HOLOPHI
unlocking the power of complex systems

Holophi Special Report – April 2012

Estimating the Potential Impact of Failure of the Fukushima Daiichi Unit 4 Spent Fuel Pool

A Local Problem for Japan or a Global Mega Crisis?

Paul C. Gailey, Ph.D. , President & CEO, Holophi CH AG
www.holophi.ch

Abstract

Extreme opinions are being voiced about the risk of global catastrophe resulting from a possible collapse of the Fukushima Daiichi unit 4 spent fuel pool. These claims are appearing mostly among the public through internet media and other non-official channels. Officials sources remain largely mute on the subject or downplay the risks. This report provides an approximate bounding of the risks using available data. The results of this analysis suggest that a nominal release of 10% of the SFP 4 inventory of cesium and strontium would represent 3-10 times the March 2011 release amounts, substantially increasing risk levels in Japan and impacting marine life. Release of 100% of the SFP 4 inventory, or 30-100 times the March 2011 release amounts, could result in significant global impact.

Introduction

More than a year after earthquake and tsunami that devastated areas of Japan in 2011, new alarms are being sounded concerning the state of the unit 4 spent fuel pool (see Note 1). Although the unit 4 reactor was not operating at the time of the tsunami, its fuel was being stored, along with a large quantity of spent fuel assemblies, in a pool within the unit 4 building. This building was seriously damaged by a hydrogen explosion. The spent fuel pool, which is located about 30 meters above ground, is considered to be in danger of collapsing.

The infrastructure for moving the fuel assemblies was rendered inoperable by the explosion, and high radiation levels make it extremely difficult to clear debris, perform repairs, or construct a new system for removing the assemblies. The cooling system for the spent fuel pool was also destroyed by the explosion, and Tepco has positioned temporary hoses to pump water into the pool for cooling. They have also installed steel pillars to help support the pool.

Reason for Concern

The unit 4 spent fuel pool (SFP) contains 1300-1500 spent and active fuel assemblies. Because the structure of the unit 4 building was damaged by an explosion, the spent fuel pool is in danger of collapsing. If the pool collapses or develops serious cracks allowing the cooling water to drain, the fuel rods will be exposed to the environment. These concerns are elevated by a recent report that additional large earthquakes (magnitude 7) are expected in the area (Tong et al., 2012).

Spent fuel pools are not protected in the same way as reactor cores, and the unit 4 building is seriously damaged. Thus, there is no obvious second line of defense protecting the environment from the radioactive fuel and secondary isotopes if water cooling is lost. Together, the fuel rods currently produce about one megawatt (MW) or more of waste energy in the form of heat (see Note 2) even though they are not operating in a reactor. This heat must be removed through the use of cooling water to avoid damage to the fuel rods including possible melting, fire, explosions and release of radioactive material.

If cooling water for the spent fuel pool is lost – either by collapse of the pool, formation of cracks in the pool, or other factors – a major release of radioactive material could result. Given the large amount of heat generated by the fuel rods, the temperature would rise quickly. These rods are surrounded by zirconium cladding, and at high temperatures, this cladding catalyzes hydrogen production, can generate additional heat, and even explode and burn (NRC, 2006).

The water surrounding the fuel rods in the spent fuel pools serves two purposes: First, it conducts heat away from the fuel assemblies to avoid overheating. Second, it provides shielding from the extremely high radiation levels near the rods. If a collapse or breakage of the unit 4 spent fuel pool occurs, the loss of shielding by the cooling water could critically increase radiation levels in the entire Daiichi complex. High radiation is already a serious problem limiting worker and even robot access to the plant to perform repairs and mitigation, and to maintain cooling of the other spent fuel pools and reactors. Thus, a catastrophic failure of the unit 4 spent fuel pool could potentially cascade into additional releases from the other spent fuel pools and reactors.

