INSTITUTE FOR ENERGY AND
ENVIRONMENTAL RESEARCH

6935 Laurel Avenue, Suite 201
Takoma Park, MD 20912

Phone: (301) 270-5500
FAX: (301) 270-3029
e-mail: ieer@ieer.org
http://www.ieer.org

Phone: (301) 270-5500
FAX: (301) 270-3029
e-mail: ieer@ieer.org
http://www.ieer.org

DECLARATION OF DR. ARJUN MAKHIJANI IN SUPPORT OF EMERGENCY PETITION TO SUSPEND ALL PENDING REACTOR LICENSING DECISIONS AND RELATED RULEMAKING DECISIONS PENDING INVESTIGATION OF LESSONS LEARNED FROM FUKUSHIMA DAIICHI NUCLEAR POWER STATION ACCIDENT

I, Arjun Makhijani, declare as follows:

Introduction and Statement of Qualifications

1. I am President of the Institute for Energy and Environmental Research ("IEER") in Takoma Park, Maryland. Under my direction, IEER produces technical studies on a wide range of energy and environmental issues to provide advocacy groups and policy makers with sound scientific information and analyses as applied to environmental and health protection and for the purpose of promoting the understanding and democratization of science. A copy of my curriculum vitae is attached.

2. I am qualified by training and experience as an expert in the fields of plasma physics, electrical engineering, nuclear engineering, the health effects of radiation, radioactive waste management and disposal(including spent fuel), estimation of source terms from nuclear facilities, risk assessment, energy-related technology and policy issues, and the relative costs and benefits of nuclear energy and other energy sources. I am the principal author of a report on the 1959 accident at the Sodium Reactor Experiment facility near Simi Valley in California, prepared as an expert report for litigation involving radioactivity emissions from that site. I am also the principal author of a book, *The Nuclear Power Deception – U.S. Nuclear Mythology from Electricity "Too Cheap to Meter" to "Inherently Safe' Reactors"* (Apex Press, New York, 1999, co-author, Scott Saleska), which examines, among other things, the safety of various designs of nuclear reactors.

3. I have written or co-written a number of other books, reports, and publications analyzing the safety, economics, and efficiency of various energy sources, including nuclear power. I am also the author of *Securing the Energy Future of the United States: Oil, Nuclear and Electricity Vulnerabilities and a Post-September 11, 2001 Roadmap for Action* (Institute for Energy and Environmental Research, Takoma Park, Maryland, December 2001). In 2004, I wrote "Atomic Myths, Radioactive Realities: Why nuclear power is a poor way to meet energy needs," *Journal of Land, Resources, & Environmental Law,* v. 24, no. 1 at 61-72 (2004). The article was adapted from an oral presentation given on April 18, 2003, at the Eighth Annual Wallace Stegner Center Symposium entitled, "Nuclear West: Legacy and Future," held at the University of Utah S.J. Quinney College of Law. In 2008, I prepared a report for the Sustainable Energy & Economic Development (SEED) Coalition entitled *Assessing Nuclear Plant Capital Costs for the Two Proposed NRG Reactors at the South Texas Project Site.*

4. I am generally familiar with the basic design and operation of U.S. nuclear reactors and with the safety and environmental risks they pose. I am also generally familiar with materials from the press, the Japanese government, the Tokyo Electric Power Company, the French government safety authorities, and the U.S. Nuclear Regulatory Commission ("NRC") regarding the Fukushima Daiichi accident and its potential implications for the safety and environmental protection of U.S. reactors.

5. The purpose of my declaration is to explain the reasons I believe that although the causes, evolution, and consequences of the Fukushima accident are not yet fully clear, the accident is already presenting new and significant information regarding the risks to public health and safety and the environment posed by the operation of nuclear reactors. I will also explain why I believe that integration of this new information into the NRC's licensing process could affect the outcome of safety and environmental analyses for reactor licensing and relicensing decisions by resulting in either the denial of licenses or license extensions or the imposition of new conditions and/or new regulatory requirements. It could also affect the NRC evaluation of the fitness of new reactor designs for certification. It is therefore reasonable and necessary to suspend licensing and re-licensing decisions and standardized design certifications until the NRC completes its review of the safety and regulatory implications of the Fukushima accident.

