

A comparative institutional analysis of the Fukushima nuclear disaster: Lessons and policy implications[☆]

Masahiko Aoki, Geoffrey Rothwell^{*}

Department of Economics and Stanford Institute for Economic Policy Research, 579 Serra Mall, Stanford University, Stanford, CA 94305-6072, USA

HIGHLIGHTS

- We review damage to Fukushima Dai-Ichi on March 11, 2011, from the Tōhoku earthquake and tsunami.
- We find that delays in coordinated action led to a cascading series of accidents at Fukushima.
- We suggest unbundling of the publicly purchased Tokyo Electric Power to pay for accident damages.
- We suggest the creation of a Japanese Independent System Operator to manage unbundled transmission assets.
- We propose establishing an open-interface, rule-based independent nuclear regulator in Japan.

ARTICLE INFO

Article history:

Received 28 December 2011

Accepted 25 October 2012

Keywords:

Nuclear power

Electricity regulation

Comparative institutional analysis

ABSTRACT

This paper analyzes the causes, responses, and consequences of the Fukushima nuclear power plant accident (March 2011) by comparing these with Three Mile Island (March 1979) and Chernobyl (April 1986). We identify three generic modes of organizational coordination: modular, vertical, and horizontal. By relying on comparative institutional analysis, we compare the modes' performance characteristics in terms of short-term and long-term coordination, preparedness for shocks, and responsiveness to shocks. We derive general lessons, including the identification of three shortcomings of integrated Japanese electric utilities: (1) decision instability that can lead to system failure after a large shock, (2) poor incentives to innovate, and (3) the lack of defense-in-depth strategies for accidents. Our suggested policy response is to introduce an independent Nuclear Safety Commission, and an Independent System Operator to coordinate buyers and sellers on publicly owned transmission grids. Without an independent safety regulator, or a very well established "safety culture," profit-maximizing behavior by an entrenched electricity monopoly will not necessarily lead to a social optimum with regard to nuclear power plant safety. All countries considering continued operation or expansion of their nuclear power industries must strive to establish independent, competent, and respected safety regulators, or prepare for nuclear power plant accidents.

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1. Introduction

The Tōhoku earthquake of magnitude 9.0 off the coast of Japan, and the accompanying tsunami with the surge of more than 12 m, hit the Fukushima nuclear power plant on the afternoon of March 11, 2011. The earthquake triggered the immediate shut down of nuclear

reactors at the power plants owned by Tokyo Electric Power Company (TEPCO) at Fukushima (6 Boiling Water Reactors, BWRs, at Fukushima-Dai-ichi, and 4 BWRs at Fukushima-Dai-ni). However, hydrogen explosions and fuel core meltdowns, or "melt-throughs," at the Fukushima reactors occurred within a few days because there was no power to drive the pumps to cool them. This catastrophe has generated, and will generate, enormous economic costs as described below, although there were no fatalities directly associated with the nuclear power plant accident itself.

This nuclear catastrophe has not only created a global public debate about the social costs and benefits of nuclear power, but also poses a host of engineering and social scientific research questions. This paper is concerned with the question of whether the Fukushima catastrophe was an inevitable consequence of a natural disaster "beyond the conceivable hypothetical possibilities" (*soteigai*), as the

[☆]We thank Brad Carson, Tatsuo Hatta, Koichiro Ito, Tony Knowles, Satoshi Kusakabe, Kenji Kushida, Keita Nishiyama, Takashi Shimada, Frank Wolak, and colleagues at Stanford University and the Pacific Northwest National Laboratory for their comments and suggestions. This work has been partially funded by the National Energy Policy Institute. This paper reflects the views of the authors, and not those of colleagues, officials, or funders.

^{*}Corresponding author.

E-mail address: rothwell@stanford.edu (G. Rothwell).

then-incumbent management of TEPCO claimed. http://www.nytimes.com/2012/10/13/world/asia/tepcos-admits-failure-in-acknowledging-risks-at-nuclear-plant.html?_r=0. Or, whether there were inherent structural shortcomings in Japan's "nuclear industrial complex." What kinds of industrial restructuring, institutional reform, and public policies might be needed to avoid its recurrence? Our theoretical framework is comparative so that our treatment is not only relevant to the current Japanese situation, but also has general relevance for risk management at plant, industrial, and governmental levels for nuclear power regulation and for innovation in alternative energy sources.

The article proceeds as follows: to motivate a comparative approach, Section 1 highlights the causes and behavioral responses to serious accidents during three major nuclear crises: three Mile Island, Chernobyl, and Fukushima. Motivated by the three events' distinctive features, Section 2 presents a simple framework for comparing three modes of system coordination under great uncertainty, and, relying on the "Comparative Institutional Analysis" literature (Aoki, 2001, 2010), it examines the nature and performance characteristics of these alternative coordination modes. This helps identify some crucial factors for risk management, as well as operational efficiency and system innovation. Section 3 applies this framework to the Fukushima case and derives policy implications, as well as possible transition routes for reforming Japan's nuclear power industry. Section 4 concludes by discussing broader lessons for mitigating the risk of nuclear accidents elsewhere, especially where regulated monopolies or state-owned enterprises dominate power industries without a clear separation of operation, monitoring and responding to serious accidents.

