Coordination under Large Uncertainty: An Analysis of the Fukushima Catastrophe

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ABSTRACT

This paper analyzes the impacts of the March 11, 2011, Tōhoku earthquake and tsunami on the Fukushima nuclear power plant in Japan. These impacts were amplified by a failure of horizontal coordination across plant, corporate, regulatory, and governmental levels, resulting in a nuclear catastrophe, comparable in cost to Chernobyl. Lessons learned include identifying two shortcomings of the typical Japanese horizontal coordination mechanism: instability under a large shock and the lack of defense in depth. The suggested policy response is to harness the power of "open-interface, rule-based modularity" by introducing an independent nuclear safety commission in Japan and an independent system operator to coordinate sellers and buyers on publicly-owned transmission grids. (Abstract WC ≈ 110, Article WC ≈ 5,500)

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Three Nuclear Power Plant Crises: Three Mile Island, Chernobyl, and Fukushima

The Tōhoku earthquake of magnitude 9.0 off the coast of Japan, and the accompanying tsunami with the surge of more than 12 meters, hit the Fukushima nuclear power plants in 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 Dai-ichi reactors occurred within a few days because there was no electricity to drive the pumps to cool them. This catastrophe has generated still-unknown public costs, symbolized by the emissions of cesium 137, equivalent to 168 times of release from the detonation of the atomic bomb at Hiroshima, although without the immediate loss of life associated with an atomic blast. (Most of the about 20,000 deaths from the tsunami were from drowning.)[1]

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This nuclear catastrophe has not only generated a global public debate regarding the social costs and benefits of nuclear power generation, but also poses serious engineering and social scientific research questions. In this paper we are concerned with the question of whether the extent of the accident at Fukushima was an inevitable consequence of a natural disaster "beyond the conceivable hypothetical possibilities" ("*soteigai"*), as TEPCO claims; or whether there were inherent shortcomings in the structure of Japan's nuclear power industry. What kinds of public policies are needed to deal with the economic and social costs of the catastrophe? How should this industry be restructured to be more robust to extreme shocks?

Our theoretical framework is comparative so that our treatment is not only relevant to the current Japanese situation, but also has relevance for public risk management, for the regulation of integrated monopolies, and for innovation in alternative energy sources. To motivate such a comparative approach, we first highlight briefly the causes and behavioral responses to the emergencies during three major nuclear crises: Three Mile Island, Chernobyl, and Fukushima.

On March 28, 1979, an equipment malfunction combined with human error led to the melting of fuel in Unit 2 of the Three Mile Island nuclear power plant with light-water-moderated-and-cooled Pressurized Water Reactors (PWRs). (Unit 2 had begun commercial operation three months earlier.) The reactor was brought under control within 100 hours without a hydrogen explosion or off-site contamination. So when U.S. President Jimmy Carter visited Three Mile Island on 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 that there was nothing to fear. The interface rules between his function as the U.S. president and the Three Mile Island 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 Three Mile Island, or in the investigation of its causes or consequences.

On April 26, 1986, operators of Chernobyl's Unit 4, a Graphite-Moderated/Light-Water-Cooled Reactor (RBMK) operating since March 1984, 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 1%. At such low power, the reactor became unstable, leading to fluctuations in power up to 100 times normal, causing a steam explosion that blew off the top of the reactor at 01:23:44 (GMT+2). 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