Statement of Facts

6. Although many details about the Fukushima reactor accident remain unclear, the general contours of the accident are described in NRC Information Notice No. 2011-08 (March 31, 2011) (NRC Accession No. ML 110830824) as follows:

> On March 11, 2011, the Tohoku-Taiheiyou-Oki earthquake occurred near the east coast of Honshu, Japan. This magnitude 9.0 earthquake and the subsequent tsunami caused significant damage to at least four of the six units of the Fukushima Daiichi nuclear power station as the result of a sustained loss of both the offsite and onsite power systems. Efforts to restore power to emergency equipment were hampered and impeded by damage to the surrounding areas due to the tsunami and earthquake.
>
> Units 1, 2 and 3 were operating at the time of the earthquake. Following the loss of electric power to normal and emergency core cooling systems and the subsequent failure of backup decay heat removal systems, water injection into the cores of all three reactors

was compromised, and reactor decay heat removal could not be maintained. The operator of the plant, Tokyo Electric Power Company, injected sea water and boric acid into the reactor vessels of these three units, in an effort to cool the fuel and ensure that the reactors remained shut down. However, the fuel in the reactor cores became partially uncovered. Hydrogen gas built up in Units 1 and 3 as a result of exposed, overheated fuel reacting with water. Following gas venting from the primary containment to relieve pressure, hydrogen explosions occurred in both units and damaged the secondary containments.

Units 3 and 4 were reported to have low spent fuel pool (SFP) water levels.

Fukushima Daiichi Units 4, 5 and 6 were shut down for refueling outages at the time of the earthquake. The fuel assemblies for Unit 4 had recently been offloaded from the reactor core to the SFP. The SFPs for Units 5 and 6 appear to be intact. Emergency power is available to provide cooling water flow through the SFPs for Units 5 and 6.

The damage to Fukushima Daiichi nuclear power station appears to have been caused by initiating events beyond the design basis of the facilities.

7. In a March 21, 2011, briefing, Bill Borchardt, the NRC's Executive Director for Operations, stated that the NRC believes that hydrogen explosions occurred on March 12, 14, and 15 in the reactors of Units 1, 3, and 2 respectively, in that order. He also stated that the NRC believed that a hydrogen explosion had occurred at spent fuel pool of Unit 4 on March 15 due to overheated spent fuel in the pool. Briefing on NRC Response to Recent Nuclear Events in Japan, Transcript at 11.

8. According to Mr. Borchardt, the NRC believes that Units 1, 2, and 3 have likely sustained some degree of core damage. *Id.* Further, he stated that the loss of emergency AC power was caused by the tsunami and not the earthquake. Therefore, he concluded that the NRC believes that the "damage in Fukushima was not really caused by the earthquake; it was the tsunami that came afterwards." *Id.*

9. At the outset of the emergency, large volumes of sea water were used to cool the reactors. The salt water injections were then replaced by fresh water injections. While judgments have changed over time, and much remains uncertain, we note here that as of March 21, Mr. Borchardt also stated that "[t]he radiation releases and the dose rates that we've seen on site, I think, were primarily influenced by the condition of the Units Three and Four spent fuel pools." *Id.* at 21.

10. The French authorities also reported that sea water was used to cool spent fuel pools Units 3 and 4. *Communiqué de presse n°17 du mardi 22 mars 2011 à 10h00 Séisme au Japon - L'ASN fait le point sur la situation de la centrale nucléaire de Fukushima Daiichi : Les travaux en vue de rétablir l'alimentation électrique se poursuivent mais la mise sous tension n'est pas réalisée Paris, le 22/03/2011 10:27*, http://japon.asn.fr/index.php/Site-de-l-ASN-Special-Japon/Communiques-de-presse (March 22, 2011). They also reported that three spent fuel pools (of Units 2, 3, and 4) appear to have experienced boiling at some point. *Note d'information : Situation des réacteurs nucléaires au Japon suite au séisme majeur survenu le 11 mars 2011 : Point de situation du 18 mars 2011 à 14 heures*, Institut de Radioprotéction et de Sûreté

Nucléaire (March 18, 2011), http://www.irsn.fr/FR/Actualites_presse/Actualites/Documents/IRSN_Seisme-Japon_Point-situation-18032011-14h.pdf -- hereafter IRSN March 18, 2011)

11. In response to the Fukushima reactor accident, the NRC announced the formation of a "senior level agency task force to conduct a methodical and systematic review" of NRC processes and regulations. COMGBJ-11-0002, Memorandum from Chairman Jaczko to Commissioners, re: NRC Actions Following the Events in Japan at 1 (March 21, 2011) (NRC Accession No. ML110800456). The purpose of the task force is to "determine whether the agency should make additional improvements to our regulatory systems and make recommendations to the Commission for its policy direction." *Id.*