2. Three nuclear power plant accidents: Three Mile Island, Chernobyl, and Fukushima

On March 28, 1979, an equipment malfunction combined with human error and miscommunication led to the partial melting of fuel in Three Mile Island (TMI) Unit 2, a light-water-moderated-and-cooled Pressurized Water Reactor (PWR). (Unit 2 had begun commercial operation three months earlier.) The plant's managers brought the reactor under control within 100 h without a hydrogen explosion or off-site contamination (President's Commission on the Accident at Three Mile Island, 1979). When U.S. President Jimmy Carter visited Three Mile Island on a cloudy Sunday, April 1, 1979, he was there to raise hope for an anxious nation. He was not there to intervene, but as an ex-nuclear submarine officer, he wanted to show the public that there was nothing to fear. The interface rules between his function as the U.S. President and the TMI Plant Manager had already been promulgated by the U.S. Nuclear Regulatory Commission (NRC) after its inception on January 19, 1975. Jimmy Carter did not involve himself with the decision-making at TMI, or in the investigation of its causes or consequences. After the release of the U.S. NRC (1983), the U.S. nuclear plant fleet's operating efficiency, as well as the hazard of unplanned outage, has been improving without serious incident. Since the TMI accident, U.S. nuclear power operators collectively nurture safety culture through the industry-regulated Institute of Nuclear Power Operations (INPO).

On April 26, 1986, operators of Chernobyl's Unit 4, a Graphite-Moderated/Light-Water-Cooled Reactor (RBMK) operating for two years, were testing the reactor's operating limits under low power. However, to conduct the test, some safety systems were disabled, and operators mistakenly reduced the power to near zero. At such low power, the reactor became unstable, leading to fluctuations, causing a steam explosion in the reactor at 01:23:44 (GMT+2), throwing up a cloud of steam and smoldering radioactive dust into the upper atmosphere. Plant managers called local firefighters, but the local population was not told of the

accident until after they were evacuated, nor was the explosion reported to the international community. When Mikhail Gorbachev, the last General Secretary of the Communist Party of the Union of Soviet Socialist Republics (1985–1991), broke his 18-day silence, he was the head of a bureaucracy that attempted to cover-up the damages throughout the chain of command, such that each higher level could claim "plausible deniability" of information known at lower levels. After the international community required an acknowledgment of the accident, the USSR continued to cover up damage information with no accounting of the health of hundreds of thousands of Soviet Army reservists sent to clean the Chernobyl site with shovels as "bio-bots," after the Soviet-era "robotas" failed.

In contrast to the previous two accidents, natural disasters triggered the accident at Fukushima. On March 11, 2011, following a magnitude 9.0 earthquake (one of the three largest in recorded history), TEPCO's BWRs in Fukushima Dai-ichi Units 1, 2, 3, and 4 began their systematic shutdowns (Units 5 and 6 were already shutdown for refueling). In shutdown mode, cooling water should have reduced the reactors' remaining decay heat. However, it soon became clear that not only was electric power from the conventional transmission grid unavailable because of earthquake damage, but also that the plant's back-up generators for emergency electric power were destroyed by the tsunami.

Facing this serious accident with total on-site power failure, the imminent question at Fukushima was, "Who had the ultimate authority and responsibility to make what decisions at these critical moments?" The Prime Minister issued a declaration of a "nuclear emergency" and established the Nuclear Emergency Response Headquarters (NER-HQ) in the Cabinet Office with himself as its Director.

However, the law that was the basis of these actions provides only a general organizational framework encompassing the central and local governments, the Nuclear Safety Commission (NSC), and relationships among concerned parties as described in Japan's *Act on Special Measures Concerning Nuclear Emergency Preparedness* (1999). The role of the NSC is a technical advisory one to NER-HQ. Besides, Article 64(3) of Japan's *Nuclear Reactor Regulation Law* authorizes the competent Minister to issue an order for a nuclear operator to take an action in a nuclear emergency that the government considers necessary, but the operator has not yet taken. Thus, the decision-making rules in a critical situation can have an element of hierarchical ordering. Yet, the sphere of decision-making authority of each stakeholder is unspecified and ambiguous.

Under this organizational framework, there can be too much demand for, or too little supply of, information across various stakeholders from each stakeholder's perspective. For example, among various stakeholders, including Prime Minister Kan and his aides, concerned Ministers, advisors from NSC, the Nuclear and Industrial Safety Agency (NISA), TEPCO headquarters, and the site manager at Fukushima (see Fig. 1), there were formal and informal exchanges of information, requests, and orders, sometimes interrupted by network difficulties, as well as mutual guessing of each other's intentions, hesitations to disclose unfavorable information or assume responsibility for decisive action; a situation that PM Kan described as a "language game" after his resignation as Prime Minister in September 2011.

During this period of clouded indecision, fuel melted in Unit 1 (March 11, 19:30); hydrogen exploded in Unit 1 (March 12, 15:36); fuel melted in Unit 3 (March 13, 09:00); hydrogen exploded in Unit 3 (March 14, 11:01); fuel melted in Unit 2 (March 14, 20:50); and hydrogen exploded in Unit 4 (March 15, 6:10) (Hatamura, 2011).