Estimated Amounts of Radioactive Material

Operation of a nuclear plant produces a number of radioactive isotopes. For this preliminary potential impact analysis, we will focus primarily on cesium, strontium, and plutonium, while noting that other radioisotopes are also of concern. Cesium and strontium are easily absorbed in plants and animals similarly to potassium and calcium, respectively. Their movement through the biosphere and long half lives (years to decades) mean that they represent substantial health hazards at relatively low concentrations. Plutonium is not as soluble and easily distributed in the environment, but is extremely carcinogenic when inhaled or ingested.

Because the various isotopes are produced by nuclear reactions during the operation of the reactors, the quantities present in the fuel rods must be estimated from calculations and measurements. For this analysis, we will use the estimated amounts below (Mertyurek et al., 2010, Pretzsch et al., 2011). If improved estimates are identified, the results of the analysis below can be easily scaled based on the new data.

Unit 4 Spent Fuel Pool

Total number of fuel assemblies *	1331 – 1535*
Tons of heavy metal	228
Estimated Cs-137	10^{18} Bq
Estimated Cs-134	10^{18} Bq
Estimated Sr-90	$6{\cdot}10^{17}$ Bq
Estimated Pu-238 thru 241†	10^{16} Bq

* Reports differ on this number, e.g. CNSC reports 1331 spent fuel assemblies + 204 new assemblies for a total of 1535 fuel assemblies. However, the 15% difference between these numbers is not critical for this analysis.

† Uranium fuel, after use in a reactor (when spent) become ~1% plutonium. We used example isotope ratios to estimate activity, reducing Pu-241 activity by a factor of 100 to reflect its lower mortality risk relative to the other Pu isotopes (Peterson et al., 2007).

Total for all Daiichi reactors and SFP's (including common fuel storage pool)

Total number of fuel assemblies	~11,400
Tons of heavy metal	~1950
Estimated Cs-137	10^{19} Bq
Estimated Cs-134	10^{19} Bq
Estimated Sr-90	$6{\cdot}10^{18}$ Bq
Estimated Pu-238 thru 241‡	$3{\cdot}10^{17}$ Bq

‡ Some assemblies included MOX fuel which contains a higher percentage of plutonium.

Base Case Scenario: Collapse or breakage of SFP 4 leads to release of 10% of contained isotopes into atmosphere (2% falling on Japan and the remaining 8% falling on the Pacific Ocean)

The total Cs-137 released in this scenario is 10^{17} Bq (100 PBq) or three to ten times the amount released during the peak discharges of March 2011. A value of 2% falling on Japan (20% of total release) is comparable to the percentage calculated to have fallen on Japan during the March 2011 release (Buesseler et al., 2012).

The total Cs-137 land deposition in Japan would be $2 \cdot 10^{16}$ Bq for a total Cs (137+134) fallout of approximately $4 \cdot 10^{16}$ Bq. Total Sr-90 is expected to be $1.2 \cdot 10^{18}$ Bq, and total Pu isotopes are approximately $6 \cdot 10^{14}$ Bq. However, we note that during the March 2011 release, a very small fraction of less than 0.01% of Pu inventory appears to have been released, compared to 3.5% of inventory released during the Chernobyl disaster (Zheng et al., 2012). The difference may have been due to the mode of release (explosion vs. burning in the case of Chernobyl). For Pu isotopes, we use here a total release of 0.1% of inventory as the mechanisms of release that could occur in a unit 4 SFP disaster can not be predicted.

We will use two bounding approaches to interpret these numbers:

Even distribution of the isotopes over the land area of Japan (~$4 \cdot 10^{11}$ sq m)	
Cesium distribution on land	~ 100,000 Bq/m^2
Soil contamination due to Cesium*	~ 2000 Bq/kg
Strontium distribution on land	~ 30,000 Bq/m^2
Soil contamination due to Strontium**	600 Bq/kg
Plutonium distribution on land	5 Bq/m^2

* using a conversion coefficient of 50 kg/m2 similar to that reported by Yasunari et al., 2011