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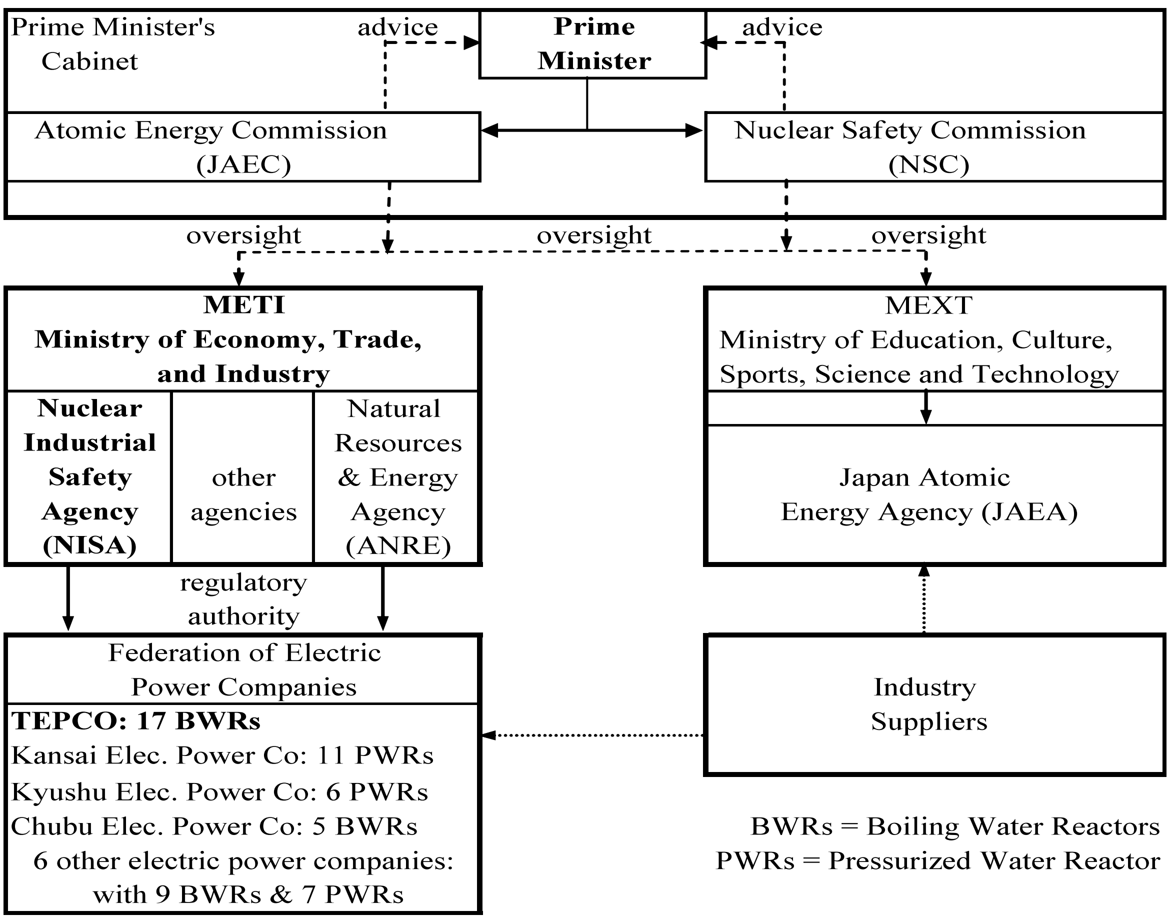
head of a chain of command that determined on the morning of the accident to forever cover up information regarding the damages. This cover up has continued with all countries of the Former Soviet Union with no accounting of the health of the 500,000 Soviet Army Reservists who shoveled chunks of highly radioactive graphite off the Chernobyl site, or the residents of Chernobyl who spent April 26, 1986, absorbing that morning's explosive radioactive release.

In contrast to the previous two cases, the crisis at Fukushima, Japan, was triggered by natural disasters. On March 11th, following a magnitude 9.0 earthquake, TEPCO's Boiling Water Reactors (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 transmission grid unavailable because of earthquake damage, but also that the plant's back-up generators had failed during the tsunami. Further, personnel at all levels were forced to take care of the personal consequences of the Tōhoku earthquake and tsunami, as well as the consequences at Fukushima Dai-ichi.

On March 11th, the imminent question was, "Who had the ultimate authority and responsibility to make decisions these critical moments?" Prime Minister Naoto Kan inspected TEPCO's ten BWRs at both Fukushima sites (Dai-ichi and Dai-ni) with the plant manager, Mr. Masao Yoshida, giving him his first hands-on experience with nuclear power. (The Prime Minister had come to distrust TEPCO through his career experience in civic movements and because TEPCO had been caught lying about the quality of Fukushima Dai-ichi Unit 1's containment in 2002.) Two top managers, Chairman Katsumata and President Shimizu, were both out of Tokyo and away from TEPCO headquarters for more than 20 hours after the earthquake. Between various stakeholders, including the Prime Minister and his advisors, the Nuclear and Industrial Safety Agency (NISA, see Figure 1), TEPCO headquarters, and Fukushima, there were continuous verbal exchanges, continuous mutual guessing of each others' intentions, and continuous hesitations to disclose unfavorable information or take decisive action; a situation that Kan described as a "language game" (presumably in the Wittgensteinian sense) after his resignation as Prime Minister. During this period of indecision, fuel melted in Unit 1 (March 11th, 19:30), hydrogen exploded in Unit 1 (March 12th, 15:36), fuel melted in Unit 3 (March 13th, 09:00), and fuel melted in Unit 2 (March 14th, 20:50); see NEA (2011) and Wikipedia (2011).

