

Evaluating and Managing Risk in the Nuclear Power Sector

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Abstract

Civil nuclear power can be a miraculous gift to society, now producing nearly 13% of the world's electrical energy. As demonstrated by Chernobyl and now by Fukushima Dai-ichi, it can also be a curse. It has also a link to nuclear weaponry and to proliferation of nuclear weapons, through common elements in the fuel cycle, including enrichment of fuel and reprocessing and separation of plutonium. These questions of safety and proliferation have been recognized from the very beginning. More recently, security of the nuclear power sector has become a recognized problem, to keep it safe from intentional, catalytic harm.

I propose that current organizations such as the Institute of Nuclear Power Operators (INPO) in the United States and the World Association of Nuclear Operators (WANO) be strengthened to carry out and to lead the way on detailed analysis of potential events and hazards in the nuclear power sector, including a frank evaluation of the societal costs of exposure of societies to relatively low doses of radioactive materials that could be disseminated in reactor accidents.

Looking ahead, I propose that IAEA be given the responsibility to certify and monitor mined geological repositories and the packaged waste forms to be shipped there, to enable the creation of competitive, commercial repositories available to all members of the NPT.

My background in nuclear power

I have long been concerned with the energy sector, having chaired in 1975 a National Academies Committee on the Solar Energy Research Institute (National Renewable Energy Laboratory), published in 1977-79 a number of paper on “The Proper Role of the Breeder Reactor,” given much testimony to congressional committees over the years on technology and security.

I have published several books on energy and nuclear power, beginning as a coauthor of an American Physical Society study in 1975, “Report to the APS by the Study Group on Light-water Reactor Safety,” in 1977 “Nuclear Power: Issues and Choices,” in 1979 “Energy: The Next Twenty Years.” More recently I published in 1997 with Georges Charpak, “Feux

Follets et Champignons Nucleaires;” in 2001 and 2002, “Megawatts and Megatons ...;” in 2005, “De Tchernobyl en tchernobyls” (with Georges Charpak and Venance Journe); and am completing updating that volume for early 2012 publication perhaps with the title, “De Tchernobyl en Fukushima Dai-ichi.”

I am fortunate, in preparing this talk, to have the benefit of the Blue-Ribbon Commission Report on America’s Nuclear Future¹, January, 2012, and, especially, the IPFM 09/2011 report, “Managing Spent Fuel from Nuclear Power Reactors: Experience and Lessons from Around the World².” I will quote liberally from the latter, including some of its graphics. In my writings and presentations for the past decade or more, I and my colleagues, Dr. Venance Journé and the late Georges Charpak, have argued that the acceptability of the nuclear power enterprise depends on competent and honest analysis and presentation of the risks, and in particular, on the choice and progress toward sufficient operating mined geological repository capacity for spent fuel from existing nuclear power reactors, as well as from the future power reactors. This is such a

¹ http://brc.gov/sites/default/files/documents/brc_finalreport_jan2012.pdf

² www.fissilematerials.org
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tendentious problem because of the long-lived radioactive material present in nuclear reactors and in the fuel cycle, especially in the spent-fuel pools at the reactor sites, and the consequences of distributing some of this material into the atmosphere or, more generally, the biosphere, by accident or intentional destruction.

I will not address *security* of the reactors and the fuel cycle, especially reprocessing plants, in view of the limitations of time and the sensitivity of that problem, but I do discuss here a suggestion for the mechanism of addressing such problems through the Institute of Nuclear Power Operators (INPO) in the United States and the World Association of Nuclear Operators (WANO) in the world.

Unfortunately, in both the commercial and the government sectors, “risk management” priorities often come down to managing public perceptions about prospects and events, as evidenced by emails in several countries following Fukushima Dai-ichi, in which officials argue that their priority is to maintain the nuclear power sector in a good light, even before these officials knew of the facts in regard to the disaster. Only by addressing

directly the analyses of independent groups—some of them extremely competent and fair, others as biased as government sponsors of nuclear power themselves—can public confidence be achieved.