** no conversion coefficient was found for strontium, so value for cesium is used as a first approximation

Distribution of isotopes on land estimated by comparison to March 2011 release *	
Area in East Fukushima prefecture and around Fukushima NPP	
Cs-137 + Cs-134	12000 – 40,000 Bq/kg
Sr-90	3600 – 12,000 Bq/kg
Pu isotopes**	3 – 10 Bq/kg
Neighboring Prefectures	
Cs-137 + Cs-134	1500 – 5000 Bq/kg
Sr-90	450 – 1500 Bq/kg
Pu isotopes**	0.4 – 1.25 mBq/kg
Tokyo Prefecture	
Cs-137 + Cs-134	600 – 2,000 Bq/kg
Sr-90	180 – 600 Bq/kg
Pu isotopes**	0.15 – 0.5 mBq/kg

* Scaling results of Yasunari et al., 2011 using ratio of 10% of SFP 4 isotope inventory estimates above to March, 2011 release amounts

** Scaling measurement results of Zheng et al., 2012 using Cs-137/Pu deposition ratio of $2 \cdot 10^6$

Ocean Contamination (base case with 8% of SFP 4 inventory falling on ocean)

Ocean Contamination for uniform distribution over 500 km x 500 km area	
Cs-137 + Cs-134 Surface Deposition	640,000 Bq/m2
Cs-137 + Cs-134 Volume Concentration*	6400 Bq/m3
Large marine life bioaccumulation**	~ 1200 Bq/kg
Ocean contamination based on scaling of Buesseler et al., 2012 results for March 2011 release	
Near-shore Cs-137 + Cs-134Δ	210 – 8000 Bq/m3
Off-shore Cs-137 + Cs-134‡	6 – 1400 Bq/m3
Large marine life bioaccumulation**	360 Bq/kg

* Using 100 m mixing depth
** Using bioaccumulation factor of ~180 for Thunnus alalunga near Japan from Rowan and Rasmussen, 1994.
Δ Using 7000 – 80,000 Bq/m2 typical range from Buesseler et al., 2012 with 100 m mixing depth
‡ Using 200 – 14,000 Bq/m2 typical range from Buesseler et al., 2012 with 100 m mixing depth

Discussion of Base Case Scenario Results

The most important factor in a bounding exercise of this type is the estimate of total isotopes in the unit 4 SFP and percentage released. Determination of these amounts is complicated by the fact that the isotopes other than uranium are produced during reactor operation and the amounts vary depending on reactor operating conditions, position of a rod in the reactor and along the rod, and storage time following operation. We believe the above inventory values represent reasonable first order estimates, but they are critical to the analysis and should be modified if additional information is identified.

The unit 4 SFP was generating about 2 MW of waste heat in March 2011. This amount is decreasing with time but likely remains above 1 MW at this time (see Note 2). If cooling water is lost either by collapse of the pool or development of a large crack and water leak, the temperature of the fuel assemblies will quickly rise. The zirconium cladding on the fuel rods begins to crack at about 1200 C, and oxidation begins at 1300 C. Oxidation of the cladding in the presence of steam results in an exothermic reaction producing 5.8 MJ/kg of Zr, which can add to the heating of the fuel and also produce hydrogen.

The course of events following a loss of cooling water is unknown and depends on many factors. Radioactivity releases from the Fukushima Daiichi reactors so far appear to have resulted from a number different processes. For example, the very low plutonium releases (possibly 100,000 times less than Chernobyl as a fraction of plutonium present), suggest that it resulted from shattering of fuel rods during the hydrogen explosions (Zheng et al., 2012). The prolonged fires at Chernobyl may have volatilized plutonium by heating.

Although the unit 4 reactor does not use MOX fuel, plutonium is created as a by product of reactor operation and spent fuel is about 1% plutonium isotopes. Extensive studies have been performed to determine the rates and mechanisms of plutonium volatilization (Gelbard et al., 2003). The fraction of plutonium aerosolized can vary over a wide range depending on temperature, air flow, the presence of water vapor, and other factors. Thus, the plutonium values measured from the March 2011 release may or may not be representative of any future events. As noted above, fully 3.5% of plutonium fuel at Chernobyl was released during that crises.

