MEMORANDUM

To: Friends of NRDC
From: Christopher Paine, Nuclear Program Director
Date: June 14, 2011
Re: The Fukushima Nuclear Accident and Its Implications for Nuclear Power in the U.S. and Globally

This memorandum briefly summarizes: the course of the Fukushima accident and subsequent releases of radiation; key questions for Japan posed by the accident; the U.S. response to date; the implications of the accident for a fresh safety assessment US reactors; and NRDC's general approach to nuclear power generation. NRDC's approach potentially includes advocating for the shutdown of: certain older reactors that continue to operate with known defects and vulnerabilities in densely populated urban areas; and other reactors that may be reassessed as posing excessive risks, due to the size of the population that could be harmed in a serious accident and the small likelihood of staging a successful evacuation.

Course of the Fukushima Accident. In response to the tremors of the March 11Tohoku earthquake—at magnitude 9 the largest ever recorded near Japan —11Japanese reactors performed emergency shutdowns as designed. Of the six units at the Fukushima Daiichi plant, three were operating at the time of the earthquake, and these were successfully shut down: the fission chain reactions in the cores were stopped by the rapid insertion of neutron-absorbing control rods, and emergency diesel generators switched on to replace the normal supply of electricity to the plant from the local power grid, which was knocked out by the quake. To reach "cold-shutdown," however, requires continued cooling of the core to remove the residual heat created by the radioactive decay of short-lived elements produced in the core by fission. Trouble began an hour later when the tsunami swept over the station and flooded both the seawater coolant pumps normally used to remove heat from the reactor and the backup diesel generators used to power emergency systems. Ultimately the flow of cooling water to the reactor cores could not be maintained because of what is called a "station blackout," in which both off-site power and on-site emergency diesel generator backup power were lost, followed a few hours later by the exhaustion of the reserve batteries.

As cooling systems failed in the reactors, the cores heated up, water surrounding the fuel evaporated, nuclear fuel became exposed to air, and the fuel temperature continued to rise. Major core melting occurred in three of the reactor units at Fukushima—including complete core melt in the oldest reactor, Unit 1—within a day of the earthquake and tsunami. Hydrogen gas was produced by the hot exposed fuel, and this was initially vented into the secondary containment building rather than to the outside, causing the three explosions at Fukushima Daiichi. The explosions damaged the reactor cores, containment, equipment, buildings and – importantly – also damaged the spent fuel pools. Reportedly 647 tons of spent nuclear fuel is stored outside the containments in pools located at the tops of the six reactor buildings. We assess the Fukushima accident as vastly more severe than the partial meltdown of Pennsylvania's Three Mile Island nuclear reactor in 1979, but with an estimated radiation release to the atmosphere to date that is approximately 1/6 of what is calculated to have occurred during the USSR's 1986 reactor explosion at Chernobyl, in what is now Ukraine.

Radiation release. The highest radiation measurements reported by the Japanese government in the first days of the accident were taken within the plant boundary adjacent to the damaged reactors, and were very high dose rates – sufficient to cause severe radiation sickness in addition to genetic damage and heightened cancer risk – over a period of hours or less. Even at the plant boundary, reported radiation levels were such that the threshold of the annual limit for nuclear plant workers would be reached in a matter of hours. Off site, the Japanese government confirmed radioactive iodine and cesium has been detected in the water supplies of Fukushima city, neighboring prefectures, and in Tokyo 135 miles southeast from the reactors. Fallout (surface deposition of radioactivity) from the reactor disaster has been measured in twelve prefectures surrounding Fukushima Daiichi. Radiation from the Fukushima accident was recorded world-wide, including in US air, rainwater and milk, but at low levels not of a health concern to individuals due to dilution and dispersal over the 5,000 mile westward drift from Fukushima Daiichi to the United States west coast.