This assessment has two aspects—the detailed analysis and assessment of the probability of various accidents, and an evaluation of their consequences on health and the economy. There is in the nuclear power sector a widespread reluctance to address objectively the question of potential injury from low-dose exposure to radiation, despite responsible reports like that of BEIR-7³ that assess the incidence of lethal cancers in the adult population as above 0.05 per person-sievert (p-Sv), and a total incidence of cancer of about 0.1 per p-Sv.

Some fragmentary analyses of the health effects of Fukushima Dai-ichi have been made, for instance by the French Institute of Radioprotection and Nuclear Safety (IRSN) on various assumptions as to evacuation of areas beyond the presently defined exclusion regions, and I provide here my own assessment on that same basis.

³ *Health Risks from Exposure to Low Levels of Ionizing Radiation: BEIR VII Phase 2*. Washington, DC: The National Academies Press, 2006.
<http://www.nap.edu/openbook.php?isbn=030909156X>

I begin with Table 2 of the IRSN Report (in English)⁴ of May 16, 2011. Comparing Chernobyl and Fukushima Dai-ichi, IRSN writes,

“The external collective dose received over 4 years by the population of 270,000 people in Chernobyl was 7,300 person.Sv⁵.

“The projected external collective dose over 4 years for the 70,000 people in Fukushima is 4,400 person.Sv. Therefore, without evacuation during the 4 years after the accident, the radiological consequence of the Fukushima accident from external exposure would reach 60% of that of Chernobyl and could be in the same order of magnitude.”

Assuming a dose-response coefficient of 0.05 lethal cancers per person-Sv, the 4400 p-Sv of the Fukushima accident would lead to 220 deaths from cancer for a population in which one expects some 14,000 people to die of cancer from other causes.

⁴ <http://tinyurl.com/7pn5w24> French version: <http://tinyurl.com/7sub5qn>

⁵ But the “Chernobyl Forum” Report of September 2005 states a lifetime exposure of 60,000 p-Sv and a corresponding toll from cancer of 4000 deaths. Had the Forum included the full 600,000 p-Sv documented by the 1993 UNSCEAR report, the corresponding expectation of cancer deaths would be 40,000.

Table 2: Deposits, external doses projected at 10 and 70 years and affected populations

Deposits of caesium (137 + 134) (Source MEXT)	> 300,000 Bq/m ²	> 600,000 Bq/m ²	> 1 million Bq/m ²	> 3 millions Bq/m ²	6 - 30 millions Bq/m ²
External dose at 10 years (70 mSv per MBq/m ²)	> 19 mSv	> 38 mSv	> 63 mSv	> 190 mSv	380 - 1,900 mSv
External lifetime dose (70 years) (160 mSv par MBq/m ²)	> 41 mSv	> 82 mSv	> 136 mSv	> 408 mSv	816 - 4,080 mSv
Affected population (excluded the no-entry zone)	292,000	69,400			
		43,000	26,400		
			21,100	3,100	2,200

The IRSN Report concludes with the following paragraphs,

“These dose levels do not take into account other exposure pathways, such as immersion within the plume and internal contamination resulting from inhalation of particles in the plume, as well as internal

doses already received or to be received from contaminated food ingestion.

“The total effective doses (external + internal) could be increased considerably according to the type of deposit (dry or wet), diet and source of food.

“The level of external doses projected in upcoming years - up to 4 Sv lifetime in the most contaminated areas (30 million Bq/m² of cesium-137 + 134) - requires the implementation of protective actions such as evacuation of population.

“According to the ICRP recommendations in radiation emergency situations, the selection of the highest protective reference level, i.e. 20 mSv, would avert external doses above this level for 15,000 to 20,000 people.

”If the Japanese authorities decide to take an even more protective reference level, for example 10 mSv for the 1st year, the averted external doses for the affected populations (70,000 people) would be much higher if the evacuation is quickly prescribed. An evacuation one

year after the accident would result in a 59% decrease of the projected external dose for this population; evacuation three months after the accident would result in an 82% decrease.