12. Chairman Jaczko's memorandum specifies both a near-term review and a longer-term review. For the near-term review, the Commission required the task force to evaluate issues "affecting domestic operating reactors of all designs" in areas that include "protection against earthquake tsunami, flooding, hurricanes; station blackout and a degraded ability to restore power; severe accident mitigation; emergency preparedness; and combustible gas control." *Id.* at 1. The Commission instructed the task force to complete the report in 90 days. In the meantime, the task force was instructed to provide a 30-day "quick look report" and another "status" report in 60 days. *Id.*

13. The "longer term" review would begin "as soon as NRC has sufficient technical information from the events in Japan with the goal of no later than the completion of the 90 day near term report." *Id.* at 2. The longer-term study should "evaluate all technical and policy issues related to the event to identify additional research, generic issues, changes to the reactor oversight process, rulemakings, and adjustments to the regulatory framework that should be conducted by the NRC." *Id.* For the longer-term effort, the Commission instructed the task force to "receive input from and interact with all key stakeholders." *Id.* The Commission specified that within six months after commencing the evaluation, the task force should "provide a report with recommendations, as appropriate, to the Commission." *Id.*

14. The "Task Force to Conduct a Near-term Evaluation of the Need for Agency Actions Following the Events in Japan" ("Task Force") has formed and its charter has been approved. The Task Force aims to accomplish the following:

- "Evaluate currently available technical and operational information from the events that have occurred at the Fukushima Daiichi nuclear complex in Japan to identify potential or preliminary near-term/immediate operational or regulatory actions affecting domestic reactors of all designs, including their spent fuel pools. The task force will evaluate, at a minimum, the following technical issues and determine priority for further examination and potential agency action:

    - External event issues (e.g. seismic, flooding, fires, severe weather)

    - Station blackout

- Severe accident measures (e.g., combustible gas control, emergency operating procedures, severe accident management guidelines)

• 10 CFR 50.54 (hh)(2) which states, "Each licensee shall develop and implement guidance and strategies intended to maintain or restore core cooling, containment, and spent fuel pool cooling capabilities under the circumstances associated with loss of large areas of the plant due to explosions or fire, to include strategies in the following areas: (i) Fire fighting; (ii) Operations to mitigate fuel damage; and (iii) Actions to minimize radiological release." Also known as B.5.b.

• Emergency preparedness (e.g., emergency communications, radiological protection, emergency planning zones, dose projections and modeling, protective actions)

• Develop recommendations, as appropriate, for potential changes to NRC's regulatory requirements, programs, and processes, and recommend whether generic communications, orders, or other regulatory actions are needed."

Charter for the Nuclear Regulatory Commission Task Force to Conduct a Near-Term Evaluation of the Need for Agency Actions Following the Events in Japan at 1 (April 1, 2011) (NRC Accession No. ML11089A045).

15. With respect to the longer-term review, the Charter states that the short-term report will make: "[r]ecommendations for the content, structure, and estimated resource impact…." *Id.* at 1.

Statement of Professional Opinion

16. I agree with the Commission's approach of conducting a long-term investigation of the regulatory implications of the Fukushima accident, in addition to its short-term investigation of whether immediate actions are needed. In my opinion, the longer-term investigation is necessary to address a number of respects in which the Fukushima accident is unprecedented in the sense that its characteristics are not anticipated in NRC safety regulations or environmental analyses. Thus, it is providing new and significant insights into the inadequacy of NRC regulations to protect public health and safety and the inadequacy of NRC environmental analyses to evaluate the potential health, environmental and economic costs of reactor and spent fuel pool accidents. This significant new information covers the following major topics:

o Unanticipated compounding effects of simultaneous accidents at multiple co-located reactor units, including spent fuel pools.
o Unanticipated risks of spent fuel pool accidents, including explosions.
o Frequency of severe accidents and explosions.
o Inadequacy of safety systems to respond to long-duration accidents.
o Nuclear crisis management with contaminated control and turbine buildings that have lost power
o Unanticipated aggravating effects of some emergency measures.
o Health effects and costs of severe accidents
o The hydrogen explosions at Fukushima and their implications for aircraft crash evaluations.

Unanticipated compounding effects of simultaneous accidents at multiple co-located

reactor units, including spent fuel pools.

