Organizations under Volatile Uncertainty: An Analysis of the Fukushima Catastrophe

By Geoffrey Rothwell*

Economic theory and observation suggests organizations attempt to structure themselves to efficiently manage information flows to maximize their objectives. Aoki (2010) describes three information structure archetypes:

- "top-down-mode" with hierarchical control, also known as "H-mode;"
- "continuous-negotiation-mode" with horizontal coordination, previously known as the Japanese-mode, or "J-mode"; and
- "rule-based-mode" with self-organizing, independent modules ("M-mode") each with an assigned function, operating within open, established, interface rules.

When U.S. President Jimmy Carter visited the light-water-moderated-and-cooled Pressurized Water Reactor (PWR) at Three Mile Island on Sunday, April 1, 1979. He visited solemnly to raise hope for an anxious nation. He did this as its leader and healer, laying his hands on the plant, not because he was there to intervene, but because as an ex-naval submarine officer, he had slept beside PWRs in deep waters, and wanted to show that there was nothing to fear 100 hours after the accident happened: Jimmy Carter laid the disaster to rest. The interface rules between his function as the U.S. president and the plant manager had already been promulgated by the U.S. Nuclear Regulatory Commission (NRC) with and since its inception on January 19, 1975.

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 after the April 26, 1986, steam explosion of Unit 4 of Chernobyl's Graphite-Moderated/Light-Water-Cooled Reactor (RBMK in Russian), he was the head of a chain of command that determined on the morning of the accident to cover up as much information as possible regarding the damages. This cover up continues today with no accounting of the health of the 500,000 Soviet Army Reservists, "bio-bots," who shoveled chunks of highly radioactive graphite (charred and contaminated charcoal) off the Chernobyl site (about two minutes per bio-bot in reused protective clothing and gas-masks without dosimeters), when instruments died in the robots originally tasked to do the job.

When Japanese Prime Minister (PM) Naoto Kan flew around the Fukushima site in a helicopter with the plant manager, Mr. Masao Yoshida, on March 12, 2011, the day after the tsunami hit, he was participating in the continuous-negotiation-mode among relevant players. Later, based on his bonding with Mr. Yoshida, PM Kan believed that he could participate in the Fukushima crisis management, one in which he had no previous personal experience.

These three approaches to managing a nuclear power plant accident can be described as "rule-based," "top-down," and "continuous-negotiation," respectively. Vertical control (hierarchical-mode) corresponds to a structure where each member has a specific task and has had job-specific training. The benefit of this structure is that managers know the technical possibilities of the firm and its employees. The disadvantages include information transmission delays and errors.

Second, an alternative approach is a continuous-negotiation-mode where teams are responsible for all functions. Personnel rotate through each task and eventually have a broad knowledge of the complete process. When a problem arises, the team addresses the problem with its own resources.

Third, Aoki (2010) proposes an "M-Mode" of interacting modules within a meta-structure of openness and rule-based decision making. The ideal type of the M-Mode structure is Silicon Valley. However, M-mode can be applied to organizing the manufacture of nuclear power plants (e.g., in sets of Small Modular Reactors, see Rothwell 2011). While the present paper focuses on the effectiveness of the continuous-negotiation-mode under volatile uncertainty, it assumes the lessons learned from rapid M-mode economic growth and the introduction of market discipline into the electric utility industry (see Rothwell and Gomez, 2003) since the publication of Aoki (1990).

Aoki (1990, p. 8) states that the relative advantage of continuous-negotiation "depends on such factors as the learning ability of personnel, the ease of communication between operating units, and the degree of economies of specialization with regard to the variety and volatility of market demand." Aoki then proposes the following hypothesis:

* Geoffrey Rothwell is with the Department of Economics, Stanford University. He thanka T. Amemiya, B. Carson, G. Coles, R. Graber, B. McDowell, B. Rasin, A. Seward, B. Smoter, K. Whattam, F. Wolak, and T. Wood for their comments and support. This work is being partially funded by the National Energy Policy Institute. Dr. Rothwell may be reached at geoffreyrothwell@yahoo.com
See footnote at end of text. A detailed Appendix is available from the authors.

> "When environments for planning (e.g., markets, engineering process, development opportunity) are *stable,* learning at the operational level may not add much information value to prior planning, and the sacrifice of economies of specialization in operational activities may not be worthwhile. On the other hand, if environments are *extremely volatile or uncertain,* decentralized adaptation to environmental changes may yield highly unstable results. In both these two contrasting cases, the H-mode may be superior in achieving the organizational goal. In the intermediate situation, however, where external environments are *continually changing but not too drastically,* the J-mode is superior. In this case, the information value created by learning and horizontal coordination at the operational level may more than compensate for the loss of efficiency due to the sacrifice of operational specialization." *(emphasis added*)

Aoki's hypothesis was tested empirically with information on nuclear power plants in Rothwell (1996). At these plants, operating periods can be characterized as environments that are "continually changing but not too drastically." Following Aoki, the horizontal information structure (J-mode) would be superior during operation. In contrast to operating periods, at nuclear power plants there are forced outages that can be "extremely volatile or uncertain" (many forced outages begin with the automatic insertion of control rods into the reactor core to stop the nuclear fission reaction; this is also known as a "scram," because in the early days of nuclear reactor operation, all personnel would scramble to the exit with an automatic shutdown). So, following Aoki, the Hierarchical-mode (H-mode) should be superior during outages.