On March 15th, during a meeting starting at 05:30, involving the Prime Minister, his staff, and TEPCO officials, dual hydrogen explosions damaged the roof of Unit 2 (06:10) and in the reactor building of Unit 4 (06:14). It is unclear what TEPCO officials might have known about the state of their melted reactors at the start of the meeting, but with televised explosions during the meeting, the Prime Minister became furious and sent the Minister of the Ministry of Economy, Trade, and Industry (METI) to TEPCO's headquarters to set up and co-chair the committee supervising crisis management with TEPCO's President. While information sharing among stakeholders improved after the meeting on March 15th, the usual method of making decisions in Japan failed in March 2011, and the Prime Minister resigned in September 2011 under the mounting public criticism of his failure to effectively mobilize and coordinate available resources to respond and contain the impacts of the disaster.[2]

Figure 1: Japan's Nuclear Industrial Complex Organizational Chart



Source: http://www-pub.iaea.org/MTCD/Publications/PDF/CNPP2011_CD/countryprofiles/Japan/Japan2011.htm

Three Prototypical Organization Architectures

These three episodes may be regarded as unique events in extraordinary circumstances, but each of them is indicative of information architectures in and around the respective nuclear power plants, and the associated mode of response to an extraordinary event. To understand their distinctive features, imagine a system composed of many units designed for specific tasks or functions, with three methods of connecting them: (1) the "open-interface, rule-based modular" mode, (2) the "top-down" or "vertical-control" mode, and (3) the "horizontal-coordination" mode.

The first, the "open-interface, rule-based modular" mode, is a system composed of units; each specialized in a particular function and connected through *ex ante* agreed upon interface rules. As long as it is following the rules, each unit can "encapsulate" its own function without intervention by other units. The information systemic properties of this mode have been theoretically analyzed by Cremer (1990) and Aoki (2001, Ch. 4), and applied to an interpretation of the post-IBM industrial organization of the information and communications industry by Baldwin and Clark (2000).

The idea of modularity can be applied to various levels: the engineering design of a plant, organizational architecture, and industrial organization. At the level of nuclear power plant design, a pressurized water reactor (PWR) can be considered as a set of equipment modules inserted into a nuclear-grade concrete structure. These modules are (1) the reactor, (2) the steam generator, (3) the turbine-generator-condenser, (4) the transformer and electrical equipment, (5) the cooling and plumbing systems, and (6) instrumentation and controls. In recent designs of Small Modular Reactors (SMRs), based on naval reactors, the reactor and steam generator are being integrated into a single module, which can be installed in increments (45-200 MWe) to more closely match local demand conditions. Most SMRs have passive safety systems that do not require active intervention to activate, see Rothwell (2011).

One of the known advantages of the modular mode is its ability to self-organize innovation. Baldwin and Clark (2000) explain how multiple modules pursuing the same function can lead to the selection of the best performing module through evolutionary competition. In environments where uncertainty is very high, a mechanism allowing for duplication, substitution, splitting, and the addition of modules according to open interface rules can create higher option values in spite of the costs of duplication. It is analogous to the gains from multiple experiments when possible experimental outcomes are uncertain. An analogy to this is the defense-in-depth in the design of the nuclear plants where multiple backup devices to correct engineering failures are built into the structure, and their operation are successively triggered according to *ex ante* design rules. Below, we apply the concept of modularity at the firm and industrial levels, and discuss its importance to the safety, efficiency, and innovation of nuclear power generation.

The second, the "vertical-control mode," is the one most familiar to economists and organizational theorists. It is conceptualized as a system in which constituent units are arranged in an "upside-down" tree structure, and (command and report) information flows only along vertical control lines, and rarely across horizontal levels. It is known that such a mode performs relatively well when there is a low degree of uncertainty because scarce information processing capacities are held at the top of the chain of command (Aoki 1986). However, as can be seen after the Chernobyl explosion, rigorous applications of this mode may not be conducive to dealing with a crisis when speedy use of on-site information is critical.

The third, the "horizontal-coordination mode," at the most generic level is one in which information about evolving environments is shared among constituent units engaged in complementary functions, and decisions on respective outputs are continually adjusted/negotiated among them. The theoretical properties of such mechanisms have been analytically studied by Aoki (1986), Cremer (1990), Alonso, Dessein, and Matouschek (2008), and others. It is known to perform better than the vertical-control mode if the environment changes continually, but not drastically, and if functions of constituent units are technologically complementary. Aoki (1990) wrote (emphasis added), "if environments are *extremely volatile or uncertain,* [horizontal coordination mode] adaptation to environmental changes may *yield highly unstable results*."

