities, but none have any specific plans yet. In the case of KEPCO, which has 11 reactors in Fukui Prefecture, there has been talk in a few communities in the prefecture about hosting an interim storage facility, but no plans have materialized. A special committee established by the city council of Gobo in Wakayama Prefecture asked KEPCO in December 2009 to examine the possibility of building an interim storage facility in the city. KEPCO responded positively in February 2010 saying that a literature survey indicated it was possible but avoided giving a definite answer ([Katsuta, Takubo, 2011](#)).
- There have been some reports from internal sources that the structure of the dry cask storage facility at the Fukushima Daiichi nuclear plant was damaged, although no reports indicated any safety concerns with the spent fuel stored in the casks. This might lead to more interest in dry cask storage.
- On the other hand, the trauma from the Fukushima disaster might lead to opposition to building any new interim storage facilities—either at nuclear power plant sites or off-site. Nevertheless, even with a small number of nuclear reactors back on-line, the demand for storage capacity will certainly increase. ([Katsuta, Takubo, 2011](#)).

6.4.2 Rokkasho Radioactive Waste Storage Facility

On 20 April 1984, FEPC communicated to the governor of Aomori Prefecture that the FEPC had a plan to establish radioactive waste storage facilities among other nuclear facilities.⁵⁴ Three months later, on 27 July 1984, the FEPC disclosed a more concrete plan and requested the governor of Aomori Prefecture and the head of Rokkasho village to provide their endorsement. The FEPC planned to build the facilities in the Mutsuogawara Industrial Park, Rokkasho-mura,

As is customary, the FEPC had been negotiating on land acquisition ahead of the official announcement and even had a deal in hand. Aomori Prefecture had established the Mutsuogawara Industrial Park in the late 1960s, in the hope of inviting a petrochemical and steel industry complex.

⁵⁴ The FEPC proposal included three facilities, enrichment, reprocessing and waste disposal facilities.

Their wish, however, did not come true and their investment had become a major burden. Thus, it was an easy for the FEPC to get permission to locate its nuclear complex in the industrial park. Still, the FEPC had to deal with major opposition movements from local landowners and fishermen's union before plant construction could proceed ([Yoshioka, 2013](#); [JNFL, 2017c](#); [Keidanren, 2009](#)).

6.4.3 Rokkasho Low-Level Waste (LLW) Disposal Center

JNFL applied for permission to enter the low-level, radioactive waste (LLW) disposal business in April 1988 and was granted approval in November 1990. It immediately started construction of the LLW disposal center the same month and started operations in 1992 ([JNFL, 2017d](#)). The disposal facility has a capacity of 80,000 m³ (400,000 200-liter waste drums). As of October 2017, JNFL has been approved to operate the disposal facilities with a total capacity of 80,000 m³. JNFL has received 299,211 drums of LLW, as of 31 March 2018. The company has been seeking permission from Aomori Prefecture to build additional disposal capacity. The new facility would handle 600,000 m³ of waste. Construction cost for the LLW disposal facility is estimated to be about \$1.6 billion per 200,000 m³ (equivalent to about one million 200-liter drums), according to JNFL, total construction costs for the entire 600,000 meter³ capacity would be about \$4.8 billion ([JNFL, 2018](#)).

As discussed earlier, radioactive waste in Japan is classified into four categories (L1, L2, L3 and TRU waste) according to radioactivity concentration and the origin of the waste. The JNFL accepts the L2 type of LLW but their disposal operations are limited to waste that has been generated by the operation of domestic nuclear power plants which are owned by electric utility companies. This waste contains small amounts of mostly short-lived radioactive material, such as cobalt-60 (Half-life is about 5 years). Each category of LLW has a different disposal concept. For L2 type waste, JNFL would dispose of it in a concrete pit buried at a depth of ten meters or more at JNFL's site.

6.4.4 Rokkasho High-Level Waste Storage—Vitrified Waste Storage Center

JNFL was granted approval to conduct high-level radioactive waste (HLW) management in April 1992. In May 1992, JNFL started construction of the HLW facility. In April 1995, the Vitrified Waste Storage Center (VWSC) started operation. The VWSC was hastily established to receive reprocessed waste that was scheduled to be returned to Japan from overseas, primarily from BNFL in Sellafield of UK and COGEMA (now AREVA NC) of France (See Figure 6.6).

- Even before the Rokkasho VWSC started operations, the first of 12 shipments of vitrified waste had been returned to Japan from France in February 1995. The last shipment from France arrived in Japan in 2007.
- The 12 waste shipments amounted to 1,310 canisters, containing almost 700 tons of vitrified HLW, were packed in heavy steel shipping casks. The shipment of 520 canisters of vitrified HLW from the UK commenced early in 2010 and took over six years to complete.
- A total of 1,830 canisters have been delivered. JNFL's Vitrified Waste Storage Center (VWSC) has the capacity for 2,880 canisters and as of end of 2016, the VWSC was about 64 percent full ([JNFL, 2017e](#)).

- The VWSC facility is a temporary stand-in for permanent deep ground geologic disposal facility that the Japanese government has been working to establish. To codify that principle, in March 2006 the JNFL signed an agreement with Aomori Prefecture and Rokkasho village and the adjoining municipalities of Misawa city, Tohoku town, Higashidori village, Yokohama town and Noheji town regarding safety measures and the need to preserve the environment in connection with the storage of spent fuel and the handling of spent fuel for active testing (JNFL, 2017c; WNA, 2017b, 2017c).

The waste belongs to the ten Japanese power utilities that were ultimately responsible for its storage and disposal, but they could not accept the waste because they had little space for storage at their facilities or at their nuclear station sites. Thus, they are stored in the VWSC facility for 30-50 years prior to final disposal (JNFL, 2017e). Meanwhile, storage capacity for spent fuel in Japan is filling up, including all the nuclear plant sites, the Rokkasho complex and the Recyclable-Fuel Storage Company (RFSC) (See Table 6.3).

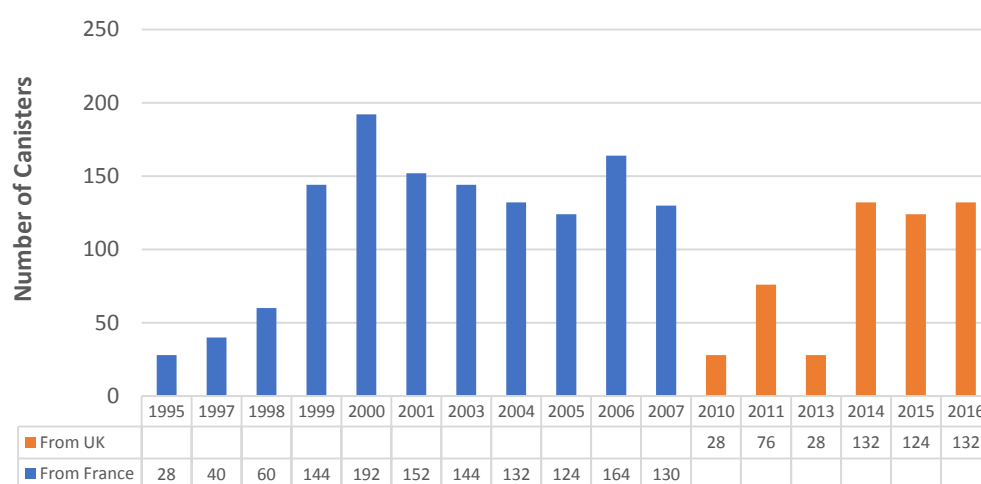


Figure 6.6 Return of Processed High-Level Waste from the UK and France

Notes: Total of 18 shipments and 1,830 canisters. The 1999 shipment from France was delivered in two shipments, making a total of 12 shipments from France. Shipments from UK were 6.

Source: WNA, 2017d.

Table 6.3 Japan's Current Spent Nuclear Waste Disposal Management⁵⁵

Storage Sites	Cumulative Spent Nuclear Fuel Waste	Maximal Storage Capacity	Operational Status
Nuclear plant sites (As of September 2016)	1,664 canisters; and 14,830 tU spent fuel in their cooling pools	70% full	In-house storage only
Mutsu Recyclable-Fuel		A temporary storage up	Waiting for

⁵⁵ Does not include Japan's plans for the Deep Geological Repository. See discussion at Section 6.3. Table 6.1 shows the amount of spent fuel accumulated at individual nuclear plant sites.

Storage Company (RFS)			to 50 years. 3,000 tU or 288 dry metal casks initially; 5,000 tU ultimately	final approval
RRP's Cooling Pool		2,951 tU fuel from Japan's 50 power reactors are temporarily stored in the pool	The pool has the capacity of 3,000 tU and is roughly 98 percent full.	Open but nearly full.
RRP Facilities	Low-Level Radioactive Waste Disposal Center		A total capacity of 80,000 m ³ (400,000 of 200-liter waste drums) of L2 type of low-level radioactive waste.	Open only for L2 type LLW
	Vitrified Waste Storage Center	1,830 canisters from France and UK (Transfer of 1,310 canisters from France completed in 2007; 520 returned from the UK since 2010. Remaining 370 canisters are expected from the UK in the future).	The vitrified Waste Storage Center has the capacity for 2,880 canisters. The storage is 54 percent full.	Open only for vitrified canisters

Sources: Takamatsu, 2010; WNA, 2017d; FEPC, 2016; JNFL, 2017f, 2018.

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Chapter 7:

Decommissioning Nuclear Facilities

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Abstract

As of 2018, Japan had 21 reactors in its decommissioning program—a three-fold increase in the program since 2011. This presents a qualitatively new challenge for Japan’s nuclear industry and government overseers. Even this number is likely to increase. Utilities that own 14 reactors have not yet decided on whether to pay for upgrades or to permanently shut them down. At Fukushima, there is no existing technology that can effectively find and retrieve melted fuel that leaked out of the pressure vessels and into the environment. Meanwhile, cost estimates for decommissioning have been increasing as Japan gains first-hand experience in disassembly and disposal of complex, radioactive materials. METI has formulated a plan to secure more funds for decommissioning (non-Fukushima) reactors, but this means higher electricity rates overall. Even with this plan, METI has concerns that power companies will be unable to pay for decommissioning.

7.0 Magnitude of the Challenge

As of July 2018, Japan had a total of 21 nuclear reactors in its decommissioning program. This represents a three-fold increase in the number of reactors in the program since 2011 and presents a qualitatively new challenge for Japan’s nuclear industry and government. Prior to 2011, Japan was decommissioning or had completed work on just five reactors. Since then, 15 power reactors plus Monju FBR have been added to the program.

Even this number is likely to increase—substantially. The utilities that own some 14 reactors have not yet decided on whether to pay for the costly upgrade process to meet new safety requirements. Instead, they may decide to permanently shut them down. As mentioned earlier, the TEPCO CEO announced that his company is considering decommissioning the four Fukushima Daini reactors, in addition to the six at Fukushima Daiichi that are already slated for decommissioning. Other owners are grappling with trade-offs between age of their reactors, design life, power capacity, fuel storage, and vulnerability to natural disasters. If all 14 are scheduled for decommissioning, Japan would have to cope with technical, economic, and social consequences of closing down 35 reactors—an unprecedented challenge.

The problems of decommissioning are numerous:

- Japan’s nuclear industry will be facing a steep learning curve in managing the decommissioning of all these reactors. So far Japan has decommissioned one reactor (completed in 1995). This was the small experimental JPDR reactor. It had a power output of 12 MWe. Reactors slated for decommissioning have power levels of 500 MWe or more.
- Japan already is overwhelmed by the volume of spent fuel currently in storage. Added to that is the large amount of radioactive waste that would be generated from decommissioning dozens of reactors. There is little room to store spent fuel and other radioactive waste at individual plant sites. Moreover, Japan’s plans to build a deep underground geological waste disposal site and has been subject to repeated delays.

- Japan lacks decommissioning technology for ordinary light water reactors (LWRs) and also is faced with less-common reactor technology, such as the graphite-moderated, carbon dioxide gas-cooled reactor (GCR). JPAC owned and operated Japan's first commercial nuclear reactor, Tokai, which is a GCR. It started operation in 1966 and ended in 1998 and had a power output of 166 MWe. This type of reactor takes a much longer time to decommission than LWRs.
- There is no existing technology that can solve the problems being faced by nuclear engineers at the Fukushima Daiichi nuclear plant. An international team of researchers is trying to invent new technology that would help find and retrieve melted fuel that leaked out of the pressure vessels and into the environment. Funds and expertise, both in short supply, are being monopolized by this enormous challenge. Moreover, these resources are not available to handle other decommissioning projects at other power plant sites—there is no end in sight to this problem.
- Many of the reactors are likely to be decommissioned before they have completed their full operational lives. Decommissioning funds for these reactors were to be set aside on a regular basis during the lifetime of the reactor. If lifetimes are shortened, there might not be sufficient funds available for decommissioning.

Details on the reactors that are in the decommissioning program are in Table 7.1. Total decommissioning costs for the 21 reactors amount to over \$12 billion, not including the costs for Fukushima Daiichi, which currently is estimated by the Japanese government to be \$80 billion. That estimate is uncertain, and the cost could increase substantially in the coming years. Additionally, based on the experience with the JPDR, the decommissioning costs associated with the other reactors are likely to increase.

7.1 Japan's Experience in Decommissioning Reactors

The decommissioning process involves decontaminating the facility to reduce residual radioactivity, dismantling the structures, removing contaminated materials to appropriate disposal facilities, storing used nuclear fuel until it can be removed from the site for disposal or consolidated storage, and releasing the property for other uses. The owner of the reactor remains accountable to the NRC until decommissioning has been completed and the agency has terminated its license ([Nuclear Energy Institute \(NEI\), 2016a](#)).

- JAERI (now JAEA) completed the decommissioning of the Japan Power Demonstration Reactor (JPDR) in 1996. The 12 MW BWR was Japan's first reactor and operated for 14 years, from 1963 to 1976.
- Decommissioning took 20 years and cost \$312 million. The JPDR was originally constructed for \$45 million, a mere 15 percent of decommissioning cost ([Tanaka, et al., 1997](#); [Schmittem, 2016](#); [METI, 2005](#); [STA, 1964](#)).
- Other than the spent fuel that was shipped to UK, the JPDR generated a total of 24,400 tons of waste, including 3,770 tons of radioactive waste (See Figure 7.1).

Table 7.1 Japan's Nuclear Reactor Decommissioning Program: Reactors, Years of Operation, Costs of Decommissioning

Note. As of 10 July 2018, JAIF listed 21 reactors scheduled for decommissioning. On 14 June 2018, TEPCO announced TEPCO was considering decommissioning all four Fukushima Daiichi reactors. This table tentatively includes the four reactors in the expectation that an official decision is forthcoming.

Nuclear Reactor	Type	MW (Net)	Operator	Operating Time	Amount of Waste (tons)	Stage of Decommissioning	Decommissioning Cost
JPDR	BWR	45 MWt 12.5 MWe	JAERI (JAEA)	10/63-3/1976 (13 years)	Radioactive: 3,770 Non-radioactive: 20,700	Dismantling completed in March 1996. ⁵⁶ All radioactive waste has been stored at the JAEA buildings or buried under ground on the site. It needs a final disposal site.	\$312 million ⁵⁷
Fugen	ATR	165	PNC (JAEA)	11/1978-3/2003 (25 years)	L1: 500 L2: 4,400 L3: 45,500 Clearance objects: Not yet established. Non-radioactive waste: 311,600 ⁵⁸	Decommissioning started in February 2008 to be completed in 2029. Dismantling in the non-reactor area is ongoing. The spent fuel was removed from the core and placed in the storage pool. It is currently being transferred to the	\$747 million ⁵⁹

⁵⁶ METI, 2014. "Hairo o Enkatsu ni Susumeru tame no Kaikei Kanren Seido no Kadai (Issues of Accounting-related Systems to Efficient Advance Decommissioning)," Material 4, the Agency for Natural Resources and Energy, November 2014, http://www.meti.go.jp/committee/sougouenergy/denryoku_gas/denkiryokin/hairo_wg/pdf/003_04_00.pdf, (accessed 3 November 2017).

⁵⁷ Soichiro Oshima et al, 2005. "Genshi-ro Kaitai ni kakawaru Haishi Sochi Hiyo Hyoka Shuho no Kento—COSMARD o mochiita Haishi Sochi Hiyo no Keisan— (A Study of the Evaluative Method of Cost at the time of Nuclear Reactor Decommissioning—Calculation of Decommissioning Cost thorough the COSMARD method—)," JAERI, September 2005, http://www.iaea.org/inis/collection/NCLCollectionStore/_Public/37/022/37022206.pdf, (accessed 2 November 2017).

⁵⁸ Yasumitsu Nawata, 2015. Gen'patsu no Haishi Sochi o meguru Genjo—Hosha-sei Haiki-butsu no Shobun-to Sama-zama na Kadai (Current Situation surrounding Nuclear Reactor Decommissioning Measures—Various Issues including Radioactive Waste Disposal and Others)," Rippo to Chosa, No. 379, October 2015, the House of Councilors, http://www.sangiin.go.jp/japanese/annai/chousa/rippou_chousa/backnumber/2015pdf/20151001080.pdf, (accessed 3 November 2017).

						Tokai reprocessing center.	
Tokai (Japan's first commercial nuclear reactor)	British Magnox Gas Cooled Reactor (GCR)	166	JAPC	7/66-3/1998 (32 years)	L1: 1,600 L2: 13,000 L3: 12,300 Clearance object: 41,100 ⁶⁰ The spent fuel was to Sellafield, UK, for reprocessing.	Decommissioning started in 2001 and is expected to be completed in 2025. All spent fuel was shipped to the UK in June 2001. The 1% of L1 waste will be buried at 50-100 meters deep. Dismantling of the non-reactor area was complete and request made to NRA to bury L3 waste at 2.5-meter underground for 50 years. Demolition of facilities that generate L2 waste will not be undertaken due to the lack of disposal site. No plans for the final disposal site for the waste. ⁶¹	\$883 billion
Hamaoka 1	BWR	540	Chubu	3/73-1/09 (36 years)	L1 40 L2 370 L3L 9,990	The two reactors were permanently shut down following the 2007 earthquake and are now	\$3 billion ⁶⁴

⁵⁹ JAEA, 2016. "Genshi-ro Haishi Sochi Kenkyu Kaihatsu Senta (Fugen) Haishi Sochi ni kakawaru Jimoto Kigyo no Hatten, Koyo Sokushin-saku (Development and Employment Promotion of Local Businesses related to the Fugen Decommissioning Measures)," 19 May 2016, <https://www.jaea.go.jp/04/fugen/haishi/activity/img/EmploymentPromotion.pdf>, (accessed 3 November 2017).

⁶⁰ Yasumitsu Nawata, 2015. Gen'patsu no Haishi Sochi o meguru Genjo—Hosha-sei Haiki-butsu no Shobun-to Sama-zama na Kadai (Current Situation surrounding Nuclear Reactor Decommissioning Measures—Various Issues including Radioactive Waste Disposal and Others)," Rippo to Chosa, No. 379, October 2015, the House of Councilors, http://www.sangiin.go.jp/japanese/annai/chousa/rippou_chousa/backnumber/2015pdf/20151001080.pdf, (accessed 3 November 2017).

⁶¹ Yasumitsu Nawata, 2015. Gen'patsu no Haishi Sochi o meguru Genjo—Hosha-sei Haiki-butsu no Shobun-to Sama-zama na Kadai (Current Situation surrounding Nuclear Reactor Decommissioning Measures—Various Issues including Radioactive Waste Disposal and Others)," Rippo to Chosa, No. 379, October 2015, the House of Councilors, http://www.sangiin.go.jp/japanese/annai/chousa/rippou_chousa/backnumber/2015pdf/20151001080.pdf, (accessed 3 November 2017).

					Clearance object: 34,050 Non-clearance object: 155,500 ⁶²	written off. The decommissioning started in November 2009 to be completed in 2036. The operator has found no disposal site for the waste, which would remain in the buildings for the time being. ⁶³	
Hamaoka 2	BWR	840	Chubu	11/78-1/09 (31 years)	L1: 50 L2: 570 L3: 8,860 Clearance object: 43,680 Non-clearance object: 198,200 198,200 ⁶⁵		
Fukushima I-1	BWR	460	TEPCO	3/71-3/11 (41 years)		Reactor 1-3 were seriously damaged in the 3:11 disaster, Reactor 4 was slightly damaged and the other two undamaged. All 6 reactors, however, were written off and are to be decommissioned. The operator expects Reactor 1-4 would take 30-40 years to decommission.	\$80 billion ⁶⁶
Fukushima I-2	BWR	784	TEPCO	7/74-3/11 (38 years)			
Fukushima I-3	BWR	784	TEPCO	3/76-3/11 (37 years)			
Fukushima I-4	BWR	784	TEPCO	10/78-3/11 (33 years)			

⁶⁴ Marc Schmitter, 2016. "Nuclear Decommissioning in Japan: Opportunities for European Companies," European Cluster Initiatives, 15 June 2016, <https://www.clustercollaboration.eu/eu-initiatives/reports/nuclear-decommissioning-japan-opportunities-european>, (accessed 3 November 2017).

⁶² Yasumitsu Nawata, 2015. Gen'patsu no Haishi Sochi o meguru Genjo—Hosha-sei Haiki-butsu no Shobun-to Sama-zama na Kadai (Current Situation surrounding Nuclear Reactor Decommissioning Measures—Various Issues including Radioactive Waste Disposal and Others)," Rippo to Chosa, No. 379, October 2015, the House of Councilors, http://www.sangiin.go.jp/japanese/annai/chousa/rippou_chousa/backnumber/2015pdf/20151001080.pdf, (accessed 3 November 2017).

⁶³ Yasumitsu Nawata, 2015.

⁶⁵ Yasumitsu Nawata, 2015.

⁶⁶ According to METI's Tokyo Electric Company Reform · Fukushima Daiichi Problem Committee as of December 2016, the total decommissioning cost of Fukushima Daiichi 1-6 will increase to \$80 billion from \$20 billion estimated in 2013 (METI, 2016. "Toden Kaikaku Teigen (An) (Tokyo Electric Reform Proposal (Plan))," Tokyo Electric Reform· Fukushima Daiichi Problem Committee, 20 December 2016, http://www.meti.go.jp/committee/kenkyukai/energy_environment/touden_1f/pdf/008_01_00.pdf, (accessed 19 December 2017).

Fukushima I-5	BWR	784	TEPCO	4/78- 3/11 (33 years)		Reactors 4 and 5 were written off, reportedly, to appease the public.	
Fukushima I-6	BWR	1100	TEPCO	10/79- 3/11 (32 years)		They will be used for decommissioning training. There is no storage site for the waste, which, thus, would remain on site.	
Fukushima II-1	BWR	1100	TEPCO	4/82-3/11 (28 years)		Candidate for decommissioning, but no official decision as of 2018.	
Fukushima II-2	BWR	1100	TEPCO	2/84-3/11 (27 years)		Candidate for decommissioning, but no official decision as of 2018.	
Fukushima II-3	BWR	1100	TEPCO	6/85-3/11 (26 years)		Candidate for decommissioning, but no official decision as of 2018.	
Fukushima II-4	BWR	1100	TEPCO	8/87-3/11 (24 years)		Candidate for decommissioning, but no official decision as of 2018.	
Genkai 1	PWR	559	Kyushu	10/75-4/15 (40 years)	L1: 100, L2: 800, L3: 2,010. Non-radioactive waste: 4,120. The waste will be delivered to the waste disposal licensees. ⁶⁷	The reactor is more than 40 years old. Decommissioning will take 28 years, to 2043. By 2021, spent fuel will be removed and some will be stored in the plant's cooling pools and some will be transferred to the Rokkasho reprocessing plant by 2029. The secondary steam supply	\$364 million ⁶⁸

⁶⁷ Kyushu Denryoku, No date. "Genkai Genshi-ryoku Hatsuden-sho 1-go-ki Haishi Sochi Keikaku-sho no Gaiyo ni tsuite (About the Outline of the Genkai Nuclear Plant Unit 1 Decommissioning Measure Plan)," Attachment, <http://www.kyuden.co.jp/var/rev0/0049/8566/NXTzAsQe.pdf> (accessed 26 November 2017); Saga Shimbun, 2015. "Hairo no gomi, Ikiba naku, Genkai 1-go-ki ga Hairo Keikaku Shinsei, Hoshasei Haiki-butsu 3000 ton, Shikichi-nai ni Maizo mo (With No Place for Waste from Decommissioning, Application for Genkai 1 Decommission Made, Radioactive Waste 3000 tons, might be Buried at the Site)," 23 December 2015, <http://www.saga-s.co.jp/articles/-/35542>, (accessed 3 November 2017); JAIF, 2015. "Kyushu Electric Power Submits Application for Genkai-1 Decommissioning Plan," 28 December 2015, <http://www.jaif.or.jp/en/kyushu-electric-power-submits-application-for-genkai-1-decommissioning-plan/>, (accessed 3 November 2017).

⁶⁸ Mainichi Shimbun, 2015. "Genkai Gen'patsu 1-go-ki, 28-nen-kan de Hairo ni, Kyuden ga Keikaku (Genkai 1 to be Dismantled, After 28 years, Kyushu Electric Plans)," 22 December 2015, <https://mainichi.jp/articles/20151223/k00/00m/040/045000c>, (accessed 3 November 2017).

						system and the main reactor vessel and the steam generators will be disassembled by 2036. The containment and buildings will be demolished in 2043.	
Ikata 1	PWR	566	Shikoku	9/77-5/16 (39 years)		The reactor was 40 years old. Decommissioning commenced for Ikata 1 in May 2016. Decommissioning is expected to complete in 2056.	\$400 million ⁶⁹
Ikata 2	PWR	890	Shikoku	3/82-3/18 (37 years)		The reactor is small and 36 years old. It will take \$1 billion to extend its life to 60 years. The owners decided in March 2018 to decommission because upgrading is not economically feasible.	\$400 million ⁷⁰
Mihama 1	PWR	340	Kansai	11/70-4/15 (45 years)	Radioactive waste: 5,040 ⁷¹	The reactor is more than 40 years old. Decommissioning to complete in 2045. No disposal site has been decided.	\$680 million ⁷²
Mihama 2	PWR	600	Kansai	7/72-4/15 (43 years)			

⁶⁹ Sankei, 2016. "Shikoku-den, Ikata 1-go-ki o Hairo, Kaitai 30-nen, Kokunai 42-ki ni (Shikoku Electric to Decommission Ikata 1, 30 years to dismantle, 42 Reactors Remaining), 10 May 2016, <http://www.sankei.com/west/news/160510/wst1605100036-n1.html>, (accessed 3 November 2017).

⁷⁰ Nihon Keizai Shimbun, 2018. "Ikata 2-go-ki Hairo wo Kettei, Shikoku-Den, Jimoto Ehime-ken ni Hokoku (Shikoku Electric Decided to Decommission Ikata 2, Informed Ehime Prefecture)," 27 March 2018, <https://www.nikkei.com/article/DGXMZO28618440X20C18A3EAF000/>, (accessed 16 April 2018).

⁷¹ WNN, 2016. "Decommissioning plans submitted for three Japanese units," World Nuclear News, 12 February 2016, <http://www.world-nuclear-news.org/WR-Decommissioning-plans-submitted-for-three-Japanese-units-1202164.html>, (accessed 3 November 2017).

⁷² Mainichi Shimbun, 2016. "Gen'patsu 3-ki no Hairo Hiyo 1000-okuen-cho mikomu, Fukui Tsuruga to Mihama (Decommissioning Costs Estimated at More than 1000-okuen for Fukui's Three reactors Tsuruga 1 and Mihama 1 and 2), 13 February 2016. Mainichi Shimbun, 13 February 2016, <http://mainichi.jp/articles/20160213/k00/00m/040/159000c>, (accessed 3 November 2017).

Oi 1	PWR	1175	Kansai	3/79-3/18 (40 years)			\$1,160 million ⁷³
Oi 2	PWR	1175	Kansai	12/79-3/18 (40years)			
Shimane 1	BWR	460	Chugoku	3/74-4/15 (42 years)	HLW: 60 Intermediate-level waste: 670 LLW: 5,350 Other radioactive waste: 20,680 ⁷⁴	The reactor is more than 40 years old. To be decommissioned over 30 years to 2045. The reactor itself will be dismantled starting in 2030.	\$380 million ⁷⁵
Tsuruga 1	BWR	357	JAPC	3/70-4/15 (46 years)	HLW: 40 Intermediate-level waste: 1990 Low-level waste: 10,760 Total solid waste: 20,600	The reactor is more than 40 years old. To complete decommissioning in 2039. No disposal site has been decided	\$360 million ⁷⁶
Monju	FBR	280	PNC (JAEA)	5/71- 12/16 (46 years)	Radioactive waste: 26,700 ⁷⁷	Decommissioning will take some 30 years. Spent fuel will be removed from the reactor and	More than \$3.75 billion,

⁷³ Nihon Keizai Shimbun, 2017 “Oi Gen’patu 1·2-go-ki no Hairo Kettei, Kanden, Saisan Awazu (Kansai Electric Decided to Decommission Oi 1 and 2, because of Lack of Financial Advantages),” 22 December 2017, <https://www.nikkei.com/article/DGXMZO24951780S7A221C1MM0000/>, (accessed 13 January 2018).

⁷⁴ WNN, 2016. “Decommissioning plans submitted for three Japanese units,” 12 February 2016, <http://www.world-nuclear-news.org/WR-Decommissioning-plans-submitted-for-three-Japanese-units-1202164.html>, (accessed 3 November 2017).

⁷⁵ NEI, 2016. “Plans submitted for decommissioning unit 1 of Japan’s Shimane NPP,” 10 May 2016, <http://www.neimagazine.com/news/newsplans-submitted-for-decommissioning-unit-1-of-japans-shimane-npp-4886230>, (accessed 3 November 2017).

⁷⁶ Mainichi Shimbun, 2016. “Gen’patu 3-ki no Hairo Hiyo 1000-okuen-cho mikomu, Fukui Tsuruga to Mihama (Decommissioning Costs Estimated at More than 1000-okuen for Fukui’s Three reactors Tsuruga 1 and Mihama 1 and 2), 13 February 2016. Mainichi Shimbun, 13 February 2016, <http://mainichi.jp/articles/20160213/k00/00m/040/159000c>, (accessed 3 November 2017).

⁷⁷ Asahi Shimbun, 2017. “Monju, 22-nen made ni Nenryo Toridashi Hairo Keikaku o Teishutsu (Monju, Fuel will be Removed by 2022, the Decommissioning Plan Submitted),” 6 December 2017, <http://www.asahi.com/articles/ASKD60C1KKD5ULBJ01M.html>, (accessed 12 December 2017).

						placed in the onsite storage pool for 6 years. The fuel along with sodium coolant and other radioactive waste will be taken from Fukui Prefecture to France for reprocessing. The Rokkasho plant is not equipped for handling MOX from fast reactors.	including \$2.25 billion for maintenance, \$1.35 billion for dismantling and an initial \$150 million for defueling and preparation ⁷⁸
25 reactors (includes 4 Fukushima Daiichi units, each 1100MW)		16,797 MW					\$92 billion, not counting JPDR cost, which is largely paid.

Source: The table was based on sources, including JAIF, 2018a, 2018b; OECD, 2011; WNA, 2017a.

⁷⁸ WNA, 2017. "Decommissioning," Japan's Nuclear Fuel Cycle, Updated August 2017, <http://www.world-nuclear.org/information-library/country-profiles/countries-g-n/japan-nuclear-fuel-cycle.aspx>, (accessed 2 November 2017).

According to JAEA, highly radioactive waste (HLW) totaled 1,660 tons and was placed in special containers and stored at the waste disposal facility on site. Very low radioactive waste totaled 1,670 tons and was placed in special containers and buried underground in near-surface trenches at the site, which were backfilled with cement and protected levels by concrete walls (Tanaka, et al., 1997).

Secondary waste generated by the decommissioning process amounted to 440 tons and is being kept in the storage building. At the time, Japan had no clearance criteria for secondary waste, or a permanent disposal site. Thus, all radioactive solid waste generated by JPDR's decommissioning is in storage at the present JAEA site. It has been segregated and packed in containers and stockpiled, according to the in-house management plan (Tanaka, et al., 1997).

JAEA used a relatively detailed classification and categorization scheme radioactive waste. Of the total amount of radioactive waste, a significant portion was eligible for clearance, if the clearance criteria in the European countries were to be applied. For example, 60 percent of metal waste was emitting less than 0.4 Bq/g of beta/gamma nuclides. The rest (with slightly higher radioactivity) was packed into the steel containers or 200-liter drums and is stored in the storage building (Fujiki, Nakamura, 1997; Tanaka, et al., 1997).

- The disposal facility has been functioning in the preservation stage since October 1997 and might be maintained that way for as long as 100 years, because some of the highly radioactive waste will remain hazardous until then, according to the JAEA. All the non-radioactive waste has been disposed of at off-site locations (Shiraishi, et al., 1999).
- The experience with the JPDR no doubt provided valuable knowledge and experience for the JAEA, but the process was completed 20 years ago and few of the technicians who carried out the decommissioning project are with JAEA today.

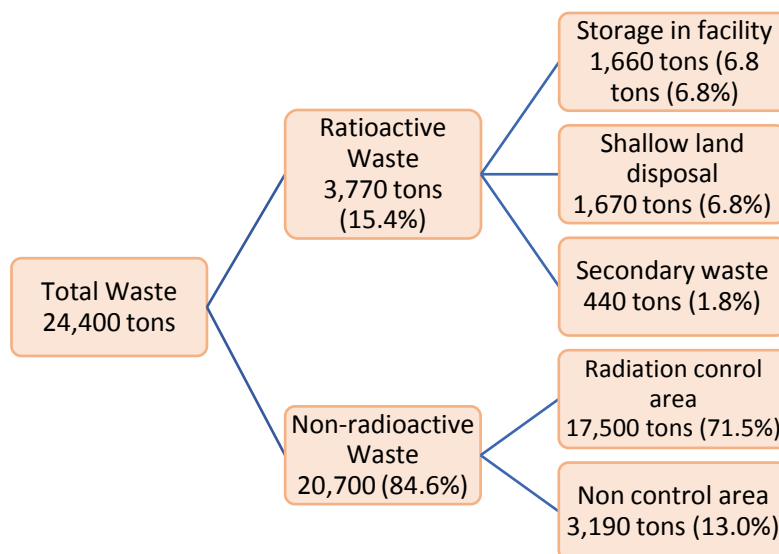


Figure 7.1 The First Decommissioning Case: Waste from the 90 MWt BWR Japan Power Demonstrator Reactor

Source: Tanaka, et al., 1997.

Globally, the experience base in decommissioning nuclear reactors is not much better. Although about 148 commercial power reactors have been retired from service, as of 2016, only 17 of them have been fully decommissioned (See Table 7.2) (Magwood, 2017). The rest are either at the point of license termination or the point where the remaining activities are limited to management of an independent spent fuel storage installation (ISFSI)—a stand-alone facility within the plant boundary constructed for the interim dry storage of spent nuclear fuel—under reduced license. As little experience as the world has, however, it does show that decommissioning can be carried out in a safe manner (NEI, 2016b).

Among those countries with decommissioning experience, the US has the most. The US currently operates 99 commercial nuclear power reactors and as of 2018, and another 34 nuclear units are shut down (see Appendix B for the status of worldwide reactor fleets).

- Of the 34, 13 have been decommissioned, which means they have reached license termination or are now acting as an independent spent fuel storage installation (ISFSI).
- Another 12 have been put in safe storage (SAFSTOR), three are entombed, one (Three Mile Island reactor 2) is in post-defueling monitored storage and five are in the process of being decommissioned (NEI, 2016b).

Germany was operating 17 power reactors until March 2011. A coalition government formed after the 1998 federal elections and started to phase out nuclear energy. When a new government was formed in 2009, the phase-out was cancelled, but then re-introduced it in 2011. Eight reactors were shut down immediately. The remaining nine are scheduled to be shut down by 2022. Of the three decommissioned reactors, two were in the ISFSI status and the site of the third reactor was restored to the level of unrestricted use (WNA, 2017b).

Table 7.2 Decommissioning of Nuclear Power Reactors (NPRs) and Expected Shutdowns Worldwide

*The Magwood data was modified based on the NEI data. ** Eighteen of 21 reactors in Japan's decommissioning program are NPRs. Three others, not included in this table, are ATR Fugen, FBR Monju and the JPDR demonstration reactor. Nine of Japan's 39 operational NPRs are approved for generating power. The Magwood data was modified based on JAIF data. *** The Magwood data was modified based on the WNA data.

§ Total is for selected countries; see Appendix B for more complete list.

Country	Permanently Shut Down	Decommissioning Completed	NPRs Operational	NPRs To Be Shut Down before 2030
US*	34	13	99	5
Canada	6		19	14
Korea	0		24	9
Japan**	18		39	8
UK	30		15	18
France	12		58	0
Finland	0		4	2
Germany***	28	3	8	9
Hungary	0		4	0

Russia	5		35	23
Belgium	1		7	7
Sweden	3		10	4
Switzerland	1		5	4
Spain	2		8	8
Italy	4		0	0
Netherlands	1		1	0
Slovakia	3		4	0
TOTALS	148	16	340^s	111

Source: Based on JAIF, 2018b; Magwood, 2017; NEI, 2017a; WNA, 2017b.

7.2 Keeping Pace with the Growing Volume of Radioactive Waste

As part of their decommissioning plans, Japan's nuclear power plant owners have estimated the amount of radioactive waste that will be generated by their plants and reported these estimates to the government as well as the press (shown in Table 7.3). While helpful, it is nonetheless an estimate and is not necessarily accurate or current. For example:

- The amount of solid waste generated by the Fukushima disaster is far greater than that of solid radioactive waste generated by the normal operations of nuclear power stations.
- A lot of solid waste at Fukushima may have relatively high dose rate. For instance, when fuel debris retrieval starts, the materials and equipment removed from around the fuel debris will likely become high-dose solid waste.

There are, however, two data points on expected waste volume compiled by the Federation of Electric Power Companies of Japan (FEPC), which at least give us a point of departure. According to the data, Japan would likely have a total of 451,000 tons of low-level radioactive waste from 57 commercial power plants, assuming that all Fukushima reactors had operated normally and was decommissioned normally. Using this number, we can estimate how much waste could be expected from the 18 NPRs that are to be decommissioned, which would be $(451,000 \div 57 \times 18 = 142,421)$. In addition, we add the estimated radioactive waste from JPDR (3,770 tons), ATR Fugen (50,400 tons) and FBR Monju (26,700 tons), which gives a total of approximately 223,000 tons. This should be considered a low-end estimate because it does not take into account the conditions at Fukushima Daiichi.

Like JPDR, all the 18 commercial NPRs as well as ATR Fugen and FBR Monju have no dedicated disposal sites. Even as early as 1997, the owner of JPDR, JAERI (later JAEA), was running out of storage space for its radioactive waste. Fujiki and Nakamura (1997) stated that to save space JAEA's predecessor processed on-site all radioactive waste generated from the Tokai research facilities under its management. All combustible low-level radioactive solid materials were incinerated, but all other solid waste had been packed in containers and stored at storage facilities. This included JPDR's decommissioning waste and total waste accumulated from laboratories since the beginning of JAERI research activities (Fujiki, Nakamura, 1997).

It is clear that the government's slow progress in the construction of a disposal site is troubling the nuclear industry. To make provision of its own, the JAPC on 16 July 2015 filed an application to

build a low-level radioactive burial facility to store the L3 low-level waste from Tokai at Tokai-mura, Ibaraki Prefecture. JAPC also submitted to Tokai-mura and Ibaraki Prefecture a plan to build a new storage/disposal facility. The facility would be built within the JAPC company site. The site is expected to be 80 m x 100 m wide and have a storage capacity of 26,400 m³ to handle 16,000 tons of waste. The storage facility is expected to open in 2018 and would be managed for 50 years (JAPC, 2015).

- The JAPC also indicated that L1 and L2 radioactive waste would require a longer period of burial and management as well as man-made structures such as concrete pits. JAPC indicated that the electric utilities are studying whether to build a storage/disposal site such as the JAPC's at present (JAPC, 2016).

Table 7.3 Estimated Weight and Volume of Waste from Decommissioning Japan's Nuclear Reactors

Notes: The 57 plants are all the commercial nuclear plants that Japan has operated since 1960s. The JPDR is a prototype demonstration and is not counted in that number. The Fukushima disaster is not accounted for in this estimate. Total volume of waste is calculated using the actual figures from Tokai and Hamaoka 1 and 2 and the compilation of the estimated volume based on the type and size of the reactors.