Data on Cs-137 releases and deposition from the March 2011 release is becoming increasingly available as noted earlier. Although measurements have focused on Cs-137, we included Cs-134 in the estimates above as it presents similar hazards and is produced in similar amounts during reactor operation. We note, however, that Cs-134 has a shorter half life of only 2 years and thus levels are some 30% lower a year later.

An additional release event, such as a unit 4 SFP failure, would obviously not result in uniform distribution of radio nucleotides over Japan. These calculations were included as a bounding exercise as it is impossible to predict how cesium and other isotopes would be transported and distributed by the weather. Our second approach using data based on the March 2011 release represents a weather scenario that actually occurred, but is unlikely to occur in precisely the same way again. In evaluating the potential impact of a SFP 4 failure, it is important to recognize that weather patterns could result in either more or less land distribution than occurred in March 2011.

These two approaches both indicate that a SFP 4 failure could present serious country-wide problems for Japan. The current limits for cesium soil contamination in Japan are 5000 Bq/m^3. The results above suggest that this limit could be exceeded over large areas and would likely be further exacerbated by Sr-90 contamination. Little work on Sr-90 contamination from the March 2011 release has been published, but it is an important and hazardous material that is rapidly absorbed by plants and animals. We also note that the contamination levels predicted above for a SFP 4 failure would be added to existing soil and ocean contamination levels, both from the March 2011 release and other sources.

Pacific ocean contamination represents an even more complex problem because it involves not only weather patterns but ocean currents and mixing as well. The rough estimates presented above are meant only as an initial bounding exercise, but do indicate that the ocean should not be considered an infinite sink for radioactive waste.

The results of Buesseler et al., 2012 suggest that ocean contamination resulting from the March 2011 release should not present an immediate hazard either for humans or the ocean environment. However, that paper does not address the greater bioaccumulation that occurs in larger fish, or the effects of other important isotopes such as strontium.

Cesium and strontium, in particular, move easily through sea life and Cs-137 and Sr-90 decay slowly with half lives on the order of 30 years. If a SFP 4 failure occurs, the above estimates suggest that significant amounts of these isotopes could be added to the amounts already present from atmospheric testing and the March 2011 Fukushima release. Impacts on human health, the ocean environment, and fishing industries need to be considered.

The biological impact of ingested radioactive materials varies according to the isotope. Risk coefficients for ingestion of Cs-137 and Cs-134 are about $3 \cdot 10^{-11}$ per pCi or $8 \cdot 10^{-10}$ per Bq (Peterson et al., 2007). This means, for example, that if 100 million people each consume an additional 100,000 Bq of radioactive cesium, an additional 8000 cancer deaths are expected. The levels of ocean contamination estimated above remain generally less than natural levels of Potassium-40 activity (about 12,000 Bq/m^3). However, each ingested radiation source adds to internal exposure and contributes to overall risk. Thus, a finding that added contamination levels are less than natural levels should not be interpreted as an indication of no risk.

Other Scenarios

The sequence of events that might follow a failure of SFP 4 is difficult to determine because so many different factors of geometry, heat dissipation, and age of the fuel rods can affect the outcome. Analytical tools and modeling programs for this purpose have been developed by governments, but appear to be classified and unavailable to the public (NRC, 2006). Because of the high level of heat generation and the presence of the zirconium cladding, it is possible that a radiological fire could ensue.

The risk of a radiological fire decreases as the time since removal of the fuel from the reactor increases. The most recent fuel rods in SFP 4 were removed from the reactor in late 2010 indicating that risk of a radiological fire is substantially reduced compared to March 2011 when the earthquake and tsunami occurred. However, heat production likely remains quite high due to the large number of fuel assemblies and close packing within SFP 4. The positioning of the fuel rods would also change unpredictably in a collapse of the fuel pool making it difficult to rule out the possibility of conditions that could lead to a radiological fire.