Rothwell (1996) empirically tested the relative performance of horizontal coordination versus vertical control with data on periods of operation and outage at most nuclear power units in the U.S. between January 1976 and December 1985. Rothwell estimated parameters that supported the proposition that the horizontal-coordination mode is associated with longer periods of operation and that the vertical-control mode is associated with shorter periods of outage, where the organizational structure of the nuclear power plant was measured with an index of hierarchy based on nuclear power plant organization charts in Olson et al. (1984) from the Final Safety Analysis Reports (FSARs) required by the U.S. NRC. Because plants are operating a higher percentage of the total time, horizontal organizations are generally superior to vertical organizations.

The 3-'11 Failure of the Japanese Horizontal-Coordination Mode at Fukushima

TEPCO is a regional integrated electricity 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. They own 17 nuclear power units at Fukushima and Kashiwazaki-Kariwa, thermal plants, and transmission and distribution grids. There was "seamless" horizontal coordination among various power generating plants, transmission, and distribution systems to meet electric power demand under regulated pricing. As a consequence, TEPCO boasted of its extremely low probability of power outage in response to seasonally fluctuating demand. However, inside the integrated system, we find that the 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 extremely similar to the earthquake damages at Fukushima on March 11th.[3] This suggests the existence of ample slack capacity. Dozens of nuclear power units were shut down subsequent to the March 11th crisis due to breakdowns, precautionary suspensions of operation, and regular maintenance, cutting the capacity of the total power supply of TEPCO by 25%. The expected power shortage during the summer of 2011 did not occur, however, and capacity use barely exceeded 90% (which was due to the collective sacrifice of millions of Japanese).

In spite of its apparent performance in the normal state of affairs, however, aspects of the horizontal-coordination mode at the corporate and industrial levels that manifested themselves in response to the natural disaster clearly failed to contain its impacts to a more reasonable level. The ambiguity in the decision-making locus and the failure of continuous-negotiation among stakeholders can be exemplified in the decision to cool reactors with seawater. New York Times (2011a) published,

> "On the evening of March 12, the Fukushima Dai-ichi nuclear plant's oldest reactor had suffered a hydrogen explosion and risked a complete meltdown. Prime Minister Naoto Kan asked aides to weigh the risks of injecting seawater into the reactor to cool it down. At this crucial moment, it became clear that a prime minister who had built his career on suspicion of the collusive ties between Japan's industry and bureaucracy was acting nearly in the dark. . . . Based on a guess of the mood at the prime minister's office, the company ordered the plant manager to stop [injecting sea water]. But the manager [Masao Yoshida] did something unthinkable in corporate Japan: he disobeyed the order and secretly continued using seawater; a decision that experts say almost certainly prevented a more serious meltdown and has made him an unlikely hero. . . . Last week, TEPCO gave Mr. Yoshida its lightest punishment of a verbal reprimand for defying the order."

In responding to unexpected external shocks at nuclear plants, correct and timely human actions at the site are "essential." To make the general definition of human-asset essentiality, due to Hart (1995, also see Aoki 2010, Ch. 2) more specific, human resources at the nuclear plant site are conceptualized as "essential" (or "indispensable") in the event of a sudden, major shock, if the (marginal) effectiveness of top management direction cannot be enhanced only with the vertical control of physical assets without complementary inputs of local human resources. If this condition holds so that human resources at the top management level and plant level are reciprocally essential, the specific tasks of information processing and decision-making of each level in the event of a sudden shock should be made distinct and their interactive mode should be clearly specified *ex ante*. In this way, expertise at the regulatory, corporate, and plant levels are best used in coordinating with each for coping with a crisis without delay and mutual interventions in others' expertise. This is the power of open-interface, rule-based modularity in a highly complex system subject to high uncertainty. But this is possible, provided that (1) regulators have specified clear rules that nuclear generating entities have to follow *ex ante* and in the case of emergency, (2) top management is capable of designing intra-organizational rules regarding the division of responsibility in the case of emergency, and (3) there is essential expertise at the plant level to follow these rules. The impact of the March 11th catastrophe was amplified by ad hoc negotiations among multiple stakeholders in the midst of an emergent crisis, some of whom lacked professional knowledge of nuclear engineering or valuable information.[2]

