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This paper began with an invitation from Japan a month after the disaster at Fukushima I Nuclear Power Plant began on March 11, 2011. The paper was to be presented six months later (October 30) — at a conference where I was already scheduled to present a paper on the use of imaginary cases in ethics (Davis, 2012). The disaster was still very much the province of journalism. Its outlines certainly lacked the stability of history. Of course, even history, though it generally seems stable, is not entirely so, being subject to dispute here and there and to radical revision every now and then. At first, Fukushima’s facts changed almost daily — if by “facts” we mean those descriptive propositions about which there is general agreement. After a while, the changes were less frequent and more a matter of addition than correction. Today, a year after I began work on the paper, the outline of the disaster seems settled. Dispute now concerns only details, such as how much land, if any, will have to be abandoned for some years, how many premature deaths are to be expected because of radiation released during the disaster, and so on. At some point, I had to stop worrying about the facts and report my reflections. I stopped worrying about the facts on October 15, 2011. Since then, I have changed “a fact” only when a reader or auditor pointed out that it was no longer fact.

I am an oddity in science and technology studies (STS) because I focus not on science and technology but on scientists and technologists. Indeed, I do not write about “scientists” in general or “technologists” in general but about specific professions, for example, chemists or engineers. While most STS scholars seem to focus on science and technology, I focus on scientists and technologists.

Three Nuclear Disasters and a Hurricane: Some Reflections on Engineering Ethics

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Abstract

The nuclear disaster that Japan suffered at Fukushima in the months following March 11, 2011 has been compared with other major nuclear disasters, especially, Three Mile Island (1979) and Chernobyl (1986). It is more like Chernobyl in severity, the only other 7 on the International Nuclear Event Scale; more like Three Mile Island in long-term effects. Yet Fukushima is not just another nuclear disaster. In ways important to engineering ethics, it is much more like Katrina’s destruction of New Orleans than like any nuclear disaster. It is (primarily) a consequence of a natural disaster, the enormous earthquake and tsunami that wrecked much of northeast Japan. One lesson of Fukushima, one shared with Katrina, concerns the different roles engineers have at different stages in an engineering project (planning, designing, management, and operations). In the planning stage, engineers seem to have relatively little power to affect certain early large-scale trade-offs between public safety and public welfare. Another lesson may be the importance of not leaving complex technical systems untended. The events that made the disasters at Three Mile Island and Chernobyl inevitable lasted only a few minutes or hours; the events that made the disasters in New Orleans and Fukushima inevitable were spread over several days. Fukushima avoided a more serious disaster because the plants were not abandoned in the way New Orleans was. A third lesson concerns our ideas of heroism, especially our sense that heroism is sometimes one’s duty. An engineer’s duty sometimes includes protecting others from harm even at the risk of the engineer’s life.

Keywords: Chernobyl, Fukushima, Katrina, Three Mile Island, precautionary principle
The nuclear disaster that Japan suffered at Fukushima has been compared with other major nuclear disasters, especially, Three Mile Island (1979) and Chernobyl (1986). It is more like Chernobyl in immediate destructiveness, the only other 7 on the International Nuclear Event Scale (the upper limit of which is 7). It is more like Three Mile Island in probable long-term effects (though Fukushima’s long-term effects are likely to be substantially worse than Three Mile Island’s). To date, Chernobyl seems to have directly killed thirty-one people, and more workers, to a lesser extent, have died of cancer related to the disaster. There have also been over 200,000 and 1,000,000 premature deaths worldwide, to have forced the permanent abandonment of a city of over 30,000 (Pripyat), and to have ruined perhaps a 100,000 square kilometers of farmland. Over 600,000 people lost their homes to contamination. (All information about Chernobyl here and below is drawn from Wiki, “Chernobyl”), a source valuable both because it is easily accessible and regularly updated.