L1: Relatively high level radioactive waste

L2: Relatively low level radioactive waste

L3: Very low level radioactive waste

CL: Waste below the Clearance Level

NR: Nonradioactive waste

Estimated Waste by Type and Size of Nuclear Power Plant (tons)							
	BWR			PWR			GCR
	Small	Medium	Large	Small	Medium	Large	
L1	50	70	80	120	190	200	1,540
L2	760	830	850	710	1,230	1,720	8,950
L3	5,530	6,750	11,810	1,850	2,570	4,040	12,300
CL	9,710	9,750	28,490	3,970	8,080	11,660	41,100
NR	130,620	220,430	495,420	187,150	215,750	477,300	128,700
Total	146,670	237,830	536,650	193,800	227,820	494,920	192,590

Source: FEPC, 2015.

In the US, several nuclear power plants completed decommissioning in the 1990s without a viable site for disposing of their spent nuclear waste because the federal government has not been able to secure a geologic repository as planned. Accordingly, the US Nuclear Regulatory Commission (NRC) implemented regulations allowing licensees to sell off part of their land once it meets NRC release criteria, while maintaining a small parcel under license for storing the spent fuel. These stand-alone facilities, called independent spent fuel storage installations (ISFSI), will remain under license and NRC regulation. Licensees are responsible for security and for maintaining insurance and funding for eventual decommissioning. This appears to have become a popular practice worldwide (NRA, 2015).

- Regardless of these interim solutions, Dickman (2017) of Argonne National Lab. states that decommissioning cannot be completed until the federal government meets its obligation to remove the spent fuel—and the Congress must act in order for that to happen.

7.3 Challenges in Decommissioning Magnox Reactors

A more serious problem with decommissioning is the difficulty of disposing of certain types of reactors or those that have had accidents. Since 2001, JAPC has been in the process of decommissioning Tokai, a 160 MWe UK Magnox design, Tokai was Japan's first commercial nuclear reactor and was in service for 32 years from 1966 to 1998. Tokai's decommissioning process has been extended from 20 years to 25 years due to the difficulties presented by the Magnox design.⁷⁹ All the spent fuel was removed from Tokai from March 1998 to June 2001 and shipped to Sellafield, UK, for reprocessing (Wise, 1996). Since the fuel removal, the reactor has been in the safe storage to allow radioactivity to decay (2001-2019).

Meanwhile, the dismantling and removal of all the sections other than the reactor area are in progress (2001-2024). The steam generators are being removed (from 2006 to 2019), the auxiliary buildings are being dismantled (from 2012 to 2024), the reactor and its building will be demolished from 2019 to 2024 and all other buildings will be dismantled from 2024 to 2025. The site will be ready for re-use in March 2026, according to the schedule (JAPC, 2017).

JAPC, however, might be underestimating the difficulty of decommissioning the Magnox reactor. None of the gas-cooled graphite moderators of the Magnox reactors have been fully dismantled. For example, the UK's Nuclear Decommissioning Authority (NDA) has started dismantling 29 UK reactors, 25 of them early Magnox types with graphite moderators. One of the first to be dismantled was the Berkeley nuclear power station (2 x 138 MWe), closed for economic reasons in 1989, after 27 years of operation. Defueling was completed in 1992, the cooling ponds were then drained, cleaned and filled in and the turbine hall was dismantled and demolished. The reactor buildings are

⁷⁹ Costs for decommissioning gas-cooled reactors are much higher per unit of capacity than for light water reactors – at least five times for Magnox. This is due to the large volume of material and the need to dispose of a lot of graphite moderator. Decommissioning waste volumes per unit capacity for Magnox are ten times those for western light water reactors. See also the subsection on graphite (WNA, 2017c. "European reactors," *Decommissioning Nuclear Facilities*, Updated 8 September 2017, <http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-wastes/decommissioning-nuclear-facilities.aspx>, (accessed 17.11.04).

in an extended SAFSTOR period. Ultimately, they too will be dismantled, leaving the site to be leveled and landscaped. The same pattern is being followed at the other UK reactor sites ([WNA, 2018](#)).

- A 2006 report commissioned by the Electric Power Research Institute (EPRI) states, “The graphite moderators of retired gas-cooled nuclear reactors present a difficult challenge during demolition activities. As a result, utilities have not dismantled any moderators of CO₂ cooled power reactors to date” ([WNA, 2018](#)). According to the UK NDA’s plan, the Berkeley site would enter care and maintenance stage in 2022, the final site clearance would begin in 2070 and the final site clearance would be achieved in 2079. An average length of time from the start of the care and maintenance stage to the final site clearance is as long as 66 years, according to the NDA.
- There is no established standard for how long the decommissioning of Magnox type reactors should take. According to Holt of British Nuclear Fuels plc., some initial studies consider that the complete dismantling of the reactors within about 20 years of station shutdown is technically feasible, assuming the use of remotely operated equipment. After a time, the long lived radionuclides begin to dominate radiation levels. The rate of reduction falls dramatically after about 80 years or so after shutdown. The maximum benefit from decay is achieved about 130 years after reactor shutdown, at which time Magnox reactors’ internal radiation levels are such that full remotely operated dismantling equipment is no longer required and hence the dismantling process is much less complex, according to Holt ([2017](#)).

7.4 Challenges in Decommissioning Fukushima Reactors

Seven years has passed since the Fukushima Daiichi accident and Japan has been making progress with short-term plans for site clean-up. Contaminated-water management has been making a progress owing to the creation of a land-side impermeable wall by freezing soil walls. Fuel removal operations from the spent-fuel pools also has progressed well, and the outdoor work environment has improved. On the other hand, long-term goals, such as locating and retrieving melted fuel-debris from the reactors, reactor interior investigation and related R&D, have been making little progress. These are a complex and daunting of challenges and no applicable technology exists to support this type of clean-up.

As a result, Japan had to invest in development of new enabling technologies. It established an R&D organization, called the International Research Institute for Nuclear Decommissioning (IRID), in August 2013. IRID consists of Japan’s nuclear research organizations, including JAEA, AIST, electric utilities and nuclear reactor manufacturers. In August 2014, the NDF was given the responsibility to provide management oversight of IRID’s R&D projects. The NDF will ensure that IRID focuses on development of mid- and long-term decommissioning technologies. The NDF will also supervise the work of TEPCO’s Fukushima Daiichi Decontamination and Decommissioning Engineering Company, which has responsibility for executing the actual decommissioning tasks. The NDF will be the main body interacting with METI and TEPCO to implement these tasks ([IRID, 2018a](#); [NDF, 2017a](#)).

Of greatest concern to the government is that Units 1, 2 and 3 all suffered core meltdowns and the molten fuel breached the reactor pressure vessels, falling to the bottom of the primary containment vessels (PCV). In the case of Units 1 and 3 the melted fuel may have interacted with the concrete support pedestal, resulting in chemical reactions that are not yet well understood. According to the NDF, all the PCVs may have been breached and are leaking water (TEPCO, 2017a).

- There are water leaks at two locations at the bottom of the PCV of Unit 1, including one through a work access opening.
- There is at least one water leak in the PCV of Unit 3 and radioactive material is present near a work access opening (NDF, 2017b).

A report by TEPCO, IRID and JAEA indicates that the grating of Unit 2's PCV has sustained damage and distortions caused by falling fuel debris. None of the three entities suggest that the PCVs have been damaged, but TEPCO said that it will conduct research on the findings. The report also indicates that fuel debris has spread out on the pedestal of Reactor 3 but the PCV shell is presumed not to have been affected (TEPCO, 2018; IRID, 2018b; Mizokami, (2017)). Regardless of TEPCO's report, NDF indicated that all three RPVs and PCVs were damaged (See Table 7.3) (NDF, 2017b).

There continue to be serious difficulties in assessing the condition of the PCVs, ascertaining the whereabouts of the fuel debris and how to retrieve the debris. Various remotely controlled robots have been deployed but have had longevity problems due to high levels of radiation. The longer it takes to map the location of debris, the greater the uncertainty as to its status:

- In the mid- to long-term, the state of fuel debris can change, complicating the task of removing it. Radioactive materials can leach from fuel debris and become granular or fragmented due to oxidation. If the volume of fuel debris in highly mobile forms increases due to leaching or granulation, the risk may rise for this form of fuel debris to flow into a circulated cooling system if a major loss of containment functions occurs again.
- Additionally, if granular and fragmented fuel debris with high mobility have high concentrations of nuclear fuel materials, there is an undeniable possibility of it accumulating at one place and causing local criticality (NDF, 2017a).

Despite all the help from private-public organizations, the clean-up and decommissioning of the Fukushima Daiichi Nuclear Plant is subject to considerable delay and uncertainties. The latest plan announced in September 2017 shows that the removal of melted fuel debris from Units 1 and 2 is now scheduled to take place around FY2023, instead of FY2020 (the date in the plan announced in June 2015). Similarly, the retrieval of the melted fuel debris from Unit 3 was delayed to mid-2018 (previously FY 2017) (Ishii, 2017).

Spent fuel at Unit 3 is in the spent fuel pool at the top level of the reactor building. Removal of the spent fuel is under way. To reduce radiation levels on the reactor building operating floor, decontamination and installation of shields were completed in June and December 2016, respectively and the installation of a cover for fuel removal started in January 2017 (METI, 2017a). No end to the challenges can be foreseen. No one really knows how long the decommissioning work will take, and it could be decades (McCurry, 2016).

- One indicator of the scope of the tasks to be done can be seen in the NDF's R&D roadmap. It lists over 80 separate tasks divided among 14 categories, ranging from how to collect and manipulate fuel debris to investigating technologies for in-depth inspection of the interior of PCVs.
- Many of the tasks border on basic research, such as how to predict, evaluate, and prevent criticality events—a much needed bit of knowledge to reduce risks during the retrieval and storage of fuel debris.
- Engineers will need to expect the unexpected. As we noted, there are no credible estimates of the amount of radioactive waste on-site or the amount that will be generated during fuel retrieval and dismantlement operations.
- The tasks are planned to be done over the next year or two, so it is likely that many more tasks will be added in the coming years (McCurry, 2016).

In addition to the reactor clean-up and decommissioning, Fukushima has contaminated water to deal with. On June 19, 2013, TEPCO discovered contaminated groundwater at the Fukushima Daiichi plant between the turbine buildings and the sea port. Analysis indicated that the main source of the contamination was water in cable trenches leading to circulation pumps near the shore. On Aug 19, 2013, TEPCO announced that contaminated water also leaked from an above-ground tank. Moreover, TEPCO estimated approximately 1,000 tons of groundwater flow every day underneath Reactor 1 to 4. At its peak, some 400 tons of this water flowed into the basement of the reactor buildings (MOFA, no date; TEPCO, no date).

During the crisis, a hundred tons of water was poured on each of the three melted cores. The toxic water was pumped out and treated by a complex water-processing system that can remove 62 different types of radioactive materials except tritium. The water is stored in the tanks at the plant site, but the amount of water is continuously increasing. As of September 2017, the tritium water in storage exceeded 1 million tons. The plant site is quickly running out of space for tanks and TEPCO is contemplating releasing the water into the ocean (MOFA, no date; Japan Times, 2017; Osumi, 2017).

- A number of mitigation measures have been implemented to deal with contaminated water, including pumping of groundwater away from buildings (from May 21, 2014), installation of impermeable walls, and the installation of additional multi-nuclide removal equipment, or 'ALPS', (operations commenced from September 2014) (See Figure 7.2) (Cabinet Office, 2016).

Some successes have been achieved with these measures. The subdrain system⁸⁰ and the sea-side impermeable wall have started to work, reducing the groundwater to less than half. TEPCO pumps groundwater from around the building, decontaminates it and stores it in tanks. As of 7 July 2017, the amount of groundwater flowing into the basement has decreased to 120-130 tons a day and the cumulative groundwater in the basement was reduced by half to less than 50,000 tons compared to the time of the nuclear accident. TEPCO planned to double the capacity of the sub drain by November 2017. Another success was the installation of additional multi-nuclide removal equipment 'ALPS,' that removes most toxicity from the water except tritium.

⁸⁰ The subdrain system is a group of 41 wells installed near and around the reactor and turbine buildings. Each day 300 to 500 tons of groundwater are pumped out to prevent water from entering the reactor facilities.

However, the \$320-million impermeable frozen wall, which was completed earlier 2017, has experienced delays and questions about its effectiveness. An expert panel with the NRA examined the latest TEPCO report in August 2017 to assess how far and how successful the project has been and concluded that the ice wall was not working. The panel decided that a new plan was necessary to prevent groundwater mixing with radioactive substances (TEPCO, 2017b; Reuters, 2017; McCurry, 2016; Yamakawa, Miyao, 2017; METI, 2017b).

- There has been no change to the 2020 target date for removing contaminated water that has accumulated in the reactor buildings because of the need to cool the melted fuel in the reactors (NEI, 2017b).

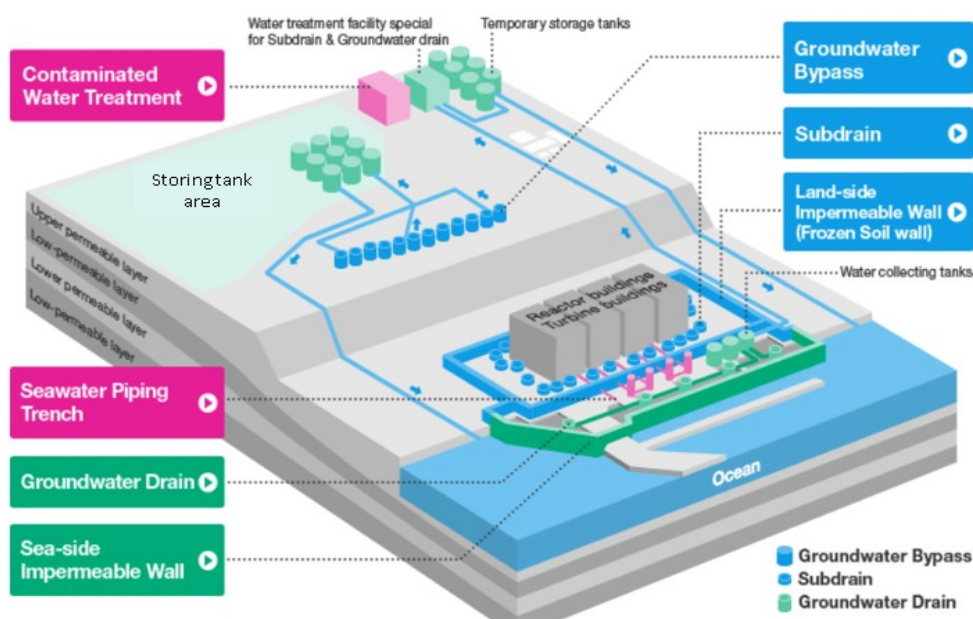


Figure 7.2 Facilities and Management for Water Management at Fukushima Daiichi
Source: TEPCO, 2018.

7.5 Increasing Cost of Decommissioning and the Quest for Funds

The decommissioning of an intact nuclear reactor is a costly undertaking, and, in most countries, the plant operator or owner is responsible for paying the decommissioning expenses. (The costs of decommissioning Fukushima's Daiichi Units 1, 2, and 3 are a special case, which we discuss). In Japan, the electric power companies that own nuclear reactors are responsible for building up the necessary funds for decommissioning their reactors. In 1964, Japan included a clause in the METI's 1964 Electricity Business Law (No. 170) that the METI minister can order electric utilities to reserve funds to cover the depreciated real estate of a nuclear reactor. The power companies with nuclear power reactors started to set aside funds in 1988 under the Nuclear Power Station Dismantlement Reserve System. In 1989, the reserve system became a formal Ministerial Ordinance, the Reserve for Decommissioning Measures, Reactor Law No. 30, 1989.

- Under the system, the power companies would estimate decommissioning costs for each of their reactors every year and calculate the reserve funds for each based on the assumption that the reactor would operate for 40 years. The law assumes that decommissioning would take 20 to 30 years and costs would be \$360-\$490 million for small 500 MW-class reactors, \$440-\$620 million for medium 800 MW-class reactors and \$570-\$770 million for 1,100 MW-class reactors. The power companies are to make a deposit each year for 40 years to reach the target cost for decommissioning (METI, 2013).

Cost estimates for decommissioning have been increasing, however, as Japan gains first-hand experience in disassembly and disposal of complex, radioactive materials the greater amount of time required to perform these complex tasks. For example, in 2014 METI's General Resources and Energy Study Committee estimated that the decommissioning cost for a 1100–1380 MWe reactor would be at \$558 to \$934 million, which could be as much as 20 percent more than previous forecasts (METI, 2014).

The increasing costs of decommissioning have had a financial impact on how the power companies plan to pay for decommissioning and the regulations that the government has put in place to ensure that enough money was available. In 2013, the Nuclear Power Station Dismantlement Reserve System was revised to extend the duration of time for reserve accumulation from 40 years to 50 years. After a reactor shuts down after 40 years of power generation, the operator could still collect fees from the ratepayers for another ten years to cover decommissioning costs. The measure was to help power companies that could not accrue sufficient fees from ratepayers due to a reactor's premature shutdown. METI argued this change made sense because even if a reactor had ceased power generation, some facilities, such as the reactor containment vessel and the water pumps, were still being operated until decommissioning was complete and therefore should be paid for by the ratepayers. In 2015, however, the 50-year rule was rolled back to 40 years (METI, 2016a).

In April 2016, Japan implemented the full liberalization of electricity retail business that allowed the startup and entry of new energy producers, including those who sell renewable energy. At the same time, METI formulated a new plan that would secure funds for decommissioning of some (non-Fukushima) reactors as well as Fukushima damage compensation and decontamination. Some reactors had shut down prematurely due to the Fukushima nuclear accident and had not saved up enough funds for decommissioning. Under the new plan, new power companies will pay for the necessary costs along with the existing power retailers. Any company that uses the existing power grid to transmit their power to customers will be obliged to pay a consignment fee or *takuso kin* because they are using the grid that the existing power companies own and operate. METI ruled that both the nuclear power companies and the new energy companies must share responsibility for paying decommissioning and accidents-related costs. These costs will in turn be passed onto to ratepayers. Ratepayers that do not directly use nuclear power also must pay the fee (METI, 2016b).

- The surcharge will be 0.0007¢ for 1kW/h, which would be about \$2.16 per year for an average household (Matsumoto, et al., 2017). The surcharge will be levied to all consumers of electricity, regardless of whether they use nuclear power or any other type of electricity. The plan does not require Diet approval and will take effect in 2020 (Mainichi Shimbun, 2017).

At present, METI has indicated six reactors are eligible for this reimbursement plan (See Table 7.4). The total amount that is to be paid off to the nuclear power reactor owners would be \$924 million to meet their reserve shortfalls. Other reactors might become eligible for the plan in the future (METI, 2016a).

- As mentioned earlier, in addition to these surcharges to ratepayers, the clean-up costs from the Fukushima accident will also be passed on to ratepayers. Decommissioning costs remain the responsibility of TEPCO.

Table 7.4 Nuclear Reactors Eligible for METI's New Plan and Amount of Reimbursement (\$ Million)

Eligible Nuclear Plants	Kansai Electric Mihama 1,2	Chugoku Electric Shimane 1	Shikoku Electric Ikata 1	Kyushu Electric Genkai 1	JAPC Tsuruga 1	Total
The Eligible Amount	273	134	217	208	92	924

Source: METI, 2016a.

Despite these new regulations, the health of the decommissioning reserve funds still remains in doubt. METI has estimated that the total cost of decommissioning 50 reactors (except for Fukushima units 1, 2, 3 and 4) would be about \$29 billion, or about \$580 million per reactor (METI, 2016a). METI also indicated that the total reserves that have been set aside, as of the end of 2015, amount to \$17 billion, or slightly more than half the total required. Moreover, since the 3.11 Fukushima disaster, all power reactors—except for a few—have been shut down. So, over the last six years, power companies have been unable to collect fees for the decommissioning reserve fund. Thus, the 1989 ordinance (Reserve for Decommissioning Measures) is not working the way it was envisioned.

Furthermore, another problem has emerged: diversion of the reserve funds for decommissioning. JAPC reportedly has diverted its decommissioning reserve fund to other uses. Diversion of funds is permitted if it is temporary. According to the Asahi Shimbun, JAPC has been using the reserve funds to pay for construction of two new reactors (Tsuruga 3 and 4). Two of JAPC's reactors, Tokai and Tsuruga 1, have been already scheduled for decommissioning and a third, Tsuruga 2, will likely enter the decommissioning program because it sits on geologic faults. According to JAPC's own plans, it should have \$1.3 billion in its reserve fund, but, as of March 2017, just \$198 million was in the fund.

- Making matters worse, JAPC has asserted that the reserve fund was legitimately redirected to new constructions, perhaps Tsuruga 3 and 4, but, according to press photos, there are no signs of nuclear construction on the building site. Thus, it seems that more than a billion dollars has gone missing (Sasai, 2017a).

Under the circumstances, the Japanese government has been careful about securing the decommissioning funds for the six Fukushima Daiichi reactors. TEPCO was ordered to reserve as much as \$80 billion for decommissioning the six Fukushima Daiichi reactors (up from \$20 billion in 2014) . The Cabinet of Japan decided on 7 December 2017, as part of a revision of the Atomic Energy Damage Compensation and Decommissioning Support Agency Law that TEPCO must save up about \$3 billion every year in its reserve fund for the next 30 years. The Law allows METI to make unannounced visits to TEPCO and conduct audits of funds to make sure the set asides are being made. The bill was passed into law on 11 May 2017 ([Sasai, 2017b](#)).

Because of increasing costs of decommissioning Fukushima and the consequences for reactor decommissioning more generally, METI has concerns that some power companies will have difficulties paying for decommissioning in the future. METI has envisioned three scenerios in which the power companies might not be able to pay their costs—unexpected expenses incurred during operation, unexpected early shut-down of operations, and unexpected decommissioning prior to the planned end of operation ([METI, 2016c](#)) (See Figure 7.3).

Today, all of the 54 reactors that were operating on the eve of 3.11 have encountered at least two of these three scenarios. All have experienced lengthy shutdowns since 3.11, some have experienced costly upgrades to meet new regulatory safety standards and some are faced with unexpected decommissioning requirements due to reassessments of local seismic risk. Unexpected decommissioning requirements could be devastating for reactor owners because these costs could be as much as initial reactor construction, take longer to complete and reserves are not yet sufficient. Under such conditions, METI might devise new rescue measures or tweak the Dengen Sampo. Inevitably, the costs to pay for decommissioning will be placed on the general public, who will be forced to get involved and pay the the mistakes of the government and industry bureaucracy.

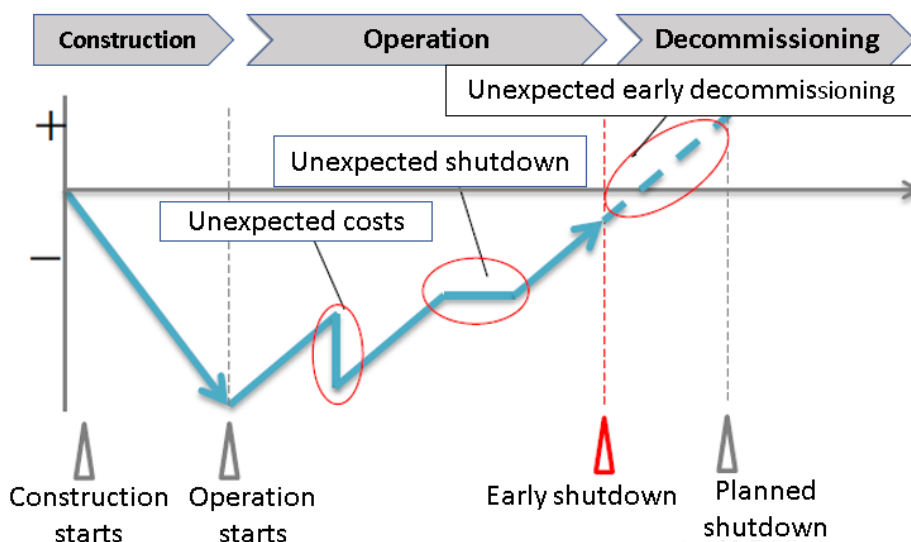


Figure 7.3 Three Scenerios where Nuclear Power Companies Might Encounter Difficulty Source: Based on METI, 2016c. “Translation provided by the authors.

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Chapter 8:

Status and Health of Japan's Nuclear Industry

CHAPTER 8: Status and Health of Japan's Nuclear Industry

Abstract

As of 2018, the Nuclear Regulation Authority approved nine reactors to resume operations. This number could increase to 25 or more within the next few years. Despite these accomplishments, the industry could be witnessing a false dawn. The pace of restart operations has been sluggish because the industry has not found much encouragement in the government's energy policy and new regulatory measures are increasing costs. Higher costs have delayed nine reactor projects. Industry surveys show a declining business base, downward trends in sales, number of employees, and R&D. The public has become more wary about the management of nuclear facilities and data falsification by power company employees. Fewer professors and students are entering nuclear studies and research facilities and national R&D budgets for nuclear science and engineering are shrinking. These cutbacks are part of a broader secular decline in science and engineering investment across Japan.

8.0 A False Dawn

There is no question that Japan's nuclear industry has sustained a series of severe blows since the events at Fukushima. All power reactors were closed down during their periodic re-inspections and the government required each to meet stringent new safety criteria before they could restart. Costs of maintaining idle power reactors have grown day by day, costs of restarting reactors have substantially increased, and the nuclear industry sees the outlook for business as "bad." It seems like a perfect storm. Yet with all these troubles, there is some reason for the industry to think the worst might be over:

- The government has adjudicated and approved restart operations for nine reactors (as of July 2018). This is up from just two reactors in 2015.
- All nine reactors are PWRs with the capacity to generate a total of 9,130 MWe. The reactors that have restart approval are Takahama 3 and 4, Oi 3 and 4, Genkai 3 and 4, Sendai 1 and 2, and Itaka 3 (See Table 8.1).
- Although Itaka 3 was approved for restart, operations were suspended on 13 December 2017 by the Hiroshima High Court. The court judged there were no assurances Ikata 3 would be secure when Mt. Aso erupted. The suspension is temporary and the order expires on 30 September 2018. (JAIF, 2018a; Nikkei, 2017).
- Another five reactors have had their plans to come into compliance with new safety regulations adjudicated by the NRA and are on a path to get restart approval.

The industry also has restart applications pending for another eleven reactors. It is entirely possible that 25 out of the 54 pre-Fukushima reactors could be back in operation within the next few years (NRA, 2018). Could it be that the nuclear industry is slowly recovering and is becoming viable again? The answer to this question is that it is more likely the industry is witnessing a false dawn. Nuclear power will continue to decline unless the industry, government and academic institutions take concerted action to remedy some of the systemic problems in the industry. To begin with, the recovery of reactor operations has been sluggish because the industry has not found much encouragement in the government's energy policy. Indeed, the government has stated that:

- “The dependency on nuclear power generation will be lowered to the extent possible through energy savings and introduction of renewable energy, as well as improvements to the efficiency of thermal power generation.” (METI, 2018a, 2018b).

The industry also is faced with a less supportive socio-political environment in Japan:

- The general public is more aware of the consequences of nuclear power accidents and has less faith in government policies to promote nuclear safety.
- The number of college professors specializing in nuclear fields is declining, and the number of students entering nuclear-related fields has fallen precipitously, reducing the pool of available talent for the future.
- Meanwhile, the government also is struggling with the increasing costs of Fukushima damage compensation, decontamination of the land, dismantlement of the damaged reactors, and disposal of contaminated water at the Fukushima Daiichi plant.

Problems are not limited to existing reactors, either. The costs and adverse impacts of the nuclear disaster have affected the feasibility of constructing of new reactors. Moreover, as the nuclear industry’s economic performance declines, the pressure to cut corners on safety will inevitably increase. If the situation does not improve before too long, the nuclear industry’s health and viability will be in fundamental jeopardy.

8.1 Status of Japan’s Nuclear Reactor Fleet

Of the 39 operable reactors—those that are not among the 15 that entered the decommissioning program after 2011—25 are in adjudication review or have completed the review. No application has been rejected so far. Owners of the remaining 14 reactors have not yet applied for adjudication review (See Figure 8.1). While it is uncertain, the owners probably are contemplating retiring them. Four of the reactors, Onagawa 1 and 3, Shika 1, and Genkai 2, have small power outputs in the range of 525-825 MWe. Onagawa 1 and Genkai 1 are also 34 and 37 years old, respectively. The other six, Kashiwazaki Kariwa Units 1-5 and Hamaoka 5, are known to lie on seismically vulnerable faults, as mentioned earlier.

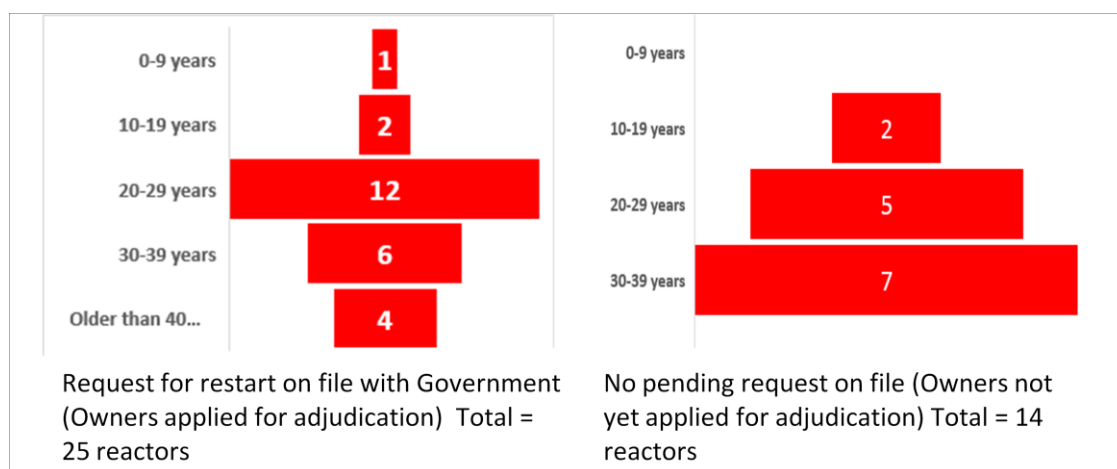


Figure 8.1 Age Profile and Adjudication Status of Japan’s Power Reactors, as of 24 May 2018.
Source: JAIF, 2018a.

Table 8.1 Status of Japan's Nuclear Reactors Applying for Adjudication

Applications for Adjudication under New Regulations, Approval for Construction to Upgrade, and for Operations, as of 10 July 2018

Reactor Owner	Reactor Name and Type		Output MWe	Operation Start	Age	Status	New Regulatory Adjudication Review			Note
							Application filed	NRA Approval	Restart of Operation	
Japan Atomic Power Company	Tokai 2	BWR	1100	1978	39	Outage (2011.03.11~	2014.05.20			Life Extension to 60 years applied, 2017.11.24
	Tsuruga 2	PWR	1160	1987	31	Outage (2011.05.07~	2015.11.95			
Hokkaido Electric	Tomari 1	PWR	579	1989	29	Outage (2011.04.22~	2013.07.08			
	Tomari 2	PWR	579	1991	27	Outage (2011.08.26~	2013.07.08			
	Tomari 3	PWR	912	2009	8	Outage (2012.05.05~	2013.07.08			
Tohoku Electric	Onagawa 1	BWR	524	1984	34	Outage (2011.03.11~				
	Onagawa 2	BWR	825	1995	22	Outage (2010.11.06~	2013.12.27			
	Onagawa 3	BWR	825	2002	16	Outage (2011.03.11~				
	Higashi-dori 1	BWR	1100	2005	12	Outage (2011.02.06~	2014.06.10			
Tokyo Electric	Fukushima Daini 1	BWR	1100	1982	36	Outage (2011.03.11~	On 2018.06.14, TEPCO CEO informed the Governor of Fukushima Prefecture that TEPCO is considering			

	Fukushima Daini 2	B W R	1100	1984	34	Outage (2011.03.11~	decommissioning Fukushima Daini Reactor Units 1-4.			
	Fukushima Daini 3	B W R	1100	1985	33	Outage (2011.03.11~				
	Fukushima Daini 4	B W R	1100	1987	30	Outage (2011.03.11~				
	Kashiwaza ki Kariwa 1	B W R	1100	1985	32	Outage (2011.08.06~				
	Kashiwaza ki Kariwa 2	B W R	1100	1990	27	Outage (2007.07.05~				
	Kashiwaza ki Kariwa 3	B W R	1100	1993	24	Outage (2007.07.16~				
	Kashiwaza ki Kariwa 4	B W R	1100	1994	23	Outage (2007.07.16				
	Kashiwaza ki Kariwa 5	B W R	1100	1990	28	Outage (2012.01.25~				
	Kashiwaza ki Kariwa 6	A B W R	1356	1996	21	Outage (2012.03.26 ~	2013.09.27	2017.12.27		
	Kashiwaza ki Kariwa 7	A B W R	1356	1997	21	Outage (2011.08.23 ~	2013.09.27	2017.12.27		
Chubu Electric	Hamaoka 3	B W R	1100	1987	30	Outage (2010.11.29 ~	2015.06.16			

	Hamaoka 4	B W R	1137	1993	24	Outage (2011.05.13 ~	2014.02.14			
	Hamaoka 5	A B W R	1380	2005	13	Outage (2011.05.14 ~				
Hokuriku Electric	Shika 1	B W R	540	1993	24	Outage (2011.03.01 ~				
	Shika 2	A B W R	1358	2006	12	Outage (2011.03.11 ~	2014.08.12			
Kansai Electric	Mihama 3	P W R	826	1976	41	Outage (2011.05.14 ~	2015.03.17	2016.10.05		Life Extension to 60 years approved, 2015.11.26
	Takahama 1	P W R	826	1974	43	Outage (2011.01.10~	2015.03.17	2016.04.20		Life Extension to 60 years approved, 2016.06.20
	Takahama 2	P W R	826	1975	42	Outage (2011.11.25 ~	2015.03.17	2016.04.20		
	Takahama 3	P W R	870	1985	33	Operational	2013.07.08	2015.02.12	2016.02.26	
	Takahama 4	P W R	870	1985	33	Operational	2013.07.08	2015.02.12	2017.06.16	
	Oi 3	P W R	1180	1991	26	Operational	2013.07.08	2017. 05.24	2018.04.10	
	Oi 4	P W R	1180	1993	25	Operational	2013.07.08	2017.05.24	201806.05	

Chugoku Electric	Shimane 2	B W R	820	1989	29	Outage (2012.01.27 ~	2013.12.25			
Shikoku Electric	Ikata 3	B W R	890	1994	23	Operational	2013.07.08	2015.07.15	2016.09.07	Court suspended operation, 2016.09.07
Kyushu Electric	Genkai 2	P W R	559	1981	37	Outage (2011.01.29 ~				
	Genkai 3	P W R	1180	1994	24	Operational	2013.07.12	2017.01.18	2018.05.16	
	Genkai 4	P W R	1180	1997	20	Operational	2013.07.12	2017.01.18	2018.06.19	
	Sendai 1	P W R	890	1984	34	Operational	2013.07.08	2014.09.10	2015.09.10	
	Sendai 2	P W R	890	1985	32	Operational	2013.07.08	2014.09.10	15.11.17	
Total	39 reactors		38,718 MWe	Reactor age summary 0-19 years: 4 20-39 years: 32 Over 40 years: 3			25 reactors filed for restart (24,990 MWe)	14 reactors received approval (14,320 MWe)	9 reactors cleared for operation (9,130 MWe); operation of one reactor halted by court order	

Source: JAIF, 2018b.

With respect to new reactor construction, new safety regulations have delayed nine reactor projects, three of which were under construction prior to the 3.11 accident. Six other projects had been in various stages of planning. All the proposed reactors are to be advanced types, either advanced boiling water reactors (ABWRs) or advanced pressurized water reactors (APWRs) (See Table 8.2) (JAIF, 2018c). One plant, J-Power's Oma plant, resumed the construction on 1 October 2012 and filed application for adjudication on 16 December 2014. All the other projects have been suspended.

According to JAIF, plans for these reactors have not progressed because the electric utilities are unsure about the future of nuclear industry or are financially strapped. The power companies likely have declining income due to the prolonged operational shut-downs of their nuclear plants. Also, the Fukushima nuclear disaster has created a financial burden not only for TEPCO but for other electric companies as well, which have had to shoulder some of the damage compensation payments. Moreover, the new safety regulations are stringent, making it very costly to upgrade a reactor to meet the new standards. Anti-nuclear protests also are more powerful, and most of the general public is against nuclear power. All these factors likely are making the electric utilities hesitant to move ahead.

The status of the three reactors that are under construction and the six reactors that are in pre-construction planning are as follows:

- ***The Oma Nuclear Plant.*** The town of Oma, Shimokita-gun, Aomori Prefecture, has been interested in hosting a nuclear plant since 1976. The Electric Power Development Company (EPDC) (now J-Power) once considered building a prototype ATR there. The ATR plan was cancelled in 1995 because the Federation of Electric Power Companies (FEPC)—one of the investors—withdrawed from the project with doubts about the ATR's economic feasibility. In 1995, the Atomic Energy Commission (AEC) decided to build an advanced boiling water reactor (ABWR) (instead of an ATR) that would operate entirely with MOX fuel. Construction of the Oma Plant started in May 2008 with plans to start power operations in March 2012. J-Power applied for adjudication and approval of the plant under the new regulations in December 2014. The Nuclear Regulation Authority (NRA), however, has been investigating geologic faults at the Oma nuclear plant. The NRA decision may not be forthcoming any time soon. J-Power had delayed the planned date of operation from 2021 to 2022 and delayed it again to late 2023. Also, Hakodate City, Hokkaido, has been suing J-Power to stop plant construction because Hakodate is located within 30 km of the plant, across the Tsugaru Strait (J-Power, 2018; Nihon Keizai Shimbun 2015).
- ***TEPCO's Higashidori 1 and Tohoku Electric's Higashidori 2.*** The Higashidori nuclear plant is in the village of Higashidori, Shimokita-gun, Aomori Prefecture. The plant site is co-owned by TEPCO and Tohoku Electric. TEPCO began construction of Higashidori 1 in January 2011 and suspended construction after the Fukushima disaster. Tohoku Electric had been prepared to start construction of Higashidori 2 for some time, but an NRA survey team investigating the plant site has largely concluded that a fault line running through the plant site is active. Chances that either Higashidori 1 or 2 will be completed are slim (NRA, 2015).

Table 8.2 Nuclear Reactors under Construction or in Preparation for Construction, as of 24 May 2018

Notes on Status are provided by the authors based on various sources.

	Utility	Name of Reactor	Type of Reactor	Capacity (MW)	Start Construction	Start Operation	Submitted Application to be Qualified under New Regulations; *Notes on Status
Under Construction	J-Power	Oma	ABWR	1,383	2008.5	Undecided	2014.12.16; *Geologic faults under investigation
	Tokyo Electric	Higashi Dori 1	ABWR	1,385	2011.01	Undecided	*Existence of active faults suspected.
	Chugoku Electric	Shimane 3	ABWR	1,373	2005.12	Undecided	*Safety measures construction under way.
In Preparation for Construction	Japan Atomic Power	Tsuruga 3	APWR	1,538	Undecided	Undecided	*The plan abandoned because of the existence of active faults.
		Tsuruga 4	APWR	1,538	Undecided	Undecided	
	Tohoku Electric/TEP CO	Higashi Dori 2	ABWR	1,385	Undecided	Undecided	*Existence of active faults suspected.
	Chugoku Electric	Kaminoseki 1	ABWR	1,373	Undecided	Undecided	*Delayed by anti-nuclear protests and delays in the adjudication process.
		Kaminoseki 2	ABWR	1,373	Undecided	Undecided	
	Kyushu Electric	Sendai 3	ABWR	1,590	Undecided	Undecided	*In NRA adjudication process.

Source: JAIF, 2018c.