As a result, the estimated amounts of radioactive isotopes, such as iodine¹³¹ and cesium¹³⁷, emitted into the atmosphere amounted to about one-tenth and one-eighth, respectively, of

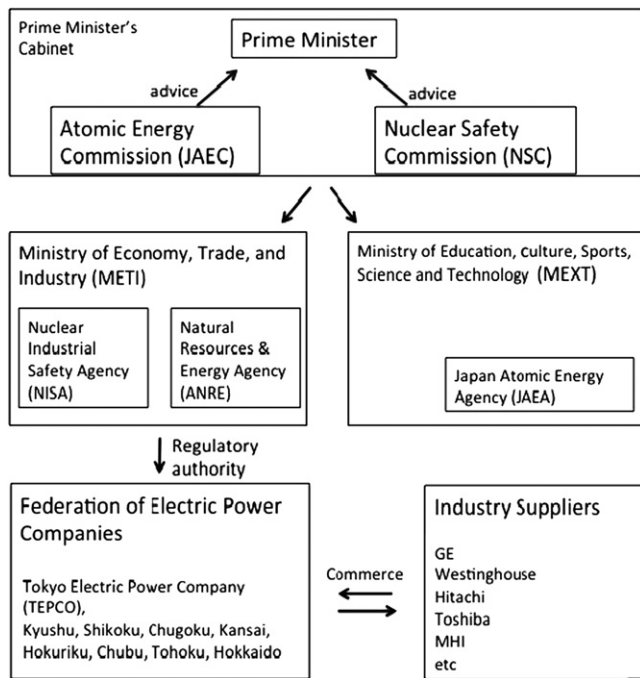


Fig. 1. Japan's Nuclear Industrial Complex Organization Chart.

those from Chernobyl (see *Kitazawa Report* (Kitazawa, 2012) pp. 45–49). While its long-term radiological health hazard is expected to add little above the background radiation (which, unfortunately, includes the fallout from the Hiroshima and Nagasaki blasts), enormous economic costs have already been incurred for compensating residents and businesses for temporary or permanent evacuations and damages inflicted on farming and fishing (estimated above \$60 billion).¹ Now that all units at Fukushima Dai-ichi are in “cold shutdown” (declared on December 16, 2011), the melted reactor interiors are so dangerously radioactive that it could be ten years before the reactors can be dismantled. While short-lived isotopes decay, the balance of the plant must be decontaminated, in particular, the water used to cool the reactors. TEPCO expected decommissioning to be finished in 2051. We will not know the total decommissioning cost for a half-century, and it is likely to be many multiples of the decommissioning cost of TMI.

The Shimokobe Report (Shimokobe, 2011) estimated the total cost of decommissioning to be \$13.6 billion by multiplying the decommissioning cost of TMI by 0.4 (for the four units at Fukushima Dai-ichi), plus the extra costs associated with decontaminating the cooling water, etc. (See Pasqualetti and Rothwell, 1991, on estimating decommissioning costs.) However, at Fukushima, some of the reactors have suffered from fuel melting through the reactor pressure vessel, which is much more costly to dismantle than when the fuel is contained within the reactor, as it was at TMI.

After the “accident phase” at Fukushima was “over,” the government, the Diet, TEPCO, and an independent private foundation formed fact-finding commissions. In addition, the U.S. NRC

formed a task force to review insights from the accident and derive regulatory implications for the U.S. These commissions and task force have published their interim and final reports, based on interviews and public hearings of large numbers of stakeholders, including ex-PM Kan and top managers of TEPCO at the time of the accident, research findings after the fact, examinations of documents including formal and informal memos of meetings at NER-HQ, etc. These committees include the following.

- (1) “Investigating Committee on the Accident at the Fukushima Nuclear Power Stations of Tokyo Electric Power Company,” formed by the Cabinet on June 7, 2011; chaired by Prof. Yotaro Hatamura, a risk management specialist. Its *Interim Report* and *Final Report* were published on December 26, 2011, and on July 23, 2012; we refer to them as the *Hatamura Reports* (Hatamura, 2012).
- (2) “Commission for Investigating the Management and Financial State of TEPCO,” formed by the Cabinet on May 24, 2011; chaired by Kazuhiko Shimokobe, a corporate attorney. Its final report was published on October 3, 2011; we refer to it as the *Shimokobe Report*.
- (3) “Independent Investigation Committee on the Fukushima Nuclear Accident,” formed by the Rebuild Japan Initiative Foundation (RJIF) on October 14, 2011; chaired by Dr. Koichi Kitazawa, former Chair of the Japan Science and Technology Agency. Its *Research and Investigation Report* was published in February 2012; we refer to it as the *Kitazawa Report* (Kitazawa, 2012).
- (4) “TEPCO’s Committee for Investigating the Fukushima Nuclear Disaster,” formed by TEPCO on June 21, 2011; chaired by Masao Yamazaki, then-Vice President of TEPCO. Its report was published June 20, 2012, before its 2012 stockholders general meeting; we refer to this as the *TEPCO Report* (TEPCO, 2012).
- (5) “National Diet of Japan Fukushima Nuclear Accident Independent Investigation Commission” (NAIIC), formed by the Diet of Japan on October 7, 2011; chaired by Prof. Kiyoshi Kurokawa, former President of the Japan Academic Council. Its report was published in July 5, 2012; we refer to it as the *Kurokawa Report* (Kurokawa, 2012).
- (6) “The Near Term Task Force,” formed by the U.S. NRC to review insights from the Fukushima accident and its report published in July 2011; see U.S. NRC (2011).