In contrast, the radiation released from the Fukushima plant, though significant, will, it seems, leave little long-term contamination, except at the plant itself and in a plume perhaps fifty km beyond. At least six workers have exceeded lifetime legal limits for radiation and more than three hundred have received significant radiation doses. Estimates of future cancer deaths due to accumulated radiation exposures in the population living near Fukushima have ranged from none to a non-peer-reviewed “guessimate” of a thousand. No one died in the explosions at the plant or from subsequent radiation exposure. The evacuation of hospitals in the exclusion zone may have caused as many as forty-five more deaths. The earthquake or tsunami, rather than the nuclear accident, seems to be responsible for the few hundred deaths in what remained of the plant. (For details, see Wiki, “Fukushima Daiichi”.)

Three Mile Island

Three Mile Island was a “normal accident”, that is, it began with ordinary failures of equipment and practice within a plant itself operating normally. Perrow 1984 also describes Three Mile Island as a “normal accident”. While I agree that it was a “normal accident” in my sense, my use of that term is somewhat different. I mean by that accident a product of what engineers normally do rather than a product of incompetence, negligence, corruption, or other unusual conduct (such as experimentation).

During the night of March 27–28, 1979, workers were engaged in routine cleaning of a blockage in one of Reactor 2’s two cooling loops (filters for the secondary cooling loop). At 4 am, the pumps feeding the polisher stopped. We still do not know the cause of the stoppage. When a bypass was supposed to open, it did not open, and some polisher’s main feed-water pumps were stopped. These also shut down. No longer receiving water, the steam-driven generators stopped and the reactor core and its primary coolant vessel lost cooling. At 6 am (two hours after the incident began), the operators did not respond to these indications. At 7 am (almost three hours after the incident began) did the operators make an extensive investigation of the disaster, a second lesson.

The mechanical failures were compounded by the late hour of the accident. Workers and holding tanks were too high and used a backup valve to shut off the coolant venting through the relief valve. But, by then, about 120,000 liters of coolant had already leaked from the reactor core. When, by 7 am (almost three hours after the incident began) did contaminated water reach radiation-activated alarms. Then, the radiation in the primary coolant water was around three-hundred times higher than usual. The plant was seriously contaminated and the reactor’s core had suffered a partial meltdown.

The Nuclear Regulatory Commission (NRC) was extensive in its investigation of the disaster, a typical engineering response. Its report included recommendations for changes in controls, quality assurance, maintenance, operator training, management,
and communication of important safety information. There was no finding of negligence or more serious wrongdoing having caused the disaster, no suggestion that major redesign of nuclear plants was needed, and no proposal to rethink the place of nuclear energy in the generation of electricity. ( Rogovin 1980, pp. 89-93, focused mainly on changes in emphasis and procedures at the NRC; Kemeny 1979, pp. 61-73, focused on "attitudinal" and "attitudinal reports" do, however, contain much criticism of other aspects of how Three Mile Island operated.

Chernobyl

Chernobyl was not a normal accident. Its cause was an engineering experiment which, though successful, lacked proper approval. That is not to say that the experiment was unjustified, fundamentally improper, or indeed abnormal.

Even when not actively generating power, nuclear reactors require cooling to remove heat produced by the natural decay of nuclear fuel. Chernobyl’s pressurized water reactors (different in design from Three Mile Island’s used water flowing at high pressure to remove waste heat (about 28,000 liters of water an hour). After an emergency shutdown, the core could still generate a significant amount of residual heat. If not removed, the heat could cause core damage (as it did at Three Mile Island). If the power grid failed, power to run the plant’s cooling system might be unavailable from outside for far too long.

Chernobyl’s reactors had three backup diesel generators. Each generator required fifteen seconds to start up but took over a minute to attain the speed required to run one of the main coolant pumps. Chernobyl’s engineers judged this one-minute power gap unacceptable. Too much can happen in a nuclear reactor in a minute when the cooling system is not working. Analysis indicated that only one bridge to the reactor would have been de-fueled while 5 and 6 were in cold shutdown and would have happened even if the Fukushima nuclear power plant, one of the twenty-five largest in the world, had never existed. The nuclear disaster is a byproduct of that larger natural disaster.