- ***Tsuruga 3 and 4.*** The NRA discovered that an active fault runs through the Tsuruga plant site. JAPC in March 2015 announced that it will abandon plans to construct Tsuruga 3 and 4 ([Sankei, 2015](#)).
- ***Kaminoseki 1 and 2.*** Chugoku Electric planned to build two nuclear plants in Kaminoseki-cho, Kumage-gun, Yamaguchi Prefecture, in the early 1980s. It conducted surveys from 2005 to 2009 and decided to build Kaminoseki 1 and 2. The utility applied for permission to begin construction and in 2010 started to clear forest areas and reclaim part of the sea shore. The work was disrupted and delayed several times by anti-nuclear protesters and in December 2013 Chugoku Electric filed a new application for adjudication under the new safety regulations. In April 2014, a revised application was filed. Preparation of the building site has been suspended because the NRA has not granted permission to build the plants ([NRA, 2014](#)).
- ***Shimane 3.*** The Shimane Nuclear Plant is one of the oldest nuclear power plants in Japan. It is in Kashima-cho, Matsue-shi, Shimane Prefecture. Shimane 1 started operations in 1974 and Shimane 2 in 1989. Chugoku Electric began to build Shimane 3 in December 2005. The nuclear fuel was expected to be loaded into Shimane 3 in June 2011, with operations set to start in March 2012. Both steps have been suspended due to the Fukushima nuclear accident. Chugoku Electric has informed the governor of Shimane Prefecture on 4 April 2018 that an application for adjudication and approval of Shimane 2 under the new regulations will soon be submitted. The company indicated that the plant has been completed, but they were engaged in safety measure construction to comply with the new regulations ([Chugoku Electric, 2018](#)).
- ***Sendai 3.*** The Sendai Nuclear Plant is located at Gumizaki-cho, Satsuma Sendai-shi, Kagoshima Prefecture and is owned and operated by Kyushu Electric. The Sendai Nuclear Station has operated two reactors (Sendai 1 and 2) since 1984 and 1985, respectively. Both were shut down in 2011. The two reactors were approved to start operations under the new regulations in August and September 2015, respectively. They were the first reactors permitted to operate since Fukushima. Sendai 3 might be adjudicated and approved under the new regulations because it likely has the same safety and geological characteristics as Sendai 1 and 2 ([Kyushu Electric, 2016](#)).

8.2 The Nuclear Industry's Declining Business Base

Every year the JAIF conducts an industry survey of the health and status of Japan's nuclear industry ([JAIF, 2017a](#)). In 2017 the survey was sent out to 393 companies; 253 replied with valid responses regarding conditions in 2016. The respondents included 11 electric companies, 10 trading firms and 232 manufacturers of nuclear reactors, heavy machinery and fuels, construction companies and service companies. Of note is that the electric power companies are the purchasers of products and services of the other companies.

A summary of the survey shows what appears to be a modestly improving picture (See Figure 8.2). Standing orders across the industry have been trending up over the last three years and were just shy of \$20 billion in 2016. Standing orders have not yet returned to levels seen in 2010, however, which at \$24 billion was highest seen since the 1990s. Measures of industry-wide sales and electric company nuclear-related expenditures have also been trending up and in 2016 were well off the lows seen in 2012.

The total number of employees in the nuclear industry declined 2.7 percent in 2016 compared to the year before. All of this decline occurred among suppliers and manufacturers. The electric utilities actually grew by 2.5 percent, hiring 328 new employees, but this was not enough to offset the loss of 1,616 employees among suppliers and manufacturers (See Figure 8.3).

Employment among suppliers and manufacturers has undergone a long secular decline since the early 1990s, when it exceeded 49,000 employees. Over the next 12 years, employment fell 30 percent (to 31,000) as Japan's economy ground to a halt and the number of new reactor construction starts fell to less than a handful. Employment did pick up slightly following 3.11, no doubt because of the need for contractors to help with decontamination and clean-up around Fukushima. But employment levels have drifted down since 2013 as new construction remains suspended and government approval of upgrades to existing reactors has until recently proceeded slowly.

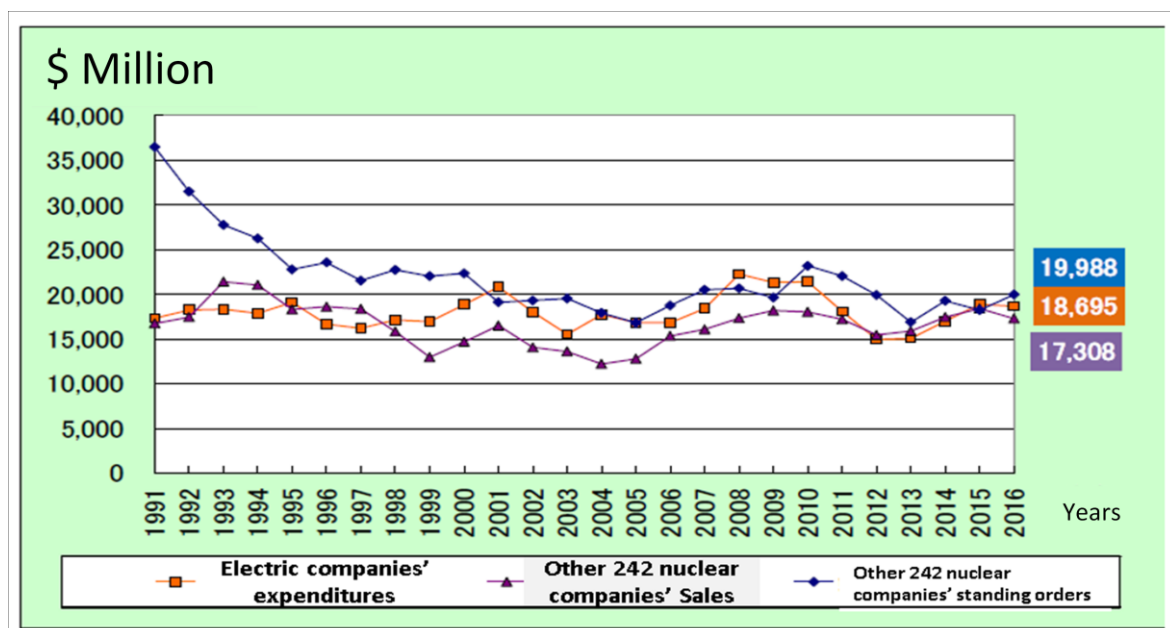


Figure 8.2 Status of Japan's Nuclear Industry: Power Company Expenditures and Total Sales and Standing Orders of Other Nuclear Businesses

Note: The eleven power companies purchase nuclear reactors, heavy machinery, fuels, construction and other services from the 242 manufacturing companies and trading firms.

Source: JAIF, 2017a.

In 2016 the nuclear industry as a whole made the largest capital investment (\$1.2 billion) since 2011. The increase was due to the need to comply with stringent safety regulations that came into force in 2013. Whether future capital investment continues at this level is unclear, however. One warning sign is the continued steady decline in the industry's R&D investment since 2010. In 2016 it was \$159 million, 54 percent below R&D investment levels in 2010 (See Figure 8.4).

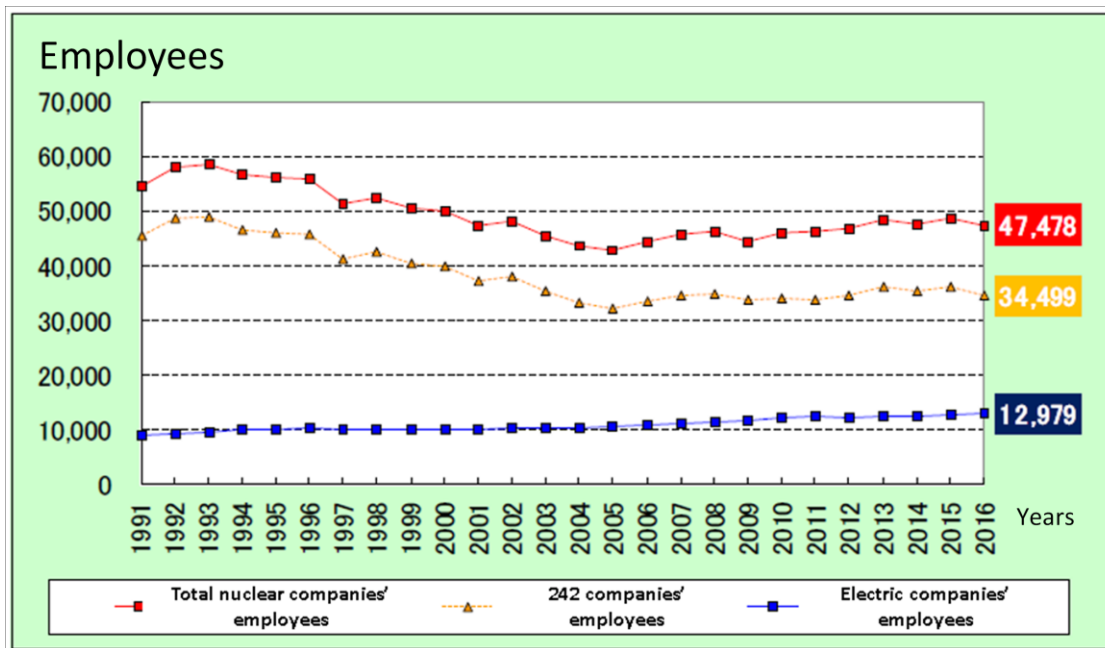


Figure 8.3 Status of the Japan's Nuclear Industry: Trends in Number of Employees
Source: JAIF, 2017a.

At the same time, government's nuclear R&D budget in the General Account has been declining since the early 2000s. By 2013, the R&D budget was suddenly reduced to less than half of what it was a decade earlier (See Figure 8.5). The AEC explained that this was due to a legislative change. On 20 June 2012, Japan revised the Atomic Energy Commission Establishment Law, which specified that the nuclear R&D budget can fund research and development of safety measures but must not fund the implementation of these measures (AEC, 2012). So the nuclear R&D budget was cut to reflect this limitation.

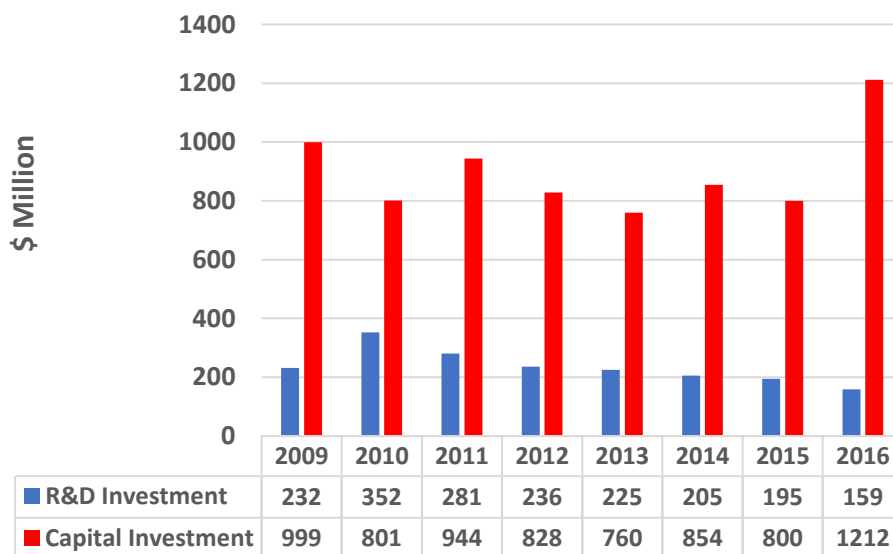


Figure 8.4 Status of Japan's Nuclear Industry: Private Sector Capital and R&D Investment Source: JAIF, 2017a.

The government nuclear R&D budget actually increased in 2016. The primary impetus for this increase was the growing need for new technology to assist in the clean-up of Fukushima. The Fifth Science and Technology Basic Plan (for 2016- 2010), for example, included a list of strategically important tasks, such as technology for decommissioning of the Fukushima Daiichi reactors, enhancement of safety, human resource development, and international cooperation on nuclear R&D and its utilization. It also included nuclear fusion technology development.

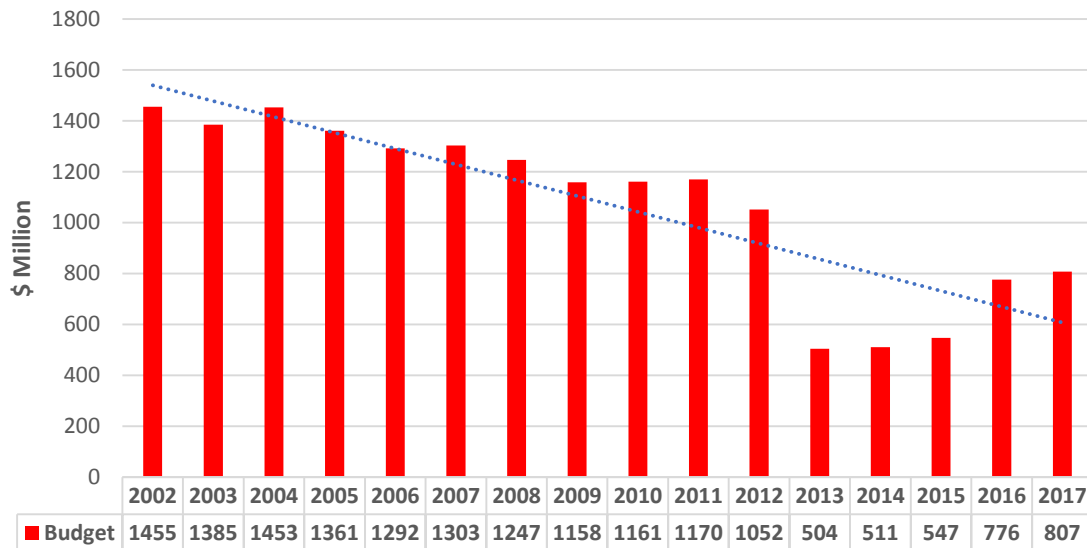


Figure 8.5 Status of Japan's Nuclear Industry: Government Nuclear R&D Budget, 2002-2017
Source: AEC, various years.

Given these trends, it is not surprising that the JAIF survey shows that respondents viewed the business environment for nuclear power as generally bad. Respondents were slightly less pessimistic in 2017, with 79 percent feeling that the business outlook was bad, compared to 84 percent in earlier years (See Figure 8.6). Respondents also believed that shutting down reactor power operations had a very negative impact on their business, particularly on sales and maintenance of technology. The majority of the nuclear industry hopes that the government would help the industry by promoting consistent nuclear policies, restoring plant operations at the earliest opportunity, and restoring the public's trust in nuclear power (See Figure 8.7).

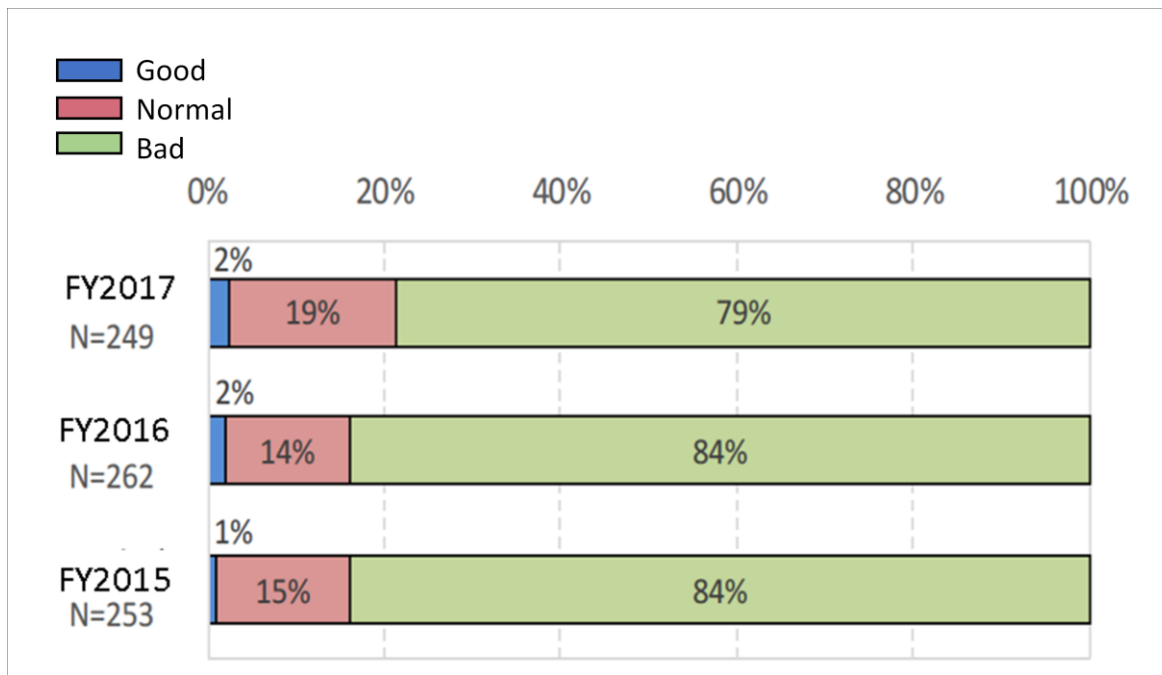


Figure 8.6 Status of Japan's Nuclear Industry: Company Views of Business Outlook
Source: JAIF, 2017a

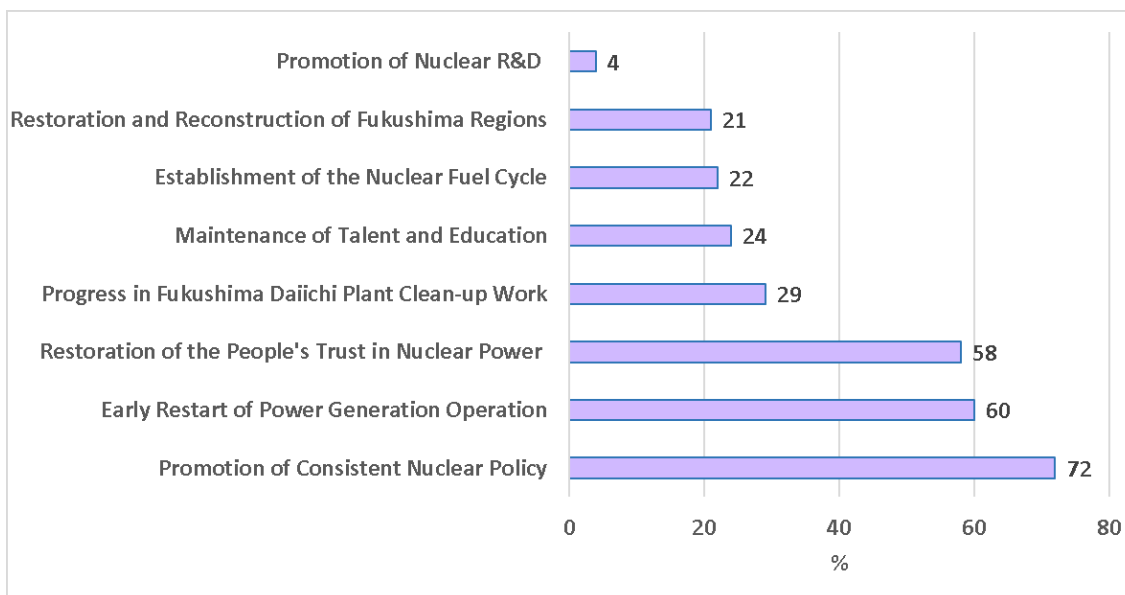


Figure 8.7 Status of the Japan's Nuclear Industry: Industry's Expectations of Government
Source: JAIF, 2017a.

8.3 Data Falsification and Flagging Public Support for Nuclear Power

The Japanese people have been rather uncertain and their opinions somewhat changeable about nuclear power. They tended to leave nuclear policy decisions to the government while their own attitudes remained fluid. For example, during the 1980s the public favored nuclear power by a wide margin, but support eroded after Chernobyl. By the 2000s, however, public opinion shifted and was evenly split (40 percent for and 40 percent against the promotion of nuclear power). ([Organization for Economic Cooperation and Development \(OECD\), 2010](#)).

A key reason for the public's lack of trust in nuclear power was the increasing number of data falsification incidents that were being reported by the government regulators. In 2002, NISA reported that TEPCO had deceived regulators by concealing defects in the construction of reactors and equipment. A letter sent to METI by a contract worker in July 2000 indicated that there were 6 cracks in the shrouds of TEPCO reactors he had inspected, but TEPCO had recorded three in its self-inspection record. This mis-reporting appeared to be a violation of the Electricity Business Act (Law No. 170, 1964) regulations, which specifies that nuclear power companies must keep and preserve records of periodic self-inspections of its facilities. NISA initiated an investigation in January 2001 and published a report of its findings on 1 October 2002:

- It found that there were 29 cases of data falsification involving 13 reactors and facilities. These cases included the non-reporting of cracks and other flaws in the shrouds, dryers, spray spargers, ICM housing, access holes, shroud head bolts, jet pumps, and jet pump set screws and wedges ([NISA, 2002](#)).
- NISA held a press conference on 29 August 2002 to disclose TEPCO's reporting violations. A TEPCO executive also held a press conference on the same day and emphasized that some equipment had flaws, but these were not serious enough to cause safety problems. Nonetheless, the TEPCO President and four other executives resigned on 2 September, taking responsibility for the reporting violations. METI gave TEPCO a strong admonition ([METI, 2004](#)).

A more widespread case of data falsification was discovered in the fall of 2006. METI found that many power companies had been falsifying their data documents or preparing documents improperly. As a result, METI directed NISA to launch a major investigation of all power generation facilities including nuclear, hydroelectric, and thermal power generation facilities. METI published its evaluation report 20 April 2007, giving administrative reprimands to the offending power companies. According to NISA, there were 98 cases of wrongdoing at nuclear plants. Eleven of them violated the Act on Regulations of Nuclear Source Materials, Nuclear Fuel Materials and Reactors (the so-called Nuclear Reactor Law) and the Electricity Business Act (See Table 8.3) ([FEPC, no date](#)).

These violations contributed to the general state of distrust of the nuclear power industry. In the wake of Fukushima, public attitudes quickly hardened against nuclear power. According to the Japan Atomic Energy Relations Organization (JAERO), an organization working to promote nuclear power, its 2014-2017 opinion surveys show that most of the respondents—about 62-64 percent—felt that nuclear power should be discontinued at once or gradually reduced. At the same time, fewer respondents—seven percent in 2017 versus 12 percent in 2015—supported the use of nuclear power. In effect, a small minority of the public now think that nuclear power should be increased or maintained at the level prior to the 3.11 nuclear accident. In the same survey, more than 20 percent of the respondents could not decide whether they were for or against nuclear power (See Figure 8.8). Thus, a small but significant segment of the public still might be reachable by arguments, backed up by concrete actions, that nuclear power could be reliable, cost efficient, and most importantly, safe.

Table 8.3 Evaluation of the Results of METI's Comprehensive Safety Investigation:
Violations of Existing Laws

Class of Violation	Definition of Class			Number of Violations
I	Those that conflicted with regulations in the Nuclear Reactor Law or the Electricity Business Act, and safety was compromised or likely compromised.			11
II	Those that conflicted with laws, but safety was not compromised or could not be compromised, up until 20 April 2007			38
III	Those that conflict with the law or did not comply with laws.			40
IV	Other errors and mistakes.			9
Total				98
Class I Details	Name of Nuclear Plant	Timeframe	Circumstance	
Hokuriku	Shika, Reactor 1	June 1999	Concealment of a criticality accident while the reactor was not in operation due to the unexpected withdrawal of three control rods (during a periodic regulatory inspection)	
TEPCO	Fukushima Daiichi, Reactor 3	November 1978	Concealment of a criticality incident due to the control rod withdrawal; falsification of the incident	
	Fukushima Daini, Reactor 4	Oct 1988-Jan 1990	Falsification of data in the construction plan for the control rod drive mechanism and data on the inspection before use	
	Kashiwazaki Kariwa, Reactor 1	May 1992	Falsification of data about the activation of residual heat removal cooling system pump	
Chugoku	Shimane, Reactor 2	May 1998	Failure to check other systems during the repair of leakage of cooling water in a diesel engine	
	Shimane, Reactor 1	June 2001	Failure to check other systems during the repair of the main shutoff valve of the high-pressure injection system	
Japan Atomic Power Company	Tsuruga, Reactor 2	January 1994	Failure to check other systems during changing parts for the emergency diesel generator	
	Tsuruga, Reactor 1	September 1995-March 2000	Concealment of corrosion of the exterior of the condensate storage tank	
	Tsuruga, Reactor 2	April-December 1996	Concealment of the duration of a primary coolant leak	
	Tsuruga, Reactor 2	July 1997	Improper manipulation of the equalizer valve during inspection of the leak rate of the containment vessel	
	Tokai, Reactor 2	Prior to 2001	Falsification of data of the gas flow rate during inspection of a gas system function test	

Source: FEPC, no date.

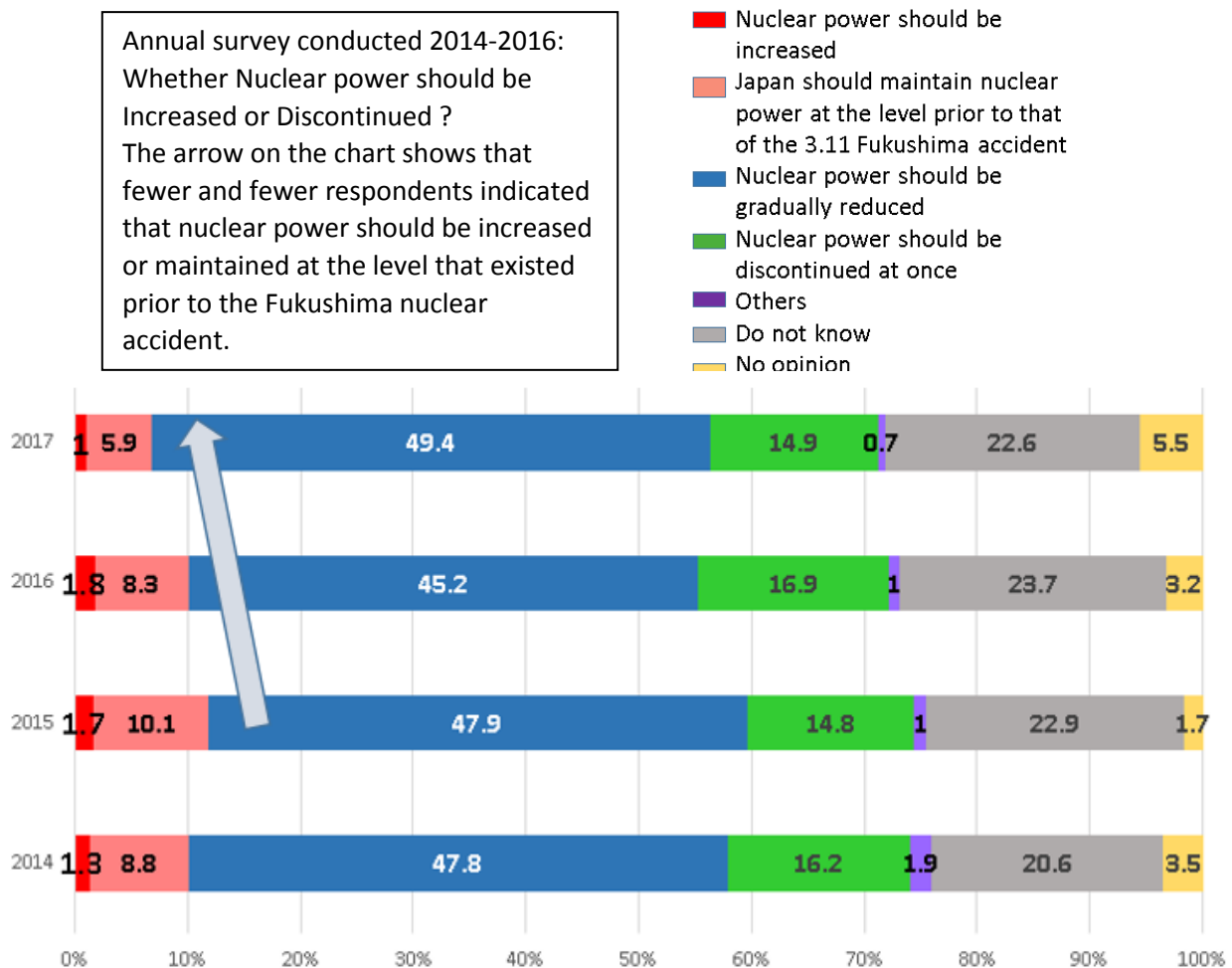


Figure 8.8 JAERO's Public Opinion Survey on Nuclear Power
Source: Japan Atomic Energy Relations Organization (JAERO), 2018.

8.4 Recruiting New Employees from a Shrinking Talent Pool

The Fukushima accident has had a palpable effect on the number of Japanese who are willing to join the nuclear industry. According to the JAIF survey, in the years before the accident, over 70 percent of the companies in the industry felt that they were able to hire as many new employees as they needed; after the 3.11 accident about 50 percent of the companies were able to hire whoever they wanted (See Figures 8.9).

Another trend tracked by JAIF suggests the recruitment problem is rapidly becoming acute. The JAIF holds a jobs seminar in March every year in Tokyo and Osaka (See Figure 8.10). The total number of student attendees at the seminar peaked in March 2011 (the FY 2010 seminar) at about 1,900. Student attendees declined to 496 in March 2012, a quarter of the previous seminar. The number of attendees has hovered around 400 since then, even though the number of companies attending the seminars has more than doubled. These trends signal that there is a real and growing shortage of qualified entry-level talent.

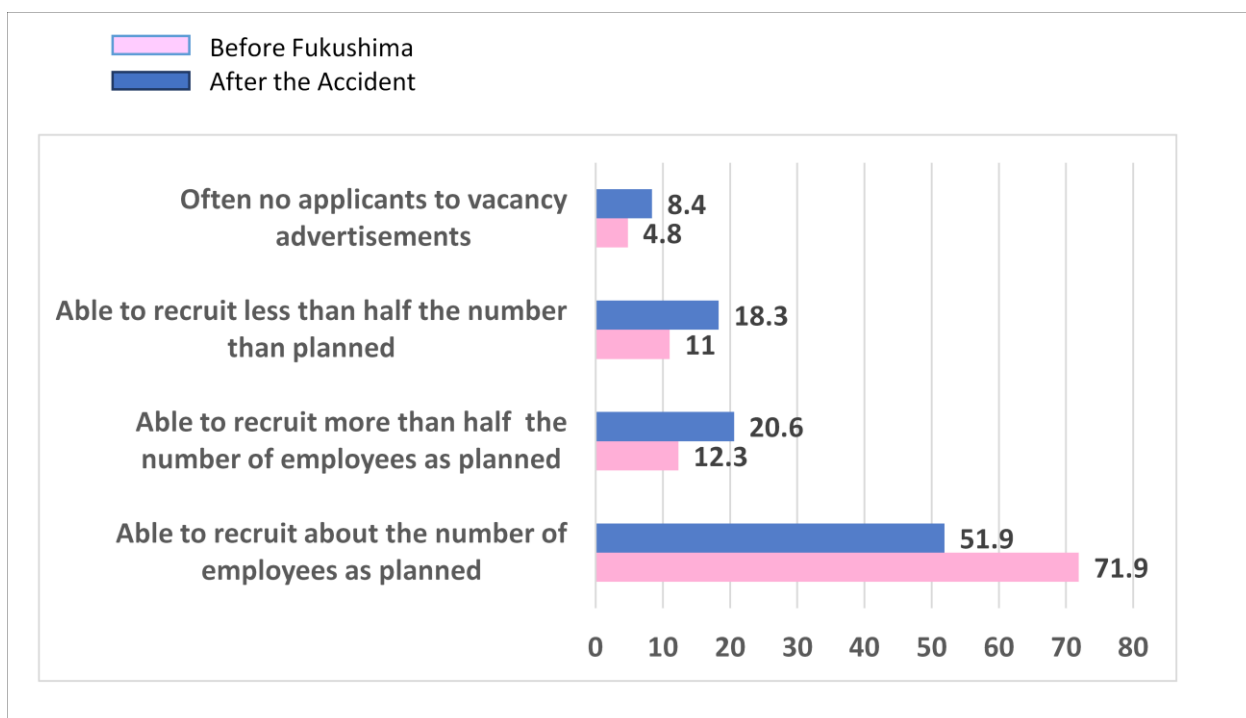


Figure 8.9 Company Perspectives on Recruitment Shortfalls, FY2017
Source: JAIF, 2017a.

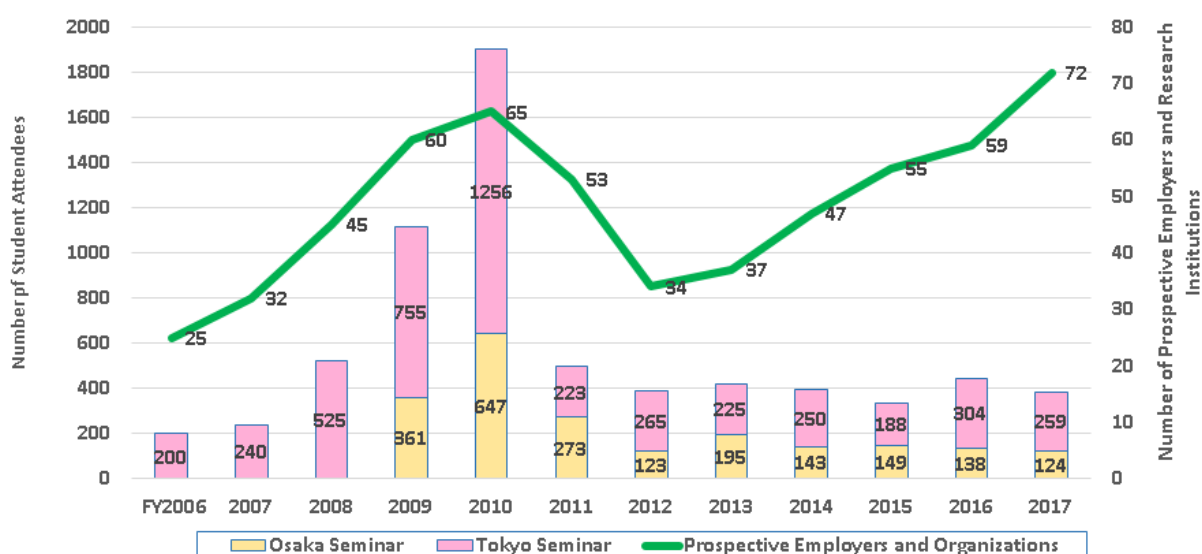


Figure 8.10 JAIF Seminars: Number of Student Attendees and Prospective Employers
Note: JAIF holds seminars each March, e.g., the 2017 Seminar is held in March 2018.
Source: JAIF, 2017b.

While the decline in available talent coincided with the Fukushima accident, the causes of the recruitment shortfall go back several decades. Statistics on student enrollments in nuclear studies presented by the Atomic Energy Society of Japan (AESJ) show that there has been a long-term decline in the number of students entering nuclear-related fields (See Figure 8.11). This decline

follows, by a few years, and probably was caused by, a secular decline in the business base for the nuclear industry ([Atomic Energy Society of Japan \(AESJ\), 2016a](#)).

The data on student populations from the AESJ covers a wide swath of students participating in various nuclear-related majors at the undergraduate and graduate level in Japan's universities. The rapid expansion of the nuclear industry in the 1960s gave universities the incentive to expand their nuclear studies programs. For two decades beginning in the mid-1970s over 2,000 students were enrolled in nuclear studies every year. Starting in the mid-1990s, the number of students began a decade-long decline and hit bottom in 2008 with total student enrollments below 500. The number of undergraduate students declined the most: in 2008 enrollments were less than 15 percent of levels achieved in the mid-1990s. Enrollments have increased since 2008 but still are 30 percent of levels achieved in the mid-1990s. This dramatic decline in the student population no doubt was due to the slow-down in construction of new reactors and a decline in the number of new jobs—from 1992 to 2002 there were only four new construction starts. More broadly, electric utilities and nuclear-industry suppliers and manufacturers were faced with a slow-growth economy and set about to cut costs wherever possible, especially by reducing the number of new hires. Seeing declining growth in the nuclear industry and the growing unpopularity of nuclear power, students likely found other fields more attractive.

The long-term consequence of declining student enrollments has resulted in a shrunken pool of skilled talent. At the very time that the government and industry are looking to upgrade or replace nuclear reactors with safer models, the workforce necessary to carry out those tasks is in short supply. This shortfall cannot be remedied quickly. Demographic trends alone indicate that the number of college age Japanese has declined by about 30 percent (by 2.8 million) since the mid-1970s and this cohort will continue to shrink for the foreseeable future. If nothing is done, the number of students entering nuclear studies will be unlikely to grow much beyond current levels. At the same time government pronouncements that “dependency on nuclear power generation will be lowered to the extent possible” are particularly dispiriting to prospective students. Taking these factors together, the nuclear industry will find it progressively harder each year to find qualified talent.

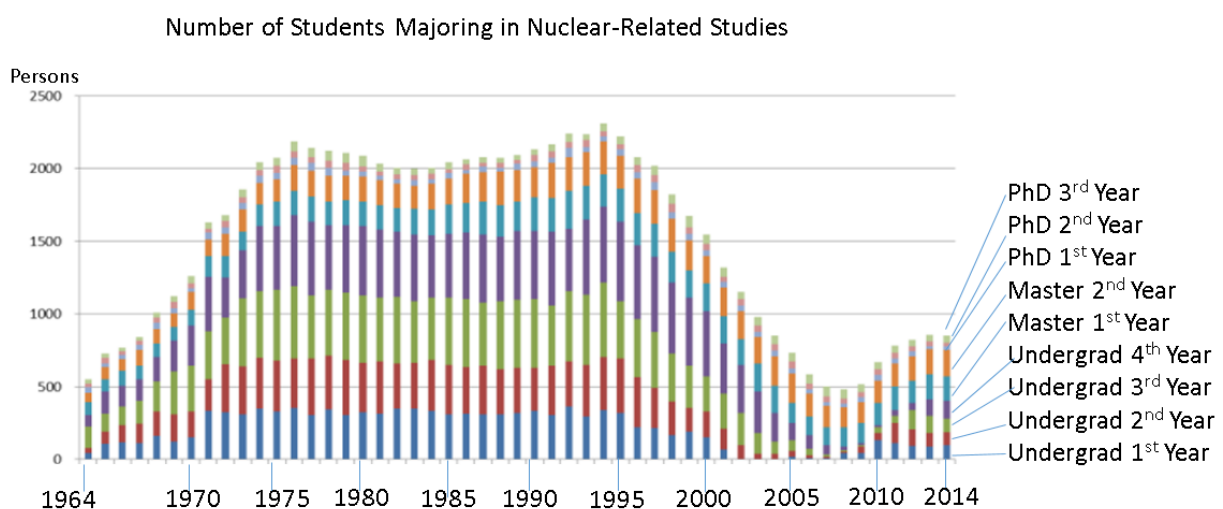


Figure 8.11 Trends in University Level Students Majoring in Nuclear-Related Studies

Source: AESJ, 2016a.

While total student enrollments have increased slowly since 2008, systemic problems remain, especially with respect to the number and experience levels of advanced students.

- According to Professor Takayuki Terai of the University of Tokyo's International Department of Nuclear Energy, after the Fukushima accident students applying for nuclear-related studies at the University dramatically declined by about half ([Hosokawa, 2017](#)). He observed in 2017 that he hoped the bottom of the decline had been reached. If the situation did not improve, he could not “help but think that there would be a serious blow to the Japanese nuclear industry, the country's total technical capacity and national security.”
- For the September 2011 class, Professor Terai explained that there were 61 applications competing for the 22 openings for the master's program, and 7 applications for 11 openings in the PhD program. The following September, there were 36 master's applicants and 3 PhD applicants— half the number of the previous year's applications. The number of master's program applicants remained stagnant in the years following; there were 39 applicants for the September 2013 class and 37 applicants for the September 2014 class. The number increased to 44 for the September 2017 class. The number of PhD applicants increased to 10 for the September 2014 class and has been continuing at this level since then. ([Hosokawa, 2017](#)).
- While the number of applications is slowly recovering, there are some trends that point to a continuing decline in Japan's nuclear skill base. More than half of the PhD applicants are now foreign students; about 60 percent of them are from China and South Korea and the rest are from Turkey, Indonesia and other countries. For the master's program, less than half of the applicants (about 40 percent) are Tokyo University graduates and the others are from other universities. Also, two-thirds of those students from other universities plan to major in radiation medicine or other applications and one third of them want to major in nuclear energy studies ([Hosokawa, 2017](#)).