If a radiological fire develops and further cooling is impossible, more than 10% of the radioactive material of SFP 4 could be released. Results for the base case scenario above can be directly scaled to estimate the impact of a larger percentage release.

Release of 100% of the cesium, strontium, and other isotopes would scale the base case results by a factor of ten and would clearly present a dire situation for areas of Japan, marine life in the Pacific ocean, and the global environment. A release of 100% of the SFP 4 cesium and strontium from SFP 4 would represent a 30 – 100 times larger release than occurred in March 2011.

Loss of shielding provided by the pool water would also result in extremely high radiation levels in the immediate area. Such extreme radiation levels can make it impossible for human workers or robots to enter the area and attempt cooling operations or other mitigation strategies. Concerns have further been raised that high radiation levels from a SFP 4 failure may prevent access and maintenance to the nearby common fuel pool and the rest of the Daiichi nuclear plant. The total inventory of radioisotopes at the plant is roughly an order of magnitude greater than the SFP 4 inventory.

Conclusions

The risk of radiological fire and a major radioactivity release decreases as time passes and the waste heat output of the SFP 4 inventory declines. Whether or not a radiological fire would occur during a rapid loss of cooling water or a collapse of the pool is impossible to determine with certainty because of the many unknowns. Government agencies and national laboratories, which have developed detailed models for such situations, may be able to provide a reasonable estimate of probabilities. However, we have not been able to locate any such analysis for the current situation even though more than a year has passed since the March 2011 explosions and radiation releases.

Given available information, the most reasonable assumption is that a radiological fire remains possible. Based on spent fuel heat decay curves, the fuel in SPF 4 is probably still producing more than 1 MW of waste heat that is not easily dissipated without cooling water. A radiological fire would likely result in a major release of radioactive isotopes as there is currently no significant barrier between SFP 4 and the environment. The exact amount of material that would be volatilized and/or released into the ocean is also impossible to determine.

A high risk of large earthquakes in the coming months along with the extremely damaged and unstable state of the reactor 4 building mean that the potential modes of a SFP 4 failure are unknown. Would a large crack occur, leading to sudden loss of cooling water but with the pool walls remaining largely intact, impeding heat dissipation? Or would the pool collapse leading to a disordered and unpredictable configuration of the fuel assemblies as they fall some 30 meters?

We can conclude at this point only that the potential exists for severe additional contamination of Japan, parts of the Pacific ocean, and other parts of the world due to atmospheric and ocean transport. If there is no further damage to SFP 4 before fuel removal, or if damage occurs but cooling is maintained and radiological fires or hydrogen explosions are avoided, releases of radioactive material may be minimal. According to media reports, work to remove the SFP 4 radioactive material is currently scheduled for late 2013.

The situation is thus one of undetermined event risk, but extreme consequences if the event does occur (the event being SFP 4 failure with radiological fire or other mode of major radioactivity release). This event risk may be substantial based on available information. Depending on the nature of the failure, the consequences could be mainly confined to Japan and nearby ocean areas, or could extend to varying degrees of global impact. The former case is relevant for release of a small percentage of SFP 4 inventory while the latter case would result following a substantial percentage release from SFP 4 and possibly additional releases from surrounding inventory at the Daiichi plant.

Our recommendations based on this bounding analysis are as follows:

1. Governments and other organizations with advanced modeling capabilities should immediately conduct an analysis of SFP waste heat levels and the possibility of radiological fire in the event of SFP 4 failure, and make the results publicly available.

2. If there is still a significant possibility of radiological fire and large additional releases of radioactive material within the coming months, immediate action should be taken to accelerate removal and/or protection of the SFP 4 contents. Although the technical challenges of such an operation are enormous, the potential impact of a failure is great enough that international resources should be quickly mobilized to address this issue.

3. Industries potentially affected by major additional radioactivity releases in Japan should draw up contingency plans to prepare for the impact of further events. If an earthquake or other event results in SFP 4 collapse, events will unfold very quickly leaving no time for emergency planning.

