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Editorial

Fukushima: There Are Lessons to Be Learnt, on Both Sides

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On Friday March 11, at 2.46pm (5.46am GMT), an earthquake of magnitude between 8.9 and 9.1 (Richter scale) hit the superficial submarine crust, about 10 km below sea level and about 120 km south-east of the east coast of Japan. Minutes later, a tsunami wave of up to 10 m reached the north-east coast of Japan. Less than two hours later, the Tokyo Electric Power Company (TEPCO) announced that over 4 million households were without power because of the quake-induced power generation and transmission failures. In particular, TEPCO stated that units 1, 2 and 3 at the Fukushima Daiichi nuclear plant and units 1 to 4 at Fukushima Daini stopped automatically because of the quake. This was the beginning of the worst nuclear accident of the last two decades (the Tschernobyl tragedy dates back to 1986).

One of the unfortunate consequences, negligible as it is when compared to the loss of more than 25,000 lives and to the billion euros damage, was the triggering of a series of completely irrational "denounces of the (long known!) scarce safety of nuclear plants", "accusations of negligence on the part of TEPCO", general statements against the use of nuclear powerplants to generate electricity, and similarly general statements about the need to a "quick return" to renewable energy sources. This editorial focuses on this explosion of irrationality, because unfortunately there is nothing we can do about the other, incommensurably more serious consequences, *i.e.*, the loss of lives, land and infrastructures, and the radioactive contamination.

I am no supporter of nuclear power: my students know it, my colleagues know it, my publication record shows it [1–4], and often in public forums I have spoken against the continued deployment of such a technology. But—both as an educator and as a researcher—I find the subitaneous emergence of such a radical opposition unfair, unfounded and malicious. Let me critically analyse the succession of events (as it was made public by the available press releases), to try to arrive at a more balanced assessment of the state of affairs:

(1) An earthquake 8.9 Richter is the most damaging event recorded in historical times: the amount of energy released by such an event is roughly equivalent to that released by the explosion of 30 billion (10^9) tons of TNT. In the non-numerical Mercalli scale, such an event is assigned a "magnitude XII" and is described as one that completely sweeps away every man made structure. The available pictures show instead that only relatively little damage was suffered by the reactors structures as a direct consequence of the quake: thus, the accusation of "poorly engineered structures" seems, to say the least, unjustified, because it is clear that the failure was not induced by the earthquake. Obviously, most of the metallic scaffolding, the cranes, most of the aerial pipes and electrical lines, the fuel and water pipelines were literally eradicated by the event: but what would have happened if the Fukushima plants had been coal fired? In a structural sense, the damage would have been worse, because of the stricter regulations imposed on nuclear facilities. The hypocritical statements hastedly released by energy managers and politicians all over the world about the "inherent unsafety" of nuclear plants is a sad demonstration of their general willingness to cynically exploit a human tragedy to try to ride the popularity roller-coaster.

(2) The tsunami hit at night and virtually without warning. The available videos show a wave between 5 and 10 m high, scarcely breaking because of the smooth slope of the coast: though to my knowledge no image exists of the exact moment in which the wave hit the plants, its power was enough to sweep away all of the ground-anchored structures, including some reinforced concrete walls and pillars, some of the roads and most of the electrical lines. As a matter of fact, the tsunami was the real culprit of the failure of the Diesel-powered emergency cooling units. Again, is it credible to blame "poor engineering" for the failures of these structures? Those of us who have been to Banda Aceh in 2005 have seen wreckage carried inland by the wave for more than 5 km, and to more than 200m elevation: the entire surface layer of land was scorched away by the sea... had Sumatra also been "poorly engineered"?

(3) The seriousness of the damage was surely not properly assessed in the first couple of days. In my opinion though, the many critical remarks on the TEPCO actions reported in the press were based on inaccurate and incomplete evaluations. With the current hindsight, it appears that the behaviour of TEPCO was indeed (almost) at par, and that their handling of the accident was—under the given conditions—excellent. This is exactly one of the "lessons" that we anti-nuclearists ought to learn.