Horizontal 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 then to implement horizontal coordination (with continual information sharing and negotiation among multiple units) in the normal state of affairs, but switch to the modular mode of coordination with the emergence of a large shock? This is unlikely, because actions of constituent units of corporate organizations are normally taken on the basis of 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 in response to a sudden shock. As chaotic exchanges among the stakeholders during the March 11th crisis, they tended to behave as they had been in the normal course of events. If so, how can aspects of the modular mode of coordination in a crisis situation be incorporated into the Japanese power industry in spite of its path-dependent reliance on horizontal coordination within the context of an integrated monopoly? It can be done only through a fundamental institutional innovation made possible by applying the principles of open-interface, rule-based modularity in a broader context of industrial organization and regulation.

Un-bundling the Three Functions of the Integrated Regional Electricity Monopolies

Modularity can be applied to the Japanese electric power industry by splitting the integrated regional monopolies into separate corporate entities based on their functions: generation, transmission, and retail distribution. More concretely, a Japanese Independent System Operator (JISO) could own and operate the transmission grid to which potential electric power suppliers, retailers, large corporate customers, and independent generators, could be assured equal access to power. To avoid problems like those of the 2000−2001 California power crisis, as well as to provide incentives for investments (including investments in safer nuclear plants), rules for the matching and safety monitoring need to be carefully designed and implemented by the ISO with the support from information technology.

We first suggest the way how a transition to such industrial restructuring may be possible. There were some discussions within the government and the Ministry of Economy, Trade, and Industry in the late 1990s and the early 2000s as regards the possibility of separating generation and transmission. However, reforms did not materialized under strong political resistance of the regional electric power monopolies who argued it being detrimental to the "quality supply of power."

Now the situation has changed dramatically in the aftermath of the March-11 catastrophe. TEPCO will be short of cash soon in meeting all the accumulating Fukushima liabilities and the costs of decommissioning the Units 1-4 at the Fukushima Dai-ichi, and in the worst case scenario its net value will be negative.[4] However, coping with this situation through formal bankruptcy procedures will be costly in terms of the public welfare associated with secure electric power supplies and the stability of financial markets (TEPCO is the largest non-financial corporate bond issuers in Japan, with its outstanding long-term debt of 11.3 trillion yen with a net value of 1.6 trillion yen as of March 31, 2011). Thus, an infusion of public funds into TEPCO is inevitable, for which purpose the "Nuclear Damage Support Organization" was established in September 2011. It is expected that this organization may expend as much as 5 trillion yen.

However, public expenditures on TEPCO need not, and should not, be made to bail TEPCO out of its potential insolvency with its corporate form intact. The Japanese government could invest in TEPCO as a measure to spin-off TEPCO's transmission grid, and place its ownership and operation in a new corporate entity acting as the JISO.[5] As in many European countries, Japan could create an independent equal-access transmission system. Public-ownership is based primarily on the experience in electricity deregulation that the transmission grid is a natural monopoly, unlike generation. See Rothwell and Gomez (2003). Generators of varied types (including existing nuclear plants, after passing stress tests), as well as regional retail suppliers, may also be independently incorporated. Supplies and demands may be matched through the spot market operated by the ISO. However, to avoid problems like those of the 2000−2001 California power crisis, and to provide incentives for investment in power generating capacity, spot markets can be augmented with the following three measures. First, retail distributors and large consumers can be engaged in long-term fixed-cost contracts with supplies to restrain the potential exercise of "short-term" market power by suppliers. In the 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).[6]

Second, on the consumer side, consumers can contract for power supply for a specified quantity limit under a fixed price, and pay a current spot market price (e.g., a day ahead price) beyond the limit, while "rolling over" unused quantities, as in cell phone service (Bushnell, Hobbs, and Wolak 2009). Such dynamic pricing mechanisms can be supported with the introduction of Internet-friendly smart meters and smart grids. It will certainly motivate consumers' (particularly, large, industrial customers) behavior 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 a extra productive capacity to avoid black outs. With long-term contracts on both sides of the electricity market, consumers with excess supply can release these quantities in spot markets.