4. Members of the public, particularly in Japan and the U.S., should pressure authorities to perform accurate and honest assessments of risks, to prepare plans to handle further earthquakes or other damage to SFP 4 and the rest of the plant, and to accelerate mitigation activities.

In closing, we note that the above analysis is a rough estimation of potential impact in lieu of in-depth, detailed analyses from official agencies. It addresses only the SFP 4 question and does not discuss ongoing problems with other reactor cores at the site. We also did not include the numerous unpublished radiation measurements performed by the public and others. These measurements may well represent important findings, but are not suitable for inclusion in a bounding analysis of this type until verified.

Although we reviewed a number of papers discussing worldwide fallout from the March 2011 event, we did not directly estimate impact to other countries in this report. There are so many variables associated with transport of radioactive material that we felt it most useful to focus on Japan and nearby areas of the Pacific ocean. Official reports and published papers so far are generally not reporting substantial impact of the March 2011 release on other countries. As additional results are published, or at the request of our clients, we may revisit this issue in a future report

References:

Alvarez R, et al., *Reducing the Hazards from Stored Spent Power-Reactor Fuel in the United States*, Science and Global Security, 11:1-51, 2003

American Nuclear Society Special Committee on Fukushima, *Fukushima Daiichi: ANS Committee Report* (including Appendices), March 2012. Available from http://fukushima.ans.org .

Argonne National Laboratory, *Spent Fuel*, Information Sheet, April 2011.

Buesseler KO, et al., *Fukushima-derived radionuclides in the ocean and biota off Japan*, Proceedings of the National Academies of Sciences, PNAS 2012 109(16)5984-5988 (published ahead of print April 2, 2012)

Canadian Nuclear Safety Commission, *CNSC Fukushima Task Force Report*, INFO-0824, October 2011

Eckerman KF, Leggett RW, Nelson CB, Puskin JS, Richardson ACB, *Cancer Risk Coefficients for Environmental Exposure to Radionuclides*, Federal Guidance Report No. 13, U.S. Environmental Protection Agency, EPA 402-R-99-001, September 1999.

El-Jaby, A (Canadian Nuclear Safety Commission), *Fukushima Daiichi NPP Event and Associated Radioactive Source Term – CNSC's Initial Response*, Presentation at WNU Summer Institute, 2011 (8x8 rod assemblies, 13.9 cm x 13.9 cm, 208 kg fuel, 103 kg Zircaloy cladding

Gelbard F, Murata KK, and McClellan Y (Sandia National Laboratories), *A Review of Plutonium (Pu) Combustion Releases in Air for Inhalation Hazard Evaluation*, Sandia Report SAND2003-3253, 2003.

Lujaniene G, Bycenkiene S Povinec PP, and Gera M, *Radionuclides from the Fukushima accident in the air over Lithuania: measurement and modeling approaches*, J of Envr. Radioactivity, in press, available online December 27, 2011.

Makhijani, A (Institute for Energy and Environmental Research), *Post-Tsunami Situation at the Fukushima Daiichi Nuclear Power Plant in Japan: Facts, Analysis, and Some Potential Outcomes*, March 16, 2011

Mertyurek U, Francis MW, Gauld IC (Oak Ridge National Laboratory), *SCALE 5 Analysis of BWR Spent Nuclear Fuel Isotopic Compositions for Safety Studies*, ORNL/TM-2010/286, December 2010.

Ministry of Education, Culture, Sports, Science and Technology-Japan, *Results of the Nuclide Analysis of Plutonium and Stronium by MEXT*, September 30, 2011

National Research Council of the National Academies, *Safety and Security of Commercial Spent Nuclear Fuel Storage: Public Report*, , ISBN: 0-309-10511-0, 2006. Available from National Academies Press, http://www.nap.edu;catalog/11263.html .