(4) The first sign that things were not exactly "under control" came on Saturday, when TEPCO announced that pressure was rising in reactor #1 (see Figure 1A for a description of the normal operating conditions): though our "soon-to-be-antinuclear" politicians and TV anchormen did not understand it immediately, this fact was bad news for us engineers, because it signalled that the cooling circuits had been malfunctioning for a while (the inertia of the vessel is not negligible): Figure 1B shows the situation after the failure of the cooling systems. Water increased its boiling rate in the fuel core, the level of the liquid decreased, and the bars became partially or totally exposed (*i.e.*, practically uncooled, Figure 1C). The venting of steam from reactor #1 could not prevent an explosion, which happened on the same afternoon. Two days later (Monday 14), reactor #3 had a hydrogen-induced explosion (Figure 1D), and soon after reactor #2 had another one, in the cooling chambers within the containment building (Figure 1E),

leading to release of radioactive material and debris into the building: another consequence of the cooling water circuits failure. In spite of the absence of radiation leaks at this point, on Monday most media started talking about a "nuclear holocaust". Some blamed TEPCO of having underestimated the danger of explosion and of not having taken all necessary steps to prevent it. Now, the only way to effectively cool those vessels would have been to flood them: but, 2 days after the tsunami, there simply were not enough infrastructures in operation that would have allowed a massive water pumping into these two (and another one, as we shall see shortly) reactors. Here lies a critical point from which nuclear plant operators ought to learn a lesson: in "maximum impact disaster situations", a steady and reliable supply of water can come only from Diesel-powered emergency pumping stations, that ought themselves to be designed in such a way as to remain at least partially operational immediately after the event. Notice that the back-up batteries powering the emergency circulation pumps were themselves partially damaged by the earthquake and by the tsunami, and did not operate for long.

(5) On Wednesday 16 and Thursday 17, increasing pressures were detected in reactors #3 and #4, due to insufficient cooling. While #4 could be brought back under control, #3 could not, and the consequences became obvious in the next days: main containment damage, radioactive leaks, another explosion, and partially molten core.

(6) Another problem, first officially reported on Thursday 17, was the partial (reactor #3) and almost total (reactor #4) exhaustion of the water level in the spent fuel pool: partial damage to the fuel rods was also announced for reactor #4.

(7) As of the time of the first writing (April 11), the following facts have been ascertained:

a. It appears that the molten core of reactor #2 leaked from the reactor pressure vessel into the primary containment, and from there into the environment;
b. At reactor# 2, extremely radioactive material continues to ooze out of the reactor pressure vessel, and the leak may widen with time (this is an unconfirmed statement from private sources); it appears that TEPCO's difficulties in providing accurate information on radiation are not a result of software problems, but stem from damage to measurement instruments caused by radiation;
c. Broken pieces of fuel rods have been found outside of reactor #2, and are now being buried for temporary protection. The pieces may be from rods in the spent-fuel pools that were flung out by hydrogen explosions;
d. Some of the radiation readings at reactors # 1 and #3 over the last week were as high as 3300 rems per hour (that is, 33 Sievert/hour: the accepted level of "immediately deadly exposure" is about 10 Sievert/hour);
e. After the new earthquake of April 11, off-site emergency power was lost and water injection pumps for reactors #1, 2 and 3 are once again out of service;
f. The repeated reports of "flashes of extremely intense radioactivity" appear to confirm that some continued spontaneous fission might occur in pockets of the molten cores;
g. Nitrogen has been pumped into the primary containment vessel (PCV, drywell) to prevent a possible hydrogen explosion there. This indicates that hydrogen is escaping from a leaky reactor pressure vessel into the PVC;

h. It is very unlikely that a closed water cooling cycle can be reestablished for any of the three reactors. But continuing the current "feed and bleed" procedure (presently the reactors are continuously flooded with external water, Figure 1F) will increase the release of highly radioactive water to the environment. Other means publicly suggested for the "cooling", like for example covering the cores with sand/boron/lead, would not work in the present situation.