Third, competition in electricity supply can be accomplished by first introducing "cost-based dispatch" (Wolak, 2003a). In a market with cost-based dispatch, modular generating companies submit their start-up, no-load, and variable costs, or supply schedules contingent on spot market prices, to the ISO. The ISO then requests power per hour from the generating companies to minimize total cost and maximize reliability in meeting electricity demand. The ISO thus facilitates energy trading in the spot market based on marginal cost of generators. Consequently generators compete based on their cost of production. The clearing price in the spot market is equal to the cost of production of the last generating unit dispatched. For an application of cost-based dispatch in Latin

America, see Falconett and Nagasaka (2009). Given the present state of information and communication technology, the operation of such smart grids should be feasible in Japan.

Further, a de-centralized, modular structure can be more innovative and environment friendly. With an electricity/information transmission system 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 on a level playing field. The system as a whole can then self-organize its innovation through evolutionary selection from among those modules rather than through *ex ante* planning by a corporate headquarters. As Baldwin and Clark (2000) argued, such modular competition in innovation can create option values not possible under hierarchical control of innovation. Further, modular competition has favorable incentive impacts on each module not available under the integrated corporate system, because the extra innovative effort increases the marginal probability of finding the best technology (Aoki and Takizawa, 2002). Readers can observe the remarkable speed of innovation in the information, communications, and pharmaceutical industries in the last several decades largely due to the development of modular industrial organizations (e.g., Powell et al., 2005).

By competitively linking suppliers and customers through a Japanese electric/information transmission system should yield incentives for energy conservation, on the one hand, and the development of alternative energy sources and power storage, on the other. Various firms outside the traditional electric power sector may become active players, e.g., members of industries in information technology, co-generators such as steel plants, plug-in automobile, architectural design and construction, and new generations of batteries and electric equipment manufacturers. The definition of Schumpeterian innovation is "creative destruction and recombination." Unbundling the integrated Japanese electricity generation, transmission, and distribution system of private, regional monopolies, and re-combining human and physical resources in these modules into a system of self-regulating markets with an electric/information transmission system would be institutional innovation in the open-interface, rule-based modularity sense.

From this perspective, the public debate regarding nuclear energy in Japan as an all or nothing choice is misplaced, because there could be a way to apply the power of modularity for more effective monitoring of nuclear energy generation and development. A group of nuclear energy plants (or groups of thermal plants) can be modularized as autonomous corporate entities that internalize highly-qualified human resources, subject to transparent rules stipulated by an autonomous regulatory agency. The modular system is thus conducive to shock-resistance, operational efficiency, and innovation at the plant, corporate, and industrial levels, with possible complementarities among them.

However, potential benefits of modularity cannot be realized unless it is also applied to the regulatory level. In the current Japanese system of integrated regional electricity monopolies, nuclear plants are placed under a two-tier control by corporate managers and regulators. The TEPCO CEO has never been anyone having primary expertise in nuclear engineering, but someone skilled in government relations or business negotiations. TEPCO exercised enormous market power not only as a regulated monopoly in the supply of electric power, but also in terms of enormous purchases in wide-ranging markets, such as industrial equipment, fuel, financial services, real estate, and advertising. They are able to shift cost burdens to regulated tariffs, resulting in electric power prices in Japan that are 50% higher than in the U.S. and South Korea. The primary concern of the top management of TEPCO has been to secure its position as a regional monopolist, and accumulate monopoly profits. On the other hand, the government safety regulator, the Nuclear and Industrial Safety Agency, is a division of the Ministry of Economy, Trade, and Industry, which promotes nuclear energy development; see Figure 1. Nuclear and Industrial Safety Agency cannot autonomously monitor the safety of nuclear power generation and encourage nuclear energy development. There has been implicit and explicit collusion between the regulator and the regulated, entrenching both in a self-promoting "nuclear-industrial complex."

We have suggested that one important factor to control the risk of crisis at nuclear plants is to prepare a defense-in-depth, that is, to install modular devices *ex ante* from among which one can be successively mobilized after another fails. One of human factors that aggravated the impact of the natural disaster was the failure of this precautionary mechanism, as symbolized by the failure of a back up generator installed close to the sea level in spite of the possible risk of tsunami.