17. Perhaps the most unprecedented feature of the Fukushima accident is that three reactors and four spent fuel pools have been stricken at the same site. In the entire history of nuclear power, there has not been another major accident (level 5 or above) that has involved multiple major sources of radioactivity -- including multiple reactors and multiple spent fuel pools. For instance, the Fukushima Daiichi complex is the first to have experienced multiple hydrogen explosions in various facilities, all as part of the same event.

18. The NRC has long followed the practice of allowing new reactors to be built at existing sites, without examining the consequences of simultaneous failure of existing and new reactors through common mode failures such as complete station blackouts and loss of fresh water supply. The NRC also proposes to co-locate a significant number of new reactors at existing reactor sites. Examples include Bellefonte, Calvert Cliffs, Comanche Peak, Fermi, North Anna, Shearon Harris, Turkey Point, the South Texas Project, and Vogtle.

19. But the Fukushima accident graphically demonstrates that NRC's failure to evaluate the safety and environmental implications of co-locating multiple reactors was incorrect. Specifically, when a new reactor is to be sited at a location where there are existing reactors, the entire system at the site should be re-examined in addition to whatever additional impacts the new unit(s) might create. The EISs for these new reactors and the designs on which they rely should consider the significant new information revealed by the Fukushima accident about the potential for simultaneous multiple failures and accidents in existing and new reactors and/or spent fuel pools.

Unanticipated risks of spent fuel pool accidents, including explosions.

20. Another unprecedented feature of the Fukushima accident is that an explosion occurred in Unit 4 despite the fact that there was no fuel in the reactor. The entire core had been unloaded into the spent fuel pool prior to March 11, 2011; the reactor was down for maintenance. A loss of cooling apparently led to boiling and to hydrogen generation, which appears to be the likely cause of the major explosion and ensuing damage to the reactor building of Unit 4. Further, as noted above the spent fuel pools of Units 2 and 3 also appear to have experienced boiling of the cooling water at some point. It should be noted that much detail remains to be learned about all three spent fuel pools, especially as to what went on in the first week of the accident.

21. The apparent occurrence of spent fuel pool accidents at Fukushima significantly undermines the NRC's conclusion that high-density pool storage of spent fuel poses a "very low risk." *The Attorney General of Commonwealth of Massachusetts; the Attorney General of California; Denial of Petitions for Rulemaking,* 73 Fed. Reg. 46,204, 46,207 (August 8, 2008). That conclusion is all the more subject to question in light of the fact that spent fuel in U.S. pools is typically packed more tightly than in the pools at Fukushima. U.S. reactors, including reactors that are candidates for license renewal, use high-density pool storage for spent fuel. Fukushima indicates that the NRC policy that allows such storage needs to be revisited. Given that onsite storage of spent fuel may continue for decades, these circumstances also call for a thorough reexamination of the spent fuel storage capacity, spent fuel pool location, and configuration of new reactor designs. For instance, should the construction and use of above ground-level spent fuel pools in reactor buildings be allowed, as is the case with the advanced boiling water reactor

("ABWR")? The NRC should examine the potentially exacerbating relationship between reactor core accidents and spent fuel pool accidents, for both existing reactor designs and new reactor designs. In addition, environmental impact statements ("EISs") for license renewal and new reactor licensing should reexamine the relative costs and benefits of measures to mitigate the environmental impacts of pool fires and/or explosions. Measures would include reducing the density at which fuel is stored in pools, using dry storage for as much of each reactor's inventory of spent fuel as safety will allow, and dry storage of all spent fuel at closed reactors, a few years after closure.