Just as the number of students majoring in nuclear-related studies has declined, so has the number of professors. According to a report prepared by MEXT, the number of professors teaching nuclear science and engineering in Japan's universities has fallen from 438 in 2005 to 345 in 2013—a decline of 20 percent ([MEXT, 2016](#)). Moreover, the number of young professors, especially those younger than 40 years old, has fallen at least as much; there were 121 professors who were younger than 40 years old in 2005, but that number fell to 93 in 2013, a 23-percent drop (See Figure 8.12).

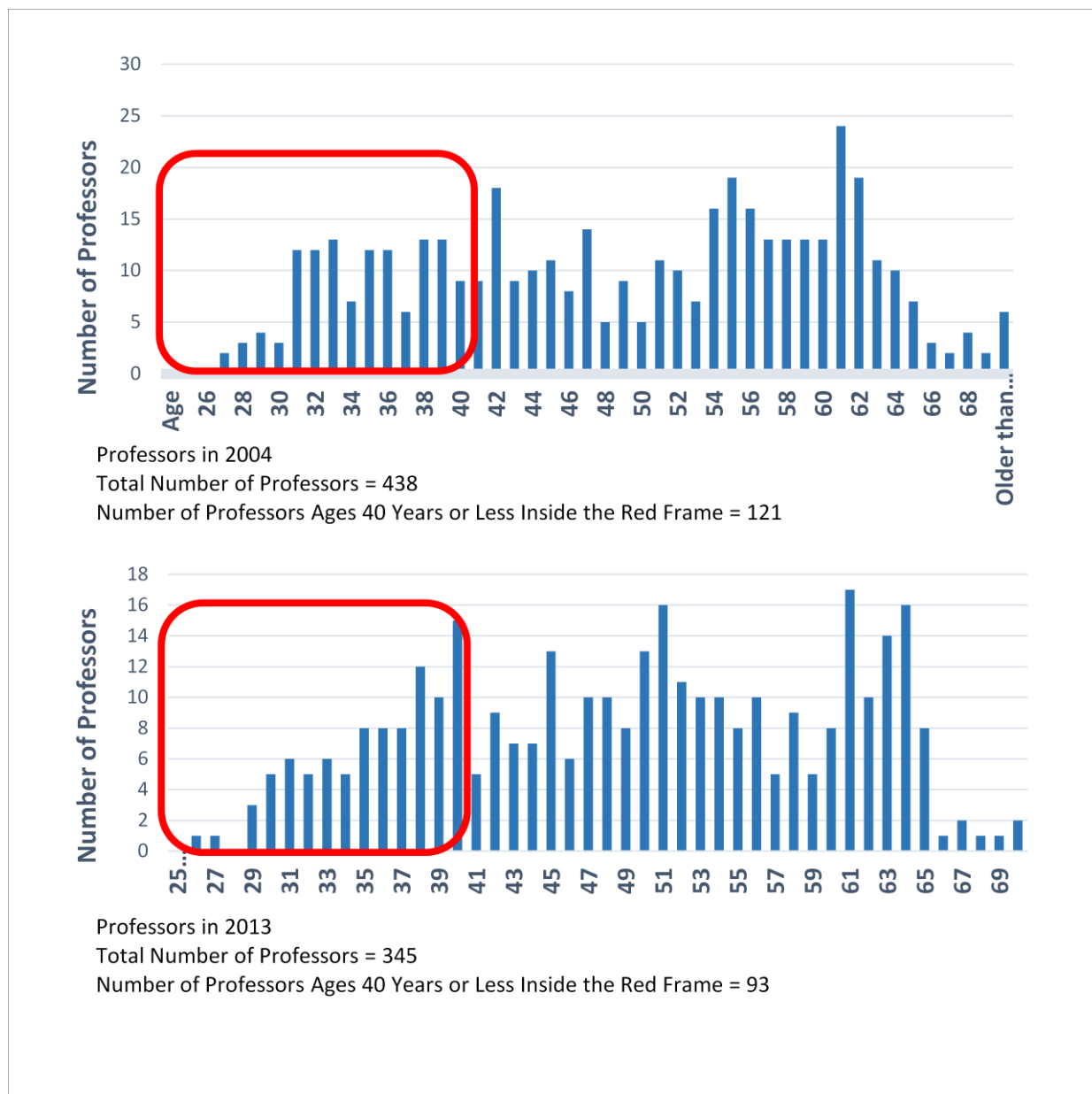


Figure 8.12 Declining Number of University Professors Teaching Nuclear Science and Engineering. Source, MEXT, 2016.

At the same time, the general quality of teaching facilities is suffering. The 2016 interim report by MEXT's Nuclear Human Resources Working Group described the sad state of affairs pertaining to experimental reactors and related facilities at universities and nuclear research institutions. According to various sources, including the 2016 MEXT report, Japan had about 20 research reactors and critical assemblies operating during the peak period during 1970 and 1985. The number of the facilities had declined to about 11 by the time of the Fukushima Daiichi accident. Then, all facilities ceased operation as they went through the adjudication process to comply with the new safety regulations. Thus, no experimental reactors or critical assemblies were operating from 2014 until 2017 ([AESJ, 2016b](#); [MEXT, 2016](#)).

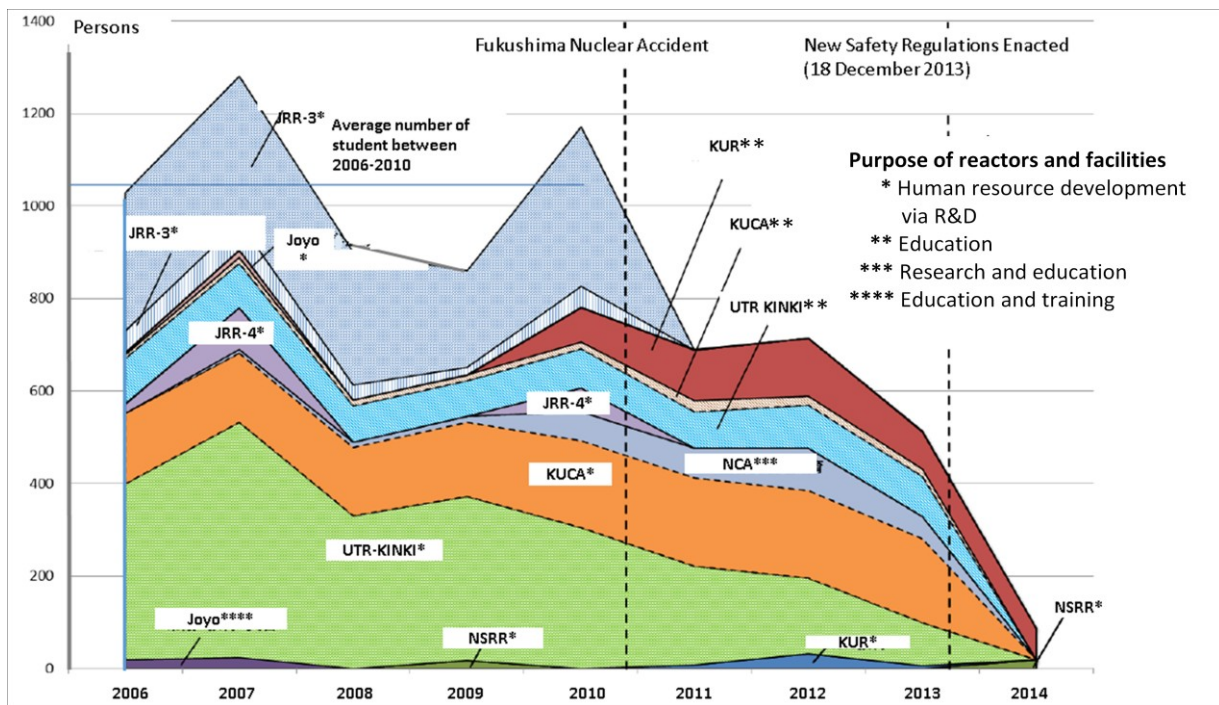
- As of July 2018, six of the 11 facilities, including four experimental reactors (KUR, UTR-KINKI, JRR-3 and NSRR) and two critical assemblies (KUCA and STACY),

have received approval for operation. Four facilities have started their operation, as of July 2018 (See Table 8.4).

- Of the 11 facilities, two (JRR-4 experimental reactor and TCA critical assembly) have been scheduled to be decommissioned. Two others (FBR Joyo and NCA critical assembly) have been suspended with no decision.
- It is not certain as to what would happen to JAEA's FCA (Fast Critical Assembly). FCA had been using highly enriched uranium (HEU), but at the 2014 Nuclear Security Summit (NSS), Japanese and U.S. leaders agreed to remove and dispose of all HEU and weapons-grade plutonium from the FCA. At the final NSS in 2016, it was announced that with US assistance, the removal of all HEU and plutonium from the FCA had been completed. (Nuclear Threat Initiative, 2017; US Department of State, 2011). No information is available whether the FCA had applied for adjudication for conducting operations with low enriched uranium.

The lengthy adjudication process and the declining number of experimental research facilities have been detrimental to the education of students and university faculties. They have had less opportunity to gain live operational experience, hands-on training and lab work. During the period from 2006 and 2010, an average of 1,200 students per year had opportunities to conduct research and experiments at those facilities. After the Fukushima accident, fewer and fewer students had access to the opportunities, and no opportunity after 2014 (until 2017). Moreover, many of those facilities are becoming old; the age of the six facilities that were approved for operation were 57, 54, 44, 40, 28 and 23. The last two (JRR-3 and STACY) were renovated in 1990 and 1995, respectively. While JAEA offered its view that those facilities should be renovated or replaced with new ones, there is no clear government policy as to what to do with them (AEC, 2017; AESJ, 2016b).

Figure 8.13 Educational Use of Experimental Reactors and Critical Assemblies. Source:



AESJ, 2016b

Table 8.4 Status of Research Reactors at Research and Educational Institutions

* Tentative date for starting operation.; ** Decision pending; *** Little information is available on the FCA operation.

- Scheduled to be decommissioned

	Owner	Reactor Name	Year Criticality Achieved	Educational Purpose	Thermal Capacity	Approval of for Operation	Start of Operation
Research Reactors	Kyoto University	KUR	1964	General research, material irradiation, production of radioactive isotope production, material irradiation, medical irradiation, education and training	5MW	2016.09.21	2017.08.29
	Kinki University	UTR-KINKI	1961	Education and research for nuclear energy	1 W	2016.05.11	2017.04.12
	JAEA	JRR-3	1990	Beam experiment, fuel · material irradiation, radioactive isotope production, education and training	20MW	2017.11.24	*2020.10.31
		JMTR	1968	Material irradiation for safety research for power reactors	50MW	-	-
		NSRR	1975	Research, education and training of fuel failure behavior at the time of reactivity accident	300kW/ 23,000 MW pulses	2018.01.31	2018.06.28
		Fast Breeder Joyo	1977	Verification of basic technology of FBR, fuel and material irradiation tests, verification of innovative technology for future reactor development	140MW	**	**
		JRR-4	1965	Medical irradiation, education of nuclear reactor technicians, analysis of radiation	3.5MW	-	-

Critical Assembly	Toshiba	NCA	1963	Reactor physics experiment of nuclear power reactors and fuel element research	200MW	**	**
	Kyoto University	KUCA	1974	Critical assembly for general research, education and training	100W	2016.05.11	2017.06.21
	JAEA	FCA (Fast Critical Assembly)	1967	Criticality experiment and reactor physics research of FBR	2,000W	***	***
	JAEA	STACY	1995	Criticality experiment and criticality safety research for nuclear fuel cycle facilities	200W	2018.01.31	*2019.09
		TCA (Tank-type Critical Assembly)	1962	Reactor physics research, education and training for light water reactor	200W	-	-

Source: AESJ, 2016b; JAIF, 2018d.

Despite some upward trend in recent years, the long term decline in the nuclear R&D budget, discussed earlier, has had an undeniably negative impact on many academic activities. There are declines in the number of university professors in the nuclear fields, smaller student populations, the reduction in technical research opportunities, and cutbacks in R&D programs. These trends will adversely impact the nuclear industry's scientific and engineering talents for years to come. We can already see the consequences of this decline in such metrics as patent activity related to nuclear energy. Japan's patent activity, which was well above the global average from 2012-14, fell below the global average for 2014-2016 ([United States National Science Board on Science and Engineering Indicators 2016 and 2018](#)). The sharp decline over the last decade in government R&D spending for nuclear energy is not unrelated, of course. It is as if the government decided to put the nuclear industry on a starvation diet.

The cutbacks in nuclear energy R&D are part of a broader secular decline in science and engineering investment. Japan simply is not keeping up with other technologically advanced countries. From 2000 to 2015 the US, EU, and China all increased the number of researchers by 40 to 100 percent, while Japan's science and engineering workforce barely grew at all. Slow growth is showing up in the number of Japan's science and engineering publications: although Japan was a major producer for several decades, its output has trended downward since 2013. For the nuclear industry, this becomes a vicious circle: cuts in research spending means fewer research opportunities, which discourages those who are considering a career in the field, which leads to less progress in improving reactor safety, which makes the field less desirable, encouraging more cutbacks in nuclear studies.

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Chapter 9:

Creating a Zero-Accident Nuclear Energy Culture

CHAPTER 9: Creating a Zero-Accident Nuclear Energy Culture

Abstract

How can nuclear accidents be minimized and limited in scope? To answer that difficult question, the authors examined material and non-material strategies that might be required to build and maintain a highly safe nuclear power infrastructure. Remedying social and cultural components of an accident causal chain—unresponsiveness to new risks, management underestimation of safety risks, cultural impediments—would likely have the greatest impact on safety but also would be the most difficult to fix. The relentless and obsessive management style of Admiral Rickover points to one approach that could improve safety. The Kemeny Commission looking at Three Mile Island Nuclear criticized the mindset that technology can be used to design-out the need for human intervention. Establishing a safety culture at the most senior management level clearly is a paramount goal, if it is coupled with other actions that could overcome the weakness of traditional Japanese organizations and national culture.

9.0 Upgrade or Build Anew?

Considering the range of problems and shortfalls listed above, achieving a truly zero-accident nuclear infrastructure would be an unrealistic goal, both in terms of required investment and the inherent limitations of government and industry decision-making. Nevertheless, before Japan decides to pursue a way forward for the long term for nuclear power, it is worth trying to understand what would be required to ensure that nuclear accidents are minimized and limited in scope. To inform this discussion, the authors estimated a range of investments, both material and non-material, that might be required to build and maintain a nuclear power infrastructure, assuming different accident frequencies and severity, as well as what incentives might be required to achieve a zero-accident mindset in both government and industry.

With respect to future investments, there is a great deal of uncertainty in understanding costs, especially accident costs, because past safety standards have not been sufficient to eliminate accidents and methodologies to inform future cost-safety trade-offs do not appear to have a great deal of credibility. To illustrate the range of uncertainty in costs, we consider two cases: a set of moderate improvements, including upgrading and hardening, for 25 existing reactors (the number that is currently pending licenses to restart or have already restarted). Another course of action would be to construct a new fleet of 25 highly advanced reactors. Key factors bearing upon cost include the following:

Capital Costs. Japan's government and electric power industry invested roughly \$130 billion over the past 50 years to build a total of 57 power-generating reactors, or an average of \$2.3 billion per reactor (Asura, 2011). A large majority of these reactors were based on so-called Generation II designs that were introduced in the 1960s. Today, a Generation III advanced boiling water reactor (ABWR) would cost \$4 billion to build (Yoshida, et al., 2005). Assuming an advanced reactor that was consistent with a goal of near zero-accidents would cost at least \$4 billion and Japan were to aim for a fleet of 25 ABWRs, capital costs would amount to at least \$100 billion, spread over the next decade or so. Additional costs would be incurred to locate these new reactors in geologically "quiet" areas.

Upgrading and Hardening to Meet New Regulations. Japan could also invest in upgrades to its existing reactors. In 2014 METI estimated a total of about \$17 billion would be needed to harden all the reactors except those that were planned for decommissioning. There were 40 dormant reactors as of 2014, so the cost of upgrades amount to an average of \$425 million per reactor (Sawa, 2014). While this seems like a desirable goal, the hardening program would apply to reactors that are based on technology and designs dating back to the 1960s and some of these reactors are located near seismically active geologic faults.

Operation and Maintenance (O&M) and Fuel Costs. Japan incurs costs for operation and maintenance of each reactor every year, whether it is generating power or not. Our review shows that prior to 3.11 annual O&M costs were rapidly increasing and reached at least \$4.6 billion in 2010 for the fleet of 54 power reactors (JAIF, 2010). This works out to about \$85 million per reactor ($\$4.6\text{B} / 54 = \$85\text{M}$). Costs include periodic inspections that all operating nuclear reactors must undergo every year, including some upgrades and construction modifications. Finally, according to JAIF, the power companies paid a total of \$3.88 billion for fuel and materials for 54 reactors in 2010. This amounts to \$72 million per reactor (JAIF, 2010). Total O&M and fuel therefore amounted to about \$157 million ($\$85\text{M} + \$72\text{M} = \$157\text{M}$) per active reactor per year, or an estimated \$3.43 billion per year for a fleet of 25, which comes to \$34 billion over ten years. This total does not take into account additional personnel, training and maintenance that would be needed to operate and maintain the advanced technologies and achieve near zero-accident criteria. To achieve this goal, we suggest increasing funding for O&M by at least 50 percent (from \$85 million to \$128 million). This would bring total annual operating costs to \$5 billion ($\$128\text{M} + \$72\text{M} = \$200\text{M}$; $\$200\text{M} \times 25 \text{ reactors} = \$5\text{B}$). Ten year costs would be \$50 billion, which we use for both cases.

Decommissioning and Waste Disposal Cost. Once a nuclear reactor has reached the end of its useful life, it needs to be decommissioned and the spent fuel disposed of permanently and safely. IAEA notes that there is no universally accepted standard for developing decommissioning cost estimates (IAEA, 2013). Cost estimates fundamentally depend on the reactor condition, decommissioning plans and basic assumptions about the desired end-state. As a result, historical comparisons vary widely, from \$300 million per reactor to more than \$1 billion. Germany, for example, has set aside \$2.5 billion per reactor (Dorfman, 2017). For our calculation, we assume decommissioning costs of \$1 billion per reactor. Japan already has 18 power-generating reactors in its decommissioning program (See Table 7.1 in Chapter 7), for a total estimated cost of more than \$92 billion. These costs include \$80 billion for decommissioning Fukushima Daiichi's six reactors, three of which were severely damaged. Over the next decade, many of the remaining reactors will come due for decommissioning. For the upgrading and hardening case, we assume over the next ten years 14 more reactors will enter the decommissioning program⁸¹ (at a cost of about \$15 billion); for the case where the entire reactor fleet is replaced with 25 advanced reactors, all of the remaining 39 reactors would enter the decommissioning program (at a cost of about \$40 billion).

The total costs that we have discussed so far are summarized in Table 9.1, assuming either moderate improvements by upgrading and hardening or total replacement of the entire fleet with the most advanced technology and upgraded maintenance. We selected a period of ten years because that would be the minimum time needed to replace a fleet of 25 reactors with new

⁸¹ We assume 14 of the 39 reactors that currently are not on the decommissioning list would be placed in the decommissioning program over the next ten years, leaving 25 reactors for future operations.

technology.⁸² For replacement of the entire fleet, costs for locating power plants in seismically quiet areas would be additional (and substantial). The table shows that Ten-Year costs are more than twice as much for replacement of the reactor fleet as compared to upgrading and hardening the existing fleet. This disadvantage is reduced when costs of accidents are factored in, however, as we discuss in the following section.

Table 9.1 Estimated Range in Ten-Year Costs of Future Nuclear Reactor Fleet

Ten-Year Costs for Japan's Reactor Fleet	Moderate Improvements and Hardening	Build 25 Advanced Reactors
Capital cost of 25 new reactors	0	\$100B
Harden existing fleet of 25 reactors	\$17B	0
Operations, Maintenance, Inspection and Fuel Cost ⁸³	\$50B	\$50B
Decommissioning 14 to 39 reactors	\$15B	\$40B
Total	\$82B	\$190B

This table was constructed by the authors based on verifiable data discussed above.

9.1 Cost and Frequency of Accidents

Accident Frequency and Damage Costs. In addition to the costs noted above, we also must consider accident costs associated with nuclear power. As we noted in Chapter Five, costs of future accidents are largely unknowable. Matsuo, (2016) in reviewing eight separate estimates of nuclear accident risk costs, found them to vary widely. Nonetheless, we can still use as a point of reference a range of costs associated with past accidents. The Fukushima disaster, for example, would approach a Worst Case, while Three Mile Island would represent a Less Severe event. Even in these cases, there are many assumptions and uncertainties involved in estimating what constitutes actual accident costs (for example, agreed definitions for direct and indirect costs). Thus, any estimate should be treated as a rough order of magnitude cost:

- As a point of departure, we pegged the cost of a Less Severe event to approximate accident costs accident at Three Mile Island. This accident involved a partial core meltdown (that was contained within the reactor vessel) and a very modest release of radiological material. Costs were estimated by the Recovery Engineering Manager to have been \$10 billion in facility cleanup, decontamination and economic hardship to area residents (DeVine, J., 2013).
- For a Worst Case, the cost could be over \$1 trillion. We have considered the estimate of the Japan Center of Economic Research (JCER) of \$700 billion, which consisted of the cost of land decontamination (\$300 billion), reactor decommissioning and water decontamination (\$320 billion), and damage compensation (\$80 billion) (Kobayashi, et al., 2017). The JCER

⁸² The maximum number of reactors that Japan has had under construction at one time is 4. The average is under 2. We assumed a construction rate of at least 2.5 starts per year to replace all 25 reactors in ten years.

⁸³ Ten Year costs are the annual operations, maintenance and inspection, and fuel costs noted above, multiplied by 10.

estimate of damage compensation at \$80 billion, however, is unrealistically low. According to MOF, the total Japanese debt that will have accrued for nuclear damage compensation by the end of FY2018 (March 2019) is \$483 billion. We consider that the Worse Case would be the adjusted sum of the JCER estimate and the cumulative expenditures of the MOF: $700 - 80 + 483 = \$1103$ billion. Our own estimate for a Worst Case starts with a “floor” of \$700 billion, which is the JCER’s high estimate. There is the distinct possibility, based on rapidly changing estimates from METI and the MOF that costs could grow beyond \$1 trillion within the next few years.

Taken as a whole, we have a range of costs that span several orders-of-magnitude (from \$10 billion at the low end to \$1 trillion at the high end). We consider these as reasonable upper and lower bounds of costs of a future major accident.

An equally important variable is the time period between accidents over which costs would be incurred and paid for by the Japanese people. Nagaoki of the Atomic Energy Commission of Japan assumes that accident frequency could, in a pessimistic case, occur once in 500 reactor years (based on the historical record in Japan). For a fleet of 50 reactors, Nagaoki calculates this would imply an accident frequency of once in ten years. We scale his estimates to a fleet of 25 reactors, which would mean an accident frequency of once in 20 years (Nagaoki, 2013).

For an optimistic case, Nagaoki suggests meeting the IAEA standard of once in 100,000 reactor-years (one reactor operating for one year equals one reactor-year), implying one accident in 4,000 years for a fleet of 25 reactors. Given that on a worldwide basis we have experienced 17,000 reactor years, we suggest this is an aspirational goal vice one that is anchored in the historical record. A more realistic, optimistic goal might be one accident in 140 years, which is the worldwide historical record, or one accident in 1,000 years for a fleet of 25 reactors, which is consistent with calculations by Wheatley and Sovacool (Wheatley and Sovacool, 2016). The reasoning is as follows:

- Japan’s nuclear power industry has operated 1,675 reactor-years. During this period, there have been 3 accidents that resulted in core-meltdowns, or one major accident on average every 558 reactor-years (1,675 divided by 3). Assuming Japan plans to operate about 25 reactors in the future, that implies one major accident in about 20 years ($558 \text{ reactor-years} \div 25 \text{ reactors} = 22 \text{ years}$). On a worldwide basis, there have been 5 major accidents in 17,000 reactor-years, or one major accident in 3,400 reactor-years. For a fleet of 25, that rate implies one major accident in about 140 years ($3,400 \text{ reactor-years} \div 25 \text{ reactors} = 136 \text{ years}$).

To pay for the cost of a disaster on the scale of Fukushima, we assumed this period would be about 20 to 40 years. We selected 20 years for the Worst Case based on the historical record of major reactor accidents and the estimated number of reactors that would be in operation. If Japan plans to operate about 25 reactors, one major accident could be expected to occur approximately every two decades in this case and therefore we would expect costs of any future accident would be paid out over that same period of time. Hardening of existing reactors or complete replacement with a modern fleet could reduce the frequency of future accidents, but there are too many uncertainties to know how to correlate future improvements with accident frequencies—whether it is one accident in 40, 140, or a 1,000 years. In any case, most of the cost of an accident would be incurred in the first few decades. Also spreading the payback period much beyond 40 years raises questions of

generational theft, where one generation shifts the burden of paying for an accident to the next and subsequent generations. For these reasons, we selected 40 years as payback period in the Less Severe case.

9.2 Total Costs

Total Costs to Generate Power. How do the combined costs of capital investment, fleet hardening, operations, maintenance and inspections and accident costs impact the total cost of nuclear power, especially given the need to modernize Japan's nuclear power infrastructure? Our estimates of total Ten-Year costs for the two different cases are presented in Table 9.2:

- We calculated expected accident costs for ten years as follows: For the Moderate Improvement case, we assumed an accident rate of once per 20 years and that accident costs would be incurred over that period. So, half of the cost would be incurred in ten years (example: $\$1000\text{B} \div 20 \text{ years} \times 10 = \$500\text{B}$). For the Advanced Reactor case, we assumed accident frequencies would exceed once in 140 years, but the accident would be paid for in 40 years. Thus, we calculated that only one-quarter of accident costs would be paid in ten years ($\$100\text{B} \div 40 \text{ years} \times 10 = \$25\text{B}$).
- If capital investments on the order of \$100 billion were made to newly construct 25 advanced reactors, along with enhanced operations and maintenance as part of a determined effort to achieve a near zero-accident level of safety, accident costs might be less than \$100 billion, possibly as low as \$10 billion—comparable to the Less Severe case. In this case, Japan might be able to build and operate a reactor fleet for ten years for about \$215 billion with the expectation that if accidents did occur they would be limited in scope.
- If we assume that moderate improvements and hardening of 25 existing reactors would cost \$17 billion, a severe accident might occur more often, perhaps once in 20+ years and range in cost from \$100 billion to \$1 trillion. In this case, total Ten-Year costs for the reactor fleet could be as low as \$130 billion but could also be substantially more if Japan experiences a run of bad luck.

The cases we have discussed are not a forecast of future costs, only what costs might be incurred under different conditions. They are presented in the belief that the 2011 Fukushima nuclear accident has become a turning point for Japan and that the nuclear policy and regulatory landscape in Japan are ripe for change (METI, 2015; Suzuki, 2015; Vivoda and Graetz, 2015).

If Japan decides to completely replace its reactor fleet with the most modern technology and embrace the necessary changes in its managerial culture, there is a decent chance that another major reactor catastrophe could be avoided for a very long period of time. But implementation costs for this case would be high and over the long run might not be politically sustainable.

Table 9.2 Range in Ten Year Costs for Japan's Nuclear Reactor Fleet, Including Accidents

Note: Does not include the cost of subsidies and special taxes

Ten-Year Costs for Japan's Reactor Fleet	Moderate Improvements and Hardening	Build 25 Advanced Reactors
Capital cost for 25 reactors	0	\$100B
Harden existing fleet of 25	\$17B	0
Operations, Maintenance, Inspection and Fuel: Status Quo and Enhanced	\$50B	\$50B
Decommissioning 17 to 40 reactors	\$15B	\$40B
Sub-Total	\$82B	\$190B
Expected Accident Costs for fleet of 25 Reactors⁸⁴		
\$100B to \$1000B incurred once in 20 years; costs for a Ten-Year period shown	\$50B to \$500B	
\$10B to \$100B incurred once in 140+ years but paid for in 40 years; costs for a Ten-Year period shown		\$3B to \$25B
Total Ten-Year Costs Including Accidents	\$132B to \$582B+	\$193B to \$215B

This table was constructed by the authors based on verifiable data discussed above.

For example, if Japan were to embark on establishing an advanced reactor fleet, costs to ratepayers for electric power in the short run will undoubtedly go up, at least by \$16 MWh for all sources of electric power.⁸⁵ Paying for this rate increase, on top of the already costly electric power that Japan's electric utilities produce today with fossil fuels will drive up costs generally for all goods and services that depend upon electric power. Nonetheless, a policy that promotes a zero-accident culture, backed up by substantial funding and determined government and corporate leadership, would have the better chance of avoiding costly accidents and ultimately could be far less costly than embarking on a less rigorous course of action.

⁸⁴ We calculated expected accident costs for ten years as follows: For the Moderate Improvement case, we assumed an accident rate of once per 20 years and that accident costs would be incurred over that period. So, half of the cost would be incurred in ten years (example: $\$1000B \div 20 \text{ years} \times 10 = \$500B$). For the Advanced Reactor case, we assumed accident frequencies would exceed once in 140 years, but the accident would be paid for in 40 years. Thus, we calculated that only one-quarter of accident costs would be paid in ten years ($\$100B \div 40 \text{ years} \times 10 = \$25B$).

⁸⁵ This cost increase to rate-payers assumes additional capital costs of \$100B would be spread over ten years, or \$10B per year. We add to that \$40B for decommissioning costs (at \$4B per year) and \$2B per year in increased O&M costs (See discussion on Operations and Maintenance in support of a zero-accident goal), for a total of \$16B. Spread over Japan's average annual electric power output of roughly one billion MWh, these additional costs would amount to \$16 per MWh.

If Japan chooses to make moderate improvements and hardening, costs would be more reasonable and manageable in the short run. Such a course of action would be particularly attractive as the government and industry grapple with the ever-increasing costs of the Fukushima disaster. However attractive these savings might be in the short run, the historical record has shown that Japan has had a larger number of nuclear accidents than any other country with a comparable nuclear infrastructure, as well as more serious and complicated accidents, save Russia. Thus, for this riskier course of action to be successful, dramatic changes would be required in how the nuclear power industry is managed and how the government regulates and guides the industry.

9.3 Impediments to an Effective Safety Culture

Determining whether safety is best served by renovating the reactor fleet is but one step in achieving an effective safety culture. Remedying the social and cultural components of an accident causal chain—unresponsiveness to new risks, management underestimation of safety risks, cultural impediments—would likely have the greatest impact on safety but also would be the most difficult to fix. The Chairman of the Fukushima Nuclear Accident Independent Investigation Commission (Diet of Japan, 2012) said as much in the Commission’s final report, citing the mindset that supported the negligence behind the disaster.

The Government of Japan established the Nuclear Regulation Authority in 2012 to ensure that oversight of nuclear power is done objectively and that stringent safety standards are put in place. The NRA is making substantial progress in establishing these safety standards, but progress in achieving a change in mindset toward promoting safety across the nuclear power industry is slow. The industry needs both negative and positive incentives so that managers regard effective safety practices as a source of profit and negligence toward safety as a source of loss.

This is not the first time a Commission has determined that a “mindset” contributed to a nuclear accident. In 1979, following the accident at Three Mile Island, President Carter established a commission chaired by John Kemeny to investigate the accident, assess the emergency response, and make appropriate recommendations.⁸⁶ The Commission’s key finding focused on people:

- In considering management’s responsibility for how the plant’s operators performed, the Commission encountered the word “mindset” over and over. Popular discussions of nuclear power plants tend to concentrate on questions of equipment safety. ... But as the evidence accumulated, it became clear that the fundamental problems are people-related problems and not equipment problems. When we say that the basic problems are people-related, we do not mean to limit this term to shortcomings of individual human beings -- although those do exist. **We mean more generally that our investigation has revealed problems with the "system" that manufactures, operates, and regulates nuclear power plants.** There are structural problems in the various organizations, there are deficiencies in various processes, and there is a lack of communication among key individuals and groups. (Emphasis added.)

⁸⁶ Excerpts are from The Report of the President’s Commission on Three Mile Island: The Need for Change, the Legacy of TMI (October 1979).

- [Management] concentrated on equipment, assuming that the presence of operators could only improve the situation -- they would not be part of the problem. After many years of operation of nuclear power plants, with no evidence that any member of the general public has been hurt, the belief that nuclear power plants are sufficiently safe grew into a conviction. One must recognize this to understand why many key steps that could have prevented the accident at Three Mile Island were not taken. The Commission is convinced that this attitude must be changed to one that says nuclear power is by its very nature potentially dangerous, and, therefore, one must continually question whether the safeguards already in place are sufficient to prevent major accidents. **A comprehensive system is required in which equipment and human beings are treated with equal importance.** (Emphasis added).

The Commission's call to integrate technology and human decision-making struck home. In some ways this finding was to be expected. Nuclear energy is a complex science that is intellectually very distant from how most people think about sources of electric power. Nuclear scientists and engineers do little to remedy the mindset that technology can be used to design-out the need for human intervention—what we would call a technology bias. As a result designers place a premium on perfecting reactor technology and less emphasis on the human component.

The tension between technology and human decision-making is nothing new. It crops up from time to time in commercial aviation, where crashes have occurred not because of the failure of a flight-critical component but because the crew was making decisions based on faulty or conflicting information. Recognizing this vulnerability, aviation experts have designed procedures to account for flawed decision-making, called Crew Resource Management (CRM). While retaining a command hierarchy, the concept fosters a less authoritarian culture, where co-pilots are encouraged to question captains if they observe them making mistakes. Some notorious airplane crashes, such as Air France flight 447 in 2009, were at least partly the result of the crew not following CRM procedures. In the case of flight 447, a jammed air speed pitot tube caused the highly automated aircraft to revert to manual control. One crew member reacted by placing the aircraft in a nose up configuration that brought on a stall. In response to the stall, another crew member took control and pushed his control stick forward to lower the nose and recover from the stall; however, the first crew member was still pulling his control stick back, lifting the nose up. The two inputs cancelled each other out. The crew were not cooperating with each other and it was not clear who was in charge of what. The analogy between the confused decision-making in the cockpit of flight 447 and the decisions made by operators at TMI is not exact, but it is informative.

In the case of Three Mile Island, following an automatic SCRAM of the reactor, a pressure relief valve became stuck in the open position, allowing thousands of gallons of water to flow out of the reactor cooling system. The stuck valve and loss of coolant were unknown to the operators. In fact, they believed the opposite to be true: that the reactor and its pressurizer were receiving too much water. This led operators to (incorrectly) limit the amount of cooling water flowing into the reactor, which ultimately resulted in the uncovering of the fuel and core damage. The Kemeny Commission pointed out that the failure of the operators to take correct action was the combined result of inadequate training, poorly designed human/machine interfaces, a torrent of uncoordinated warning messages in the control room, inadequate indicators of reactor status, all compounded by a management structure where decisions were made by three separate authorities.⁸⁷

⁸⁷ They were Metropolitan Edison (operator and part owner), General Public Utilities Service Corporation (holding company and owner), and the TMI site personnel.

The Commission went on to criticize the regulatory posture of government overseers, both in terms of how the complexity and burden of regulations impact operations and safety and how regulatory strategy may channel safety practices to focus primarily on large-scale failures and give less attention to small problems that could get out-of-hand:

- “We note a preoccupation with regulations. It is, of course, the responsibility of the Nuclear Regulatory Commission to issue regulations to assure the safety of nuclear power plants. However, we are convinced that regulations alone cannot assure safety. Indeed, once regulations become as voluminous and complex as those regulations now in place, they can serve as a negative factor in nuclear safety. The regulations are so complex that immense efforts are required by the utility, by its suppliers, and by the NRC to assure that regulations are complied with. The satisfaction of regulatory requirements is equated with safety. “
- “This Commission believes that it is an absorbing concern with safety that will bring about safety -- not just the meeting of narrowly prescribed and complex regulations. We find a fundamental fault even with the existing body of regulations. While scientists and engineers have worried for decades about the safety of nuclear equipment, we find that the approach to nuclear safety had a major flaw. It was natural for the regulators and the industry to ask: "What is the worst kind of equipment failure that can occur?" Some potentially serious scenarios, such as the break of a huge pipe that carries the water cooling the nuclear reactor, were studied extensively and diligently, and were used as a basis for the design of plants. A preoccupation developed with such large-break accidents as did the attitude that if they could be controlled, we need not worry about the analysis of "less important" accidents.”
- “Lesser accidents may develop much more slowly and their control may be dependent on the appropriate actions of human beings. **This was the tragedy of Three Mile Island, where the equipment failures in the accident were significantly less dramatic than those that had been thoroughly analyzed, but where the results confused those who managed the accident.**” (Emphasis added.)

While a natural disaster set in motion the nuclear accident at Fukushima, like TMI, the response to the crisis at Fukushima was hampered by a lack of information, contradictory information, and general confusion. Two hours after the earthquake struck, TEPCO announced that operators could not determine the water level in the reactor cores of Units 1 and 2 and had no assurance that the systems to supply additional water were working. The lack of reliable water level data meant that analysts did not know how much makeup water was entering the reactor vessels at what times during the accident, a critical piece of information for understanding the effectiveness of emergency water-injection strategies (Lochbaum, et al., 2014).

The day after the earthquake Lochbaum comments that video tapes from the conference link between Fukushima and TEPCO headquarters reveal a chaotic scene:

- Tempers flare as Masao Yoshida, the plant superintendent, and his team are besieged with orders and counter-orders from TEPCO headquarters, which was also getting instructions from the prime minister’s office.
- Yoshida later told government investigators he believed TEPCO’s chain of command during the accident was “disastrous”(Lochbaum, et al. 2014).

The lesson from these and other accidents lies in understanding the importance of getting immediate and accurate assessments on the status of an unfolding incident in a reactor in an understandable way. Another lesson is the critical importance of learning from exercises and training for severe events, especially those that can grow out of seemingly innocuous out-of-family occurrences. This is critical to preventing the incident from becoming an accident. Doing this reliably under crisis conditions in a way that assists (and not confuses) the decision making by on-site operators is the real challenge. The solution is not just better technology; it is how technology interacts with operators and contributes to successfully backing out of a crisis.

9.4 The Rickover Approach to Safety

There is one example in world history of a major nuclear program where a policy of zero nuclear accidents was established as an operating principle. This was in the US Navy nuclear submarine program. It was accomplished by Admiral Hyman G. Rickover during the Cold War. Admiral Rickover directed the development of US Naval nuclear propulsion and controlled its operations for three decades. President Eisenhower had enough confidence in Rickover that the United States Atomic Energy Commission put Rickover in charge of building the world's first commercial power station at Shippingport.

The most important reason for the plant's success was the managerial style of Rickover. Early on, Rickover realized the potential danger of nuclear power: "No carelessness can be tolerated anywhere, for the entire chain of events can prove disastrous." Any person who knowingly violated procedures answered directly to Rickover. As one former company official put it, "You always knew who was in charge." Rickover mandated an organizational arrangement for Shippingport that emphasized tight control over all contractors and centralized decision-making by his Naval Reactors office. As Rickover stated, "All we have to have is one good accident in the United States and it might set the whole reactor game back for a generation." ([Beaver, 1987](#)).

Rickover's brusque and demanding management style often offended his superiors, but his iron-fisted management, coupled with deep expertise on nuclear matters, established a record of zero reactor accidents—as defined by the uncontrolled release of fission products into the environment subsequent to reactor core damage ([Bowman, 2003](#)). Rickover had an obsessive fixation on safety and quality control and displayed an unyielding temperament in dealing with bureaucracy. According to Martin Sieff, the accident-free record of the US Navy reactor operations stands in stark contrast to that of the former Soviet Union, America's primary competitor during the Cold War, which had fourteen known nuclear submarine accidents with many fatalities ([Johnston, 2007](#)).