“This policy for preventing the risk of developing long-term leukemia and radiation-induced cancer has been clearly understood by the Japanese authorities as shown in the map of population evacuation beyond the initial zone of exclusion of 20 km reported to the IRSN knowledge on May 16, i.e. the 66th day after the accident (Figure 10). The prescribed evacuation area seems to meet the 20 mSv reference level - the most protective dose value within the range recommended by the ICRP in an emergency situation. This decision made by the Japanese authorities proves retrospectively the relevance of the IRSN's radiological assessment map - the first to have been published worldwide, 28 days after the accident.”

However, the results of the IRSN study and the expected consequences in cancer deaths are underestimated. The citation above indicates that the dose projected to four years is 4400 person-Sv, the dose to ten years would be about 9000 person-Sv, and according to the Table, the dose to 70 years

is 2.15 times the dose to ten years. Thus the dose for 69,400 persons would be 19,350 person-Sv. In addition, one needs to take into account the much larger number of persons exposed to a slightly lower level. According to the Table, there are 292,000 persons for whom the lifetime exposure (70 years) will exceed 41 mSv. This means a supplementary contribution to the projected dose exceeding 11,972s person-Sv, because this category of exposure ranges extends from 41 mSv to 82 mSv. Perhaps the IRSN would advise that these persons be evacuated in the forthcoming four years, which would permit to reduce the external dose to four years of exposure; but the decision to evacuate whether obligatory or not, needs to take into account the probability of cancer if the evacuation is not performed. Based on the IRSN study, the lifetime projected dose would be $11,972 + 19,350$, or about 31,000 person-Sv, which corresponds to 1550 cancer deaths, assuming a dose-response coefficient of 0.05 lethal cancers per person-Sv.

An equal number of cancers are to be expected which will be survived, thanks to surgical treatment or chemotherapy.

These estimates do not take into account the internal dose from food, for which the Japanese government is now reducing the acceptable contamination level.

But my conclusion is different from those who are unwilling to accept the multiplication of two numbers—the dose-response coefficient of 0.05 lethal cancer per p-Sv, and the collective radiation dose. My conclusion is that society must understand that some negative influence on the population always exists—whether in the cost of technology or in the consequence of technology, and that this must be compared with the benefits of those technologies. So if the probability of such an accident can be maintained acceptably low so as not to eliminate much of the benefit of energy production from nuclear power, then even these major disasters should be acceptable.

It is important, however, in considering mandatory or even voluntary evacuation, to take into account the potential hazards (even health hazards) associated with disruption of normal life. If this were the equivalent of 1% loss of life from cancer, it would indicate that evacuation

would be harmful rather than beneficial, for avoided doses of 200 mSv or less. Societal damage or compensation for those not evacuated could be based on estimated individual dose: with 0.05 lethal cancer per p-Sv and a nominal \$5 million value per premature death averted, this would correspond to compensation of \$0.25 million per p-Sv. For those evacuated, under the arbitrary assumption of 1% equivalent loss of life from evacuation the compensation might be \$50,000 per evacuee plus an amount similarly proportional to the dose, as with those who are not evacuated⁶. In the case of Fukushima Dai-ichi, compensation for not evacuating 292,000 people (<82 mSv each) would be less than \$21,000 each, or \$6.1 billion. That such compensation can be provided fairly is demonstrated by the performance of Kenneth R. Feinberg in administering such funds for victims of the World Trade Center attack and the BP Deepwater Horizon oil spill⁷.

I have my own experience in documented correspondence⁸ with the IAEA about the intentionally misleading report of the Chernobyl Forum, where

⁶ For a reasoned treatment of risk, see "Risk-Benefit Analysis," 2d Edition, by Richard Wilson and E.A.C. Crouch, Harvard University Press, October 2001, ISBN 9780674005297.