At the time of the quake, 2:46 pm, Reactor 4 had been de-fueled while 5 and 6 were in cold shutdown for planned maintenance. The remaining three reactors had shut down automatically. When they shut down, the on-site emergency diesel generators would have started up thirteen on-site emergency diesel generators. These would ordinarily have provided enough power to operate the reactors’ control and cooling systems until the loss of connection to the national grid could be restored. Had the earthquake been the only disaster to hit the Fukushima plant on March 11, there would have been little to discuss here. The tsunami changed that.

The plant was protected by a seawall designed to withstand any tsunami up to 5.7 meters, but the great wave that struck forty-one minutes after the quake was fifteen-meter. It flooded the entire plant, including generators and electrical switchgear in reactor basements. It also broke the remaining connection with the national electrical grid. All conventional power for cooling and control would have been lost. Only one backup remained: emergency batteries, able to run some of the monitoring and control systems for up to eight hours. Replacement batteries and mobile generators were soon dispatched to Fukushima, but collapsed bridges, debris-strewn roads, and similar obstacles delayed them. The first replacements did not arrive until 9:00 pm (six hours after the first call went in).

The arrival of the replacement batteries and mobile generators did not end the crisis, however. They had to be installed. The normal connection points were in flooded natural disaster. There was also difficulty finding suitable cables. Work to connect batteries and generators was still continuing twenty-four hours after the quake when there was an explosion in Reactor 1’s building. The side walls of the upper level were blown away, the side walls of the upper level were blown away, the roof collapsed, and debris covered much of the floor and machinery.

The roof of the building was designed to provide ordinary weather protection, not to withstand an explosion or to act as containment for the reactor. In the Fukushima reactors, the primary containment surrounded the reactor’s pressure vessel. The top floor had no roof, simply water filled pools for storing new fuel ready to be craned into the reactor and used fuel ready for disposal.

This first explosion was probably caused when

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Fukushima

The disaster at Fukushima fits neither of these patterns. The accident was not normal or the result of an engineering experiment. It was also not the result of operator negligence, incompetence, or misconduct. The maintenance experiment focused on refinements in the switching sequences of the electrical supplies for the reactor. The experiment was begun with an automatic emergency shutdown. Because no

danger to the reactor was anticipated, the engineers did not formally coordinate the experiment with either the reactor’s chief designer or scientific manager. Indeed, the experiment did not even have the approval of the onsite representatives as the Soviet nuclear emergency manager. Only the director of the plant approved it (and even his approval did not follow standard procedures).

The experiment began just after 2:23 am on April 26, 2011, when the reactor was displaced before the dampening rods displaced coolant before inserting the control rods to the rods’ upper limit, but the rapid reduction in the power during the initial shutdown and subsequent operation at less than 200 MW led to increased dampening of the reactor core by the natural damped core (an unwanted effect of uranium that absorbs neutrons at a high rate). To counteract this unwanted high-absorption, the operators withdrew additional control rods from the reactor core.

Then, about the time the experiment ended, there was an emergency shutdown of the reactor. The shutdown started when someone pressed the button of the reactor’s emergency protection system. (We do not know whether the button was pressed as an emergency measure, by mistake, or simply as a routine method of shutting down the reactor upon completion of the experiment.) Because of a flaw in the design of the graphite-tip control rods, the reactor core overheated when the dampening rods were displaced. The reactor operators quickly realized the danger. The emergency shutdown therefore briefly increased the reactor rate in the lower half of the core. A few seconds later, even after the shutdown, there was a massive power increase, the core overheated, and seconds later this overheating produced the first explosion. Some of the fuel rods fractured, blocking the control-rod columns and causing the control rods to become stuck at one-third insertion. Several more explosions followed, exposing the reactor’s graphite moderator to air, causing it to ignite. Since the reactor lacked a containment (a thick concrete shell), the fire in the reactor sent a plume of highly radioactive smoke into the atmosphere, causing dangerous fallout over a huge area (as much as five-hundred km away)—and, eventually, less dangerous fallout over much of the world.

The effort to halt the nuclear contamination and avert a much greater disaster soon involved over 500,000 workers and an estimated eighteen billion roubles, crippling the Soviet economy.