In his evaluation of the Three Mile Island accident, Rickover observed that he was often asked how he ran the Naval Reactors Program—often with the expectation that he could tell them some simple, easy procedure which made the Naval program function. He concluded that, unfortunately, there is none. Any successful program functions as an integrated whole of many factors. Trying to select one as the key will not work. Each element depends on all the other elements. This is something that can be learned only through personally experiencing operating responsibility and making hard decisions. A lack of operating experience in people responsible to evaluate the competence of organizations leads too often to focusing on trivial details or on vague generalizations. He observed that attaining competence and reliability in a nuclear operation is difficult, but recognizing them is

not. In fact, with experience in operations, it is possible to lay down certain management objectives which are essential to safety, and are observable and verifiable. Rickover listed seven:

1. Require Rising Standards of Adequacy. Excellence is achieved by raising standards and goals when lower thresholds of competence have been reached.
2. Be Technically Self-Sufficient. It is essential that decision-making managers not only have extensive technical training themselves, but that they also have expert analytical and engineering resources readily available within their own organization. It is insufficient to rely solely, or even primarily, on outside contractors or consultants for technical support, a practice which is commonly used.
3. Develop the Capacity to Learn from Experience. Since we are dealing with persons and machines which cannot be made perfect, it is important to recognize that mistakes will be made. We must do our best to design machines having tolerance for mistakes and to continue to improve them through experience. This process of evolutionary improvement, the basis for much of our most useful technology, depends on a capacity to acknowledge mistakes and to determine and correct their underlying causes, whatever the cost. An inability or unwillingness to learn from experience is intolerable in nuclear operations.
4. Respect Even Small Amounts of Radiation. It is incumbent on nuclear plant operators to minimize personnel radiation exposure by all reasonable means.
5. Require Relentless Training. It is vital that the mental abilities, qualities of judgment, and level of training be commensurate with the responsibility involved in operating a nuclear station. A management's attitude toward excellence in operation and its understanding of how to achieve excellence are both revealed in the quality of training provided.
6. Face Facts. There is a disposition common to all operating organizations to minimize the potential consequences of problems, especially when blame may attach to the reporter. It is a human inclination to hope things will work out, despite evidence or doubt to the contrary. A successful manager must resist this temptation. This is particularly hard if one has invested much time and energy on a project and thus has come to feel possessive about it. Although it is not easy to admit what a person once thought correct now appears to be wrong, one must discipline himself to face the facts objectively and make the necessary changes—regardless of the consequences to himself. The man in charge must personally set the example in this respect. He must be able, in effect, to “kill his own child” if necessary and must require his subordinates to do likewise. Facing up to difficulties, regularly informing higher levels of management of them, and determining and correcting their root causes involve attitudes and practices which are essential to operating competence.
7. Require Adherence to the Concept of Total Responsibility. Operating nuclear plants safely requires adherence to a total concept of responsibility wherein all elements are recognized as important and each is constantly reinforced (See inset). Training, equipment maintenance, technical support, radiological control, and quality control are essential elements, but safety is achieved through integrating them effectively in operating decisions. Management's understanding of this principle at the corporate and plant levels is a valid measure of competence (Dickenson College, 1983; Rickover, 1982).

Admiral Rickover on Responsibility

Admiral Rickover realized the importance of having total Responsibility. He once said:

Responsibility is a unique concept: it can only reside and inhere in a single individual. You may share it with others, but your portion is not diminished. You may delegate it, but it is still with you. You may disclaim it, but you cannot divest yourself of it. Even if you do not recognize it or admit its presence, you cannot escape it. If responsibility is rightfully yours, no evasion, or ignorance, or passing the blame can shift the burden to someone else. Unless you can point your finger at the person who is responsible when something goes wrong, then you have never had anyone really responsible.

--Admiral Rickover, 1992 (from Lambert, 2009).

9.5 Japan's Basic Policy for Nuclear Energy and Attempts at Reform

Can Japan's nuclear industry learn from the experiences at Fukushima, TMI, and many other nuclear incidents? More importantly, can it adopt and accept the relentless and obsessive management style of an Admiral. Rickover to ensure a nuclear power infrastructure has, as its top goal, a culture of zero nuclear accidents? As Japan's nuclear industry contemplates the lessons learned from the Fukushima disaster, along with the nuclear power industry's long and concerning record of incidents and accidents, Admiral Rickover's management objectives and the observations of the Kemeny Commission are now more relevant than ever. The critical link in their assessments were the strengths and weaknesses of management, both on-site in the boardroom. Based on reviewing their reports, it is clear that changes must be made to the policies and management of the nuclear power industry. But without management's leadership and support, change will not happen.

Japan's managers are universally known and respected for their relentless pursuit of quality and willingness to sacrifice almost anything for the company. Perhaps the very characteristics found in Japanese business can be bent to the purpose of achieving a truly accident-free nuclear culture. Given the flaws that are present in the design, location, construction, maintenance and operation of Japan's existing nuclear power plants, the country's business and government leaders may have reached the point where they are ready to embark on a different path to achieve reliable and safe electric power.

There is some reason for hope. In its 2017 Basic Policy for Nuclear Energy, the AEC called for the government and industry to let go of the "safety myth." It pointedly stated there is no such thing as "zero risk" and an accident is bound to happen. In recognizing this inevitability, government and industry should strive to improve safety so as "to minimize residual risk and prevent it from actualizing." This represents a profound change in how Japan's nuclear regulatory agencies think about the issue of nuclear safety. The AEC's Basic Policy goes on to cite several important goals:

- Establish a safety culture that overcomes weakness of traditional Japanese organizations and national culture. Nuclear energy-related organizations, instead of falling into

groupthink, should clarify the decision-making roles and responsibilities within the organization and establish an environment that facilitates continuous improvement.

- Case studies relating to operations and management, including those focusing on human errors, should be continuously collected and analyzed to improve nuclear operations. Senior management should commit to risk management comprehensively, based on the results of risk assessments of a wide range of scenarios.
- In conveying nuclear information to the public, engineers should avoid a formal, one-sided style of communication and instead engage in a dialogue that keeps in mind trans-scientific arguments and furthers mutual understanding. Each and every person should have an opportunity to form their own views on nuclear energy based on a data base of scientific information and evidential facts. These data must be available to the public.
- With respect to R&D, the nuclear industry should pursue concrete organizational management improvements, not just reforming attitudes, but introducing management techniques and systems to maximize outcomes.
- Upgrading and improving basic facilities and equipment is a pressing issue. The government and academia should focus on building and operating the basic facilities and equipment that are needed.
- The government should set up a centralized monitoring system for determining the storage, processing and disposal conditions of various types of radioactive waste; and for promoting comprehensive waste disposal policies. It should encourage nuclear industry and R&D institutions to secure disposal sites and to address the problem of aging and deteriorating facilities.
- Anxiety about the declining number of personnel and the difficulty passing on knowledge to the succeeding generation is increasing. Highly trained nuclear energy- personnel will be needed for as long as there is nuclear energy use—including the need for decommissioning and waste management. An effective solution would include the government, industry, R&D institutions, and universities to engage in publicity campaigns to recruit personnel.

These are all laudable goals. Indeed, we present recommendations and actions in this chapter that build upon AEC's Basic Policy. The AEC in most cases accurately identified the problems in government and the nuclear industry, but it does not lay out solutions. For example, it calls for preventing the recurrence of severe accidents and the reduction of its impact once they occur, but there is no discussion of the management changes that would be required to bring about this result. Aside from a reference to adopting risk management and analyzing past accidents, the Basic Policy does not address how to build a safety culture. Moreover, the Basic Policy has not been articulated or advocated by other ministries and oversight agencies, so there is a real question as to whether there is "buy-in" across the government and whether the policy will have a long term impact.

It is not beyond expectations of the Japanese people that members of Japan's nuclear industry and nuclear oversight agencies should, borrowing words of the Kemeny Commission, finally recognize that having an absorbing concern with safety will bring about safety. The greatest unknown in addressing this question is whether Japan's leaders will understand and accept the critical importance of achieving an accident-free culture and put in place individuals that have the experience and drive to achieve that goal.

9.6 Adherence to Principles of Program Management

One critical ingredient, in our view, that needs to be addressed as a first step is the development of effective Program Managers in the nuclear field. These are strong, disciplined leaders who have the authority to manage the wide-ranging and complex programmatic details of technical programs, which nuclear power programs certainly are. These leaders would provide integrated oversight and ensure that program risk (both cost and technical) are fully understood and that back-up capabilities are in place to hedge against failure. Program Managers would ensure that the technical and human dimensions of NPR operations are knitted together and function effectively, from the earliest planning phases thru operations and decommissioning.

This is already being done by the nuclear industry in such areas as on-site power and emergency cooling, but it is missing in areas that are deemed not mission-critical, but in fact, are. Examples where additional redundancy and resilience would have been valuable abound:

- Single Points of Failure in Plant Design. Both FBR Joyo and FBR Monju experienced these types of failures. In the case of FBR Joyo, the irradiation test subassembly failed to disconnect from its handling apparatus, which limited access to reactor fuel and led to a multi-year shutdown of the reactor. In the case of FBR Monju, the 3-ton fuel transfer apparatus dropped onto the reactor vessel head plug. The cause was linked to a malfunction of the gripping structure of the lifting machine. It was just good fortune that the transfer apparatus was not lifting a fuel assembly when the unit failed. In both cases, the operation of the reactor was dependent on the reliable operation of a single external, but very important component, which if it failed, would bring reactor operations to a halt. And that is what happened.
- Failure to Meet Performance Requirements. In the case of the vitrification process at the RRP, operators encountered difficulty in controlling the glass furnace temperature, problems with accumulation of platinum group elements that impact glass pourability, bricks falling to the bottom of the furnace and clogging of nozzles that prevented the liquid waste from flowing into the vitrification canisters. Moreover the furnace was too small for the RRP's plant and needed to be scaled up. These problems all stem from performance and design limitations that should have been caught and assessed in a requirements review. That clearly did not happen and remedial actions required six years to fix.
- Testing and Simulation Shortfalls. Post accident simulations of the Fukushima NPRs showed that existing computer models could not predict many of the events and characteristics that occurred as the accident unfolded. Without accurate simulations, it is very difficult to create designs that are credibly resilient under future accident conditions. Future nuclear development programs should make use of detailed test and simulation protocols that are informed by historical data on NPR events. For example, data reported by France, the UK, and the United States on their civilian power reactors indicates that on average over the last decade there have been 6 to 12 reportable events per reactor per year. Taken together, this represents a data base of well over 10,000 events. Very few of these events had serious safety implications, but taken together these events present a mosaic of design and operational issues and trends that could be used to model plant operations and provide clues as to how to improve safety. This type of analysis is encouraged in the AEC's Basic Policy for Nuclear Energy, which calls for analyzing case studies and then making effective improvements based on the analysis.

These are the kinds of challenges that Program Managers would identify and manage. They would set milestones, review interim steps, establish independent review teams, undertake risk reduction R&D, oversee acquisition, and ensure that all activities were properly funded. In effect, these leaders would be the senior officer in a corporation or government agency who would perform the following tasks:⁸⁸

- Generate a high-level set of requirements and an initial concept of operations that are intended to satisfy an urgent need.
- Identify potential technologies to satisfy the need.
- Sign off on government contracts to directly to develop the critical technologies.
- Oversee system studies performed by the government and potential acquisition contractors in order to get the best and most creative ideas on architectural approaches.
- Select critical technologies and as well as alternatives.
- Establish system performance specifications.
- Decide on cost and schedule commitments, based on contractor inputs, independent cost estimates, and experience.
- Determine how program teams are aligned (which contractor would be prime and who would be subcontractor).

This process gives Program Managers the flexibility to continually make trade-offs in performance and schedule and cost. In the end, the performance expected of a program is embodied in a system performance document, which is approved by the Program Manager and is understood in the context of cost and schedule commitments. The most important factor contributing to the success of a technically complex program is an understanding and acceptance by all that the Program Manager is in charge of the program. Ambiguities in the chain of command, as we noted in Chapter 5, can be fatal.

Individuals who have the requisite experience to perform the role of Program Manager are difficult to find. The best have had long careers as senior system engineers and have the following characteristics:

- They have solid technical foundations and have effectively practiced their technical skills early in their careers. They can be drawn from any technical field—no specific discipline is especially well-suited to producing good system engineers.
- They are good communicators, able to communicate up, down and across a program.
- They can see the big picture, understand the vision, including goals, objectives, priorities of a program, and help program teams achieve that vision.
- They are able to sort out what is important from what is not. The good system engineer drives risk, performance, schedule, and cost trades across the enterprise and seeks the best value solution regardless of contracts, requirements, specifications or politics.
- They work aggressively across technologies that may actually not be in their fields; they do not try to do the jobs of subordinate managers.

⁸⁸ These points are drawn from “The Lost Art of Program Management in the Intelligence Community” by Edmund H. Nowinski and Robert J. Kohler, *Studies in Intelligence*, Volume 50, No. 2 (Nowinski, 2006)..

- They keep customers informed.
- They constantly look for issues to be addressed and resolved, and, when they find them, they force rapid resolution.
- They are willing to work programs from beginning to end.

We note that in Japan the concept of Program Manager, often called Project Manager, appeared in the early 2000s and has grown in familiarity and acceptance in the business community. For technically complex programs, especially those funded through the government, Program Managers often have been recruited from the academic sector where they hold the rank of Professor. They typically maintain their affiliation with their college or university while serving as Program Manager. This practice works well for complex scientific research projects, such as space exploration, and we think that such an arrangement could work as well for ensuring safety projects are properly executed in the nuclear industry, providing the chain of command is clear and individuals have the experience noted above.

9.7 Rebuilding the Talent Pool and Changing the Culture

If Japan were to institute a strong top-down managerial commitment to nuclear power safety, it would first need to lay the foundation for that commitment by encouraging more college-bound students to major in nuclear studies. Nuclear science and engineering must be promoted at all levels of education—middle school, undergraduate, and graduate. Right now, however, trends in academia are headed in a less favorable direction. Top flight students view careers in other fields to be far more attractive, and it is not hard to understand why: nuclear R&D has been drastically cut, statements from government leaders give the impression that the nuclear industry's days are numbered, and the public's perception of nuclear energy is generally negative.

To turn things around, the government and industry should develop a clear plan of action to persuade young people that nuclear power is a desirable and respected career field—one that broadly benefits society and where government and industry place safety above all else. Those values must be taught in Japan's universities. Indeed, rebuilding the talent pool by promoting educational opportunities offers the perfect point of leverage for changing the existing culture of the nuclear industry. Future engineers and scientists should be taught the core principles of safety as moral values, the history and underlying human and technical causes of accidents, the social and economic components of safety, and how nuclear businesses should be managed to promote a zero-accident environment.

Nuclear studies departments should build curriculums that address safety and risk as central to the development of nuclear power and should recognize that safe practices can only be achieved by being attentive to the human dimension of safety. It should be seen as a societal obligation of the profession. Progress is being made in changing curriculums but it has been slow. Most nuclear studies departments do not offer courses on the human (or cultural) dimension of nuclear safety practices. Funding cutbacks have made it all the more difficult to establish new courses and conduct original research in this area. As examples, the Reader might wish to examine curriculums of the Tokyo Institute of Technology, Kyoto University, and Tokyo University for how these institutions treat the cultural and human dimension of nuclear studies.

There are precedents for kick-starting such an effort. One example was a program to promote science and technology education by US President Eisenhower. He recognized that the United States was falling behind in science skills and set about to establish a program of incentives that would encourage students to enter fields of science and mathematics. In its first four years of operation (1959-1962) the US Congress authorized \$4 billion (in current dollars) for loans, fellowships, and other forms of educational support. The program continued in various forms for another ten years (Flattau, 2006).

By most measures the program was a success. Data were not systematically collected at the time, but it is clear from anecdotal reports that the quality of teacher instruction in the sciences improved, both in terms of the number of teachers who held advanced degrees and in the student/teacher ratio. The number of students qualifying for loans because of superior preparation in science, mathematics, and engineering, increased eight-fold over four years. Most significantly, the number of doctoral degrees awarded in engineering, math and computer sciences increased four-fold between 1960 and 1970.

As Japan brings more of its idle reactor fleet on-line (and decommissions others), it will need access to more top-flight scientists and engineers to manage this process as well as to ensure operations take place in a zero-accident environment. A program of education such as the one started by President Eisenhower could help reverse negative trends in the availability of skilled talent and could also create incentives for changing the safety culture. The effect of such a program would be further magnified if Japan were to reverse the cuts it has made in nuclear R&D. Students who see a bright future in nuclear studies would be more inclined to choose this field for their career. Even if Japan were to decide to abandon nuclear power it would still need a highly educated workforce to deal with decommissioning and disposal of radioactive material. Safety will need to be a top priority for generations to come.

The promotion of science and engineering education comes with a cost, as did Eisenhower's initiative. The level of funding for the Eisenhower education initiative offers a point-of-departure for what funding levels might be required in Japanese universities. While it is beyond the scope of this book to identify programmatic trades, it seems to us that a portion of Japan's Power Source Location Measure (an element of Dengen Sampo) could be shifted from providing local subsidies to enhancing educational opportunities in nuclear studies. Ultimately towns and prefectures that are hosts to nuclear facilities would benefit from the arrival of new scientists and engineers who have received advanced degrees in nuclear-related fields. Moreover, a deeper talent pool would create the opportunity for building a zero-accident culture—a goal that every town should support.

9.8 Rebuilding the Public's Confidence in Nuclear Power

Japanese public opinions toward nuclear power has been fluid but mostly negative since the 1990s. The Fukushima disaster hardened the views of the majority who have been against nuclear power. Changing the public's attitude toward nuclear power now, if it is possible at all, will be a long, slow, and painful process that will span generations. Certainly no headway is possible if the government and nuclear industry attempts to downplay or cover up accidents, safety infractions, or just bad decision-making. Even the most trivial event that goes unreported could strengthen public opposition to nuclear energy.

Perceptions are so ingrained that there likely is nothing that can be done to change the minds of those who want to phase out nuclear power. Those who have no opinion or are undecided are potentially reachable but it would take many concrete actions over years to convince this segment of the public that “this time it’s different.”

To get back on a path that builds confidence in nuclear power will require absolute openness and transparency, values that have not come easily to government and private sector managers. More than that, Japan’s nuclear industry will need to demonstrate through its investment decisions, operational behavior, and the training and education of its future workforce that it has a commitment to safety that is unwavering and long-lasting—much like that of Admiral Rickover. This requires nothing less than the adoption of a commitment to a zero accident culture and a corresponding change in corporate and government culture.

Changes that would gain public trust would include complete and timely disclosure of any incident or accident, holding managers accountable for activities that do not conform with ethical standards (See discussion of a Code of Ethics, below), and a commitment to teach the ethical conduct of nuclear engineering at colleges and universities. The public is good at reading the sincerity of its leaders: no one questioned Rickover’s commitment to safety because he lived and breathed it every day. The Japanese public will expect to see that same degree of commitment from its senior leaders. Without it, no speech, communication campaign, expert opinion, or financial subsidy will have any effect. Nuclear power will have no future. A good place to start would be complete disclosure of the costs of nuclear power, including subsidies for construction and operations, as well as a detailed accounting of the cumulative costs associated with the Fukushima disaster.

9.9 Creating a Practical Incentive System for Safety

The nuclear industry needs both negative and positive incentives so that managers regard effective safety practices as a source of profit and negligence toward safety as a source of loss. One step in that direction would be to require the industry to build into their business plans estimates of the recurring costs of nuclear accidents and then to set aside profits to cover these costs, much like banks set aside funds to cover non-performing loans. This would depart from the current industry practice of participating in risk pools or purchasing liability insurance up to \$1.2 billion specified by law (The Law concerning the Compensation of Nuclear Damage, 1961, Law No. 147). Under current practice once the insurance policy is in place power companies have little incentive to proactively improve safety and are generally motivated by the threat of government enforcement action to abide by regulatory requirements.

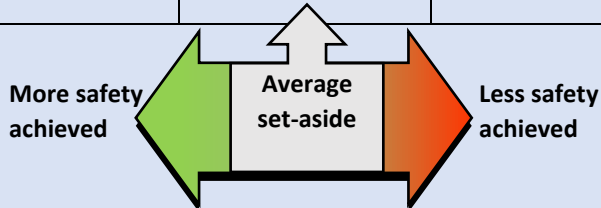
Set-asides, on the other hand, would be linked to safety evaluations of nuclear power plants as conducted by the NRA. If the level of safety increases, cost set-asides for accidents as set by the NRA would decline and company profits would increase. Reactor operators who receive a lower grade would find their accident set-asides for future accidents would increase and their profits decline. Through competition, safer designs and operations would create conditions for power companies to prosper. A point of departure for evaluating industry commitment to safety could begin with considering compliance with a Code of Ethics, discussed further below. Thus, through enforcement of stringent safety standards as well as the establishment of financial incentives to invest in safety, a mindset of promoting safety would be promulgated throughout the industry.

To illustrate how set-asides work, we have calculated how power companies would price into their generating cost a “safety premium” associated with their achieved levels of safety. For this calculation, we express safety levels in terms of the expected severity of an accident, e.g., damage to the reactor core and the frequency of occurrence. These are defined by the historical accident record or what could be expected through moderate improvements or total modernization of a fleet of 25 reactors. This methodology is similar to Nagaoki (2013), but he proposes establishing a mutual aid (risk pool) system. We, on the other hand, recommend plant owners set aside a portion of their profits to cover future accident costs, with the amount of the set-aside tied to safety levels that the operators achieve (See Appendix C for details on our methodology and assumptions).

Exemplar set-aside requirements are illustrated in Table 9.3 for accidents that would involve damage to the reactor core. At the start of a set-aside program, we suggest that all power plants be treated the same and that companies set aside funds to pay for an “Intermediate” accident that would cost about \$100 billion. In rough terms, the set-aside would amount to a 25 percent “safety premium” above the average cost of one MWh of nuclear power (which currently is \$98). By way of comparison, in Japan it currently costs \$137 to generate one MWh using liquefied natural gas (LNG) (METI, 2015), which is 40 percent more than the average cost of one MWh of nuclear power.

As power companies worked to meet the NRA’s safety standards, some companies would likely achieve results sooner or go beyond what is actually required. The NRA could give these companies higher safety grades and reduce the required set-aside, possibly as low as a few cents per MWh, or a fractional percent of generating costs. Companies with a below average safety record would see their set-asides increase to well above \$33 per MWh. As a result, companies would be rewarded for investing in safety improvements. Those with lower risk would see their costs fall and profits increase. As companies become acclimated to this process, set-asides could be extended to accidents with less severity (e.g., INES Level 1, 2, 3) with set-asides adjusted accordingly.

Table 9.3 Exemplar Set-aside Requirements Based Upon Assessed Safety Level

Relationship Between Estimated Accident Severity, Time Between Accidents and Exemplar Set-Asides per MWh			
Expected accident severity based on safety level assessed by NRA	Less Severe	Intermediate	Worst
Period to pay for accidents, in years, as assessed by NRA	40	20 to 40	20
Expected Range in Accident Cost	\$10B	\$100B	\$1000B
Cost of Accident per MWh (basis for range in set-aside amounts)	\$1.63	\$16 to \$33	\$325
Exemplar set-asides per MWh generated, depending upon level of safety achieved by power company			

Source: Created by the authors.

9.10 A Code of Ethics to Promote a Zero-Accident Culture

A code of ethics can help clarify an organization's mission and values, linking them with standards of professional conduct. The code can be used as a touchstone for the values an organization wishes to foster in managers and employees and can provide benchmarks against which individual and organizational performance can be measured. Additionally, a code is a central guide and reference for employees to support day-to-day decision making, particularly when it comes to safety issues. A code gives employees a basis to raise ethical considerations when confronted with dilemmas where safety might be traded off for schedule or cost reasons.

One of Japan's first ethical codes was published in 1938 for the Japan Society of Civil Engineers. More than two decades later this was followed by codes for the Institute of Professional Engineers and the Information Processing Society of Japan. Other engineering fields adopted codes in the late 1990s. The Atomic Energy Society of Japan (AESJ)⁸⁹ Board of Directors began to draft a code in 1998, despite a lack of interest among its members. AESJ leaders were concerned about reports of data falsification that had arisen in connection with the Monju sodium leak, the JCO criticality accident, and the Nuclear Engineering and Services' spent fuel transport casks. A code was finally published in 2001 and has been updated every two years, up until the Fukushima accident. ([AESJ, 2018b](#)).

2001 Code of Ethics. The first Code of Ethics for members of the nuclear profession was organized into eight chapters, covering 1) the peaceful use of nuclear energy, 2) promoting safety, 3) improving the members' technical skill, 4) cautioning against undertaking work beyond the member's professional capability, 5) the importance of providing accurate information and the member's responsibility for public disclosure of safety information, 6) the need to have a fair and just attitude and to have independent judgment, 7) the requirement to pursue professional duties under a contract within the boundaries of the Code, and 8) the need to feel proud about the member's nuclear work. (For the 2018 version of the Code see Appendix E). ([AESJ, no date](#)).

2003 Code of Ethics. Following the 2002 TEPCO data falsification incident (See section 8.3), the AESJ issued a revised Code of Ethics to strengthen the moral and ethical standards of members and their organizations. New goals were added to discourage reflexive obedience and unwillingness to question authority. For the first time the responsibility of management is called out to enhance safety and to treat fairly employees who disclose safety information to protect the public.

In 2004 a serious accident occurred at the Mihama Nuclear Plant in Fukui prefecture. The plant, owned and operated by KEPCO, was preparing for a regularly scheduled inspection. The accident happened about 3:30 pm on 9 August at the 28-year old Reactor 3. A 56-cm (22-inch) diameter stainless-steel condensate pipe installed in the ceiling of the plumbing room suddenly burst, spraying massive amounts of water and pressurized steam heated to as much as 400 degrees. Eleven workers were in the plumbing room preparing for the regulatory inspection. Four died almost instantly from shock and cardiac arrest; another worker died 17 days after the accident. Six

⁸⁹ The AESJ is a one and only nuclear membership association in Japan that includes researchers, scholars, students, corporations, plants, governments' officials and employees in all fields of nuclear power generation, radiation, reprocessing and environmental sciences. The AESJ at present has about 7,000 individual members and about 230 organizational members ([AESJ, 2018a](#)).

others received serious burns. The rupture occurred because the pipe wall had eroded due to a downstream vortex. An investigation revealed that the pipe wall had thinned from an initial 10 mm to just 1.4 mm. Regulations required the pipes to be replaced when the walls eroded to a thickness of 4.7 mm. Nine months before the accident a subcontractor company had alerted the operators to the need for inspections, but the warning was ignored (Wein, 2013; Citizen's Nuclear Information Center (CNIC), 2004; Kansai Electric Power Company (KEPCO), no date).

Kyoko Oba, Chair of the AESJ Ethics Committee, stated that the 2004 Mihama plant accident alerted the committee to the importance of safety in the work place. The number of goals in the Code increased from 38 to 43, but most of the additions in the 2005 code focused on how to regain and rebuild the public's trust in nuclear power. For example, Chapter 5 called on members to ensure the accuracy of their information, to fulfill their responsibility for public disclosure, and endeavor to gain public trust (new text).

2007 Code of Ethics. The 2007 code emphasized the need to appreciate the consequences of past nuclear disasters—lessons learned from past accidents—and to listen to others' opinions and criticisms. With respect to potential conflicts between contractual duties and potential violation of law that was highlighted previously, the Code weakened the goal somewhat by delinking contractual duties from any legal issues: "The members shall observe the laws and social convention as a member of the society and fulfill in good faith the contract governing their work."

The other notable change was to introduce climate change into the Code in Chapter 1: "The members shall recognize that while the use of nuclear energy can be a solution to the environmental problems through the reduction of CO₂, it could be a negative legacy for the future mankind and the biosphere because of the radioactive waste. The members were asked to always try to maintain balance with environmental protection of the earth."

2009 Code of Ethics. Changes to the 2009 Code made it more abstract and hortatory. With 45 goals, it was difficult to understand and apply. Some examples:

- **1-4. Attention to Assurance of Nuclear Security.** Members shall recognize that nuclear materials and radioactive materials could be used for terrorist purposes and members should pay ample attention to nuclear security (new goal).
- **3-3. Learning from Experience.** The member shall learn lessons from their experience. Especially, they should learn from their experience of nuclear accidents and disorders as much as possible, strive to prevent recurrence of similar accidents, share information and try to pass on technology and knowledge. The members shall learn from past lessons (new text).

Fukushima Nuclear Disaster and the 2018 Code of Ethics. The AESJ was shocked by the Fukushima nuclear accident. According to then Chair Kyoko Oba, the AESJ was aware that major nuclear accidents could happen at nuclear plants, such as at Three Mile Island or Chernobyl, but there was complete surprise that such a serious accident could happen in Japan (AESJ, 2014). The Ethics Committee stopped functioning for a period and did not issue a revised Code until January 2018 (See Appendix E for a full translation of the Code).

In 2016, Haruki Madarame, former Chairman of the Nuclear Safety Commission and former AESJ Ethics Committee member, provided his analysis of the reactions of the nuclear power industry to past accidents. He made his presentation at the 19th Ethics Committee study meeting. Madarame

noted that the nuclear power industry learned nothing from past accidents—rather, the industry argued that many accidents did not happen at nuclear power plants so there was no need to do anything differently (See Table 9.4). The industry acknowledged that some self-inspection data had been falsified, but they excused that behavior, explaining that the falsification was not serious enough to cause safety problems. Moreover, they argued that Fukushima was a natural disaster and so they were not to blame for the accident (Madaramé, 2016).

Table 9.4 Responses of Nuclear Industry Regarding Accidents and Data Falsification

Date	Accident or Data Falsification Event	Reaction of Nuclear Power Companies	
		Industry's Reasoning	Industry's Response
December 1995	Monju Sodium Leak	Problem was unique to PNC's character	Not our problem
October 1998	Falsification of data related to spent fuel transport containers	Manufacturers fault	Not our problem
September 1999	JCO criticality accident	Special case occurring at fuel fabrication facility	Will not happen at a nuclear power plant.
August 2002	TEPCO falsification of data		Maybe there were some problems in data reporting, but these problems were not serious enough to cause safety problems.
March 2007	NISA inspection of nuclear power companies that committed data falsification		
June 2017	Radioactive contamination at JAEA site	There are problems at JAEA, too!	Not our problem
August 2010	Uncontrolled drop of Monju In-Vessel Fuel Transfer Machine	We thought that they had learnt the lesson!	Not our problem
March 2011	Fukushima Daiichi Nuclear Accident	Natural disaster	Not our fault

Source: The authors created the table based on Madaramé (2016),

Considering these defensive responses, one key question naturally arises: why did the Code of Ethics have no measurable effect on the behavior of the nuclear industry? The complexity and number of individual goals could be one reason. However well-intentioned, some of the 45 goals were conceptually so abstract that it limited their utility. Another possible reason was that later editions of the Code tended to stray from the initial purpose of promoting ethical conduct and instead moved toward setting performance goals (e.g. improving resistance to terrorist attack).

Perhaps most important, the Code placed the bulk of responsibility for safety on individual members at the working level and avoided holding corporations accountable as responsible entities. For example, the 2009 Code had only one goal (8-2) that singled out corporate leadership; and in this case, leaders were called on to act “with full recognition of their business responsibilities and accountability so that they will be a role-model within the organization. Moreover, leaders shall

have the courage to prevent misconduct and misbehavior in the organization.” In other words, leaders were simply being asked to do their job and not tolerate violations of business practices or the law—a very low bar.

The 2018 Code represented a decided improvement in holding leadership accountable. Three goals were added that spelled out management’s responsibilities:

- **7-3. Importance of Establishing a Proper Environment in the Organization Based on the Code.** Managers shall make sure the actions of all individuals are based on the Code and that they are watchful for activities that impede adherence to the Code.
- **7-4. Establishing Appropriate Procedures for Complaints.** Managers shall have proper procedures to handle complaints swiftly and ensure that complainants are not disadvantaged.
- **7-5. Securing a Safe Working Environment.** Managers shall ensure there is a safe and secure environment for activities.

With these improvements, the Code is more than a set of exhortations. If it were simplified and rewritten to ensure that adherence to the Code could be measured, the Code could then be linked to goals in the AEC’s Basic Policy for Nuclear Energy. This would further the process of strengthening a culture of safety and regaining public trust. For example, the set asides we discuss in the previous section could be linked to how faithfully corporations encourage and abide by the Code. Corporations that score low in their adherence to the Code should expect to see their required set-asides increase.

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Chapter 10:

Prospects for a Hydrogen-based Society as an Alternative to Nuclear Energy

CHAPTER 10: Prospects for a Hydrogen-based Society as an Alternative to Nuclear Energy

Abstract

Japan is the least likely country to start a revolution, but its new energy policy, if implemented successfully, could revolutionize Japan's economy, society, and energy infrastructure. The new energy policy calls for the creation of a Hydrogen Society in which citizens will use hydrogen as their primary energy source. Hydrogen fuel would be produced from renewable sources and be used to generate electricity at home and power vehicles via fuel cells. The policy came into force in April 2014, was updated in 2017, and is intended to guide Japan's energy development for the next 25 years and perhaps beyond. The new energy policy would substantially reduce Japan's dependence on nuclear power as well as oil and gas-fired thermal power plants and greatly strengthen development of fuel cell systems that use hydrogen. Implemented in three broad phases over several decades, the policy would promote development of fuel cells that are less costly, more efficient, and more durable and develop hydrogen production, storage, and transport, and fueling systems to support the widespread use of fuel cells. This chapter examines how Japan formulated a policy and legal framework in the 1990s to promote fuel cell and hydrogen development, compares Japan's investment and policy strategy to those in the United States and the European Union, identifies the challenges Japan will face in establishing a Hydrogen Society, assesses the potential economic benefits it might enjoy if the Hydrogen Society policy succeeds, and offers recommendations to more fully integrate the hydrogen infrastructure with other initiatives to promote economic growth and a cleaner environment.

10.0 Japan's Policies for Fuel Cells and Hydrogen Technology

As we have seen from our examination of Japan's nuclear energy policies and programs, Japan is a country of long-term planning and steady, even persistent, policy implementation that might not yield immediate results but which ultimately could provide foundational capabilities for the nation. The policies discussed in this chapter could be considered as an alternative path to achieving energy independence. They encompass two interrelated, multiphase policy initiatives that could supplement nuclear energy and, given the challenges that face the nuclear industry, perhaps largely replace it as a source of electric power. These initiatives would seek to 1) broadly establish practical fuel cell technologies for a variety of applications and 2) embed these technologies in a Hydrogen Society⁹⁰ that relies on hydrogen as a primary source of energy to generate electricity and power vehicles. The two initiatives are mutually complementary. The first initiative will not become practical unless hydrogen production, storage, transport, and fueling technologies are developed and widely deployed. The second initiative will not be realized if the first initiative does not yield practical and inexpensive fuel cell technologies that can provide a hydrogen fuel source that is enough to meet demand.

Both initiatives will take decades to play out. The first initiative, which began with a few modest initiatives in the early 1990s, has already taken more than two decades to yield preliminary results; the second, which kicked off in 2015 and will require at least two to three decades before a hydrogen-fueled society can become widely available. Despite the long wait, Japan's government and industry are enthusiastic about the two initiatives because achieving these goals is of vital national importance. These policies, if successfully implemented, would ensure Japan's future

⁹⁰ METI now refers to this program as the Basic Hydrogen Strategy.

economic growth, energy security, and environmental health. It is also possible that these policies might lay the foundation for an energy infrastructure that is less dependent on nuclear energy.

10.1 Competencies in Fuel Cell Science and Technology

It is something of a paradox that Japan has put in place a policy to promote fuel cell systems, given that Japan historically has not been a technology leader in this field. Indeed, a detailed review of some 180 government and private sector fuel cell programs indicates that until the 1990s, Japan had not been credited with significant fuel cell accomplishments, nor had it successfully brought fuel cell products to market (Behling, 2013). In contrast, Europe and the United States have had a long record of scientific discoveries and technical developments pertaining to fuel cells. Indeed, European scientists and engineers invented or discovered all the first fuel cell types that are known today, and the United States developed and brought almost all of the first fuel cell products to market (see Table 10.1). One exception to the rule, and of import, was the proton exchange membrane fuel cell (PEMFC). The PEMFC was invented by General Electric in 1955. Ballard, a Canadian company, started to develop it in 1984, and the world was surprised by its rapid progress. By 1994, Ballard and Daimler had introduced the world's first fuel cell vehicle, NECAR 1, triggering a global fuel cell race among major industrialized governments (Behling, 2013).

Table 10.1 Absence of Fuel Cell Achievements by Japan in the Early Years

	Europe	Japan	United States
Fuel Cell	William Grove invented the first fuel cell	*	*
Alkaline Fuel Cell (AFC)	Bacon invented and developed the first AFC	*	Commercialized the first AFC for space
Phosphoric Acid Fuel Cell (PAFC)	*	*	Developed and commercialized the first PAFC
Molten Carbonate Fuel Cell (MCFC)	Operated the first MCFC	*	Developed the first commercial MCFC
Solid Oxide Fuel Cell (SOFC)	Discovered the first SOFC	*	Developed the first modern SOFC
Proton Exchange Membrane Fuel Cell (PEMFC)	*	*	Invented the first PEMFC

Source: Behling, 2014

*Indicates country/region did not invent or initiate their own market products

Profoundly impressed by the technical advances in Europe and the United States, Japan enacted a series of laws to foster innovation, inventiveness, and entrepreneurship. The first and most important was the Science and Technology Basic Law, enacted in November 1995. The law identified the most important science and technology areas upon which Japan should focus its efforts, and it provided a solid bureaucratic foundation on which Japan could build scientific and

technological competence. To flesh out the implementation of the Science and Technology Basic Law, Japan also enacted the Law Promoting Technology Transfer from Universities to Industry (referred to as the TLO Law) in May 1998. Its purpose was to facilitate technology transfer and encourage industry-academia R&D collaboration. Moreover, in 1999, Japan enacted Article 30 of the Law on Special Measures for Industrial Revitalization. The law permitted inventors to retain patents derived from government-funded projects. It made it easier for the holder of such patents to engage in entrepreneurial activities. Previously, all patents derived from government projects reverted to the government.

Japan also enacted the National University Corporation Law in 2004, which changed the status of national universities from a government entity to a special corporation to make it easier for universities to engage in for-profit businesses. Japan also enacted the New Education Basic Law in December 2006, which included supporting industry as an appropriate university mission. These laws have worked well to enhance universities' inventiveness and creativity as well as to provide them with the necessary flexibility to engage in collaborative R&D with businesses ([Behling, 2013](#)).

- As a result of these efforts, by the middle of 2013, approximately 200 University-Industry Collaborative Research Centers had been established and approximately 2,000 venture companies created, demonstrating the private sector's increasing interest in seeking R&D assistance from universities (see Figure 10.1) ([Behling, 2014](#)).

10.2 Japan's Fuel Cell R&D Program in 1992

In the early 1990s, Japan's Ministry of Economy, Trade, and Industry (METI, formerly MITI) took note of significant fuel cell developments in Canada and implemented a modest 8-year fuel cell R&D project in 1992 (the New Sunshine Program). The project had two phases: Phase I (1992–1995) (a total budget of \$6.6 million) focused on the development of 1 kW modules for stationary and portable applications, and Phase II (1996–2000) (a total of \$33 million) focused on the development of 5-10 kW portable, residential, and distributed power generation systems. In August 1999, a METI committee reviewed the results of the program and assessed that Japanese fuel cell capabilities had caught up with the technology levels of the foreign counterparts. It also concluded, however, that Japan would need a long-term R&D effort to bring the technology to a point where it would be cost-competitive with other power generation products on the market ([Behling, 2013](#)).

