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Postscript: The "Hydra-Headed" Fukushima Nuclear Crisis

In ancient Greek mythology, the hydra was a serpent-like beast with many heads that guarded the entrance to the Underworld. Its breath was so deadly that even its footprints were reputed to poison men to death. In the past few weeks, the nuclear industry may have met its hydra in the form of an accident in the Fukushima Prefecture of Japan. Chapter 3 of this book on "normal accidents" documented historical safety and reliability issues with nuclear power plants, and also predicted that at least four serious core damage accidents would occur between 2005 and 2055. One of these four accidents has just happened at the Fukushima Daiichi nuclear power plant in Japan, where an earthquake and tsunami have caused emergency backup generators to fail and the pressure vessels at some of its reactors to explode. Spent fuel pools at the facility have caught fire, fuel assemblies have melted down, and dangerous levels of radiation have been reported. At the time of writing, more than 200,000 residents have been evacuated from a 30-km safety zone and 160 people have been exposed to "hazardous" levels of radiation, in addition to 21 fatalities (7 from first responders and plant operators and 14 elderly persons killed during the evacuation).

The Fukushima Daiichi facility houses six of Japan's 55 reactors and is one of Japan's 17 nuclear power plants, which together generate about

30% of the country's electricity. The Fukushima Daiichi plant, 150 miles (240 km) outside of Tokyo, relies on boiling water reactors which circulate water through the core and convert it into steam to drive an electric generator. The first unit at Daiichi was connected to the grid in November 1970 and the sixth unit was connected in March 1979. Owned and operated by the Tokyo Electric Power Company (Tepco), each reactor is loaded with 12-feet-long fuel rods made of radioactive uranium-235 pellets surrounded by zirconium alloy, with some relying on more toxic mixed oxide (MOX) fuel containing a mixture of uranium-235 and plutonium.

Chronology of Events

The story so far — and it is still unfolding — starts with a 9.0-magnitude earthquake that struck 370 km northeast of Tokyo, 24.5 km below the ocean, at 2 a.m. on Friday, March 11, 2011.[1] The quake, the fifth largest in the world on record, sent 12-meter-high tsunami waves sweeping across rice fields, tossing cars and boats, engulfing entire towns, and reaching as far as 10 km inland in some places such as Miyagi Prefecture. The quake also induced substantial damage at Tepco's Fukushima Daiichi power plant, forcing plant operators to begin an emergency shutdown.

This shutdown involved moving control rods below three of the six operating reactors — the other three had been closed for maintenance at the time — into the core to absorb neutrons and stop the chain reaction. The shutdown proceeded as planned within minutes of the quake, but other reactions in the reactor still produced substantial decay heat. When the tsunami waves crashed into the power plant one hour later, the shutdown reactors were still as powerful as a commercial jet engine at full throttle in a very confined space.

The tsunami itself physically washed away all of the plant's backup diesel generators, and its batteries provided enough electricity to cool the facility for only a few hours. It was then that all three reactors began to melt. Fukushima Daiichi's boiling water reactors are not unlike an electric kettle that operates at 550°F, below the temperature of a coal furnace and slightly hotter than an ordinary kitchen oven.[2] The nuclear reactor is like the part at the bottom of the kettle that heats the water. If the kettle cannot be turned off, and the spout is sealed because the steam is radioactive,

then the amount of water around the reactor will slowly decrease, exposing the reactor core. In the case of Fukushima, all three reactor cores started to melt to the bottom of the steel pressure vessel and react with the steam, causing temperatures to rise above 5,000°F.[3] These high temperatures compromised the reactor vessel and surrounding containment systems, releasing radioactive materials throughout the plant.

On Saturday, March 12, operators at the facility responded to the melting reactors by venting some of this radioactive steam to reduce the stress on containment structures. However, the resulting hydrogen gas somehow found a spark and exploded, blowing the roofs off the buildings surrounding both reactors 1 and 3 and severely injuring four workers. Because the cooling systems for each reactor had malfunctioned, the operators began to flood them with seawater laced with boric acid.

On Sunday, March 13, authorities started detecting abnormally high radiation levels around the plant and in the nearby prefecture, and distributed iodine tablets to residents. Three people randomly selected from a group of 90 tested positive for radiation exposure, and Chief Cabinet Secretary Yukio Edano cautioned that other explosions might be eminent.