While topics covered by these reports are broad, some basic points appear to be more or less common in all the findings except for the TEPCO Report (TEPCO, 2012). This provides a basis for our discussion of the properties of coordination mechanisms during serious (nuclear) accidents.

- (1) There were too many micro-interventions by the NER-HQ. As an example, a visit by PM Kan to the site on the morning of March 12, 2011, interfered with the preparation of venting of hydrogen at Unit 1. In addition, NER-HQ’s attempts to obtain information directly from the site marginalized the engagement of layers of competent, intermediate bureaucrats.
- (2) TEPCO management did not exercise strong leadership during the crisis expected of a “concerned nuclear operator.” For example, between March 14 and 15, 2011, when the risk of a hydrogen explosion in Unit 2 was mounting, they sought the NER-HQ’s permission for their personnel to evacuate the site, which NER-HQ rejected. This incident reduced NER-HQ’s trust in TEPCO’s top management, and the Prime Minister ordered the formation of the Joint Emergency Headquarters within TEPCO’s headquarters, directed by the METI Minister and the President of TEPCO. This was seen as an improvement in information flows between the accident site and the

¹ See World Nuclear Organization, “Japan is not party to any international liability convention but its law generally conforms to them. Two laws governing them are revised about every ten years: the *Law on Compensation for Nuclear Damage* and *Law on Contract for Liability Insurance for Nuclear Damage*. Plant operator liability is exclusive and absolute, ... For the Fukushima accident in 2011 the government set up a new state-backed institution to expedite payments to those affected The government bonds total JPY 5 trillion (\$62 billion). The new institution ... will also operate as an insurer for the industry, being responsible to have plans in place for any future nuclear accidents.” <http://www.world-nuclear.org/info/inf67.html>.

headquarters, but the *TEPCO Report* (TEPCO, 2012) vehemently denies that TEPCO tried to abandon Fukushima.

- (3) At the site, Plant Manager Yoshida exercised strong leadership with his dedicated staff laboring in the dark with increasing levels of contamination, while their families struggled with the tsunami's results at their homes. Although they sometimes made mistakes in judgment dealing with the four nuclear reactors having varied vintages and engineering characteristics, they finally succeeded in overcoming the critical situation without proper emergency preparedness and risk-mitigating procedures. For example, on March 12, 2011, Plant Manager Yoshida ordered the continued injection of seawater to cool Unit 1, secretly defying TEPCO headquarters, which was misreading or misunderstanding NER-HQ's apprehensions or hesitations.

Comparison of these findings with the cases of TMI and Chernobyl point to an important theoretical question concerning effective coordination mechanisms in the event of serious accidents: what is to be the division of responsibility between the off-site system decision apex (corporate headquarters) and the on-site director? For example, Plant Manager Yoshida's decision to use seawater for cooling is widely applauded by the public as having prevented a more serious accident. On the other hand, one of the reports cautions against praising his "runway" behavior, even if his judgment were right in retrospect, "the site manager cannot substitute for" what is the government's responsibility (Kitazawa Report, (Kitazawa, 2012) pp. 118–119, 302). Such opposing views provide excellent points of discussion on the organizational causes and consequences of nuclear power plant accidents.

Should the onset of serious nuclear accidents be considered as more or less inevitable, beyond human control? Should we expect a nuclear power plant accident every 10,000 reactor-years? Subsequent to the nuclear disaster, the *TEPCO Report* (TEPCO, 2012) insisted that the magnitude of the tsunami had been beyond any hypothetical possibility (*soteigai*). However, warnings of possible natural disasters of that magnitude were known before the catastrophe.

A historical document, *Nihon Sandai Jitsuroku* (the last of the six national histories, *rikkokushi*, covering the reigns of Seiwa, Yozai, and Koko, compiled in 901), recorded a tsunami of similar magnitude in Tōhoku in July 869 referred to as the "Jyokan-Sanriku" earthquake. According to this document, the number of deaths from this disaster was more than 1000 in a population of 7 million, approximately proportional to 20,000 deaths in a population of 127 million in the 2011 Tōhoku disaster. The Japanese nuclear regulator, industry officials, and TEPCO's management dismissed this and other historical data as exaggerations, typical of historical narratives. Recent geophysical research confirmed, however, that tsunamis caused by earthquakes greater than magnitude 8.0 took place six times in Tōhoku during the last 6000 years.

Based on such historical and scientific research, concerns over the inadequacy of defenses against a tsunami were expressed by scientists at meetings of the Advisory Committee on Energy and Natural Resources reporting to the Minister of METI in June and July 2009. The Committee's *Interim Report* did not reflect these warnings. According to the *Hatamura Interim Report* (Hatamura, 2011), TEPCO did a confidential simulation study of the possible impacts of tsunamis with 10–15 m surges at Fukushima. Nevertheless, TEPCO delayed reporting the results to the NISA until March 7, 2011, four days before the disaster, and well after the 40-year-old Fukushima Unit 1 (which entered commercial service on March 26, 1971) was re-licensed. TEPCO released the confidential report on October 3, 2011 (JAIF, 2011).

This episode indicates that (1) if the warnings based on scientific studies outside TEPCO had been taken seriously earlier

by the regulatory agency, and (2) if the relocation of back-up power sources had been accordingly implemented, the natural disaster's consequences could have been less serious, particularly if Unit 1 had been closed in anticipation of the end of its 40-year life. The failures are indicative of the regulatory framework, as well as that of the corporate governance structure of Japan's nuclear power industry. However, the unstructured coordination in the accident phase has the same root cause as the lack of sufficient preparation. Therefore, what is the relationship between how the Japanese nuclear power complex coordinates its operations during a normal state and how it coordinates its operations during an emergency state?