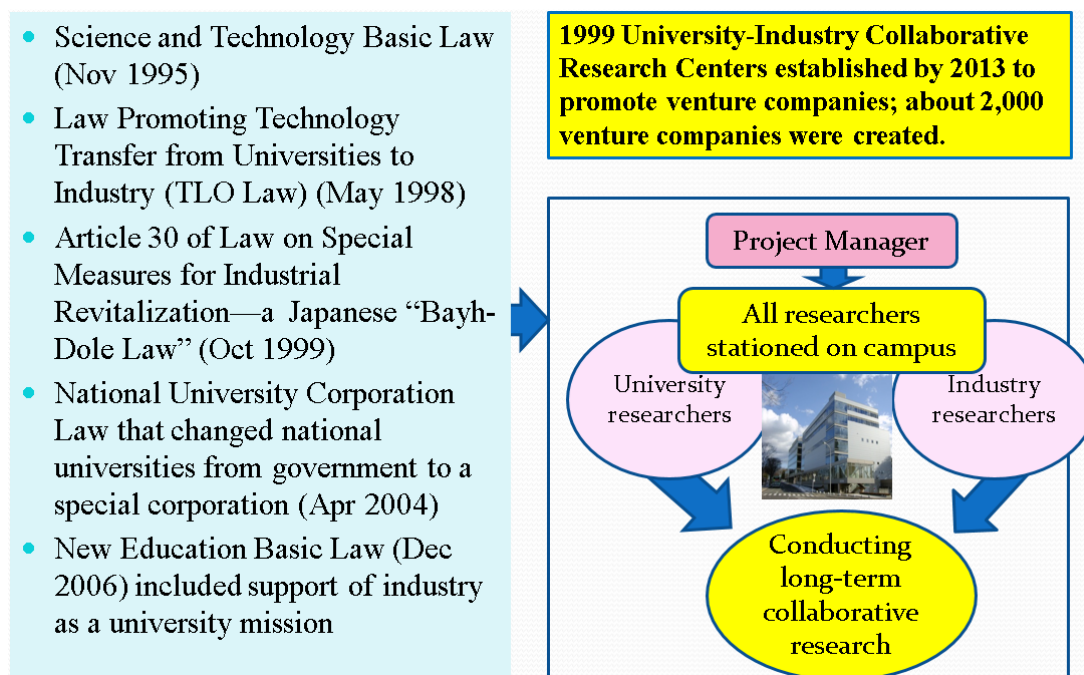


Figure 10.1 Laws to Remedy Science and Technology Deficiencies in Japan
Source: Behling, 2014

Thus, in December 1999, Japan’s Prime Minister implemented the Millennium Project to expedite the development of fuel cell vehicles (FCVs) and residential cogeneration systems and bring them to the market by 2015 ([The Cabinet Office, 1999](#)). To facilitate this goal, he directed the establishment of safety standards and certification systems for FCVs, fuel cell standardization, and hydrogen infrastructure standards to support commercialization. He also directed that an advisory group be formed to advise METI on fuel cell policy formulation. The Millennium Project directives were swiftly acted upon:

- In December 1999, METI established the Fuel Cell Commercialization Strategic Council (FCCSC), now subsumed under the Basic Hydrogen Strategy, to give strategic advice to the director of METI’s Agency for Natural Resources and Energy (ANRE).
- In December 1999, METI formulated a 4-year fuel cell development strategic plan to be implemented from 2000 to 2004.
- In March 2001, METI established the Fuel Cell Commercialization Conference of Japan (FCCJ), an industry association that would cooperate with the government for the commercialization of fuel cells.
- In August and December 2001, METI adopted Japan’s strategic fuel cell roadmaps to define the pathway to fuel cell commercialization.

The FCCSC, the METI advisory council, immediately set to work and drew up a roadmap to guide Japan’s policymakers and industry for the next two decades (see Table 10.2). In April 2000, METI implemented the 4-year fuel cell development strategic plan (2000–2004) to develop and commercialize fuel cell technology. It was widely recognized that fuel cell technology was not an easy technology to master in a short time. The technology was beset by problems involving high cost, inefficiency, and inadequate durability. In parallel with the fuel cell R&D program, therefore,

the government implemented a series of enabling policy initiatives to support the program. In March 2001, for example, the Japanese cabinet adopted the Second Science and Technology Basic Plan, which identified the importance of fuel cell technology as essential for the country's energy security. Japan also implemented the New National Energy Strategy in 2006, the Next-Generation Automobile Fuel Initiative in 2007, and the Prime Minister's Initiative, namely, the Cool Earth—Innovative Energy Technology Plan, in 2008, all of which facilitated and expedited the fuel cell development program.

Table 10.2 Japan: Promotion Schemes and Schedules for Fuel Cell Development, circa 2000

Time period	Developmental stage and goals	Actions
2000–2005	Base Building and Technology Validation	• Creation and implementation of technology development strategy • Implementation of Millennium Project to build the system foundation (standards and standardization) • Validation testing (collection of data on operation characteristics, public education) • Establishment of fuel cell fuel quality and standard
2005–2010	Introduction to Market Goal: 50,000 fuel cell cars, 2.1 GW stationary power-generation units	• Step-by-step creation of fuel supply system in preparation for product introduction starting about 2003 • Initial product purchases by government and public organizations and fuel cell companies
2010–2020	Product Diffusion Goal: 5 million fuel cell cars, 10 GW stationary power generation units	• Establishment of fuel cell infrastructure, cost reduction, market expansion and development with no subsidy • Product distribution in the public sector

Source: “Heisei 17, Post Evaluation of Research and development Policy, Solid Polymer Fuel Cell/Hydrogen Energy Use Program,” METI, June 2006.

In due course, a framework for fuel cell technology development and collaboration emerged. It was broadly based and rests upon a three-legged framework consisting of government, academia, and industry (see Figure 10.2). The collaboration between academia and industry has been underway since 1995. Government and industry collaboration initially was established through the efforts of the Fuel Cell Commercialization Strategic Council in 1999 and the Fuel Cell Commercialization Conference of Japan (FCCJ) in 2001.

The government sector has included the Prime Minister and all relevant government ministries. METI has primary responsibility for administering fuel cell and hydrogen policies and programs. The METI administrative structure for fuel cell programs is also broadly based. METI policy bureaus were supported by the New Energy and Industrial Technology Development Organization (NEDO) program managers and the National Institute of Industrial Science and Technology (AIST) research infrastructure. Concurrently, fuel cell policy initiatives in most cases were supported by a cluster of ministries, including the Ministry of Education, Culture, Sports, Science and Technology (MEXT), and in other cases were directed by various Prime Ministers and the Prime Minister's Council for Science and Technology Policy (Behling, 2014).

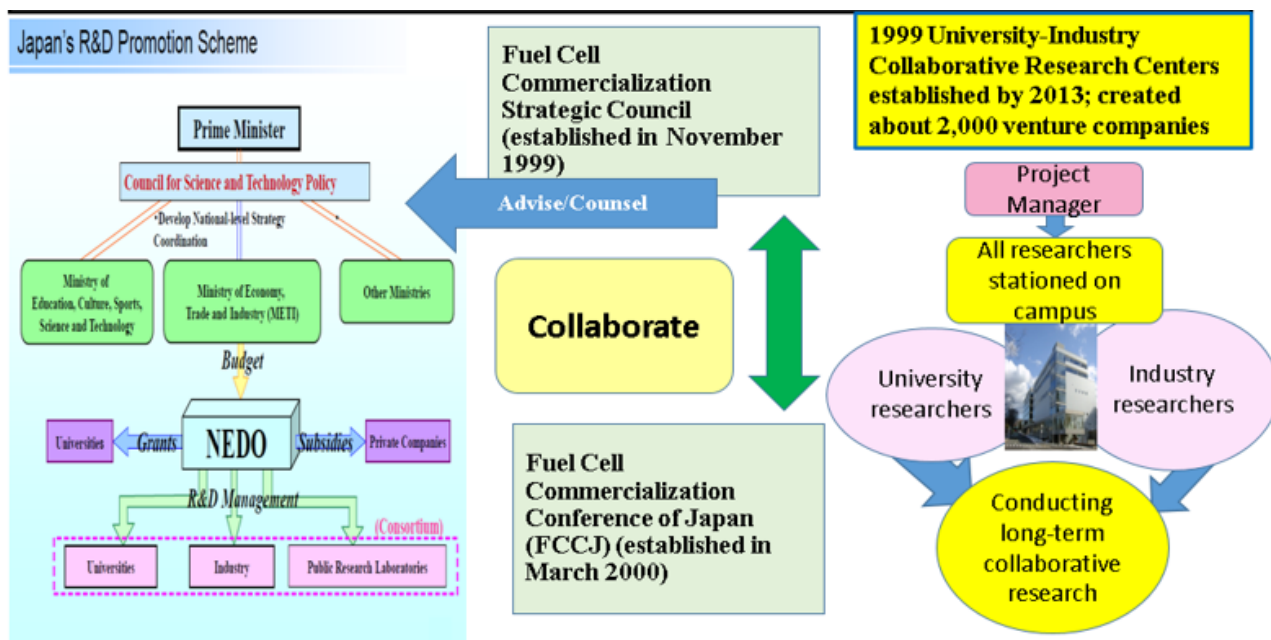


Figure 10.2 Japanese Trilateral Fuel Cell Development Framework

Note: Japan formed its fuel cell and hydrogen policy framework in 1999. The government policy program is supported by the Japanese Diet, the Prime Minister, government ministries, industry, and academia.

To support its fuel cell program and ensure vigorous fuel cell R&D activities, the government allocated a stable and continuous budget totaling \$4.6 billion for the 16-year period from 2000 to 2015. The budget peaked at \$352 million in 2005 and tapered down to \$175 million in an expectation of fuel cell commercialization in 2009. By 2012, however, the government realized there was need for a stepped-up R&D program to reduce fuel cell cost, improve efficiency, and increase durability. It also recognized the need for subsidies for products entering the marketplace. As a result, the budget was rapidly increased and reached an annual rate of almost \$400 million in 2014.

10.3 The Global Fuel Cell Race Heats Up

By the early 2000s, many major developed world governments felt the need to initiate or step up their fuel cell development programs, creating a global fuel cell race. In addition to Japan, the key contenders included the United States and the European Union and its member states.

United States. Since 1993, the United States has had a small fuel cell R&D budget under the Partnership for a New Generation of Vehicles. In 2002, it launched a FreedomCAR Initiative to develop FCVs, and in 2003, it began a Hydrogen Fuel Initiative to develop a hydrogen fuel supply infrastructure.⁹¹ To coordinate and manage the government and industry collaboration, a

⁹¹ In September 2001, Behling, N. wrote a research paper titled "The Global Fuel Cell Race: Can the United States Win?" that was published by CENTRA Technology, Inc. The paper was noticed by the Bush Administration and became

FreedomCAR and Fuel Partnership was formed by the Department of Energy (DOE), three US automakers (GM, Ford, and Chrysler), and several industrial gas manufacturers. The partnership was formed to promote fuel cell and hydrogen development activities (see Figure 10.3). To fund these initiatives, the US government fuel cell budget rapidly increased, reaching a peak of more than \$200 million in 2008. By 2011, however, the budget had declined to approximately \$100 million and stayed at that level in the following several years (see Figure 10.5). It has been reported in a 2010 review by the National Academies that executives of the automakers stopped attending the executive steering group meeting at some point and that the group had not met for two years, showing the total lack in the interest of stakeholders in the government fuel cell program (NAP, 2010).

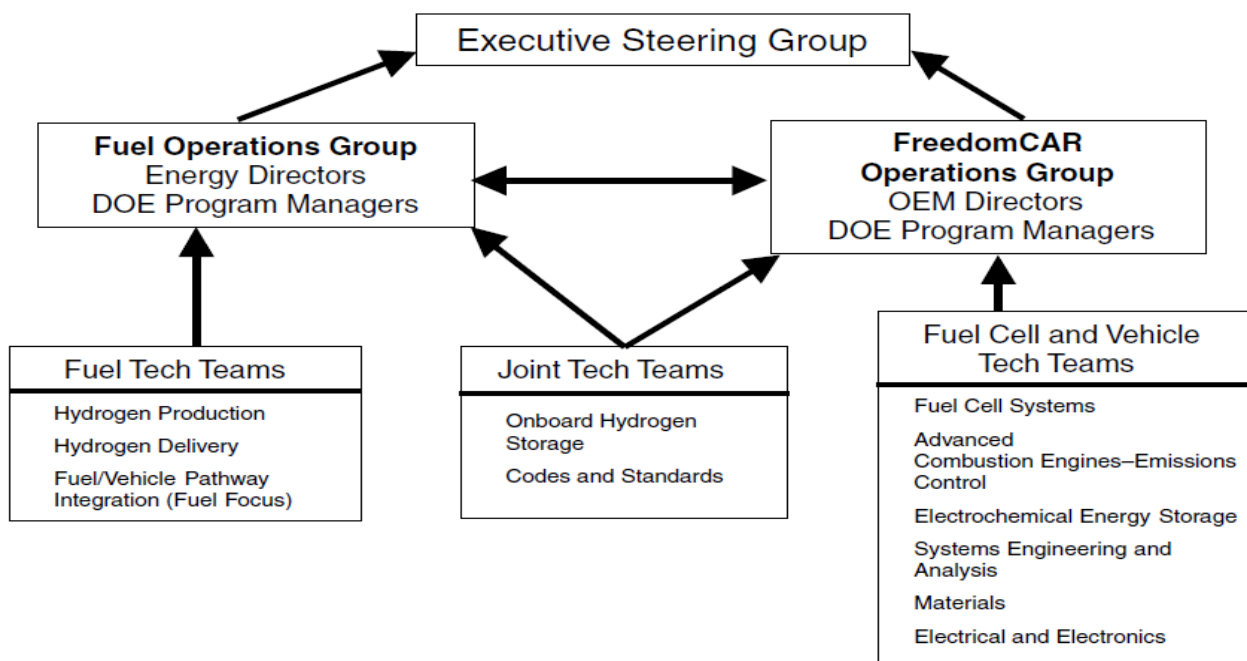


Figure 10.3 FreedomCAR and Fuel Partnership Organizational Structure

Note: OEM represents original equipment manufacturer.

Source: DOE, 2005

European Union (EU). In the early 1990s, the EU and its member states sponsored several fuel cell projects such as the Joule II Program as part of the EC's Third Framework Program (FP3) that ran from 1990 to 1994. The Joule II Program aimed to develop a small-to-medium-sized PEM FCV. The project was noteworthy for the substantial funding provided (\$4.8 million), particularly because it took place during the early years of this type of research.⁹² Approximately a dozen individual European governments, including France, Germany, Italy, and the UK, had various levels of interest in fuel cells and contributed a budget equal to EU FP funding. The total budget for fuel cells was \$64 million during the EU FP3. During FP4, from 1994 to 1998, Europe rapidly increased its fuel cell budget to a total of \$116 million. It was increased again to \$290 million

the basis for the establishment and implementation of the FreedomCAR Initiative in 2002. Behling also assisted in formulating the Hydrogen Fuel Initiative in 2003.

⁹² An exchange rate of \$1/€1 is used.

during FP5 (1998–2002), and to \$628 million for FP6 (2002–2006) (see also Figure 10.5). Despite these budget increases, a post-FP6 review in 2007 concluded that European fuel cell technology lagged the United States and Japan by at least five years (EU, 2007). To remedy this situation, the EU allocated a total of \$940 million for FP7 (2006–2013) and entrusted the management of the fuel cell R&D program to a public-private partnership called the Fuel Cells and Hydrogen Joint Undertaking (FCH JU), which consists of representatives of the European Commission (EC), fuel cell and hydrogen industries, and research communities (see Figure 10.4). The FCH JU structure closely resembled that of the US FreedomCAR and Fuel Partnership. Following FP7, the EU implemented the Horizon 2020 program (2014–2020), funding it at a level of \$1.33 billion. It continues to entrust its management to FCH JU (Behling, 2013).

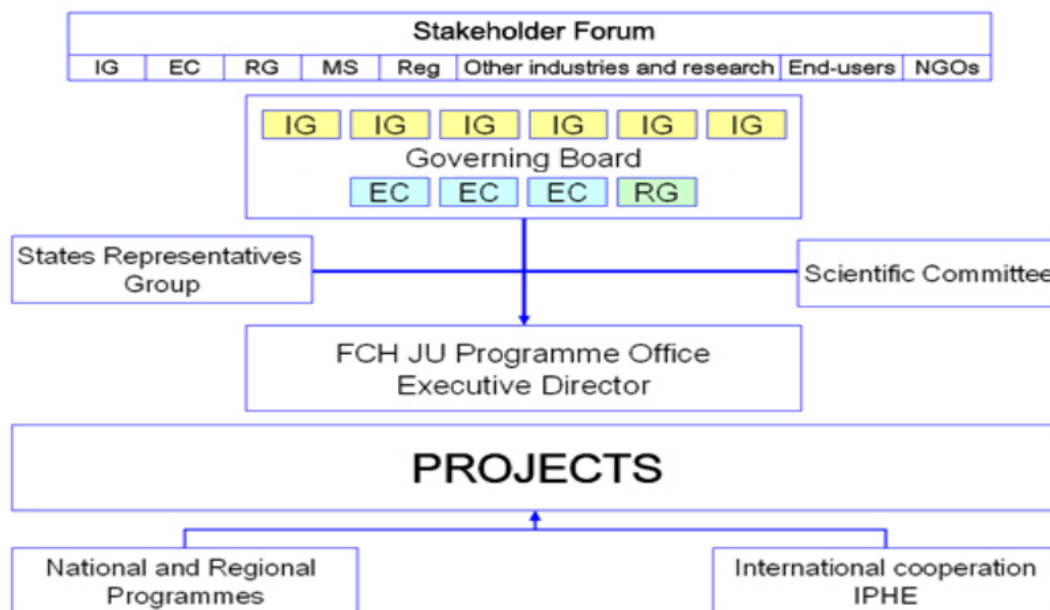


Figure 10.4 Fuel Cell and Hydrogen Joint Undertaking (FCH JU) Governing Board Structure

Source: FCH JU, <http://www.fch.europa.eu/page/governance>, accessed June 30, 2015.

Notes: IG refers to industry groupings (six seats); EC refers to the European Commission (three seats); and RG refers to research grouping (one seat). The Stakeholder Forum is open to all those with an interest in fuel cells and hydrogen technologies.

10.4 Comparative Budgetary and Patent Trends

Since the early 2000s, Japan, the United States, and the EU have together spent billions of dollars developing fuel cell technology. Japan spent a total of \$4.1 billion during the past 14-year period of 2002–2015.⁹³ The United States spent a total of \$1.9 billion during the same period, and Europe spent a similar amount. Overall, Japan has spent twice as much as the others.

⁹³ To make a comparison of the three government entities, we limited the timeframe to the 14-year period from 2002 to 2015 because the US FreedomCAR Initiative started in 2002.

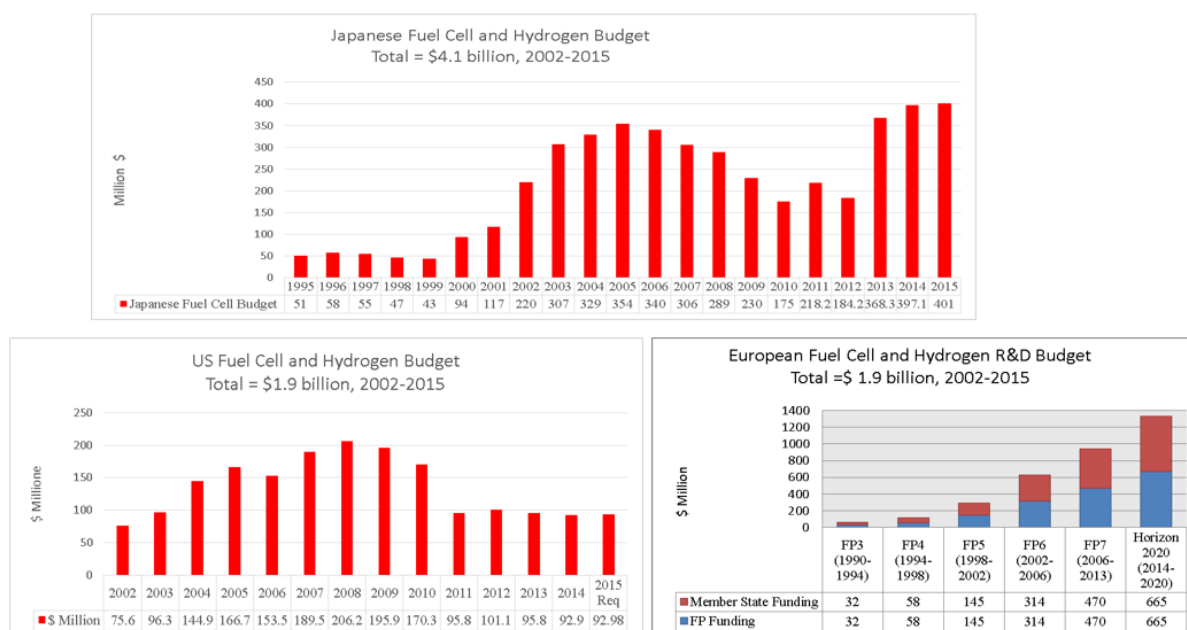


Figure 10.5 Fuel Cell and Hydrogen Budgets of Japan, US, and Europe, 2002–2015

Source: Created by the authors, 2015..

If we consider the domestic funding situation of individual countries, however, the total spending amounts look somewhat different. On the surface, the three government entities appeared to have similar R&D funding strategies, which typically meant that the government would fund half the project cost and participating corporations or research institutions would assume responsibility for funding the other half. The government budget is a critical factor for the success or failure of any R&D project, but the willingness of the private sector to cooperate with the government and invest larger amounts of its own capital can make a major difference in the project outcome. If we take this factor into consideration, the budget totals during 2003–2015 appear starkly different:

Japan. Japan traditionally places a high value on close collaboration among the government, industry, and academia. In addition, Japan’s industry consists mainly of major corporations with deep pockets that are willing to go beyond their co-share responsibilities. Indeed, it is acknowledged that Japanese automakers have spent a substantial amount of their own funds to develop fuel cell vehicle technology without government assistance. According to interviews and site visits conducted by one of the co-authors in the late 1990s, we assess that the Japanese corporations that participated in government projects invested at least twice as much as the government (Williams, 1996) and that the Japanese government and corporate cumulative combined fuel cell R&D spending during 2003–2015 likely amounted to \$12.3 billion, including government funding (\$4.1 billion), corporate cost-share (\$4.1 billion), and additional corporate R&D spending (\$4.1 billion).

EU. The EU is similar to Japan in some respects. The EU Framework Programs paid up to 50 percent of the cost of research but did not contribute to the payment of overhead or infrastructure construction, consigning a much greater financial burden to the private sector than in the United States. The European private sector—similar to the Japanese private sector—likely invested twice as much as the government. We estimate that Europe’s total combined government and private-sector spending for fuel cell and hydrogen R&D amounted to \$5.7 billion, including EC and

member state budgets (\$1.9 billion), participants' co-share (\$1.9 million), and their own out-of-pocket investment (\$1.9 million).

United States. The US private-sector participants in US projects for the most part are not in a strong financial position to invest more than a 50 percent cost share. We estimate that the US cumulative combined total government and corporate investment in fuel cell and hydrogen R&D from 2003 to 2015 was approximately \$3.8 billion, including government funding (\$1.9 billion) and corporate cost-share (\$1.9 billion).

Taking these different spending strategies into account, we estimate that the total R&D spending by government and industry was \$12.3 billion for Japan, \$3.8 billion for the United States, and \$5.7 billion for Europe. The Japanese total is twice as much as the European total and three times as much the US total. The Japanese total is more than half the grand total of the three government entities combined (see Figure 10.6).

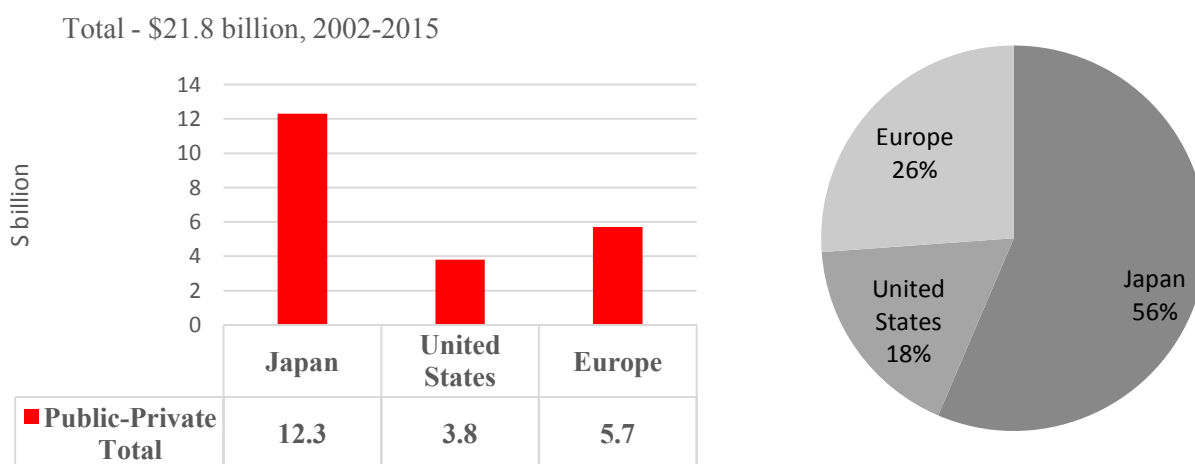


Figure 10.6 Estimated Combined Public and Private-Sector Fuel Cell R&D Investment, 2002–2015, by Japan, US, and Europe

Source: Created by the authors, 2015

In addition to budget size, the stability and consistency of the government policy affects the project outcome. Japan, the United States, and Europe each have unique characteristics and approaches to their fuel cell policy and program management. The Japanese government, regardless of which political party takes office or who the Prime Minister is, has consistently supported fuel cell technology development, in part because the laws stipulate that this technology should be a focus for development. The country is resource-poor, dependent on imported fossil fuels, and in need of energy security. Japan's government and public have long believed that fuel cell technology could promote the country's economic growth and strengthen its energy industry.

The US fuel cell policy and program, on the other hand, has lacked consistency because US fuel cell policy originated from a single Presidential initiative in 2002. It is neither the result of a broad national or government policy consensus nor a fully vetted strategy among the scientific community or energy industry. Because the policy is narrowly based, it tends to wax and wane, depending

upon the views and priorities of each Administration. The lack of a legislated mandate makes fuel cell policy and spending priorities hostage to changing interests. Moreover, fuel cell policy has been administered by a single government department (DOE) with limited support from other departments. If a President does not explicitly champion fuel cell development, support for the program evaporates. A department head may cut the program to make room for other initiatives that hold Presidential favor. Thus, the existence of the US government fuel cell program has been precarious. Indeed, in 2010, the DOE recommended cutting the PEM fuel cell technology program budget within the DOE's Office of Energy Efficiency and Renewable Energy by nearly \$70 million, more than 40% below the 2010 level. It also zeroed out the SOFC program within the DOE's Office of Fossil Fuels (AAAS, 2011). The Congress resisted these cuts and appropriated \$170 million for fuel cells within the DOE, saving the SOFC program, but the message to industry and academia was clear: fuel cell funding is in jeopardy.

The European fuel cell program has a different type of problem. First, many European governments have different interests in energy policies, including fuel cells. The fragmentation of their interest makes it difficult for the European Commission to create a uniform European-wide fuel cell program, which has prevented it from fulfilling its research and innovation potential, at a cost to European taxpayers (EC, 2008). The EC earlier recognized that the Framework Program (FP) for fuel cell R&D was lagging behind the US and Japan, and it made a revolutionary decision to dramatically increase the FP7 budget as well as entrust the management of the fuel cell program to a public-private partnership (the FCH JU) (Green Car Congress, 2007). A post-FP7 review of the fuel cell program has had little to say about the performance of the FCH JU. The FCH JU's first annual report was published in February 2015, which suggests that the decision making is difficult and that the administrative structure is too costly (FCH JU, 2015). Despite the best of intentions to improve the program, contracting out government oversight of this important program is a misjudgment

While it is not free of shortfalls, Japan has managed to succeed in fuel cell program management and technology development and has established itself as the global fuel cell leader today. One key indicator of success is the number of fuel cell patent applications and the number of patents assigned. According to a 2012 Japan Patent Office report,⁹⁴ the total number of fuel cell patents filed globally between 2005 and 2009 totaled 42,019, of which 58 percent were filed by Japan, then Korea (12 percent), the US (also 12), and the EU (11 percent) (see Figure 10.7) (JPO, 2012).

⁹⁴ Japan Patent Office (JPO), 2012. "Analysis by Japan Patent Office," April 2012, based on data from the Derwent World Patents Index.

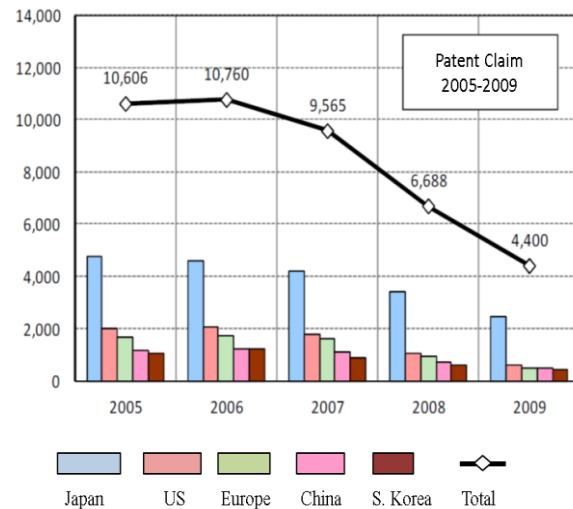
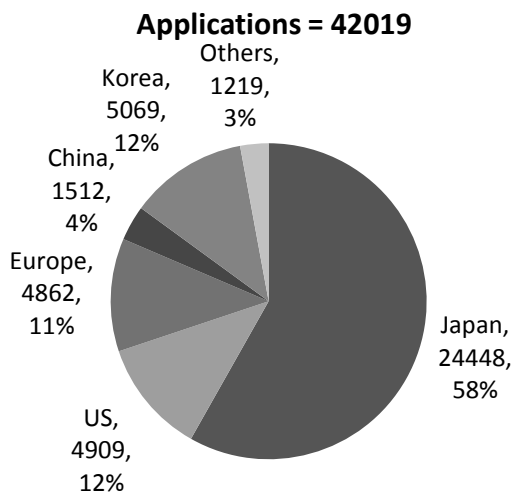


Figure 10.7 Number of Fuel Cell Patent Applications (by Country and Region), 2005–2009 Source: Analysis by Japan Patent Office, April 2012, based on data from Derwent World patent Index. Translation provided by the authors

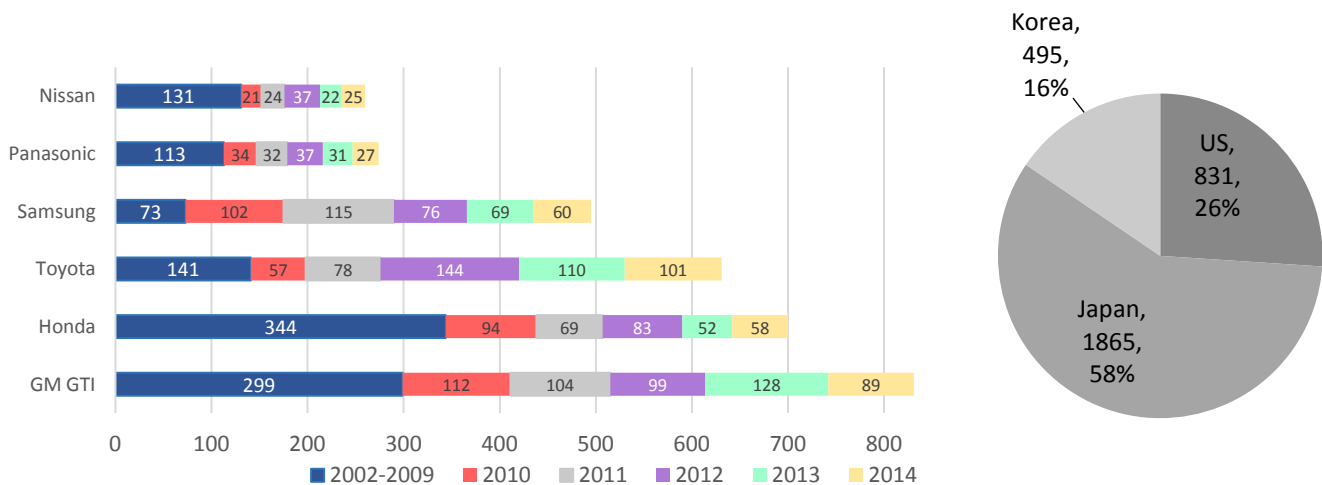


Figure 10.8 Top Six Global Fuel Cell Patent Assignees, 2002–2014 Source: Created by the authors based on the data by the Clean Energy Patent Growth Index (CEPGI), April 2015.

According to a patent review conducted in 2015 by the Clean Energy Patent Growth Index (see Figure 10.8) (CEPGI, 2015), General Motors was the world's top fuel cell patent assignee and obtained a total of 831 fuel cell patents during the period from 2002 to 2014. The same report showed that of the world's top six patent assignees, four were Japanese corporations, namely, Honda (700 patents), Toyota (631), Panasonic (274), and Nissan (260). Taken together, these four companies obtained a total of 1,865 fuel cell patents. Samsung of South Korea also ranked among the top six and obtained 495 patents. Japan is credited with 58 percent of the 3,191 patents granted to the top six assignees during the same period.

10.5 Taking a New Path to Revolutionize Energy Resources

The nuclear accident at Fukushima had profound near-term and long-term implications for Japan's energy strategy. The total closure of the nuclear power generation system for two years had serious economic, environmental, and societal consequences. First, to make up for the loss of nuclear power, the use of thermal power generation increased, leading to a dramatic increase in fossil fuel imports at heavy economic cost. In FY2011, fossil fuel imports jumped 15 percent over FY2010. By FY2013, imports had increased over 40 percent compared to FY2010 (see Figure 10.9), resulting in Japan's first trade deficit in more than 30 years. As the nation's wealth flowed overseas, Japan's current account balance fell to \$32 billion, threatening the national economy.

Concurrently, Japan's energy security became more precarious as oil prices fluctuated due to the political instability surrounding oil exporting nations and increasing energy demands from competing economies. Furthermore, Japan's energy self-sufficiency—the share of power generation derived from domestic resources of the nation's total power generation—declined to a level of just six percent, putting Japan at second from the bottom among the 34 OECD countries (see Figure 10.10).

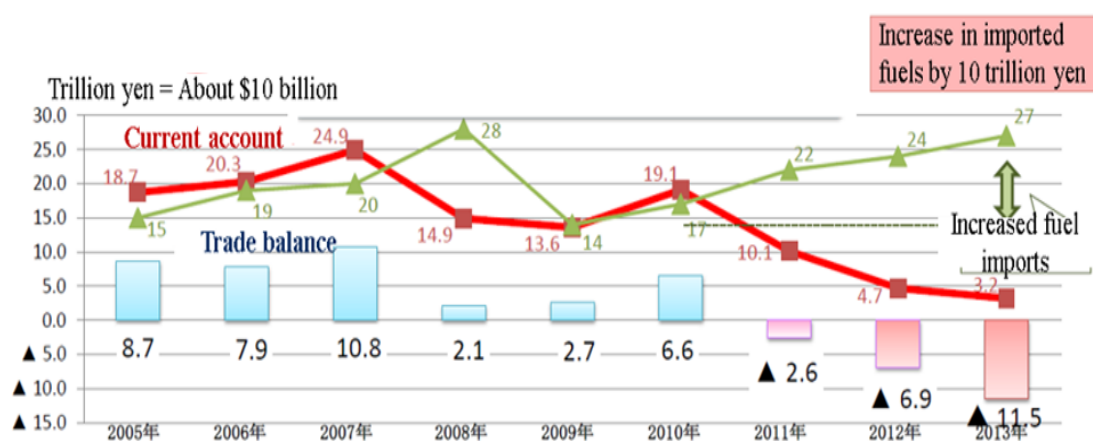


Figure 10.9 Dependency on Fossil Fuels and Its Impact on Japan's Economy Source: Ministry of Economy, Trade, and Industry (METI) and Ministry of Finance (MOF), Japan, June 2014; Modification and translation provided by the authors.

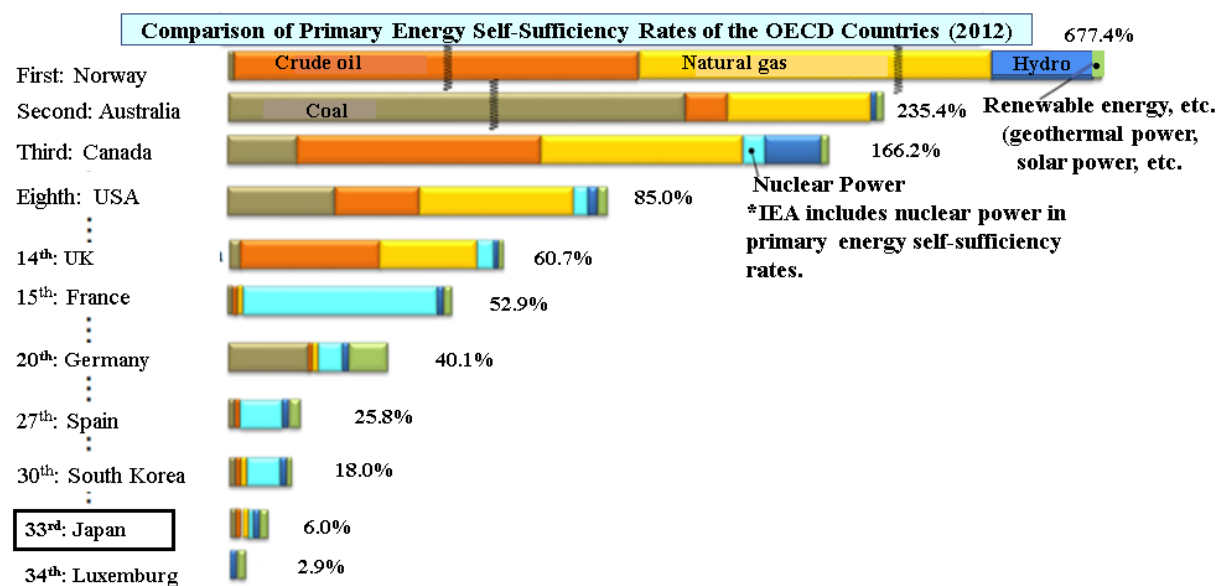


Figure 10.10 Primary Energy Self-Sufficiency Rate of the OECD Countries (2012)
Source: Created based on METI, 2014, and “Energy Balance of OECD Countries 2013,” IEA,
<https://www.iea.org/publications/freepublications/publication/WEO2014.pdf>.

Under these bleak circumstances, Japan’s policymakers conducted an all-out, zero-base energy policy review and concluded that there was no choice but to undertake a policy of transforming Japan into a Hydrogen Society. Fuel cell development became part of the new policy. It was seen that such a policy would not only promote sustainable economic growth and energy security, but would also foster a clean environment. The announcement of the decision to implement the policy was made in April 2014, based on an assessment of four factors: Japan’s economic security, energy security, energy self-sufficiency, and environmental health. It was recognized that some situational changes, such as a fall in the price of oil, might modulate Japan’s economic situation in the short term, but that alone would not lead to improvements in the other three factors. However, industrial and political pressures have recently appeared to have affected policymakers’ priorities and altered policy goals (Slater-Thompson, N., 2015). The Japanese government now calls for nuclear energy’s share of total electric power generation to be 20 to 22 percent and the share of renewable energy production to be 22 to 24 percent by 2030 (NAP, 2015). This nevertheless is a dramatic departure from Japan’s pre-3.11 energy policy.

10.6 Establishing a Council for a Strategy for Hydrogen and Fuel Cells (CSHFC)

In the run-up to the policy announcement, in December 2013 METI established a Council for a Strategy for Hydrogen and Fuel Cells (CSHFC) to advise the director of METI’s Agency of Natural Resources and Energy (ANRE) on the formulation of a Hydrogen Society policy. The council was the successor to the 1999 Fuel Cell Commercialization Strategic Council, whose guidance and advice had helped Japan become a global leader in fuel cell systems. The new council consisted of equal numbers of distinguished academicians, prominent industry leaders, and notable public-sector representatives drawn from government, industry, and academia. With the council’s establishment, the administrative structure for management and oversight of the Hydrogen Society policy was fully formed.

Japan's implementation of the Hydrogen Society policy has been swift. The policy to transition to a Hydrogen Society was made less than four months after the establishment of the new hydrogen advisory council. Japan's Cabinet also approved the Hydrogen Society policy in April 2014 in its Strategic Energy Plan. The Plan recommended that the government formulate a roadmap that would chart a path toward a Hydrogen Society. The CSHFC unveiled the roadmap, named "The Strategic Road Map for Hydrogen and Fuel Cells" on June 23, 2014 (see Figure 10.11). The roadmap has since been updated and is now named a "Scenario for Basic Hydrogen Strategy." The basic structure of the plan appears intact, consisting of three phases.