Rothwell (1996) organizes data on operation and outages from 49 nuclear power plants (with most of the nuclear power units in the U.S.) between January 1976 and December 1985; constructs an index of hierarchy based on nuclear power plant organization charts in Olsen et al. (1984) from the Final Safety Analysis Reports; and estimates parameters that support the proposition that less hierarchy is associated with higher productivity through longer periods of operation: The J-mode is associated with longer periods of operation, but the H-mode is associated with shorter periods of outage. Because plants are running a higher percentage of the total time, the hierarchical-mode is superior most of the time.

On March 11, 2011, in Fukushima, Japan, following a magnitude 9.0 earthquake, the six unit Fukushima-Dai-ichi nuclear power plant began its shutdown, when Units 4, 5, and 6 were down for refueling. Table 1 is a partial list possible earthquake damages at Fukushima. All units are based on the General Electric (GE) Boiling Water Reactor (BWR). Unit 6 was a collaboration between GE and Toshiba, and served as a model for Toshiba's construction of Units 1 and 3, and Hitachi's construction of Units 2 and 4, at the Fukushima-Dai-ni site, 10 km from Fukushima-Dai-ichi in the same seaside village.

- Water seal leaks in reactor core cooling systems
- Water leaks in reactor buildings
- Oil leaks in reactor core cooling system pumps
- Oil leaks in the transformer facility
- Fire 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
- Uneven liquefaction under the reactor site

Table 1: Possible Earthquake Damages at the Fukushima Nuclear Power Plants

See http://www.nirs.org/international/asia/reportonearthquakedamage71907.pdf .

Although the complete story has not yet been told, the continuous-negotiation-mode seems to have functioned smoothly immediately after the earthquake. However, the absence of electric power after the tsunami resulted in extreme volatility and uncertainty, and the continuous-negotiation-mode led to highly unstable results.

The "Seawater Decision"

The failure of the continuous-negotiation-mode during the Fukushima crisis can be seen in the decision to cool reactors with seawater. See chronology in Appendix A, available from the authors. The New York Times (6-13-2011), p. A1, discusses seawater:

> "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. 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."

On the other hand, Prime Minister Kan suffered a heavy punishment when he agreed to resign in exchange for votes against the motion of no-confidence in his government on June 2, 2011 (see BBC, 2011):

"Japanese Prime Minister Naoto Kan has survived a no-confidence motion brought by [Members of Parliament] critical of his handling of the earthquake and tsunami disaster. Before the motion was debated, Mr. Kan told his party he would step down when the crises were under control. He was trying to head off a rebellion by senior members of his party which could have forced him from power. . . [S]enior figures in his Democratic Party of Japan (DPJ) had indicated they would support the no-confidence motion, increasing his chances of being forced out. In a last-minute attempt to rally support, he urged a meeting of DPJ politicians to reject the no-confidence motion . . . The no-confidence motion was submitted by the main opposition Liberal Democratic Party (LDP) . . . The LDP has accused Mr. Kan of mishandling the reconstruction and relief efforts following the tsunami, as well as the Fukushima nuclear crisis. In parliament on Wednesday, LDP leader Sadakazu Tanigaki told Mr. Kan: 'You have no personal virtues.' . . . [T]he result of an opinion poll published on Wednesday suggests the public has a dim view of Mr. Kan's handling of the Fukushima crisis. In a survey of 700 adults, 79% rated his management of the crisis as poor, according to the Pew Research Center. . . . The Fukushima Dai-ichi power plant, which was badly damaged by the tsunami, is still leaking radiation."

In the March 11th Fukushima catastrophe, TEPCO's and government officials' behaviors revealed that the typical continuous-negotiation-mode of decision making was not at all appropriate to addressing the volatile uncertainty following the tsunami at Fukushima. At times it converted itself to a typical hierarchical-mode organization with the station manager making decisions, as encouraged by the IAEA and the U.S.

But at no time since has the situation converted to an open-rule-based modular system where each "module" (e.g., plant manager, TEPCO management, Japanese Atomic Energy Agency, Nuclear and Industrial Safety Agency, Prime Minister and aides, DPJ, defense forces, etc.) of the decision-making structure is linked through simple, open, and transparent interface rules. Indeed, PM Kan exploded in anger because he suspected TEPCO was withholding information from him (after TEPCO requested an evacuation of the site on March 14th) at a meeting (March 15, 5:30am) in Tokyo less than one hour before the dual hydrogen explosions damaged the containment and roof of Unit 2 (March 15, 6:10am) and in the reactor building and the spent fuel pool of Unit 4 (March 15, 6:14am), following hydrogen explosions on television on March 12th at 3:36pm and March 14th at 11:00am. Were TEPCO officials withholding information at the March 15th meeting? What did they know and when did they know it?