The Accident Today. Now three months into the disaster, the situation at Fukushima remains very serious. Approximately 80,000 residents within the "Restricted Area" – the 20-kilometer radius zone around the damaged nuclear plant – have been evacuated, and a further 10,000 residents are evacuating from counties further out, in the northwest direction from the plant within the most intense radioactive plume. A further "Emergency Preparation Evacuation Area" has been established between 20 and 30 kilometers from the damaged plant impacting another 60,000 residents. These municipalities covered under the Japanese government's evacuations were chosen because the annual expected radiation dose would be higher than 20 milli-Sieverts (mSV), or six-and-a-half times the average background dose Americans receive from natural sources of radiation over a year (one sievert represents the absorbed dose of radiation that roughly corresponds to the threshold for onset of acute radiation sickness resulting in prompt death if untreated.) To get a sense of the risk from long-term exposure to 20 mSV, in a group of 100 people exposed to 20 mSV per year over their lifetimes, about 16 would get cancer as a result of this radiation exposure, and 8 would die from their cancer. The elevated incremental cancer risk represented by shorter term exposures at this level, while still significant and hazardous to human health, should nonetheless be compared to the immediate consequences of the quake and tsunami itself, apart from the nuclear accident: more than 15,000 immediate fatalities, more than 8000 officially listed as missing but not yet confirmed dead, and more than 300,000 buildings destroyed.

In April the Japanese utility which owns the plant – TEPCO – released a two-step plan for reducing and controlling the continued radiation releases to the air and ocean and providing stable cooling at the plant, leading to cold shut-down of the four reactors by the end of 2011 at the earliest. The long-term strategy is to entomb the damaged reactors as was done with the Chernobyl Sarcophagus. Direct cost estimates for the accident to date exceed 10 billion dollars, but assessments of the full damage to the reactor cores, containment and spent fuel pools are on-going, including the use of radiation-hardened robots. There still remain fundamental unanswered questions about the causal factors and extent of the Fukushima nuclear accident.

Key Questions for Japan. The precipitating events for the Fukushima Daichi nuclear accident -- the magnitude 9.0 Tohoku earthquake followed by a massive 15 meter (49 foot) tsunami at the plant (the tsunami height was recorded as high as 38 meters – 125 feet – across the Japanese north Pacific coast), both exceeded the "design basis" of the Fukushima nuclear units, the latter by a wide margin. But the plant was known to be located in an active tectonic plate subduction zone, where the North American and Pacific Plates collide, capable of generating very powerful earthquakes with the particular type of energy release that can trigger devastating tsunamis. Despite experiencing precipitating events of the same magnitude, and loss of primary emergency core cooling in all of its four units, the nearby Fukushima Daini nuclear plant managed to implement a backup method of emergency core cooling, followed by recovery of the main emergency core cooling systems, and it reached cold shutdown for all for units three days after the quake.

A basic conclusion to be drawn from these underlying facts is that the roots of the nuclear disaster experienced at the Fukushima Daichi are much more complicated than a nuclear plant simply being struck by some random, supposedly unforeseeable event. Going forward, the Japanese and international investigations of the accident will have to probe a number of critical issues:

(1) How were the plants original seismic design criteria determined, and why was the seismic risk to the plants, including tsunami risk, not reevaluated in light of modern geophysical knowledge about the earthquake/tsunami potential in the region;

(2) What role did the well-known inherent vulnerabilities of the obsolescent General Electric (GE) Mark I Boiling Water Reactor (BWR) design play in the evolution of the accident and the release of radionuclides to the environment?

(3) Did TEPCO's documented record of misleading regulators result in critical safety systems at the plant being in a degraded or insecure condition? Why, for example, were emergency diesel generators positioned in the basements of the turbine buildings, where they were vulnerable to

flooding? Why did the valves in the hydrogen vent pipe system -- a critical safety upgrade added to this design in the 1990's -- fail to open?

(4) Did Japan's lack of a truly independent and effective nuclear safety regulator leave important vulnerabilities at the plant unexamined, or possibly noted but not remedied?

In the wake of the quake and tsunami and the ongoing struggle to reach safe shutdown at Fukushima, Japan's nuclear fleet is running at less than half its rated capacity. If this situation persists, the cost of fossil replacement power alone will add trillions of yen to the cost of recovery from the quake. The most recent news reports suggest that Japan is significantly revising its current reactor building program, which originally projected adding 14 new nuclear units by 2030 and increasing the share of nuclear power in Japan's generation mix from 30 to 50 percent. Instead, it appears that Japan will ease up significantly on nuclear expansion and try to fill the gap by increasing renewable power generation and energy efficiency.

The U.S. Response. The Nuclear Regulatory Commission (NRC) is nearing the end of an initial "90-Day Effort" to review the safety status of the US nuclear fleet in light of information from the Japanese event. This short-term quick response reportedly will be followed by a more in-depth "six month review." The NRC will use this information to assess the 104 operating US reactors, looking at: natural disasters, station blackouts, severe accidents and spent fuel accident prevention, and radiological consequence analysis. The result of the 90-Day Effort will be a "Quick Look" report with "limited stakeholder involvement."