⁷ http://www.washingtonpost.com/politics/kenneth-r-feinberg/gIQATdzFAP_topic.html

⁸ "More Candid Interchange is Necessary with IAEA, the UN, and European Government" by R.L. Garwin, July 19, 2008. http://www.fas.org/rlg/071908_ESOF-1a.pdf
03/09/2012

the responsible official in public relations is quoted⁹ in Nature magazine as saying:

“Melissa Fleming, a press officer working at the International Atomic Energy Agency in Vienna, who helped coordinate the report's publicity, says the scientists involved checked the press material. But she admits a decision was made to focus on the lower 4,000 figure, partly as a reaction to the inflated estimates of past decades. ‘I was sick of seeing wild figures being reported by reputable organizations that were attributed to the UN,’ she says. ‘It was a bold action to put out a new figure that was much less than conventional wisdom.’ The figure has been removed from the final summary, however, published this month”.

Closer to our topic here, is the revealing report by Ann MacLachlan¹⁰ quoted in full (translated into French) in our 2005 book, “De Tchernobyl en tchernobyls.” I provide here in the original English the statement of Tsunehisa Katsumata, president of TEPCO,

⁹ “Special Report: Counting the Dead,” <http://www.nature.com/nature/journal/v440/n7087/full/440982a.html>, *Nature* **440**, 982-983 (20 April 2006) | doi:10.1038/440982a; Published online 19 April 2006; Corrected 21 April 2006

¹⁰ [MacLachlan, Ann., October 16, 2003, 'Complacency, negligence threaten nuclear industry, WANO warns', Nucleonics Week, Volume 44 / Issue 42.](#)

Katsumata said Tepco's nuclear power division had become "a homogeneous and exclusive circle of engineers who defied checks by other divisions, including the management." Rules covering fitness for service of equipment were "not clear," he said, and didn't allow for flaws as equipment aged, encouraging personnel to ignore the rules. Media attacks on problems at nuclear facilities, he said, put the engineers "on the defensive" and encouraged them to hide faults as long as those faults didn't immediately threaten safety -- leading to 16 cases of falsification of inspection and repair records at Tepco's BWRs.

Compounding this was the engineers' attitude that "stable supply of electricity (was) the ultimate objective," leading them to make "personal decisions based on their own idea of safety," Katsumata said.

Besides initiatives to rewrite rules, revise Tepco's corporate code of conduct, and strengthen safety culture messages, Tepco is taking several measures to regain public confidence, including holding public liaison meetings. But several industry executives acknowledged it

wouldn't be easy because multiple incidents, up to and including the latest episode at Tepco, have severely eroded the Japanese public's trust, and the country's basic culture still discourages whistle-blowing.

Some ascribe this deplorable status to the profit motive, but I think that it is no less widespread among government officials and employees, who, trying to do their job, have no time or patience to understand problems with the technology or investments that they are working so hard to implement.

I move on to my final topic described in the Abstract:

“Looking ahead, I propose that IAEA be given the responsibility to certify and monitor mined geological repositories and the packaged waste forms to be shipped there, to enable the creation of competitive, commercial repositories available to all members of the NPT.”

This is addressed at length in the IPFM “Managing Spent Fuel” Report and somewhat more briefly in the Blue Ribbon Commission Report. The

IPFM Report is particularly useful here, in its extensive description of various national programs. It documents the fact that the concept of an international repository is far from new, but that it has had little traction, and suggests that the best approach is to add an international aspect or sector, perhaps, to a major national repository.

Given that almost all of the Earth's land surface is the property of one nation or another (aside from Antarctica, which is by treaty and custom prevented from being a repository) there is a certain logic behind the ISFR (International Spent Fuel Repository) deriving from a national SFR. The problem is that there is no large-scale SFR, and none in the immediate prospect, so that most states with nuclear power sectors are exploring and planning for their own national SFR. Even if one planned from the first for an ISFR, it would need to be acceptable to the host state.