Nuclear Regulatory Commission ML011870535 Appendix 1, *Thermal Hydraulics of Spent Fuel*, 2000

Peres, AC and Hiromoto, G, *Determination of Screening Level for Soil Radioactive Contamination*, Proc. Annual Intl Conf on Soils, Sediments, Water and Energy, 12(1): Chapter 20, 2010

Peterson J, MacDonell M, Haroun L, Monette F (Argonne National Laboratory, Environmental Science Division), *Radiological and Chemical Fact Sheets to Support Health Risk Analyses for Contaminated Areas*, Argonne National Laboratory, 2007.

Pretzsch G, Hannstein V, Wehrfritz M, Radioactive Inventory at the Fukushima NPP, Eurosafe, 2011. Available at:
www.eurosafe-forum.org/userfiles/2_1_%20paper_Radioact%20inventory%20Fukushima_Pretzsch_19102011.pdf

Rowan DJ and Rasmussen JB, *Bioaccumulation of Radiocesium by Fish: the Influence of Physicochemical Factors and Trophic Structure*, Can. J. Fish. Aquat. Sci 51:2388-2410, 1994.

Sailor VL, Perkins KR, Weeks JR, and Connell HR, *Severe Accidents in Spent Fuel Pools in Support of Generic Safety*, Issue 82, Brookhaven National Laboratory, NUREG/CR-4982, 1987.

Thompson, MA (Dow Chemical Co.), *Oxidation and Ignition of Plutonium*, RFP-491, 1966

Tong P, Shao D, and Yang D, *Tomography of the 2011 Iwaki earthquake (M7.0) and Fukushima nuclear power plant area*, Solid Earth, 3:43-51, 2012

Wakeford, R, *And now, Fukushima*, J. Radiol. Prot., 31:167-176

Wetherbee GA, Debey TM, Nilles MA, Lehmann CMB, Gay DA (U.S. Geological Survey), *Fission Products in National Atmospheric Deposition Program*, Open File Report 2011-1277, 2011.

www.World-nuclear.org, (Site provides a range of data and analysis regarding the Fukushima Daiichi nuclear plant and 2011 disaster

Yasunari TJ, et al., *Cesium-137 deposition and contamination of Japanese soils due to the Fukushima nuclear accident*, PNAS 108(49):19530-19534, 2011.

Zheng J, et al., *Isotopic evidence of plutonium release into the environment from the Fukushima DNPP accident*, Scientific Reports, 2:304, DOI: 10.1038/srep00304, 2012.

Notes:

Note 1: Following is an example of concern raised about this issue on an Internet site (akiomatsumura.com/2012/04/682.html).

Japan's former Ambassador to Switzerland, Mr. Mitsuhei Murata, was invited to speak at the Public Hearing of the Budgetary Committee of the House of Councilors on March 22, 2012, on the Fukushima nuclear power plants accident. Before the Committee, Ambassador Murata strongly stated that if the crippled building of reactor unit 4—with 1,535 fuel rods in the spent fuel pool 100 feet (30 meters) above the ground—collapses, not only will it cause a shutdown of all six reactors but will also affect the common spent fuel pool containing 6,375 fuel rods, located some 50 meters from reactor 4. In both cases the radioactive rods are not protected by a containment vessel; dangerously, they are open to the air. This would certainly cause a global catastrophe like we have never before experienced. He stressed that the responsibility of Japan to the rest of the world is immeasurable. Such a catastrophe would affect us all for centuries.

Note 2: Spent nuclear fuel waste heat decreases with time. According to World-nuclear and other sources, the waste heat generated by SFP 4 in spring 2011 was between 2 MW and 3 MW. The precise decay rate for this waste heat is difficult to determine because of the many isotopes present, the varying ages (relative to date of removal from the reactor), and the particular history of the fuel rods within the reactor. Fuel rod waste heat decays nominally from about 10 kW per tonne at one year after removal to 1 kW per tonne at ten years (www.fukushima.ans.org, www.world-nuclear.org). Depending on the heat decay rate applied, the current waste heat production is likely between 0.5 MW and 1.5 MW as of April 2012. Various agencies and organizations have detailed information on the fuel rod history and computational models capable of making more precise estimates.