In the meantime, recent reviews of NRC inspection documents by reporters at the New York Times and by outside investigators from the staff of Rep. Edward J. Markey and the Union of Concerned Scientists (UCS) have revealed multiple causes for concern about the performance of key safety systems at numerous US nuclear power plants.

- **Diesel Generators**: In the past eight years there have been at least 69 reports of emergency diesel generator inoperability at 33 nuclear power plants. A total of 48 reactors were affected including 19 failures lasting over two weeks and 6 that lasted longer than a month. The NRC's regulations do not require emergency diesel generators to be operational at times when there is no fuel in the reactor core, even though this could leave spent nuclear fuel pools without any backup cooling systems in the event of a loss of external electricity to the power plant.

- **Overloaded Spent Fuel Pools**: The NRC has not required its licensees to reduce the amount of nuclear fuel stored in its spent nuclear fuel pools by moving it to dry cask storage, a safer means of storage that would reduce the risk of fire and radiation release in the event of an accident. There are 66,000 metric tons of spent fuels in storage, only 16,000 of that in dry casks. The rest is over-packed in pools that were never designed to safely accommodate that much fuel.

- **Hydrogen Mitigation**: After a small hydrogen explosion occurred in the course of the Three Mile Island accident, the NRC took a stab at requiring its licensees to install hydrogen mitigation measures to prevent explosions. While NRC officials inaccurately asserted after the Fukushima accident that such technologies were absent in Japan, but required in the U.S., in reality over the years the NRC has actually *removed* its regulatory requirement for licensees to demonstrate the operability of their hydrogen mitigation systems, including the ability to operate under conditions of a station blackout.

- **Outdated Seismic Resistance Criteria:** The NRC has not factored modern geologic information into seismic safety requirements for nuclear power plants, and has not incorporated its technical staff's recommendation to do so even though the new information indicates a higher probability of core damage caused by an earthquake than previously believed. California has a record of 8 earthquakes of magnitude 7.3 or greater since 1700, including earthquakes close to both the Diablo Canyon and San Onofre nuclear power plants. The Southern California Earthquake Center assesses that there is a 46% probability of California having an earthquake of magnitude 7.5 or greater in the next 30 years. But this assessment excludes the possibility of an earthquake in the "Cascadia" subduction zone, stretching offshore from British Columbia to Northern California, which could be even more catastrophic. According to research led by University of Oregon geologist Dr. Chris Goldfiner, there is a 37% percent chance of a Tohoku-like magnitude-9 quake over the next 50 years along the Cascadia zone. Beyond the West Coast, there are two other known areas of major seismic activity in the U.S. In the Southeast, Charleston, S.C. had a 7.3 earthquake in 1886. The New Madrid seismic zone, in the central Mississippi Valley region, produced a magnitude 7.7 earthquake in Arkansas in 1811. Eight nuclear power reactors are in the seismically active West Coast, approximately 27 are near the New Madrid seismic zone, and 5 are in earthquake-prone South Carolina, where 4 new reactors are in the preliminary stages of construction using a new "modular" containment design whose seismic resistance has been questioned.

- **Multiple Simultaneous Damaging Events:** US nuclear operators are not prepared to cope with the impacts of multiple severe events striking simultaneously because the NRC's regulations do not require them to. Initially, NRC inspectors were told to limit their inspections to a plant's ability to withstand and respond to events previously contemplated by the NRC, for which regulatory requirements have been implemented, but not "beyond Design Basis events" such as those that occurred in Japan. After several NRC inspectors complained that it made no sense to limit the scope of the inspections to Design Basis Events, the guidance was changed to enable inspectors to look beyond them.

- **Concealing Safety Concerns from the Public**: According to congressional staff investigators, the NRC's post-Fukushima inspectors were explicitly told not to record any of their beyond Design Basis observations or findings in documents that would be made public as part of the Commission's review or public report(s). Instead, these findings would be entered into a private NRC database and kept secret. Inspectors were also told not to include matters in their reports that licensees had already identified. Since inspections conducted by the nuclear industry's own self-improvement organization—the Institute for Nuclear Power Operations (INPO)—were concluded before the NRC post-Fukushima inspections began, none of the reportedly dozens of issues that were identified by INPO inspectors and reported to licensees will be included in the NRC inspection reports.