As of April 28, time of the printing of this editorial, the following additional facts have been made public [6]:

i. There is a large amount (70,000 tonnes) of stagnant water with high level radioactivity in the basement of the turbine buildings of reactors #1, 2 and 3;
j. The pressure vessels of reactors #1, 2 and 3 are being flooded with fresh water using temporary electric pumps with off-site power;
k. The leakage of extremely radioactive material from reactor #2 has been stopped;
l. The spent fuel pool of reactor 4 water continues to be sprayed on by means of an externally operated pump truck;
m. Nitrogen gas is still being injected into the containment vessel in reactor #1 to reduce the possibility of hydrogen ignition in the containment vessel. The indicated pressure in the reactor pressure vessel is still increasing;
n. In reactor #1, the indicated temperature at the feedwater nozzle of the reactor pressure vessel is 132.0 °C and at the bottom of reactor pressure vessel is 110.5 °C;
o. In reactor #2 the indicated temperature at the feedwater nozzle of the reactor pressure vessel is 120.4 °C. The reactor pressure vessel and the dry well remain at atmospheric pressure. Fresh water is being injected into the spent fuel pool using the spent fuel pool clean-up system;
p. In reactor 3 the indicated temperature at the feed water nozzle of the reactor pressure vessel is 72.0 °C and at the bottom of the reactor pressure vessel is 110.7 °C. The reactor pressure vessel and the dry well remain at atmospheric pressure;
q. Spraying of anti-scattering agent at the site is continuing.

I could not find any press release from any of the people who received the highest media exposure (politicians, opinion-makers, leaders of interest groups, *etc*.) in which the above facts were discussed in a rational fashion: this convinced me to quickly accept the invitation of the Publisher to discuss the issue in this editorial.

What can we learn from this disaster? As the title indicates, both sides (pro- and anti-nuclearists) have some thinking to do:

(i) Nuclear technology is not 100% safe, and nobody has ever, or should have, expected it to be so. After all, there are more losses of lives per year in a coal mine than there are (or were, until now) for radiation exposure;
(ii) The siting of nuclear plants must be more accurately selected: if the area is on a seismic fault, additional measures must be taken at design phase to make sure that even when the "maximum harm, minimum probability" event takes place, there is no radioactive leakage into the environment. Notice that this is not an unrealistic demand: a complete redesign of the containment is probably needed, but would not affect the overall siting conditions. Some

Colleagues who reviewed this Editorial criticised the above statement, reminding me of the extremely long and difficult negotiations with local authorities and citizens' committees that make construction times unacceptably long for the industry: my response on this point is that the monetary cost of such delays ought to be compared with the "social cost" of the losses of lives and infrastructures... and the conclusions are quite obvious;

(iii) All the four reactors (originally of General Electric design) were equipped with diesel engines dedicated to their emergency cooling. The necessary cooling of the diesel themselves was assured by pumping the sea water with external loops lodged within protections able to resist to a tsunami wave of 6.5 meters height. A ten meters tsunami could perhaps not have been foreseen in the '50es, but why was no additional measure taken after the Sumatra disaster of December 2004? Once the essential cooling, and particularly the batteries, had failed, all the consequences of the following days were unavoidable: this is a "lesson" to be learned for nuclear designers;

(iv) Same remark applies to the spent fuel pools, which are cooled by pumps powered by the same diesels. The water in the pools requires a continuous secondary cooling which was no longer possible because of the diesel failures. So, all the water evaporated, the fuel superheated to 1100 C and the reaction of the zirconium of the fuel cladding with water vapour generated hydrogen which soon reached a critical concentration in the ambient air and exploded (Figure 1G), leading to a release of an aerosol of highly dangerous radionuclides (Iodium, I-131, Cesium Cs-137, and others) into the environment. The basic error was again to underestimate the height of the "worst case" tsunami wave;

(v) The cost assessment for future nuclear stations must be updated: it is very likely that when this is done, the cost of the generated kWh will no longer be competitive. The "next generations" are surely safer, but also more costly (in terms of €/kWh), and it is unlikely that licensing procedures will be simplified by the authorities as a consequence of the Fukushima accident. Some nuclear supporters have issued statements like "no major overhaul is necessary: it would suffice moving the emergency generators and their fuel tanks to a higher elevation": it appears though that some "cure" (major redesign, see point (viii) below) rather than "emergency fixes" is necessary. It is not realistic to think (or publicly say!) that the technology must be discarded, but it is rather clear that the nuclear electricity generation is not likely to increase its share of the market for many years to go;