On Monday, March 14, things became worse. Multiple explosions, again believed to come from hydrogen gas, occurred at reactors 2 and 3, further damaging what was left of the multilayered cooling systems and containment vessels, injuring 14 other workers, and exposing 190 workers to unsafe levels of radiation. About 80,000 residents within a 20-km radius of the plant were evacuated, and up to 2.8 meters of the control rods in reactor 2 were left uncovered because the pump keeping them cool failed. The reactor began to emit radioactive steam. Radiation levels at the plant exceeded 11,000 μSv per hour, enough to cause radiation sickness (400 μSv can cause temporary sterility in men). Later that evening, reactor 2 boiled completely dry, causing another explosion at the bottom of the containment vessel, leading to the fire and steam shown in Figure 1.

On Tuesday, March 15, another explosive impact shook reactor 2, damaging its suppression pool. The US Navy began repositioning its ships used in humanitarian disaster relief away from "airborne radioactivity" it had detected in the region. (Three people aboard the *USS Ronald Reagan* tested positive for low levels of radiation.) The Japanese government extended the evacuation zone to 30 km and asked roughly 180,000 residents

Figure 1: Radioactive Steam from Fukushima Daiichi's Reactors 2 and 3

to leave the area. Tepco also evacuated almost all of the plant's 800 staff, leaving only 50 workers to handle the crisis. Later that morning, a fire broke out at the cooling pond used for nuclear fuel at reactor 4, which had been shut down, venting radioactive iodine and cesium directly into the environment. Tepco prepared an emergency plan to pour water dumped from military helicopters onto the reactors. The closely spaced explosions released a surge of radiation within the plant 800 times as intense as the recommended exposure limit.

On Wednesday, March 16, a second fire broke out at reactor 4, dispersing more radioactive material into the atmosphere. Radiation levels soared inside and around the plant, and also began to rise as far as 200 km away. Indeed, radiation levels were reported to be 20 times higher than normal in Tokyo.

Since then, no more fires and explosions have been reported, although radioactive steam has emanated from the facility for the past two weeks. As of today, March 28, the government has set up a 30-km "no-fly zone" and containment perimeter as shown in Figure 2, and Prime Minister Naoto

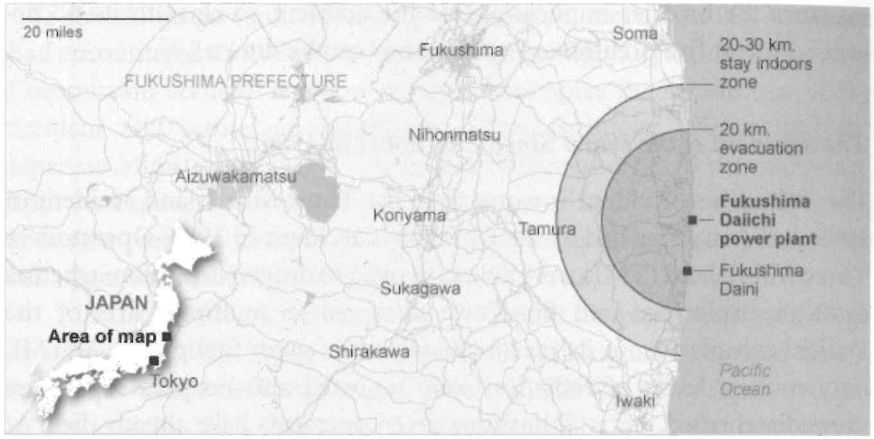

Figure 2: The 30-km Exclusionary Zone Around the Fukushima Daiichi Nuclear Power Plant[5]

Kan stated over the weekend that the situation at the Daiichi facility was "very grave and serious," with Tepco officials reporting that the containment vessel at reactor 3 had been breached, leading to "severe radioactive contamination."[4] Radiation levels at the spent fuel ponds that caught fire have been reported to be 10 million times above the normal limit due to radioactive iodine-134; and surface water nearby has shown 1,000 mSv of radiation, far above the safe limit of 3 mSv. A monitoring post nearby has also measured radiation levels in the sea 1,850 times higher than normal. Traces of radioactive iodine have been detected as far away as Heilongjiang Province in China.