Because most of those directly involved in the Chernobyl disaster soon died of radiation poisoning, there are many uncertainties about the exact sequence of events. Nonetheless, we can be sure that the actual disaster would not have occurred had the experiment not been carried out. Chernobyl was as much an engineering disaster as Three Mile Island: both the immediate and underlying causes were ordinary engineering decisions, whether in operation or design.

Fukushima
hydrogen collected under the roof. Exposed fuel rods became very hot and reacted with steam, oxidizing the cladding and releasing hydrogen. The hydrogen would have leaked upward. Safety devices normally burn such hydrogen to prevent an explosive concentration. These systems seem to have failed when the electrical power did.

Reactor 1’s containment survived the explosion. There was no large leak of radioactive material, though it seems there was a significant amount of damage. This was not surprising: the Fukushima plant could have been designed to have its containment vessels withstand explosions. It seems, however, that the Fukushima disaster might have become at least as devastating as Chernobyl. Even with those heroic efforts, several weeks passed before the plant could be shut down and brought back under control. One generator at Reactor 6 was restarted on March 17 (six days after the quake) allowing some cooling at Reactor 5 and 6, though not enough. That is as true of Katrina as of earlier disasters, than most cities. Engineers did not found New Orleans even with the support of a simple earthen levee) was a mistake. It is replacing the canal’s I-walls with heavily-braced T-walls locked down by twenty-one meter-high piles angled out in two directions. The use of simple levees was also judged a mistake. The Corps is now “armoring” all levees where they seem vulnerable to overtopping, that is, covering them with something water will not soak through or quickly drain (with even the changes in design that government was unwilling to pay for without a major disaster and may yet lose interest in paying for before the work is complete).

**Conclusions**

We can, I think, distinguish four sorts of engineering decision in these four case studies: planning, designing, management, and operations. (In a different context, I would include “disposal” in this list. I do not include it here only because none of these disasters concerns disposal as such, though Fukushima’s problems were due, in part, to fuel rods waiting disposal.) By planning, I mean decision as to what to build and where to put it, and the upper limit of its budget. For such decisions, engineers are most important for vetoing certain options, for example, a location where the risk of earthquake makes safe construction too expensive. They are also important for suggesting alternatives, for example, conservation or a gas-fired plant rather than a nuclear plant. Engineers are not, at least, not in the business of being “savers”. One important function they have is helping to define problems—or re-define them when it becomes clear that the client or employer has not asked the right question.

But, for any large undertaking such as a nuclear plant or flood control system, engineers are generally only one party in a complex social decision in which the other parties include employer, government officials, experts of various sorts (such as geologists), banks, and civil society (or “the public”). Perhaps the most important engineering contributors can make to planning is developing minimum standards for evaluating and responding to specific risks and benefits of the technology in question. By designing, I mean the actual drafting of specifications. Floor plans are an example. Floor plans on necessity to construct or modify the technological artifact in question. Once planning has set limits, engineers are generally free to work within those limits, for example, to design against a 500-year, 1,000-year, or 10,000-year quake.

**Katrina**

When it struck New Orleans on August 29, 2005, Katrina was a category 3 hurricane, a large storm but no larger than storms that strike the Gulf Coast almost every year. The top of the hurricane scale is 5. Ike was nonetheless unusually destructive because it moved so slowly that anything in its path was subject to heavy rains and high winds for many hours. The rain and high winds were worse for Task Force, 90% of the residents were evacuated from the city (IPEF) issued its (draft) Final Report. IPEF was an independent team of more than one-hundred-fifty international and national experts from more than fifty different government organizations, universities, and private companies. The U.S. Army Corps of Engineers commissioned IPEF a few weeks after Katrina hit New Orleans. It was to analyze how the levee system performed. Though many questions of detail remain unsettled, this nine-volume report, is (more or less) the last word on both the causes of the Katrina disaster and means of preventing similar disasters.