There remain unsettling issues, such as, when will Unit 1 come under TEPCO control? (It was not under control on June 15th, when this paper was submitted.) Apparently, the radiation level has been rising linearly from April 18th to April 27th to May 15th to June 4th. When will it start falling?

There remain unanswered questions, such as, how much damage is there to the reactor pressure vessels of Units 1, 2, and 3? When Representative Edward Markey (D-MA) told the public what the NRC had suspected, i.e., that molten fuel might melt through the reactor pressure vessels, the NRC retracted its suspicion. However, on May 17th, TEPCO confirmed that molten fuel (at 2,800° C) had probably caused stress fractures in the lower head of the reactor pressure vessel in Unit 1, and on June 7th, the Japanese government began an inquiry to determine if there had been any "melting through" the reactor pressure vessels. Did any of the vessels "melt through"? What will this mean for decontamination and decommissioning, D&D? (On D&D economics, see Pasqualetti and Rothwell, 1991.)

Another puzzling question concerns "recriticality." Criticality would occur if the molten fuel could have generated a self-sustaining nuclear fission reaction. This would be classified as a "criticality accident," such as the one at the Tokai-mura fast reactor fuel fabrication facility on September 30, 1999, where a self-sustaining chain reaction with a sufficiently high level of reactivity in a specific geometry lasted about 20 hours (http://www.world-nuclear.org/info/inf37.html). On March 12th, PM Kan asked Prof. Madarame whether injecting seawater could cause a criticality accident, and the professor's response was that the chances of such a thing happening were "non-zero." (NYT, June 13, 2011)

Had there been criticality accidents in Units 1, 2, or 3, the Prime Minister could have been the hero, and the plant manager could have been accused of being the disobedient employee without "personal virtues." On May 2nd, Prof. Matsui in "Deciphering the Measured Ratios of Iodine-131 to Cesium-137 at the Fukushima Reactors," http://arxiv.org/abs/1105.0242, using seawater samples, concluded that a criticality accident might have occurred 10-15 days after March 11th, i.e., between 3-21st and 3-26th. Have there ever been any criticality accidents at Fukushima?

Finally, there is the worrisome issue of finding plutonium in samples outside the plant on March 21st and 22nd, which was not reported until March 28th (CNN, "TEPCO says plutonium found on quake-damaged plant grounds"). On March 28th, TEPCO concluded that the levels of plutonium were not greater than background levels of plutonium, from, for example, Hiroshima, Nagasaki, and the atmospheric testing of atomic and hydrogen weapons during the 1950s in the Pacific. However, TEPCO has not issued a statement on the molten MOX in Unit 3. Compare their silence on molten MOX to their earlier announcement of loading MOX into Fukushima Dai-ichi Unit 3 on August 2010:[1]

"In plutonium-thermal ("plu-thermal") power generation, plutonium is removed from spent fuel and mixed with uranium to produce MOX (Mixed oxide composed of uranium and plutonium) fuels for use in existing nuclear power plants. This effective utilization of limited uranium resources is expected to contribute significantly to securing stable energy supply in the future. To promote the introduction of plutonium-thermal power generation, electric power companies in Japan are making various efforts to obtain broad public acceptance of this new power generation method. At TEPCO, we have loaded MOX fuel into Unit 3 at the Fukushima Daiichi Nuclear Power Station in August 2010, and are steadily working our way toward the implementation of plutonium-thermal power generation." (emphasis added) http://www.tepco.co.jp/en/challenge/csr/nuclear/cycle-e.html

TEPCO is a rate-of-return-regulated monopoly electricity generator, transmitter, and distributor in one of the largest metropolitan areas in the world with one third of Japan's electric power assets. Its political power rivals that of the Japanese government. To encourage a more open-rule-based structure in the Japanese "nuclear village," TEPCO and the Japanese (nuclear) electric utilities should be "modularized" into competing generating companies by selling their transmission and distribution assets to the Japanese government in exchange for payments to Fukushima victims, Fukushima's decontamination and decommissioning, and nuclear power plant upgrades, for example, to TEPCO's Kashiwazaki-Kariwa, the world's largest nuclear power plant, where 5 units remain disabled almost four years after a magnitude 6.8 earthquake on July 16, 2007, with warnings 45 months before March 11, 2011.

Footnotes

[1] To experience the silence, google <<"molten MOX" & TEPCO>>; on June 15, 2011, there were only 8 hits, none at www.tepco.co. Compare this with the noise resulting from a search for <<MOX>> on the TEPCO web site: http://www.tepco.co.jp/en/index-e.html.

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