Broader Implications

In the wake of Fukushima, Germany has already declared a three-month moratorium on its plan to prolong the life of its nuclear plants and has shut down seven of its oldest facilities. Switzerland has announced that it is reassessing its nuclear program and has suspended plans to replace its nuclear reactors. Chinese planners have also stopped approval for all nuclear power plants, and have halted all plants in construction (though it is unclear how long this moratorium will last).[6] While it is difficult to

measure the broader implications of the accident so close to its occurrence, at least five preliminary conclusions can be drawn.

The Accident Is the Worst Since Chernobyl in 1986

The Fukushima accident is worse than the Three Mile Island accident in 1979, but not yet as bad as the Chernobyl accident in 1986. Operators at Three Mile Island (TMI) were able to avoid a hydrogen explosion; whereas multiple explosions and fires have occurred at multiple parts of the Daiichi complex, from its reactor vessels to its spent fuel ponds. At TMI, only modest levels of radiation were reported and no plant operators immediately died, yet at Fukushima seven operators have already died. At TMI, only one reactor was in trouble; whereas four of Fukushima's reactors have suffered melting fuel, loss of coolant, and/or exposed fuel cores. Currently, the International Nuclear and Radiological Event Scale classifies the accident as level 6, one step down from the most serious level 7 (Chernobyl) and above level 5 (TMI).

The Accident Has Revealed a Culture of Secrecy, Cover-Ups, and Misinformation

Immediately after the earthquake, Tepco reported that efforts to shut down the reactors had been successful and that there was nothing to worry about. Even while the reactor cooling systems were failing and radiation levels were spiking around the plant, Yukio Edano, the chief government spokesman, stated that "there are no reports of leakage from any nuclear-power plants at the moment and no signs of any leakage."[7] Similarly, on Saturday, March 12, when hydrogen explosions destroyed containment structures, authorities insisted that no harmful gases had been released and that the explosion had released only "water vapor that was part of the cooling process," despite the fact that monitoring stations around the plant showed that radioactive cesium and iodine had escaped containment structures. Even the Prime Minister apparently was not getting the full story from Tepco, and somewhat infamously marched down to their offices to demand to know "what the hell is going on."[8] Tepco officials did not release knowledge about radioactive exposure until the United States Seventh Fleet publicly announced that the

USS Ronald Reagan and *USS George Washington*, more than 280 km away, had encountered a low-level radioactive plume. The US Nuclear Regulatory Commission accused Tepco of trying to downplay the seriousness of the accident and setting an insufficient safety perimeter.[9] Tepco and the Japanese Ministry of Health, Labor, and Welfare also raised the maximum limit on exposure for workers in an emergency to 250,000 μSv, 2.5 times above the previous limit, so they could ingeniously claim that workers were still operating within "government limits."[10]

Already, past incidents involving Tepco and the plant itself have come to surface. In 2002, Tepco's vice president and chairman resigned after a scandal in which the utility was accused of falsifying safety repair records in 29 cases. In 2003, Tepco had to shut down all 17 of its nuclear power facilities after it emerged that they had covered up reports showing cracks in the structures of some reactors.[11] Tepco was also repeatedly warned that their power plants were not built to withstand earthquakes greater than 6.5 on the Richter scale, and needed special equipment. In July 2007, another earthquake shut down seven reactors, three of them permanently, at Tepco's Kashiwazaki plant on the west coast of Japan. Tepco was yet again urged to upgrade its safety plans. In December 2008, the International Atomic Energy Agency (IAEA) specifically warned that seismic safeguards at Japanese nuclear power plants were "outdated and inadequate."[12]

These defects become especially pertinent when one realizes that the Fukushima Daiichi plant was not the only facility damaged in the quake. Initially after the tsunami, five other nuclear power plants in Japan declared a "state of emergency." Cooling systems malfunctioned at three reactors at the Fukushima Daini facility about 80 km south of Sendai and close to the Daiichi facility, forcing operators to vent radioactive steam to reduce pressure and also to declare a 10-km evacuation zone. This facility was much newer than Daiichi, having been connected to the grid in 1981 and 1987. Excessive radiation levels and a fire in the turbine house were recorded at the Onagawa facility about 70 km north of Sendai, and its reactors entered service between 1983 and 2001 (thus partially refuting the idea that Daiichi's age made it vulnerable to the quake). Cooling pumps damaged by the earthquake also failed at the Tokai nuclear power plant in Ibaraki Prefecture.