IPEF reports a “system” that grew up piecemeal, only in part under the control of the Corps of Engineers, the government agency officially in charge of waterways. In some places, the system failed because a levee or other barrier was not high enough, often because of unanticipated subsidence rather than original design error. In other places, the system failed because, though high enough, the barriers were not designed for the forces to which they were in fact subject (an unusually slow-moving storm). Design of floodwalls along three canals was “particularly inadequate”. A series of increments added to the existing plan, but those structures actually constructed “systematically increased the inherent risk in the system without recognition or acknowledgment” (IPEF 2006, I-2). Many of the failures in the system would not have occurred had implementation of plans for reconstruction not been delayed for almost twenty-five years by inadequate funding, new laws governing the environment, and simple inefficiencies of government (IPEF 2006, I-2)

For some important “decisions”, there was no decision-maker at all. The decisions were a mere byproduct of poor communication, poor information, poor coordination, or some combination of these.

The most important lesson IPEF drew from its analysis is unsurprising: The way to avoid similar disasters is to use larger safety factors (“conservative design”) and good materials (“higher quality, less erodible”). (IPEF 2006, I-3)
A nuclear plant that will fail slowly rather than quickly or cool rather than heat up if left alone. Only when a planning limit is too strict do engineers have a reason to restart the planning process, for example, by suggesting higher capital budget be raised to provide an adequate margin of safety.

By management, I mean overseeing the operations of a plant, including choosing, training, and directing operators. Designing is not technical—and is therefore not the domain of the engineers. But, for nuclear plants or flood control systems, the managers will typically be engineers. For engineers, part of technical management is remaining alert to possible improvements in staff, procedures, and equipment. So, for example, a manager who noticed that operators at Three Mile Island often missed readings on an important gauge because equipment blocked their view of it should recommend, or order, that the control board or control room be redesigned to improve the view.

By operations, I mean actually doing what is necessary for the plant or other technical artifact to work. While engineers do not, in general, operate plants, they do constitute most of the operators in a nuclear plant. So, for example, at Chernobyl, they pushed the buttons that moved dampening rods into the core. While operators can be reprimanded, and their acts reversed, they are, while acting as operators, completely in control of what happens. The problem is part of what we noted in our discussion of the three nuclear disasters is how quickly things can go wrong. What goes wrong in a nuclear plant does not, of course, go seriously wrong for just one reason. Because engineers typically design nuclear plants with a large safety factor, several systems must fail before anything goes seriously wrong. But, given the complexity of a nuclear plant, it is reasonable to expect that things will now and then be going wrong—even with proper maintenance and inspection, technical systems sometimes fail unexpectedly. That being so, it is also reasonable to expect (given the laws of statistics) that all of the independent systems will fail together sooner or later. One of the “systems” that may fail at any given time is the human operator—whether because of distraction, fatigue, poor training, misjudgment, or sheer stupidity.

How likely is a catastrophic failure at any moment? Not very. Perhaps only 10^-4 at any time. But over many years and many reactors even such small risks add up. One author recently calculated that there are:

450 nuclear power plants in the world. There have been 4 meltdowns in history, one each at Chernobyl and Three Mile Island and two so far at Fukushima, as partial meltdowns count as meltdowns. That is a ~1%-5 failure rate. (Lindsay, 2011)

This calculation means nothing unless the four meltdowns are statistically significant, that is, a good predictor of what will happen over, say, the next hundred years (rather than a chance occurrence of events—like winning the lottery three days in a row). No it is an empirical reminder that even a low-probability event will, given a large enough population, become highly probable.

If we look at our four disasters, two—Three Mile Island and Chernobyl—seem unrelated to any ordinary planning or design failure. Of course, with a higher budget, the Three Mile Island plant might have had more working backups for its cooling system; for Chernobyl it might have had a concrete containment for its reactor or a better way of controlling core temperature. But that will always, or at least almost always, be true.

Engineering is about making things “safe enough” rather than “absolutely safe”.

How safe is “safe enough” is at least as much a social decision as an engineering decision. But it is an engineering decision in part. For small risks, engineers may well make the final decision. Even concerning the largest risks, engineers will be consulted and their opinion given considerable weight. No decision-maker was ever overruled by overly-engineers on the 9/11 attack, or to have the decision (more or less figuratively) blow up in her face.