(vi) Absolute priority ought to be given to increase the research investment in the next generation of nuclear reactors (the so-called III+ and IV generations), so that their technology may reach sufficient maturity in the shortest possible time (generation III+ is already pre-licensed in the US). The problem is that the evolution of the designs of nuclear power plants is a very complex and gradual process which requires huge efforts and time. Generation IV will be ready in the 2040's only through gradual improvements of the present reactors of the generation III+. Only countries that operate the present reactors have sufficient know-how and operational experience to design and build these new reactors. In this perspective, contrary to what is being said in these days, not a reduction or a halt, but additional funding of research into "safer" reactors would be necessary;

(vii) This editorial makes no reference to the possible effects on sea and land life, because experts unanimously agree that it is too early to make a decently documented statement on this issue (this is a "lesson" for anti-nuclearists!);

(viii) An analysis of the consequences of the accident suggest that absolute priority ought to be given to the development and implementation of pro-active measures that can ensure a minimum amount of refrigeration to the most critical areas of the plant: not only the core and its containment, but also the spent fuel pool. Another vital measure is that of avoiding losses of contaminated water and/or another material, "insulating" somehow the above-the-ground structures from below, to protect both the aquifer and the nearby natural water reservoirs (lakes, rivers, sea). There have been in the past some very credible proposals for "intrinsically safe reactors" that have never been taken too seriously either by the industry or by the regulatory agencies: perhaps it is time to reassess this issue (another "lesson to be learned" for nuclear supporters).

Figure 1. (**A**) Scheme of the Fukushima BWR reactors (adapted from [5]); (**B**) Power failure, cooling systems operating to a minimum or not at all; (**C**) Three fourth of the core exposed; Zr+steam reaction; H_2 & radionuclides aerosols into the dry well; (**D**) Atmospheric release of aerosols & H_2. H_2 explosion; (**E**) Reactor #2, H_2 explosion in the condensation chamber. Release of fission products, contamination of water in the chamber; (**F**) Reactors flooded; steam release into atmosphere; (**G**) Dry-out of the spent fuel pool. Core melt in air, large radioactive release.

(**A**)