Subsequent to the March 11th catastrophe, TEPCO insisted that the magnitude of the tsunami had been beyond any hypothetical possibility ("*soteigai*"). However, warnings of possible disaster of that magnitude have been published. A historical document, *Japan's Three Emperors' Historical Records* ("*Nihon Sandai Jitsuroku*"), compiled in 901, recorded a tsunami of similar magnitude in Tōhoku in 895, the "Jyokan-Sanriku" earthquake. (It documented that the number of deaths from this disaster was more than 1,000 in a population of 7 million, approximately equal to 20,000 deaths in a population of 127 million today.) This and other historical data were dismissed by the

Japanese government and industry officials as an exaggeration typical of historical narratives. Recent geo-physical research confirmed that tsunamis caused by earthquakes greater than magnitude 8.0 took place six times in Tōhoku during the last 6,000 years. On the basis of such historical and scientific research, concerns over the inadequacy of defenses against a tsunami were expressed by a scientist at official meetings at the Ministry of Economy, Trade, and Industry discussing the safety regulation of Fukushima ("*sogo shigen enerughi chosakai*") in June and July 2009. The warning was not effectively reflected in TEPCO's interim report. According to a recent finding of the "Investigation Committee on the Accident at the Fukushima Nuclear Power Stations", TEPCO did a simulation study of the possible impacts of tsunamis with 10-15 meter surges at Fukushima, but delayed reporting the results to the Nuclear and Industrial Safety Agency until March 7th; the report was made public only on October 3rd.

The defect of placing the regulatory agency under the umbrella of the Ministry of Economy, Trade, and Industry has become generally accepted in Japan. The government's decision stipulates that a new regulatory agency would be placed under the Ministry of Environmental Protection, absorbing the functions of the Nuclear and Industrial Safety Agency and some of those in the Ministry of Education, Culture, Sports, Science and Technology (MEXT, see Figure 1). However, it is still problematic to place a regulatory agency under a government ministry, in which the head of the agency reports to a minister. This is so because the safety regulator's decisions could be influenced by interest-group politics, but also because it would be difficult to recruit professional regulators versed in nuclear engineering under the closed personnel rules and practices of the Japanese administration. Japan needs a truly independent regulatory commission without pressure of interest groups, including TEPCO. Without such modularization of the regulatory structure, safe and reliable nuclear energy development in Japan might not be possible.

Summary: Two Major Factors

We have described some of the basic human factors that exacerbated the March 11th natural disaster at TEPCO's Fukushima nuclear power plant, transforming it into a catastrophe similar to Chernobyl. There were two major factors: one was the failure of the reactor cooling systems, leading to reactor nuclear fuel melting, and another was the delay of action, such as cooling the reactors with seawater. Confused and unstructured information exchanges and negotiations among the various stakeholders, lacking professional knowledge, on-site information, and clear decision-making authority, were responsible for the former. The latter was caused by mistakes in the risk assessment of possible natural disasters and the subsequent failure of defense-in-depth against a massive tsunami. For this compromise of public safety TEPCO must be held responsible.

The essence of these problems can be said to stem from an aspect of the coordination mechanism inherent in Japanese industrial organizations, that is, the horizontal-coordination mode. In this mechanism, stakeholders or constituent system units, either at the plant, corporate, industrial, or regulatory level, tend to share information relevant to their complementary stakes, engaged in continual negotiations over these stakes. Such a mechanism may function relatively smoothly and well by fine-tuning reaction to continually and mildly changing environments. However, as economic analysis has made clearer, and events such as the Fukushima catastrophe empirically revealed, the horizontal-coordination mode may fail in the event of a sudden, major shock. An alternative to the horizontal-coordination mode is the open-interface, rule-based modular mode. In this, modules specialized in specific functions may be interconnected under *ex ante* designed inter-face rules. We discuss reasons why such a mode may perform better in terms of (1) defense-in-depth, (2) response to sudden, massive local shocks, (3) efficient industrial organization of network industries, such as electric power and information technology, and (4) self-organization of innovation.

We question whether the Japanese nuclear power industry can be reformed in a direction incorporating some aspects of the modular mode into its traditional horizontal-coordination mode. We argue that a solution to the financial difficulties of TEPCO caused by (1) the natural accidents and (2) TEPCO's own human errors and concealing information is to introduce modularity in the electric power industry, beginning with government's investment in TEPCO as a transitory measure to spin-off transmission assets to establish an independent JISO. Transmission grids in quasi-public ownership can serve as infrastructure for introducing the modular mode of industrial organization to encourage the Japanese power industry to be safer, more efficient, more innovative, and more environmentally friendly. In conjunction with such industrial reform, the nuclear regulatory structure must be replaced by an independent and professional regulatory agency. This reform would be the application of open-interface, rule-based modularity to public administration.