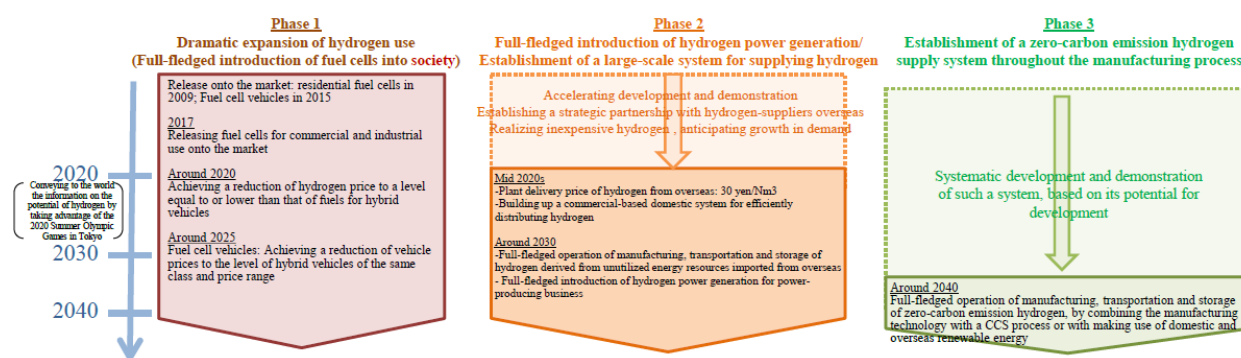


Figure 10.11 Japan's Strategic Roadmap for Hydrogen and Fuel Cells

Source: "The Strategic Road Map for Hydrogen and Fuel Cells," ANRE, June 23, 2014.

Phase 1 of the roadmap aims at expanding the use of fuel cells and hydrogen and includes rapid market expansion of small residential cogeneration systems, namely, Ene-Farm, that have been installed in individual homes since 2009. Cumulative sales surpassed 120,000 units as of the end of FY2014 (March 2015) (ACEUCJ, 2015). Japan expects to install 1.4 million residential fuel cell units by 2020 and 5.3 million by 2030 (see Figure 10.12). Japan also aims at introducing larger-output 5 kW solid oxide fuel cell (SOFC) cogeneration units for business/industry use, which are currently in a demonstration stage. In addition, Japan has started marketing fuel cell vehicles (FCVs) in 2015 and started the construction of the first of some 100 hydrogen refueling stations (HRSs) in four major metropolitan regions, to be completed by the end of FY2015 (March 2016) (see Figure 10.13). Japan also hopes to market Ene-Farm and FCV overseas.

Currently, however, none of the fuel cell products or the hydrogen refueling stations are cost-competitive without subsidies. Ene-Farm subsidies were expected to end in 2016, at which time manufacturers hoped to lower costs below \$7,000-\$8,000, which they viewed as cost-competitive (see also figure 12). Subsidies are still continuing, however. Toyota's FCV "Mirai" is priced at \$70,000, and central and local governments' subsidies would lower the price to less than \$50,000.

Hydrogen refueling stations in Japan are also two to three times as costly as their foreign counterparts. The Japanese government has regulations on the types of materials to be used for storage devices and the design specifications for equipment to be used at hydrogen refueling stations. These regulations are far more stringent than those of foreign counterparts. Current devices and equipment are made with Japan's latest technology and are thus highly costly because they are new and not yet mass-produced. The government hopes to lower the cost through

deregulation, mass production, and system simplification (see Figure 10.14). In addition, there are plans to advance PEMFC and SOFC and hydrogen technologies through basic research conducted at Japan's Fuel Cell and Hydrogen Centers of Excellence under a government R&D program (see Figure 10.15) (NEDO, 2014).

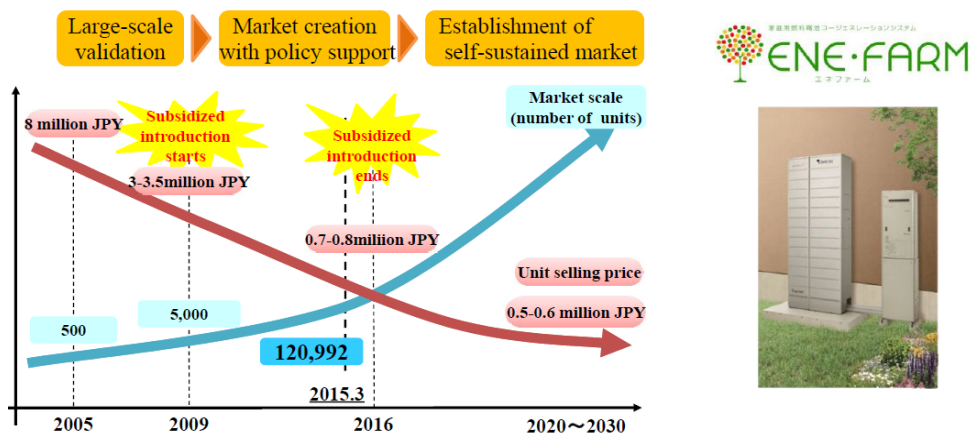


Figure 10.12 Plans for Ene-Farm Residential Fuel Cells

Note: Units installed: 120,992 as of March 2015; expect 1.4M by 2020, 5.3M by 2030.

Source: New Energy and Industrial Technology Development Organization (NEDO, 2015)

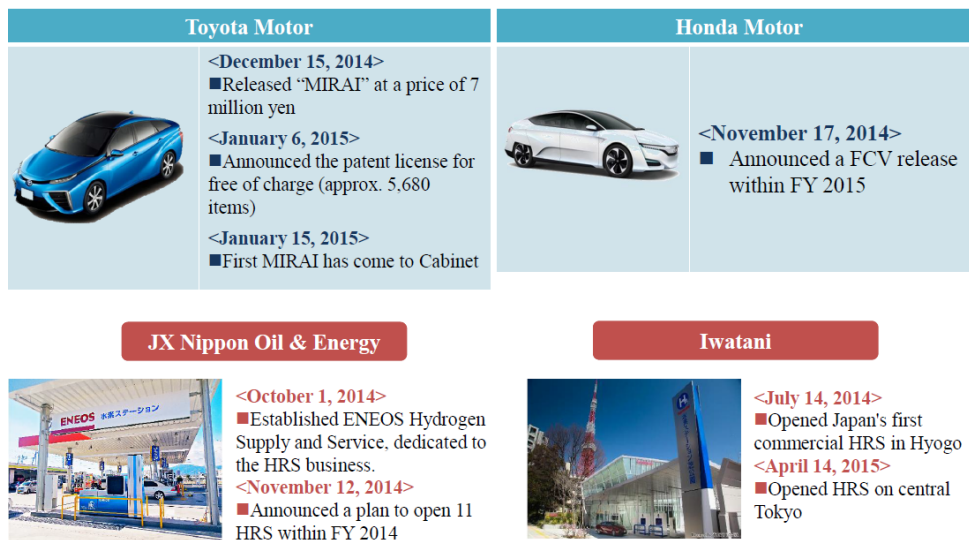


Figure 10.13 Recent Trends in FCV and HRS

Source: NEDO, 2015.

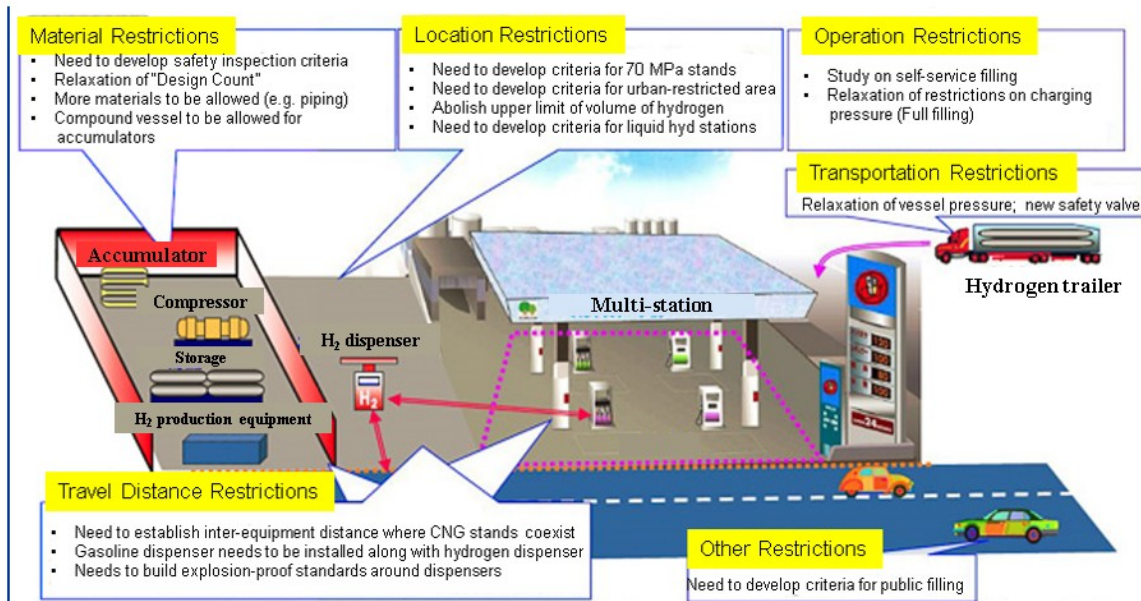


Figure 10.14 Government Regulations under Review for Streamlining
Source: METI, 2015.

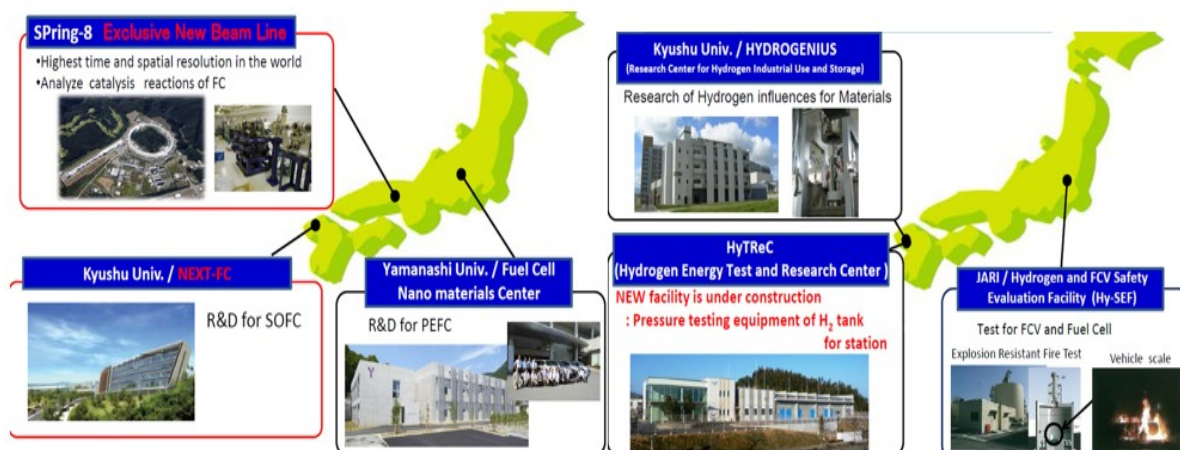


Figure 10.15 Fuel Cell and Hydrogen R&D Activities
Source: Created by the authors based on NEDO data, 23 May 2013

Phase 2 aims to establish hydrogen production, storage, and transport capabilities by the 2020s using overseas unutilized energy. To achieve this goal, Japan plans to tap abundant petroleum gas and brown coal reserves that are available overseas but not exploited and other low-cost renewable energy sources to produce hydrogen on-site. It will employ carbon capture and storage (CCS) technology and transport hydrogen to Japan as chemical hydride or liquid hydrogen. Two such demonstration efforts are under way, one by Kawasaki Heavy Industries using liquid hydrogen (see Figure 10.16) and another by Chiyoda Corporation using a chemical hydride nicknamed SPERA hydrogen (see also figure 16).⁹⁵ Japan plans to use these hydrogen sources to promote hydrogen

⁹⁵ SPERA hydrogen is an organic chemical hydride, methylcyclohexane (MCH). MCH can be stored and transported in liquid form under ambient temperature and pressure with no loss. MCH offers superior storage density and stability, and permits use of the existing oil and natural gas transportation and storage infrastructure. (Source: Chiyoda Press

power generation, which will ultimately lower hydrogen costs and accelerate the adoption of FCVs and other hydrogen technologies.

Phase 3 aims to advance hydrogen production technologies and establish a completely CO₂-free, low-cost, safe, and stable hydrogen supply infrastructure (Shinka, 2014). To achieve this, Japan would work to further reduce the cost and increase the efficiency of CCS technology, thereby enabling CO₂-free hydrogen supply chains from overseas as well as CO₂-free hydrogen power generation and manufacturing systems in Japan. As part of this effort, Japan is to develop hydrogen production technologies from renewable energy sources, including water electrolysis, photocatalysts, and high-temperature test nuclear reactors (HTTRs).⁹⁶ In addition, Japan will pursue research on ammonia as a hydrogen energy carrier, including producing ammonia from renewables, the separation and generation of hydrogen from ammonia, the use of ammonia in fuel cells, and direct ammonia burning for power generation. Japan hopes these R&D initiatives will establish a completely CO₂-free hydrogen supply infrastructure by 2040.

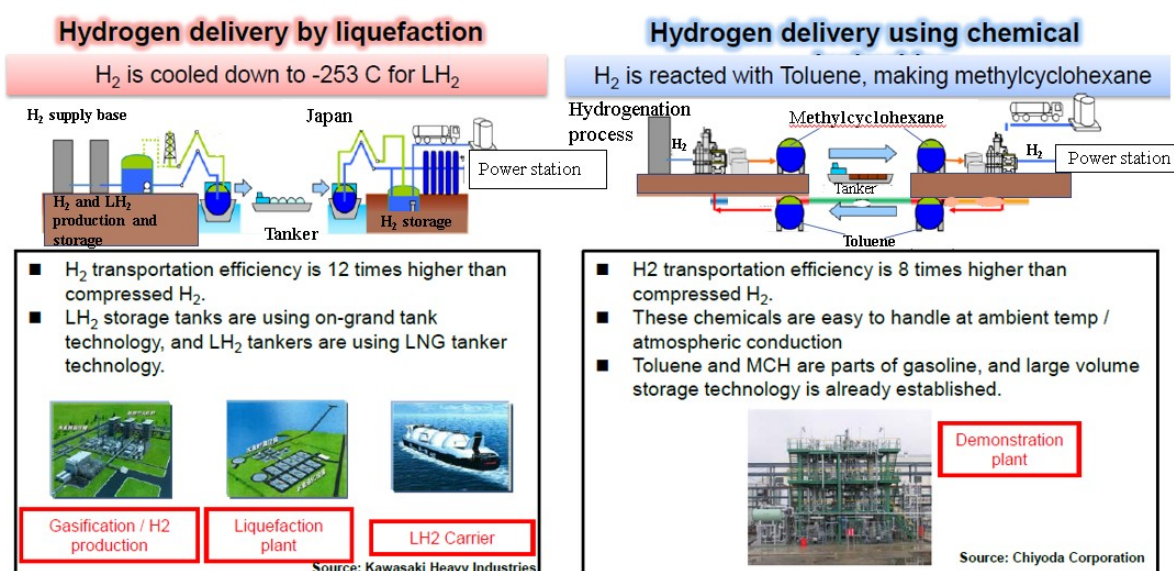


Figure 10.16 Hydrogen Production, Transport, Storage Supply Chain Concepts
Source: METI, 20 November 2013.

10.7 Challenges Ahead

Undoubtedly, Japan will not have a Hydrogen Society for many years. Today, for example, few of the necessary components of a Hydrogen Society are fully mature and functional. Japan's hydrogen production technologies from renewable sources and water are in a developmental stage; hydrogen-use technologies, including fuel cell stationary systems and FCVs, are at an early

Release, October 24, 2014.) Chiyoda was awarded a Jules Verne Award for this effort at the 20th World Hydrogen Energy Conference (WHEC2014) from the International Association of Hydrogen Energy (IAHE) on June 18, 2014.

⁹⁶ The HTTR is a graphite-moderated gas-cooled research reactor in Oarai, Japan, operated by the Japan Atomic Energy Agency. It uses long hexagonal fuel assemblies, unlike the competing pebble bed reactor designs. HTTR first reached full design power of 30 MW (thermal) in 1999. Other tests show the core can reach temperatures sufficient for hydrogen production. (Source: "HTTR," Wikipedia, modified November 24, 2014).

commercialization stage; hydrogen power generation technology is nonexistent, hydrogen storage, transportation, and supply chains have yet to be established, and no hydrogen supply infrastructure has been established. For these reasons, Japan faces major challenges in developing technologies and establishing the necessary infrastructure to create a Hydrogen Society.

Perhaps the greatest of the challenges facing Japan is to increase R&D involving hydrogen-use technology, especially for PEM and Solid Oxide fuel cells. Hydrogen-use technology is a fundamental component of a Hydrogen Society, and without it, there will be no use for hydrogen, hydrogen production systems, a hydrogen supply infrastructure, or a Hydrogen Society. Japan has funded PEMFC and SOFC R&D for a long time, but these systems still suffer from high cost, inefficiency and insufficient durability, although these problems are less serious as a result of technology development (Behling, 2013). While some products, such as Ene-Farm residential cogeneration units and FCVs, have been able to enter the commercial market, these systems are still very costly and require subsidies for market survival. More research is needed to solve these problems.

In FY2015, for example, Japan allocated approximately \$400 million to fuel cells—the largest fuel cell and hydrogen budget ever (see Figure 10.17). The bulk of the funding, however, was allocated to subsidies and demonstration projects, with only \$45 million (or about 10 percent) set aside for fuel cell R&D. This may not be enough. Japan needs dramatic innovations and breakthroughs to eliminate the remaining fuel cell challenges and firmly establish hydrogen-use technology for a future Hydrogen Society. Expanding R&D activities would also encourage new generations of scientists and engineers to enter the field. As Sasaki suggests, Japan must foster young engineers as part of the country's growth strategy (Sasaki, 2015). These researchers would enable more rapid development of hydrogen production, storage, and transport technologies and thereby help eliminate the need for subsidies for hydrogen technologies and products in the future.

	Major Programs	\$ Million
Line Items	Hydrogen Use Technology R&D	45
	Hydrogen Supply Chain Demonstration Project	38
Subsidies	Ene-Farm Subsidies	150
	Subsidies for Fuel Cell Vehicles in the Clean Energy Automobile Subsidies	About 58
	Hydrogen Supply Infrastructure Subsidies	110
Total		\$401 million

Figure 10.17 Japanese Fuel Cell and Hydrogen Budget Items, 2015

Sources: Created by the authors, 2015.

Another challenge for Japan is the need to build the optimal energy infrastructure for a Hydrogen Society. This would, first and foremost, require substantial renewable energy sources to generate hydrogen. Renewable energy generates no CO₂ emissions, or at least is carbon neutral, and greater use of renewable energy would reduce fossil energy use and lower CO₂ emissions. Today, 10 percent of Japan's energy production comes from renewable sources, but a number of studies indicates that the share of energy from renewables could greatly increase in the world in the future vis-à-vis non-renewables (see Figure 10.18).

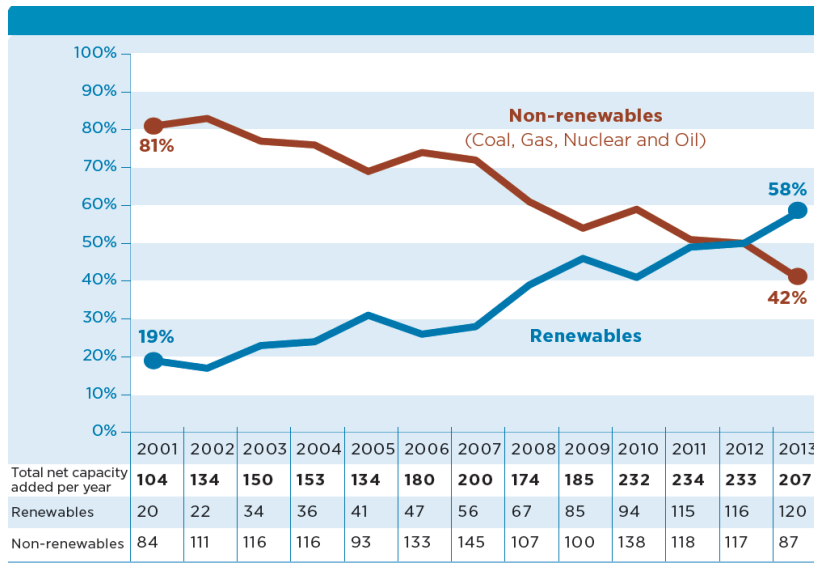


Figure 10.18 Renewables as a share of global capacity additions (2001–2013)
Source: IRENA Database, 2015.

One of METI’s advisory committees recently proposed that the share of renewable energy production in Japan should be 22 to 24 percent by 2030 (WNN, 2015). Another study commissioned by the Ministry of Environment suggested that Japan has great potential for development of renewable energy sources, which could account for a third of energy production in 2030 (Iwata, M., Hoening, H., 2015; JFS, 2015). According to Forbes magazine, Japan has nine times Germany’s renewable energy resources, and yet Japan produces approximately nine times less of its electricity from renewables (excluding hydropower) than Germany produces (Lovins, A., 2014). It is well known that Japan sees itself as having few resources, but Japan is as rich in renewable energy resources as many other countries.

It is also worth noting that renewable energy encourages advancements in economic, social, and environmental goals. For example, a recent Japanese study, which was quoted in a 2015 IRENA review that examined a 2030 target of 14 to 16 percent for renewables, found that the benefits were two to three times higher than the costs—including savings in fossil fuel imports, CO₂ emission reductions, and economic ripple effects (IRENA, 2015). Renewable energy production also creates jobs and employment. According to a 2015 IRENA review, renewable energy employed an estimated 7.7 million people in the world in 2014 (excluding large hydropower), an 18 percent increase from 2013 (IRENA, 2015; IRENA, 2014).

10.8 The Impact of the Hydrogen Society Policy on Japan’s Economy

Given the large investments in hydrogen technologies, Japan would likely expect to see benefits in terms of reduced hydrogen technology costs and growth in the economy.

The forecast in NEDO’s Hydrogen White Paper indicates that the Japanese market for hydrogen and fuel cells will be approximately \$10 billion in 2030 and approximately \$80 billion in 2050 (see Figure 10.19), a major return on investment.

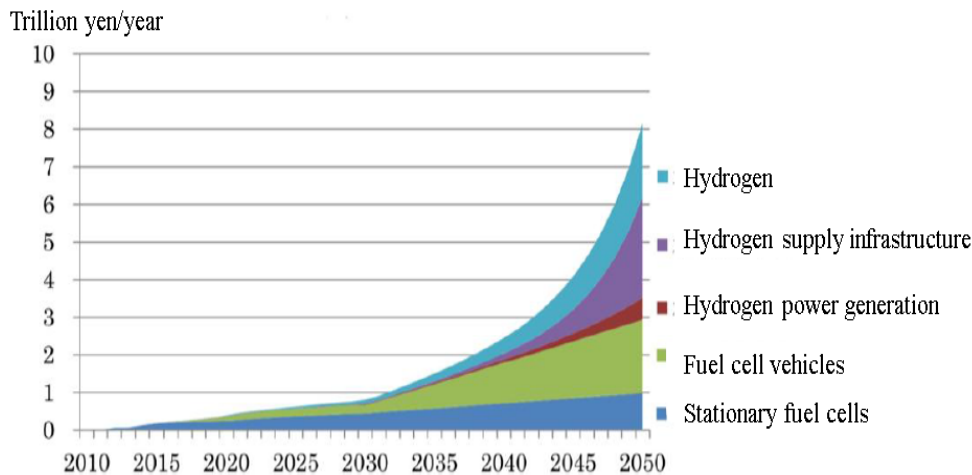


Figure 10.19 Forecast of Japanese Hydrogen and Fuel Cell Market in Japan

Note: the value of the Y axis is in trillion yen, which equates to \$10 billion.

Source: NEDO, 30 July 2014

Multiplier effects will also be important if the Hydrogen Society policy is to be successful. Because the policy is both large-scale and long-term, it is essential that a Hydrogen Society be fully integrated with Japan's concept of a "smart community." A smart community uses digital technologies and information and communication technologies to enhance the quality and performance of community services while reducing costs and resource consumption. The idea originated in Europe, prompted by major technological, economic, and environmental changes (Komninos, 2012). In the aftermath of the 3.11 earthquake and tsunami, Japan recognized the need to address economic hardship in many villages and cities in rural areas and began implementing a smart community initiative to provide assistance to these areas.

In 2011, Japan started to subsidize the creation of a smart community in four villages and cities. At present, it sponsors seven smart communities, including those in Yokohama City, Toyota City, Keihanna Science City, and Kitakyushu City (Morozumi, 2014). In Japan's vision of a smart community, each city will function as a self-governing energy system that will have sustainable economic growth, energy security, and environmental well-being. In each community, all homes, commercial buildings, factories, and open spaces will have power generation facilities that make full use of wind power, solar power, fuel cells, hydrogen, and other renewable energy power generation. Each community has a central control center that regulates and balances the community's energy supply and demand throughout the day to conserve and optimize energy. The community is equipped with advanced IT networks, accumulators, and batteries to administer energy management in an area-wide manner (Tobe, 2013).

The success of each policy will clearly depend upon the success of the other. By combining these two policy initiatives—the Hydrogen Society and the smart community—the chances of success will increase. The success of the Hydrogen Society policy, in particular, will depend upon how well specific hydrogen initiatives can meet the energy and transport needs of a smart community. While the Hydrogen Society roadmap does not yet reflect milestones for applying hydrogen-fueled

systems to a smart community, there are some hints that Japan’s policymakers are thinking along these lines.

Japan examined its own future growth potential in five strategic industry areas and published its conclusions in “Industrial Structure Vision 2010” (METI, 2010). A key area included the environment and energy, which encompassed smart communities, next generation automobiles, and renewable energy sources. The study concluded that with the proper incentives, Japan’s energy industry could grow from the current ¥30 trillion (\$300 billion) to ¥86 trillion (\$860 billion) in 2020, and the Japanese automobile industry could grow from ¥123 trillion (\$12.3 trillion) to ¥151 trillion (\$15.1 trillion) (see Figure 10.20).

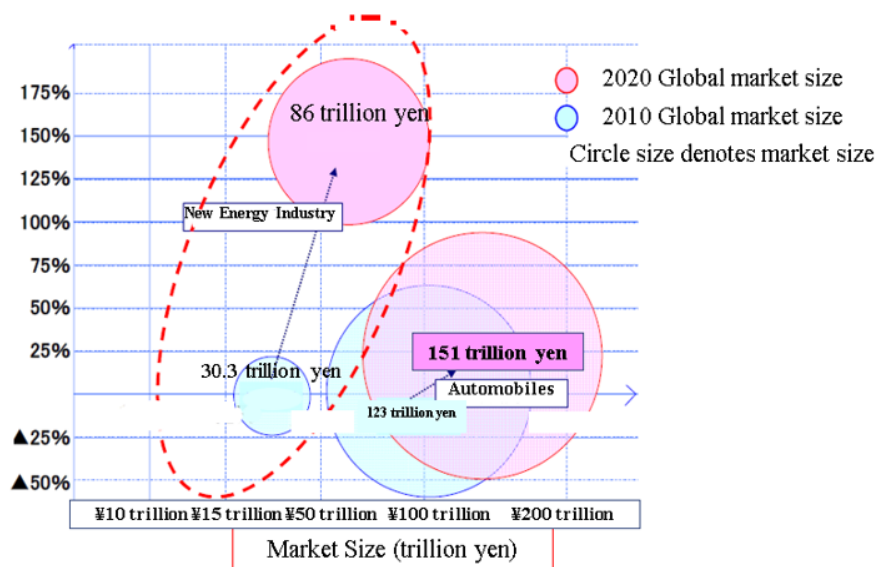


Figure 10.20 New Energy and Next Generation Automobile Market Potential, 2010–2020
Source: ANRE, METI, November 2011; translated by the authors.

Integrating the Hydrogen Society and smart communities (see Figure 10.21) will undoubtedly lead to a wide range of competitive products for the marketplace that would provide Japan with an opportunity for strong economic growth. Products derived from these policy initiatives could combine goods and services, including fuel cells, accumulators, and batteries; solar, wind, and hydrogen generators; IT networks, software, distribution lines, and infrastructure construction; maintenance, service, and education. Such an integrated product mix can only be produced by a country that has wide-ranging fuel cell and hydrogen-related intellectual property, a strong commitment to a clean environment (as proven by Japan’s world-highest ISO14001 certification) (Managi, 2010), advanced technologies, expert manufacturing skills, information technology and software capabilities, and a highly capable service and maintenance infrastructure.

Japan’s industry has deep “bench strength” in all the above areas. Its government has put policies and funding in place to promote a Hydrogen Society. Moreover, there is an emerging political consensus that Japan should move away from nuclear power and aggressively pursue a Hydrogen Society that is efficient, fully integrated to meet daily needs, and good for the environment. To strengthen this strategy, Japan should place special focus on expanded R&D in key energy areas, such as energy conversion and storage technology, and explicitly integrate the Hydrogen Society

policy with the establishment of smart communities. Making these policy changes would go a long way toward convincing the rest of the world to buy into a new hydrogen economy. If Japan's government and industry can successfully achieve global acceptance of hydrogen as a foundational energy source, Japan's own economy will be revitalized, and the country will be able to successfully transition to a Hydrogen Society.

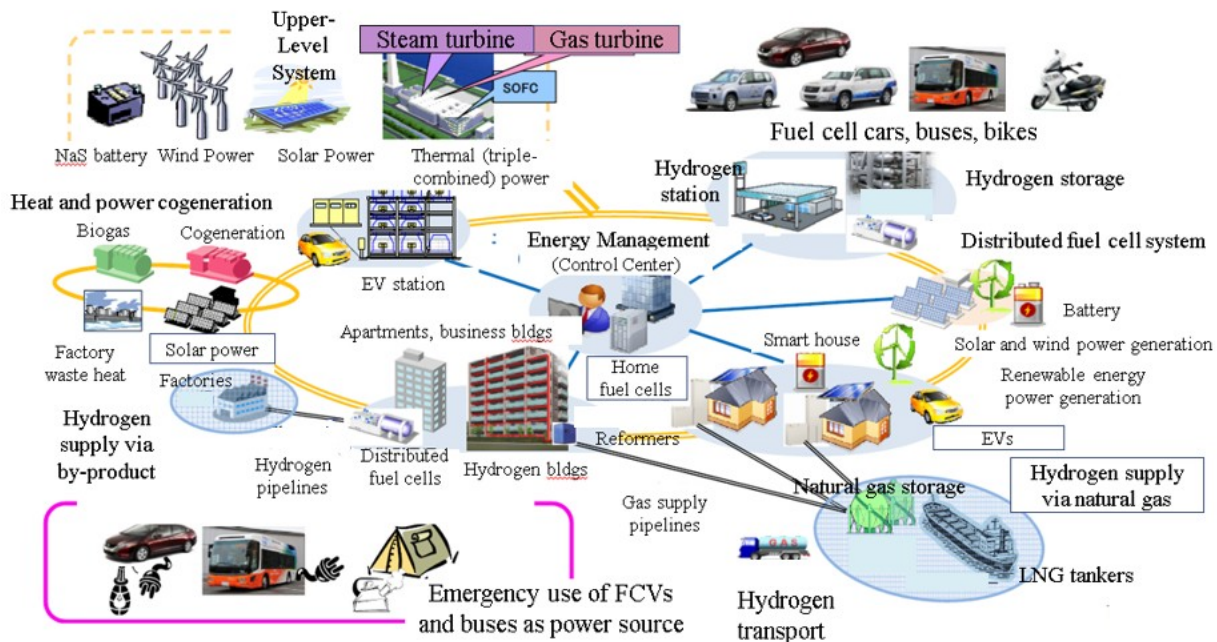


Figure 10.21 Image of Smart Community in a Hydrogen Society Source: Chihiro Tobe, ANRE, METI, 18 September 2013. Translated by the authors.

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Chapter 11:

Conclusions

CHAPTER 11: Conclusions

Abstract

If Japan wishes to increase the share of renewable energy as a way to reduce dependency on the existing nuclear infrastructure, the country must first reach a consensus on the future of nuclear energy. Safety is a dominant concern, as is how to store radioactive waste and the cost of decommissioning older reactors. Developing hydrogen and fuel cell technology is a potential alternative to nuclear energy, but the technologies pose a number of challenges. Nonetheless, integrating hydrogen as power sources into Japan's energy mix is critical to laying the foundation for future renewable energy sources.

11.0 Nuclear Energy and Hydrogen Alternatives

From the beginning of this dissertation effort to research the status of Japan's nuclear power industry, it was clear that the prevention of future accidents would require development of solutions to a set of engineering and technical issues—how high to build a sea wall, determining the risk of geologic hazards, or identifying improvements in worker training, for example. If risk and uncertainty in the future were properly understood in every circumstance, it would be possible to avoid these accidents in the future. But going deeper, it became clear that the nuclear industry faced fundamental problems with respect to safety and that solutions could be very far off. For this reason, this dissertation also required looking at the feasibility of hydrogen as an alternative energy source and what might be required for this energy source to supplement or even replace nuclear energy. The conclusions with respect to these two energy alternatives are summarized here.

11.1 The Nuclear Energy Alternative

Based on a review of the accidents and incidents that have occurred with respect to nuclear energy, the human dimension appears to be the common thread that runs through all events and represents the most important factor that needs to be addressed, no matter where it occurred in the nuclear fuel cycle. As Professor Kurokawa said of the Fukushima disaster:

- *What must be admitted—very painfully—is that this was a disaster “Made in Japan.” Its fundamental causes are to be found in the ingrained conventions of Japanese culture: our reflexive obedience; our reluctance to question authority; our devotion to ‘sticking with the program’; our groupism; and our insularity”*

Culture can be an enormous benefit to a people, enabling them to achieve both economic and social prominence. This has been the case with Japan. But culture can also be a hindrance in solving complex multi-faceted problems, such as those that pertain to maintaining safe and reliable nuclear power. Here, safety fundamentally depends on finding the right balance between technical safety measures and the role of human relationships in managing safety practices. Excellence in engineering and science are examples of Japan's technical virtuosity. No problem associated with nuclear power can be solved without the skill and expertise that resides in Japan's nuclear industry. But there are no silver bullets when it comes to addressing the cultural limitations that have contributed to an accident or made the accident worse than it should have been.

Having an historical perspective is equally important. Knowing “how we got here” often provides clues to solving complex technical/cultural trades. Japan’s energy strategy, for example, has its roots in energy choices made decades ago, which were driven by fear that the country might become hostage to foreign energy suppliers. At the time of the first oil shock in 1973, approximately 80 percent of Japan’s total electric power was derived from fossil fuel-based thermal power imported from abroad. Concerns over the vulnerability (and high cost) of foreign oil and gas supplies spurred Japan to consider other energy sources. Hydrogen production technology, fuel cells, and other renewables were at the time immature and very costly. Nuclear power generation technology, on the other hand, already had a successful track record, and was viewed as “semi-domestic” due to the modest cost of uranium. By 2012, Japan had succeeded in increasing the share of total power generated by nuclear power plants to nearly 30 percent. Plans were in place to increase it to 50 percent by 2030 (WNA, 2015).

Until the Fukushima disaster, the plan for nuclear energy seemed reasonable. Nuclear power had served Japan well. The historical record shows that it enabled Japan to diversify its power generation mix without encumbering much land area; it improved the reliability of the power system; it reduced dependence on foreign oil and limited exposure to fuel price movements in international markets; and it helped lower CO₂ emissions. Japan’s nuclear power industry made substantial investments in nuclear technology, established itself as a world leader in the technology, and committed large sums to developing the power infrastructure throughout the country.

Despite all the positive attributes associated with nuclear energy, this power source has one inherent characteristic that plays to the all-too human foible of valuing near-term returns over long-term costs. In the case of severe nuclear accidents—however rare they might be—the residual effects of an accident could linger for many decades, or even many centuries. This factor is all the more daunting because we do not yet have a full understanding of the social and economic consequences of rare events that unfold over very long periods of time. Because of these uncertainties, Japan’s nuclear power industry still faces an uncertain fate, despite the government’s desire to restart reactors.

The scale of the issues is so great that ultimately the Japanese government with the consent of the public can determine the future of Japan’s nuclear power industry. First, it must hear and understand public concerns about nuclear power. Safety is the dominant concern, particularly in relation to cleaning up radioactive debris, managing radioactive waste, and decommissioning retired plants. Next, the government must weigh the social and end-to-end economic costs of nuclear power against investments that could be used to substantially increase the share of renewable energy in Japan’s energy mix. It may well be that non-nuclear renewables would be less costly and safer over very long periods of time and have greater social acceptance than incrementally extending the current nuclear energy policy.

Nuclear waste is a second critical problem. No country has opened a permanent disposal facility to isolate the most long-lived and highly radioactive wastes produced by commercial reactors. The cumulative global total of spent nuclear waste is expected to double to more than 700,000 tons in 2040. Japan currently has nearly 15,000 tons of nuclear waste in cooling pools at nuclear plants, which are 70 percent full (FEPC, 2016). Progress on establishing deep underground disposal repositories has been minimal. Meanwhile, radioactive debris from the Fukushima clean-up effort continues to accumulate. In timeframes that are meaningful to humans, disposal of radioactive waste can never be achieved. It will always be with us, whether stored above or below ground.

Decommissioning nuclear plants is a third critical problem. The IEA estimates that the global cost of decommissioning nuclear plants that are retired through 2040 would be more than \$100 billion (IEA, 2014). This will be a daunting task because a great many uncertainties exist, reflecting the relatively limited experience to date in dismantling and decontaminating reactors and restoring sites for other uses. As of 2018, Japan had 21 reactors in its decommissioning program—a three-fold increase in the program since 2011. This presents a qualitatively new challenge for Japan’s nuclear industry and government overseers, requiring skills that are in short supply. With respect to Fukushima there is no existing technology that can solve problems such as to how to find and retrieve all the bits of melted fuel that leaked out of the pressure vessels. Moreover, as the number of reactors to be decommissioned increases, so will the complexity of the tasks and the associated costs. For example, the total estimated cost for the 20-year-long decommissioning task for Japan’s Tokaimura reprocessing plant is expected to be \$1 billion (Schneider, 2014), but the program has been subject to frequent delays. Looking across the retired reactor fleet, we can expect costs to continue to increase, which will ultimately lead to higher electricity rates overall.

If Japan wishes to increase the share of renewable energy as a way to reduce dependency on the existing nuclear infrastructure, the country must first reach a consensus on the future of nuclear energy. Japan has made substantial investments in nuclear infrastructure over many decades. Phasing out or substantially reducing that infrastructure and replacing it with renewable energy will not be easy. Storage of contaminated waste and decommissioning tasks will still be necessary, whether or not existing reactors are returned to service.

11.2 The Hydrogen Alternative

Integrating hydrogen as power sources into Japan’s energy mix is critical to laying the foundation for renewable energy sources. The Ministerial Council on Renewable Energy noted in 2014 that hydrogen has favorable characteristics as a fuel due to the fact that use of hydrogen emits no carbon dioxide and that hydrogen can be used as an energy carrier to store, transport, and use renewable energy. Japan therefore can take advantage of hydrogen technologies as a means to access abundant renewable energy resources and unused energy resources from overseas.

Nevertheless, hydrogen presents some formidable challenges that will require substantial R&D to solve. Because the hydrogen atom is so small it can insinuate itself into various metals, causing embrittlement that can affect the longevity and performance of a machine or metal structure. Hydrogen also affects the tribology of metal surfaces that come in contact with each other. Oxide layers, which protect many metals against wear and corrosion, are not renewed after they are worn away in a hydrogen environment. Specialized solid lubricants therefore are required. Transport and storage of hydrogen also presents difficulties, not only because of embrittlement, but because the volume energy density of hydrogen is so low (the volume energy density of hydrogen gas is 1/3000th of gasoline). Hydrogen must be kept under very high pressure or cooled to a liquid (−423.17 °F) in order to store usable amounts of fuel. These measures impose a cost penalty; liquid hydrogen is the most costly to create and also has losses of 1 percent per day as the liquid “boils off.”

Another critical challenge for the Hydrogen Society is the requirement to increase in parallel the availability of renewable energy sources. A Hydrogen Society would, first and foremost, require

substantial renewable energy sources to generate hydrogen that would be used to store energy. Renewable energy could generate hydrogen that could power fuel cell vehicles or directly fuel hydrogen combustion engines. Renewable energy generates no CO₂ emissions, or at least is carbon neutral, and a greater use of renewable energy would reduce fossil energy use and thus lower CO₂ emissions. Additionally, a Hydrogen Society would require substantial investments in fuel and storage infrastructure.