The longer-term review by the NRC will be inter-agency (for example including FEMA) and have "significant stakeholder involvement." While immediately endorsing President Obama's call for a review, which has already produced the aforementioned NRC Review, NRDC President Frances Beinecke has also written President Obama asking that an independent commission, similar to the Kemeny Commission that investigated the Three Mile Island Accident, be appointed to prepare a comprehensive independent view of the safety challenges facing the US nuclear fleet, and the adequacy of the NRC's proposed regulatory responses.

Response by Other Countries. In the wake of the accident, the current German government headed by Chancellor Angela Merkel has sharply reversed field, ordering the immediate shut-down of Germany seven oldest nuclear power plants, and pledging a complete phase-out of nuclear power in Germany by 2022 in concert with a massive program to increase deployment of renewables and energy efficiency. A public referendum in Italy on June 12-13 overwhelmingly rejected a 2009 law that had laid the groundwork for construction of new reactors in Italy by some of Europe's largest nuclear utilities. Switzerland too announced that it was backing away from plans to build nuclear reactors and would phase out nuclear power by 2034. While not backing away from any nuclear projects already approved for construction, China announced that it would proceed more carefully with the siting of new plants and revamp its federal law and organizations for regulating nuclear safety. A global slow-down in the nuclear "renaissance" appears inevitable as nuclear safety standards are reviewed and tightened across the world in the wake of the accident, additional countries scale-back or opt out of their planned commitments to nuclear power generation, and plentiful natural gas supplies displace planned nuclear projects, at least in the short run.

Critical safety issues for US reactors. The accident and its aftermath cast a stark light on at least four sets of reactor safety issues in the United States:

(1) *Is the "design basis" of current plants – which specifies the expected severity of the natural and man-made challenges to the operational safety of each plant at its individual location – adequately protective in light of changing technical knowledge regarding the severity of these challenges*? For example, Japan over the last four years has experienced two major earthquakes resulting in the simultaneous disabling or destruction of multiple nuclear units. Each of these events were well outside the nominal seismic "design basis" of the plant, and yet they happened. A tsunami that struck the west coast of Japan in the early 1990's sent a wall of water 30 feet high slamming into the coast, and yet Fukushima's sea wall on the east coast remained at a mere 13 feet above sea level.

(2) *Are the inherent design characteristics and nominal expected performance of current reactor backup power, emergency core cooling, gas-venting, and containment systems sufficient to reliably minimize the harmful effects from expected design-basis events*? Do NRC safety regulations incorporate an accurate scientific understanding of the temperature thresholds and rate of hydrogen production involved in a core overheating scenario? Are there more severe "beyond design basis" events that should now be included in the design basis, potentially requiring costly modifications to aging reactors? The aging GE Mark 1BWRs involved in the Fukushima accident have known design weaknesses, including: an undersized primary containment that requires frequent deliberate venting (filtered in the US reactors) of radioactive gases to avoid an explosive breach of containment in a major loss-of-coolant accident; and spent fuel pools located above and immediately outside of the primary containment, where they are more vulnerable to hydrogen explosion and fire threats in an accident scenario.

(3) *Is the actual inspected and verified condition of key safety and backup power systems in our aging reactors sufficient to reliably perform all of their assigned tasks on any given day should disaster suddenly strike*, or do inspections reveal an uneven pattern of intermittent or partial readiness for such systems, which in turn raises the prospect of a complex interaction of small failures leading to a massive system failure? In the case of the Fukushima reactors, inadequate maintenance of critical backup systems has already been documented, and may have been a contributing factor in the accident. In the U.S., the Los Angeles Times recently reported that until the problem was discovered in October 2009, PG&E's Diablo Canyon nuclear power plant "operated for 18 months with flawed valves that would have prevented cooling water from automatically flowing into the reactor core in an emergency."

(4) *What is the size of the population at risk around aging US reactors that face significant safety challenges, and what is the likelihood of a timely and successful evacuation* of this population in the event of a serious accident that poses an actual or imminent threat of harmful off-site releases of radioactive contamination? If substantial reliance on public evacuation, as just demonstrated by Fukushima, continues to be necessary to protect the public from the consequences of a major nuclear accident, when does the population size, density within and around the potentially affected area make prompt evacuation an infeasible and even dangerous option?

