POLICY FORUM

NUCLEAR POWER

Nuclear safety regulation in the post-Fukushima era

Flawed analyses underlie lax U.S. regulation of spent fuel

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The March 2011 Fukushima Daiichi nuclear accident prompted regulators around the world to take a hard look at their requirements for protecting nuclear plants against severe accidents. In the United States, the Nuclear Regulatory Commission (NRC) ordered a "top-to-bottom" review of its regulations, and ultimately approved a number of safety upgrades. It rejected other risk-reduction measures, however, using a screening process that did not adequately account for impacts of large-scale land contamination events. Among rejected options was a measure to end dense packing of 90 spent fuel pools, which we consider critical for avoiding a potential catastrophe much greater than Fukushima. Unless the NRC improves its approach to assessing risks and benefits of safety improvements—by using more realistic parameters in its quantitative assessments and also taking into account societal impacts—the United States will remain needlessly vulnerable to such disasters.

Spent nuclear fuel must be cooled in water-filled pools immediately after discharge from reactors. After cooling for a few years, transfer of spent fuel to air-cooled dry storage casks becomes practical. In the United States, the NRC allows spent fuel to remain in pool storage until a geologic repository for spent fuel becomes available. To minimize storage costs, utilities pack the pools about as densely as possible, and only when they are full, do they make space for newly discharged hot fuel by buying dry casks to store the fuel that has cooled the longest.

Dense-packed spent fuel would be susceptible to catching fire if an accident or terrorist attack caused a loss of the pool's cooling water. Oxidation by steam of a small fraction of the zirconium in the fuel cladding would liberate sufficient hydrogen gas to potentially cause an explosion and destruction of the building covering the pool. Explosions of hydrogen gas generated by steam reactions with uncovered reactor cores destroyed buildings covering three Fukushima Daiichi reactors, exposing their fuel pools to the environment (see the photo).

Fortunately, in Fukushima, the spent fuel remained covered with water. For almost a month, however, Tokyo Electric Power Company overestimated the water level in the densely packed spent fuel pool of unit 4 and did not add enough water to keep up with the rate of evaporation. A month after the earthquake, when the utility finally measured the water level directly, it had fallen from 7 to 2 meters above the top of the stored fuel. Fortuitously, water had leaked into pool 4 from the adjacent reactor cavity—which does not ordinarily contain water—keeping the spent fuel covered and preventing a fire (*1*).

Unit 4 at the Fukushima Daiichi nuclear power plant, damaged by an explosion on 15 March 2011.

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Thirty-year half-life cesium was the main radioactive contaminant that forced relocation of large populations following the Chernobyl and Fukushima accidents. NRC contractors at Sandia National Laboratory estimated that, had there been a fire in pool 4, 100 times as much cesium-137 would have been released to the atmosphere than actually leaked from the damaged Fukushima reactors (*2*). If that had happened, depending on weather conditions, cesium-137 contamination would have forced long-term relocation of between 1.6 million and 35 million people, instead of 150,000, from Japan's East Coast (*3*).

After Fukushima, the NRC evaluated whether to require nuclear power plants to reduce the risk of a catastrophic spent fuel fire by transferring fuel that had cooled for >5 years from pools to safer dry storage casks. The NRC had two primary options for imposing a "backfit" such as this on already-licensed nuclear power plants. The first was to declare that the change was needed to provide "adequate protection" of public health and safety.

In its technical evaluation, the NRC estimated that, for a typical U.S. Mark I boiling-water reactor at Peach Bottom in Pennsylvania, a spent fuel fire in a dense-packed pool would require relocation of 4.1 million people from an area of 24,500 km^2—50 times as many as the corresponding values for a fire in a low-density pool (*4*). However, neither this finding nor a broader regulatory analysis of all U.S. plants persuaded the NRC to change its view that high-density pool storage provides "adequate protection" according to its interpretation of the Atomic Energy Act, which does not provide criteria for determining adequate protection (*5*).

Given this decision, under the NRC's self-imposed rules, the backfit could be adopted only if the monetary value of the resulting reduction in risk to the public were to exceed the cost of implementation and the increase in safety were "substantial" (*6*). In the decades since NRC adopted this "backfit rule," it has based determinations increasingly on quantitative assessments of risk, defined as the product of probability and consequences. The quality of these complex calculations depends strongly on the validity of the input assumptions, and they typically have large uncertainties that the NRC fails to fully account for in its regulatory decisions. These characteristics also introduce opportunities for the NRC to produce risk assessments that justify, rather than inform, its decisions. In any case, no matter how large the consequences of an accident, if the NRC estimates a low enough probability, the risk will be too low to justify major expenditures on mitigation.

Thus, although the NRC backfit analysis found that the huge quantity of fission products released by a dense-packed pool fire

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could be dramatically reduced by lowering the fuel density, it estimated that the probability of a fire resulting in a large release would be small—on the order of 4×10^{-6} per pool per year, although with a large uncertainty (7×10^{-7} to 3×10^{-5}).