Frequency of severe accidents and explosions

22. The NRC must also re-examine the frequency per reactor per year of spent fuel pool accidents as well as the frequency of core damage events. The NRC's current spent fuel damage assessments are based on a best estimate of a spent fuel pool fire probability of about $2x10^{-6}$ per reactor-year, including the probability of structural failure during a seismic event NUREG-1353, *Regulatory Analysis for the Resolution of Generic Issue 82, "Beyond Design Basis Accidents in Spent Fuel Pools"*, at 5-5 and Table 5.1.3 (1989). This means one such accident for every 500,000 reactor-years. The NRC's estimate of the frequency of spent fuel pool loss of cooling from all causes other than earthquake-induced structural failure is even lower: $1.5x10^{-7}$. The conditional probability of a fire in the event of a loss of cooling is estimated to be 1.0 for a PWR and 0.25 for a BWR. *Id.* at 4-36. Based on this, the overall probability estimate in NUREG-1353 for a non-seismic-induced spent fuel pool fire for a PWR is $1.5x10^{-7}x1.0 = 1.5x10^{-7}$; for a BWR it is $1.5x10^{-7}x0.25 = 4x10^{-8}$ for a BWR – in the latter case is it one spent fuel pool fire every 25 million reactor-years. Hydrogen explosions originating in the spent fuel pool were not considered. Further, at least two spent fuel pools at Fukushima (Units 3 and 4) that seem to have experienced boiling as well as the destruction of the portions of the reactor building that are a barrier between the pool surface and the environment. According to the French safety authorities, the spent fuel pool in Unit 2 also experienced boiling. IRSN March 18, 2011 *op. cit.* One reactor building, that of Unit 4, appears to have experienced a hydrogen explosion, with the hydrogen apparently emanating from the spent fuel pool (see Paragraph 7 above). The explosion destroyed a good part of the reactor building. Any damage to the spent fuel pool structures and equipment, to the fuel assemblies in the pools, as well as to the racks remains to be fully assessed. It appears that the only way that a significant amount of hydrogen could originate in a spent fuel pool is through uncovering of the spent fuel and the reaction of the zirconium in the fuel rods with steam. Explosions destroyed substantial portions of the reactor buildings of Units 1 and 3 as well; it appears that there were also significant releases of radioactivity from the spent fuel pool of Unit 3. In view of these facts, the NRC's estimate of loss of cooling probability accompanied by a fire is far too low, probably by orders of magnitude. It appears that the overall principal initiating event in the station blackout and failure of emergency core cooling was not the earthquake but the tsunami, though the earthquake may have caused equipment damage that led to or contributed to some of the spent fuel pool problems. This indicates that the non-earthquake station blackout probabilities will need to be revisited. Further, the NRC's list of events leading to spent fuel structural failure does not include hydrogen explosions due to loss of emergency core cooling in the reactor (NUREG-1353, *op. cit.*, Table 4.7.1 at 4-36), which appears to have been the cause of the damage to the structures of reactor buildings 1 and 3 and possibly to the spent fuel pool of Unit 3. It may be that many details of the analysis will be different for each of the four spent fuel pools. Whatever the details, the events so far make it

quite clear that the NRC needs to thoroughly reevaluate the probability of severe spent fuel pool accidents as well as the kinds of events that could initiate damage and major releases of radioactivity from spent fuel pools. Further, in view of the fact that three BWRs appear to have had core damage, the NRC also needs to evaluate whether presently operating reactors, notably (but not only) BWRs, meet the Commission's target of limiting annual core damage frequency to the 10^{-4} to 5×10^{-5} per reactor-year range for reactors (NUREG-1353, *op. cit*., at ES-2 and ES-3).

23. In conducting its review, the NRC needs to thoroughly revisit its methods for estimating the probabilities and mechanisms of hydrogen explosions and fires in spent fuel pools (with and without a natural disaster component) as well as the methods for estimating hydrogen explosions, and meltdowns in existing and new light water reactor designs. For instance, the computer code used in evaluating the accidents assumes that "[t]he geometry of the fuel assemblies and racks remains undistorted." NUREG-1353, *op cit*. at 4-8. To judge by the photographs and videos of the damage, this assumption is unlikely to be correct at least for spent fuel pools in Units 3 and 4. As another example, hydrogen generation due to partial uncovering of spent fuel but with water still remaining in the pool is not included. Rather, the computer program assumes that "[t]he water drains instantaneously from the pool." *Id.* This is important because if the investigation confirms that hydrogen was indeed generated in the spent fuel pool of Unit 4, the exothermic zirconium-steam reaction that creates it would be an additional source of heat for causing the accident to develop more rapidly and destructively than assumed by the NRC.

24. More generally, the events at three reactors and four spent pools have drastically changed the underlying frequency data that should go into the estimation of the probability of severe accidents at light water reactors. As a result, integration of the Fukushima data into NRC analyses of risks could lead to significant changes in design of new reactors and also lead to modifications at existing reactors, as would be required for protection of public health and safety under 10 CFR 50.109. Specifically, the Fukushima accident indicates that the basis of the NRC's conclusion in NUREG-1353 that dense storage of spent fuel in pools is safe and that dry storage is not warranted is incorrect.