At the Fukushima Daiichi plant itself, some of its reactors were supposed to be decommissioned because of design faults but had their operating licenses extended for 10 years at the request of Tepco.[13] Tragically, in 2002, an advisory group recommended that Tepco raise its maximum projected tsunami level at Fukushima Daiichi and increase the height of its backup generators, but the company merely responded by raising a single pump by eight inches.[14] In October 2010, the Nuclear Safety Commission of Japan cautioned Tepco that their facilities, including Daiichi, were at a "residual risk concerning earthquakes and tsunamis" and that cooling systems needed to be retrofitted.[15] The Commission also warned that backup diesel generators were vulnerable to corrosion from seawater and rainwater.[16] Moreover, workers at the Daiichi facility failed to inspect about three dozen pieces of key cooling system equipment ten days before the March 11 earthquake.[17] One Tepco engineer has even come forward to argue that the Daiichi reactors may have been relying on flawed steel in its containment vessel, and that he had warned plant officials of a "time bomb" but was ignored.[18]

As one commentator pointed out, "This is an industry with a long record of cover-ups of dangerously damaged facilities, and cover-ups of safety violations, and unreported radioactive leaks, and inadequate waste storage protections, and napping guards, and more radioactive leaks, and more radioactive leaks, and on and on."[19] *The Economist* also wrote that the "country's nuclear industry has a long history of cover-ups and incompetence"[20] and "a shameful record of cover-ups, lackadaisical crisis management, and an inbred complicity between regulators and utilities."[21] Worryingly, these problems are not unique to Japan — it emerged a week after the Fukushima accident that almost 30% of nuclear power plants in the US had concealed defects, bungled repairs, and failed to report safety violations, suggesting that the trend may be industry-wide.[22]

Human Error Played a Key Role in Exacerbating the Accident

Human errors in design, operations, maintenance, and emergency response certainly played their part in causing and worsening the situation. The plant was not designed to withstand a 9.0-level earthquake, and it was also constructed to house all six of its reactors in close proximity to

each other in order to reduce costs and make moving equipment easier. However, the tsunami washed over Daiichi's backup generators, explosions at the first reactor hindered efforts to cool the other reactors, and multiple reactor fires distracted operators from cooling the spent fuel ponds. The Daiichi facility stores its spent fuel within the reactor building to make loading and unloading simpler, but this meant that meltdowns and fires affected both reactors and spent fuel simultaneously.[23] When the cooling systems failed at Daiichi, military helicopters attempted to dump water from the air and firefighters used water cannons; unfortunately, these did not cool the reactors as planned, since they were designed for forest fires and riot control.[24]

As one engineer admitted, "the earthquake and tsunami we had last week both exceeded our engineering assumptions by a long shot."[25] A former director of the Fukushima Daiichi plant stated that "we can only work on precedent, and there was no precedent. . . . [W]hen I headed the plant, the thought of a tsunami never crossed my mind."[26] Daiichi relied on reprocessed MOX fuel to minimize the need for fresh uranium ore; however, this meant that when reactor 3 failed, its plume was more dangerous because it had greater amounts of plutonium. When the fuel cladding started to melt at reactors 1 and 3, workers had to evacuate the control rooms as radiation levels were 1,000 times above the safe level, making it even more difficult to monitor and control events — another contingency that had not been anticipated.

Ultimately, it is the human element that adds a degree of unforeseen risk to any nuclear power accident. As Matthew Bunn from Harvard University has written:

> [With Fukushima Daiichi,] people have not adequately thought through the possibility of multiple traumas that could be caused by the same initiating event. . . . This reinforces the view that whenever someone says there is less than a one-in-a-million chance of a complex system failing, there is more than a one-in-a-million chance they have made unjustified assumptions in their estimate.[27]

In Japan, it was not the "nuclear parts" of the station that went wrong initially, but "conventional ones" such as pumps and backup generators. Or,

as John Vidal has concluded, "it's easy to be wise afterwards, but the inquest will surely show the accident was not due to an unpredictable natural disaster, but by a series of highly predictable bad calls by human regulators."[28] The sobering lesson appears to be that it is impossible to design a nuclear power plant for all unknowns.

The Full Cost of the Accident Will Be Quite Large

We already know that the Fukushima Daiichi accident will bring with it a suite of terrible technical, economic, environmental, and sociopolitical costs.