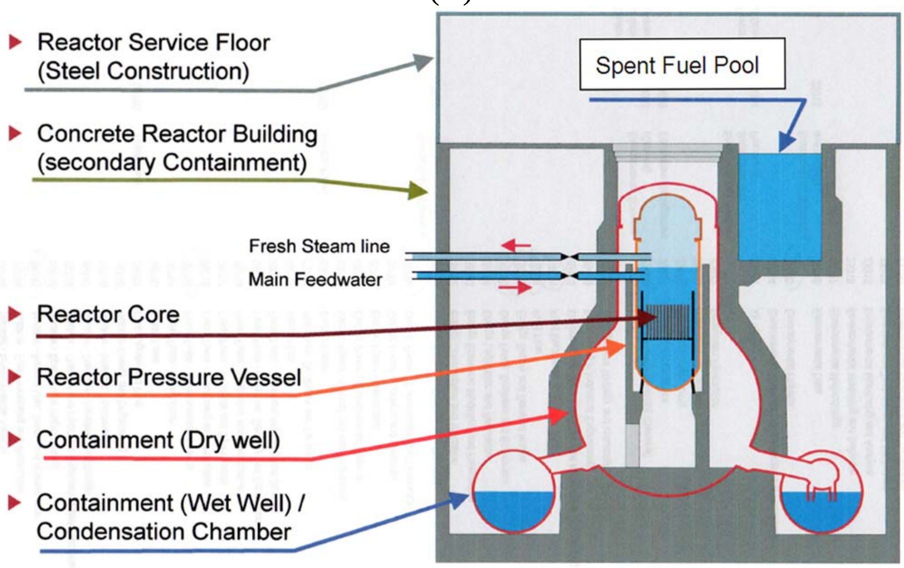
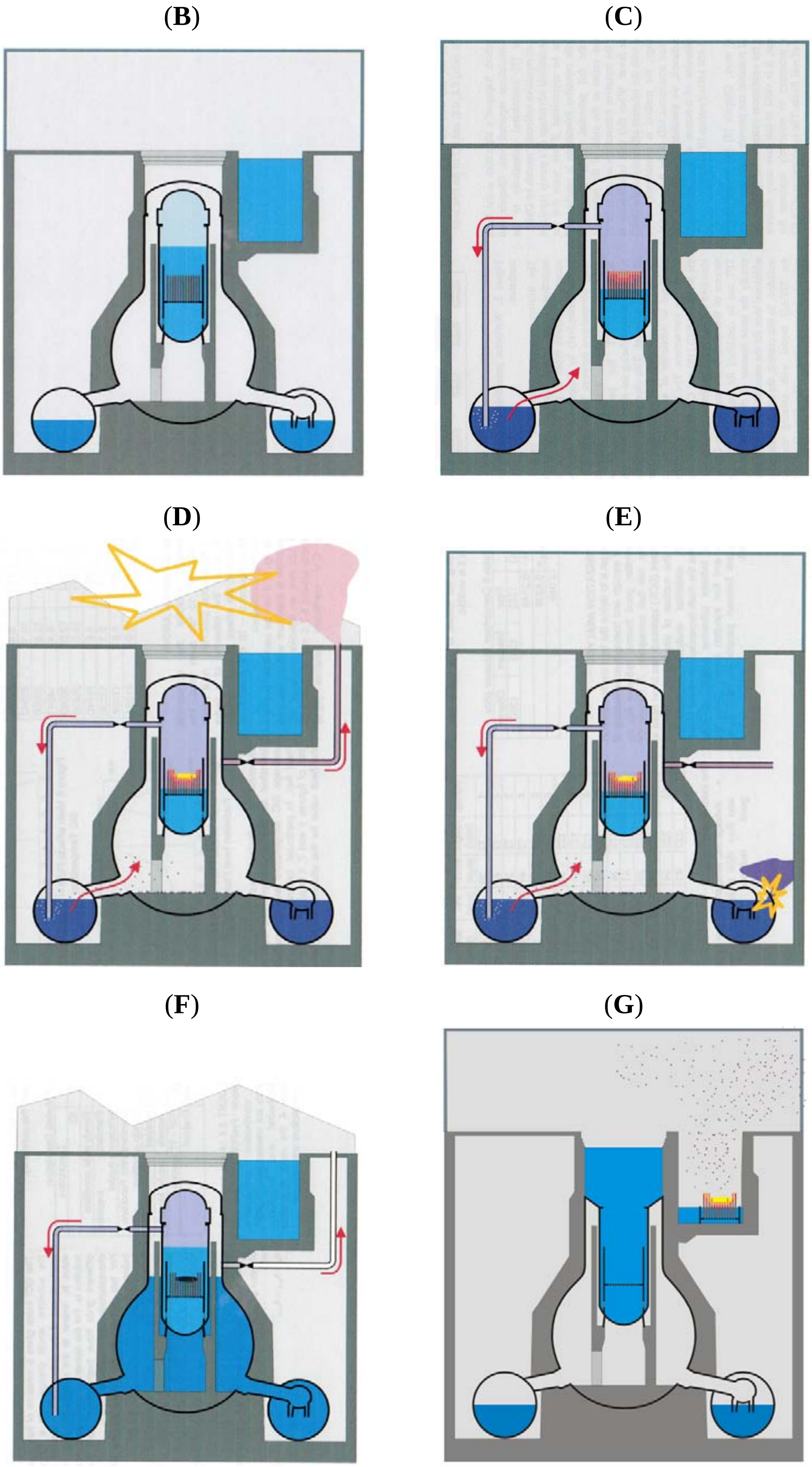


Figure 1. *Cont.*



At this point, the consequences for the continuous implementation of nuclear reactors are yet unknown: from the point of view of an energy engineer, it is to be hoped that the tragic accident leads to a better design of the next generation water reactors, and possibly to the development of an "intrinsically safe" nuclear fission technology that may spare us in the future such unbearable damage to our environment. Opponents of nuclear technology—which I am and remain!—would though be better advised not to use the Fukushima accident as an argument.

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