3. Three modes of system coordination and their comparative properties

The previous discussion of nuclear power plant accidents alludes to a possibility of three modes of coordination in the event of a serious accident, or more abstractly in an environment facing large, convoluting uncertainties. They are crudely identifiable in terms of the relationship between the on-site unit (where a critical event happens) and the off-site system decision apex (which is responsible for the system wide performance) in a system's reaction to a large shock.

Namely, their relations may be (1) differentiated and specialized according to previously determined rules of law (as in the case of TMI), (2) hierarchically ordered (as in the case of Chernobyl), or (3) subjected to *ad hoc* negotiation (as in the case of Fukushima). However, it is hardly expected that each of these possibilities can or will become viable only in an isolated event of a shock. Their workings would be related to how the stakeholders in a system coordinate their decisions in a normal environment, as well as how the system anticipates and prepares for possible serious shock. There would be then some degree of homomorphism in systemic coordination across the three states: the "normal" state, the "emergency-drill" state, and the "emergency" state. However, which coordination mode works better depends on the nature of the system's environment, as well as on characteristics of various instruments and resources that a system possesses to achieve its objectives. They may include, among others, technologies, stakeholders' competences and preferences, and the governance structure.

To approach this complex issue, we first identify three modes of organizational coordination in generic terms and, relying on the existing literature of comparative institutional analysis, examine what factors are crucial in determining the performance characteristics of each. The three coordination modes are distinguished by (1) the distribution of information processing, (2) the route and level of communications, and (3) the distribution of decision-making authority among constituent units to achieve the system's common objective. The three modes are as follows.

M-Mode: The "open-interface/rule-based *modular*" mode: a system composed of units; each specialized in a particular function and connected through *ex ante* agreed upon interface rules. As long as each unit is following these rules, (1) each unit can "encapsulate" its own information processing, (2) makes a decision on its own action without intervention of other units, and (3) communicates its actions only according to *ex ante* rules. For example, the division of labor between the U.S. President and the TMI Plant Manager represents a pre-determined modular (encapsulated) approach to nuclear power plant risk management.

V-Mode: The "top down" or "*vertical control*" mode is the one most studied in classical organizational theory. It is a system in which constituent units are arranged in an "upside-down tree" structure, in which information (command and report) flows

only along vertical control lines, and rarely across horizontal levels (and can result in disciplinary action).

H-Mode: The “horizontal coordination” mode: In this mode, information about evolving environments is pooled and shared among constituent units engaged in mutually complementary actions with respect to the system’s objective, and decisions on actions are adjusted and negotiated among them. As discussed more below, we consider the chaotic response prevailing in Japan at the time of the Fukushima nuclear disaster as a dysfunctional or degenerated example of the H-Mode.

The following propositions synthesize the theoretical literature comparing these organizational coordination modes:

Proposition 1. If the system’s environment is very stable, the Vertical V-Mode based on *ex ante* planning can function comparatively well in achieving its system objective. If the system’s environment continually changes, the Horizontal H-Mode can function comparatively better, if stakeholders’ competences are equally distributed across units (Aoki, 1986, 1990). (Rothwell, 1996, empirically verified this proposition by analyzing data on periods of operation and outage at U.S. nuclear power plants.) However, when the environment changes drastically (i.e., with a large shock), the H-Mode may yield highly unstable outcomes (Aoki, 1990). Thus, the H-Mode may be superior in terms of “just-in-time” coordination in the normal state of affairs, but not in terms of “just-in-case” response. If a drastic change occurs in the local environment of a constituent unit, the H-Mode cannot respond to it in a timely and appropriate manner that fits the situation (Fukushima is an illustration of this).

Proposition 2. If uncertainty facing different units differs significantly among the units, the Modular (M)-Mode performs comparatively better, if the actions of constituent units are not strongly complementary (dampening destabilizing dynamic feedback effects). If the actions of constituent units are substitutable, M-Mode performance does well (Cremer, 1990).

Corollary 2A. Suppose the system includes (1) an on-site unit subjected to a sudden, large shock, and (2) headquarters responsible for controlling its overall effects. Suppose the stakeholder’s competence at the site is “essential” (in the sense of Hart, 1995), i.e., the marginal effectiveness of action at headquarters cannot be enhanced without the proper input of on-site information and resources. If this is the case, specific information processing tasks and decision-making on-site and headquarters should be, and can be, made distinct and their interactive mode should be clearly specified *ex ante*. If the response to an emergent on-site shock needs to be swift, and specific to prevent its effect from propagating throughout the system, decisive on-site action is better delegated to the site before an emergency.

Corollary 2B. Under the conditions in Corollary 2A, the off-site headquarters should commit before an emergency not to intervene in on-site decision-making. Proprietary-based governance will not work in this case, because it can only hurt the incentives of on-site stakeholders (this is an adaptation of Hart’s theorem on property rights, see Hart, 1995).