Inadequacy of safety systems to respond to long-duration accidents

25. U.S. reactors appear to have insufficient backup power capacity to maintain safety equipment during a prolonged severe accident. The Fukushima accident, in which the emergency diesel generation system started but then failed very soon after the tsunami and the battery backup ran out of power in eight hours. The accident illustrates the serious environmental risk posed by insufficient backup power when catastrophic events destroy both offsite power supplies and onsite infrastructure. These risks need to be taken into account in safety and environmental analyses for all prospective NRC licensing decisions. The fact that there was a complete station blackout at Fukushima accompanied by a failure of fresh water supply that forced sea water use for days (*Communiqué de presse n°17 du mardi 22 mars 2011 à 10h00 Séisme au Japon - L'ASN fait le point sur la situation de la centrale nucléaire de Fukushima Daiichi : Les travaux en vue de rétablir l'alimentation électrique se poursuivent mais la mise sous tension n'est pas réalisée Paris, le 22/03/2011 10:27*, http://www.asn.fr/index.php/Haut-de-page/Presse/Actualites-ASN/Communique-de-presse-n-17-du-mardi-22-mars-2011-a-10h00) clearly points to the need for a full review of the depth (in terms of number of levels) of backup systems, the length of time of emergency power supply operability, the location of these power supplies, and the relation of the power supplies to ad hoc

emergency pumping and emergency water supplies, including in the context of potential major damage to multiple units at a single site.

Nuclear crisis management with contaminated control and turbine buildings that have lost power

26. Another critical and unanticipated feature of the Fukushima accident is that the control rooms of Units 1, 2, and 3 became highly contaminated in the course of the first week of the accident, according to the French safety authorities. IRSN March 18, 2011 *op. cit.*. This has made re-establishment of normal cooling more difficult, apart from the question of on-site or offsite power supply. Turbine buildings also became contaminated with radioactive water in the course of the accident. *Fukushima Daiichi Nuclear Power Station: the result of measurement of sub drain*, http://www.tepco.co.jp/en/press/corp-com/release/betu11_e/images/110331e18.pdf and *The detection of radioactive materials in the water on 1st basement of turbine building at the site of Fukushima Daiichi Nuclear Power Station: Press Release* (Mar 31,2011), http://www.tepco.co.jp/en/press/corp-com/release/11033112-e.html.

27. The loss of power in and radioactive contamination of the control rooms and turbine buildings points to the need to review the piping and ventilation arrangements of these facilities, and the likely need to isolate them more thoroughly from contaminated air and water during beyond-design-basis accidents. Based on the information available so far about the Fukushima event, the risks of turbine building contamination would appear to be greater for boiling water reactors than for pressurized water reactors since steam generated from primary water is used to directly drive the turbines; in PWRs the heated primary water is routed to steam generators and not to the turbines.

Unanticipated aggravating effects of some emergency measures

28. Light water reactors are not designed to be cooled by sea water. Thus, the fact that TEPCO was forced to use sea water for emergency cooling for an extended period is a critical feature of the accident that needs evaluation. For instance, salt from sea water deposited on the fuel rods may have blocked or partially blocked some cooling channels during the accident. This raises the question of whether the use of sea water may have aggravated the fuel damage. It also raises the question of whether salt deposits may have interfered with the neutron absorption capacity of the control rods thereby increasing the likelihood of an accidental criticality. An understanding of these issues is important to the understanding of the accident and to any design and or emergency operations changes that may be needed.

Health effects and costs of severe accidents

29. While a detailed evaluation will take time and more data, the Fukushima accident indicates that the health consequences of a severe reactor accident and/or spent fuel pool fire could be significantly greater than estimated by the NRC in EISs for license renewal and new reactor licensing. For instance, the NRC estimates an average population risk (population dose multiplied by probability) in a 50-mile radius of only 16 person-rem per year per spent fuel pool – or 480 rem in 30 years. The dose estimate was recently used in the 2009 draft Generic Environmental Impact Statement ("GEIS") by the NRC. *Generic Environmental Impact*