Simpler is the concept of IAEA regulation of the repository and of its waste forms—intact spent fuel for one, and packaged high-level waste for another. According to the IPFM Report, IAEA has not objected to the suggestion that it be the regulator and inspector for such activities.

Naturally, IAEA, which is an information gathering and disseminating organization and has no physical enforcement capability, would need to be buttressed by U.N. forces or commitments from IAEA member states in order to provide force, if necessary, to prevent or repel intrusions on the ISFR or its operation.

An international group of investors, including states themselves, could provide the commercial entity that would design, site, and manage the ISF, which would evidently be a massive undertaking. Its purpose would be profit, but profit from operations in a very limited field. An alternative to siting on land would be, technically, to have an ISFR mined in the sea bed, on the abyssal plain that at a depth of 5 km underlies most of the open ocean.

Although I and my colleagues have long advocated ISFRs, they have been banned by custom and national law. However, the Council of Europe on July 19, 2011, as noted in the IPFM Report, specifically authorized European states to share repositories and even to contract with a third, non-EU, state to have a joint repository. Clearly, there are many

obstacles, not the least of which is the long-term nature of the work, and the limited profit that could be made. Given that the sustained existence of fission energy depends on the presence of SFRs, the value of an SFR would far exceed its cost. Thus, if one ascribed for spent fuel disposal one U.S. cent per kWh rather than 0.1 cents as is the present charge to handle the spent fuel, the overall cash flow from a single 1000 MWe reactor would be \$10,000 per hour or some \$80 million per year for the disposal of spent fuel. For the 300 full-size reactors in the world today, that would be about \$24 billion annually.

Note, however, that the Apple Corporation capitalization (the product of the price of its stock and the number of shares) has just passed \$500 billion, to see that venture capitalists are not likely to vie with one another even at a gross cash flow of \$10/MWh (the equivalent of one U.S. cent per kWh) for the spent-fuel disposal sector.

While I don't see an ISFR as an add-on to an operating national SFR, I can see it as a major factor in planning and siting a national SFR. The initiative would likely come from a country that has a large existing

population of reactors, and also plans for a major nuclear power sector in the future. The United States and Russia are two, and China, despite its small current nuclear sector, certainly fits this description. All three have vast land areas.

The Blue Ribbon Commission Report and the IPFM account of successful national SFR programs in Sweden and Finland emphasize “consent based” approach to siting of facilities—a concept outstanding for its good sense rather than its novelty.

Siting several (competing) ISFR on the sea bed would solve some problems, and pose others. First there is the legal question, associated with potential harm to the shared resource of the sea itself. Then there is the technical problem of mining and other operations at great depth—far beyond the 2 km depth of the Deepwater Horizon well in the Gulf of Mexico. Evidently, the entire operation on the sea bed would have to be performed remotely, and much of that operation is such that there would be essentially no vision through the seawater, in view of the mud that would be created by the boring machines. Choices would need to be made

about the storage casks. They would not have to withstand potential km depth of glaciation in the open ocean, but they would need to survive the pressure of seawater at depth—500 bar at 5 km depth.

Returning to the national siting of an ISFR, there is the daunting problem of maintaining security for 100 millennia or more. That would be eased by an all-thorium fuel cycle, but that would do nothing for the existing reactor fuel or for the decades before uranium fission fuel might be phased out.

I have long called for a World Breeder Laboratory that would develop calculation and simulation tools and experimental programs for validating them. After some decades, if the much advanced analysis showed the opportunity for a breeder reactor that was safer than LWRs and competitive with them, one might build a single one of several candidate classes of breeders. The same or a different world laboratory could be devoted to analysis of various options for an ISFR, building on the analysis that has been done thus far in the national programs.

Overhanging all this is the question of future support for the security and tending of the ISFRs after fission power has been replaced by fusion or other advanced and potentially less hazardous technology. And, through the glacial eras that are sure to come, will humanity give the necessary attention to the safety and security of a spent-fuel repository?