Now that all units at Fukushima Dai-ichi are in "cold shutdown" (declared on December 16th), the interiors of the melted reactors are so dangerously radioactive that it will 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. The decommissioning is expected to be finished in 2051. While the “accident phase” at Fukushima Dai-ichi is over, the private and social costs, or the engineering implications, of what happened are yet to be clarified. If open-interface, rule-based institutions are not introduced into the nuclear industry, lessons might not be learned before an accident similar to Three Mile Island, Chernobyl, or Fukushima happens again in Japan, Asia, or elsewhere.

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Footnotes:

1. Cesium 137 has a "half-life" of 30 years, i.e., after 30 years one-half of the cesium 137 released from Fukushima will have decayed; after 60 years one-quarter of the cesium 137 will remain, etc. This can be compared to the 8-day half-life for radioiodine-131 and the 24,100-year half-life of plutonium-239. For example, after 300 years only 0.1% of the cesium-137 remains, whereas after 300 years, 99% of the plutonium-239 remains.

2. What happened at the Fukushima nuclear plants during the earthquake and tsunami, as well as the ensuing human errors, are being examined by the "Investigation Committee on the Accident at the Fukushima Nuclear Power Stations" appointed by the Kan government. The committee is headed by Professor Yotaro Hatakemura specialized in crisis management, and its members include lawyers, engineers, geologists, and other specialists, who do not have any financial interest in the industry or positions in the government. The 700-page interim report was made public on December 26, 2011, after hearing from 456 people. The committee found, among others, that elements of human error at the plant site. Control room operators at Fukushima on the afternoon of March 11th were assuming that the emergency cooling system was operating and were communicating this erroneous assumption to off-site managers. This lead to a delay in cooling Unit 1, which lead to a cascade of accidents at the other units (New York Times 2011b). A similar series of events compounded equipment malfunction with human error and miscommunication between the plant and outside experts and managers was the cause of the Three Miles Island disaster. See the President's Commission on the Accident at Three Mile Island (1979). Were the lessons learned from Three Mile Island incorporated into emergency preparedness in Japan? Will the lessons learned at nuclear

power plant accidents be incorporated into the Japanese nuclear power industry without drastically reforming the industry and its regulation? We believe that a serious restructuring must occur if the nuclear power industry in Japan is to be operated safely. See our reasoning below.

3. Damages at Kashiwazaki-Kariwa, the world's largest nuclear power plant, included water leaks in the reactor buildings; water seal leaks in the reactor core cooling system; oil leaks in the reactor core cooling system pumps; oil leaks in the transformer facility; fires in the transformer facility; loss of power to and from the transformer facility; water leaks in the backup diesel generator facility; loss of power to the liquid waste disposal system; cracks in the cooling water intake system; radioactive contaminated water leaks; and uneven liquefaction under the reactor site. Only two of the seven units at Kashiwazaki-Kariwa have operated since July 16, 2007. These two units are Advanced Boiling Water Reactors (ABWRs) that have been operating since 1997.

4. The "Commission for Investigating the Management and Financial State of TEPCO" set up by the Kan government made public its final Report on October 3, 2011. It estimates the cost of decommission of Fukushima reactors 1-4 at 1.081 trillion yen and one-time costs of compensation for damages at 2.61 trillion yen in 2011, followed by annual compensations estimated at 1.24 trillion yen for fiscal year 2012 and 0.90 trillion yen thereafter. (The cost of decommissioning was estimated by multiplying the cost of decommissioning Three Mile Island by 4 units, plus the extra costs associated with decontaminating the cooling water, etc; on the cost of decommissioning Three Mile Island, see Pasqualetti and Rothwell, 1991). According to a simulation study by its Task Force, the net value of TEPCO could be negative in 2013 without the operation of the

nuclear plants and an increase of retail tariffs. The function of this Commission was absorbed into the "Nuclear Damage Support Organization," chartered in September 2011.

5. A JISO could be created within the domain of TEPCO and, contingent on its success, the transmission systems of other regional electricity monopolies could be added.

6. One of the important factors of the 2000−2001 California electricity crisis was the creation of an artificial short supply, engineered primarily by Enron before it declared bankruptcy in September 2001, to aggravate the impact of a shortage of hydroelectricity from the Pacific Northwest due to draught. This caused an 800% price spike in wholesale electricity prices in 2000. See Wolak, Nordhaus, and Shapiro (2000). Simultaneously, a cap was imposed on retail electricity tariffs. As a result, huge losses were incurred by the three regional electricity monopolists in the wholesale market, operated by the California Independent System Operator, and one of them, Pacific Gas & Electric, owner and operator of the Diablo Canyon nuclear power plant, declared bankruptcy in April 2001.