The severity of damage at the power plant itself is quite significant: the moment operators started pumping seawater to cool the reactors, they became too corroded to ever generate electricity again. Tepco has estimated that it will need at least US$25 billion in loans for repairs and to find new sources of electricity to replace the Daiichi plant.[29] This is to say nothing of the lost revenue from the plant, the sunk costs in the facility, and the financial burden of having to contain and decommission it. This last phase will likely be as expensive as the multibillion-dollar operation at Chernobyl, where the reactor site was entombed in concrete and buried in sand.[30] Already at least 7 plant workers have died and 47 have been injured in the explosions and fires,[31] in addition to 14 elderly persons who died during the evacuation as they were moved from hospitals, and many more have suffered from severe radiation exposure.[32] Some workers have already been exposed to radiation levels high enough to cause sterility and hemorrhaging; and they have required treatment for radiation sickness, nausea, vomiting, diarrhea, and plummeting blood counts.[33] The most recent breach of the reactor on March 25 exposed workers to 100,000 times more radioactivity than normal.

More broadly, the accident has had economy-wide implications such as blackouts throughout Tokyo, the collapse of the Japanese stock market, and rising prices for coal and natural gas. Rotating power outages due to the closure of Fukushima Daiichi have occurred in Tokyo and eight other prefectures, with more than 10% of Japanese households without electricity. These blackouts have depressed economic output and made it harder for the economy to recover from the earthquake. Panic, especially over

radiation, has hit the financial markets, with Japanese stocks falling by 6.2% on the day of the quake and by 12% on the day the partial meltdowns were revealed. Due to a combination of panic and lack of electricity, Japanese auto manufacturers have closed down factories, airlines have canceled their flights to Japan, and US$364 billion of wealth has been wiped off the Tokyo Stock Exchange. Tepco saw its shares drop by 25%, while Toshiba's fell by 20%.[34] Moreover, global prices for liquefied natural gas have risen as more cargoes are diverted from Europe to Japan to make up for its shortfall in electricity.[35] Global uranium prices have dropped by 25%, while gas and coal prices have increased by 13.4% and 10.8%, respectively, underscoring the global ramifications of Fukushima.[36]

Environmentally, the radioactive plume from Fukushima has spread far beyond Japan. Radiation levels in Tokyo were recorded to be 100 times higher than normal (measured at 5,575 μSv per hour), and the IAEA has measured potentially harmful levels of radiation as far as 130 miles away from the facility. Figure 3 shows a child being tested for radiation in Fukushima Prefecture. Radiation 1,600 times higher than normal has also been detected far off the coast of Japan, most likely from contaminated

Figure 3: A Family Being Tested for Radiation Exposure in Fukushima Prefecture, March 12, 2011

cooling water that has gradually drained off the Daiichi site. The city of Iwaki has suffered radioactive rain and has told its 340,000 citizens to stay indoors; city planners fear that radiation from Fukushima has contaminated its reservoirs of drinking water.[37] The Health Ministry of Japan has reported excess amounts of radioactive elements on canola, chrysanthemum greens, and spinach, as well as contaminated milk at 37 dairy farms in four prefectures.[38] The Health Ministry has also warned that tainted food has likely already been sold and consumed. Radioactive iodine-131 has been detected in Tokyo's water supply, forcing government spokespersons to declare it unsafe for infants and to start distributing bottled water.[39] Taiwan has detected radiation on imported fava beans from Japan; and Singapore has detected radioactive substances on imported Japanese wild parsley, rapeseed, mustard, and perilla leaf from four prefectures, including two far away from the Fukushima plant.[40] More than three dozen countries have banned Japanese imports of vegetables, fruit, dairy products, meat, and fish.[41] Meanwhile, a low-level radioactive plume has already spread across the Pacific Ocean, the Aleutian Islands in Alaska, and the West Coast of the United States.[42] Scientists at the Comprehensive Nuclear-Test-Ban Treaty Organization expect the plume to circulate the world in 10–15 days.[43] Residents in Russia have been buying potassium iodide pills, as have hundreds of thousands of people residing in coastal Chinese cities.