Proposition 3. These propositions and corollaries are based on the assumption that all stakeholders in each mode share a notion of the fair division of the system’s performance outcome based on contributions of respective stakeholders (technically represented by the Shapley value). If and only if this is true, then the individual stakeholder’s pay-off maximization will align with system maximization (Aoki, 2012). If the stakeholder of a specific constituent unit becomes entrenched in particular rent-seeking behaviors, the advantage of a mode could be lost.

Proposition 4. One of the known advantages of the Modular M-Mode is its ability to self-organize innovation through competitive intellectual property markets. By incorporating multiple modules pursuing the same function in a system, the system selects the best module through evolutionary competition. In environments where uncertainty is very high, such a mechanism allowing for duplication, substitution, splitting, and the addition of modules according to open-interface rules can create high option values (Baldwin and Clark, 2000) and high innovative incentives (Aoki and Takizawa, 2002) in spite of duplication costs. This is analogous to the gains from multiple experiments when possible experimental outcomes are highly uncertain.

Proposition 5. Analogously, consider the “defense-in-depth” strategy for preventing serious accidents and mitigating their possible damages. This strategy is to install independently operating, modular systems that can be successively mobilized. This requires redundancy in safety measures and a “philosophy of defense-in-depth” (U.S. NRC, 2011). This is different from a monolithic approach to the risk assessment in which safety measures are designed for a hypothetical degree of risk, e.g., 10^{-5} . As exemplified in the Fukushima case, if the hypothesis fails, then *ad hoc* negotiations among the stakeholders can become dynamically unstable, leading to system failure.

4. Un-bundling integrated regional electric utilities by applying the power of modularity

The structure of the U.S. electric utility industry approximates the M-Mode in that there are hundreds of electricity generating entities, some are rate-of-return regulated, some compete in power markets, and some are state owned. With so many different ownership and regulatory combinations, a modular structure has evolved to encapsulate entity rights and communication responsibilities. Further, in terms of nuclear safety, the U.S. NRC limits itself to safety rule making, and the monitoring and enforcement of these rules, while these rules assign on-site response to accident sequences to on-site management (Corollary 2A). However, this system also experienced the 2001–2002 California electricity crisis caused by the exercise of market power by some electricity traders taking advantage of bugs in the initial version of the market software. Since then, the stability of the U.S. electricity industry has improved in terms of price stability.

In contrast, the Japanese industry was once considered as having organized itself on H-Mode principles (Aoki, 1990; for its historical legacy, see Aoki, 2012). Before the Fukushima disaster, TEPCO was considered an iconic, successful representative of this traditional Japanese mode. It was a regional integrated monopoly that supplied 29% of Japan’s power in 2010 to twenty-four million households and more than two million businesses in the Tokyo metropolitan area. TEPCO owns 17 nuclear power units at Fukushima and Kashiwazaki–Kariwa, thermal plants, and transmission and distribution grids. TEPCO claimed they practiced “seamless” coordination among their business units to meet electric power demand continuously under regulated prices.

Consequently, TEPCO boasted of its extremely low probability of power outage in response to seasonally fluctuating demand. However, inside the integrated system, lengths of voluntary and involuntary outages at TEPCO’s nuclear power plants have been high, for example, following the earthquake at Kashiwazaki–Kariwa on July 16, 2007, which damaged the plant in ways very similar to the earthquake damages at Fukushima. This suggests the existence of slack capacity. However, dozens of nuclear power units were shut down subsequent to the Fukushima crisis due to breakdowns, precautionary suspensions of operation, and regular maintenance, cutting total power supply of TEPCO by 25%. The

expected power shortage during the summer of 2011 did not occur due to the collective sacrifice of scores of millions of Japanese.

Actually, behind the claim of “seamless” coordination among various functional units, bureaucratic compartmentalization was creeping into TEPCO’s organization. The TEPCO Chairman and CEO have never had primary expertise in nuclear engineering, but in government relations or business negotiations. TEPCO exercised enormous market power not only as a regulated monopoly in the supply of electricity, but also in terms of enormous purchases in wide-ranging markets, such as industrial equipment, fuel, financial services, real estate, and advertising. TEPCO was able to shift costs to regulated tariffs, resulting in electric power prices that were 50% higher than in the U.S. and South Korea before March 2011.

Also, the division of nuclear power engineering within TEPCO came to be highly entrenched because of (1) its reliance on very specialized experts, (2) the sharing of an exclusive sense of community (an “us-versus-them” mentality), and (3) the absence of effective corporate and regulatory monitoring. The government safety regulator, the NISA, was a division of the METI, which promotes nuclear energy development; see Fig. 1.

Thus, NISA could not autonomously monitor the safety of nuclear power generation. It is problematic to place a regulatory agency under a government ministry, in which the head of the agency reports to a minister, because interest-group politics could influence the safety regulator’s decisions. There was an implicit and explicit collusion between the regulator and the regulated, entrenching both in a self-promoting nuclear industrial complex. They had not effectively responded to scientific or public warnings of possible natural disaster while regulators as well as top management of TEPCO, lacking both expertise in nuclear engineering and motivation of monitoring, did not intervene. It is telling that the entrenched group of nuclear specialists, bound by mutual beliefs, was nicknamed the “nuclear power village” within TEPCO, reminiscent of the legacy of the closed community norms prevailing within Japanese villages in the Edo period (1603–1868) (Aoki, 2012). The Fukushima nuclear disaster dramatically revealed a consequence of these elements of the degenerated H-Mode (Proposition 3).