NRDC's Stance on Nuclear Power Generation. NRDC remains skeptical of nuclear power's competitive commercial prospects and overall environmental sustainability, given its high capital costs, radioactive wastes, thermal pollution, and fuel cycle linkages to both environmental harms and weapons proliferation. We oppose subsidized expansion of nuclear power generation at the expense of clean renewable power generation and efficiency, and it is important to remember that not one utility or electricity generating company in the United States has been able to commercially finance a new nuclear plant in more than 30 years. That said, the public health impacts from routine operation of the nuclear fuel cycle in the United States, while certainly not zero, have been dramatically less than those of fossil fuels, especially coal. The nuclear utility industry also has an excellent worker safety record and has improved the reliability of its power plants significantly over the past two decades.

We also cannot preclude the possibility that environmentally acceptable nuclear fuel cycles might be developed and implemented that could substantially remedy the drawbacks noted above. Also, given that nuclear power provides nearly 20 percent of U.S. grid-connected electricity, accounts for even larger fractions of electricity in a number of other advanced industrial countries, and is expanding rapidly in China, replacing that power would require a significant increase in carbon dioxide and other fossil fuel emissions. Therefore nuclear power it is both a political and technical reality that we must cope with and manage responsibly as we make the transition to a sustainable clean energy economy.

Like many others, in the wake of the Fukushima accident, NRDC is reengaging with lingering nuclear safety concerns that for the last several decades have lain dormant in the public mind and been left largely to the "professionals" at the NRC to manage. The accident has predictably caused long inattentive media organizations to review the spotty inspection record of current nuclear plants, and the NRC's cozy relationship with industry, and the results give cause for concern. We have urged the White House to appoint an independent commission to review the implications of the accident for US regulation of nuclear power, including both licensing and relicensing decisions. While our skeptical -- but also practical and non-ideological -- approach to nuclear power continues, the accident highlights the need for effective regulation, particularly for older reactors that have designs that may leave them more vulnerable to natural or man-made disasters. We need to redouble our efforts to push for effective regulation as the public reassesses the role of nuclear power.

Depending on the energy efficiency and supply alternatives available in a given region within a given time period, these older and less disaster-resistant nuclear units—many of which already have or could soon receive license extensions to operate for another 20 years—impose some unattractive trade-offs:

> -- endure a continuing higher-than-prudent risk of a nuclear accident by letting them operate longer, or;
> -- retire them early and endure the increased emissions and environmental damage that comes with increased use of fossil fuels, or;
> -- invest in essential but costly upgrades to 45-year-old reactor designs that will nonetheless not achieve the increased levels of nuclear safety potentially achievable in a modern design.

The more we are positioned to replace ageing, higher-risk nuclear capacity with cleaner and safer renewable generation and efficiency, the less severe these tradeoffs will be. For each area of the country, these particular tradeoffs will likely be different, and various combinations of early phase-outs, interim life extensions, safety upgrades, and replacement power scenarios are possible. But even in the most benign policy environment supportive of dramatically increasing renewable energy and efficiency, which is clearly not the national political environment we are in today, there could still be harmful carbon emissions and other environmental impacts from nuclear retirements in the short term, as it will take time in many regions to scale-up the clean energy alternatives to replace generating capacity on the gigawatt scale characteristic of most reactors.

In some areas of the country with regulated utility markets and captive ratepayers, lower financing (and hence capital) costs may be achievable for a new generation of reactors with (as yet unproven) passive emergency core cooling systems, designed to kick in without operator intervention in the event of an accident. Substitution of these modern, safer units for aging older units with known safety deficiencies is one possible remedy to the risks posed by our aging nuclear fleet, but is not a short-term remedy to a pressing safety concern, as construction of a new nuclear power plant typically takes 5-7 years.

In the short term, the path forward will likely involve region-specific mixes that combine several of these approaches:

> -- Early retirement of some nuclear units that are in the worst condition or have the worst operating histories and environmental records;
> -- Unloading of spent fuel from densely packed and vulnerable pools into more secure, hardened, air-cooled cement and steel "dry casks," which can safely store the fuel on the surface for another 60-100 years, allowing time for the development of one or more permanent repositories.
> -- Back-fits and modifications to other units to make their nuclear safety and emergency response systems more robust;
> -- Deployment of some new nuclear capacity with so-called "passive safety" systems, which

operate in a crisis to cool the reactor without the need for operator intervention;
-- Substitution of efficient combined cycle natural gas-fired generating capacity, and most importantly:
-- Vastly increased deployment of renewables, energy storage, industrial waste-heat recycling, combined heat and power systems, and end-use energy efficiency.