Statement for License Renewal of Nuclear Plants Appendices, Draft Report for Comment, NUREG-1437, Volume 2, Rev. 1 at E-35 (July 2009). *See also* NUREG-1353, *op. cit.*, at ES-3. The estimate of 480 rem in 30 years translates into a probability of just 0.27 fatal cancers over 30 years in a population of more than 2.5 million (using a risk factor of 0.000575 fatal cancers per rem). The NRC's best estimate of the total population dose dose in the event of an accident was 8 million person-rem (NUREG-1353, *op cit*. at 5-4, Table 5.1.2) – which translates into 4,600 excess cancer deaths in a fifty-mile radius. The NRC put the worst case population dose estimate at just over three times the best estimate – 26 million person-rem. NUREG-1353, *op cit*. Table 5.1.2 at 5-4. But if the probability is much higher for a single failure and if multiple failures can happen at the same site, then the number of expected fatal cancers would be higher, all other things being equal. Further, it is necessary to consider that the spent fuel pools in the United States are more typically full than the ones at Fukushima. In its review of Fukushima, the NRC should revisit the higher of the health damage estimates for spent fuel pool accidents at closed power plants in a 1997 study by Brookhaven National Laboratory. R.J. Travis, R.E. Davis, E.J. Grove, M.A. Azarm, *A Safety and Regulatory Assessment of Generic BWR and PWR Permanently Shutdown Nuclear Power Plants,* BNL-NUREG-52498, NUREG/CR-6451 (Brookhaven National Laboratory, 1997), http://www.osti.gov/bridge/product.biblio.jsp?osti_id=510336. NUREG-/CR6451 estimated the worst case population dose in a 50 mile radius at 81 million person-rem for both BWRs and PWRs. *Id*. at Tables 4-1 and 4-2. This is more than three times higher than in the estimate in NUREG-1353 cited above.

30. The Fukushima accident also indicates that the economic costs of a spent fuel pool accidents may be much higher than the current estimates used by the NRC. In NUREG-1353, the worst case property damage was estimated at $30 billion (1988 dollars) in a 50-mile radius. *Id.* at Table 5.1.2. That amount is about $50 billion in 2010 dollars (constant 2010 dollar estimates calculated using the Gross Domestic Product deflators of the U.S. Department of Commerce, as published by the St. Louis Federal Reserve at http://research.stlouisfed.org/fred2/data/GDPDEF.txt and rounded to the nearest $10 billion). But in the Brookhaven study, the worst-case property damage in a 50-mile radius was estimated at $280 billion for BWRs (*Id*. at Table 4-2), which would be about $370 billion in 2010 dollars – or more than seven times the NUREG-1353 estimate cited above. The worst case damages in a 500-mile radius were estimated at $546 billion for U.S. boiling water reactors ("BWRs") plus 138,000 excess cancer deaths (*Id*. at Table 4-2) with a high population density. The damage amount would be about $720 billion in 2010 dollars. Results were slightly higher for pressurized water reactor spent fuel pools. *Id*. at Table 4-1. The overall 500-mile population density assumed in the Brookhaven study was lower than the population density near several U.S. reactors, notably in the Northeast. Further, the Brookhaven study itself notes its calculations would not "reasonably envelope" the situation (including projected population growth) at certain locations where there are reactors close to major metropolitan centers. "There are several existing plant sites (i.e., Indian Point, Limerick, and Zion) that precede the issuance of R.G. 4.7 and exceed the site population distributions generally considered acceptable by current NRC policy.") *Id.* at 3-4 and footnote at 3-4. Moreover, certain assumptions of the 1997 Brookhaven study may prove optimistic especially in densely populated areas. For instance, the study assumes that the population could be evacuated in one day, should evacuation become necessary. *Id.* at 3-8. As another example, the relocation radius was only 10 miles, as per NUREG-1150. *Id*. at 3-8 and NUREG-1150, *An Assessment for Five Severe Accident Risks: An Assessment for Five U.S. Nuclear Power Plants: Final Summary Report*, U.S. Nuclear Regulatory Commission, Office of

Nuclear Regulatory Research Vol. 1 at 2-20 (December 1990), http://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1150/v1/sr1150v1-intro-and-part-1.pdf. The relocation radius around Fukushima is greater than 10 miles. Moreover the U.S. advised its citizens early on to evacuate within a 50-mile radius of Fukushima Daiichi. This indicates that emergency management criteria and procedures need to be revisited.

31. In view of the severe crisis with multiple units at Fukushima in a densely populated industrialized country where there has been both direct and indirect economic damage, the 1997 Brookhaven study provides a reasonable starting point for a reevaluation of spent fuel accident consequences. Of course, Fukushima shows that the results of the Brookhaven study must be reviewed in the context of the potential for multiple failures at a single site in both reactors and spent fuel pools. Evacuation and population assumptions will likely need to be changed. As a result, both the monetary damages and health effects estimates may have to be revised upwards, possibly by substantial amounts in densely populated areas. Further, Fukushima is showing that there has already been indirect economic damage in industries like shipping and manufacturing that are not directly affected by fallout. While, the long-term and overall direct and indirect costs of the reactor and spent fuel damages from the Fukushima accident will take time to be tallied, it is clear that they will be enormous.