What organizational lessons can be drawn from analyzing these events? Can those lessons be incorporated into the Japanese nuclear power industry without drastically reforming the industry and its regulatory framework? Recall Proposition 1 that the H-Mode coordination may be superior in terms of “just-in-time” coordination in the normal state of affairs, but not in terms of “just-in-case” preparation. Would it be possible to use H-Mode coordination in the normal state of affairs, but switch to modularity after a large shock (Corollary 2A)? This is unlikely, because actions of constituent units of corporate organizations are normally taken based on their shared beliefs about others’ expectations and actions in the normal state of affairs (see Aoki, 2010, Ch. 2, on “corporate culture” as a common framework for intra-corporate games). Such a matrix of expectations is not malleable with a sudden shock.

Furthermore, M-Mode coordination is gaining in its comparative advantage with the commercial deployment of distributed electricity generating technologies (Proposition 2). In addition, modularity is more innovation enhancing (Proposition 4) and has more affinity to defense-in-depth (Proposition 5). Therefore, the orientation of reforming Japan’s nuclear power industry should be in the direction of incorporating more elements of modularity at the levels of the plant, the firm, the industry, and the regulator. Historically, there were discussions within the MITI in the late 1990s, and its successor METI in the early 2000s, regarding the possibility of separating Japanese power generation from transmission. However, such reform did not materialize under strong

political resistance of the regional electric power utilities. They argued it would have been detrimental to the “quality supply of power.” This is a case of Stigler’s “regulatory capture” (Stigler, 1971), where the Japanese nuclear safety regulator was captured by the regional electricity monopolists.

Now the situation has changed dramatically in the aftermath of the Fukushima nuclear disaster. TEPCO will be short of cash in meeting all disaster related liabilities and the costs of decommissioning Fukushima Dai-ichi Units 1–4. According to a simulation study discussed in the *Shimokobe Report*, the net value of TEPCO could be negative in 2013 without nuclear plant operation and without increases in retail tariffs. Thus, the Nuclear Damage Liability Facilitation Fund (NDF) was established by the government in September 2011 to mediate the injection of public funds into TEPCO on the condition that the METI Minister approve the NDF–TEPCO joint management plan. The Minister approved such a plan in April 2012, NDF now owns a majority of voting stock of TEPCO and a new corporate board, dominated by outside, independent directors, was appointed at the stockholders’ meeting of TEPCO in June 27, 2012.

One possible scenario is to transform TEPCO into a holding company similar to the one through which the public-owned monopoly of telephone communications, NTT, was restructured in 1999. Another possibility is to functionally separate generation from transmission under the supervision of an independent commission. Alternatively, electricity generation of various types (including operations of existing nuclear plants, after passing stress tests) and retail, could be spun off as independent corporate entities, or acquired by existing corporations outside the traditional power industry. These require revisions of Japan’s *Electricity Utility Law* that specifies the current industrial structure of integrated regional utilities, which is assumed to take two years to implement. In any case, it is likely that the crucial transmission grids will remain under state ownership. Public ownership of grids is based primarily on the experience in electricity deregulation that the transmission grid is a natural monopoly (Rothwell and Gomez, 2003).

If suppliers and customers of power were linked through a functionally neutral electric and information transmission system on a competitive basis, incentives would be created for energy conservation, on the one hand, and the development of alternative energy sources and power storage, on the other. Various power generators, including nuclear, thermal, hydro, solar, wind, geothermal, and other renewables, can be connected as mutually autonomous modules (e.g., as independent corporate entities) and compete for investor attention. In addition, various firms outside the traditional electric power sector may become active players in the system, for example, members in fields such as information technology, thermal-power cogeneration (e.g., steel, petrochemicals), the plug-in automobile industry, architectural design and construction, and new generations of batteries and electric equipment manufacturing. The system as a whole can then self-organize its innovation through evolutionary selection from among these modular players rather than through *ex ante* planning by an integrated monopoly such as TEPCO (Proposition 4).

The remarkable speed of innovation in the information, communications, and pharmaceutical industries in the last few decades could be largely due to the development of modular industrial organizations. Unbundling electricity generation, transmission, and distribution in one way or another, and re-combining human and physical resources could unleash institutional innovation under the implementation of the open-interface/rule-based modularity mode. Recall Schumpeter’s definition of innovation: “creative destruction and recombination.”

Finally, the clear separation of nuclear plant management and their regulator is imperative. After the disaster, the Japanese

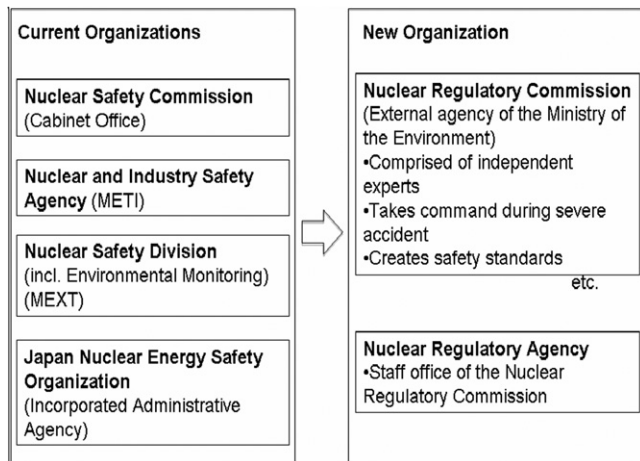


Fig. 2. Reorganizing Japan's Regulation of the Nuclear Industrial Complex.

government proposed to remove the regulatory agency, NISA, from the METI (see Fig. 1), and place the Nuclear Power Regulatory Agency (NPRA) under the Ministry of Environmental Protection. However, this proposal was met with heavy public opposition. In response, the Diet enacted a law in June 2012 to create the Nuclear Regulatory Commission composed of five specialists, with the NPRA serving as its secretariat. (See Fig. 2.) This Commission is charged with regulatory rule making and with a right to directly “command” the site in the case of nuclear emergency. While improving the present situation, these *ad hoc* arrangements at the time of a crisis do not appear consistent with Corollary 2A.