11.3 Fuel Cell Development

Perhaps the greatest of the challenges facing a Hydrogen Society is the development of economically viable fuel cells to generate power. Hydrogen-use technology like automobiles is a fundamental component of a Hydrogen Society, and without it, there will be almost no use for hydrogen as a power source. Japan has funded fuel cell R&D for a long time, but these systems still suffer from high cost, inefficiency and insufficient durability, although these problems are less serious as a result of technology development (Behling, 2013). While some products, such as Ene-Farm residential cogeneration units and fuel cell vehicles (FCVs), have been able to enter the commercial market, these systems are still very costly and require subsidies for market survival. More research is needed to solve these problems.

What makes fuel cell technology so difficult to master? The answer is simple. Fuel cell operations are complex and the necessary research has not been systematically done to master them. History is full of stories in which fuel cell companies developed moderately functional fuel cells, scaled them up for commercial applications (often with government assistance), and rushed the product to market. Companies subsequently found that their fuel cells did not work well. No matter how many times problems of cost or efficiency or reliability occurred, there was the belief that problems could be fixed with a little more time and a little more money. The fuel cell industry was looking for tactical fixes when strategic solutions were needed. Furthermore, the costs of fuel cells have never been reduced to the level necessary to encourage their wide-spread use without subsidies.

The challenge of making low-cost reliable, efficient fuel cells is rooted in the complexities of how they operate, which involves multiple chemical and physical interactions at the atomic level. Perhaps no advanced technology on the market today—including airplanes, computers, or even nuclear reactors—requires the scale, magnitude, and range of scientific, physical, and engineering knowledge that fuel cell technology requires.

Japan's scientists are making progress, however. Scientists have successfully applied advanced research tools to understand fuel cell operations at the atomic level and are developing theories to explain details of fuel cell processes. Some examples suggest that this type of work, if integrated into a single collaborative effort, could achieve groundbreaking discoveries that would ultimately lead to viable commercial products:

- Researchers at Tohoku University demonstrated how computational chemistry can advance fuel cell development. They linked computationally obtained images with the images obtained from transmission electron microscopy and proved for the first time how computational chemistry can duplicate real-life degradation in fuel cells. They have used this discovery to develop a theory of such phenomena, which will help to lay the groundwork to fix the problem.

- Researchers at Yamanashi University and Waseda University, working with others at Shimadzu Corporation, Fuji Electric, and Hitachi, have imaged the oxygen distribution within a fuel cell stack for the first time. They used a chemical reagent that emits light of a specific wavelength when oxygen is present and captured an image of oxygen distribution with a charge-coupled device camera. The visualization of the inner working of a fuel cell stack could reveal mechanisms of fuel cell deterioration.
- Researchers at Kyushu University have succeeded in obtaining 3D temperature distributions with thin in-line thermocouples to improve the understanding of water behavior, leading to improved water management. Others have made considerable progress in development of carbon-free electrocatalysts, helping to fundamentally reduce the problem of carbon corrosion.

Over past decades, the Japanese government, along with other governments worldwide, have worked vigorously to help their fuel cell industries build technical capabilities that yielded little economic return. These efforts rested on an assumption that fuel cell technology could be developed into commercially viable products, given enough investment and time to make incremental improvements through applied research and product development. Despite the best of intentions, Japan's fuel cell industry continues to rely on government assistance for survival, including funding for demonstration projects, tax incentives, and subsidies for lowering purchase costs and building a hydrogen infrastructure.

To accelerate progress in fuel cell (and hydrogen) technologies, the most viable path ahead is to place greater priority on basic research. Japan's government should support a basic research strategy and do so as a matter of urgent national priority. Indeed, an expanded fuel cell R&D program sponsored by Japan's government should focus primarily on adding basic research as a key component to the traditional mix of applied research and product development activities that Japan has been implementing for years.

Once these technologies are fully understood and the mechanisms that effect performance are known, the hydrogen and fuel cell industry would be able to produce commercially feasible products, test them, and acquire solutions to remaining problems within the basic R&D framework. Large-scale simulation, best exemplified by the automotive and aerospace industries, if also implemented, would expedite the commercialization building up from materials and fundamental understanding all the way to manufacturing and distribution of products to the marketplace.

If hydrogen and fuel cell applications are to be successful, basic research must first be successful. Although basic research, applied research, and product development always co-exist, basic research should be the core mission that is supported by the government and be given the highest priority. Without this protection, basic research will not be able to compete with other research activities. At the same time, however, a government-sponsored basic research program will not be successful unless it links basic scientific research and hypotheses generation to technology development and the empirical data acquired by industry. Throughout the life of the project, therefore, the hydrogen and fuel cell industry should have complete access to research findings and discoveries and be encouraged to apply these to product development and manufacturing activities.

Industry should give the government continuous feedback on whether hydrogen and fuel cell technologies were becoming more durable, efficient, and cost effective. It is essential that industry

be fully integrated with the project from start to finish and that companies receive strong incentives to share their information and assurance that proprietary data will be protected. The repeated cycle of hypothesis, verification, and data exchange between basic research and applied research and product development will yield improvements in knowledge of fuel cell performance with every step.

Major technical hurdles can be overcome through intense, massive investment of resources in a concentrated period. As a first step toward this goal, a senior committee of top leaders from national research laboratories, industry, and funding agencies should be assembled under the leadership of the New Energy and Industrial Technology Development Organization (NEDO) and charged with preparing a detailed blueprint for implementing a hydrogen and fuel cell basic research development plan. Among other actions, the committee should identify specific areas of research to be explored. Probable areas of emphasis might include the discovery and detailed characterization of fuel cell electrochemical processes and operations; development of a theoretical understanding and empirical validation of underlying causes that drive cost and performance shortfalls, such as embrittlement and cell degradation; and exploration of transformational technologies that would enable creation of revolutionary fuel cell types, catalysts, and enabling hydrogen technologies that use new, less expensive materials.

11.4 A Way Forward for Nuclear and Hydrogen Alternatives

Considering the status of Japan's nuclear industry and the limited progress that has been made over the last decade on hydrogen-based technologies, this dissertation outlines steps that government, industry, and academia could take to accelerate progress in both fields. These steps are similar to those enacted in 2002 by US President Bush to support fuel cell and hydrogen development. The policy recommendations and proposals that were implemented at that time, which I helped prepare, led to the creation of a major new US federal program that advanced the development of hydrogen and fuel cell technologies.

In the same vein, the goals for Japan's twin energy alternatives would be to create and manage a nuclear power infrastructure that is as safe as humanly possible and invest in alternative energy sources that could serve as "off-ramps" from nuclear if the situation warrants. Without the development of a Hydrogen Society, Japan would have few alternatives should the present-day strategy of incrementally restarting nuclear reactors not succeed. With commitments to both nuclear energy and a hydrogen alternative in place, Japan would have feasible options for successfully achieving its quest for safe, economically viable, and secure forms of energy. Steps include the following:

For the Nuclear Alternative

- 1) Recognize at the most senior level, and at every level further down, the entire nuclear industry must articulate the need for a culture of safety, explicitly recognizing that an absorbing concern with safety is the only way to bring about safety. This will demand a change in mindset—not just in complying with a narrowly prescribed and complex set of regulations but in recognizing that any successful nuclear program must function as an integrated whole of many factors, both in technical and in human terms, and must be managed with that recognition in mind.

- 2) Recognize in budgetary terms that genuine safety improvements will require new plant construction and advanced storage and disposal capabilities, and most of all, training and advanced education of its workers, which will be costly.
- 3) Create Program Management positions for major nuclear programs across industry and government and fill them with iron-willed, qualified, experienced, individuals who are charged with instilling a safety culture throughout their organizations.
- 4) Clean up ambiguous chains of command so that all understand who is responsible for safety (implement the Rickover responsibility principle). The government should clearly identify who is responsible for decommissioning and decontamination of the Fukushima reactors.
- 5) Follow what the Atomic Energy Basic Law (1955) decreed. The second article of the law specified that Japan should develop nuclear energy according to three principles, *minshu* (democracy), *jishu* (independence), and *kokai* (public disclosure). The government has largely disregarded two of the three principles—democracy and public disclosure. The government must openly ask the Japanese people to consider and choose the options they wish to have with respect to nuclear energy, e.g., whether they want no nuclear programs, a scaled down program with no fuel reprocessing and no fast breeder reactors, a dramatically rebuilt nuclear fleet, or some other set of options.
- 6) Implement the Basic Policy for Nuclear Energy's requirement for building a comprehensive data set of nuclear-related events and analyze these in order to improve safety. This data set should be shared continuously across the nuclear industry and within government and academia.
- 7) Develop and promote the use of Dengen Sampo to directly improve corporate behavior as it pertains to safety as well as promote viable new industries in the areas near nuclear sites. It could, for example, change the way funds are allocated to improve training and education related to safety of nuclear operations.
- 8) Take concrete steps to improve safety in a manner that clearly informs the public. Safety protocols need to be understood not only by nuclear plant workers but also must be understood and accepted at an operational level by the public. This should be implemented slowly and carefully, brick by brick, so that ultimately the public once again has confidence in the nuclear power industry.
- 9) Put in place a set of business incentives to improve safety practices that are keyed to corporate profitability, vice just relying on insurance pools to cover liabilities.
- 10) Institute a comprehensive and long-term set of educational incentives to rebuild the pool of scientists and engineers that the industry will need to renew itself; design this educational program to effect a cultural change in the government and industry, where safety is the central component of nuclear power.
- 11) Apply a revised Code of Ethics in safety assessments. While the Code of Ethics was prepared by a private sector organization (the AESJ), it could be adapted as a framework for assessing how well nuclear facilities are adhering to sound safety practices. To make this feasible, however, would require buy-in from the NRA and some rewriting of the Code so that it is simpler and easily understood by those outside the nuclear engineering community. If this were done, metrics and performance benchmarks based on the Code could be established and linked to requirements for setting aside funds to cover costs of future accidents.

For the Hydrogen Alternative

- 1) The Government of Japan should appoint a Ministerial Committee to identify and assess basic research advances and technological opportunities for fuel cells that would have the potential to greatly support and enable a Hydrogen Society.
- 2) The Committee should define a roadmap to ensure full documentation and understanding of the operational behavior of fuel cell types that has the potential for a Hydrogen Society. It also should assess the current understanding of fuel cell components, materials, and chemistry and specify what performance simulators and models should be developed to depict and understand fuel cell operations and thereby predict future operational behavior.
- 3) Implement a feasible plan that would facilitate achieving these goals to include, for example, prototype development and testing under real-world conditions.
 - Provide viable policy and management initiatives for the development of Japan's hydrogen and fuel cell industry, and identify specific near-term and long-range strategies for accomplishing these initiatives and the responsible agents of change.
 - Redefine Japan's future power generation policy to ensure that all power sources, including nuclear power, renewable energy, hydrogen-based power, and energy storage and transport technology, are fully integrated in terms of construction, interconnection, and concepts of operation. An example of the benefits of integration could be the development and widespread use of advanced energy conversion technologies to store large amounts of power in chemical or mechanical form during periods of low demand and convert it back into electricity during high demand.
 - Integrate nuclear power and renewable technology into the efficient production of hydrogen, starting with the development of enabling technologies (e.g., smart grid management tools) and the demonstration of these technologies.

Collaboration between nuclear and hydrogen energy sources could benefit both alternatives. Power companies could produce hydrogen with the surplus nuclear power that would be available when renewables are at maximum output. This surplus power could be sold to gas suppliers and converted into chemical or organic compounds suitable for transport and long-term energy storage. This stored energy could be converted back into electricity when needed by means of clean-energy fuel cells that are coupled to carbon sequestration systems. At the same time, the power companies could start new business areas for direct hydrogen power generation. For example, high temperature reactors could produce hydrogen that companies could use directly via hydrogen-powered turbines or advanced fuel cells. Expanded use of hydrogen could boost R&D on fuel cells and accelerate the expansion of a Hydrogen Society. The power companies would also have options to retain, expand, or exit the nuclear power generation business.

Each of these initiatives flows out of lessons learned from nuclear incidents and accidents that have occurred throughout Japan's long experience with nuclear power, as well as from the progress Japan has made in hydrogen-based technology and fuel cells. The first eleven recommendations can help improve nuclear safety in some dimensions, but only if there is a commitment at every level of government and business to achieve a zero-accident culture, and a willingness to make the costly investments to achieve that goal. The last set of three recommendations could provide Japan with options to build a clean-energy Hydrogen Society that could supplement a nuclear power alternative or replace it if circumstances made it appropriate.

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APPENDIX A: Cancelled Nuclear Power Reactors

Notes: Commercial nuclear power plants in Japan that were cancelled or withdrawn due to Anti-Nuclear Protests. The table does not include experimental reactors or those reactors with site conditions that were found unsuitable to build and withdrawn by the electric utilities. Some reactors, such as Fukushima Daiichi Reactor 7 and 8, were withdrawn by the utilities for socio-political reasons. They are not included in the list.

Appendix A Table Cancelled Nuclear Power Reactors

Year of cancellation or Withdrawal	Planned Nuclear Plants	Planned Site	Sponsoring Electric Company
1960	Mitsu Nuclear Plant	Tatsuno-shi (formerly Mitsu-cho), Hyogo Prefecture	Kansai Electric
1968	Koza Nuclear Plant	Shirahama-cho (formerly Hikigawa-cho), Nishimuro-gun, Wakayama	Kansai Electric
1970	Ajiro-Misaki Nuclear Plant	Ajiro-Misaki, Kaiyo-cho (formerly Kainan-cho), Kaifu-Gun, Tokushima Prefecture	Shikoku Electric
	Taro Nuclear Plant	Taro-cho, Shimohei-gun, Iwate Prefecture	Tohoku Electric
	Kasumi Nuclear Plant	Kami-cho (formally Kasumi-cho), Kinomaki-gun, Hyogo Prefecture	Kansai Electric
1972	Kakui-jima Nuclear Plant	Kakui-jima, Hinase-cho, Bizen-shi (formerly Wake-Gun), Okayama Prefecture	Chubu Electric
	Kumano Nuclear Plant	Ichiura, Kumano-shi, Mie Prefecture	Chubu Electric
1973	Hamasaka Nuclear Plant	Shin-onsen-cho (formerly Hamasaka-cho), Mikata-gun, Hyogo Prefecture	Kansai Electric
1974	Saga Nuclear Plant	Kuroshio-cho, Hata-gun, Kochi Prefecture	Shikoku Electric
1976	Obama Nuclear Plant	Tagarasu, Obama-shi, Fukui Prefecture	Kansai Electric
1979	Gamoda Nuclear Plant	Shirikui, Tsubaki-cho, Anan-shi, Tokushima Prefecture	Shikoku Electric
	Anan Nuclear Plant	Anan-shi, Tokushima Prefecture	Shikoku Electric
1981	Nachi Katsuura Nuclear Plant	Nachi-Katsuura-cho, Wakayama Prefecture	Kansai Electric

1982	Aoya Nuclear Plant	Ketaka-gun, Tottori Prefecture	Chugoku Electric
1983	Tamagawa Nuclear Plant	Kaminoseki-cho, Kumage-gun, Yamaguchi Prefecture	Chugoku Electric
1988	Hikigawa Nuclear Plant	Hikigawa-cho, Nishimuro-gun, Wakayama Prefecture	Kansai Electric
	Kubokawa Nuclear Plant	Shimanto-cho (formerly Kubokawa-cho), Takaoka-gun, Kochi Prefecture	Shikoku Electric
1992	Hamamasu Nuclear Plant	Hamamasu-mura, Ishikari-shi, Hokkaido	Hokkaido Electric
1994	Hohoku Nuclear Plant	Hohoku-cho, Toyoura-gun, Yamaguchi Prefecture	Chugoku Electric
1995	Hagi Nuclear Plant	Hagi-shi, Yamaguchi Prefecture	Chugoku Electric
1997	Kushima Nuclear Plant	Kushima-shi, Miyazaki Prefecture	Kyushu Electric
2000	Ashihama Nuclear Plant	Minami-Ise-cho (formerly Nanto-cho)/Taiki-cho (formerly Kisei-cho), Watarai-gun, Mie Prefecture	Chubu Electric
2001	Miyama Nuclear Plant	Kihoku-cho (formally Miyama-cho), Kitamuro-gun, Mie Prefecture	Chubu Electric
2003	Makimachi Nuclear Plant	Makimachi, Nishi-Kanbara-gun, Niigata Prefecture	Tohoku Electric
	Suzu Nuclear Plant at Takaya-machi	Takaya-machi, Suzu-shi, Ishikawa Prefecture;	Hokuriku Electric, Chugoku Electric, Kansai Electric
	Suzu Nuclear Plant at Jike-machi	Jike-machi, Suzu-shi, Ishikawa Prefecture	
2005	Hidaka (Oura) Nuclear Plant	Oura, Hidaka-cho, Hidaka-gun, Wakayama Prefecture	Kansai Electric
	Hidaka (Ao) Nuclear Plant	Ao, Hidaka-cho, Hidaka-gun, Wakayama Prefecture	
2006	Kumihama Nuclear Plant	Kumihama, Kumano-gun, Kyoto	Kansai Electric
2009	Amakusa Nuclear Plant	Amakusa-shi, Kumamoto Prefecture	Kyushu Prefecture
2013	Namie · Odaka Nuclear Plant	Manie-machi, Futaba-gun, Fukushima Prefecture; Odaka-machi, Soma-gun, Fukushima Prefecture	Tohoku Electric

Source: Table created by the authors based on various sources, including

- 1) Cho, H., 2014. Genshiryoku Hatsuden ni taisuru Yugu Seisaku no Genjo to Mondai-ten (The Current Status and Problems of the Preferential Policy for Nuclear Power Generation), Gendai Shakai Bunka Kenkyu (Modern Socio-Cultural Research), No. 58, March 2015, pp.1-15);
- 2) Tominaga, C, 2015. “Nenpyo 4, Genshiryoku Hatsuden-sho Kensetsu to no Tatakai—Ricchi Hantai Undo to Gen’patsu Sosho (Chart 4, Battle with Nuclear Power Plant Construction—Construction Protest Movement and Nuclear Power Plant Lawsuits),” Gender History, 4 July 2015. http://ch-gender.jp/wp/?page_id=10773, (accessed 16 February 2018);
- 3) Asura, 2016. “Genpatsu Keikaku o Oidashita Basho ga Nihon ni was 34-kasho mo atta, Nihonjin to shite Hokori ni Omou (There were 34 Cancelled Nuclear Plant, I am proud of it as a Japanese),” Blog, <http://www.asyura2.com/16/genpatu45/msg/716.html>, (accessed 18.09.13).

APPENDIX B: Worldwide Nuclear Power Reactor Fleet Statistics (as of end-2017)

Decimal numbers are rounded off.

Only those countries with more than 10 reactors are listed.

Country	Operational reactors	Installed capacity (GW)	Electricity generation (TWh)(2017)	Share of electricity generation (%)	Under construction
USA	98	99	805	20	2
France	58	63	379	72	1
China	45	43	248	4	13
Japan	39*	39	29	18	2
Russia	37	29	188	18	6
S. Korea	24	23	141	27	5
India	22	6	35	3	7
Canada	19	14	96	15	0
Ukraine	15	13	86	55	0
United Kingdom	15	9	64	19	0
Other	79	62	448	--	18
World	451	400	2519	18	54

* With respect to Japan, as of October 2018, nine of 39 nuclear reactors are operational; the rest remain in a caretaker status.

Source: The authors created the table based on World Nuclear Organization (WNO), World Nuclear Power Reactors & Uranium Requirements, November 2018, <http://www.world-nuclear.org/information-library/facts-and-figures/world-nuclear-power-reactors-and-uranium-requireme.aspx> (accessed 12 November 2018); WNO, Nuclear share figures, 2007-2017, April 2018, <http://www.world-nuclear.org/information-library/facts-and-figures/nuclear-generation-by-country.aspx> (accessed 12 November 2018).

APPENDIX C: Impact of Accident Costs on Cost of Power (in MWh)

Assumptions

Three cases considered: Less Severe, Worst Case and Intermediate. For the Less Severe case, we assumed total accident remediation costs of \$10 billion and a time between accidents greater than 140 years, with a payback period of 40 years. For Worst Case, we assumed a Fukushima-level disaster, with accident costs of \$1000 billion and a payback period of 20 years. For the Intermediate case, we assumed costs and time between accidents would lie somewhere between Less Severe and Worst Case; we used 20 to 140 years as a measure of accident frequency, \$100 billion in costs and payback periods of 20 to 40 years as illustrative.

Fleet of 25 reactors in operation, each with 1000 MW capacity and each delivering 700 MWh output (70 percent use rate).

Cost of nuclear power is 9.8 yen (or \$0.098) per kWh, or \$98 per MWh. (The 2015 cost of nuclear power is calculated to be 10.1-yen kWh (METI Nuclear Power Cost Working Group, 2015).⁹⁷ We subtracted 0.3 yen (accident remediation cost) from 10.1 yen to get 9.8 yen. We use 9.8 yen per kWh as the base cost to calculate cost for a MWh for the accident cases.

Accident Cost Calculation per MWh of power generated:

$$(\text{Total Accident Remediation Cost}) / ((\text{Payback Period in Years}) \times (8760 \text{ Hours per year}) \times (700 \text{ MWh output rate}) \times (25 \text{ reactors in use})) = \text{Accident Cost per MWh of operation. See Table A.1.}$$

Example: For the Less Severe case the calculation would be: $(\$10,000,000,000) / ((40) \times (8760) \times (700) \times (25)) = \$1.63$ Accident Cost per MWh

For Intermediate case: $(\$100,000,000,000) / ((40) \times (8760) \times (700) \times (25)) = \$16.3$ (about \$16);
 $(\$100,000,000,000) / ((20) \times (8760) \times (700) \times (25)) = \$32.6$ (about \$33)

For a Worst Case: $(\$1,000,000,000,000) / ((20) \times (8760) \times ((700) \times (25))) = \$326$ (about \$325)

⁹⁷ Source: Nuclear Power Cost Working Group, Choki Enerugi Jukyu Mitoshi Sho-linkai ni taisuru Hatsuden Kosuto-to no Kensho ni kansuru Hokoku-an (Draft Report on Verification of Nuclear Power Generation Cost to the Subcommittee of Long-Term Energy Supply and Demand Prospect), the Agency of Natural Resources and Energy, Nuclear Power Cost Working Group, the 6th Meeting, Material 1, April 2015, http://www.enecho.meti.go.jp/committee/council/basic_policy_subcommittee/mitoshi/cost_wg/006/pdf/006_05.pdf (accessed 17.05.23).

Appendix C Table: Calculation of Risk Premium (per MWh of power generated)

	Cases		
	Less Severe	Intermediate	Worst Case
Accident frequency, in years	140-1,000	20 to 140	20
Period to pay for accident, in years	40	20 to 40	20
Total accident remediation cost	\$10B	\$100B	\$1000B
Accident cost per MWh (risk premium)	\$1.63	\$16 to \$33	\$325
\$98 MWh cost + accident cost per MWh power generated	\$100	\$114 to \$131	\$420+
Reference cost: 1 MWh generation cost from LNG power plant	\$137		

APPENDIX D: Abbreviations and Acronyms

ABWR	Advanced boiling water reactor
AEC	Atomic Energy Commission of Japan
AFC	Atomic Fuel Corporation
AHM	Auxiliary Handling Machine
ANRE	Agency of Natural Resources and Energy
APWR	Advanced pressure water reactor
ASME	American Society of Mechanical Engineers
ATR	Advanced Thermal Reactor
BN	Belgium's Belgonucleaire
BNFL	UK's British Nuclear Fuels Limited
BWR	Boiling water reactor
CCT	Core Confirmation Test
CEA	Commissariat à l'énergie atomique et aux énergies alternatives (The French Alternative Energies and Atomic Energy Commission)
CEO	Chief executive officer
COGEMA	Compagnie générale des matières nucléaires
CNIC	Citizens' Nuclear Information Center of Japan
CRIEPI	Central Research Institute of Electric Power Industry
Cs-137	Cesium-137
CP	Chicago pile
EMSA	Energy Measures Special Account
EPDC	Electric Power Development Company
EPRI	Electric Power Research Institute
ESDA	Energy Supply Demand Account
FBR	Fast Breeder Reactor
FCI	Framatome Connectors France
FEPC	Federation of Electric Power Companies of Japan
FY	Fiscal year
GE	General Electric
GOJ	Government of Japan
GNF-J	Global Nuclear Fuel-Japan
GRERC	General Resources and Energy Research Committee
GyEq	Gray equivalent
HALW	Highly active liquid waste
HLW	High-level waste
HM	Heavy metal
HTGR	High temperature gas-cooled reactor
HTTR	High temperature gas-cooled test reactor
IAEA	International Atomic Energy Agency
ICRC	International Critical Review Committee
IEU	Intermediately enriched uranium
IHI	Ishikawajima-Harima Heavy Industries
IHX	Intermediate Heat Exchanger

INES	International Nuclear and Radiological Event Scale
INS	International Nuclear Services
IRID	International Research Institute for Nuclear Decommissioning
IPFM	International Panel on Fissile Materials
IRSN	Institut de Radioprotection et de Surete Nucleaire
ISFSI	Independent spent fuel storage installation
ISO	International Organization for Standardization
IVTM	In-vessel transfer machine
J-MOX	Rokkasho MOX Fuel Fabrication Plant
JAEA	Japan Atomic Energy Agency
JAERI	Japan Atomic Energy Research Institute
JAIF	Japan Atomic Industrial Forum
JAPC	Japan Atomic Power Company
Jbaudit	Japan Board of Audit
JCER	Japan Center for Economic Research
JEA	Japan Electric Association
JMA	Japan Meteorological Agency
J-MOX	Rokkasho MOX Fuel Fabrication Plant
JNC	Japan Nuclear Cycle Development Institute
JNES	Japan Nuclear Energy Safety Organization
JNFI	Japan Nuclear Fuel Industry Limited, a forerunner of JNFL
JNF	Japan Nuclear Fuel Conversion
JNFL	Japan Nuclear Fuel Limited
JOGMEC	Japan Oil, Gas and Metal National Corporation
JPDR	Japan Power Demonstration Reactor
JRR-1	JAERI Research Reactor-1
JSFR	MHI's Sodium-cooled fast reactor
KEPCO	Kansai Electric Power Company
LDP	Liberal Democratic Party
LLW	Low-level waste
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas
LWR	Light Water Reactor
MCC	Mining and Chemical Combine
MDF	MOX Demonstration Facility
MEXT	Ministry of Education, Culture, Sports, Science and Technology
METI	Ministry of Economy, Trade and Industry
MHI	Mitsubishi Heavy Industries
MITI	Ministry of International Trade and Industry
MNF	Mitsubishi Nuclear Fuel Company
MOF	Ministry of Finance
MOFA	Ministry of Foreign Affairs
MOX	Mixed oxide fuel
MWd/t	Megawatt day per ton
MWe	Megawatt electric
MWh	Megawatt hour
MWt	Megawatts thermal

NADCSA	Nuclear Accident Damage Compensation Support Account
NCP	UK's Nuclear Chemical Plant
NDA	UK's Nuclear Decommissioning Authority
NDF	Nuclear Damage Compensation and Decommissioning Facilitation Corporation
Jbaudit	The Board of Audit of Japan
NEA	Nuclear Energy Agency, OECD
NEDO	New Energy and Industrial Technology Development Organization
NFI	Nuclear Fuel Industries
NIRS	National Institute of Radiological Sciences
NISA	Nuclear and Industrial Safety Agency
NHK	Nihon Hoso Kyokai, Japan's national public broadcasting organization.
NPR	Nuclear Power Reactor
NRA	Nuclear Regulation Authority, Japan
NRC	The US National Regulatory Commission
NSC	Nuclear Safety Commission of Japan
NUMO	Nuclear Waste Management Organization of Japan
NuRO	Nuclear Reprocessing Organization of Japan
O&M	Operation and Maintenance
OECD	Organization for Economic Co-operation and Development
PBq	Petabecquerels
PCV	Primary containment vessel
PFRF	Plutonium Fuel Research Facility
PHWR	Pressurized heavy water reactor
PNC	Power Reactor and Nuclear Fuel Development Corporation
PSDA	Power Source Development Acceleration
PSDAA	Power Source Development Acceleration Account
PSDAT	Power Source Development Acceleration Tax
PSDM	Power Source Diversification Measure
PSLM	Power Source Location Measure
PSLRM	Power Source Location Region Measure
PSUM	Power Source Utilization Measure
PWR	Pressurized water reactor
Pu	Plutonium
Pu-240	Plutonium-240
PuO ₂	Plutonium dioxide
QST	National Institutes for Quantum and Radiological Science and Technology
R&D	Research and development
REP	Rokkasho Enrichment Plant
RETF	Recycle Equipment Test Facility
RFS	Recyclable Fuel Storage Company
RIST	Research Organization for Information Science and Technology
RRP	Rokkasho Reprocessing Plant
RVL	Rokkasho Vitrification Laboratory
RWMC	Radioactive Waste Management Funding and Research Center
SADF	Surrounding Area Development Fund
SAFSTOR	Safe storage
SGN	Saint-Gobain Nucléaire of France

SMM	Sumitomo Metal Mining
SMP	Sellafield MOX Plant
SST	System start-up tests
STA	Science and Technology Agency
SWU	Separate Work Unit
tHM	tons of heavy metals
tMOX:	tons of plutonium and uranium mixed oxide
TWh	terawatt hour
TEPCO	Tokyo Electric Power Company
TPM	Total Productive Maintenance Award
TRU waste	Transuranic waste
U	Uranium
U-235	Uranium-235
UCS	Upper core structure
UF	Uranium fluoride
UF ₆	Uranium hexafluoride
UO ₂	Uranium dioxide
U ₃ O ₈	Triuranium octoxide
USNRC	United States Nuclear Regulatory Commission
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
USEIA	US Energy Information Administration
US EPA	US Environmental Protection Agency
VWSC	Vitrified Waste Storage Center
WH	Westinghouse
WNA	World Nuclear Association
WNN	World Nuclear News

APPENDIX E: 2018 Code of Ethics from the Japan Atomic Energy Society

Approved at the Board of Directors Meeting on 31 January 2018. Below is the author's unofficial translation of the 2018 chapter list and code of ethics.

CODE CHAPTERS

1. Behavioral Principle

The members shall recognize that it is their responsibility to contribute to the betterment of human life and the preservation of global environment as their responsibility and act accordingly.

2. Public Priority and Sustainability Principles

The members shall commit to the development of the peaceful use of nuclear energy and radiation, with the public safety as the priority.

3. Truth Principle

The members shall actively pursue the latest knowledge, always respect facts, and act with their own judgment.

4. Integrity and Honesty Principle

The members shall comply with laws and regulations and social norms, execute their work in good faith to comply, fulfill the accountability to society, and try to gain the trust of society.

5. Expertise Principle

The membership shall have pride as a nuclear expert, deeply recognize the impact of technology involved and study hard. Also, the members shall actively communicate the results to the society, develop the technology and strive to educate and develop human resources.

6. Excellence Principle

The members shall always be aware that nuclear power requires a comprehensive technology, humbly recognize its limitations for their professional skills, deepen their understanding of the areas outside of their own field, and always have a spirit of cooperation.

7. Enhancing Organizational Culture

The members shall work to foster an organizational culture where the members can respect this Code of Ethics and act as an individual.

CODE OF ETHICS

Chapter 1. Behavioral Principle

1-1. Basic Policy for Nuclear Energy Use. Nuclear energy is used widely not only as energy but also as radiation in medical, agricultural, industrial fields. The members shall have pride and ideal that they are contributing to the betterment of human lives and preservation of the earth environment and strive to develop nuclear energy with professionalism and independence.

1-2. Fostering Tireless Efforts and Challenging Spirit. The members shall pay unremitting efforts to solve various problems in research, development, application and education, aim at further development, have a broad view and explore new possibilities.

1-3. Demonstrating Leadership. The members shall each clarify their responsibility and role, demonstrate a positive attitude and act and play a leadership role in each hierarchy.

1-4. Trust Through Engineers' Behavior. The members shall not only enhance safety of the technology but also gain the trust of society by the behavior of themselves as engineers.

Chapter 2. Public Priority and Sustainability Principles

2-1. The Balance of the Use of Nuclear Energy and Safety. The members shall constantly remember various nuclear accidents and disasters in the past and constantly recognize the potential dangers of their technology and the fact that there are risks regardless of whatever safety measures were undertaken. Based on this recognition, the members shall always aim at higher safety levels and strive to achieve them.

2-2. Limited to Peaceful Use. The members shall limit the use of nuclear energy to only peaceful purposes. The members shall never participate in any nuclear weapons research, development, manufacture, acquisition and use, based on their dignity and honor. In addition, the members shall pay utmost attention to organizations and information handling so that they would not engage in nuclear proliferation because of their actions.

2-3. Pay Attention to Ensuring Nuclear Security. The members shall recognize that nuclear material and radioactive substances could be used in terrorism and pay sufficient attention to assurance of nuclear security.

2-4. Harmony with the Earth Environment. The members shall recognize that nuclear power generation can be contribute to the solution of environmental problems by reducing of carbon dioxide emissions, But the members shall recognize that nuclear power has problems, such as radioactive waste disposal and long-term burial and strive the solution of these problems.

2-5. Ensuring Labor Safety. The members shall strive always to ensure the safety and prevention of accidents to protect those who work at the nuclear facilities. are making efforts to prevent disasters and ensure the safety of people who work at nuclear facilities.

2-6. Warning against Economic Priority. In managing the design, construction, operation and maintenance of nuclear facilities, the members shall not let economy take the priority.

2-7. Warning Against Placing Efficiency as Priority. The members shall not improve the efficiency of nuclear facilities and work procedures without conducting an ample review of safety.

2-8. Warning against Regulatory Compliance as Sufficient Purpose. The members shall not be satisfied only with compliance laws and regulations in their research, development, use, education work. The members shall aim at further improvement of safety.

2-9. Warning against Overconfidence of Technology Maturity. The members shall not be overconfident in nuclear safety but believe that there would be new technical problems in the future. They shall remain cautious about new events from happening and prepare in advance.

Chapter 3. Pursuit of Latest Knowledge

3-1 Review Recent Information. The members shall strive to gain information widely domestically as well as abroad so that their knowledge for their work is always up to date. The members shall understand that information regarding safety could impact on the public and the environment, and therefore member should conduct a careful review.

3-2. Respect for Scientific Facts. The members shall respect facts and, when encountering scientifically obvious mistake, shall not shall point out the mistakes firmly and encourage rectifying them.

3-3. Action based on their Own Judgment. The members shall not accept information given to them uncritically and fall into wrong group thinking. They shall always gather correct information, make their own judgment based on related professional knowledge and act.

Chapter 4. Integrity and Honesty Principle

4-1. Act Honestly. The Members shall carry out their work in good faith. Also, in such a case where they might bring disadvantage to other organizations or individuals, the member shall explain to the employer or the client in advance.

4-2. Caution regarding Contracts. The members shall not conclude contracts that might

violate laws and regulations. In case there are potential conflicts of interest, the members shall not engage in the work unless they can disclose the fact to their employers and clients and can clearly explain to any third party.

4-3. Compliance with Rules and Prevention of Rules from Becoming Meaningless. The members shall observe laws and regulations in good faith. On the other hand, they shall always ensure the validity of the laws or revise the laws to prevent the discrepancy between the provisions of the various rules and conditions.

4-4. Social Harmony. The members shall always listen to the voice of the society and strove to create harmony with the society through two-way communications.

4-5. Entrusted from the Society. The members are sort of entrusted by the public as a group of engineers that deal with nuclear technology. The members shall always act with the recognition that they are required of special responsibility and ethics.

4-6. Warning to Members Against Relaxation. The members shall not become overconfident about the nuclear safety and feel relaxed about it. The member shall recognize that the public trust can only be gained by the fact that those who deal with nuclear technology fully recognize the risk, act with tension, listen to other opinions and criticisms carefully, and make continuous efforts.

4-7. Disclosure of information. The members shall make efforts to actively disclose the information concerning nuclear safety. Particularly concerning such information that is indispensable to the public safety, the members shall work on their organization to swiftly disclose the information and prioritize the safety of the public.

4-8. Warning against Concealment and Handling of the Confidential Information. The members shall recognize that information concealment would destroy good relationships with the society and make efforts to appropriately and actively disclose information. However, regarding those information that is deemed inappropriate for public disclosure such as nuclear non-proliferation and nuclear material protection, the members shall try to explain the reason why it cannot be disclosed.

4-9. Accountability. The members shall have the responsibility to always stand in the position of the other party and explain in a timely manner about the purpose, methods and results of their professional activities so that even those who are not professionals would understand easily

Chapter 5. Expertise Principle

5-1. Continuous Learning. The members shall strive to explore unknown territories, conduct self-study and deepen their understanding of related fields, and in performing their duties, always try to have a balance among them. Through the experience and knowledge that they

obtained, the members shall contribute in the development and improvement of nuclear-related studies and technologies.

5-2. Expertise. The members shall recognize that required specialized skills and abilities required for ethical action will change along with the society, and always try to acquire the capabilities that can respond to social demands.

5-3. Acquisition of New Knowledge. The members shall learn academic knowledge and technology that progress daily, related laws and regulations but also hone their professional skills and improve technology necessary for safety assurance. Refrain from acting as an expert with old knowledge and practices.

5-4. Accurate Knowledge, Safety Knowledge and Technology Acquisition and Transfer. The members shall not only observe laws and regulations but also in the activities related to nuclear expertise, strive to improve necessary professional knowledge and improve technology for safety assurance. Further, they shall continuously acquire accurate knowledge and transfer.

5-5. Learning from Experience, Sharing and Inheritance. The members shall learn the lessons from experience. Especially about accidents and malfunctions, they shall pay attention and study not only failures but also good practice and made efforts to prevent recurrence or similar situations. They shall espouse information sharing and inheritance.

5-6. Improvement of Professional Capacity of Stakeholders and Environment. The members shall not only hone their own skills but also create an environment for skill development through providing study opportunities especially to those who are under their supervision and those who are working close by.

5-7 Courtesy of Offering Easy-to-Understand Scientific Facts. The members shall strive to offer scientific facts and professional knowledge to the public in such a way that they would understand accurately and easily so that they can make their judgment.

5-8. Contribution to the International Community. While Japan has a wealth of experience in the peaceful use of nuclear energy, the country is among parties to nuclear disasters. The members shall learn knowledge and lessons deeply from this experience and contributes to improve technologies and safety of nuclear power in Japan as well as in the world.

Chapter 6. Excellence Principle

6-1. Needs a Multidisciplinary Approach. The members shall fully recognize that nuclear technology consists of various, wide-ranging technologies and in securing nuclear safety, try to approach it from the comprehensive point of view so that there would be no gaps between these professional boundaries.

6-2. Self-Assessment. The members shall always humbly question ask if the safety of the task

that they are trying to accomplish would not be undermined because of the lack of their ability.

6-3. Development of Human Resources with a Broad Perspective. The members shall foster and maintain in their organization such an environment where they can develop talents that have not only expertise but also a broad perspective.

Chapter 7. Enhancing Organizational Culture

7-1. Basic Principles of Individual Conduct in the Organization. The members shall foster the corporate culture in their organization in which they can freely discuss ethical and safety issues and act. If inadequate, they shall try to change the corporate culture, including the organization and structure environment, atmosphere.

7-2. Problem Solving in the Organization. The members shall recognize the weight of their role that accompanies with their responsibility and authority and make the utmost effort for the enhancement of safety. When the members cannot improve unsafe situations with their own authority, approach stakeholders, including those with authorities and improve the situation.

7-3. Importance of Establishing a Proper Environment in the Organization Based on the Code. Members with management responsibilities in an organization shall recognize the meaning and importance of this Code of Ethics, tell those individuals in the organization, member and non-member, that they should act based on this Code of Ethics, and try to set up an environment to do so. Also, members shall be constantly watchful of activities in the organization, actively remove those factors that impede the activities based on this Code and make a continuous effort to improve and enhance the environment.

7-4. Establishing Appropriate Procedures for Complaints. Members who have management responsibility in an organization shall prepare proper procedures in advance for handling complaints about nuclear safety. To deal with such charges fairly, the organization shall conduct swift investigations and disclose findings, with consideration that the complainant will not be disadvantaged.

7-5. Securing a Safe Working Environment. Members who have management responsibility in an organization shall make efforts for ensuring safety by securing the environment that serves as the basis for activities.

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