The NRC's cost-benefit analysis did not account for the possibility of a terrorist attack, which cannot be quantified but should not be ignored (*7*). In addition, the NRC made a series of assumptions that tended to minimize the estimated health and economic consequences of a high-density release. After making these assumptions and ignoring uncertainties, the NRC found that the probability-weighted benefits to the public from transferring spent fuel to passively air-cooled dry cask storage did not justify the estimated cost of $5 billion to the nuclear utilities (about $50 million per reactor).

A recent National Academy of Sciences study (on which author F.v.H. served) found that the NRC cost-benefit analysis—unreasonably, in our view—excluded accident consequences beyond 50 miles and underestimated consequences in a number of other ways (*4*). In response to a petition by the state of New York, the NRC acknowledged that its assumption in such calculations, that virtually all the relocated population could return home within less than a year, was inconsistent with the experience in Japan, where some of the relocated population is just beginning to return after 6 years (*8*). NRC computer output made public as a result of the New York hearing also showed that the NRC analysis assumed radiation dose standards for population relocation that were much less restrictive than those recommended by the Environmental Protection Agency (EPA) or those that were applied by Soviet and Japanese authorities after the Chernobyl and Fukushima accidents. If the EPA guidance were followed, we estimate that the average area evacuated as a result of a spent fuel fire in a densely packed pool at the Peach Bottom plant would increase about threefold (*3*). Correcting for the above errors would have made the NRC's central estimates of the benefits of expedited transfer of spent fuel to dry cask storage greater than the costs (*9*).

The NRC argues that, even if the benefits of a backfit exceed its costs, it should be subjected to a "safety goal screening" to determine whether the safety enhancement is "substantial." The screening criteria set limits on the health risks from accidents to individuals living close to nuclear plants. The NRC's analysis met these limits by assuming a rapid and long-duration evacuation of these close-in areas. For the small doses that the NRC staff estimated that members of the public would incur after returning to their decontaminated towns, the health risk would be less than the NRC's safety goals as long as the frequency of a spent fuel fire in the United States was less than once every 4 years (*3*).

Yet health risks to individuals are not synonymous with societal risks. When its safety goal policy was first developed in the 1980s, the NRC considered but rejected including a "societal risk" in addition to an individual health–risk threshold for regulatory action (*10*). The NRC's failure to adopt such a criterion has long been criticized. Imposing a reasonable constraint on the cumulative societal impact of accidents would compel the NRC to lower the risk of a large-scale land contamination event that could drive millions from their homes and businesses for years (*11*, *12*). The psychological trauma and economic cost of even one such event would be unacceptable. In our view, if the NRC were to use more realistic quantitative assessments and give weight to societal impacts, a requirement to expedite transfer of spent fuel to dry casks would be justified.

The NRC's skewed approach to nuclear reactor safety regulation appears to be in part a result of pressure from the nuclear utilities and a Congress sympathetic to the utilities' complaints of overregulation. This is the well-known phenomenon of "regulatory capture." Former U.S. Senator Pete Domenici described how he curbed the NRC's regulatory reach by threatening to cut its budget by one-third. He believed that, partly in response to this pressure, the NRC committed to adopting "risk-informed regulation" (*13*). Risk-informed regulation would be legitimate if the underlying methodology and data were sound and uncertainties were properly accounted for. But the NRC relied on flawed calculations and ignored their uncertainties when it rejected expedited transfer of spent fuel from pool storage.

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Many in Congress are opposed to additional costly regulations, fearing that more nuclear power plants will become unprofitable and shut down. Recently, chairs of the NRC's Senate oversight committee and subcommittee insisted on "strict application and adherence to the Backfit Rule" (*14*). If a spent fuel–pool fire were to occur, however, under the Price-Anderson Act of 1957, the nuclear industry would be liable only for damages up to $13.6 billion, leaving the public to deal with damages exceeding that amount (*15*). A fire in a dense-packed fuel pool could cause trillions of dollars in damages (*9*).

To reduce the risk and invest in infrastructure, Congress could consider allocating $5 billion for casks to store spent fuel. The federal government is already reimbursing nuclear utilities almost $1 billion per year for casks needed to store older spent fuel because the Department of Energy has not fulfilled its commitment to remove the fuel to an underground repository or interim storage site (*16*, *17*). States also could act to reduce the risk. As part of its policy to reduce fossil fuel use, New York recently decided to mandate subsidies totaling about $500 million per year for continued operation of four nuclear power reactors (*18*). Illinois has adopted a similar policy, and other states are considering the same. States could condition such subsidies on agreements by utilities to end dense-packing of spent fuel pools.

The larger problem of NRC regulatory capture will be dealt with, however, only when pressure from the concerned public outweighs that from the nuclear industry. ■

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