Hydrogen explosions and implications for aircraft crash evaluations

32. The Fukushima accident has revealed significant new information about the potential effects of hydrogen explosions. The estimated Unit 1 generation of hydrogen was 300 to 600 kg; for Units 2 and 3 it was 300 to 1,000 kg. Estimates were by an expert commissioned by AREVA. Matthias Braun, *The Fukushima Daiichi Incident*, AREVA, April 15, 2011, at 18, http://www.wdr.de/tv/monitor//sendungen/2011/0407/pdf/areva-fukushima-report.pdf. This indicates an urgent need to revisit the issue of aircraft crashes, deliberate or accidental, at existing reactors and spent fuel pools. The energy of the estimated amounts of hydrogen involved in the Fukushima explosions is far smaller than fuel in fully-loaded commercial jetliner – a type of crash that must be evaluated under NRC regulations. Five thousand gallons of jet fuel (not at all unusual for larger passenger jets -- the largest ones have much larger fuel capacities) have an energy content about four times as large as the largest estimate of the hydrogen explosions (1,000 kilograms of hydrogen gas) at Fukushima. Indeed, in light of Fukushima even a smaller, regional jet crash needs to be taken into account, especially for older BWRs. Such damage needs to be evaluated both in the safety and environmental analyses. For instance, the Fukushima accident has demonstrated that evacuation planning in the circumstances of a natural disaster that is combined with a reactor accident is far more challenging than assumed by NRC emergency planning regulations.

Conclusions

33. As discussed above in pars. 16 through 32, the Fukushima accident has already revealed an enormous amount of new information regarding the safety vulnerabilities and environmental risks that need to be taken into account in licensing of new reactors, the re-licensing of existing reactors, early site permits, emergency procedures for protecting the civilian population, and approval of standardized reactor designs in rulemakings.

34. I believe that if the significant new information emanating from the Fukushima Daiichi accident is taken into consideration in NRC safety and environmental analyses, it is likely to fundamentally alter the outcome of those analyses in important ways. In the safety arena, consideration of this new information is likely to result in more rigorous regulation with respect to issues such as loss of offsite power, hydrogen explosion prevention, the siting of more than one reactor at a single site, spent fuel accident and reactor accident probabilities, the re-racking of spent fuel pools, permitting extended storage of spent fuel in pools after decommissioning, and emergency planning.

35. In the environmental and health arenas, consideration of this significant new information is likely to result in higher accident probability estimates, new accident mechanisms for spent fuel pools, higher accident cost estimates, and higher estimates of the health risks posed by light water reactor accidents. These increased risk and cost estimates will lead to much more serious consideration of alternatives for avoidance or mitigation of environmental risks. For instance, although the Commission has long rejected low-density pool storage combined with dry onsite storage as an alternative for mitigating the effects of catastrophic pool fires, that option may now prove to be very cost-beneficial. Present policy also does not require the transfer of all spent fuel from pools into dry casks at closed sites, as soon as safely possible after closure. A change of policy would be indicated by the scale of the disaster at Fukushima. In view of the large variation in potential damage and differences in emergency response needs, a plant-specific analysis will also be needed, including for all reactors in the Northeast.

36. It is likely that more (and more expensive) protective features will be needed to ensure a level of safety and security that will avoid the kinds of disastrous consequences occurring at Fukushima Daiichi. It is also likely that additional measures involving significant costs will have to be taken to reduce the likelihood and consequences of multi-reactor and/or spent fuel disasters. In light of this new information, a comparison between the economic attractiveness of a proposed new nuclear reactor or a proposed re-licensing of an existing reactor that might need modifications with other less risky and less expensive energy sources (such as wind, solar, and storage technologies such as compressed air) may well result in a decision that licensing of new reactors and re-licensing of existing reactors is not cost-effective.

37. Therefore, I believe it is reasonable and necessary for the NRC to suspend licensing and re-licensing decisions and standardized design certifications until the NRC completes its review of the regulatory implications of the Fukushima accident.

The facts presented above are true and correct to the best of my knowledge, and the opinions expressed therein are based on my best professional judgment.

Arjun Makhijani

______________________________ 19 April 2011

Dr. Arjun Makhijani Date