5. Making the interface rules in the modular system stable and innovation enhancing

The M-Mode of coordination is defined as a system in which constituent units are linked only through explicit, open-interface rules, and each unit can encapsulate its own information processing within itself. With the electric power industry, the operator of the transmission grid can mediate such coordination by setting rules for information exchange for supply and demand. Such rules can limit the exchange of information among modular units simply to prices and quantities at designated moments in time. How can rules for the matching between demands and supplies be designed and implemented from a long-term perspective without sacrificing short-term efficiency? Regarding the implementation of electricity market reforms, we discuss some final points:

First, retail distributors and large consumers can negotiate and settle on long-term contracts with constraints on their potential exercise of short-term market power. In the electric power industry, suppliers may be able to create monopoly power by creating artificial shortages by deliberately shutting down their plants for unscheduled maintenance, if only the spot markets are to be used (Bornstein, 2002; Wolak, 2003b). Long-term contracts can both constrain the artificial creation of short-term monopoly power by suppliers and facilitate long-term investment planning.

Second, on the consumer side, consumers can contract for power for a specified quantity under a fixed price, and then pay a current spot market price (e.g., the “day ahead” price) beyond the limit, while rolling over unused quantities, as in cell phone service (Bushnell et al., 2009). Such dynamic pricing mechanisms can be supported by introducing Internet friendly smart meters and smart grids. This would motivate consumers’ (particularly, large, industrial customers) to respond to changing supply conditions. Under

the present situation, TEPCO is obligated to meet forthcoming demand under regulated prices to consumers, being forced to maintain extra productive capacity to avoid black outs. With long-term contracts on both sides of the electricity market, consumers with excess supply could release these into spot markets.

Third, competition in electricity supply can be accomplished by first introducing “cost-based dispatch” (Wolak, 2003a; Falconett and Nagasaka, 2009) in which generating companies submit their start-up, no-load, and variable costs, or supply schedules contingent on spot market prices, to an Independent System Operator (ISO). The ISO then requests power per hour from generating companies to minimize total cost and maximize reliability in meeting electricity demand. The ISO facilitates energy trading in the spot market based on the marginal cost of generators. Consequently, generators compete based on their production cost. The clearing price in the spot market is equal to the cost of production of the last generating unit dispatched. Given the present state of information and communication technology and the expertise that TEPCO already possesses on the upstream side, the operation of such smart grids should be feasible in Japan.

This paper has primarily dealt with the most recent experience at the Fukushima nuclear disaster. However, our intention is comparative, and to derive general lessons from it for making the electric power industry more efficient, safer, and innovative. Particularly, the scrutiny of fundamental cause of the Fukushima nuclear disaster and subsequent, on-going transformation of Japan’s power industry may hopefully offer valuable lessons for countries such as China, where two-dozen nuclear power plants are being built, and more than 100 plants are being planned, yet there is no clear-cut institutional separation between safety regulation and industrial plan implementation (Rothwell, 2003).

Comparing Japanese and Chinese nuclear safety regulatory requirements, Japan’s nuclear industry uses (either in operation or active construction before March 2011) 1 reactor type (light water reactors, LWRs) with 2 nuclear suppliers of Boiling Water Reactors, BWRs, and Pressurized Water Reactors, PWRs, with 8 reactor models (BWR-2: 1; BWR-3: 2; BWR-4: 5; BWR-5: 18; ABWR: 6; PWR-2 loop: 8; PWR-3 loop: 9; and PWR-4 loop: 7). The Japanese nuclear safety regulator has not been able to effectively regulate (e.g., in re-licensing) older models with one or two units, such as the BWR-2 with one unit (Tsuruga-1 connected to the transmission grid since November 1969) and BWR-3 with two units, Fukushima Dai-ichi Unit 1 among them.

On the other hand, China’s nuclear industry uses 2 reactor types (LWRs and heavy water reactors, HWRs, with helium gas reactors under development) with 5 nuclear suppliers (Canadian HWRs, Chinese PWRs, French PWRs, Japanese–American PWRs, and Russian PWRs) with 7 reactor models (Canadian CANDU: 2; Chinese Nuclear Plant, CNP-300 MWe: 1; CNP-600: 6; CNP-1000: 24; French European Pressurized Reactor, EPR: 2; Japanese–Westinghouse Advanced Passive-1000: 4; and the Russian VVER: 2). With so many reactor types and suppliers, China’s nuclear power industry has had much technology transfer, but its nuclear safety regulator will have its hands full with so many orphaned units. Unless China, as well as other countries where new nuclear power plants are being or will be built, establishes a strongly independent and highly professional nuclear safety commission, its quest for safe nuclear power could be derailed by another accident.

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