Engineers generally evaluate risk by multiplying the harm’s (net) by the harm’s probability. This method of risk analysis works reasonably well for small harms. The method does not, I think, work at all well for the largest harms—that those, even if highly improbable, would be intolerable if realized—such as destruction of the earth or even the sort of devastation Chernobyl produced. For such intolerable harms, engineers should, I think, adopt precautionary principle like those used in prudence in planning: if we (society at its rational best) would reject any plausible benefit in exchange for suffering that harm, we (that part of society making the decision) should as well. This is, I think, a reminder that part of what makes engineering so reliable is that it accepts risk in a way that is more working enough. The analogy with prudence in planning suggests that part of what makes engineering so reliable is that it accepts risk in a way that is more working than “absolutely safe”.

For me, what is special about Fukushima compared

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other engineers may not be able to make the necessary changes immediately because of budget or schedule, or at all because changes that they have already made bar the improvement in question. Engineers may also find an alternative way to achieve the same end. For these reasons (and perhaps others), nuclear plants, however alike at birth, tend to grow into noticeably different individuals, much as botanical plants do.

Some people, especially philosophers, seem to think of those who stayed on at Fukushima—those who, for example, worked in the dark in waist-high radioactive water to restart the generators—as engaged in “suprerogatory” conduct, that is, as engaged in conduct above and beyond what morality requires. The engineers I have discussed this with seem to view the conduct as heroic but required (supposing the “workers” in question to be engineers). An engineer who left when needed would have acted unprofessionally; he would have failed as an engineer even if he left to save his life or look after his family. Engineering sometimes requires heroism (a significantly higher standard than proposed in Alpern 1983) — or so the engineers I have talked with about this seem to think.

Acknowledgments

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References


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Abstract

This paper claims that the use of several moral tests to assess the ethics of a new policy is unavoidable. All the efforts to make credible a methodological monism – by critical or reductionist strategies – have been unsuccessful; moreover, it must be acknowledged that even if there were a single test, when applied successively or by different people it would usually give divergent results. The main aim of the paper is to propose a pluralistic procedure of ethical decision-making, using a set of proper ethical tests (such as utilitarian, Kantian, Christian, principlist and casuist) in the frame of an “ethical Delphi” procedure intended to make convergent the supposed variety of verdicts. This pluralist testing process, made by moral experts, is only a fraction of a more complex procedure intended to deliver social sanction for a new moral policy. This longer procedure also shows that the adoption of a new moral policy, rule or law is not only a question of passing a strict ethical test, but also a political (i.e. multi-criteria) decision. In general, the adoption of a new moral rule does not rely solely on an ethical test, but is essentially the outcome of a complicated social agreement. That is why in academic applications of the usual moral tests we do not take a moral decision on a new case, but merely simulate it.

Key words: ethical decision-making, ethical pluralism, ethical Delphi, pluralist model

Decisions about the moral value of an action, rule or public policy cannot be reduced to a verdict resulting from the application of traditional tests based on the major ethical theories, despite the fact that handbooks still unanimously support this view. The history of ethical test results is more one of surprises than one of predictability. You would expect, for instance, that people who adopt the same moral doctrine do this in order to approach issues in the same way, including the moral assessment of actions. We all believe that this is the main reason it is useful to embrace the same moral creed. Therefore it seems strange to find that several members of the Romanian Parliament, all active supporters of Christian morality, assessed the legalisation of prostitution in opposing ways. On the other hand, it is also strange that two people who adopt different ethical theories – precisely because they offer distinct explanations of moral phenomena – can frequently assess actions in the same manner. When a utilitarian and a Kantian – or a follower of Christian ethics and one of Muslim ethics – debate issues, it is somehow surprising to see them judging situations in the same way in most cases, despite the fact they declare themselves to be supporters of opposing ethical beliefs. Are these beliefs really opposing? In general, it appears that use of tests based on distinct or even opposing theories, such as utilitarianism and Kantianism, can result in different verdicts, but in most cases it results in convergent ones (Kantian and utilitarian moral duties are, ultimately, the same). On the other hand, if we dogmatically adopt a single theory and apply the same test repeatedly to the same action we usually get similar results, but some divergent ones also appear (see the cases of divergent utilitarian assessments of the same case given as examples in the textbooks).