A final social and political impact, although hard to measure, has been a delayed humanitarian response to the earthquake, fear and anxiety, and panic buying. Disaster relief and humanitarian efforts following the earthquake and tsunami have been hampered by worries over radiation and uncertainty over the Fukushima accident. Many Fukushima residents claim that they would have fled the affected nuclear area, but did not have any fuel to make the journey. They have also reported that outsiders were not willing to come and get them because of fears of radiation.[44] Relief organizations such as the Red Cross Society and Tokyo Fire Department have suspended and withdrawn some of their evacuation and emergency response operations due to radiation concerns.[45] Fears of a complete meltdown have prompted panic buying of basic necessities in Tokyo and elsewhere, with supermarket shelves empty and shortages of basic goods. (To be sure, such fear and anxiety may have been worse in other cultures; most people in Japan have been stoic and resilient in the face of

Fukushima, with little complaining among evacuees and Tokyo people still waiting in line to pay their taxes two days after the quake struck.) Some corporations and embassies have also asked their citizens to move from affected areas in Japan, with the US State Department approving the departure of government personnel and several European countries urging their nationals to leave Japan altogether.

The Accident Was Unnecessary Given Japan's Renewable Resource Base

Although the vision of hindsight is often perfect, the Fukushima accident was avoidable insofar as Japan could have chosen instead to invest entirely in renewable energy resources. In 2009, Japan had roughly 290 GW of installed electrical capacity. Many experts and Japanese policymakers have argued that nuclear power is "unavoidable" for the country, given its lack of domestic resources. Yet, Japan has a total of 324 GW of achievable potential in the form of onshore and offshore wind turbines (222 GW), geothermal power plants (70 GW), additional hydroelectric capacity (26.5 GW), solar energy (4.8 GW), and agricultural residue (1.1 GW).[46] If policymakers had embarked upon a path of investing in these renewables instead of nuclear facilities, the Fukushima Daiichi accident would never have occurred. Japan certainly has enough renewable energy potential to displace all 50 GW of its nuclear power plants, let alone every existing conventional power plant connected to the grid in 2010.

Conclusion

For nuclear power to be safe, for all risks to be known, Japan and other countries embracing nuclear energy need not just properly designed plants and safety procedures, but also good governance, accountability, and transparency. The Fukushima Daiichi nuclear accident was born from the opposite conditions, in a culture of secrecy, incompetence, and cover-ups. Perhaps one of the scariest things about the accident is that it is not a worst-case scenario; in Japan, far less than 1% of the radioactivity within the reactors was released and only 5% of its nuclear fuel was damaged. (Even for Chernobyl, only 3–4% of the radioactivity in the reactor core was

released.) The grave and growing consequences of Fukushima — upwards of US$25 billion in damages to the plant, plus another few billion dollars for containment and decommissioning, 21 deaths and scores of injured and irradiated workers, rotating electricity blackouts, jittery global financial markets and rising fossil fuel prices, contaminated food and water, and compromised humanitarian relief for the earthquake and tsunami, to name a few — are *not* the worst that nuclear power plants can do when they malfunction. One does not need a lot of damage to a reactor or spent fuel pond to cause widespread misery. Taken together, the nuclear crisis, earthquake, and tsunami have been called a "triple disaster" that constitute what the Japanese are now calling the worst national crisis since World War II.

As *The Economist* eloquently summed up in their special briefing of the accident:

> Simply put, you can't trust the stuff. Somewhere, eventually, reactors will get out of control. One did at Three Mile Island in Pennsylvania in 1979. One did at Chernobyl in 1986. Now three have done so again . . . a bit like three Three Mile Islands in a row, with added damage in the spent-fuel stores. . . . Nuclear power thus looks dangerous, unpopular, expensive and risky. It is replaceable with relative ease and could be forgone with no huge structural shifts in the way the world works.[47]

The next nuclear disaster — and there will be one, as long as plants remain operating — may have nothing to do with an earthquake or tsunami, but may be caused by a terrorist attack, or a flood, or a design flaw, or a volcano, or simple human error. If there were no alternatives to nuclear power, then perhaps its collection of risks would be tolerable. But when so many viable alternatives exist that happen to be cheaper, less damaging, less dependent on subsidies, and safer, we do not need a world with more Fukushima meltdowns. Given the systemic risks involved with nuclear power, this book argued that a nuclear renaissance was unlikely to occur before Fukushima. Now, we have yet another strong reason to abandon nuclear power facilities in favor of energy efficiency and renewable energy technologies.

As one article proclaimed, the Fukushima crisis has been a problem of "hydra-headed complexity."[48] The analogy is apt, for in many ways the dangers of Fukushima are akin to the poisonous footprints of the hydra: invisible, implacable, and deadly. To successfully defeat the hydra in Greek legend, Heracles had to cut off all of its heads. Perhaps we will never be truly safe from accidents like Fukushima until we do the same to the nuclear industry.

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